Independent Study Report
Brevard County, Florida
Shore Protection Project

Independent Coastal Expert Team

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Final Report
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Executive Summary

This study concludes that the Canaveral Harbor Federal Navigation Project has caused erosion damages to the shoreline of Brevard County over a distance of 10 to 15 miles south of Canaveral Harbor. These erosion damages have negatively impacted the Brevard County Shore Protection Project. This project has been constructed in two reaches, a 9.4 mile long North Reach immediately south of the harbor and a 3.4 mile long South Reach located more than 20 mile south of the harbor. Erosion damages from Canaveral Harbor have been confined mainly to the North Reach of the Shore Protection Project and to the region between the North and South Reaches. The South Reach has not been adversely impacted.

Despite prior beach fills in the North Reach, the volume of unmitigated erosion damage before construction of the North Reach Shore Protection Project in 2001 exceeded the amount of sand fill planned during the 50-year lifetime of that project. Three different estimates of unmitigated sand volume were obtained using historic shoreline data obtained from two different sources, including the US Army Corps of Engineers and from the State of Florida Department of Environmental Protection. Estimates of unmitigated erosion damage from Corps data ranged from 6.1 to 7.5 million cubic yards, with a mean value of 6.8 million cubic yards, while the State data suggested an unmitigated volume of 6.6 million cubic yards. These may be compared with a planned lifetime nourishment volume for the North Reach of 6.6 million cubic yards.

The conclusion, based on use of beach survey data from either the Corps of Engineers or the State of Florida, is that 100% of the beach fill in the North Reach can be considered as mitigation to offset prior unmitigated erosion damages from the harbor. Cost-sharing for the North Reach Shore Protection Project should therefore be adjusted to reflect a 100% federal responsibility. No erosion damages could be attributed to Canaveral Harbor in the South Reach of the Shore Protection Project, therefore cost-sharing for the South Reach should remain unchanged.

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Background

Section 310 of Public Law 106-53 directed the Secretary of the Army to retain the services of an independent coastal engineering expert to assess the damages to the Brevard County Shore Protection Project attributable to the Canaveral Harbor Federal Navigation Project. The Secretary was further directed by Congress to mitigate for these damages, with the costs of mitigation to be allocated to the Federal Navigation Project as Operation and Maintenance costs.

Study Timeline

An Independent Coastal Expert (ICE) Team initiated work on December 11, 2001 under a Scope of Services prepared by the U.S. Army Corps of Engineers Jacksonville District in cooperation with Olsen Associates, Inc., consultants representing the non-Federal sponsor, Brevard County.

The ICE Team met in Jacksonville, FL with representatives of the US Army Corps of Engineers (USACE) and Brevard County, on January 13-15, 2002 to initiate the independent study. At that meeting, representatives of the Government and the County made presentations to the ICE Team outlining their positions. Both parties also provided documents pertinent to the study. The ICE Team then toured the shoreline in the vicinity of Canaveral Harbor with representatives of the Government and the County.

A second meeting was held in Jacksonville on April 12, 2002, at which time the ICE Team presented initial findings and delivered a Preliminary Report. Given the accelerated time schedule between the first and second meetings, the Preliminary Report summarized work completed to date, as well as work still in progress as of April 2002. The intent of this report was to provide the Government and the County with a general sense of the ICE Team's study methods and initial findings. Review comments on the Preliminary Report were provided to the ICE team by the Government and the County through 21 June 2002.

A third meeting was held in Jacksonville on August 28, 2002, at which time the ICE Team presented final conclusions and delivered a Draft Report. Between April and August, the ICE Team had finished all outstanding analysis work from the Preliminary Report. Review comments from the Preliminary Report had been considered by the ICE Team and responses were incorporated into the Draft Report. Both the County and the Government prepared verbal comments on the Draft Report at the August 28 meeting. Subsequent written comments were received from both parties by September 18, 2002. These review comments were reviewed by the ICE Team and appropriate responses have been incorporated into this Final Report.

Objectives

There are three general objectives of the independent study. The first is to determine the amount of beach erosion along Brevard County, Florida, that is attributable to the Canaveral Harbor Federal Navigation Project. The second is to determine the amount of this erosion that has not been mitigated by prior Federal actions. The third objective is to determine the amount by which the Federal cost-share for the Brevard County Shore Protection Project should be increased to mitigate erosion damages associated with the Canaveral Harbor Project.

These broad objectives are defined more specifically in the Scope of Services, which is included at the end of this report in Appendix J. Specific objectives may be summarized as follows:

1. Identify the volume of erosion in Brevard County attributable to the Federal Navigation Project prior to and after January 1995 when sand bypassing of Canaveral Harbor was initiated.

2. Determine the extent to which this erosion is occurring within the two reaches of the Brevard County Shore Protection Project, where the North Reach extends from 0 to 9.4 miles south of Canaveral Inlet and the South Reach extends from 21.6 to 25 miles south of the inlet.

3. Identify the extent to which this erosion has been effectively mitigated by previous beach fill projects completed prior to and after January 1995.

4. Determine the outstanding erosion impact of the Navigation Project on the Shore Protection Project that is not being addressed through these mitigation measures.

5. Determine the portion of the Brevard County Shore Protection Project (percentage or volume of both past restoration and future periodic nourishment) that is associated with mitigation of outstanding inlet-related erosion impacts

6. Determine the extent to which future beach erosion will be mitigated through planned Operation and Maintenance (O&M) operations associated with the Federal Navigation Project, in which 156,000 (+/-10%) cubic yards of sand will be bypassed annually and placed within an area extending from the inlet 15,000 ft south.

7. Determine a new cost-sharing formula for the Brevard County Shore Protection Project that incorporates mitigation to address impacts of the Federal Navigation Project.

Technical Findings

General Approach

The impacts of Canaveral Harbor on adjacent shorelines are determined by comparing post-inlet beach processes to conditions that existed prior to harbor construction. This approach is consistent with that used in other USACE documents relating to Section 111 (Rivers and Harbor Act of 1968) impacts of navigation projects on adjacent shorelines. The approach used by the ICE Team was specifically patterned after the approach used by the USACE (2000) in the Ft. Pierce, FL Shore Protection Project, which was included in documents provided by the Government to the ICE Team. In that report, post-inlet erosion trends were compared to pre-inlet erosion trends. The inlet impacts were then defined by an increase in downdrift shoreline erosion over historic rates attributed to the navigation project.

The same approach has been used in the present study of the impacts of Canaveral Harbor. One unique aspect of Canaveral Harbor, however, is that the shoreline downdrift of the harbor was generally accreting prior to inlet construction. As a result, erosion impacts of Canaveral Harbor must be defined relative to pre-inlet accretion trends. We believe that this approach is both scientifically correct and technically consistent with other USCAE analyses of downdrift impacts. It is also appropriate from a policy standpoint, as it is probable that portions of the Brevard County Shore Protection Project would not have been required if Canaveral Harbor had not been built.

Large-scale Shoreline Behavior Prior to Inlet Construction

The findings of this study are based, in large part, on the question of whether the Brevard County shoreline would have eroded or accreted if Canaveral Harbor had not been built. This is, of course, impossible to determine precisely. However, historic shoreline positions are available for three time periods prior to inlet construction, extending back as far as the late 1870's. From these, it is possible to obtain pre-inlet shoreline erosion and accretion trends. These long-term trends in shoreline change can then be projected forward in time to predict expected future shoreline positions that would have occurred if the inlet had not been constructed. This projection is possible because the beach changes in Brevard County are controlled by large-scale geomorphic processes associated with the presence and migration of Cape Canaveral.

As shown in Appendix A, and as discussed further in Appendix D, shoreline data from 1878, 1929, and 1949 show that most of the Brevard County shoreline was either accretional or relatively stable (neither strongly eroding nor accreting) prior to inlet construction. The area immediately north of the inlet was strongly accretional, with shorelines advancing at rates of more than 10 feet per year. This strong accretion trend also existed south of the inlet location, where the shoreline advanced seaward at rates of 2 to 6 feet per year over a region extending about 8 miles south of the inlet location. This encompasses the North Reach of the Shore Protection Project. Accretion at rates of less than about 1 ft/yr then extended for another 8 to 12 miles. Farther south, in the South Reach of the Shore Protection Project, the historic shoreline data show a pattern of general stability with no significant trend of either erosion or accretion prior to inlet construction.

These patterns have been well recognized. In fact, they form the basis of most USACE project reports pertaining to Canaveral Harbor. For example, the USACE (1962) states that: "The shoreline in the general vicinity [of Canaveral Harbor] was an accreting shoreline prior to opening of the harbor entrance in 1951."

Shoreline change data following inlet construction show a clear modification of these trends. North of the inlet, beaches have accreted at a rate far exceeding the pre-inlet accretion rate. South of the inlet, beaches have shown a general reversal in the pre-inlet accretion trends, with net erosion following inlet construction. This erosion is most pronounced in the first 8 to 10 miles south of the inlet and is less significant further to the south.

We note that none of the documents provided to the ICE Team gives a physical explanation for the existence of, or longshore variation in, the shoreline accretion patterns that existed prior to inlet construction. In particular, none of the documents recognizes that the shoreline south of Cape Canaveral is a classic "crenulate bay," which is a curved shoreline shape formed by wave action that is modified by refraction and diffraction due to the presence of the Cape.

To more fully understand the natural pre-inlet system, we have modeled the pre-inlet Brevard County shoreline as a migrating crenulate bay. As shown in Appendix A, an analytical formulation of a crenulate bay was found to provide a very good fit of the historical data for the shape of the Brevard County shoreline south of Cape Canaveral. With the crenulate bay shape known, we then simulated future shoreline changes in Brevard County associated with continued southward migration of Cape Canaveral.

The results of this analysis suggest that the shoreline for a distance of 15 to 20 miles south of the inlet location would have remained accretional due to Cape migration if the inlet had not disrupted the natural processes. The shoreline for another 5 to 10 miles south of this would have been relatively stable with little net change expected due to Cape migration.

Based on the agreement between model results and the historical data, and given the significant reversal from accretion to erosion over much of Brevard County following inlet construction, it is clear that the inlet has influenced shoreline changes throughout the entire North Reach of the Shore Protection Project. Results are less conclusive for the South Reach. Both the crenulate bay model and the historic shoreline data suggest that the shoreline in the South Reach was neither strongly eroding nor accreting prior to inlet construction. While data suggests that there has been some erosion following harbor construction, it is not clear whether this has been due to the inlet or whether it has been caused by other processes, such as sea level rise or storm effects.

Sand Trapped in Canaveral Harbor Navigation Channel

Harbor dredging records were analyzed to determine the volume of beach-quality sand that enters the navigation channel by littoral processes. It is known that sand has historically entered the navigation channel from both the north and south, as sand has been transported through, over, or around both jetties. This sand is deposited in shoals that form on both the north and south sides of the Canaveral Harbor entrance channel. Most of this sand has been dredged and taken offshore for disposal representing a net loss of sediment from the beach system.

Details of our dredging analysis are given in Appendix B. Excluding construction-related dredging, maintenance dredging has averaged about 635,000 cy/yr (cubic yards per year), most of which is fine sediment not originating from adjacent beaches. In our analysis, we estimated the sand-sized fraction of the overall dredge material as a function of time, and corrected the dredge volumes for sand content. This analysis suggests that beach-quality sand has been dredged and removed from the inlet at an average rate of 218,000 cy/yr over a 45 year period.

This rate of beach sand accumulation in the navigation channel is corroborated by several other studies. Appendix B shows that other estimates for sand deposition in the navigation channel, from previous Corps studies and from others, have ranged from 167,000 to 243,000 cy/yr. Bodge (1994) delineated the shoal features in the navigation channel between 1985 and 1992 and found an accumulation of 213,000 cy/yr, which compares favorably with our rate of 218,000 cy/yr rate estimated from the longer-term dredging records corrected for sand content. .

As noted, sand in the navigation channel originates from beaches both north and south of the inlet. This is indicated, in part, by the formation of well-defined shoals on both the north and south sides of the navigation channel. Bodge (1994) found that approximately 90,000 cy/yr (or 42% of his 213,000 cy/yr total) of shoal formed along the north side of the channel due to sand bypassing the north jetty, while 123,000 cy/yr (or 58% of the total) accumulated on the south side due to sand passing the south jetty. An analysis of similar estimates from other reports, also in Appendix B, supports this 42%/58% split between accumulations on the north and south sides of the navigation channel. Applying these percentages to our estimate of 218,000 cy/yr of total sand accumulation, it appears that about 92,000 cy/yr originates from sand passing the north jetty, while 126,000 cy/yr originates from sand passing the south jetty.

The south jetty was raised and sand-tightened in 1995, and the northward loss of 126,000 cy/yr had been prevented for the past 7 years or so. Prior to that, however, it seems clear that a significant amount of sand was moving northward through the south jetty. In fact, our estimate of 126,000 cy/yr agrees well with the Corps' estimate of 129,000 cy/yr, which formed the justification for the sand tightening project, e.g. USACE (1992, Rev 1993). Because the net direction of longshore transport prior to inlet construction is known to have been from north to south, the inlet has induced a localized reversal of longshore transport immediately south of the inlet. This represents a distinct loss of sand from the beach system since it is dredged and disposed offshore.

Recent data suggests that sand has been impounding against the south jetty and is now moving around the south jetty once again. Olsen Associates (2000) showed that an accretion fillet is forming against the sand-tightened south jetty due to the south-to-north longshore sediment transport. This resulted in a seaward advance of the shoreline and of the 5, 10, and 15 foot depth contours in a region extending 3,000 ft or more south of the south jetty. Sand accumulation rates were found to be 129,900 cy/yr. Harbor dredging in 2002 removed approximately 30,000 cy of sediment from the navigation channel near the seaward end of the south jetty (according to anecdotal evidence presented at the third project meeting), material that apparently was moved around the sand-tightened south jetty by wave action.

Beaches Updrift (North) of Canaveral Harbor

A key goal of our analysis has been to determine the net north-to-south longshore sediment transport rate at the inlet location prior to inlet construction. This is central to this study because it represents the ideal or desired sand bypassing rate required to offset the blockage of littoral drift by the inlet. The total volumetric impact of the inlet since construction can then be estimated, in part, by multiplying the pre-inlet transport rate times the number of years elapsed since construction.

Our analysis, in Appendix C, suggests that the average pre-inlet net longshore transport rate at the inlet location was approximately 210,000 cy/yr moving in a southward direction. Since inlet construction, this sand has been partially blocked by the north jetty, depositing on the updrift beaches, and partially intercepted by the deep navigation channel.

The transport rate of 210,000 cy/yr at the inlet location prior to inlet construction was estimated from a consideration of volumetric deposition rates on the north side of the navigation channel and updrift (north) of the inlet. As illustrated in Appendix C, the longshore transport rate at a given distance updrift of the inlet, can be estimated from the transport rate past the north jetty, and from the deposition or impoundment rate between the jetty and that updrift location.

Careful consideration of the updrift distance is critical in this analysis. In the documents provided by the Government and by Brevard County, impoundment volumes and longshore transport rates north of the inlet differ significantly from one report to another. However, this is to be expected due to the strong local variations in longshore transport rates that occur south of Cape Canaveral. Consistent with the crenulate bay analysis presented earlier, southerly longshore transport rates must vary significantly within just a few miles, and an estimate developed at one location does not represent transport rates elsewhere even just one or two miles away.

A re-analysis of longshore transport rates suggests that many earlier estimates are remarkably consistent when analyzed in terms of their distance updrift from the inlet and in terms of the time since inlet construction. This is shown in Appendix C, Figure C.5, which compiles transport rates for the first four years after jetty construction and from the long-term post-inlet period spanning 46 years after harbor construction. Results show that transport rates for both periods ranged from 350,000 to 400,000 cy/yr near Cape Canaveral, and decreased to about 90,000 cy/yr at the north jetty. Between these end point location, transport rates were highest in the four year, post-inlet period and have diminished over time since then. This is consistent with the formation of the updrift accretion filet that extended only 2,000 ft north of the inlet in the first 4 years following construction, but which has advanced more than 13,000 ft updrift over the 46-year period.

Figure C.5 also shows our estimate of longshore transport rates for the pre-inlet period. These were obtained by matching pre-inlet transport rates to the transport rates for the first 4 years after inlet construction (when the inlet effects were limited to the first 2,000 ft from the inlet). Results indicate that the natural longshore transport rate at the inlet location, prior to inlet construction, was about 210,000 cy/yr. Uncertainties in estimates of transport rates are about ∀30,000 cy or so, and pre-inlet transport rates at the inlet location could vary from about 180,000 cy/yr to about 240,000 cy/yr.

Beaches Downdrift (South) of Canaveral Harbor

Given the impoundment effects of the inlet as documented above, there is a large deficit of sand south of the inlet. This deficit should be evident in historic shoreline data as a reversal of the pre-inlet accretion trend with subsequent shoreline erosion extending for some distance south of the harbor. As a result, we have evaluated historic data for both shoreline changes and for beach volume changes for the shoreline between Canaveral Harbor and Sebastian Inlet. A complete description of our analysis is presented in Appendix D.

We analyzed historic data from various sources, including beach profile data obtained from the USACE, historic shoreline data obtained from the USACE, and historic shoreline data obtained from the Florida Department of Environmental Protection (FDEP). The historic shoreline data provided by the USACE were obtained electronically on September 12, 2002, near the end of the ICE study. This data was provided by Applied Coastal Engineering and Research (Mark Byrnes, personal communication) based on a re-analysis of historic shoreline maps to correct some errors in earlier USACE historic shoreline data. The revised USACE shoreline data was found to be in very good agreement with the FDEP shoreline data and similar conclusions can be drawn from either data set as will be shown.

The historic shoreline data includes three shoreline surveys conducted prior to inlet construction, and 15 historic shoreline surveys following harbor construction. From this data, we adopted the 1949 shoreline as a baseline representative of the pre-inlet shoreline location. This is consistent with recent analyses by Kraus et al (1999) and by Bodge (1998) for the Government and Brevard County respectively.

In order to establish pre-inlet shoreline change trends, we considered historic shoreline changes from the earliest survey, in 1878, to two subsequent surveys in 1929 and 1949. In the northern portion of the study area, extending across most of the North Reach of the Shore Protection Project, shoreline change rates from the two survey periods are in good agreement. Both clearly show pre-inlet accretion. In the southern portions of the study area, extending across the South Reach of the Shore Protection Project, the two survey periods showed somewhat different behavior, with erosion rates of about 1 ft/yr from 1878 to 1929, but with accretion rates of about 1 ft/yr from 1878 to 1949. The 20-year period from the late 1920's to the late 1940's was therefore a period of strong accretion.

Given this natural variability in shoreline change rates from the two survey periods (1878-1929 and 1878-1949), and given the limited data available, we determined that the most representative pre-inlet shoreline change rates should be based on an average of the rates from the two survey periods. In the North Reach, the average pre-inlet trend was strong accretion. In the South Reach, the average pre-inlet trend shows no net change in shoreline location, in agreement with results from our crenulate bay analysis. These results are shown in Figure D.4. This figure also shows that the averaged pre-inlet shoreline change rates obtained from the revised USACE shoreline data and from the FDEP shoreline data are nearly identical.

A review of historic shorelines after inlet construction suggests that there were two distinct time periods of shoreline change. These include: (1) a period from the construction of the harbor until the mid-1970's when the shoreline responded without the influence of beach fill activity and (2) a period from the mid-1970's to the present when shoreline change has been strongly influenced by various beach fills and sand bypassing projects.

In the period prior to the mid-1970's, the shoreline showed dramatic changes due to inlet effects extending across the entire North Reach of the Shore Protection Project. These changes included a near-inlet zone of severe erosion extending about 1.5 to 2 miles south of the inlet, a zone of shoreline accretion extending for another 4 miles south, and then a zone of less severe but widespread erosion extending for another 4 to 8 miles south. The downdrift extent of the inlet-induced erosion zone therefore extends 10 to 14 miles south of the harbor, incorporating the entire North Reach of the Brevard County Shore Protection Project and Patrick Air Force Base.

Farther south, from Patrick Air Force Base to near Sebastian Inlet, the historic data shows an average erosion of the shoreline of about 25 feet between 1949 and 1972. Erosion in this region does not show signs of a progressive southerly advance as one would expect if it were related to downdrift effects of Canaveral Harbor. Instead, this erosion occurred almost uniformly across almost 25 miles of shoreline. It therefore appears to have been caused by other natural processes, such as sea level rise or beach profile adjustment to storm activity. The exact cause of this shoreline retreat is, however, not known.

A key finding is that the zone of downdrift impacts from Canaveral Harbor includes regions of both erosion and accretion. The report by Kraus et al (1999), and the Government presentation to the ICE Team at the 13 January meeting, both claim that the downdrift impacts extend no farther than about 1.5 miles because a zone of accretion is then encountered. The historic shoreline data clearly refute this, however, and show a distinct zone of erosion extending beyond this zone of accretion to a distance of 10 to 14 miles south of the harbor.

As discussed in Appendix D, this same pattern has been observed by Galgano (1998) at most other tidal inlets on the U.S. east coast. Galgano notes that the "arc of erosion" downdrift from tidal inlets includes three regions: (1) a near-inlet zone of dramatic erosion, (2) an intermediate region of relative stability, and (3) a far-inlet region of less dramatic but far-reaching erosion. Galgano presents empirical results from other inlets that, when applied to Canaveral Harbor, suggest that the downdrift extent of the "arc of erosion" can be expected to range from 9 to 14 miles south of the harbor. This is in agreement with our direct observations from the data and supports our conclusion that the inlet impacts extend over the entire North Reach, but not the South Reach, of the Shore Protection Project.

Review comments provided by the Government on September 18, 2002 indicate a significant change in the Government position on this issue. These comments state that, using older USACE shoreline data, the zone of downdrift impacts, including erosion and accretion, extended 6.9 miles (36,500 ft) south of the inlet. This distance increased to 12.2 miles south of the inlet (in 1996) based on use of the revised USACE shoreline data. As a result, there appears to be good agreement now between our findings and those of the Government reviewers.

From the mid 1970's to 2001, the placement of about 6.5 million cy of beach fill on the beach south of the inlet, has had a demonstrably beneficial effect. Data in Appendix D shows that the 1974 fill, placed within the first 2 miles south of the inlet, spread southward over time and produced a measurable advance in the shoreline as far south as Patrick Air Force Base by 1993. More sand was placed near the inlet in sand bypassing events in 1995 and 1998 and these have partially stabilized this region. At the same time, however, the shoreline of Cocoa Beach and Patrick Air Force Base showed additional erosion by 1997 and 2000, indicating that the erosive effects of the inlet were re-established following a period of beneficial effects from the 1974 fill.

Farther south, from Patrick Air Force Base through the South Reach of the Shore Protection project, shoreline changes were generally negligible after 1972. Most areas were very stable, while some areas showed minor erosion and accretion. Anecdotal reports and photographs from County officials suggest a stronger erosion trend in this area, at times severe enough to cause significant property loss. We believe that this erosion has been mostly related to storm impacts which have eroded the upper beach, backshore, and dune. The historic shoreline data, which track changes in the high water line and which reflect long-term shoreline changes, do not show these erosion effects.

We quantified the variability in shoreline location across the entire study region by computing the standard deviation of shoreline changes based on all of the post-inlet beach surveys available. Results, in Appendix D, show that beach changes in the Mid and South Reaches of the Shore Protection Project are very small in comparison to those in the North Reach. A clear reduction in standard deviation of shoreline change occurs between 10 and 14 miles south of Canaveral Harbor, lending further evidence that this is the downdrift extent of direct inlet impacts.

As noted, Government review comments from September 18, 2002 now indicate general agreement with our findings. The zone of downdrift impacts determined by independent analysis in the Government review extends 12.2 miles south of the inlet. This extends across the North Reach and also across most of Patrick Air Force Base.

One-Line Model for the Shoreline Changes Caused by the Inlet

In addition to direct analysis of shoreline change data, we have also modeled the shoreline changes caused by Canaveral Harbor using a simple one-line analytical model for shoreline change. The Scope of Services for the ICE study prevented our running more sophisticated and widely-accepted numerical models, such as the Corps' GENESIS model. As a result, we restricted our modeling efforts to simplified analytical models that could be implemented easily but that are based on the same underlying theory as the GENESIS model. While our analytical model is highly simplified, it provides an indication of the limits of downdrift impacts based on fundamental physical principles associated with the disruption of natural longshore sediment transport by Canaveral Harbor.

One earlier study, by Walton (1995), utilized a one-line shoreline model to predict the shoreline changes caused by the inlet. Walton found that the interception of the longshore sand transport by the inlet created erosion of the shoreline for 12 miles to the south. However, his model assumed that the jetties were sand tight, allowing no sand into the inlet, and he assumed that the transport rate was uniform on up and downdrift shorelines. In Appendix E, we provide an improved model that allows the sand to pass through and around the north and south jetties of the inlet at different rates, and that allows a net gradient to exist in the transport rate from updrift to downdrift. Our new model also shows that the erosion induced by the inlet extends for many miles south of the inlet - in our case somewhat less than Walton's results but still extending for about 8 to 9 miles.

Use of a one-line model with sand transport into the inlet explains some of the unusual behavior of the Canaveral Harbor inlet. For example, prior to placement of beach fill, there was no impoundment fillet against the south jetty. The model shows that this is the result of a significant amount of sand moving northward into the inlet through the porous south jetty resulting in a re-alignment of the shoreline opposite to that which would occur if sand were stopped or impounded against the south jetty. The model also shows that the erosion south of the inlet due to southward sediment transport is augmented by the loss of material northward into the inlet. The inlet therefore induces a local reversal in the net littoral drift towards the inlet; model results indicate that this occurs one to two miles south of the inlet.

The reversal of littoral drift direction south of the inlet has been a problem with the prior placement of beach fills. Our results indicate that a large portion of the fill sand placed prior to 1995 was transported directly back into the inlet to be dredged again. The sand tightening of the south jetty in 1995 has reduced the loss of material into the inlet. However, beach fills need to be placed further south (a mile or more) to ensure that the sand does not end up back in the navigational channel and does, in fact, nourish the beach to the south.

Sand Volume Change South of Inlet

An analysis of sand volume changes downdrift of Canaveral Harbor is included in Appendix F. Despite the abundance of shoreline change data for Brevard County, few reliable measurements of beach volume change exist downdrift of Canaveral Harbor.

Based on an analysis of the USACE beach profile data, and based on an analysis of published volume computations, several problems have been uncovered by the ICE Team which, unfortunately, requires us to discount most direct measurements of beach volume change. Two major problems exist. The first is the lack of sufficient spatial and temporal resolution in beach profiles. In particular, most of the beach profile surveys extended only a few miles south of the inlet and did not cover the entire 10 to 15 mile length of shoreline where downdrift impacts are expected.

A more significant problem is that the beach profiles, which form the basis of the volume estimates, show large changes seaward of the assumed depth of closure (a depth beyond which water is too deep for significant wave-induced changes in the beach shape). In published studies, the depth of closure for Brevard County has been assumed to range from -16 ft NGVD to -20 ft NGVD. A critical problem exists with Brevard County beach profiles, as they show very large vertical offsets of 2 to 5 feet in depths ranging from -20 to -30 ft NGVD. Such large elevation differences at these depths (with associated large volume changes) invalidate most published estimates of downdrift erosion volumes. The lack of closure seen in the Brevard County beach profiles may be due to survey error, or may be due to some real (and as yet unexplained) physical process. In either event, volumes computed from beach profiles cannot be used to produce meaningful estimates of beach volume change associated with inlet impacts.

Because of these problems, we have inferred sand volume change from the historic shoreline changes documented in Appendix D. We have adopted a conversion factor of 0.92 cy of volume change per foot of shoreline change per foot alongshore, to relate shoreline change to volume change as recommended by Bodge (1998). Appendix F shows that within the first 2 miles of the inlet, this method of inferring volume change agrees very well with direct volume measurements. Beyond this distance, we rely on shoreline data as an indicator of volume change. This approach is not ideal, but the limitations in the data dictate this method of computing volume change.

In Appendix F, we have computed cumulative volume changes south of Canaveral Harbor from 1949 to 1972, 1986, and 1997 based on historic shorelines from these dates. These volume changes represent the actual or measurable beach erosion caused by the inlet. We also projected pre-inlet shoreline change rates forward in time to these same dates to estimate the cumulative sand volume change expected if the inlet had not been constructed. These represent the "unrealized" or "foregone" accretion that was prevented by inlet construction. The total volumetric impact of the inlet is then based on the difference of these two volumes.

We have then undertaken two different methods of analyzing the downdrift volumetric change data. In the first, we compute the total volumetric impact of the inlet associated with blockage and trapping of longshore sediment transport, and we then compare this to the impacts computed from downdrift shoreline changes across the entire study area. This yields an estimate for both the total volumetric impact and for its maximum downdrift extent. In the second method, we adopt a procedure recommended by the Government in their review comments from 21 June 2002 and 18 September 2002. This method entails computing downdrift impacts directly from the shoreline change data only in the North Reach over the first 9.4 miles south of the inlet.

Applying the first analysis method, we compared measured downdrift impacts to those expected from blockage/trapping by the inlet. These expected impacts include a loss of 336,000 cy/yr prior to 1995, and 210,000 cy/yr after the 1995 sand tightening of the south jetty. From these, we predict a total downdrift impact of 6.05 M cy, 10.75 M cy, and 14.2 M cy by 1972, 1986, and 1997 respectively. Of these impact volumes, about 50% are in the form of actual or measurable erosion while the other 50% are in the form of "unrealized" or "foregone" accretion that never occurred. When prior beach fill is considered, the unmitigated impacts of the harbor are found to be 6.05 M cy, 7.16 M cy, and 8.98 M cy for 1972, 1986, and 1997. Since 1972, beach fill has therefore offset only about one-third of the total downdrift impacts.

An important result of this analysis method is that the downdrift impacts of Canaveral Harbor extend between 13 and 15 miles south of the inlet. The volumetric impacts listed above were found to occur over a distance of 13 miles south of the inlet in 1972, and over a distance of 14.8 miles)in 1986 and 1997. Based on these results, the downdrift impacts of Canaveral Harbor encompass the entire North Reach and all of Patrick AFB. Impacts for 1986 and 1997 then extend a short distance into the Mid Reach of the Shore Protection Project. As of 1997, volumetric impacts did not extend to the South Reach of the Shore Protection Project.

Applying the Government's method of analysis, as suggested by the Government review comments, we can use observed shoreline changes to directly estimate the unmitigated volumetric impacts that have occurred in the North Reach alone. As shown in Appendix F, we used the FDEP historic shoreline data and computed the unmitigated impacts in the North Reach of 5.19 Mcy, 5.29 Mcy, and 7.02 Mcy in 1972, 1986, and 1997 respectively. These values are less than those in the above paragraph (6.05 Mcy, 7.16 Mcy, and 8.98 Mcy for 1972, 1986, and 1997) because total inlet impacts extend farther south well beyond the limits of the North Reach of the Shore Protection Project.

Based on the volumetric impacts above, unmitigated impact volumes in the North Reach were equal to 86%, 74%, and 78% of the total downdrift impact volumes in 1972, 1986, and 1997 respectively. On average, unmitigated impacts in the North Reach equal 79% of the total unmitigated impacts downdrift of Canaveral Harbor. The remaining 21% occur mostly in Patrick AFB and to a lesser extent in the Mid Reach of the Shore Protection Project.

We repeated portions of this analysis using the revised USACE shoreline data provided to us by Applied Coastal Engineering and Research on September 12, 2002. Our results using FDEP data for 1997 can then be compared directly to the revised USACE data from 1996, the USACE shoreline survey closest to the 1997 FDEP survey. As shown above, and in Appendix F, the FDEP data gives an unmitigated impact of 7.02 Mcy in 1997. Applying similar analysis methods to the revised USACE data gives an unmitigated impact of 7.74 Mcy in 1996. These results are in excellent agreement, with those obtained from the revised USACE data being about 10% larger than obtained with the FDEP shoreline data.

Sediment Budget

We have constructed sediment budgets for the area between Cape Canaveral and Sebastian Inlet for periods before and after inlet construction. These are shown in Appendix G, along with longshore sediment transport rates computed for the area south of Canaveral Harbor.

The results in Appendix G provide a consistent description of pre- and post-inlet longshore sediment transport rates south of Canaveral Harbor. Pre-inlet rates of net longshore transport ranged from about 350,000 cy/yr at the Cape, to about 200,000 cy/yr at the inlet location, to about 75,000 cy/yr at Sebastian Inlet some 40 miles south of the harbor. Post inlet transport rates start again start at 350,000 cy/yr at the Cape and end at about 75,000 cy/yr at Sebastian Inlet. This result for Sebastian Inlet is reported to be a reasonable estimate based on information provided by Dr. William Dally (personal communication).

After inlet construction, the sediment budget indicates about 90,000 cy/yr of sand entering the inlet from the north side and about 60,000 cy/yr entering from the south side. A reversal in longshore transport is then found south of the inlet in the North Reach of the Shore Protection Project. The 60,000 cy/yr entering the inlet from the south is less than the 126,000 cy/yr in Appendix B. This may indicate the variability in the natural system or the inherent difficulties in comparing two disparate types of data, as the 60,000 cy/yr result was inferred from shoreline change whereas the 126,000 cy/yr was obtained from analysis of dredging records.

The important result of the sediment budget analysis, illustrated most clearly in Figure G.3, is that inlet impacts on longshore sediment transport rates (and sand volume change) extend southward for about 15 miles from the inlet. Pre- and post-inlet longshore transport rates differ considerably from the inlet to a point about 15 miles south, but agree remarkably from that point south to Sebastian Inlet. This result, a 15 mile extent of inlet impacts, is in good agreement with other findings in this report.

Role of Storms on Downdrift Erosion Impacts

The role of tropical storms has been suggested by Kraus et al (1999) and by Government review comments as being a key factor in the erosion observed south of Canaveral Harbor. The Kraus et al (1999) report suggested that, in litigation over the impacts of Canaveral Harbor on downdrift properties, storms caused between 42% and 100% of the net loss of beach sand volume and erosion of the dune face. Government review comments from September 18, 2002 also suggest that storms, and not the inlet, are responsible for erosion of the dunes and "coastal fast land" which includes street ends, parking lots, and lawns.

For the purposes of the ICE study, which is intended to resolve a dispute over the long-term extent of inlet impacts across Brevard County and not to litigate over damages to specific upland property, we believe that the role of storms is over-estimated and that the conclusions of the Kraus et al study do not apply when considering the long term (50 year) impact of Canaveral Harbor on downdrift beaches.

We agree with the hypothesis of the Kraus et al (1999) report that the erosion or accretion of the portion of the beach inundated by normal tides (i.e. the shoreline) is controlled by normal longshore transport, while the erosion of the upper beach and dune (above the normal high tides) is caused primarily by storms. This suggests that our approach, basing volumetric impacts on observed changes of the mean high water shoreline, should correctly reflect the long-term beach changes associated with longshore transport and inlet impacts.

We then disagree with other aspects of the Kraus et al. (1999) report. First, the role of beach recovery after storms was neglected in that report, a factor that is critical when discussing the net effects of storms on long-term shoreline changes. Second, and more importantly, the Kraus et al. (1999) report attributes any volume of material eroded from the dune and back beach as a permanent volume loss to the system. In reality, sand eroded from the upper beach during a storm is mostly retained in the active beach system. In the long-term, storms cause little or no net loss of sand volume.

Our view is supported by recent studies by Zhang et al. (2002) which show that severe storms only cause a temporary change in shoreline position but do not affect the long-term trend in shoreline erosion or accretion. As shown in Appendix D, shoreline data collected in Brevard County in the years before and after the severe Thanksgiving Day storm of 1984 show no evidence that the storm occurred. Despite the fact that the dunes and upper part of the beach were visibly and severely impacted, the storm caused no net long-term change in shoreline (mean high water) position in Brevard County.

Beach Fill South of Inlet

Prior mitigation actions are analyzed in Appendix H, which tabulates prior beach fill and sand bypassing volumes. Reported volumes of sand placed on the beach south of Canaveral Harbor differ somewhat among the various reports reviewed as part of this study. We have tried to rectify some of the discrepancies but could not resolve all of them. As a result, we have adopted values that are most widely corroborated by several different sources.

Two other issues had to be resolved regarding the effectiveness of past fills. First, it was not clear how effective the underwater near-shore disposals placed at Cocoa Beach have been in returning sand to the active beach. The Corps claims that these fills are fully effective while Bodge (1998) claims that they are only partly effective because they were placed in water too deep to allow full landward movement of the sand. Based on a review of beach profile data, we concur with Bodge and have assigned only partial effectiveness to these fills. Second, it was not clear to what extent beach fills at Patrick Air Force Base should be included as effective mitigation. On this point we agree with the Government position. Our finding is that these fills, while not placed by the Corps, represent a very real form of mitigation to beaches extending from Patrick AFB southward. As a result, these fills should be counted as prior mitigation for the beaches of Brevard County.

Our resulting tabulation of effective fills is listed in Table 1. This suggests a total of 4,267,000 cy of fill were placed prior to 1995, a total of 6,497,000 cy were placed prior to 2001, and 11,182,000 cy have been placed as of 2002. Most of this, about 73 %, was placed in the North Reach of the Shore Protection Project, while 10% was placed on Patrick AFB, and 17% was placed in the South Reach of the Shore Protection Project.

It is noted that portions of these beach fills were cost-shared between the USACE and non-federal sponsors including the State of Florida, Brevard County, and the Canaveral Port Authority. While review comments from the County suggested that we itemize these prior payments, we disagree and believe that we should simply note the existence of the prior cost-sharing here for the record.

Table 1.
Beach Nourishment and Sand Bypassing Volumes.
In units of cubic yards.

Location	Before 1995	1995 to 2001	2002	TOTAL	%
North Reach	3,347,000	1,980,000	2,798,000	8,125,000	73%
Patrick AFB	380,000	250,000	541,000	1,171,000	10%
South Reach	540,000	0	1,346,000	1,886,000	17%
TOTAL	4,267,000 (38%)	2,230,000 (20%)	4,685,000 (42%)	11,182,000 100%	100%

Downdrift Sand Deficit and Past Mitigation

The total deficit of sand on downdrift beaches was calculated from: (1) the net southward longshore transport rate at the inlet site prior to its opening of 210,000 cy/yr which has been blocked since inlet construction and (2) the net northward transport rate of 126,000 cy/yr moving into the inlet from the south prior to the 1995 sand tightening of the south jetty.

For the period prior to 1995, this suggests that the volumetric impact rate for Canaveral Harbor on downdrift beaches was 336,000 cy/yr. The impact after 1995 is less due to sand tightening of the south jetty and is estimated as 210,000 cy/yr. As the south jetty fills with sand and some bypassing is again initiated, the future downdrift deficit could again exceed 210,000 cy/yr.

Cumulative inlet impacts on downdrift beaches can be computed by multiplying the above impact rates by the time period of interest, as shown in Table 2. We have adopted 1954 as the basis year for these computations, based on the completion of the harbor jetties in that year. Some impacts also occurred between the initial cut of the inlet in 1951 and the stabilization with jetties in 1954, but we have not included these in our computations.

Following the directive in the Scope of Services, we have computed harbor impacts from 1954 until 1995. This corresponds to the date at which sand bypassing was initiated. Impacts have also been computed through 2001, prior to the Brevard County Shore Protection Project, and 2002, after completion of the Brevard County Shore Protection Project.

From 1954 to 1995, prior to the initiation of sand bypassing, the total harbor impact is estimated as 336,000 cy/yr × 41 yrs (1954 to 1995) for a total impact of 13,776,000 cy. As shown earlier, this impact occurs in the North Reach and in Patrick AFB. In Table 2, the outstanding or unmitigated downdrift impact in 1995 can be obtained by subtracting the effective beach fill volume for these two regions of 3,727,000 cy from the total downdrift impact (excluding the 540,000 cy of fill placed on the South Reach in 1980). This gives an outstanding mitigation requirement of 10,049,000 cy in 1995.

From 1954 to 2001, prior to the recent nourishment project, the total harbor impact is estimated as 336,000 cy/yr × 41 yrs (1954 to 1995) plus 210,000 cy/yr x 6 yrs (1996 to 2001) for a total impact of 15,036,000 cy. This again is estimated to have been lost from the North Reach and from Patrick AFB. As shown in Table 2, the outstanding or unmitigated downdrift impact prior to the Shore Protection Project in 2001 can be obtained by subtracting the effective beach fill volume for these regions of 5,957,000 cy from the total downdrift impact, giving an outstanding mitigation requirement of 9,079,000 cy.

Following the recent nourishment project, using 2002 as a reference date, the total impact is estimated as 15,246,000 cy. It is interesting that this volume is comparable to, though somewhat smaller than, the total impacts estimated for the harbor in the 1962 USACE Sand Bypassing Study, of 17.5 Mcy in 50 years. The effective fill volume placed in the zone of erosion, i.e. in the North Reach and Patrick AFB, is 9,296,000 cy as of 2002. The remaining unmitigated volume deficit, after completion of the initial fill in the Brevard County Shore Protection Project, is 5,950,000 cy. This deficit would extend some 10 to 15 miles south of the inlet.

As discussed in Appendix F, most of the unmitigated impacts given in Table 2 are in the form of "unrealized accretion" that was prevented from occurring by construction of Canaveral Harbor. Without beach fill, downdrift impacts are about 50% "unrealized accretion" and 50% actual erosion. With the beach fill and sand bypassing, approximately 80% of the unmitigated impacts were in the form of "unrealized accretion" while about 20% were in the form of actual erosion relative to the pre-inlet shoreline.

There are several sources of uncertainty in the numbers reflected in Table 2. First, the pre-inlet transport rate at the inlet was estimated at 210,000 cy/yr with an uncertainty of about ∀30,000 cy/yr. Through 1995, this introduces an uncertainty in the total impact in Table 2 of ∀1.23 Mcy, suggesting that the unmitigated impact could range from 8.8 to 11.3 Mcy. Similarly, the range of unmitigated impacts is then 7.8 to 10.3 Mcy by 2001 and 4.7 to 7.1 Mcy by 2002. Other uncertainties exist in the estimated loss of sediment into the inlet from the south prior to sand tightening. The sediment budget suggested that this value may be as low as 60,000 cy/yr as opposed to the value of 126,000 cy/yr used in Table 2. As a result, over the 41 years prior to sand tightening, the impacts in Table 2 could be overestimated by as much as 2.7 Mcy.

Table 2
Summary of downdrift erosion impacts from 1954, based on the blockage or trapping of Canaveral Harbor.. These results extend throughout the entire zone impacted by Canaveral Harbor, which is estimated to be 10 to 15 miles south of the inlet.
In units of cubic yards.

	1995	**2001** Pre-project	**2002** Post-project
Total Impact	13,776,000	15,036,000	15,246,000
Prior Mitigation*	3,727,000	5,957,000	9,296,000
Unmitigated Impact	10,049,000	9,079,000	5,950,000

- for North Reach and Patrick AFB

An alternative method of computing unmitigated impacts was suggested in the Government review comments for this study. This method relies on a direct determination of volumetric impacts in a specific downdrift region based on historic shoreline positions and shoreline change rates. This approach uses the historic pre-inlet accretion rates to project the amount of expected volumetric accretion. It then uses measured shoreline change from pre-to post inlet period to estimate the actual erosion or accretion volume that has occurred to a specific date. The unmitigated impacts are then found from the differences of these two volumes.

These computations, following the Government recommended procedure, are carried out for the North Reach only, over a distance of 9.4 miles south of the inlet. For this calculation, we have used the revised USACE shoreline data provided by Applied Coastal Engineering and Research. Results of this analysis are presented in Table 3. Results are computed directly from the pre-inlet shoreline data in 1949, to 1996 and 2002. Also shown in Table 3 for comparison are results computed with the FDEP shoreline data for 1997, the last date for which FDEP survey data is available prior to the Shore Protection Project.

Results in Table 3 show that unmitigated impacts in the North Reach ranged from 7.02 to 7.74 Mcy in 1996 and 1997, based on use of either the revised USACE shoreline data or the State of Florida (FDEP) historic data respectively. These values agree to within about 10%. Following placement of the North Reach fill, the unmitigated impact in the North Reach after completion of the Shore Protection Project was 3.5 Mcy.

Table 3
Summary of inlet impacts in the North Reach within 9.4 miles south of the inlet, computed from 1949 with volumes inferred from shoreline change.
In units of cubic yards.

	1996	**1997** FDEP Data	**2002** Post-project
Unrealized accretion	5,850,000	6,640,000	7,216,000
Observed erosion or accretion	-1,890,000	380,000	3,730,000
Unmitigated Impact	7,740,000	7,020,000	3,480,000

While results in Table 2 and 3 provide a good indication of the unmitigated damages caused by Canaveral Harbor, they do not resolve the unmitigated damages for the time period of most interest, January 2001 prior to construction of the North Reach of the Shore Protection Project. In order to estimate unmitigated damages prior to the project, we can use values from Table 3, projecting forward in time from 1996 and 1997, and projecting backward in time from 2002. These projections require that beach fill volumes from the 1998 sand bypassing be subtracted from the 1996 and 1997 unmitigated volumes; and that fill volume from the 2001 Shore Protection Project be added to the 2002 unmitigated sand volume. In addition, we may make minor adjustments for the amount of erosion expected in the North Reach between the 1996-1997-2002 dates and the 2001 pre-construction date.

Results in Table 4 show that unmitigated impacts estimated from three different data sources are in fair agreement. Estimates obtained using the revised USACE shoreline data bracket the estimate obtained using the State of Florida (FDEP) data. Estimates obtained from the revised USACE data range from 6.11 Mcy to 7.52 Mcy, with a mean value of 6.81 Mcy. The estimate obtained using the FDEP data is 6.64 Mcy, which differs by only 3% from the average of the two USACE estimates.

It is noted that review comments from the Government from September 18, 2002 claim an unmitigated impact **after** the Shore Protection Project in 2002 of 2.5 M cy. Adjusting their value to represent pre-project conditions would result in an unmitigated volume similar to our estimates.

Table 4
Projections of unmitigated impacts in Jan 2001 prior to construction of
Brevard County Shore Protection Project.
In units of cubic yards.

	2001 **Projected forward from 1996 base year using revised USACE data**	**2001** **Projected forward from 1997 base year using FDEP data**	**2001** **Projected backward from 2002 base year using revised USACE data**
Base Year	1996	1997	2002
Data Source	USACE	FDEP	USACE
Unmitigated Impact in Base Year from Table 3	7,740,000	7,020,000	3,480,000
Correction for Beach Fill*	-1,035,000	-1,035,000	+2,798,000
Correction for erosion from base year **	819,000	655,000	-164,000
Unmitigated Impact In 2001	**7,524,000**	**6,640,000**	**6,114,000**

* Corrected for sand bypassing volume in 1998 (1.035 Mcy) or Brevard County Shore Protection Project in 2001-2002 (2.798 Mcy)

** Corrected for expected erosion impact due to harbor blockage of 210,000 cy/yr, of which 79% is assumed to erode from North Reach.

Impacts on Brevard County Shore Protection Project

The Water Resources Development Act of 1996 (WRDA, 1996) authorized construction of the Brevard County Shore Protection Project for the purpose of providing hurricane and storm damage reduction for two project reaches, the North Reach extending more than 9 miles south of the inlet, and the South Reach, covering about 3.4 miles and starting more than 20 miles south of the inlet. In total, the Shore Protection Project design specifies placement of 12,629,000 cy of sand. About one-third of this is to be placed in the initial fill and the remaining two-thirds are to be placed as periodic re-nourishment over a 44 year period. Of the 12,629,000 cy, 6,584,000 cy are to placed in the North Reach and 6,045,000 cy are to placed in the South Reach. Fill volumes in place as of 2002 are listed in Table 1.

Prior to construction of the Shore Protection Project, the total outstanding or unmitigated impact downdrift of Canaveral Harbor is given in Table 2 as 9,079,000 cy. Based on our findings, this impact occurs over 10 to 15 miles across the North Reach, Patrick Air Force Base, and possibly extending into the Mid-Reach of the Shore Protection Project. Within the North Reach alone, results in Table 4 suggest an unmitigated impact of 6,114,000 to 7,524,000 cy, with a mean value of 6,817,000 cy. This impact in the North Reach is therefore about 75% of the total downdrift impacts. The North Reach impact is about twice as large as the initial amount of fill actually placed in the North Reach in 2001-2002. It is also larger than the total life-time fill volume planned for the North Reach of 6,584,000 cy.

Based on these results, we find that the unmitigated damages to the North Reach of the Shore Protection Project, due to the Canaveral Harbor Navigation Project, represent 100% of the entire fill volume in the North Reach. In effect, all of the sand volume planned for the North Reach of the Shore Protection Project is required to offset previously unmitigated erosion damages caused by Canaveral Harbor. In fact, even after the 2002 Shore Protection Project, an unmitigated impact of about 3.5 M cy still remains.

As noted, most of the unmitigated damages to the North Reach are "unrealized" or "foregone" accretion that would have occurred if the inlet had not been constructed. It is our belief, based on analysis of pre-inlet shoreline accretion trends and post-inlet erosion trends in the North Reach, that beach nourishment may not have been required in this reach if the inlet had not been constructed. Without the inlet, beaches across the North Reach would have accreted significantly from 1951 to the present. Barring any seaward encroachment of development, we believe that properties would have been protected by a wide beach buffer that would have limited storm impacts, i.e. the justification for the nourishment project. We therefore believe that it is appropriate for the federal government to bear a 100% responsibility for the cost of beach fill in the North Reach.

Applying similar logic, we find no unmitigated damages in the South Reach of the Shore Protection Project due to Canaveral Harbor. As a result, 0% of the beach fill in the South Reach is required to offset erosion damages due to Canaveral Harbor. The justification for nourishment of the South Reach is storm damage reduction, and we believe that the storm damage potential in this area has not been worsened by the inlet. We therefore recommend that the existing cost-sharing arrangement should be retained in the South Reach.

Future Management Strategies

In our analysis, we compared pre- and post-inlet shoreline changes and concluded that the "unrealized accretion" was a distinct negative impact of the harbor. We documented in Table 3 that, even after placement of the initial fill from the recent Shore Protection Project, a significant amount (3.48 Mcy) of this "unrealized accretion" remains. This formed the basis for our finding of 100% federal responsibility for the North Reach of the Shore Protection Project.

Looking toward the future, one issue that remains is whether additional sand volume should be placed on the beach to make up for this remaining "unrealized accretion" deficit. Our conclusion is that the Corps of Engineers should **no**t be required to place the sand volume needed to make up for this "unrealized accretion." To do so at this time would result in a widening of the beaches beyond what is economically justified. Instead, a more practical, meaningful, and fair standard should simply be to guarantee the future maintenance of the beaches to the design specifications of the recent Shore Protection Project. This is a condition that was economically justified to prevent future storm damages to existing upland property in the North Reach.

We note, however, that survey data collected in 2002 suggest that the post-fill shoreline in portions of Cocoa Beach, and in a few other sub-reaches of the North Reach, is landward of the 1949 pre-inlet shoreline. While these shoreline positions may technically meet the design goals of the Shore Protection Project, we believe that it would be appropriate to ensure that the project shoreline is maintained seaward of the 1949 shoreline to ensure that beaches in this reach are brought back to their pre-inlet condition. This can probably be achieved by re-working the longshore distribution of beach fill within the North Reach.

Maintenance of the beach in the post-nourishment condition (or at the 1949 pre-inlet shoreline) can be achieved through a combination of periodic re-nourishment and sand bypassing. At present, the Corps' plan for re-nourishment includes placement of 516,000 cy every 6 yrs, for an average annual re-nourishment rate of 86,000 cy/yr. The plan for sand bypassing is for an average annual rate of 156,000 cy/yr, also on a six-year cycle with the placement of 936,000 cy every 6 yrs. It is our understanding that the bypassing is intended to offset losses associated with downdrift harbor impacts, while the re-nourishment is intended to offset end losses which are induced by the beach fill planform.

The proposed bypassing quantity of 156,000 cy/yr is less than the rate of 210,000 cy/yr (∀30,000 cy/yr) that we determined would be required to re-establish the transport conditions that prevailed prior to inlet construction. It is recognized, however, that bypassing the 210,000 cy/yr will lead to long-term accretion of the beaches south of Canaveral Harbor, as existed prior to inlet construction. This is a desirable goal from the standpoint of returning the system to its natural, i.e. pre-inlet, state. However, effective long-term maintenance of the beaches south of Canaveral Harbor can be achieved through bypassing less than 210,000 cy/yr.

It is our belief that the Corps' plan for bypassing 156,000 cy/yr, when coupled with the planned re-nourishment of 86,000 cy/yr, will be sufficient to maintain the beaches to the design specifications called for in the Shore Protection Project design.

We recommend that these values be adopted for the next sand bypassing event, presumably in 2004, and for the first re-nourishment, presumably in 2006. During this time, beaches in the North Reach should be carefully monitored to ensure maintenance of the shoreline positions and beach profile cross-sections specified in the Shore Protection Project design. If beaches across the North Reach show net accretion, then sand bypassing rates can be reduced somewhat. If beaches across the North Reach experience additional erosion, then sand bypassing rates should be raised to compensate for the observed erosion.

In addition, future bypassing should counter any loss of sand into the inlet around the south jetty. Since 1995, this loss of sand has been stopped by sand-tightening and lengthening of the south jetty. It is our understanding (based on anecdotal evidence) that material was recently dredged from the navigation channel near the tip of the south jetty. Once rates of maintenance dredging at this location are established, sand bypassing rates should be adjusted to equal 156,000 cy/yr **plus** the rate at which sand is moving northward around the south jetty into the harbor. This will require continued monitoring of the bathymetry in the navigation channel near the south jetty.

A final issue involves the placement location for the sand that is bypassed. Previous sand bypassing activities have placed sand very close to the inlet, generally within a mile of the inlet and in some cases adjacent to the south jetty. As long as the south jetty is sand tight, and as long as no sand moves around the south jetty into the navigation channel, such placement locations are generally acceptable. However, shoreline data documenting the spreading of the 1974 fill show that placement so close to inlet is not completely desirable for three reasons. First, some sand can get transported back into the inlet resulting in a partially ineffective fill. Second, spreading of the fill southward may take a considerable length of time to benefit eroding areas of Cocoa Beach. Third, after spreading this distance, the fill has only a marginal effect on beach width in the southern portions of the North Reach.

As a result, we recommend that sand placement near the inlet should be beyond the zone of reversal in longshore transport. This location should be determined through monitoring of downdrift beaches, but will likely be one or more miles to the south. In addition, a portion of the bypassed sand volume be placed on the beaches of Cocoa Beach, from 4 to 8 miles south of the inlet. The exact placement location should be determined through monitoring of the shoreline position. Previous beach fills in this area have been through near-shore disposal. Data suggests that these fills have not been fully effective, as some of the sand fill was placed outside the depth of closure. Future bypassing of sand to this area should use more conventional placement on the beach berm and foreshore.

Regions separating the North and South Reaches are not included in the Brevard County Shore Protection Project, but these areas have been subjected to inlet impacts. On Patrick Air Force Base, erosion has been mitigated by sand placed by the Air Force and by sand moving southward from the North Reach. The Mid Reach, located between Patrick AFB and the South Reach, has not yet been included in beach nourishment projects. This areas should be monitored to evaluate future beach change to insure that conditions there do not worsen. The recommended bypassing rate of 156,000 cy/yr coupled with the annual re-nourishment rate of 86,000 cy/yr should be sufficient to supply sand to these reaches; however, the bypassing rate needs to be increased or decreased if erosion or excessive accretion is observed.

Summary/Conclusion

As mandated by law, the Independent Coastal Expert Team examined the effects of Canaveral Harbor Federal Navigation Project on the Brevard County Shore Protection Project. The analysis involved reviewing prior works by the Corps of Engineers and Brevard County concerning the projects, analyzing field data, and, where necessary due to conflicting or missing evidence, conducting simple modeling efforts.

Our primary conclusion is that the North Reach of the Brevard County Shore Protection Project, located from 0 to 9.4 miles south of the Canaveral jetties, has been severely impacted by the construction of the navigation channel and harbor jetties. We conclude that there is a 100% federal responsibility in the North Reach. The South Reach has not been measurably affected and we conclude that there is no significant impact of the Federal Navigation Project on this reach of the Shore Protection Project.

These findings are based on several independent and corroborating pieces of evidence. These can be summarized as follows:

- Pre-project data, reinforced by our crenulate bay analysis, suggests the shoreline would have remained accretional for 15 to 20 miles south of the inlet; this trend was clearly reversed following construction of the harbor.

- Historic shoreline change data indicate a downdrift impact of 10 to 14 miles, and the standard deviation of observed shoreline change is dramatically reduced beginning 10 to 14 miles south of the inlet.

- The 1974 beach fill spread southward and produced measurable shoreline change (advance in this case) more than 10 miles south of the inlet.

- When the downdrift extent of erosion from Canaveral Inlet is compared to that at other tidal inlets, erosion impacts are expected to extend from 9 to 12 miles south of the inlet.

- The one-line model for shoreline change predicts downdrift impacts of 9 miles. Earlier modeling by Walton (1995) suggests a 12 mile zone of impact.

- An analysis of the volumetric impact suggests that the computed impact due to blockage/trapping of the inlet extends from 13 to 15 miles south of the inlet.

- A sediment budget, which includes a comparison of pre and post inlet longshore transport rates, suggest downdrift impacts of about 15 miles.

We note that Government review comments from September 18, 2002 now indicate a downdrift impact extending 12.2 miles south of the inlet. It is interesting that earlier Corps of Engineers studies suggested similar downdrift impacts distance. For example, the 1962 Sand Bypassing Study projected a similar impact. To quote the 1962 study, from Senate Document 140 (1962): "Data indicate that the recessive effect of the inlet on the shore to the south is steadily extending further southward , and during the project life [of the bypassing system] would affect about 10 miles of shoreline." This report even contains a figure showing the projected shoreline impact extending well beyond Cocoa Beach and into Patrick Air Force Base. These downdrift limits are almost exactly what we have found through our analysis.

The volumetric impact of the harbor has been computed in two different ways with consistent results. In the first method, we computed downdrift impacts over an unspecified distance based on the blockage or trapping of the inlet on longshore sediment transport. This indicated unmitigated impacts of over 9 Mcy prior to the 2001 beach fill. These impacts occur over a zone as far as 15 miles south of the inlet. In the second analysis method, we computed unmitigated impacts in the North Reach based on historic shoreline data. This method produced unmitigated impacts ranging from 6.1 to 7.5 Mcy prior to the 2001 project. Compared to the North Reach fill volume of 6.6 Mcy over the 50 year project life, and factoring in uncertainties, we conclude that 100 % of the fill is required to offset downdrift impacts in the North Reach.

Based on the evidence summarized above, and described in detail elsewhere in this report, we conclude that 100% of the unmitigated erosion damages in the North Reach of the Brevard County Shore Protection Project are attributable to the Federal Navigation Project. Accordingly, we recommend that cost sharing between the federal government and the local sponsor be re-apportioned to reflect a 100% federal responsibility in the North Reach. The data also suggest that the downdrift impacts of Canaveral Harbor do not extend significantly into the South Reach of the Shore Protection Project. Accordingly, we recommend that the cost sharing arrangements for the South Reach should remain unchanged.

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APPENDIX A
LARGE-SCALE SHORELINE BEHAVIOR

Data on shoreline changes prior to inlet construction, from the late 1870's to the late 1940's, show that most of the Brevard County shoreline was either accretional or relatively stable (neither strongly eroding nor accreting) prior to inlet construction. Figure A.1, with data taken from Kraus *et al.* (1999) and Bodge (1998), serves as an example. Additional details of pre-inlet shoreline changes are included in Appendix D.

From 1877 to 1948, the area immediately north of the inlet was strongly accretional, with shorelines advancing at rates on the order of 10 to 15 feet per year. This strong accretion trend continued south of the inlet location, where the shoreline advanced seaward at rates of 2 to 6 feet per year over a region extending about 8 miles (50,000 feet) south of the inlet location. This encompasses the North Reach of the Shore Protection Project. Farther south, in the South Reach of the Shore Protection Project located 115,000 to 135,000 south of the inlet, the data from 1877-1948 shows a pattern of general stability with slight accretion at about 1 foot per year, or less, in most areas

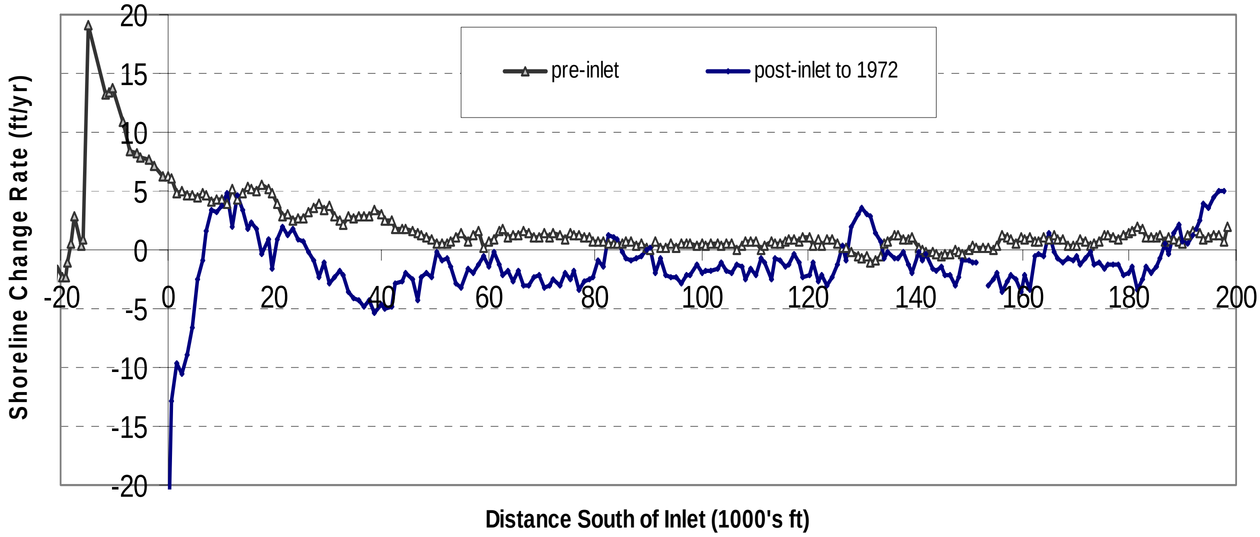


Figure A.1. Shoreline change data for pre-inlet and post-inlet periods.

Also shown in Figure A.1 are post-inlet shoreline changes south of the inlet from 1949 to 1972. These data include the effects of several beach fills, yet still show a net change from predominant accretion to predominant erosion south of the inlet. This effect is most pronounced within the first 50,000 ft of the inlet. A switch from accretion (or relative stability) to erosion also appears farther to the south, however, additional data analysis in Appendix D suggests that this may not be a direct result of Canaveral Harbor.

One issue of interest is whether the pre-inlet shoreline change trends suggested by the historic data would have continued if the inlet had not been built. Given the limited data available, we believe that this question can be best answered by considering a simple model for large-scale shoreline change. Such a model is suggested both by the observed pre-inlet shoreline changes and by the plan-form of the shoreline south of Cape Canaveral. Both of these suggest that the pre-inlet trends are consistent with a steady growth and migration of the tip of Cape Canaveral to the south or southeast over time. The Corps' (1989) report illustrates the history of the migration of the Cape southward between 1877 and 1929. It is well documented that the net direction of longshore sediment transport north of the Cape is southward. This continues to feed sand to the Cape and results in a long-term shifting of the shoreline further to the south.

The effects of this southward migration of the Cape can be modeled by first recognizing that the shoreline south of Cape Canaveral is a classic example of a crenulate bay (Yasso, 1966). A crenulate bay represents a stable plan-form shape downdrift of some sediment control feature, in this case the Cape. The stable shape has high curvature near the control feature and progressively less curvature farther away, a pattern that is evident in the Brevard County shoreline south of the Cape. For a migrating crenulate bay, longshore transport of sand is not uniform along the length of the bay shoreline. In this case, longshore transport decreases with distance south from the Cape, a factor not recognized in previously published reports.

Yasso presented a formula that quantifies the general shape of equilibrium crenulate bay planforms. This formula has been fitted to the shoreline south of the Cape to obtain a simple analytical representation for the expected long-term shoreline shape. There are other theoretical shapes that can be fit to the shoreline; for example, Silvester and Hsu (1991) suggest a parabolic curve and Moreno and Kraus (1999) suggest a hyperbolic tangent shape for engineering design. However, the results presented below are unchanged by alternative shapes. In fact, the same results could be attained by shifting the actual shoreline planform rather than the analytical form of Yasso.

Applying Yasso's curve to the shoreline south of the Cape by a least squares fitting of the shoreline gives results as shown in Figure A.2. In this figure, the scale is given in miles with the origin at the tip of the Cape. The symbol "+" denotes the location of Canaveral Harbor. The circles are then digitized points on the shoreline south of Cape Canaveral, while the solid curve is obtained from Yasso's formula. It is apparent that the formula provides a good fit of the shoreline, thus suggesting that the shoreline is, in fact, a typical crenulate bay (Yasso's curve depends on two variables, Ro and ∀; these are 0.0531 miles and 0.4385 radians respectively and the shoreline is defined in polar coordinates by the expression r = Ro exp (2 cot ∀)). The crenulate bay shape extends from the Cape down more than 40 miles to the south and encompasses the entire Brevard County shoreline of interest in this study.

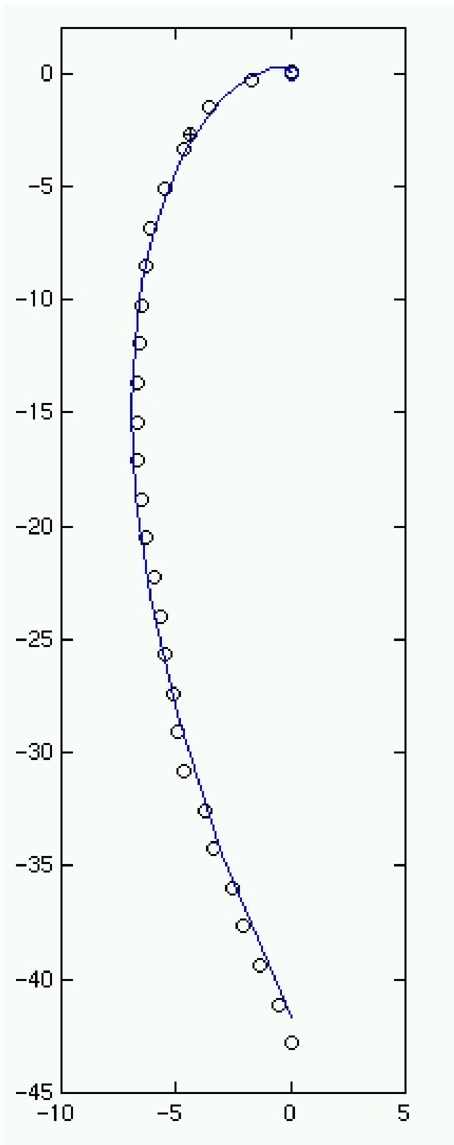


Figure A.2. Fit of crenulate bay shape to Brevard County shoreline south of Cape Canaveral. Circles are measured shoreline, solid curve from crenulate bay equation.

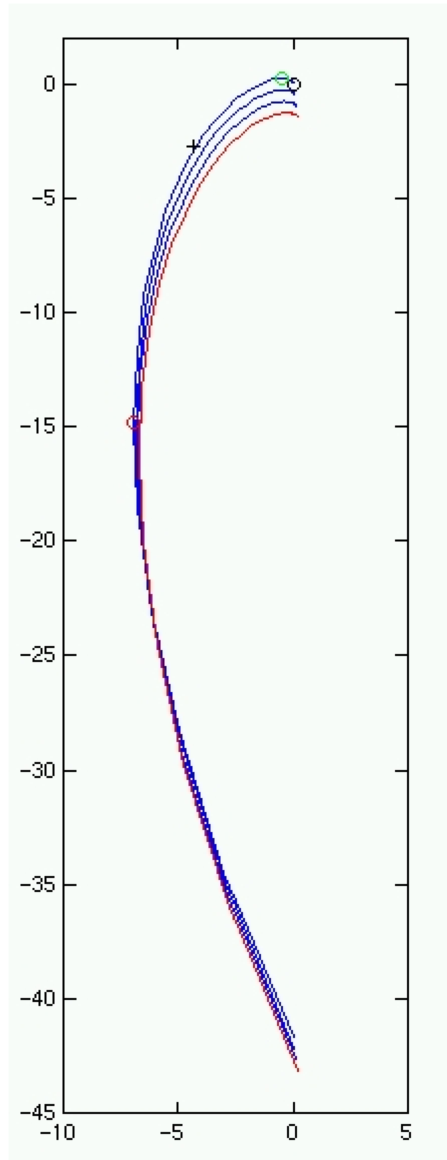


Figure A.3. Shoreline erosion and accretion patterns resulting from southward migration of Cape Canaveral

With the crenulate bay shoreline shape defined, we may now simulate the shoreline changes that are expected due to the southward migration of Cape Canaveral. The actual direction of migration was found by least squares fitting of the shoreline change given in Figure A.1 and suggests a migration to the south-southeast. Results of this analysis are shown in Figure A.3 which shows shoreline positions for future Cape migration.

This simple model for Cape migration suggests that the pre-inlet pattern shown in Figure A.1 should continue as long as the Cape continues to migrate in its historic direction. The shoreline north and south of the present inlet would continue to accrete. At a point about 23 miles south of the Cape (approximately 18 to 19 miles south of the inlet) there is a point of no long-term shoreline change. North of this point the shoreline accretes, to accommodate the migration of the Cape. To the south, the shoreline erodes. It is of interest, however, that shorelines within 5 to 10 miles either north or south of this null point would experience relative stability with a very weak background erosion or accretion. This appears to be exactly what is observed in the shoreline change data in Figure A.1. As discussed in Appendix D, pre-inlet shoreline change rates in this area fluctuate between accretion and erosion but at rates of 1 ft/yr or less.

The simulation does not include the impoundment of sand by Sebastian Inlet farther south. This would stabilize the shoreline in the area where the crenulate bay analysis suggests it should be eroding.

APPENDIX B
DREDGING ANALYSIS

Canaveral Harbor dredging records were analyzed using data provided by the Jacksonville District (Corps of Engineers, 2002). This includes all dredging performed in Canaveral Harbor and in the entrance channel. The tabulated volumes include new work such as dredging for the Trident Basin and other internal basins and channels. If all new work is excluded from the analysis, Figure B.1 presents the cumulative amount of dredging required solely to maintain the navigation channels. Maintenance dredging has been about 28,560,000 yd^3 in 45 years, at a rate averaging about 635,000 yd^3/yr.

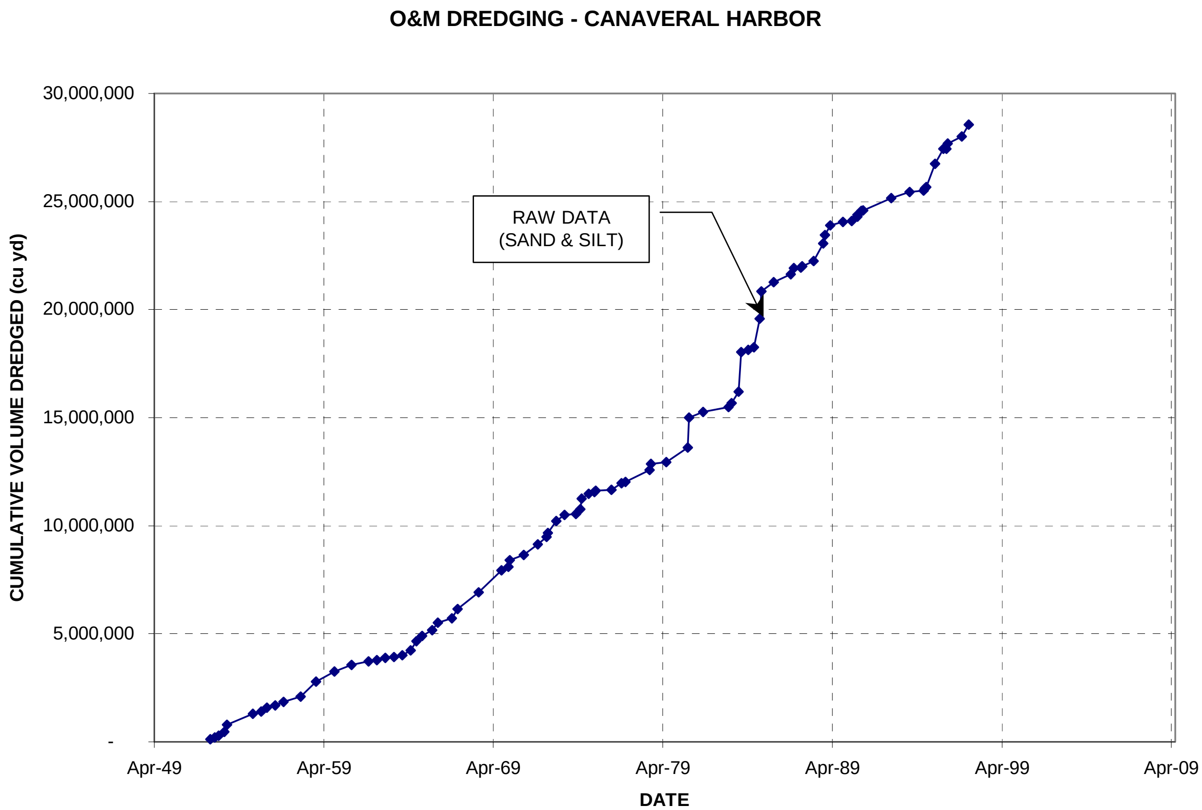


Figure B.1. Cumulative Navigation Channel Maintenance Dredging Excluding New Work, Canaveral Harbor

Not all of the material dredged from the harbor is beach quality sand. Initially most of the material was sand, however, as time progressed following the inlet cut, the sand fraction of the dredged material continuously decreased as shown in Table B.1. The Corps of Engineers (USACE, 1961) estimates that 80% of the initial 1951 dredging was sand. Knowles & Dean (1985) estimate that only 23% to 30% of the 1979 dredging was sand. Figure B.2 was derived from Bodge's (1998) estimates of the amount of sand-sized material included in the dredging.

A trendline fitted to the reciprocal of the sand fraction as a function of time gives the relationship,

$$\frac{1}{F} = 0.0832Y - 161.28$$

in which F = the fraction of sand in the dredged material and Y = the year. The relationship gives 90% sand in 1952 and 20% sand in 2000.

Table B.1 Estimated Sand Fraction of Maintenance Dredging Volumes

Year	Probable Fraction Sand (Beach Origin)	Source
1952	0.80	USACE Jacksonville (1961)
1958	0.80	Bodge (1994)
1963	0.40 to 0.50	Bodge (1994)
1979	0.30	Knowles & Dean (1995)
1991	0.23	Bodge (1994)

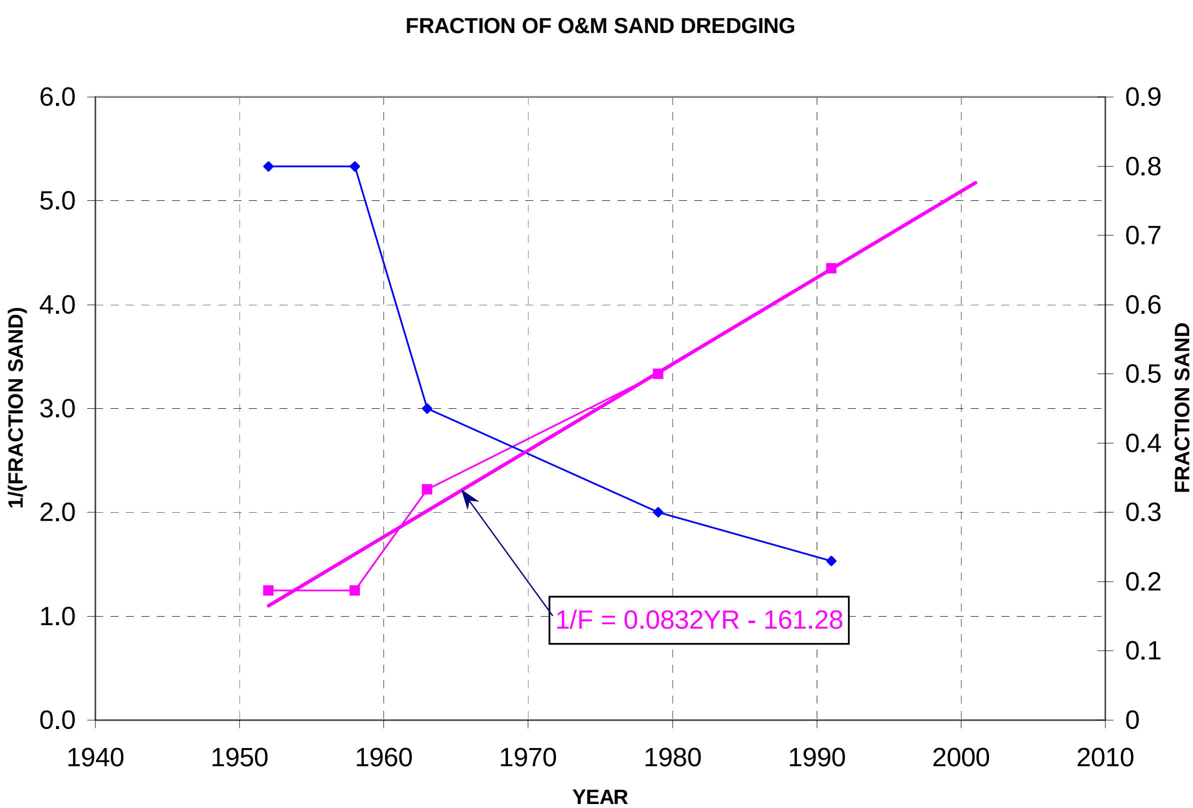


Figure B.2. Fraction of Material Removed during Maintenance Dredging that is Beach Quality Sand

The cumulative volume of sand-sized material in the maintenance dredging is shown in Figure B.3. The sand component was determined by applying the correction of Figure B.2 to the cumulative dredging of Figure B.1. The analysis suggests that the average annual rate at which beach quality sand was removed from Canaveral Harbor has been about 218,000 yd^3/yr.

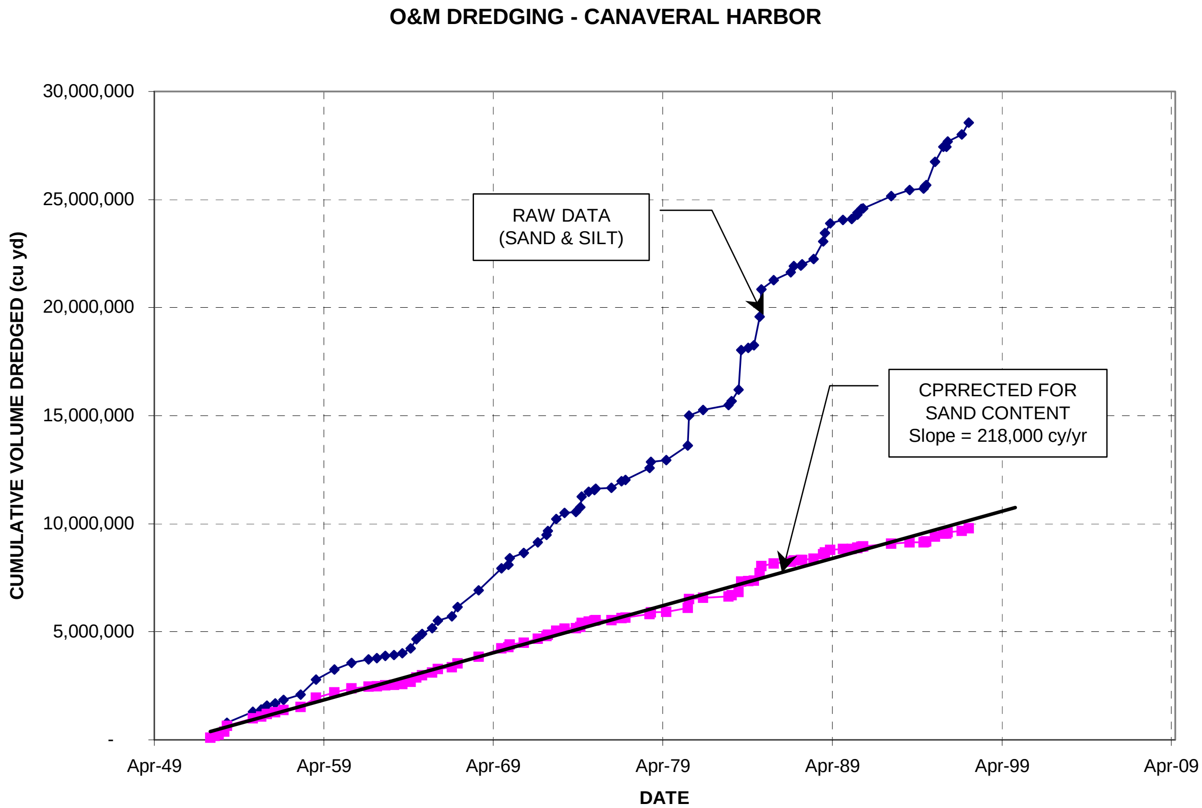


Figure B.3 Canaveral Harbor Maintenance Dredging (Cumulative Removal of All Dredged Material and Cumulative Removal of Sand-Sized Material).

Rates of accumulation of beach sand within the navigation channel were estimated in detail from hydrographic surveys (Bodge, 1994) for the period 1985-1992. Sediment of beach origin accumulated at four locations, two inside of each of the north and south jetties. Transport into the navigation channel from the north accumulated on the north side of the channel at two locations, one near the north jetty tip and the other about 1,500 feet inside the jetty. Estimated rates of accumulation at these two locations are 50,000 yd^3/yr and 40,000 yd^3/yr, respectively. Transport into the navigation channel from the south also occurred at two locations, one near the south jetty tip and the other about 1,500 feet inside the jetty. Sand accumulated at 59,400 yd^3/yr and 63,540 yd^3/yr at these two sites, respectively. Therefore, the net accumulation of beach origin sand in the navigation channel should approximate the sum of these four values or about 213,000 yd^3/yr. This is apportioned as 90,000 yd^3/yr (42%) southward and 123,000 yd^3/yr (58%) northward, both into the inlet.

An analysis of additional data provided confirmation of the 42% to 58% split between deposition on the north and south sides of the navigation channel. This is shown in Table B.2. Data in this table suggests somewhat less overall trapping (an average value of 204,500 yd^3/yr as opposed to our estimate of 218,000 cy/yr) and a somewhat greater average percentage being deposited on the north side of the navigation channel (46% as opposed to Bodge's estimate of 42%). The data from USACE (1962) and Walton (1995) should be discounted, however, as they apply only to the periods 1954-1956 and 1956-1958. These time periods are not reflective of the longer term trapping behavior, and discounting them provides strong support for the earlier estimates.

In conclusion, our analysis of dredging records from Canaveral Harbor suggests an average of 218,000 yd^3/yr of beach-quality sand enters the navigation from adjacent beaches. Of this, about 42% or 92,000 yd^3/yr enters from north of the inlet while about 58% or 126,000 yd^3/yr enters from south of the inlet. The value entering from the south agrees almost exactly with the value of 129,000 cy/yr used by the USACE (1992, Rev 1993) to justify sand tightening and lengthening of the south jetty in 1995. One source of uncertainty in this analysis is that sand could enter the navigation channel from locations other than the active surf zone. In particular, it is possible that there has been some deflation of the sea floor adjacent to the navigation channel in depths deeper then the normal depth of closure. Data provided do not allow us to quantify this effect, however.

Table B.2. Review of inlet trapping of beach sand and shoal formation on north and south sides of navigation channels

Source	**Qtrapped**	**Qnorth**	**Qsouth**	**Percent**
	cy/yr	cy/yr	cy/yr	**North Side**
Bodge (1994)	197500	83000	114500	0.42
Bodge (1994)	213000	90000	123000	0.42
Bodge (1999 letter)	220000	91000	129000	0.41
Walton (1995)	167000	84000	84000	0.50
Walton (1995)	195000	98000	98000	0.50
USACE (1987)	243000	114000	129000	0.47
Kraus et al (1999)		99000		
USACE (1992)		83000		
Dean & Knowles (1985)	243000			
USACE (1962)	167000			
USACE (1962)	195000			
	204500	**92750**	**112917**	**0.46**

The loss of 92,000 cy/yr from the north and 126,000 cy/yr from the south may appear strange since the predominant direction of longshore sediment transport was from north to south prior to harbor construction. At first, this would seem to imply that the most sand entering the channel should be coming from the north. However, it is well known that inlets can trap sand during periods of reversal in longshore transport; and, inlets can create local modifications in transport due to refraction and diffraction of waves.

A possible explanation for the larger amount of sand coming from the south jetty is that the severe recession of the shoreline adjacent to the south jetty has induced a substantial re-orientation of the shoreline with a strong localized reversal of transport toward the inlet. In addition, it has exposed the entire length of the jetty (nearly 1000 ft) to the surf zone and breaking waves. As a result, sand could move through the porous jetty along this entire distance. Since the mean sediment transport, due to the new shoreline orientation, was to the north, all sand arriving at the south jetty ended up in the channel as evidenced by the continued recession of the shoreline at the jetty.

On the north side of the inlet, however, the situation was different. Because of the accretion fillet, most of the north jetty was buried by sand so that sand could not flow through it. As the beach grew out to the end of the north jetty, and as the beach profile steepened, sand could only move around or through the jetty in a relatively narrow surf zone. At the same time, the fillet continued to grow towards the Cape. Because some of the littoral transport from the north is used to grow the fillet, this means that the amount of sand reaching the end of the jetty is less than the total amount of sediment transported towards the jetty.

APPENDIX C
BEACHES UPDRIFT (NORTH) OF CANAVERAL HARBOR

The documents provided by both the Government and the County were reviewed to determine the volumetric impoundment of sand updrift of Canaveral Harbor for both the pre-inlet and post-inlet time periods. The goal of this analysis was to determine the volume of sand trapped north of the inlet as function of the distance, *x*, updrift from the inlet. This data, when coupled with the rate at which sand passes the north jetty, can be used to re-construct longshore sediment transport rates north of the inlet.

The original data published in the literature were given in one of two formats: (1) cumulative volume impounded (in units of cubic yards) between the inlet and some specific distance updrift of the inlet, x, during some time interval, Δt, and (2) cumulative impoundment rate (in units of cubic yards per year) between the inlet and some specific distance updrift of inlet, x. All data were converted to a common format based on the cumulative impoundment rate. This format eliminates time as a variable and allows a comparison of impoundment rate as a function of distance from the inlet from all references sources. Most data were also standardized to common upper and lower bounds of: (1) an upper limit of the berm crest (also defined as the high water shoreline) and (2) a lower limit of the –17 ft NGVD depth contour.

One source of uncertainty in the analysis is that some sources list volumes north of the north jetty, some list volumes north of inlet centerline, while some are unclear about which origin was used. The north jetty is located 1200 ft north of the channel centerline so that an uncertainty of 1200 ft may exist in the updrift distance associated with each volumetric calculation. Data were converted to a common reference of the channel centerline for subsequent analysis.

The following data sources were used:

Bodge (1998) White Paper (WP) and Bodge (1994) Inlet Management Plan (IMP):
The WP gives the pre-inlet impoundment rates north of the inlet from 1887-1949 as well as the long-term post-inlet impoundment rates from 1949 to 1995. The cumulative volume of sand accreted north of the inlet were inferred from shoreline accretion rates using a conversion factor 0.92 cy/ft based on analysis of beach profiles. According to Bodge (2002, personal communication) the WP represents the “latest thinking” and supercedes the IMP.

USACE (1962) Sand Bypass Study, also in USACE (1967) Shore Erosion Study and House Document 352 (1968):
These studies give impoundment volumes for periods 1954-1956 and 1956-1958 based on USACE beach profiles. The 1962 Sand Bypass Study provides the most detail and lists volume changes for 11 locations updrift, extending from the north jetty to near Cape Canaveral, 21,000 ft north. The data for the two time periods were combined into a single data set covering the immediate post-inlet period from 1954-1958.

USACE (1992 or 1993rev) Sand Bypass Study

This study considered volumetric impoundment for 1951-1986 but only for a distance of 3,444 ft north of the north jetty. Volumes were computed from analysis of shoreline changes using a conversion of 1.04 cy/ft of shoreline change.

USACE (1996) Brevard Co Shore Protection Study

This report gives limited details but quotes volumetric impoundment data for pre- and post-inlet periods of 1929-1956 and 1956-1996 based on analysis of bathymetric surfaces. The same data were used by Kraus et al. (1999). The volumetric accretion for the pre-inlet period is identical to Kraus et al (4.1 Mcy) while the accretion for the post-inlet period is larger than Kraus et al (9 Mcy versus 8.3 Mcy). However, there is some ambiguity in the updrift distance used in this analysis. Results in USACE (1996) are listed for a distance of 15,000 ft updrift of north jetty, while Kraus et al. (1999) quote a distance of 12,000 ft updrift from the north jetty. This produces an ambiguity of 3,000 ft in location updrift between these two reports.

Kraus, Byrnes, and Lindquist (1999) in USACE TR-CHL-99-6

This report lists cumulative volumes accreted north of inlet based on two different methods: (a) analysis of bathymetric data and (b) analysis of beach profile data. The two results are not consistent and give different results for volume impounded at a given distance updrift. The bathymetric analysis is for the period 1929-1956 and 1956-1996 and is listed as being for a distance of 12,000 ft north of north jetty. The beach profile analysis is for the period 1951-1994 with intermediate profiles in 1954, 1958, and 1965/1966. Results are given for updrift distances of 10,500 ft, 13,500 ft, and 21,000 ft updrift from the channel centerline. The volumes obtained from this analysis are lower than those obtained by analysis of bathymetric data. Our speculation is that the profiles were truncated landward and seaward in such as way that they missed a substantial portion of the accreted volume.

Bodge (2001) Monitoring Study for Borrow Area

This report gives accretion rates and volumes based on beach profile analysis for the borrow site after the 1995 sand bypassing. Results show very high impoundment rates. This appears to be due to the complete trapping of longshore transport by the deep hole dredged at borrow site.

Walton (1995) Unpublished Report

The Walton report provides an independent analysis of the 1954-1958 data contained in the USACE 1962) Sand Bypassing Study. This contains some new analysis of the amount of sand bypassing the north jetty and deposited into the north side of the navigation channel.

Results for Pre-Inlet Period

Impoundment rates for the pre-inlet period are shown in Figure C.1, plotted against distance updrift from the channel centerline. Results of Bodge (1998) extend over the full distance updrift from the north jetty to Cape Canaveral (near 23,000 ft updrift). This curve shows that the cumulative impoundment rate increases with distance from the inlet. Data from USACE (1996) appear consistent with the data of Bodge. Data from Kraus et al. (1999), shown with error bars, appear to contradict other data. This may be due to the confusion over the 1200 ft uncertainty in updrift distance noted previously.

Results for Post-Inlet Period

Impoundment rates for the post-inlet period as a function of distance updrift from the channel centerline are shown in Figure C.2. Two data sets (Bodge, 1988) and USACE (1962) give values at enough locations updrift to enable trend curves to be established. These two curves differ near the inlet but then converge between 15,000 ft and 20,000 ft updrift. This appears to be related to the time periods covered by each data set. The USACE data is for the immediate post-inlet period (1954-1958) and indicates dramatic impoundment in the accretion fillet within a few thousand feet of the north jetty following jetty construction in 1954 (indicated by the steep portion of curve). The Bodge (1988) data are for the long-term average accretion rate extending over 1949-1995 and show much more uniform accretion extending for almost 20,000 ft updrift of the inlet. This is consistent with the filling of the north jetty to capacity and the subsequent extension of the accretion fillet updrift.

Other data sets are only given for a few specific distances updrift. Some appear consistent with the two trend curves while others do not. The USACE Sand Bypass Study (1992) gives a single point that appears to match Bodge's results very well. The results of Kraus et al. (1999) (bathymetric analysis, plotted with error bars) and the results of the USACE (1996) also agree well with the results of Bodge. Results of Kraus et al. (1999) (beach profile analysis) appear to be generally below the trend line established by Bodge (1988) and below the impoundment rates determined by Kraus et al. based on bathymetric analysis. For reasons stated above, it appears that Kraus's result based on beach profile analysis are anomalously low due to a truncation of volume at both the landward and seaward ends of the profiles

Results of Bodge (2001) from the infilling of the sand bypassing borrow site appear to be high relative to others. This may be explained by the fact that the borrow site likely provided a complete trap for littoral material. While it was filling, there was probably very little sand that flowed around the north jetty and into the navigation channel. All other data plotted in Figure C.2 represent impoundment with approximately 90,000 cy/yr of longshore transport past the north jetty and therefore show less deposition. When net longshore sediment transport rates are inferred from these two data sources, the results of Bodge (2001) are consistent with the other data.

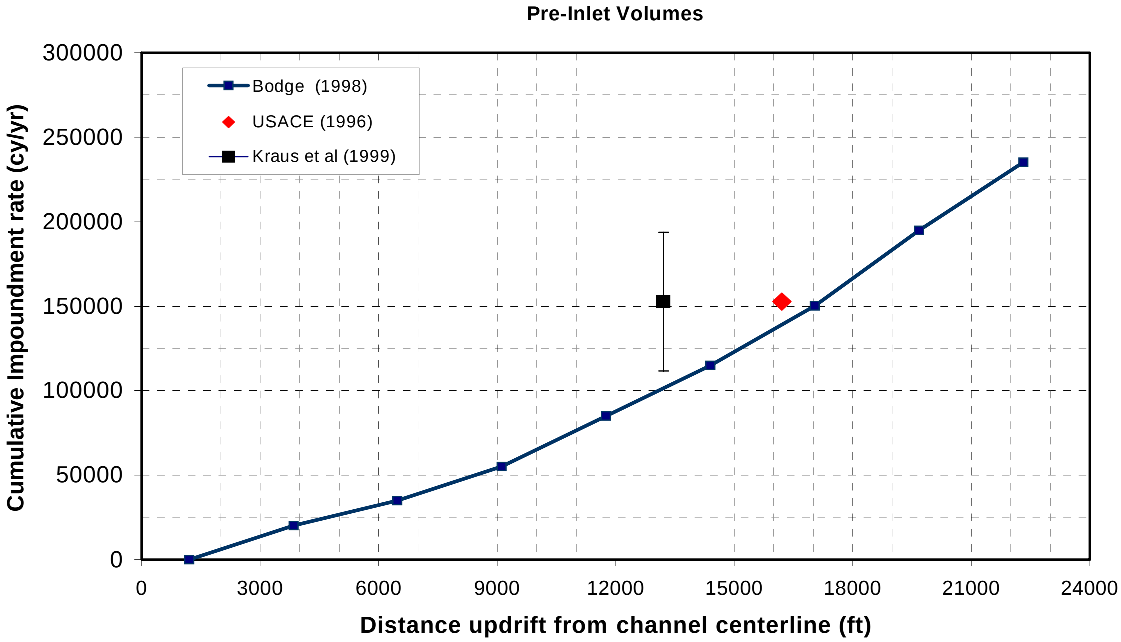


Figure C.1 Impoundment rates for pre-inlet period

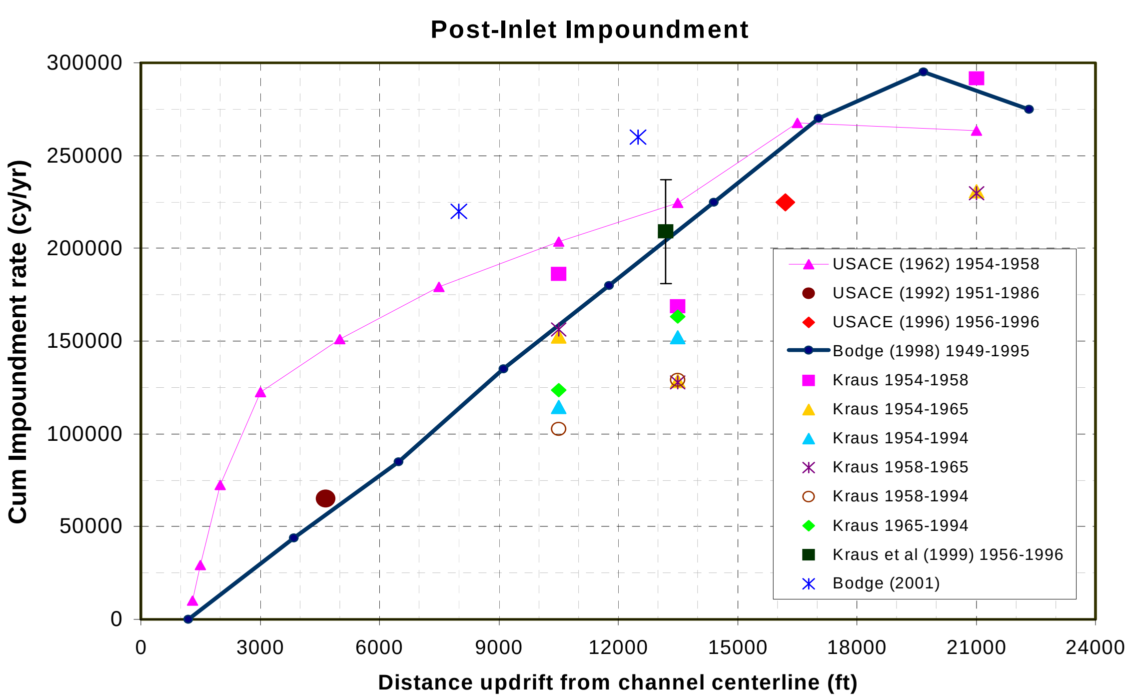


Figure C.2. Impoundment rates for post-inlet period

Analysis of Longshore Sediment Transport North of Inlet

Longshore transport rates can be inferred from the historic data by combining the impoundment rates just discussed, $Q_{imp}(x)$, with the rate at which sand has been transported around the north jetty, Q_{inlet}. As illustrated in Figure C.3, the transport rate at a given distance updrift can be established as $Q(x)= Q_{imp}(x) + Q_{inlet}$. In the literature, many values of longshore transport have been published and these often differ considerably. One reason for this disagreement is that the transport rate is a strong function of distance from the inlet and can vary considerably even over distances of one to two miles along the shoreline. As will be shown, if these distances are accounted for and if the curve Q(x) is determined, then many of the previous estimates of longshore transport make much more sense.

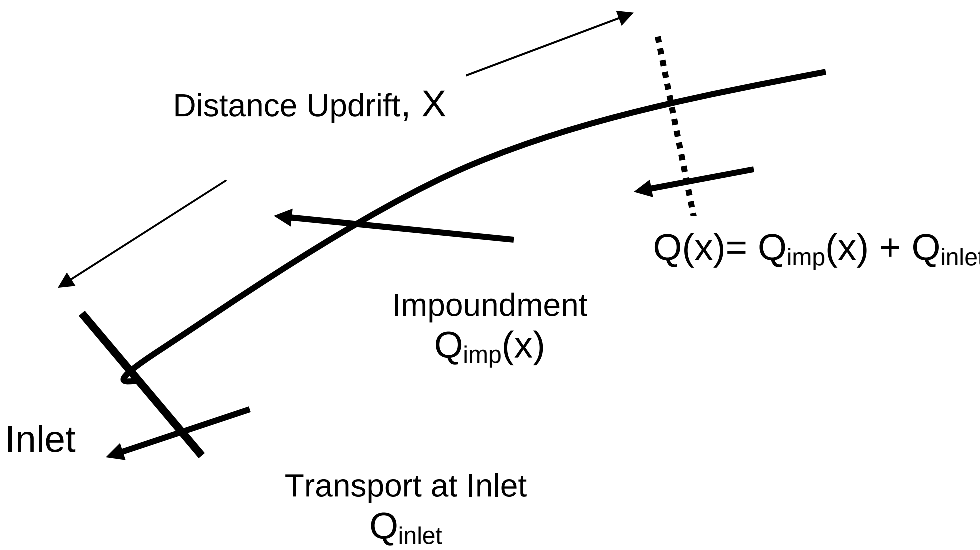


Figure C.3. Control volume approach to estimating longshore transport rate at a distance, x, updrift from the inlet

Transport Rate at Inlet, Q_{inlet}

For pre-inlet conditions, the transport rate at the inlet site is unknown. As will be discussed below, values can be assumed and combined with the impoundment rates in Figure C.1 to estimate the pre-inlet longshore transport rate.

For post-inlet conditions, the transport rate into the inlet channel can be estimated from channel dredging records and from analysis of shoal formation in the navigation channel. Numerous values have been estimated in the literature and these are summarized in Appendix B. A value of approximately 90,000 to 92,000 cy/yr seems to represent the long-term average condition.

Transport Rate as Function of Updrift Distance, x

Estimates of longshore transport for the post-inlet period can be obtained by combining the impoundment rate, $Q_{imp}(x)$ from Figure C.2, with the transport rates at the inlet, Q_{inlet} . Results are shown in Figure C.4 below.

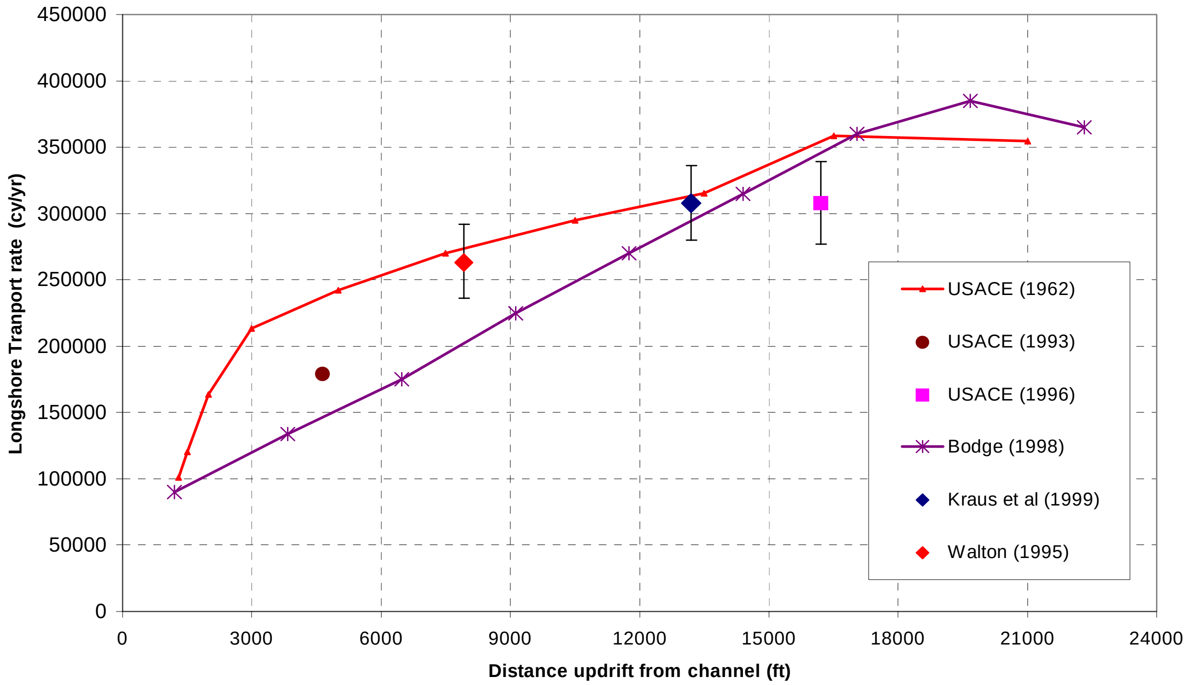


Figure C.4. Longshore sediment transport rates north of Canaveral Harbor for post-inlet period

The earliest data, from the USACE (1962), represent the 4-year period immediately after jetty construction from 1954-1958. The results from Bodge (1998) then represent the long-term average transport rates for a 46 year period from 1949-1995. A comparison of the two curves shows that the two diverge near the inlet but converge farther updrift. This appears to be due to formation and ultimate stabilization of the accretion fillet. In the USACE data, the fillet was rapidly forming and was likely confined to the region close to the inlet. Farther updrift, the inlet did not have much effect on transport rates in the 1954-1958 period. In the Bodge results, the accretion fillet is well-established and has advanced updrift. The transport rates from the two analyses converge in range of 14,000 to 21,000 ft updrift from the inlet. Here, the net longshore transport rate is estimated to be about 325,000 to 375,000 cy/yr.

These values and patterns of longshore transport are corroborated by other data. Walton (1995) gives estimated transport rates based on a re-analysis of the 1954-1958 data used by USACE (1962). Walton's values for transport rates closely match those obtained using the 1954-1958 data in the USACE (1962) report despite some different assumptions regarding the transport around the north jetty. The USACE (1992, rev 1993) data suggests a transport rate of 179,000 cy/yr at a location just 4,644 ft south of the channel centerline (3,444 ft updrift of the north jetty). This value is between the values suggested by USACE (1962) and Bodge (1998) and is based on an estimated transport around the north jetty of 114,000 cy/yr. Use of a smaller value of about 90,000 cy/yr (consistent with Bodge) would yield transport rates similar to those obtained using the Bodge data. The transport rates of Kraus et al (1999) and USACE (1996) are identical at 308,000 cy/yr and are also generally consistent with the results of Bodge for the long-term post-inlet condition.

Pre-Inlet Transport Rates

Pre-inlet transport rates also may be inferred by adding the impoundment rates (presented earlier in Figure C.1) and the transport rate past the inlet. Unfortunately, the transport rate at the inlet location is unknown so that pre-inlet transport rates cannot be determined without additional assumptions.

The approach used here was to assume values of Q_{inlet} and to then compare the resulting pre-inlet longshore transport rates to those obtained after inlet construction. It is assumed that at some point updrift from the inlet, longshore transport rates after inlet construction are similar to those before inlet construction. By matching transport rates as closely as possible in this area far updrift from the inlet, it is possible to estimate the transport rate at the inlet location prior to its construction.

Figure C.5 shows the result of this analysis. The transport rate at the inlet location was established as 210,000 cy/yr by trial-and error. When added to the pre-inlet impoundment rates (using the pre-inlet curve from Bodge (1998) in Figure C.1), the pre-inlet transport rates match the post-inlet transport rates updrift of the inlet quite closely. The pre-inlet rates in Figure C5 agree well with the immediate post-inlet transport rates from USACE (1962) from about 6,000 ft to 18,000 ft updrift. Both curves have about the same slope in this region. The curves deviate only within about 1 mile of the inlet where post-inlet transport rates drop dramatically as one would expect during the time immediately following jetty construction. Another area of departure is near Cape Canaveral more than 18,000 ft updrift which is due to the expected variability near the Cape.

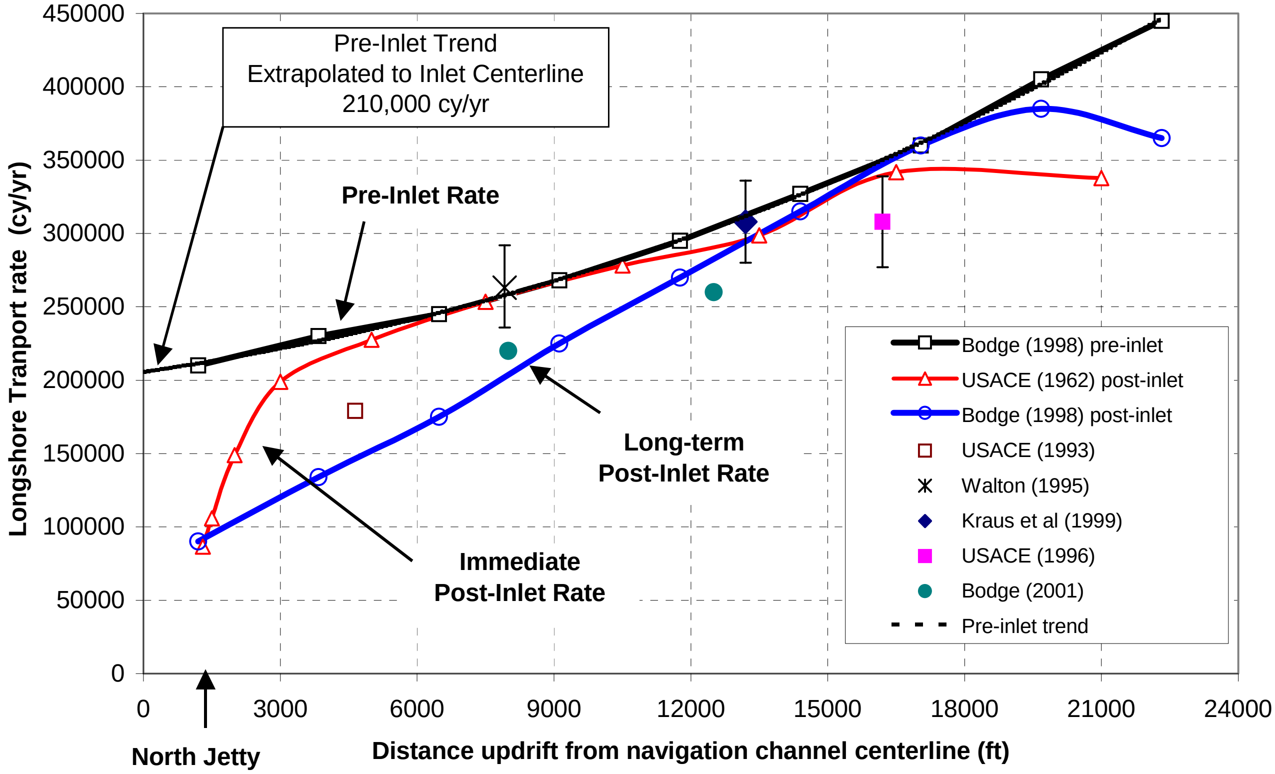


Figure C.5. Pre-inlet transport rate (black curve) estimated by matching
to post-inlet rates updrift from the inlet

The pre-inlet transport rates are significantly higher than the long-term post-inlet conditions obtained by Bodge using 1949-1995 data. This is also expected. As the north jetty fills to capacity and the accretion fillet advances updrift, transport rates are then expected to diminish and should be less than pre-inlet values. These effects should diminish with distance from the inlet.

Conclusion on Sediment Transport Rates

Based on the above analyses, we conclude that sediment transport rates past the inlet location were approximately 210,000 cy/yr prior to inlet construction. Error bars shown by other investigators, e.g. Walton (1995) and Kraus et al (1999), suggest that transport rates may vary by ∀ 30,000 cy/yr from this value. Transport rates show a strong gradient with distance updrift of the inlet. For example, at a distance of 15,000 ft (about 3 miles) updrift, the transport rate has increased to about 340,000 cy/yr. Some prior estimates of sand bypassing rates from the 1962 Sand Bypassing Study were as high as 350,000 cy/yr. These are in error since they are based, in part, on faulty assumptions (regarding transport into the inlet channel) and, in part, since they were determined at a large distance updrift of the inlet and not at the inlet location.

APPENDIX D
SHORELINE CHANGE SOUTH OF INLET

Sources of Data

Historic shoreline data for the study area were obtained from three sources. At the beginning of the project, beach profile and shoreline data were obtained from the USACE. Additional data on historic shoreline positions were then obtained from the Florida Department of Environmental Protection (FDEP) Bureau of Beaches and Wetlands Resources web site. Near the end of the project (in early September 2002), it was discovered that there were some discrepancies between the FDEP and USACE data sets. Dr. Mark Byrnes, of Applied Coastal Engineering and Research, then re-digitized the original shoreline maps using new map registry and digitizing methods, and provided revised shoreline data to the ICE Team on September 12, 2002. These revised shorelines corrected and then superceded some of the USACE shoreline data obtained earlier in the study.

The FDEP dataset consisted of historic high water shoreline measurements made by various state and federal agencies between 1878 and 2001. Shoreline positions were given at the locations of 219 FDEP survey monuments, spaced at approximately 1,000 ft intervals, from Canaveral Harbor (R-1) to Sebastian Inlet (R-219). The FDEP data includes three surveys completed prior to construction of Canaveral Harbor, in 1878, 1929, and 1949, and 11 surveys completed after construction of Canaveral Harbor from 1966, 1969-1970, 1972, 1976, 1980, 1985/86, 1993, 1997, 1999, 2000, and 2001. Of these, the most useful are from 1972, 1985/86, and 1997, as the shoreline is defined for each of the 219 survey monuments. Other surveys are of somewhat less value because they cover a limited extent (e.g. the 1976 survey extends from R-1 to R-61, while the 1980 survey extends from R-1 to R-39), or because they skipped some survey monuments (e.g. the 1983 survey was conducted at every 3rd monument, while the 1999 survey was only conducted at every 6th monument).

From the original USACE dataset, we have used beach profiles measured in the following surveys: 1951, 1954, 1958, 1965, 1972, 1985/86, and 1993/94. The various surveys covered different lengths of shorelines south of Canaveral Harbor. For example, the 1951 profiles extended only 10,500 ft south of the inlet, while the 1954 and 1958 profiles extended 34,400 ft south of the inlet. The 1965 profiles covered the entire length of Brevard County south of Canaveral Harbor, but with poor resolution (an average spacing of about 1.8 miles and some were spaced as far as 2.5 miles apart). In order to use the Corps' profile data, beach profiles were analyzed to define the coordinate locations of the mean high water (MHW) shoreline, located at +2.0 ft NGVD, for all 219 of the FDEP R-monuments. In many cases, the USACE profiles were spaced much farther apart than the FDEP survey monuments, and shorelines for intermediate range monuments were determined by interpolation.

The revised USACE shoreline positions, provided by Applied Coastal Engineering and Research (ACER), are then available for six dates. Three shorelines represent pre-inlet conditions: 1878, 1929, and 1949. Three shorelines represent post-inlet conditions: 1970, 1996, and 2002. The last two shorelines, from 1996 and 2002, were collected by Applied Coastal Engineering and Research based on GPS beach surveys conducted for the Jacksonville District. The shoreline positions in each survey were provided at 30-foot intervals along the length of the study shoreline. An interpolation routine was then applied in order to find the revised shoreline positions at each of the 219 FDEP R-monuments.

One complication of the historic shoreline data is that the vertical elevation defining the shoreline is not consistent and, in fact, is not known with certainty for some surveys. For most of the FDEP data set, and for the USACE shorelines obtained from beach profiles, the shoreline is defined by the Mean High Water (MHW) line, located at an elevation of +2.0 ft NGVD. For some of the FDEP surveys, and for the revised USACE data provided by Applied Coastal Engineering and Research, the shoreline is defined by the so-called High Water Line (HWL) which is not at a fixed elevation. This definition is used in all pre-inlet surveys from 1878, 1929, and 1949. It also appears to have been used in the 1970 FDEP shoreline and in the 1976 shoreline. The HWL is a legacy of older topographic surveys in which survey parties tried to define the "high water line" based on identifiable features on the beach. This was the case in the 1878 survey. It is also a legacy from interpretation of aerial photographs, in which shoreline maps were prepared from analysis of stereo-photos, as was the case with the 1929, 1949, and 1970 surveys.

From a quantitative standpoint, the HWL is less-than ideal because the reference feature used to define the "shoreline" can vary from survey to survey, and up and down the beach during any one survey. This is in contrast to a defined reference datum like MHW which has a specific elevation. In practice, the HWL is can be defined by any of a number of reference features found on the beach, for example: a break-in-slope at the beach berm, a debris line, a wet-dry interface, a dune toe, or a vegetation line. Because any of these references could be used to define the HWL, the elevation of the HWL shoreline can vary depending on antecedent water levels and the degree of wave runup experienced just prior to the survey. Based on a review of beach profiles from Brevard County, and based on typical beach berm elevations, the HWL is generally located between 20 and 80 feet landward of the MHW shoreline, with a mean offset of about 50 feet. An exact relationship between MHW and HWL cannot be determined, however, because of the variable elevation associated with the HWL.

In the analysis to follow, most of the results will be based on the FDEP data set, as augmented by MHW shorelines from the USACE beach profiles. These data were used in the Draft Report and have been used throughout most of the ICE study. The revised shoreline data from ACER are used to a more limited extent. These data are not fully adopted in this Final Report for several reasons. First, the data were obtained rather late in the study and time limitations prevented a complete conversion from the FDEP data to the newer USACE data. Second, the FDEP and other USACE data provided better temporal resolution of shoreline change following inlet construction. Finally, after working with the revised shoreline data, it was evident that the revised shorelines were generally similar to the FDEP shorelines and that similar conclusions could be drawn from either data source.

This last point warrants further explanation. The FDEP and revised USACE (or ACER) shorelines were compared for common survey dates (1878, 1929, and 1949) at each of the FDEP R-monument locations. Both sets of shoreline positions are based on the same original paper maps but were digitized using different methods. The FDEP shorelines were based on a traditional method in which a digitizing mouse was used to trace the shoreline directly from the original paper map. The revised shorelines obtained by ACER were based on a new method in which the original map was first scanned to obtain a digital image. This digital map copy was then displayed on a computer screen and the shoreline was determined by defining coordinates in the digital image. The newer method has at least two advantages: (1) it eliminates the problem of unsteadiness or wavering in hand digitizing and (2) the digitizer can zoom in on small sections of the shoreline and expand the scale of the original map to obtain better resolution of the shoreline. In fact, by zooming in on the digital image, ACER was able to consistently digitize the seaward edge of the mapped shoreline. They were also able to define the width of the shoreline curve drawn with a drafting pen on the original maps. Based on the scale of these maps, the thickness of this hand-drawn shoreline corresponds to an actual width in the field of 30 to 80 feet.

Based on a comparison of shoreline positions from the FDEP and revised USACE shorelines, it was found that the FDEP shorelines from are, on average, slightly landward of the revised USACE shorelines. The FDEP shorelines were found to be an average of 29, 44, and 11 feet landward of the revised USACE shorelines for the 1878, 1929, and 1949 surveys respectively. As noted above, the shoreline drawn by hand on the original maps has a width of 30 to 80 feet; and, ACER consistently digitized the seaward edge of the mapped shoreline. As a result, their shorelines are expected to be 15 to 40 feet seaward of the mid-point or mean of the hand drawn shoreline on the original maps, assuming the hand drawn shoreline wavers randomly about the line. This is almost exactly the offset found between the FDEP and ACER shorelines, indicating that the FDEP shorelines were themselves digitized with great care. Based on these findings, our conclusion is that the FDEP data provide a very good description of the mapped shoreline and can be used to evaluate long-term shoreline change with a level of confidence equal to that we could obtain by converting our work over to the revised USACE shorelines.

Location Map and Reference Locations

In the discussion to follow, shoreline positions are defined primarily by the location of the FDEP survey monuments, located at about 1,000 ft intervals from Canaveral Inlet R-1) to Sebastian Inlet (R-219). These are shown on a location map in Figure D.1. For orientation, the following shoreline reaches, associated with the Brevard County Shore Protection Project (BCSPP), should be noted:

Shoreline Reach	FDEP R-monuments	Miles South of Inlet
North Reach	R-1 to R-53	0 to 9.4
Patrick Air Force Base	R-54 to R-75	9.4 to 13.5
Mid Reach	R-76 to R-117	13.5 to 20.7
South Reach	R-118 to R-138	20.7 to 24.3
Sebastian Inlet	R-219	37.6

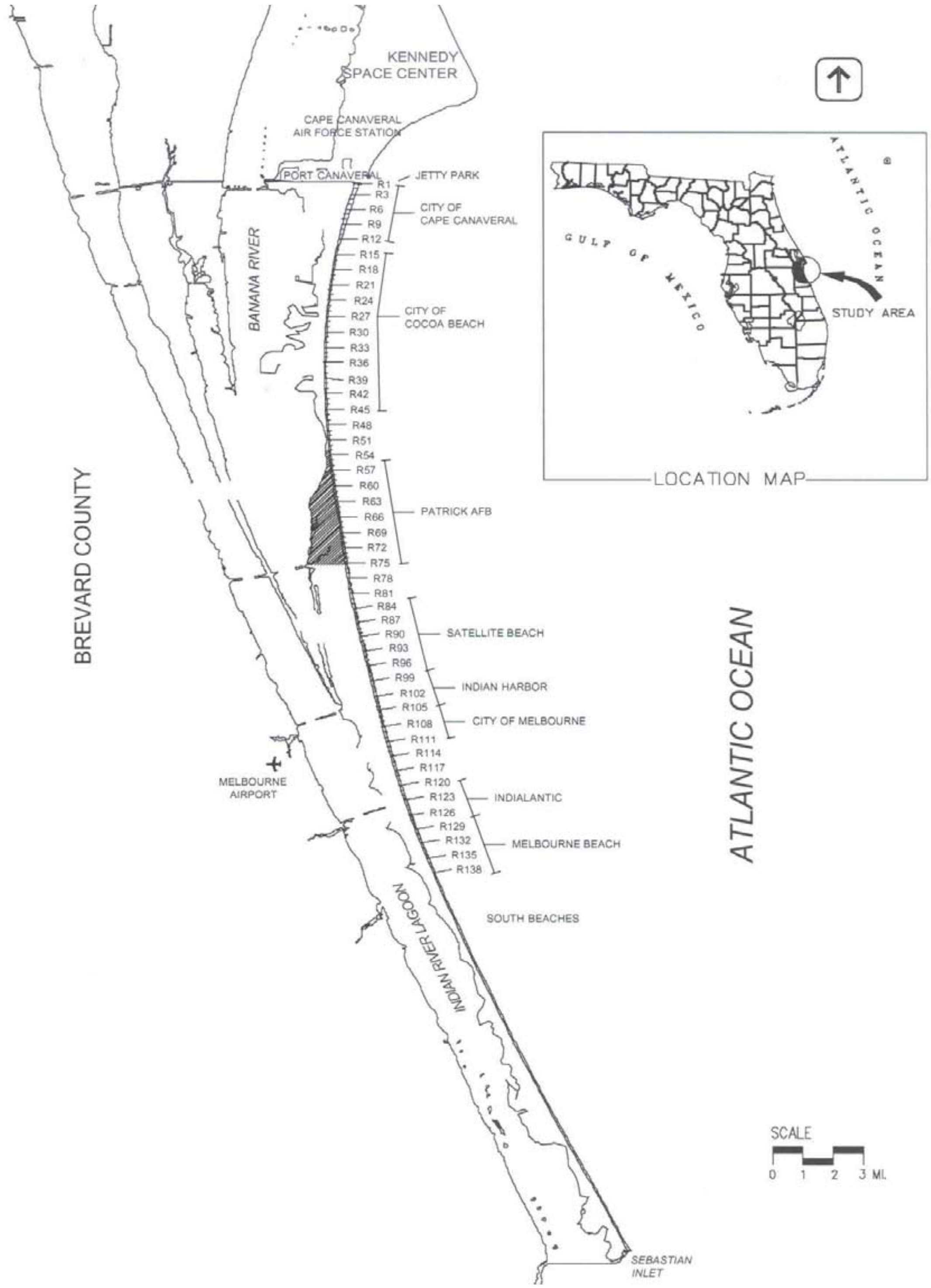


Figure D.1. Location map of study area, reproduced from Olsen Associates, Inc. (2001). Map shows FDEP survey monument locations (R-1, R-2, etc) for project area. These are located at approximately 1,000 ft intervals. North and South Reaches of the Brevard County Shore Protection Project extend from R-1 to R-53 and R-118 to R-138 respectively..

Pre-Inlet Shoreline Change

Historic shorelines prior to construction of Canaveral Harbor are available from three surveys tabulated in the FDEP data-set, or in the revised USACE dataset provided by Applied Coastal Engineering and Research (ACER). These surveys cover the time periods 1876 to 1881, 1928 to 1930, and 1947 to 1949; and, it is important to note that in each of these surveys, coverage of Brevard County was obtained over a multi-year period. As such, these surveys do not constitute a single definitive “snapshot” of the shoreline. However, these are the only historic shorelines available for the pre-inlet time period and, as such, must be adopted as representative of pre-inlet conditions. For simplicity, these surveys will be denoted by general dates as follows: 1878, 1929, and 1949.

Shoreline changes for the periods 1878 to 1929, and 1878 to 1949, are shown in Figure D.2. Shoreline change rates for these same time periods are shown in Figure D.3. Also shown in Figure D.2 are shoreline changes occurring from 1878 to 1951, based on the 1951 USACE beach survey, which covered only a small region south of the future location of Canaveral Harbor. Results are shown using the FDEP shoreline data. Similar plots showing nearly identical results can be obtained using the revised USACE data.

From 1878 to 1929, the shoreline showed strong accretion from R-1 to R-40, and slight erosion from R-68 to near R-200. On average, the region from R-68 to R-200 experienced less than 50 ft of shoreline erosion in the nearly 50 year period between surveys, giving an average erosion rate of less than 1 ft/yr. Such small erosion rates are generally considered to be within the range of survey accuracy and are not viewed as particularly meaningful. For example, Kraus et al (1999) discuss errors associated with use of these older historic surveys and conclude that shoreline change rates can only be accurately estimated to within ∀1.5 ft/yr for the period 1978 to 1928 and ∀1.0 ft/yr for the period 1878 to 1949. Accretion rates just south of the Canaveral Harbor site averaged 3 to 5 ft/yr and were as high as 8.5 ft/yr at the harbor location. These are clearly much larger than the accuracy limitations and suggest a definitive accretion trend fro several miles south of the Canaveral Harbor site.

From 1878 to 1949, the shoreline showed accretion over almost the entire study area. In the North Reach, from R-1 to about R-50, the shoreline accreted more than 100 feet at rates of 2 to 6 ft/yr. Accretion then averaged less than 50 ft, at rates of less than 1 ft/yr, over the rest of the county. These values are again at or below the limits of probably survey accuracy and cannot be used to definitively establish a strong trend. Only two small areas showed erosion during this time period: one near R-140 and one near R-160, both of which are outside the limits of the Shore Protection Project. The limited data from the 1951 survey confirms the accretion trend near the inlet.

In the 20-year period from 1928 to 1949, the beaches of Brevard County experienced net accretion almost everywhere. Between R-10 and R-210, the beaches accreted almost uniformly by about 100 ft on average, with an accretion rate of nearly 5 ft/yr. The explanation for this is not clear. This may have been related to a relatively calm period in which few tropical or extra-tropical storms affected the Brevard County coastline, as shown in Appendix I.

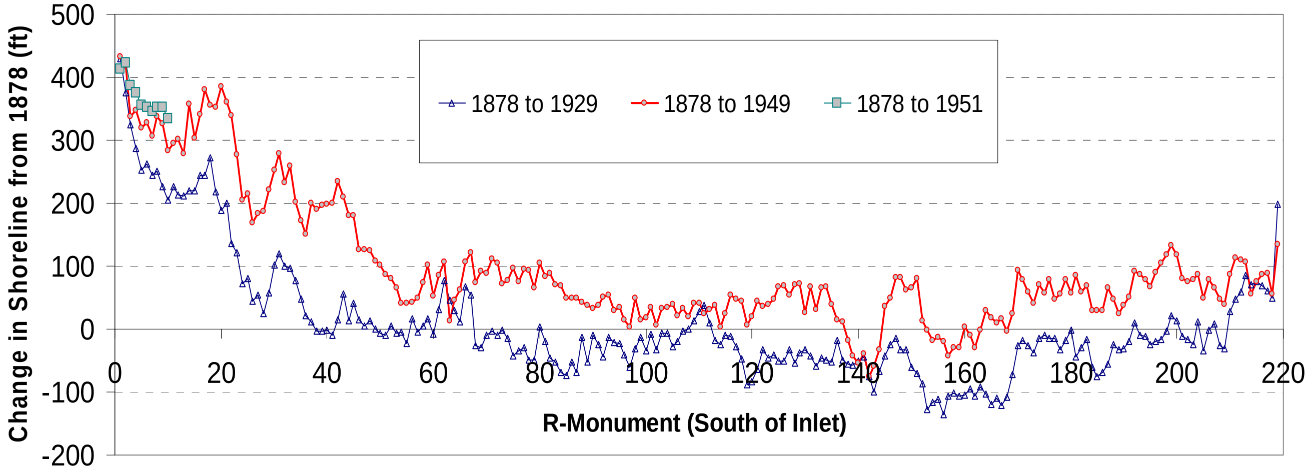


Figure D.2. Historic shoreline change prior to inlet construction relative to the 1887/81 survey

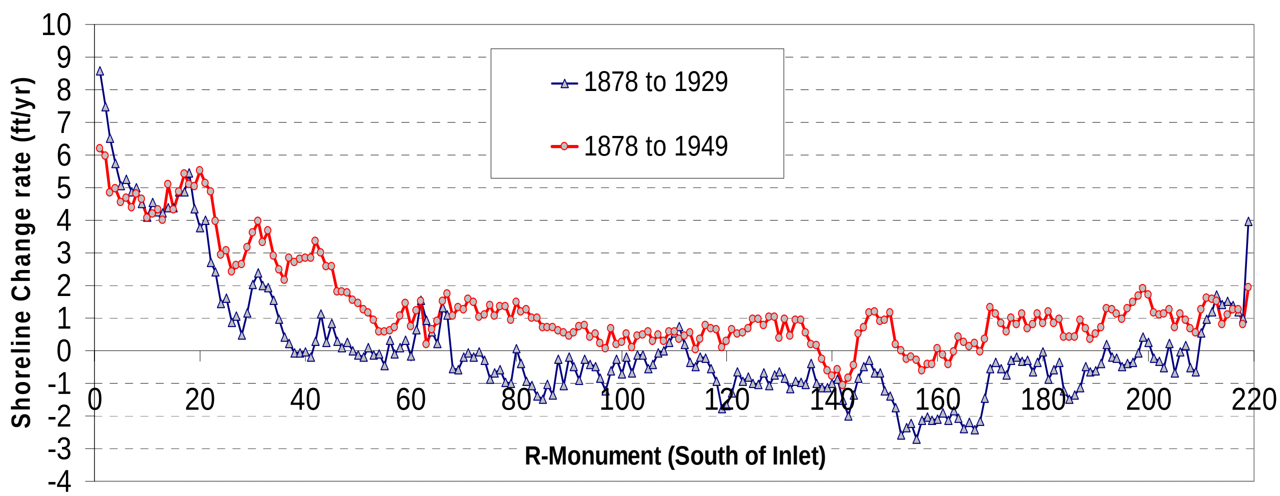


Figure D.3. Historic rates of shoreline change prior to inlet construction.

Considering the accuracy limitations of these older surveys, shorelines were clearly accreting prior to inlet construction from R-1 to R-40 (1928 survey) or perhaps to R-80 or more (1949 survey). South of these locations, the limitations on survey accuracy make it difficult to determine conclusively whether the shoreline was truly eroding or accreting. The data indicates variability in this region such that the shoreline experienced periods of erosion and accretion with little net change.

Because of the limited data, it is not clear whether the most representative pre-inlet trends in shoreline change should be based on the period from 1878 to 1929 or on the period from 1878 to 1949. One means of smoothing the shoreline change rates from the two survey periods is to simply average pre-inlet shoreline change rates for the periods 1878 to 1929 and 1878 to 1949. This averaging process partially discounts the slight erosion that occurred over the southern portion of the Brevard County shoreline prior to 1929, and also partially discounts the dramatic accretion that occurred in the 20 year period prior to the 1949 survey.

The resulting average rate of pre-inlet shoreline change, shown for the portion of the shoreline of interest between R-1 and R-219, is shown in Figure D.4. This figure shows the averaged pre-inlet shoreline change rates obtained from the FDEP data, as well as those obtained from the revised USACE shoreline data provided by ACER. Clearly there is very good agreement between these two data sources for the long-term trends in pre-inlet shoreline change.

Relative to the limits of the Shore Protection Project, both data sets indicate strong net accretion occurred in the North Reach from R-1 to about R-53 prior to inlet construction. Patrick Air Force Base, from R-54 to about R-75, showed net accretion although at a rate of less than 1 ft/yr on average. The two data sets show some disagreement in the Mid Reach, from R-80 to about R-118. Both show that the South Reach, from R-118 to R-138, was essentially stable. These results are in good agreement with the crenulate bay analysis presented in Appendix A.

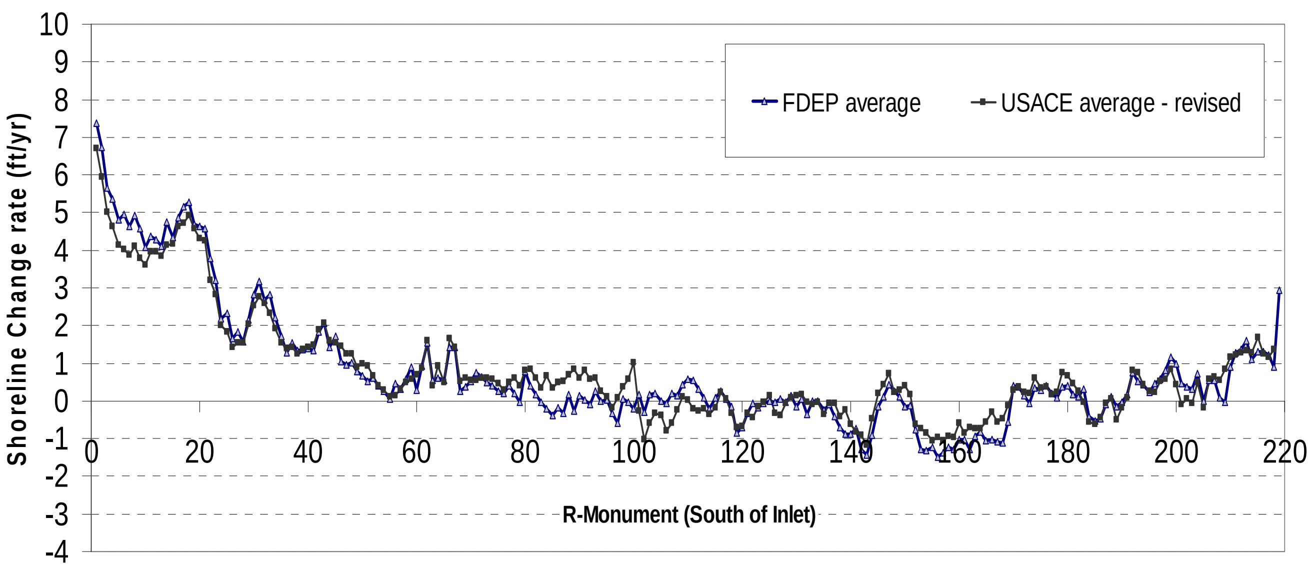


Figure D.4. Shoreline change rate prior to inlet construction, obtained by averaging rates from 1878 to 1928 and from 1878 to 1949.

Post-Inlet Shoreline Change

Shoreline changes following construction of Canaveral Harbor have occurred in two distinct phases. From the initial opening of the inlet in the early 1950's until the 1974 Trident beach fill, the shoreline for a considerable distance downdrift (south) of the inlet showed net erosion. Starting in 1974 and continuing until the present, the shoreline has been partially stabilized by beach fill activity, most notably by the 1974 Trident fill, and the 1995 and 1998 sand bypassing events. As a result, shoreline erosion is less dramatic and, in fact, large segments of the shoreline have been relatively stable during this time.

As noted, the 1951 USACE survey is of limited general use as a pre-inlet baseline survey as it extends only 10,500 ft south of the inlet (to R-10). As a result, the ICE Team, in agreement with both Bodge (1998) and Kraus et al (1999), have adopted the 1949 shoreline as being most representative of pre-inlet conditions for the entire Brevard County study area from R-1 to R-219. It is recognized that the 1949 survey uses HWL to define the high water shoreline. Most subsequent surveys use MHW instead.

Short-Term Response from 1951 to 1972

Shoreline change prior to the mid-1970's is shown in Figure D.5, for three regions: R-1 to R-60 (top panel), R-60 to R-120 (middle panel), and R-120 to R180 (lower panel). Figure D.5 compares shorelines from 1951, 1954, 1958, and 1965 (obtained from the USACE beach profiles) and from 1972 and 1976 (obtained from the FDEP) relative to the 1949 FDEP shoreline. By combining the USACE and FDEP data-sets, a consistent trend of shoreline change is apparent which persisted until the 1974 Trident fill finally started to spread to the south.

The 1951 survey shows net accretion relative to the 1949 survey, as the shoreline from R-2 to R-10 built seaward by 20 to 50 feet in this short time period. The 1954 survey shows a continuation of this trend, but with localized erosion at R-3 just south of the inlet (note that the jetties were completed in 1954). The 1954 shoreline from R-5 to R-16 showed continued accretion, with the shoreline advancing up to 85 ft relative to the 1949 baseline survey. The reason for this post-inlet accretion is not well understood but appears to be related to subtle changes in the longshore sediment transport rates induced by the inlet and navigation channel through wave refraction and diffraction. Some of this apparent accretion may also be due to the different high water definitions used and the true amount of accretion is probably less than that shown. But by 1954, the amount of shoreline advance is greater than the probable shift in position from HWL to MHW and beaches were certainly accreting in this region.

This pattern of erosion adjacent to the inlet and accretion farther south then continues in the 1958 and 1965 surveys. Both of these surveys show that erosion immediately south of the inlet becomes more severe and advances southward. The shoreline at R-3 has eroded almost 100 ft by 1958 and more than 160 ft by 1965. Much of the shoreline advance that previously occurred near R-5 to R-7 in 1954 has been reversed and the shoreline has eroded in this region by 1958 to 1965. Farther south, the shoreline from R-10 to R-16 continues to accrete, in some places advancing more than 100 feet from the 1947/49 survey. The maximum shoreline accretion appears to have occurred in 1958 near R-10.

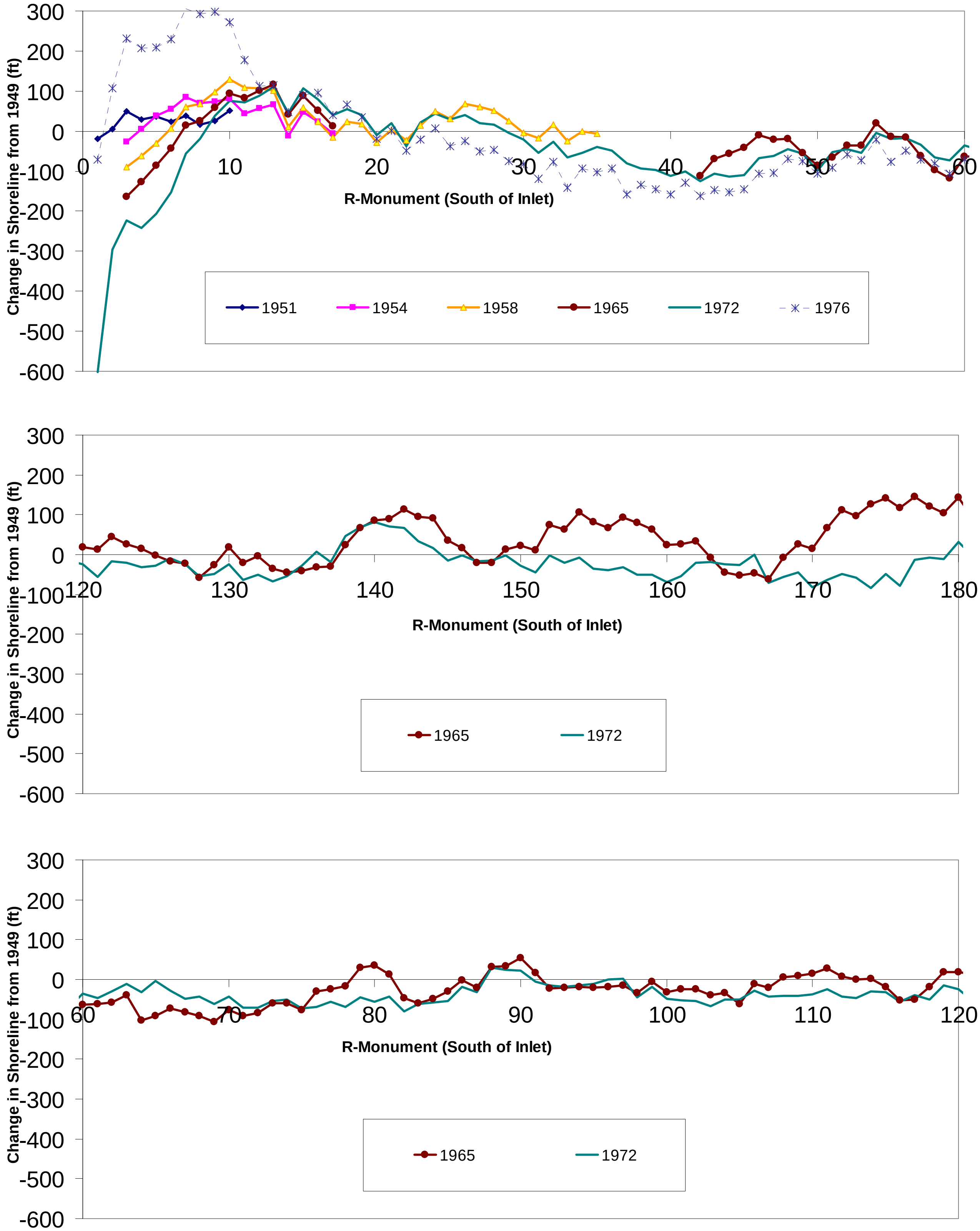


Figure D.5. Historic shorelines south of Canaveral Harbor, from inlet construction (using the 1949 shoreline as a baseline) until 1972 (pre-fill) and 1976 (post-fill).

By 1972, the shoreline near the inlet at R-1 has eroded by about 600 feet while the shoreline from R-2 to R-5 has eroded by more than 200 ft. By comparing the 1972 shoreline to the 1965 shoreline, it is clear that the zone of downdrift erosion has continued to advance to the south, reaching to R-13. The shoreline from R-14 to R-15 was then stable from 1965 to 1972, while the shoreline continued to accrete from R-16 to R-19 by 1972. As a result, both the zones of erosion and accretion show evidence of advancing or migrating to the south by 1972.

This process of progressively advancing erosion in the region from R-1 to R-13 was then arrested in the 1972 and 1974 beach fills, which placed more than 3,000,000 cy of sand on the beach in this region and which widened the beaches 100 to 300 feet seaward of the 1947/49 shoreline.

While the shoreline changes discussed above pertain to a near-inlet zone of erosion and accretion, the shoreline also eroded prior to 1976 over a broad region extending much farther south from R-20 to about R-50. It can be seen that relative to the 1958 survey, the shoreline from R-23 to R-35 (the southern limit of the 1958 survey) had eroded by 1972. This erosion then continued to 1976, even after the 1974 beach fill had stabilized the shoreline closer to the inlet. Similar evidence of erosion can be seen from R-40 to R-50, where the shoreline eroded from 1965 to 1972 and continued eroding to 1976. In places, near R-42, the 1972 and 1976 shorelines have eroded by 120 to 150 ft relative to the pre-inlet shoreline. Unfortunately, limitations in the 1965 survey (the limited number of beach profile lines plus a survey error near R-36), prevent a full definition of the 1965 shoreline between R-18 and R-42. Despite the data gaps, the trend of shoreline erosion between R-30 and R-50 is clear. This is further confirmed by the USACE (1967, 1968) study, which notes that numerous seawalls were constructed in Cocoa Beach (from R-30 to R-45) in 1967 to stop shoreline erosion.

Shoreline changes farther to the south in Brevard County, from R-60 to R-180, are also shown in Figure D.5. Two post-inlet shorelines are shown: from the 1965 USACE beach profiles and from the 1972 FDEP beach profiles. In general, the entire shoreline from R-60 to R-138 (the south limit of the South Reach) experiences slight erosion averaging about 25 feet between 1949 and 1972. This level or erosion (about half the measurement accuracy) is significantly less than that experienced farther north. Farther south, from R-138 to R-180, the 1965 shoreline shows dramatic accretion while the 1972 shoreline shows slight erosion. The reason for this dramatic reversal in shoreline behavior is not clear. However, the spatial uniformity of the erosion in this region by 1972, and the beach changes observed from 1965 to 1972, suggest that this shoreline is not directly influenced by Canaveral Harbor. Although data is limited, the shoreline changes do not reflect a southward-advancing erosion signature from Canaveral Harbor.

The occurrence of the zone of accretion from about R-8 to R-20 has been cited by Kraus et al (1999), and by USACE representatives (David Schmidt, 2002 briefing to the ICE Team) as evidence that the impacts of the Canaveral Harbor are limited to the first 7,000 to 8,000 feet south of the inlet. Shoreline data in Figure D.4 clearly refute this assertion, however, showing that erosion has occurred south of the accretion "bulge" and had reached more than 10 miles to the south to at least monument R-60 by 1972. One fact not pointed out in previous studies is that the accretion "bulge" formed to its maximum seaward extent in the very early years after harbor construction, prior to 1958. Subsequent surveys then show that the accretion "bulge" migrates to the south. This migration is accompanied by erosion on the updrift side of the "bulge", from about R-3 to R-13, and by deposition on the downdrift side of the "bulge", from about R-13 to R-20. This process did not appear prior to inlet construction and can be considered to be one of the impacts of Canaveral Harbor.

Long-Term Response 1972 to present

Shoreline changes for the period from 1972 to 2000 are shown in Figure D.6, for the region R-1 to R-60 (top panel), from R-60 to R-120 (middle panel), and from R-120 to R180 (lower panel). In keeping with the previous analysis, these figures retain the 1949 shoreline as a baseline. The major factor controlling shoreline changes during this period is the placement and subsequent spreading (or loss) of beach fill. In the region from R-1 to R-14, about 3,050,000 cy of fill were placed between 1972 and 1974, 783,000 cy was placed in 1995, and another 1,035,000 cy was placed in 1998. Another 540,000 cy was placed from R-126 to R136 in 1980. Over 850,000 cy was also placed in nearshore fills off of Cocoa Beach from R-28 to R-31 in this time period.

The advance/retreat of the shoreline associated with beach fill placement and spreading occurs most obviously from R-1 to R-30, but data suggests that this fill material spread much farther south to at least R-50 by 1993. The 1974 fill (documented here by the 1976 shoreline) was placed from R-1 to about R-12 and then appears to have spread continuously from the time of its placement until the 1993 survey, at which point the beach in the fill region had eroded almost to its 1972 pre-fill position. At the same time, the shoreline from R-12 to about R-30 shows a net advance due to the downdrift spreading of the fill, so that the shoreline was at its most seaward location by 1993. A small net advance of the shoreline from 1976 to 1993 then is found down to about R-50 or beyond.

By 1997, the shoreline near the inlet has been advanced by the first sand bypassing event. The shoreline near R-30 continued to advance, apparently due to continued downdrift spreading of the 1974 fill. Additional accretion near the inlet is evident in the 2000 shoreline due to the second sand bypassing.

From R-30 to R-60, in the Cocoa Beach area, the shoreline eroded between 1972 and 1976, built back somewhat due to downdrift spreading of the 1974 beach fill, and then eroded again by the 1997 and 2000 surveys. The 1972 shoreline is clearly seaward of subsequent shorelines, however, indicating a net erosion trend in this region. The net result is that shoreline position eroded by about 50 feet between 1972 and 2000.

From R-60 to R-180, shoreline changes have been very small since 1972. The region of Patrick Air Force Base, from R-54 to R-76, shows almost no net shoreline change. This may be due to active shoreline management by the Air Force, which included placement of about 630,000 cy of beach fill through truck hauls. From R-76 to R-100, shoreline changes are also negligible between 1972 and 2000. From R-100 to R-136, the shoreline shows a slight advance from 1972 through 1993, followed by erosion in some areas by 1997. Some effects of the 1980 Melbourne beach fill are apparent in this region. South of Melbourne, from R-140 to R-180, the shoreline was relatively stable from 1972 through 1997.

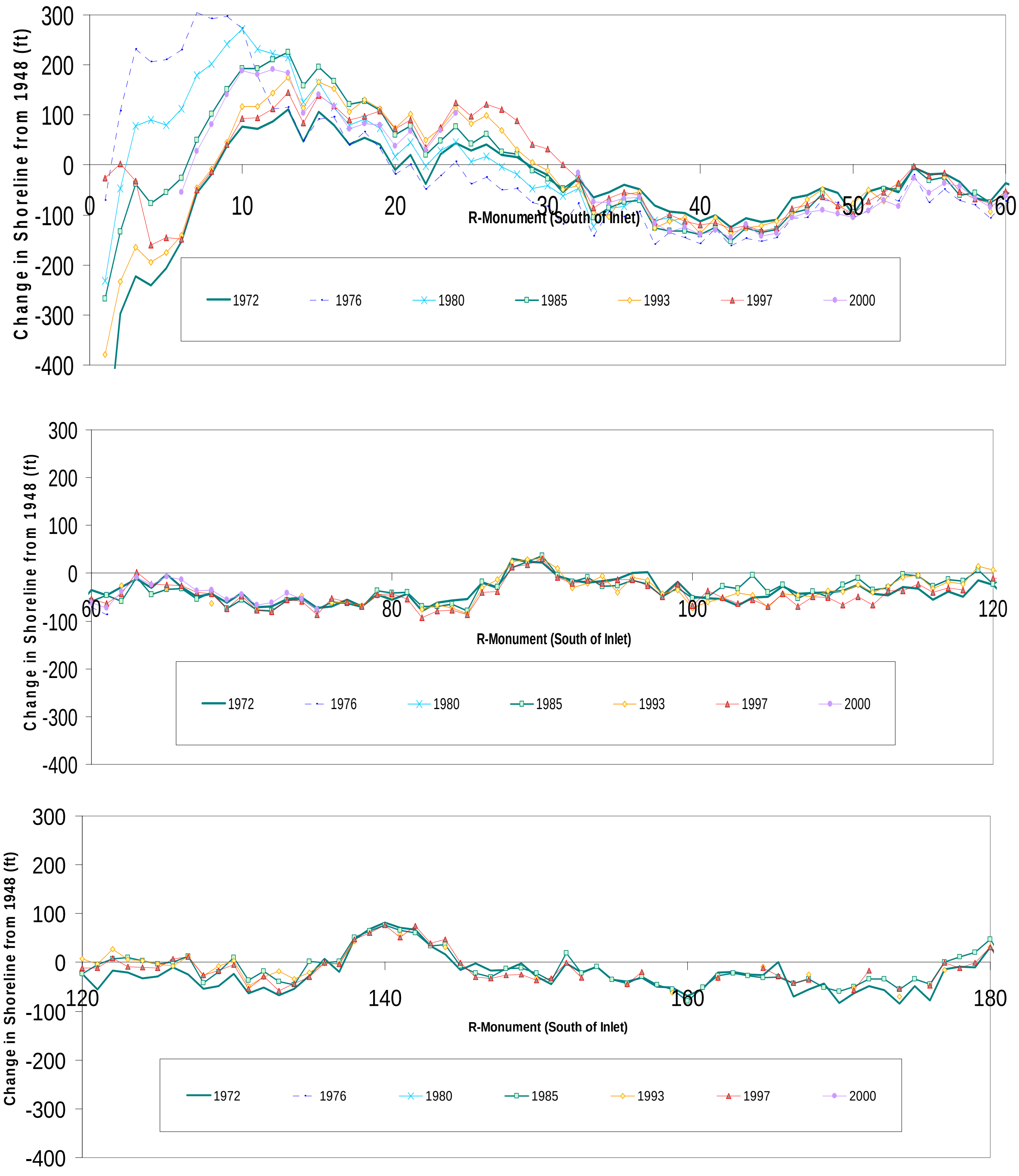


Figure D.6 Historic shorelines south of Canaveral Harbor since 1972.

Standard Deviation of Shoreline Change

One remarkable feature of the long-term shoreline behavior is the general stability of the shoreline south of R-60 or R-70. This is shown directly in the shoreline data in Figure D.6 and may be further illustrated by computing the standard deviation of shoreline changes that have occurred between 1949 and 1997. As shown in Figure D.7, the standard deviation in shoreline change is more than 100 feet near the inlet and is generally greater than about 20 ft as far south as R-60 or so. In contrast, from R-70 to R-215 (where the accretion filet at Sebastian Inlet begins), the standard deviation of shoreline change is much smaller, about 10 feet on average. Based on the noticeable reduction in the standard deviation of shoreline change in Figure D.7, it appears that the downdrift effects of Canaveral Harbor, and the effects of various beach fills placed immediately south of Canaveral Harbor, extend to about R-60 to R-70, some 11 to 13 miles south of Canaveral Harbor.

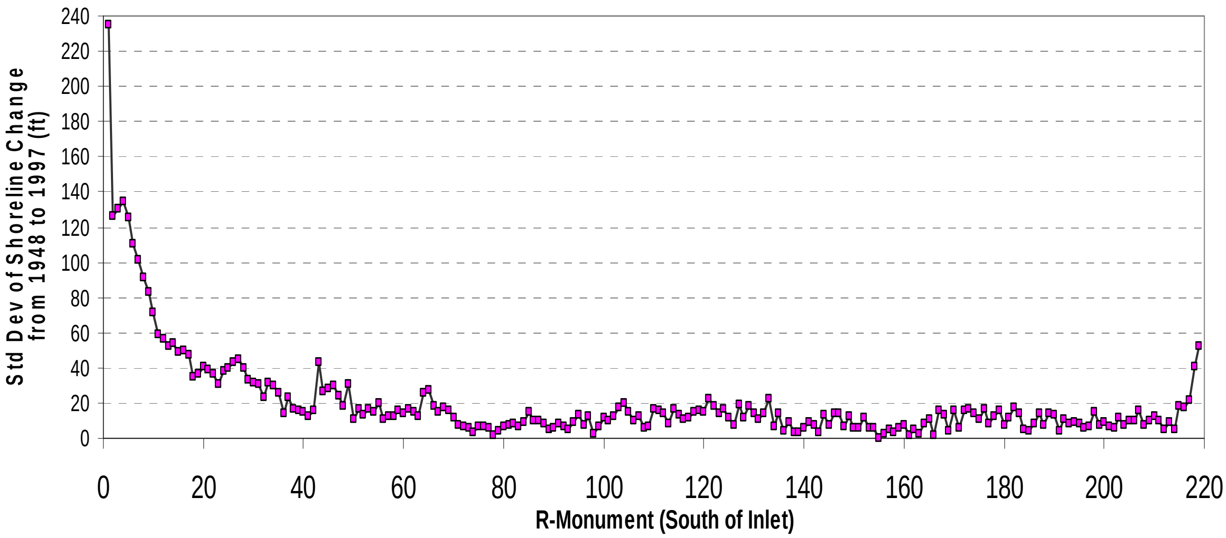


Figure D.7. Standard deviation of shoreline changes at each FDEP survey monument for all historic shorelines from 1949 to 1997.

Discussion of Downdrift Shoreline Shape

One feature of the shoreline south of Canaveral Harbor, which has complicated previous determinations of the extent of downdrift impacts, is the zone of shoreline accretion that appears in between zones of erosion. One outside study which is pertinent to this issue is a recent PhD dissertation by Galgano (1998), which evaluated the downdrift impacts of inlets on adjacent shorelines for much of the US East Coast ranging from New York to South Carolina. While Galgano did not study Canaveral Harbor, several of his findings are pertinent to the question of whether the downdrift impacts of the harbor extend beyond the accretional “bulge” that is observed from about R-10 to R-30.

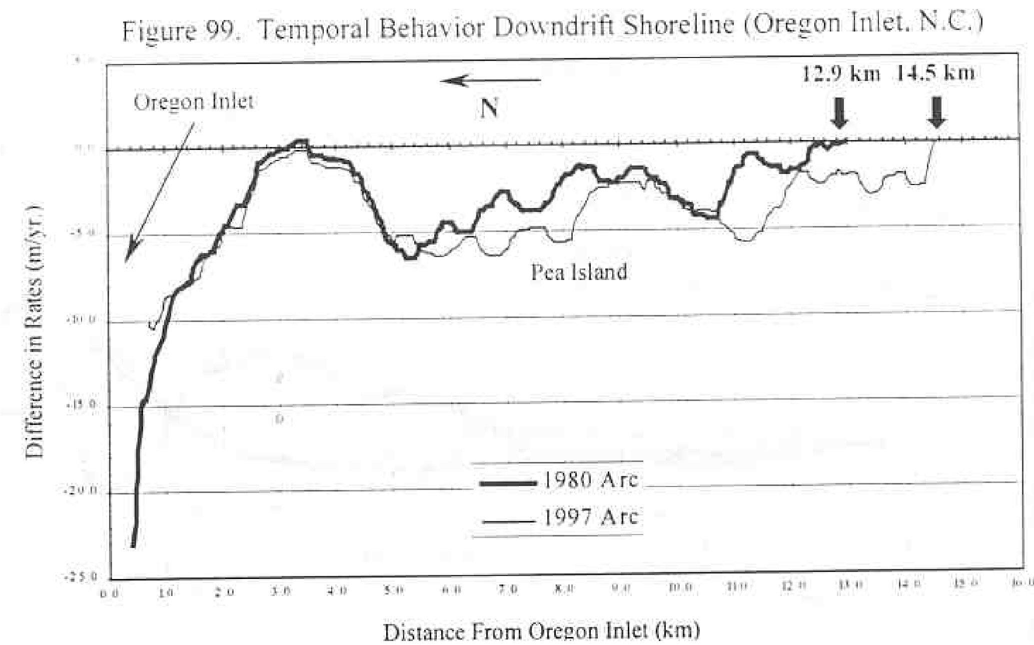
Galgano found that *most* shorelines downdrift from tidal inlets display what he termed a "double S" shoreline configuration. This could be divided into three characteristic regions, illustrated in Figure D.8, reproduced from Galgano (1998. The three characteristic regions are: (1) a near-inlet zone of severe erosion, (2) an intermediate region of mild erosion or even accretion in which the shoreline forms a "bulge", and (3) a far-field zone of erosion that may propagate for considerable distances downdrift. The three zones, taken together, form what Galgano termed the downdrift 'arc of erosion."

Galgano notes that this "double S" configuration was found to some degree in all inlets studied. He further notes that the bulge in the shoreline has lead many to falsely believe that the downdrift erosion impacts stop or are limited when this region of shoreline stability (or accretion) is encountered. In fact, the "arc of erosion" extends much further downdrift well past the "bulge" in the shoreline. This phenomenon was also recognized by Bruun (1995), who offered a simple explanation for the formation of the shoreline bulge based on localized re-orientation of the shoreline in the near-inlet zone, refraction of waves, subtle reductions in wave heights, and associated variability in longshore transport rates.

Applying the "double S" shoreline configuration to the region south of Canaveral Harbor, it is apparent that the near-inlet zone of severe erosion is limited to about the first 8,000 ft (to R-8 or so) south of the inlet. The shoreline "bulge" is quite pronounced, perhaps because the pre-inlet shoreline was so strongly accretional, and extends from about R-8 to about R-30 or so. The far-field arc of erosion then extends from about R-30 to about R-60 or so.

Further evolution of the "double S" shaped arc of erosion was then modified by the major beach fills that occurred in 1974, 1995, and 1998. These fills have prevented any further expansion of the near-inlet erosion zone and have maintained the shoreline in this zone at nearly the pre-harbor position. The sand from the beach fills has then spread to the south. This has allowed the erosion "bulge" to migrate further south and has slowed the erosion in the far-field erosion zone. Data shows the 1974 beach fill has spread to R-50 or so by 1993, offsetting any erosion trend during that time. Shorelines from 1997 to 2000 however show a subsequent erosion trend from about R-40 to R-60.

The conclusion that may be drawn from Galgano's work, when applied to the shoreline south of Canaveral Harbor, is that the downdrift impacts extend well beyond the observed "bulge" in the shoreline where accretion has occurred. Both Kraus et al (1999) and David Schmidt (personal communication) claim that the downdrift extent of impact stops at about R-8 because the shoreline transitions from erosion to accretion at this point. As Galgano points out, this argument misses the fact that the "bulge" is a normal feature within a much larger the arc of erosion, and that more subtle but widespread erosion impacts extend farther downdrift beyond the "bulge" or zone of accretion. In this regard, it is clear that beaches from Cocoa Beach to Patrick Air Force Base, 10 to 14 miles south of the inlet, have been eroding as a result of the far-field arc of erosion caused by Canaveral Harbor.



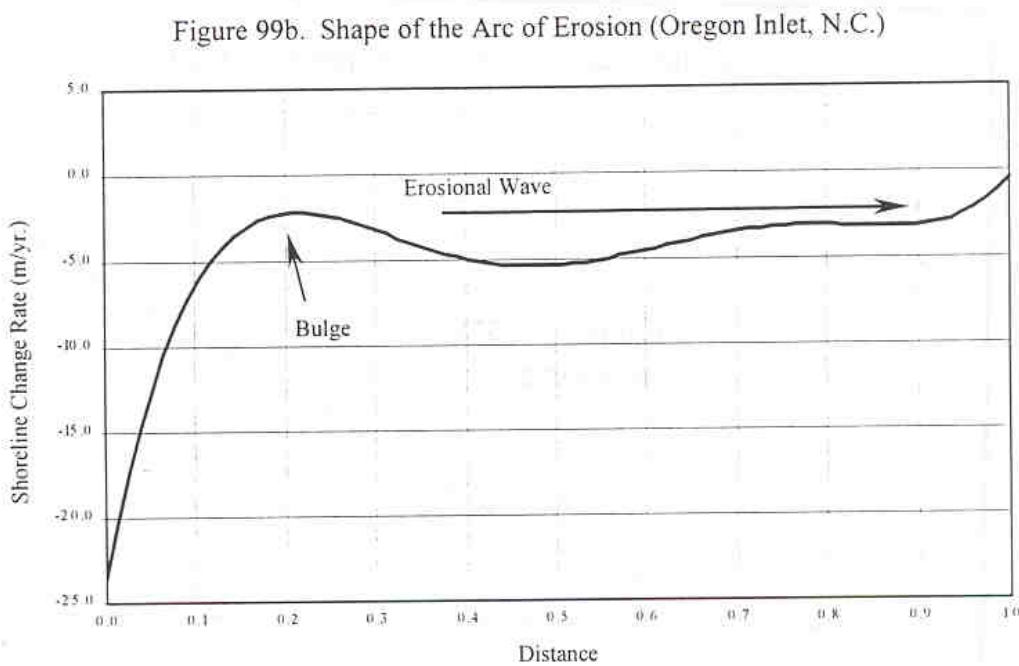


Figure D.8. Double "S" shape of shorelines downdrift of tidal inlets as observed by Galgano (1998). Top panel measured shape for Oregon Inlet, NC. Bottom panel illustrates generalized shape. Both panels illustrate that a shoreline "bulge" forms in the arc of erosion.

Galgano (1998) also quantifies the extent of downdrift inlet impacts by correlating the length of the arc of erosion to both the net longshore sediment transport at the inlet and to the time following jetty construction, both based on empirical analysis of other inlets between New York and South Carolina. Galgano's results suggest that, based on the suspected pre-inlet transport rate of 210,000 cy/yr, the downdrift impact of Canaveral Harbor should extend nearly 18 km or more than 11 miles.

Alternatively, Galgano's relationship for the downdrift extent of erosion versus time following jetty construction suggests that the downdrift impact of Canaveral Harbor should extend approximately 14 km or 9 miles, based on the 48 year age of the Canaveral Inlet jetties (1954 to 2002). However, some inlets in Galgano's data set with jetties as old as those at Canaveral Harbor had down drift erosion impacts extending as much as 19 km or 12 miles. Extrapolating Galgano's result to 2050, the approximate project life for the Brevard County Shore Protection Project, to 2050, suggest that the downdrift impacts may reach at most to about 18 miles south of Canaveral Harbor to about R-95.

These results corroborate our earlier findings that the entire North Reach of the Shore Protection Project has been impacted by erosion caused by Canaveral Harbor. The results similarly support our conclusion that direct erosion impacts probably do not extend to the South Reach of the Shore protection Project.

Comparison of Measured and Expected Shorelines

The average pre-inlet shoreline change rates in Figure D.4 provide a means by which shoreline positions can be predicted under the assumption that pre-inlet accretion trends would have continued if the inlet had not been built. These predicted shorelines can then be compared to the actual or measured shorelines to provide an indication of the degree of harbor impacts. Results of such a comparison are presented in Figure D.9. This figure shows measured shorelines for 1972, 1986, and 1997 compared to the predicted shoreline if the pre-inlet accretion trends had continues without influence from the inlet. These comparisons use the 1949 as a baseline.

In Figure D.9, the difference between the expected and measured shoreline positions represents, in a direct way, the unmitigated impacts of Canaveral Harbor. Results clearly show the three zones of downdrift impacts described in the previous section. Near the inlet, from R-1 to about R-10, the deficit in shoreline position is large in 1972 and does not really diminish despite the mitigation efforts that occur through 1997. The accretion bulge, from about R-10 to R-30, builds at about the expected rate from 1972 to 1986 but then does not grow as much as expected by 1997. The far field erosion zone clearly grows with time relative to the expected shoreline position. From R-30 to R-54, there is a large deficit which increases from 1972 to 1997. Two additional regions, one from about R-60 to R-84 and another from R-100 to near R-120 display a similar deficit that increases with time. The deficit in each region also diminishes farther from the inlet. This suggests inlet impacts may extend throughout most of the Mid Reach. In the South Reach, from about R-120 to R-140, there is some erosion in 1972 that is partially mitigated in 1986 (by the 1980 beach fill) but that returns by 1997. This region may be impacted by the inlet but the effects are rather weak and difficult to attribute fully to the inlet.

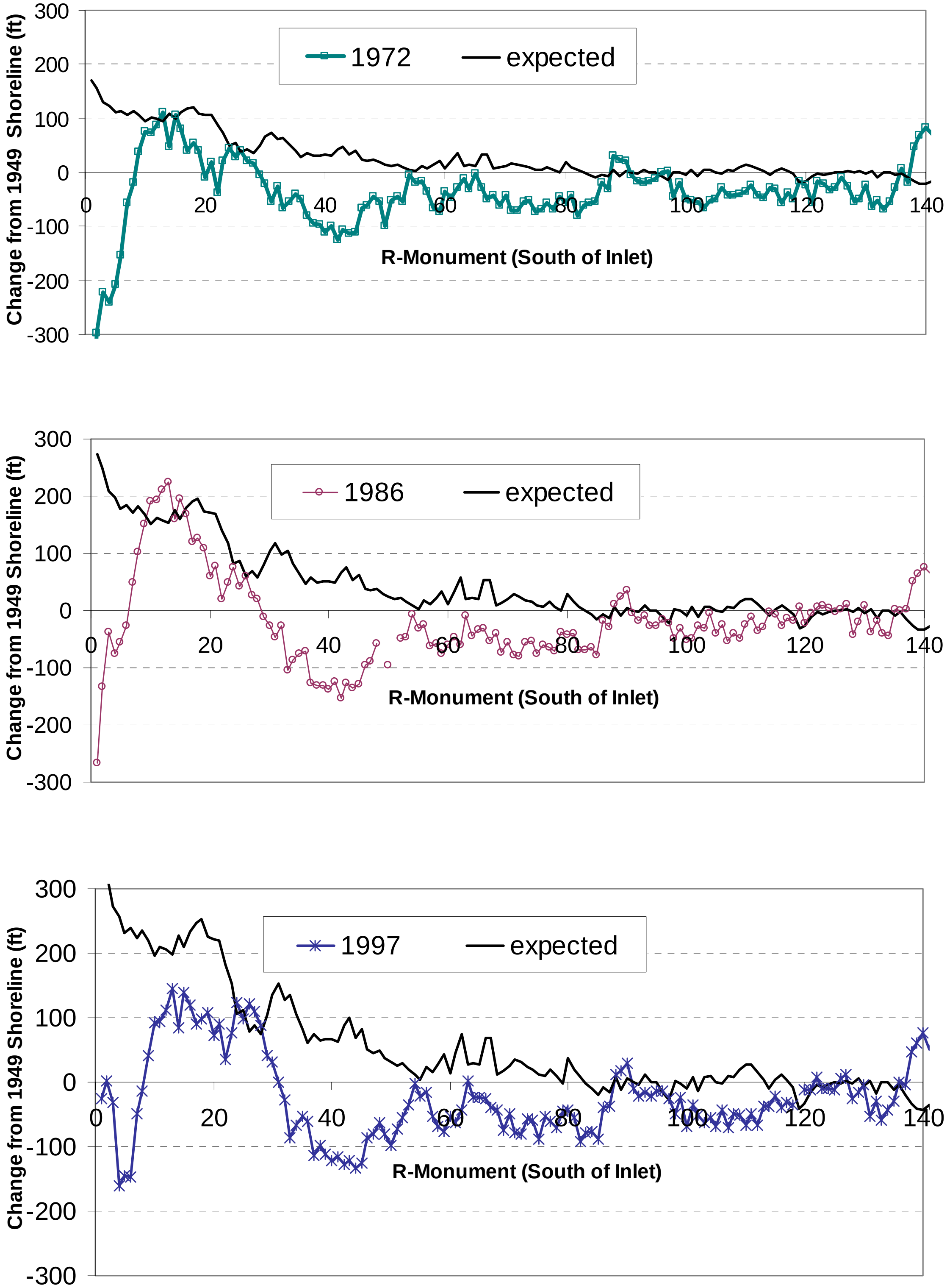


Figure D.9. Comparison of measured shoreline to those expected based on pre-inlet trends.

APPENDIX E
ONE-LINE APPROACH TO INLETS

Introduction

The Scope of Services for this study restricts the ICE Team from conducting major modeling efforts aimed at simulating post-inlet shoreline response. Normally, for a problem such as this, a one-line shoreline model such as the widely-used Corps of Engineers' GENESIS model would be applied. In reviewing past literature for the Canaveral study, we note that only one study, by Walton (1995), explicitly models the downdrift shoreline with the intent of determining the extent of downdrift impacts. Walton (1995) used an analytic solution for the shoreline evolution at an impermeable groin as a model of an inlet with sand-tight jetties. His solution predicts the growth of an accretion fillet on the north side of the inlet and erosion of the exact same magnitude south of the inlet. Walton found that the inlet-induced erosion was apparent 12 miles south of the inlet.

Walton's analytical model is based on the theory of Pelnard-Considère (1956), which has proven to be useful in a variety of contexts, such as predicting the deposition of sand at groins, and the lifetimes of beach fills (e.g., Dean 1991). The Pelnard-Considère model also serves as the basis of the numerical model GENESIS, used by the Corps of Engineers. As such, it can provide a highly simplified prediction of downdrift shoreline change that should be in general agreement with a more thorough modeling effort using GENESIS. Examples of various analytical solutions based on Pelnard-Considère's model are given by Le Mehaute and Soldate (1979) and Larson, Hanson, and Kraus (1997).

While Walton found downdrift impacts extending for 12 miles south of the inlet, several assumptions used in that model may lead to an overestimate of the length of downdrift impacts. Rather than accepting the 12-mile zone of impact, we believe that it is important to make some simple modifications to Walton's model and re-peat his calculations for the extent of downdrift impacts. While such a modeling effort is highly simplified, it is based on fundamental principles for longshore sediment transport that are widely-accepted in the coastal engineering profession.

As mentioned in this report, sand is transported into the inlet around, through, and over the Cape Canaveral jetties. Dean and Work (1993), recognizing that sand is often transported into inlets, superimposed two solutions of the Pelnard-Considère equation: the first was the same as used by Walton, the second was a sink solution, which allowed for the transport of sediment into the inlet channel from both sides equally. They were able to show that these solutions provide an asymmetric solution at the jetties - that is, the updrift side of the inlet impounds a different amount of sand than is eroded from the downdrift beach. This provides a basis for explaining the empirical even-odd analysis method (Berek and Dean, 1982) used to illustrate the effects of inlets on shorelines.

In the following analysis, we first modify Walton's model to allow a sediment flux into the inlet through (or over) each of the jetties. Furthermore, we allow this to occur at a different rate on each side so as to simulate the observed effects of 90,000 cy/yr flowing into the inlet from the north side and 126,000 cy/yr flowing into the inlet from the south side. On the updrift side, this will mean that the sand will not impound against the jetty as fast as for a sand-tight jetty

(Walton's solution) and, on the downdrift side, there will be a local reversal of the longshore transport to allow for the loss through the jetty.

In addition, our modifications allow the longshore transport toward the inlet on the updrift side and away from the inlet on the downdrift side to have different rates. Canaveral Harbor is unique because there is a strong natural decrease in longshore sediment transport rates from north to south across the harbor. In the following, we allow sand to flow toward the harbor at a rate of 210,000 cy/yr while the sediment transport rate several miles south of the inlet is only about 50,000 cy/yr. Again, this more realistic approach should provide a better estimate of the shoreline response to the inlet jetties than the traditional solution used by Walton.

Pelnard-Considère Approach

The shoreline is assumed to lie along the *x*-axis, with *y(x)* being the displacement of the shoreline from the axis. The beach profile is assumed be always in the same equilibrium profile. The conservation of sand, balancing shoreline recession or advance with changes in the longshore sediment transport rate is

$$\frac{\partial y}{\partial t} + \frac{1}{h_* + B}\frac{\partial Q}{\partial x} = 0$$

where *Q(x)* is the longshore sediment transport rate, and h_* is the depth of closure for the equilibrium profile and *B* is the berm height.

The longshore transport rate is related to the wave climate and shoreline planform by

$$\begin{aligned} Q(x) &= C_q \sin 2(\delta_b - \gamma) \\ &\approx C_q \sin 2\delta_b - 2\gamma C_q \cos 2\delta_b \\ &= Q_0 - G(h_* + B)\frac{\partial y}{\partial x} \end{aligned}$$

for small angles. Here δ_b is the incident wave angle measured from the *y* axis, γ is the shoreline normal angle, measured from the *y* axis, and

$$C_q = \frac{K\rho H_b^{5/2}\sqrt{g/\kappa}}{16(\rho_s - \rho)(1-p)}$$

In this expression, H_b is the breaking wave height, ρ is the water density, ρ_s sediment density, *p* is the porosity of the sediment in place, *g* is the acceleration of gravity, and *K* is the breaking index.

Substituting the equation for *Q(x),* into the conservation of sand equation yields the Pelnard-Considére equation

$$\frac{\partial y}{\partial t} = G\frac{\partial^2 y}{\partial x^2}$$

that can be solved for the shoreline position *y(x)* as a function of time. *G* is defined as the shoreline diffusivity, taking on values in the range of 0.002 to 0.014 m^2/s. Numerous solutions of this equation exist with coastal applications (*e.g.*, Le Mehaute and Soldate, 1979; Larson *et al.* 1997, and Dean and Dalrymple, 2002).

For a tidal inlet, prescribed by impoundment of sediment on the updrift impermeable jetty and an impermeable downdrift jetty, the solution obtained using Laplace transforms is

$$y(x,t) = \pm \tan\delta_b \left(\sqrt{\frac{4Gt}{\pi}} e^{-x^2/(4Gt)} - |x| \text{ erfc } \left(|x| / \sqrt{4Gt} \right) \right)$$

This is, in fact, the same solution as used for a shore-perpendicular groin. Here *x* is measured alongshore from the jetty and the plus/minus sign correspond to the updrift/downdrift jetties. This expression governs the evolution of the shoreline until the shoreline grows out to the length of the updrift jetty. Dean and Work (1993) show a non-dimensional plot of the upstream impoundment and the equal and opposite downdrift erosion. In this sense, the solution is and "odd" function as shoreline change on either side of the inlet has opposite signs. The boundary conditions used at each jetty is that the shoreline normal is parallel to the wave angle of incidence:

$$\frac{\partial y}{\partial x} = -\tan\delta_b,$$

and, for large $|x|$ far from the inlet, $y(x)\rightarrow 0$. This last condition means that $Q(x)\rightarrow Q_o$. This transport rate is assumed to be same on the updrift and downdrift sides of the inlet.

Dean and Work also examine the case in which sand is removed from the inlet (either by deposition on flood and ebb shoals or by dredging). They used a separate solution for this:

$$y(x,t) = -\frac{Q_R}{2G\sqrt{\pi}(h_* + B)} \left(\sqrt{\frac{4Gt}{\pi}} e^{-x^2/(4Gt)} - |x| \text{ erfc } \left(|x| \sqrt{4Gt} \right) \right)$$

where Q_R is the rate at which sediment is removed at the inlet. This solution is "even" in the sense that the solution is symmetrical on either side of the inlet. Removal of sand causes the shoreline to recede on both sides.

Using the two solutions of the Pelnard-Considère equation, one mathematically even about the inlet channel centerline and the other odd, Dean and Work examine a series of Florida tidal inlets by the Even-Odd method (Berek and Dean (1982)).

Here a new approach is taken, such that the underlying solutions no longer are either even or odd. A key revision here is that we permit more sediment to move into the inlet from one side than the other, this simulating the situation at Canaveral Harbor where more sand has entered the harbor from the south than from the north.

Revised Inlet Model

The boundary conditions at the jetties are determined by the longshore transport rate. For no transport at the inlet, we have

$$Q(0) = Q_o - G(h_* + B)\frac{\partial y}{\partial x} = 0$$

By definition, $\frac{\partial y}{\partial x} = \tan\delta_b$, when the wave angle of incidence is normal to the shoreline. This gives us

$$Q_o = G\left(h_* + G\right)\tan\delta_b, \quad \text{and} \quad \tan\delta_b = \frac{Q_o}{G(h_* + B)}$$

If the sediment transport through the updrift jetty is Q_{il} and the transport into the downdrift jetty is Q_{ir}, then, using the above equations, we find

$$\frac{\partial y}{\partial x} = \tan\delta(1 - Q_{il}/Q_o), \quad \text{for } x > 0$$
$$\frac{\partial y}{\partial x} = \tan\delta(1 + Q_{ir}/Q_o), \quad \text{for } x < 0$$

These boundary conditions imply that the orientation of the shoreline at the updrift jetty is not as large as the case for no sediment flux, that is, less than tan δ_b, while the orientation on the downdrift shoreline is larger than the orientation for normal wave incidence. This also implies that there will be a nodal point for the sediment transport on the downdrift shoreline. Near the inlet the transport will be towards the inlet, while further downcoast, the transport will be away from the inlet. The location of the nodal point will be denoted x_n.

The modified inlet solutions are now

$$y = +\tan\delta\left(1 - Q_{il}/Q_o\right)\left(\sqrt{\frac{4Gt}{\pi}}e^{-x^2/(4Gt)} - |x| \text{ erfc }\left(|x|/\sqrt{4GT}\right)\right), \; x < 0$$

$$y = -\tan\delta\left(1 + Q_{ir}/Q_o\right)\left(\sqrt{\frac{4Gt}{\pi}}e^{-x^2/(4Gt)} - x \text{ erfc }\left(x/\sqrt{4Gt}\right)\right), \; x > 0$$

The associated sediment transport is given by

-

$$Q(x,t) = Q_o + Q_o\left(1 - \frac{Q_{il}}{Q_o}\right) \text{ erfc } \left(|x| / \sqrt{4Gt}\right),\ x < 0$$

$$Q(x,t) = Q_o - Q_o\left(1 - \frac{Q_{ir}}{Q_o}\right) \text{ erfc } \left(x / \sqrt{4Gt}\right),\ x > 0$$

Nodal Point and reversal of transport Downdrift

The nodal point x_n on the downdrift shoreline is found by setting $Q(x,t) = 0$ in the last equation.

$$\frac{1}{(1 + Q_{ir} / Q_o)} = \text{ erfc } \left(x_n / \sqrt{4Gt}\right)$$

For no transport into the inlet, the left side of this equation is unity, and the solution is $x_n = 0$ as there is no nodal point for $Q_{ir} = 0$. For positive values of Q_{ir}, then the solution is $x_n = c_n\sqrt{4Gt}$. For example, for $Q_{ir}/Q_0 = 0.2$, $x_n = 0.1791\sqrt{4Gt}$. With time, the value of x_n increases—the nodal point moves alongshore, but at an ever-slowing rate, as the length of the eroding shoreline increases with time.

Extent of the Erosion

On the updrift and downdrift sides, there is a distance beyond which the inlet has no affect on the shoreline. This point, x_p, must be defined arbitrarily because the inlet affected shoreline approaches the original shoreline asymptotically. If *y(0)* is the shoreline position at the jetty, then the downdrift extent of erosion can be defined when the shoreline change is 1% of that at the jetty. This can be expressed as

$$\frac{y(x_p)}{y(0)} = \frac{1}{100} = -e^{-x_p^2/(4Gt)} - \frac{x_p}{\sqrt{4Gt}} \text{ erfc } \left(x_p / \sqrt{4Gt}\right),$$

Solving this transcendental equation for x_p numerically, we obtain $x_p = 1.606\sqrt{4Gt}$ as the extent of downdrift erosion. The point moves continuously downdrift, but also with a slower rate with time.

Filling of Updrift Jetty

The updrift solutions are valid until the shoreline at the updrift jetty grows out the entire length of the jetty. The time for this to occur is t_b, and the condition to determine it is $y(0^-, t_b) = 1$, the length of the jetty. The result is

$$t_b = \frac{1^2\pi}{4G\tan^2\delta\left(1 - \frac{Q_{il}}{Q_o}\right)^2}$$

After this time, the sediment bypasses the jetty, and Pelnard-Considére gave the solution:

$$y(x,t) = 1 \ \text{erfc}\left(\frac{|x|}{\sqrt{4Gt}}\right) \quad t > t_b$$

The problem is that the updrift fillet is not the same size for the two solutions. Therefore, the fillet area (or volume) for each solution at $t=t_b$ can be matched to make the solutions work better together. Using the area, and denoting t^* as the time for which the bypassing solution has the same area at the non-bypassing solution,

$$1\left(\sqrt{\frac{4Gt^*}{\pi}}\right) = \frac{Q_o - Q_{il}}{(h_* + B)} \ t_b$$

Substituting for t_b,

$$t^* = \frac{\pi^3 1^2}{64G \tan^2 \delta_b \left(1 - \frac{Q_i l}{Q_o}\right)}$$

This time is then used to adjust the bypassing solution.

$$y(x,t) = 1 \ \text{erfc}\left(\frac{|x|}{\sqrt{4Gt(t-(t_b y - t^*))}}\right), t > t_b$$

The associated sediment transport is then (from Eq.)

$$Q = Q_0 - \frac{G(h_* + B)1}{\sqrt{G(t-(t_b y - t^*))\pi}}$$

which grows with time to become Q_o.

Application to Canaveral Harbor

For the Port Canaveral Entrance, the model is used with the following values: (1) on the updrift side, the transport toward the inlet is 210,000 cy/yr, (2) on the downdrift side, the transport away from the inlet is 50,000 cy/yr at a distance of 60,000 feet from the inlet, and (3) transport into the inlet past the jetties is 90,000 cy/yr from the north and 126,000 cy/yr from the south for the first figure (E.1). The simulation is from 1952 to 1998, including the 1974-1975 fill. The shoreline on both sides of the inlet is shown in four-year increments in the figure. The green dots on the downdrift side show the location of the point of the littoral drift reversal direction (a nodal point), which moves to the south with time with a maximum downdrift location from the inlet of about 1.5 miles. At this nodal point, there is no net littoral drift.

The results show that the disruption of the littoral transport by the inlet increases as time goes on and the maximum effect in 1992 extended about 8 miles south of the inlet. This is significantly less than the 12 miles computed by Walton because of the modifications made here. Walton assumed a uniform transport rate north and south of the inlet. The lower 50,000 cy/yr rate assumed here downdrift of the inlet gives less overall impact than Walton. On the other hand, Walton assumed no losses to the inlet while our result has losses from both north and south.

The loss of sand into the inlet from both the north and south jetties is a loss of sand to the beaches. On the south side, the movement of 126,000 cy/yr north into the inlet comes from the south beach. Since there is a nodal point for the littoral transport, this means that there is erosion from the south beach between the south jetty and the nodal point, since the littoral transport rate changes from zero to 126,000 cy/yr in the distance from the nodal point to the inlet. (The sand tightening of the southern jetty removes most of the loss of material into the inlet from the south. This will slow the rate of shoreline erosion near the jetty.)

In Figure E.2, the same calculation is made except that the transport through the south jetty is assumed to be only 60,000 cy/yr, as indicated in the sediment budget in Appendix G. Comparing the two figures, we see that more of the 1974 fill remains in the second case and the erosion next to the south jetty is significantly less. The erosion to the south is in fact less than observed. The downdrift extent of the erosion is however about the same (over 40,000 ft to the south of the south jetty or about 8 miles).

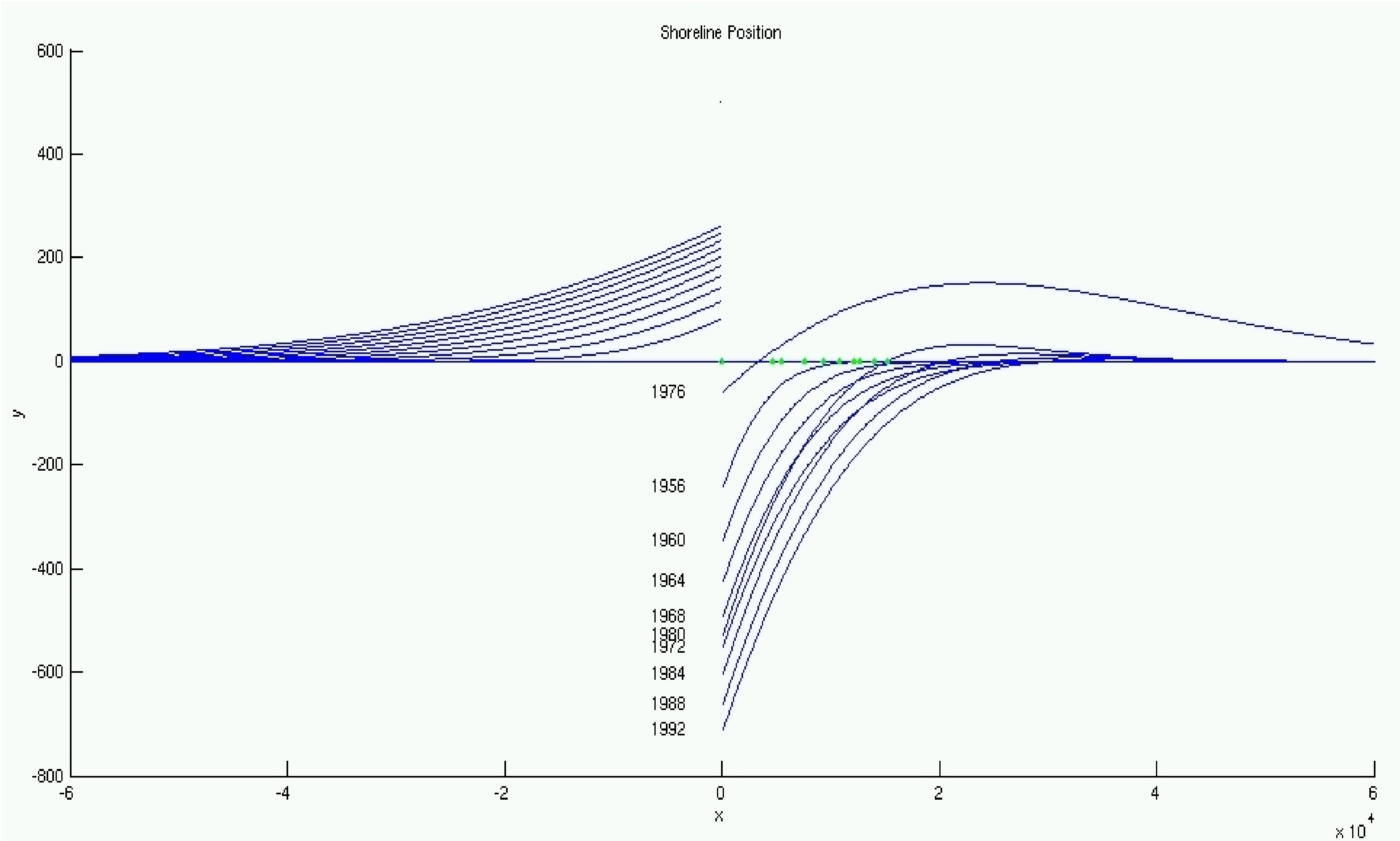


Figure E.1. Shoreline positions north and south of the inlet predicted by one-line model including sediment transport into the inlet (90,000 cy/yr from north and 126,000 cy/yr from the south jetty). The positions of the nodal point in sediment transport downdrift of the inlet are shown moving to the right (south) over time

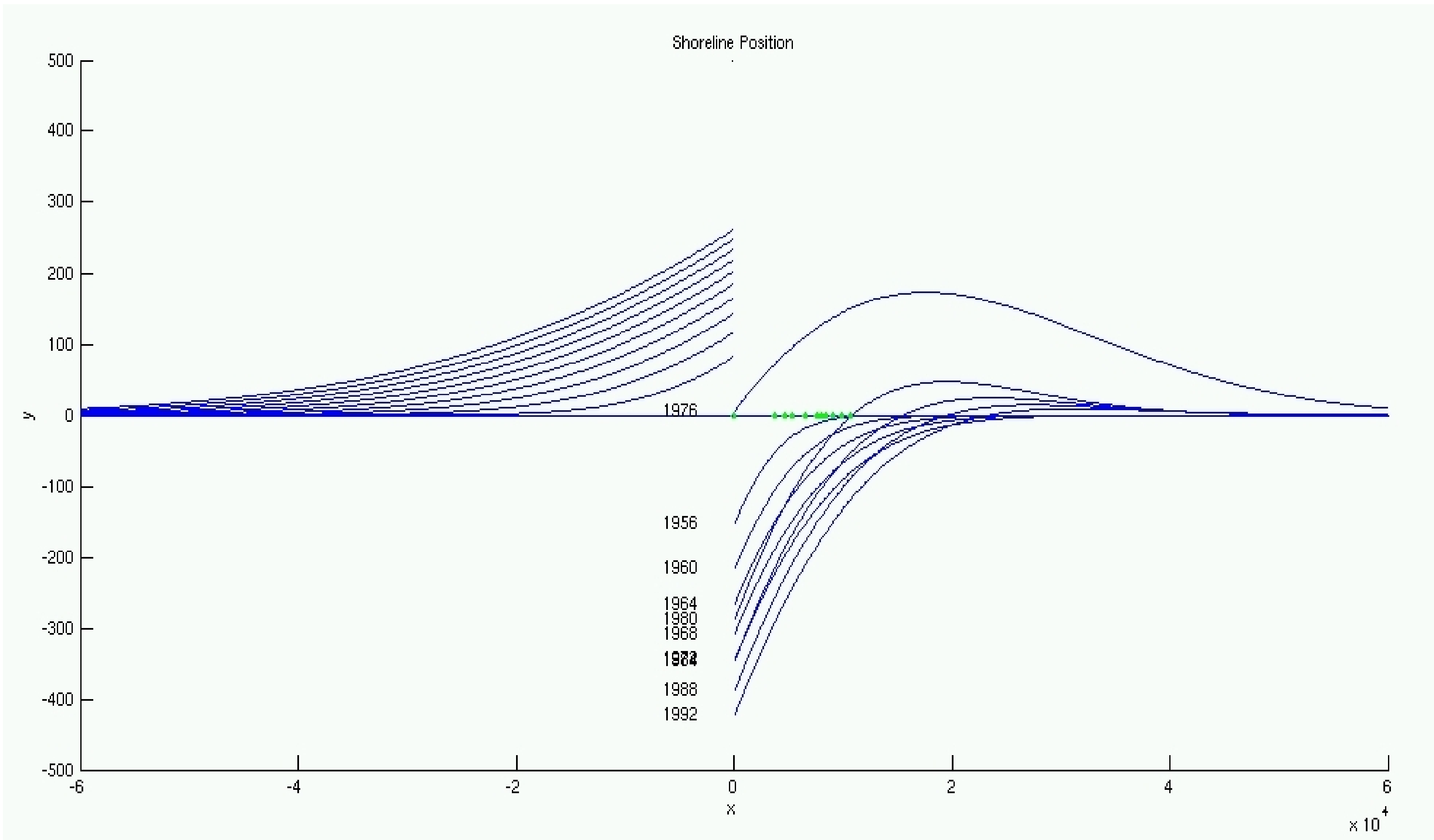


Figure E.2. Shoreline positions north and south of the inlet predicted by one-line model including sediment transport into the inlet (90,000 cy/yr from the north and 60,000 cy/yr from the south jetty). The positions of the nodal point in sediment transport downdrift of the inlet are shown moving to the right (south) over time

APPENDIX F
VOLUMETRIC EROSION SOUTH OF CANAVERAL HARBOR

Background

The volume of sand trapped in the navigation channel or udrift of the inlet must also be reflected in an equal volume of erosion south of the inlet. For Canaveral Harbor, however, the observed volume eroded downdrift will be less than that trapped updrift because the pre-inlet trend was shoreline accretion. As a result, much of the volumetric impact of the harbor has been to prevent the natural shoreline accretion. This "unrealized accretion" or "foregone accretion" represents a very real impact of the harbor on the beach system of Brevard County. The total volumetric impact of the harbor will therefore consist of two components: (1) the actual or observed volumetric erosion and (2) the "unrealized" or "foregone" accretion that never occurred.

Quantifying the volumes of both the "unrealized accretion," and the actual or measurable erosion presents a difficult problem in data analysis. The actual or observed erosion volume can be documented through direct volume computations, in which beach profiles or bathymetric surfaces are compared and the volume between them integrated in the longshore direction, or through indirect methods, in which the volume change is inferred from the longshore integration of shoreline change. The "unrealized accretion", in contrast, cannot be determined from direct volume computations because future beach profiles or bathymetric surfaces cannot be projected forward in time. In contrast, trends in shoreline change can be easily projected in time, thus allowing an estimate of the "unrealized" accretion that would have occurred if the inlet had not been constructed (see Figure D.9). Given this advantage of the indirect method, and given problems in beach profile data to be discussed below, we conclude that we must rely on the indirect computation of volume change from shoreline change instead.

Despite the difficulties with computing beach volume changes, relatively good agreement can be found near the inlet between direct volume computation and computation of volume from historic shoreline change. Figure F.1 shows a comparison between volume changes for the region 10,500 feet south of Canaveral Harbor as listed by Kraus et al (1999), based on beach profiles and measured three-dimensional bathymetry, and as computed from shoreline change using a conversion of 0.92 cy per foot of shoreline change per foot alongshore. In this two-mile long region, volume changes computed by the two methods are in very good agreement. Both methods capture the erosion prior to the 1974 beach fill, the increase in beach volume associated with the 1974 fill, the erosion following the fill until the 1995 sand bypassing, and the subsequent increase in beach volume due to sand bypassing.

Unfortunately, such good agreement is not obtained farther south with increasing distance from the inlet. In these regions, direct volume measurements are very limited. In addition, because of problems with beach profile data discussed below, volume computations become increasing unreliable with increased distance from the inlet. As documented elsewhere in this report, downdrift impacts from Canaveral Harbor extend from about 10 to 15 miles south of the inlet. For this distance, no reliable direct measurements of volume change exist for the period from 1954 to the present, and we therefore rely on volume changes inferred from shoreline change.

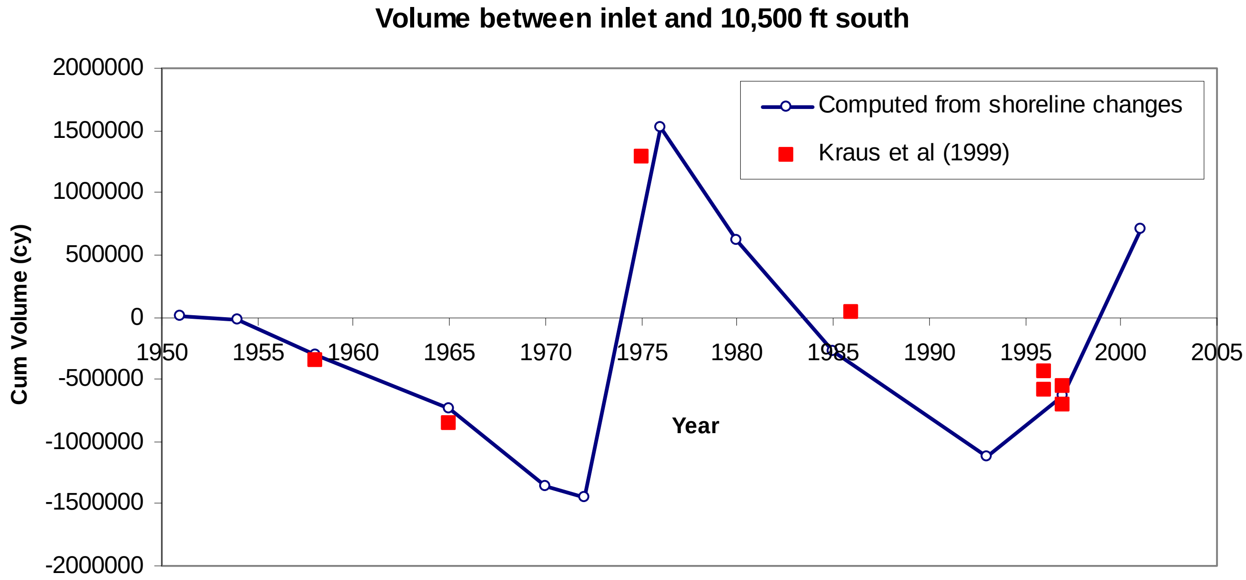


Figure F.1. Comparison of direct volume changes reported by Kraus et al (1999) to those inferred from shoreline changes for the first two miles south of Canaveral Harbor.

Problems with Direct Volume Measurements

In the initial project meeting, and in subsequent review comments, the Government representatives have repeatedly suggested that we use beach profile and bathymetric data as a basis for volume computations. In response to their suggestion, we have tried this approach; however, we have found two major problems with direct volume measurements based on use of beach profiles or bathymetric surveys. First, beach profile and bathymetric surveys south of Canaveral Harbor have been too limited in their spatial and temporal coverage. Second, beach profiles do not "close" in the offshore, producing very large changes in sand bed elevations, from survey to survey, in water depths of 20 to 30 ft beyond the assumed depth of closure. We find that these problems prevent an accurate determination of sand volume change south of Canaveral Harbor.

The first problem noted above is a lack of spatial and temporal resolution in beach profiles and bathymetric surveys for the 10 to 15 mile reach of shoreline where volume losses are expected to occur. Kraus et al (1999) document the various beach profile and bathymetric surveys and show that most are limited to the first few miles south of the inlet. The best documented region extends to a point 10,500 ft (2 miles) south, while a limited number of volume calculations which extend to a distance of 34,400 ft (6.5 miles) south of the harbor. The USACE (1962 Sand Bypass Study) similarly covers a distance of only 16,500 ft (about 3 miles) south of Canaveral Harbor. Volume computations in the USACE (1992 Sand Bypass Study) also extend only 2 miles south of the inlet. None of these studies are sufficient to document the full extent of downdrift impacts of the harbor.

Better spatial coverage is given by the USACE (1998 Brevard County Shore Protection Project) and Olsen Associates (2002). They give volumetric changes extending over most of the Shore Protection Project limits from R-1 to R-53 and from R-76 to R-137. The Olsen study also computes volume from R-54 to R-75 (Patrick AFB) while the USACE study omits this segment. While these volume computations cover the required distance south of the inlet, they cover a limited time period after 1972. As a result, they miss about 20 years of the volumetric erosion caused by the inlet and cannot be used to fully document the inlet impacts.

A second and more severe problem with historic data is that beach profiles do not exhibit 'closure" in the offshore region. One absolute requirement for computing volume change from breach profiles is that all beach change must occur landward of (or above) an assumed depth of closure. Beyond this depth, beach profile changes must be negligible and profiles must closely-agree from one survey to another.

Unfortunately, beach profiles from Brevard County do not exhibit any reasonable degree of closure. In the reports we have reviewed, previous studies have assumed a depth of closure ranging from -16 ft NGVD to -20 ft NGVD. However, beach profile data provided to us (by the USACE on CD-ROM) show large changes in beach profiles well seaward of these depths. In depths of -20 to -30 ft, beach profiles show 2 to 5 feet of vertical change and several hundred feet of horizontal change from one survey to another. Similar observations of this lack of closure have been noted by Olsen Associates (2002).

Lack of Closure of Beach Profiles

The problem with lack of profile closure is illustrated in Figure F.2 which shows four beach profiles provided to the ICE Team as part of this study.

The first profile, located near FDEP monument R-10, shows a few of the problems associated with computing the cross-sectional area of profile change from one survey to another. The initial baseline survey, from 1951, extends only to a depth of -17 ft NGVD, while the 1954 survey extends to -20 ft NGVD, and the 1958 and 1965 surveys extend to -30 ft NGVD. As a result, volumes cannot be computed relative to 1951 or 1954 unless a depth of closure of -17 ft to -120 ft is assumed. However, it is clear that significant beach profile changes occur in depths greater than either -17 or -20 ft according to later surveys. In fact, area (volume) changes between the 1958 and 1965 profiles in depths greater than 20 feet are comparable to the area (volume) changes in depth less than 20 feet.

Similar, but more severe, problems with lack of closure are found in the other three profiles R-36, R-74, and R-105. In all cases, vertical differences of 4 to 5 feet are found at the seaward end of the beach profiles, in depths between -20 and -30 ft NGVD where profiles should close. In most cases, the 1965 surveys appears anomalously lower (steeper) than the 1972 and 1986 profiles. Olsen Associates (2002) show many additional profiles, however, in which profiles measured after 1972 have exhibited a lowering once again. Two examples are reproduced in Figure F.3. These profiles shows that the 1998 and 2000 profiles are more than 4 feet lower than the 1972 and 1986 profiles in depths of -20 to -30 ft NGVD.

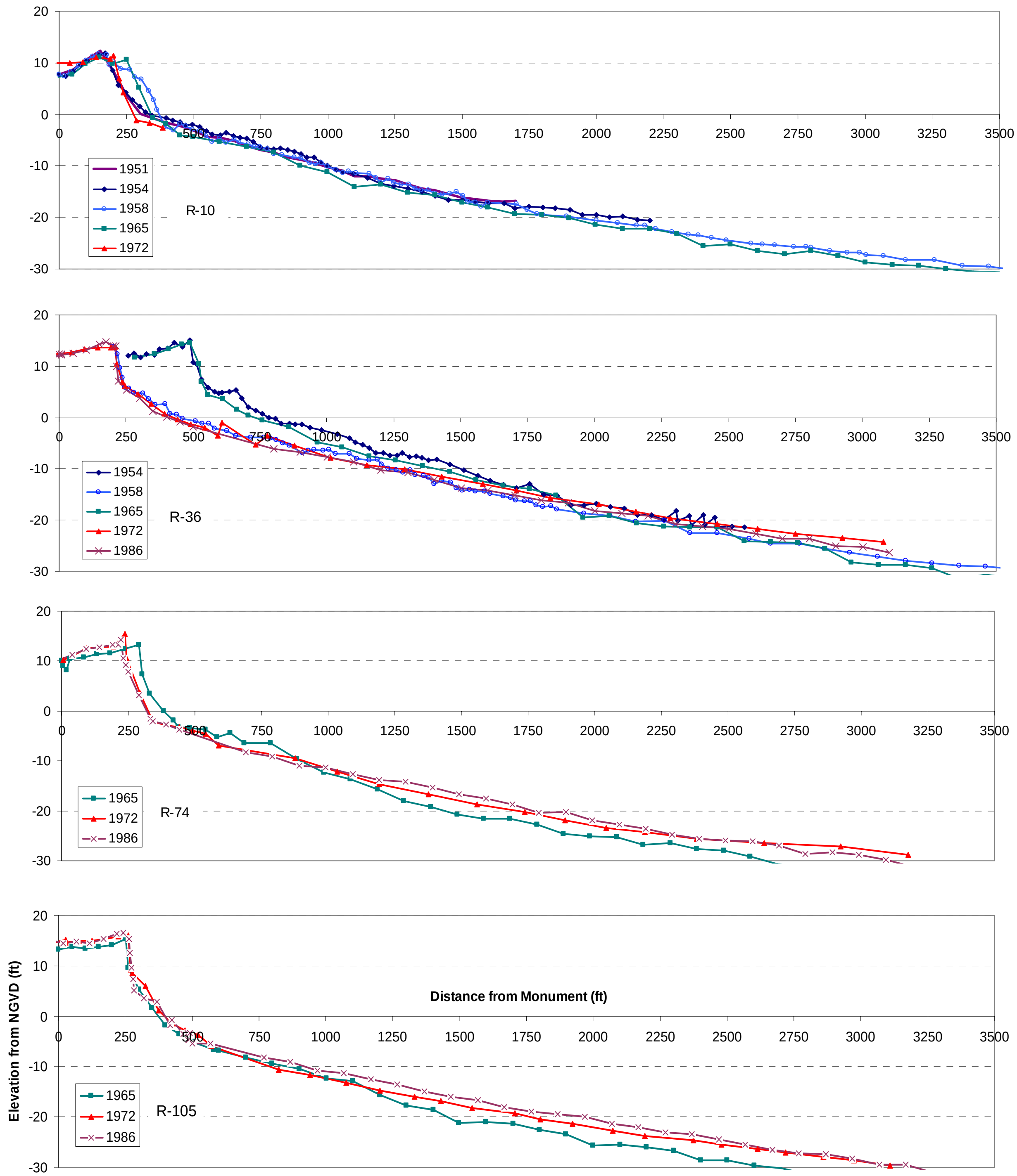


Figure F.2. Typical beach profiles from Brevard County showing lack of closure in the offshore region.

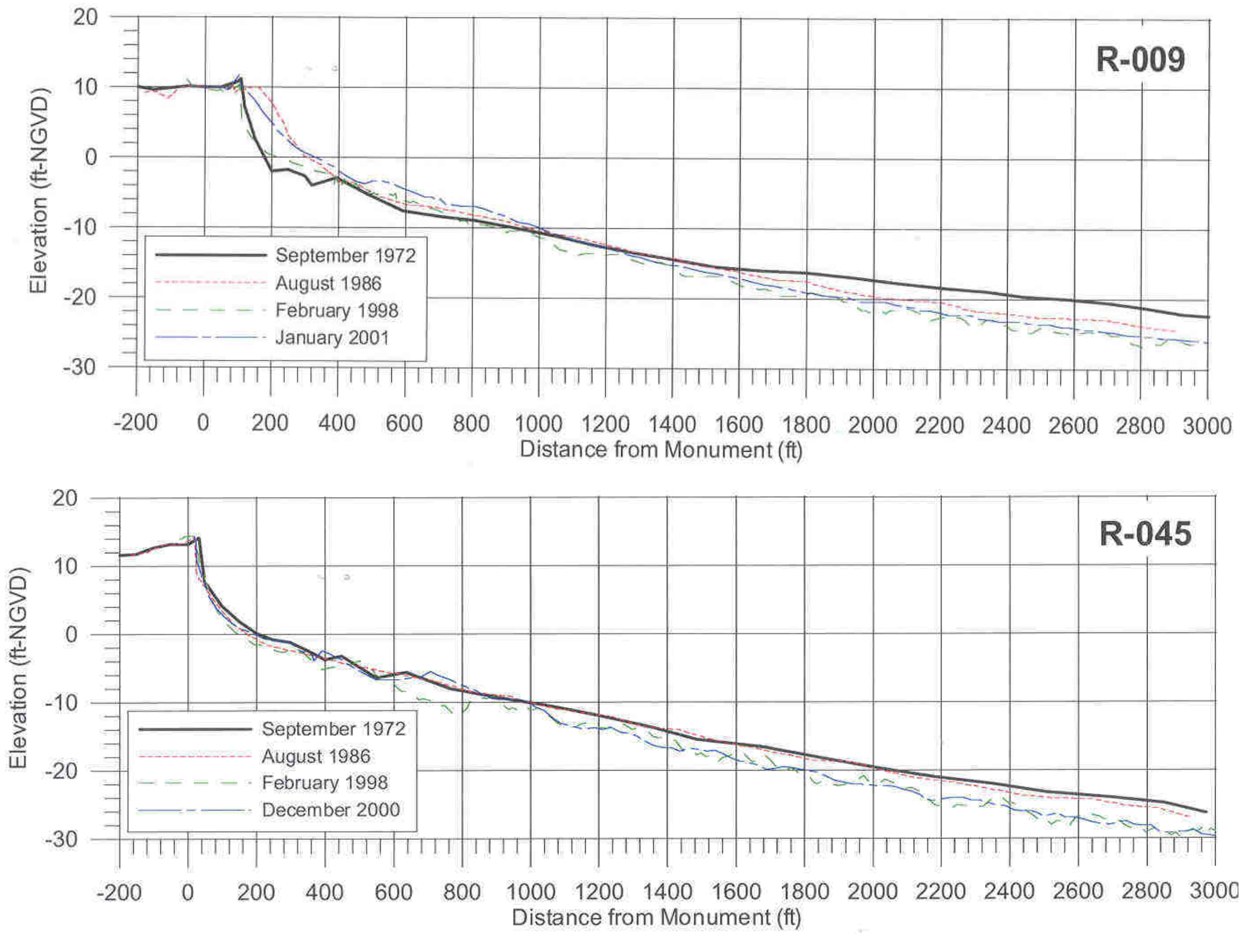


Figure F.3. Examples of beach profiles showing lack of closure, from Olsen Associates (2002)

It is not known whether these variations in offshore profiles are a real physical profile change due to sediment transport mechanisms or whether they are due to survey error. If these profile changes are real, then there is a very large onshore-offshore transfer of sediment volume in depths greater than -20 ft. This change would inflate the profiles from 1965 to 1972 and 1986, and then deflate them again by 1999 and 2000. If this profile change is real, then all previous volume computations are invalid because they have missed large volumetric gains and losses. In fact, in many cases, the sand volume change seaward of the assumed depth of closure would be greater than the volume changes above (landward) of the depth of closure. If the offshore profile changes are due to survey error, which appears more likely, then all previous volume computations are invalid due to the magnitude of the measurement error. While some modest lack of closure is tolerable, the large variability in profiles outside the assumed depth of closure in the Brevard County data invalidates any direct computation of sand volume change. In either event, it is difficult to have confidence in volume calculations based on these beach profile surveys

The lack of profile closure is further illustrated indirectly in the USACE (1968) Brevard County Study. That study compared the 1928 and 1965 bathymetry and found that, between Canaveral Harbor and Sebastian Inlet, the 18 and 30 foot depth contours shifted landward by an average of 319 and 394 ft respectively. The large movement of the 30 foot depth contour clearly indicates an error in one of the surveys or a large-scale sand loss in depths much deeper than the assumed depth of closure. The USACE study concluded that the beaches of Brevard County had lost nearly 34 million cubic yards of sand from 1928 to 1965, a result that now seems erroneous.

Others have noted these same problems. Jones and Cliburn (1987, Beach Management Plan for Brevard County, Florida) noted that volumetric erosion rates computed from beach profiles or hydrographic surveys must be "viewed critically since many of the profiles do not close offshore". They concluded that the 34 million cy loss could not be real given the general accretion observed in the Brevard County shoreline from 1928 to 1965.

Other Problems with 1954 and 1965 Surveys

Another problem illustrated in Figure F.2 is that there is an apparent error in the location of the 1954 and 1965 surveys near monument R-36 in Cocoa Beach. The 1958, 1972, and 1986 profiles are clearly located relative to one monument, while the upper portions of the 1954 and 1965 profiles are shifted 250 to 300 feet seaward. This change cannot be natural, as the profile would have eroded by 250 to 300 ft from 1954 to 1958, built seaward the same amount by 1965, and then eroded by the same amount again by 1972. Olsen Associates (2002) show that 1998 and 2001 beach profiles are consistent with the 1972 and 1986 profiles, so it would appear that the 1958, 1972, and 1986 surveys are located correctly. As a result, we must conclude that there is an error in both the 1954 and 1965 profiles.

The consequences of this apparent survey error, and of problems with lack of profile closure, are to invalidate much of the 1965 data set, especially at distances of more than a few thousand feet from the inlet. Given the coarse longshore spacing of beach profiles in the 1965 survey (an average spacing of 1.8 miles apart), the loss of this one profile leaves a large gap in the 1965 survey in the zone of downdrift erosion from Canaveral Harbor. The questionable nature of the 1965 data has implications for several previous USACE studies of volumetric erosion south of Canaveral Harbor, as both the 1967 USACE Brevard County Study and the 1992 USACE Sand Bypassing Study also base numerous conclusions on the 1965 beach profiles.

Volumetric Impact Inferred From Shoreline Change

To overcome these problems, an alternative method of estimating volume change is to infer volumetric erosion (or accretion) from shoreline erosion (or accretion). North of Canaveral Harbor, this method was shown to work well with a conversion factor of 0.92 cy per foot of shoreline change per foot alongshore. This method assumes that the entire profile translates landward uniformly as the shoreline erodes (moves uniformly seaward if the shoreline accretes), although this is not necessarily in agreement with what is observed from measured beach profiles. This method is useful, however, because it can consistently make use of the large number of historic shoreline surveys, and it can be used to predict volume change that may have occurred if Canaveral Inlet had not been constructed.

In our analysis, we computed cumulative volume change southward from the inlet relative to the 1949 baseline for three time periods: 1972, 1986, and 1997. These dates were selected because shoreline data is available at all FDEP survey monuments in these surveys. Results of our analysis are shown in Figure F.4. Measured shorelines for these dates were compared to expected shorelines (based on a continuation of pre-inlet accretion rates) in Figure D.9.

In each panel of Figure F.4, the bottom curve was developed from a cumulative integration of the measured shoreline change. For 1972, this curve does not contain any influence of beach fill and net erosion exists at all locations downdrift from the inlet. For 1986 and 1997, this lower curve reflects the cumulative volume inclusive of any beach fill. In both cases, the cumulative volume change is positive between about R-10 and R-50 due to the localized beneficial effect of the fill. Farther downdrift, the volume change becomes negative where erosion was not offset by fill.

The top curve in each panel of Figure F.4 shows the cumulative volume change projected to have occurred if the inlet had not been constructed. These curves were obtained from the cumulative integration of the expected shorelines, starting with the 1949 shoreline and projecting forward in time using the average pre-inlet shoreline change rate, as shown in Figure D.9. These curves show that strong accretion was expected from R-1 to about R-60 or R-80. Beyond this range, the curves level out because the pre-inlet shoreline was neither eroding nor accreting to any significant degree. These curves are always positive and show the amount of “unrealized accretion” that has been prevented by the construction of Canaveral Harbor.

The unmitigated volumetric impact of Canaveral Harbor can be obtained from the difference between the “unrealized accretion” (top) curve and the “observed erosion” (bottom) curve. This difference is termed “unmitigated” because it represents the remaining impact that has not been mitigated by prior beach fill.

Based on the degree of blockage imposed by the inlet, we have also computed the expected volumetric impact for 1972, 1986, and 1997 as shown in Table F.1. The total downdrift impacts have been computed from our estimates of the inlet blockage and trapping of 336,000 cy/yr prior to 1995 and 210,000 cy/yr after 1995. Unmitigated impacts are then obtained by subtracting prior beach fill from the total downdrift impacts. Results in Table F.1 suggest that unmitigated harbor impacts were 6,048,000 cy in 1972, 7,162,000 cy in 1986, and 8,984,000 cy in 1997.

Table F.1
Total downdrift impacts, prior mitigation, and unmitigated impacts for three time periods.

	1972	**1986**	**1997**
Total Downdrift Impact (cy)	6,048,000	10,752,000	14,196,000
Beach Fill (cy)	0	3,590,000	5,212,000
Unmitigated Impact (cy)	6,048,000	7,162,000	8,984,000

Referring to Figure F.4, we may now estimate the downdrift extent of inlet impacts by finding the downdrift location at which these unmitigated impacts are found. In 1972, the 6.05 M cy impact occurs at R-71, located about 13 miles south of the inlet (the difference between the upper and lower curves equals 6.05 Mcy at this point). By 1986, the unmitigated impact of 7.16M cy occurs at R-82, 14.8 miles south of the inlet. By 1997, the unmitigated impact of 8.98M cy also occurs at R-82, 14.8 south of the inlet. These results provide yet further evidence that inlet impacts extend as far as about 15 miles south of Canaveral Harbor.

Results in Figure F.4 may also be used to determine the percentage of downdrift impacts that fall into each of the two categories: (1) actual or observed erosion and (2) unrealized accretion. Results are tabulated in Table F.2, showing the two impact components relative to the unmitigated impact, and in Table F.3, showing the two impact components relative to the total downdrift impact. Table F.2 shows that the unmitigated impacts are mostly (57 to 82 percent) "unrealized accretion." Beach fill activity, primarily in 1974 and in 1995 (sand bypassing), had reduced the actual erosion deficit to 1.65 M cy or 18% of the unmitigated impacts by 1997. Table F.3 shows that, after removing the beach fill volumes, the total downdrift impacts are made up almost equally of unrealized accretion and actual erosion losses.

Table F.2
Unmitigated impacts separated into unrealized accretion and observed erosion (which includes prior beach fill) based on Figure F.4 .

	1972	**1986**	**1997**
Unmitigated Impact	6.05	7.16	8.98
Unrealized Accretion	3.43 (57%)	5.65 (79%)	7.33 (82%)
Observed Erosion **Not corrected for Beach Fill**	2.62 (43%)	1.51 (21%)	1.65 (18%)

Table F.3
Total downdrift impacts separated into unrealized accretion and observed erosion corrected to remove prior beach fills

	1972	**1986**	**1997**
Total Downdrift Impact	6.05	10.75	14.20
Unrealized Accretion	3.43 (57%)	5.65 (53%)	7.33 (52%)
Observed Erosion **Corrected for Beach Fill**	2.62 (43%)	5.10 (47%)	6.87 (48%)

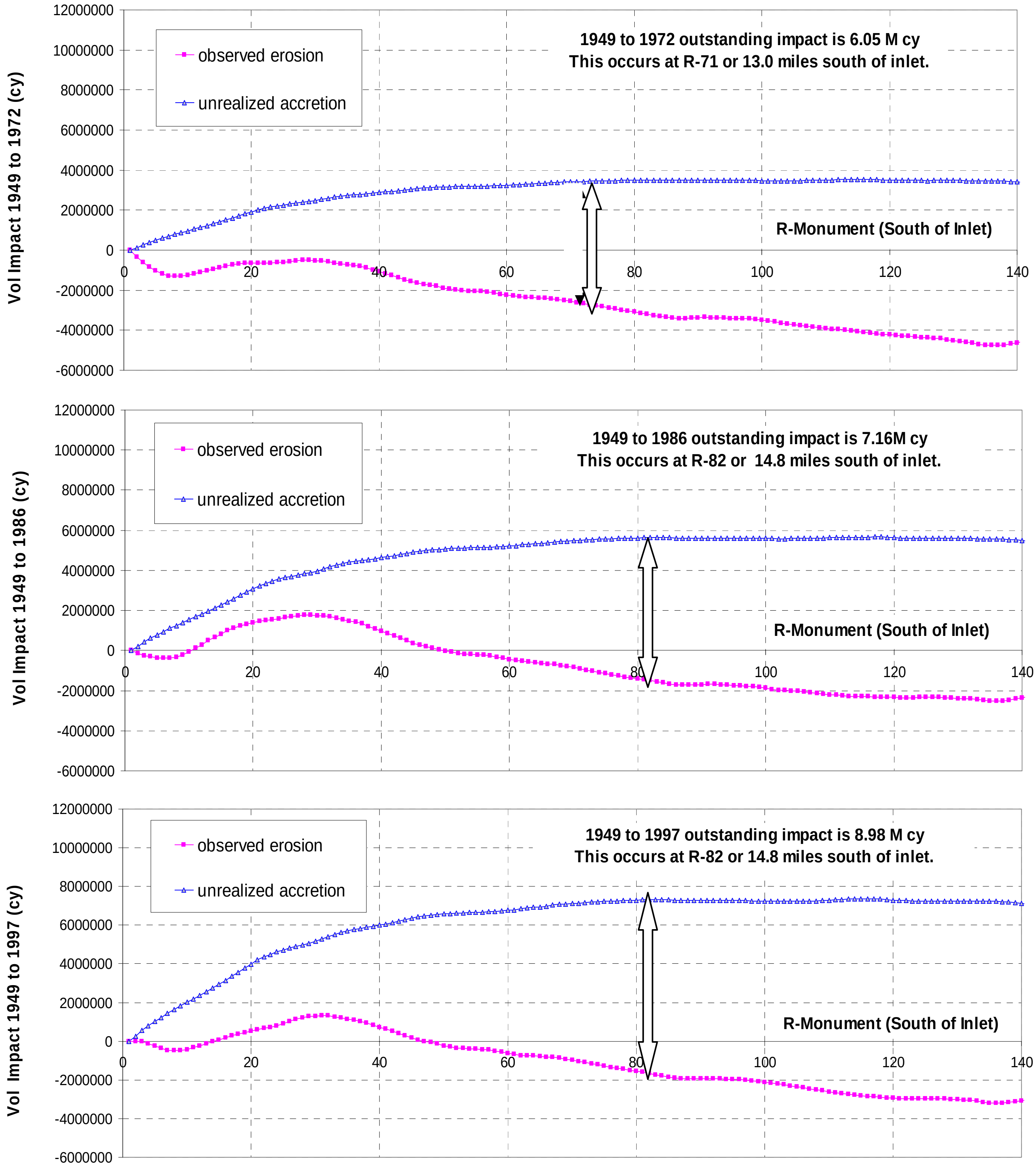


Figure F.4. Cumulative impacts of Canaveral Harbor. Lower curve is observed volume change inferred from historic shoreline positions. Upper curve is projected volume change if inlet had not been constructed. Difference between the two curves represents unmitigated harbor impacts.

Alternative Analysis of Downdrift Volume Deficit

In the review comments provided by the Government after the Preliminary Report and after the Draft Report, an alternative analysis method was introduced which directly determined the unmitigated volume impact in the North Reach of the project, from R-1 to R-53. In this analysis, the unrealized accretion was predicted by projecting the pre-inlet accretion trend forward in time. The actual erosion was determined by direct integration of the historic shorelines. This method is exactly the same as that used in Figure F.4, although that figure shows results for any distance downdrift from the harbor. Results that are consistent with the Government analysis can be obtained by simply reading values off of Figure F.4 at R-monument R-53.

Our results are shown in Table F.4 for three time periods, 1972, 1986, and 1997. From this analysis, unmitigated impacts are 5.20 Mcy in 1972, 5.29 M cy in 1986, and 7.02 M cy in 1997. The value in 1997 represents the last date prior to the Brevard County Shore Protection Project for which this analysis can be carried out.

Several aspects of the results in Table F.4 are noteworthy. First, the amount of unrealized accretion increased by about 3.5 M cy from 1972 to 1997. At the same time, the observed erosion was decreased by about 1.6 M cy as a result of beach fill. The net result is that the unmitigated impacts continued to increase by about 1.8 M cy from 5.2 Mcy to 7.0 M cy. During the same time, almost 4.7 M cy of beach fill were placed in the North Reach (mostly in the 1974 Trident Fill and in the 1995 sand bypassing). Interestingly, the effects of this fill are not fully reflected in the shoreline change data. The 1972 data shows erosion of 2.0 Mcy while the 1997 shoreline shows erosion of 0.37 Mcy. As a result, only about 1.6 M cy of the 4.7 m cy of beach fill can be identified in the shoreline change data in the North Reach. The remaining fill was lost either to the inlet through the south jetty, to the offshore, or to downdrift beaches.

It is noted that the unmitigated impacts shown in Table F.4 are less than those shown in Table F.1. The reason for this is that impacts in Table F.1 represent the total downdrift impacts, which extend past Patrick AFB, while those in Table F.4 are partial impacts computed only for the North Reach.

Table F.4
Summary of inlet impacts in the North Reach from R-1 to R-53 or about 9.4 miles south of the inlet from 1949, with volumes inferred from shoreline change using FDEP shoreline data.
In units of cubic yards.

	1972	**1986**	**1997**
Unrealized accretion	3,184,000	5,122,000	6,644,000
Observed erosion or accretion	-2,014,000	-167,000	-373,000
Unmitigated Impact	5,198,000	5,289,000	7,017,000

A similar analysis has been performed using the revised USACE shoreline data provided by Applied Engineering and Research (ACER). These results are listed in Table F.5. The unrealized accretion was obtained by projecting forward in time from the 1949 shoreline using the average pre-inlet accretion rate from this data set shown in Figure D.4. The observed erosion was obtained by integration of the cumulative volume change from the 1996 and 2002 GPS shoreline surveys conducted by ACER.

Several results from Table F.5 are of interest. First, it can be seen that analysis using the revised USACE data gives results that are similar to those based on analysis of the FDEP shoreline data. This can be seen by comparing the 1996 results in Table F.5 to the 1997 results in Table F.4. In 1996, the unmitigated impacts in the North Reach computed using the revised USACE data are 7.74 Mcy. This is within 10% of the value listed for 1997 using the FDEP data in Table F.4, of 7.02 M cy. This agreement provides a useful confirmation that the revised Government data and the FDEP data are consistent with one another.

A second observation from Table F.5 is that an unmitigated erosion impact of about 3.5 M cy exists in the North Reach in 2002 after completion of the Brevard County Shore Protection Project. The initial fill volume in the North Reach was insufficient to offset the more then 50 years of erosion damages experienced in the North Reach due to downdrift impacts of Canaveral Harbor.

A third observation can be made in Table F.5 regarding the unmitigated damages that existed in the North Reach prior to the 2001-2002 beach fill project. While the revised USACE dataset does not contain shoreline data for 2001, we may estimate the unmitigated damages for 2001 by adjusting the 2002 values for the amount of fill placed in the North Reach. In this case, 2.798 M cy of fill were placed in the North Reach. Adding this volume to the unmitigated impacts from 2002 gives an estimated volume of unmitigated impacts in 2001 of 6.28 Mcy. This is more than twice the volume of fill placed in the North Reach in the initial fill operations, and it is nearly equal to the 6. 58 M cy of fill planned for this area in the 50-year lifetime of the Brevard County Shore Protection Project.

Table F.5
Summary of inlet impacts in the North Reach from R-1 to R-53 from 1949 to the date indicated, with volumes inferred from shoreline change using revised USACE shoreline data from Applied Coastal Engineering and Research. In units of cubic yards.

	1996	**2001*** Pre-Project	**2002** Post-project
Unrealized accretion	5,850,000	-	7,216,000
Observed erosion or accretion	-1,890,000	-	3,730,000
Unmitigated Impact	7,740,000	6,280,000	3,480,000

* 2001 results inferred from 2002 results by removal of beach fill

APPENDIX G
SEDIMENT BUDGET FOR BEACHES BETWEEN CANAVERAL HARBOR AND SEBASTIAN INLET

A sediment budget was constructed from shoreline surveys for the area between Canaveral Harbor and Sebastian Inlet. Longshore sediment transport rates were calculated from the cumulative volume change determined as the difference between two shoreline surveys, with a correction for offshore losses due to sea level rise. Data from the 1878 and 1929 surveys was used for this purpose.

The upper curve on Figure G.1 represents the cumulative volume change between the 1878 and 1929 surveys integrated southward from Canaveral Harbor to Sebastian Inlet. Thus the difference between two ordinates on the curve represents the volume of sand accumulated on the beach per year between the two locations. The boundary value at Canaveral Harbor is approximately 200,000 cy/yr. The lower curve is the longshore transport rate taking into account offshore losses due to sea level rise as given in Appendix I. Thus the lower curve is the inferred longshore transport rate at each location assuming a boundary value of 200,000 cy/yr at Canaveral Harbor. The inferred transport rate at Sebastian Inlet is about 76,400 yd^3/yr nearly equal to the value of 70,000 yd^3/yr reported as the transport rate there.

Positive values of transport rate represent transport to the south; negative values represent transport to the north. Longshore transport is southward over the entire reach for the time before harbor construction. A downward sloping cumulative volume curve (upper curve) represents accretion since less sand is leaving a reach than is entering it. Likewise, an upward sloping cumulative volume curve represents erosion since more sand is leaving a reach than entering. Figure G.1 shows that beaches south of the harbor site were accreting from the site to about 14 miles south. From thence southward the beaches were eroding slightly to about Mile 35. From Mile 35 to about Mile 37 beaches were relatively stable; from Mile 37 to Mile 40 they were accreting. The accretion area between Miles 37 and 40 is the accretion fillet associated with Sebastian Inlet.

Figure G.2 shows the cumulative volume changes and the inferred transport rates south of Canaveral Harbor for the time following harbor construction, from 1952 until about 1972 (the upper and lower curves respectively). These volume changes and transport rates were determined from the difference between the 1949 and 1972 shorelines. The figure shows northward transport from the inlet south to about Mile 10 and southward transport from Mile 10 to Mile 40 (Sebastian Inlet). The transport rate at Canaveral Harbor was assumed to be –60,000 yd^3/yr (northward into the harbor entrance). The resulting transport rate at Sebastian Inlet is about 72,300 yd^3/yr. The transport rate curve shows erosion from the harbor to about Mile 1 (upward sloping cumulative volume curve). Between Mile 1 and Mile 5 the curve shows accretion. South of Mile 5 to Mile 15 the beaches eroded; between Mile 15 and 18, the beaches were stable; between Mile 18 and 24, eroding; between 24 and 26 accreting; between Mile 26 and 32, eroding; between 32 and 35, relatively stable; between Mile 35 and 37.5, eroding, and between Mile 37.5 and 40, accreting. This last area is the accretion fillet at Sebastian Inlet.

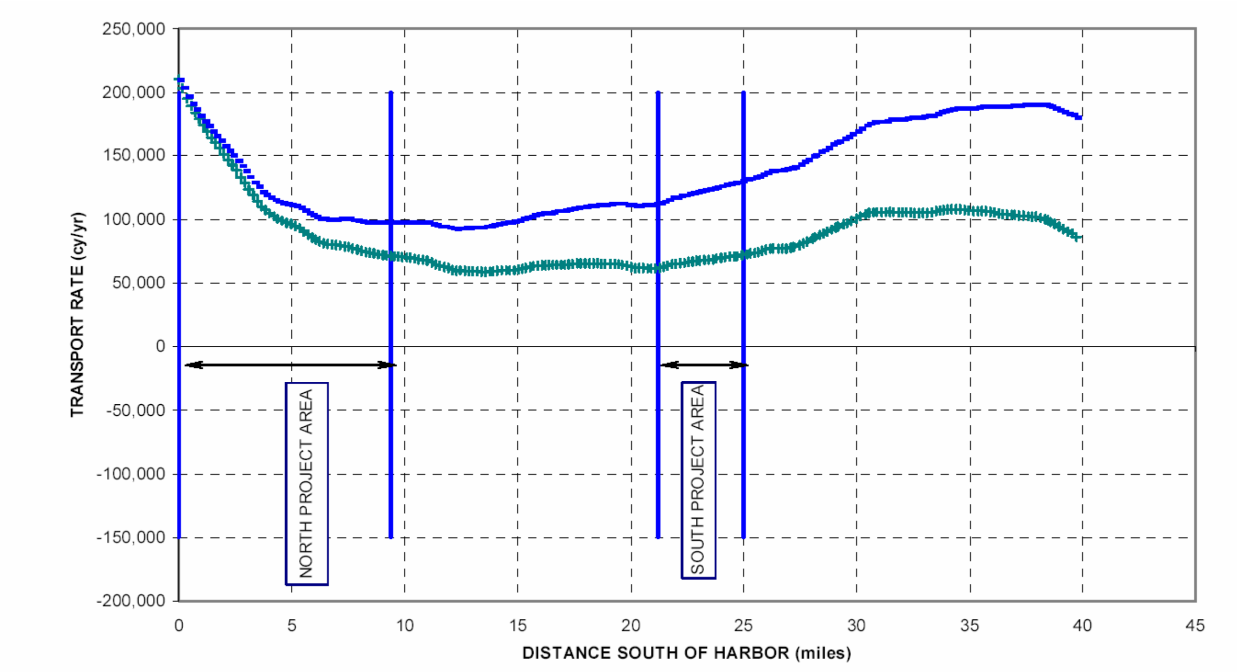


Figure G.1 Longshore Transport Rates South of Canaveral Harbor Prior to Harbor Construction. (calculated from the difference between the 1879 and 1929 shoreline surveys.)

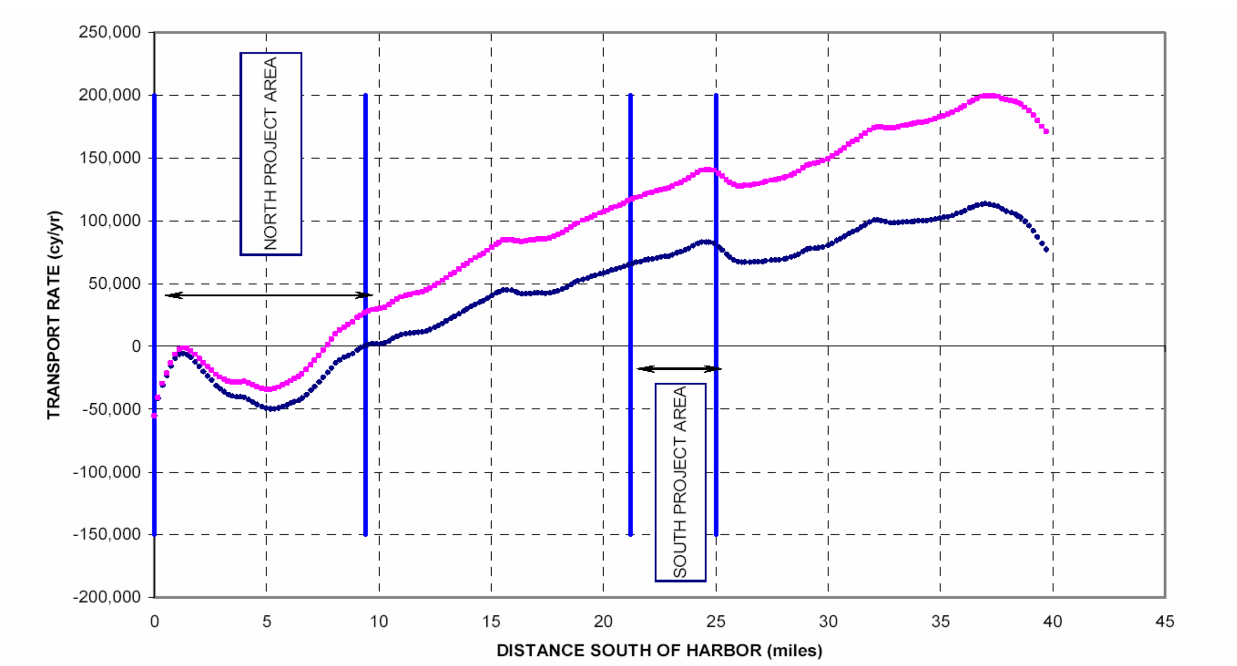


Figure G.2 Longshore Transport Rates South of Canaveral Harbor after Harbor Construction until 1972. (calculated from the difference between the 1949 and 1972 shoreline surveys.)

Figure G.3 compares the transport rate curves for the time before and after harbor construction until about 1972. The two curves are significantly different from Canaveral Harbor to about Mile 15. This suggests that the effects of Canaveral Harbor's construction extended southward about 15 miles by about 1972 or at a rate of about 0.75 miles per year. South of Mile 15 the two curves appear similar. South of Mile 15 the beaches were generally stable or eroding at about the same rate both before and after harbor construction. Only in the vicinity of Sebastian Inlet are the beaches generally accreting.

In fact, the curves in Figure G.3 were adjusted by changing the transport rate at the Canaveral Harbor boundary to superimpose the curves south of Mile 15 and to have them both terminate at a 70,000 yd3/yr transport rate at Sebastian Inlet. To achieve this matching, the post-harbor transport rate at Canaveral Harbor was set at –60,000 cy/yr (northward into the inlet). This value is about one-half of the -126,000 cy/yr that were indicted by the dredging analysis in Appendix B. Other changes could be introduced by adjusting offshore losses due to sea level rise. For example, offshore losses were calculated using a closure depth of –20 feet. A shallower closure depth would result in smaller offshore losses and raise the transport rate at Sebastian Inlet for a given Canaveral Inlet transport rate. Similarly, a shallower closure depth would allow the post-harbor transport rate into the harbor be more than the assumed - 60,000 yd3/yr. This suggests that offshore losses are probably quite close to those calculated in Appendix I.

Figure G.4 then shows the pre-harbor sediment budget developed from Figure G.3. Figure G.5 shows the post-harbor sediment budget based on Figure G.3 for the period between harbor construction in 1952 and 1972.

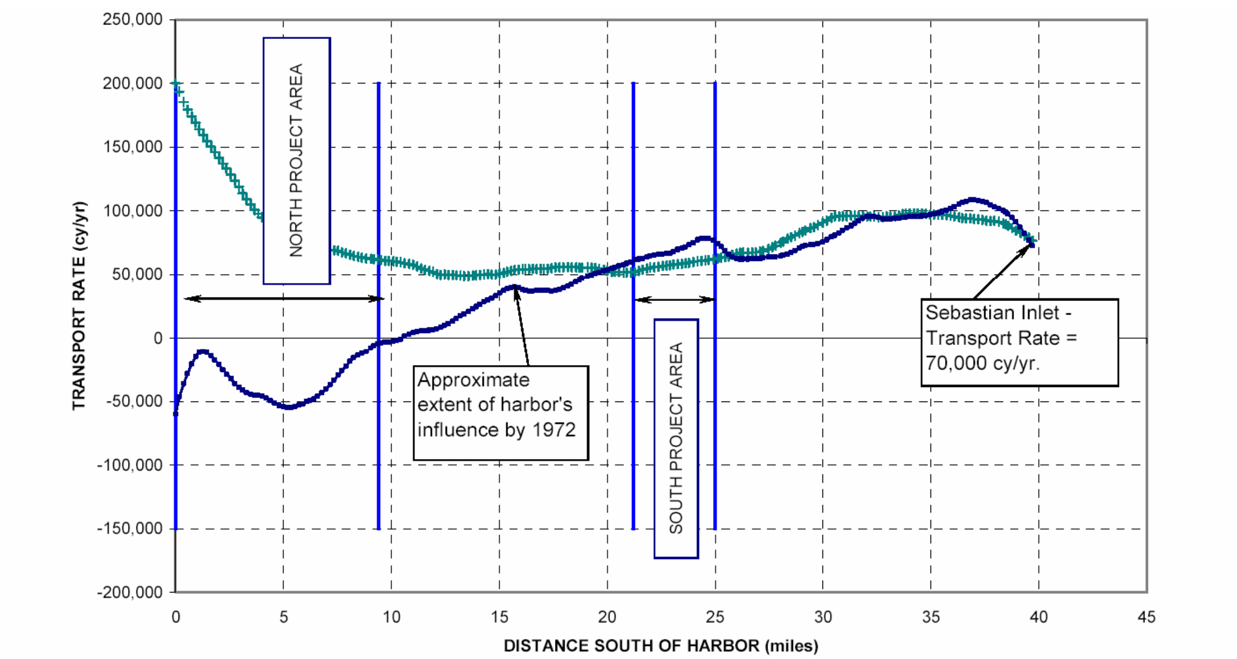


Figure G. 3 Longshore Transport Rates South of Canaveral Harbor – Comparison of Transport Rates Prior to and Following Harbor Construction.

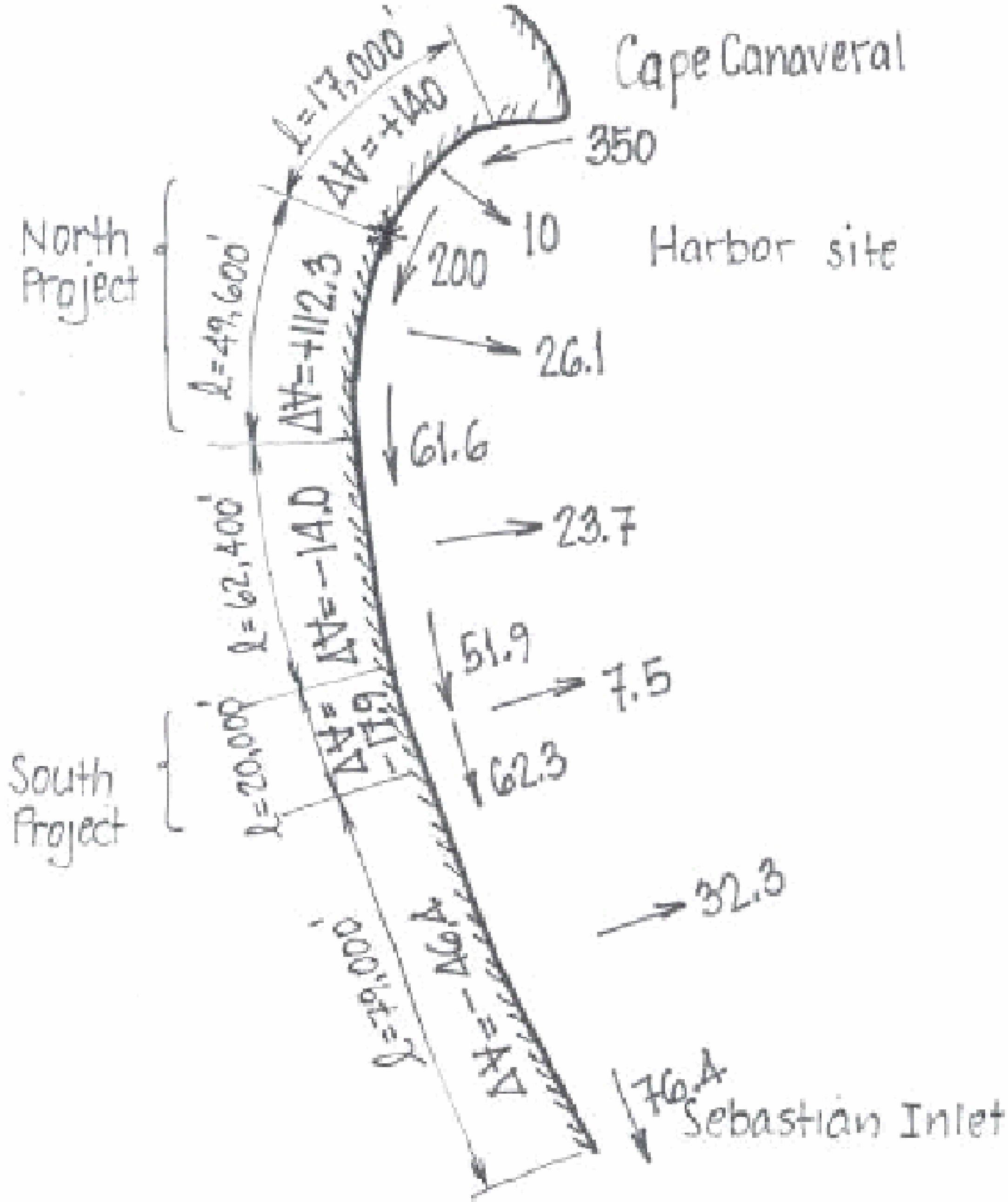


Figure G.4 Sediment Budget, Cape Canaveral to Sebastian Inlet, Prior to Construction of Canaveral Harbor.

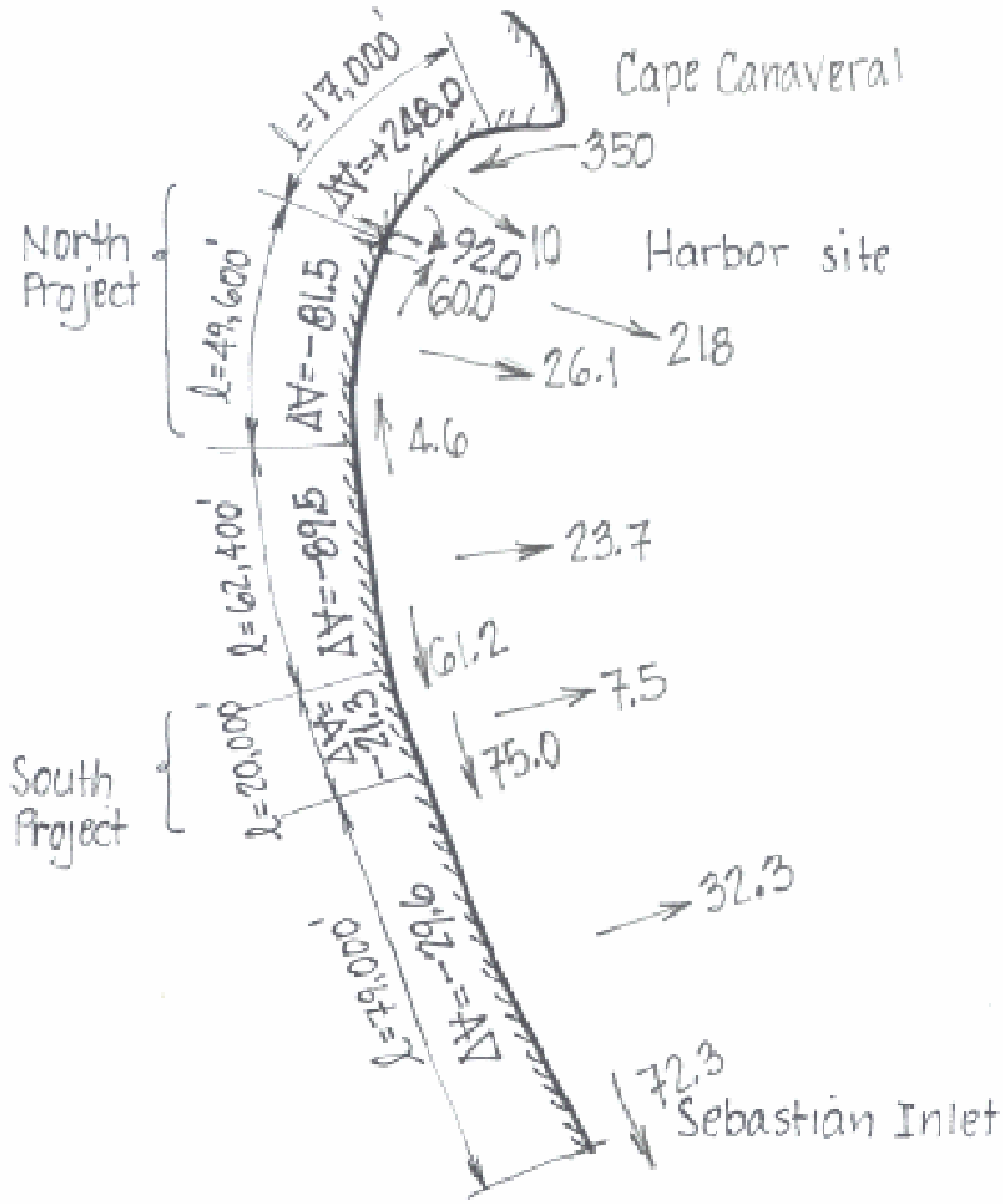


Figure G.5 Sediment Budget, Cape Canaveral to Sebastian Inlet, Following Construction of Canaveral Harbor until 1972.

APPENDIX H
ANALYSIS OF PRIOR BEACH FILLS

Quantities of sand placed on the beach south of Canaveral Harbor are listed in Table H.1. Beach fill quantities in Table H.1 are separated into fills that took place prior to initiation of sand bypassing in January 1995, those that took place after 1995 but prior to 2001, and those that took place in 2001 and 2002. For fills prior to and including the 1998 sand bypassing, these volumes were obtained from four sources: (1) the USACE (1996) Shore Protection Project report, (2) the White Paper by Bodge (1998), (3) the report by Kraus et al (1999), and (4) the sand bypassing monitoring report of Bodge (2002). Of these sources, the data given by USACE (1996), Bodge (1998) and Bodge (2002) were adopted since they showed the greatest degree of agreement. Data for recent fills, in 2001 to 2002, were obtained from Kevin Bodge (personal communication) for Patrick AFB and from Tom Smith (personal communication) for the North and South Reaches of the Brevard County Shore Protection Project.

Two issues had to be resolved with regard to whether beach fills would be credited toward effective mitigation. One issue dealt with the effectiveness of the Cocoa Beach fills. These fills were all placed through nearshore disposal in water depths of about –15 to –20 feet MLW. The USACE (1996) claims that these fills are fully effective in supplying sand to the active beach. Bodge (1998) claims that these fills are only partly effective because their depth of placement puts much of the sand outside of the active beach profile. The ICE team reviewed beach profile data and agreed with Bodge's arguments regarding the limited effectiveness of these fills. At least one-half of the sand volume was placed seaward of the accepted –17-foot closure depth where it has remained and has not provided effective beach fill. As a result, we have adopted effective fill volumes that are somewhat smaller than those actually placed.

A second issue had to do with the fills placed on Patrick Air Force Base. These fills were not placed by the Corps of Engineers as part of any Corps mitigation effort. However, we believe that they should be considered as effective mitigation. The Patrick AFB property is located within the zone of inlet-induced downdrift erosion. Any sand added to the beach at this location, regardless of which agency placed the sand, should be counted as mitigation for eroding beaches south of Canaveral Harbor.

Based on the above arguments, we have determined the effective fill quantities from each fill and, in the last column of Table H.1, the cumulative effective fill volumes. This shows an effective fill volume of 3,887,000 cy prior to the 1995 sand bypassing. Bypassing through 1998 raised the effective volume 6,497,000 cy. Recent fills from the Brevard County Shore Protection Project, and on Patrick AFB, have raised the total fill volumes to more than 11 million cy.

It is noted that the differences between the data used here and that tabulated by Kraus et al (1999) are not large. Through 1996, Kraus et al list a total in-place fill volume of 6.28 M cy. This compares to our estimate of 6.994 M cy minus 1.035 M cy from the 1998 sand bypassing or 5.96 M cy in place. These differ by about 5% which we consider to be within the limits of accuracy of any volumetric measurements.

Table H.1
Beach fill activities credited toward mitigation south of Canaveral Inlet.

Date	Location		In-Place Volume	Effective Volume	Cumulative Effective Volume
	City	R Monuments	cy	cy	cy
1972	Cape Canaveral	0-14	200,000	200,000	200,000
1974	Cape Canaveral	0-14	2,850,000	2,850,000	3,050,000
1980	Ind/Melbourne	126-136	540,000	540,000	3,590,000
1992	Cocoa Beach	28-31	158,000	79,000	3,669,000
1993	Cocoa Beach	28-31	200,000	50,000	3,719,000
1994	Cape Canaveral	5-11	100,000	100,000	3,819,000
1994	Cocoa Beach	28-31	135,000	68,000	**3,887,000**
1995	Cape Canaveral	0-8	783,000	783,000	4,670,000
1995	Cocoa Beach	28-31	322,990	122,000	4,792,000
1980-1995	Patrick AFB	53-75	380,000	380,000	5,172,000
1996	Cocoa Beach	34-38	40,000	40,000	5,212,000
1998	Cape Canaveral	0-14	1,035,000	1,035,000	6,247,000
1996-1998	Patrick AFB	53-75	250,000	250,000	**6,497,000**
2001	Patrick AFB	53-75	541,000	541,000	7,038,000
2001-2002	North Reach	Jan-57	2,798,000	2,798,000	9,836,000
2002-2003	South Reach	118-136	1,346,000	1,346,000	**11,182,000**

Spreading of 1974 Beach Fill

The largest beach fill placed during the study period is the 1974 Trident fill; and shoreline data taken in 1972, 1976, 1980, 1985, and 1993 provide an indication of the degree of spreading of this fill to provide mitigation to downdrift beaches. Figure H.1 shows the 1976, 1980, 1985, and 1993 shoreline positions relative to the pre-fill 1972 shoreline.

The initial placement was confined to the region from R-1 to R-12 as shown by the 1976 shoreline. The shoreline south of the fill area, from R-20 to R-60, eroded somewhat between 1972 to 1976. By 1980, the fill had clearly spread southward with shoreline advance evident to the limit of the 1980 survey at R-39. This pattern continued in 1985 and 1993. By 1993, the fill was essentially gone in the placement area (R-1 to R-12). Much of the fill spread north past the south jetty and into the inlet. The remaining fill spread south, with the bulk of the fill located between R-10 and R-34 but with some of the fill spreading as far south as R-60.

The spreading of the beach fill provides further evidence that the effects of Canaveral Harbor extend to at least R-60 or about 11 miles south of the harbor. The beach fill clearly spreads to the south well beyond the “bulge” in the shoreline (zone of accretion) that exists from R-10 to R-30.

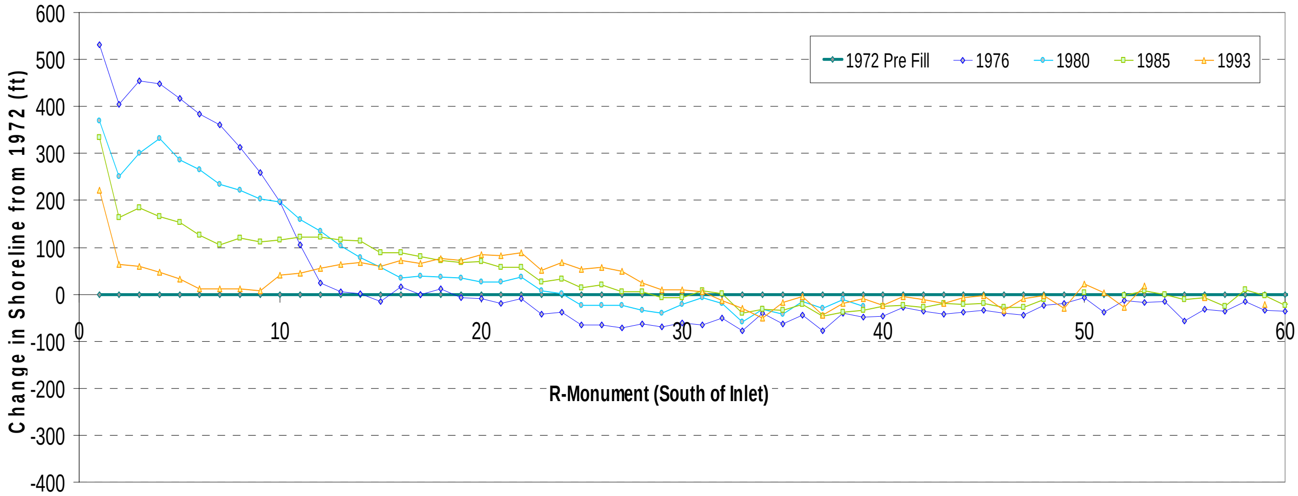


Figure H.1. Spreading of 1974 Trident Beach Fill from placement area downdrift to about R-50 to R-60.

APPENDIX I
OTHER ENVIRONMENTAL FACTORS:
STORMS AND SEA LEVEL RISE

Analysis of Storm Effects

The ICE reviewed information provided about storms and their effect on the beaches of Brevard County. The number of tropical storms effecting Brevard County is shown in Figure I.1. No similar data was located on the number of extra-tropical storms (northeasters) effecting Brevard County. Nor was any information located which would indicate the degree of severity of storms.

The rate at which tropical storms occurred in Brevard County during the 30-year period from 1945 to 1975 was greater than the rate prior to and following that period. Between 1899 and 1944 the rate of tropical storms affecting Brevard County was about 0.6 storms per year. In the period between 1945 and 1975 the rate increased to about 1.7 storms per year and following 1975 the rate decreased to about 0.5 storms per year. These numbers differ only slightly from those found by Kraus et al (1999).

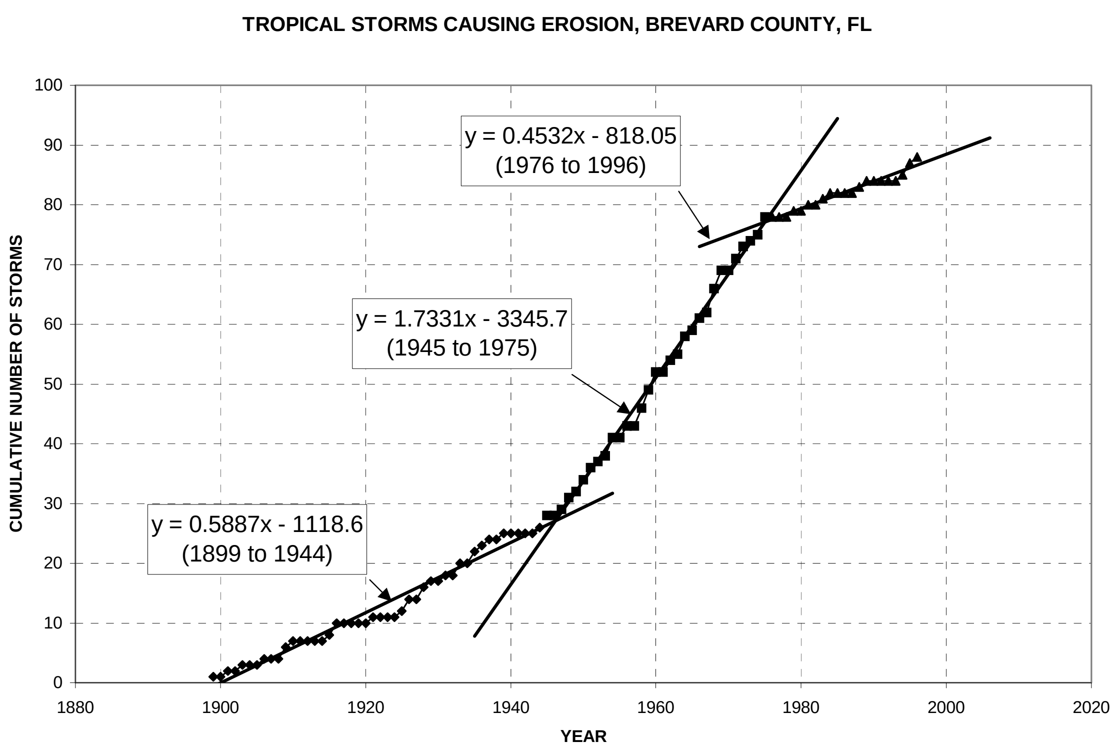


Figure I.1 Cumulative Number of Tropical Storms Affecting Brevard County, 1899 to 1996.

The increased rate of tropical storms for the period just after harbor construction has been suggested as a main cause of erosion to the beaches of Brevard County. We believe that storms are important agents for moving sand, however, we do not believe that the increased rate of storm activity shown in Figure I.1 has had a major influence on the observed downdrift from Canaveral Harbor. As outlined in other sections of this report, the reversal in shoreline change trends from accretion to erosion that has occurred 10 to 15 miles south of the harbor has been caused by the harbor and is not strongly linked to storm activity.

It is well known that tropical storms and northeasters provide the mechanisms that transport large quantities of sediment both alongshore and across the shore. The response of the beach to storm waves and wave-induced longshore currents is to move sand from the shore face and deposit it offshore, or to move large quantities of sand alongshore. In many documented cases of storm impacts, storms have caused severe erosion of the berm and dunes while, at the same time, producing an advance of the shoreline due to the cross-shore transfer of sand an flattening of the beach profile.

Wave conditions that prevail between storms also transport sand but at lower rates. In particular, it is well documented that on a stable shoreline, most of the sand that erodes from upper portions of the beach profile during a storm returns in the form of beach recovery after the storm. Such beaches will erode during major storms and recover in between storm events with no net loss of beach sand volume and with little change in shoreline position. On the Brevard County shoreline, which was accreting prior to inlet construction due to crenulate bay migration, storms would cause short-term erosion but not a net reversal from accretion to erosion.

In general, storms are part of the normal sediment transport process. It is the harbor construction that alters the prevailing processes. The increased storm frequency may have caused a more rapid beach adjustment to the harbor-induced changes; however, a different or changed beach response is the result of harbor construction and not of the storms themselves. Because the rate of northeast storms is not known, no definitive conclusions can be drawn from the increased rate of occurrence of tropical storms shown in Figure I.1.

In addition, data in Figure I.1 do not indicate any change in the overall severity of storms. No information of this kind was included in the literature provided to the ICE team for this study. It is known from Corps reports that the most severe storms of record, the Thanksgiving Day storm of 1984, cause an average shoreline erosion of only 21 feet in Brevard County. A comparison of shoreline data from 1972, 1976, 1980, and 1985 shows, however, little noticeable effect of this storm in shoreline locations. In fact, shoreline positions in 1985 months after the storm were seaward of their location prior to the storm.

The cycle of beach erosion during storms and recovery after storms is sometimes neglected, giving a false impression of storm effects. For example, Kraus et al (1999) modeled onshore-offshore sediment transport and profile adjustment for three storms (two northeasters and one tropical storm occurring between 1984 and 1994) using the numerical model SBEACH. Such a model produces erosion of the dunes and deposition offshore with, by definition, no net loss of sand volume. In the simulations, however, the starting profile for each successive storm was the final profile of the preceding storm. They further assumed that the volumetric erosion from each storm could be added cumulatively. This analysis is not correct because it disregards any profile recovery between storms. While any individual storm can result in significant shoreline recession, offshore transport and sand storage in an offshore bar, the sub-aqueous profile recovers significantly between storms. The impact of successive storms is not cumulative even if the storms may be closely spaced in time. The sub-aerial profile may take longer to recover depending on the wind climate and the width of the dry beach at a site.

We also note that recent studies have suggested that severe storms only cause a temporary change in shoreline position but do not affect the long-term trend in shoreline erosion or accretion. Of particular relevance to the present study, Zhang, et al. (2002) investigated the impact of storms on the long term shoreline trend along the barrier islands of the U.S. East Coast. Zhang et al (2002) evaluated long-term shoreline erosion in the mid-Atlantic states from the mid-1800's to the present, including shoreline data collected after the severe March 1962 northeaster. This data sets shows that, while the March 1962 storm caused a large retreat in shoreline position, this was not evident in the shoreline data collected in the 1970's and 1980's. These later shoreline surveys showed that the beach had recovered and rebuilt to a position consistent with the long-term erosion trend in the shoreline. As a result, the authors concluded that sea level rise and sediment supply (longshore transport) were responsible for the long-term trend in shoreline recession, and that storms cause only a temporary increase in erosion over the background trend.

To quote from the Zhang paper: "barrier beaches along the U.S. East Coast recover to their long-term trend positions after storms regardless of severity.[indicating] that storms are not responsible for long-term beach erosion. In other words, if long term erosion was event-driven, one would expect that larger storms would result in more net shoreline retreat than smaller ones, which is not supported by the available data. Other factors, including sea level rise and variations in sediment supply, determine long-term beach erosion."

Consequently, increased storm frequency during the period from 1945 to 1975 will have resulted in a more rapid movement of the beaches to their new, evolving equilibrium position but will not have permanently changed the position of that new equilibrium. The new shoreline position to which storms drive the shoreline is the position dictated by the reduction in sediment supply due to the harbor and by offshore losses associated with sea level rise. In fact, it is the interrupted sediment supply due to the harbor and offshore losses associated with sea level rise that prevent full recovery of Brevard County beaches following storms.

Effects of Sea Level Rise

One environmental factor which may be important for long term beach change is relative sea level rise. A shown by the Bruun Rule (Bruun, 1962), a rise in mean level must be accompanied by erosion of the shoreline with a transfer of sand to the offshore. In this section, we investigate the magnitude of this effect for the shoreline of Brevard County.

The mean monthly sea level at two water level recording stations, Miami Beach and Daytona Beach, are shown in Figures I.2 and I.3 respectively. Based on linear regression lines fit to the data, the rate of increase in mean sea level at Miami Beach is 1.96 mm/yr while the rate at Daytona Beach is 2.28 mm/yr. Interpolating for the Cape Canaveral area gives a rate of 2.2

mm/yr or 0.00722 ft/yr. Obviously, these rates are averages for the period dating since the late 1920s.

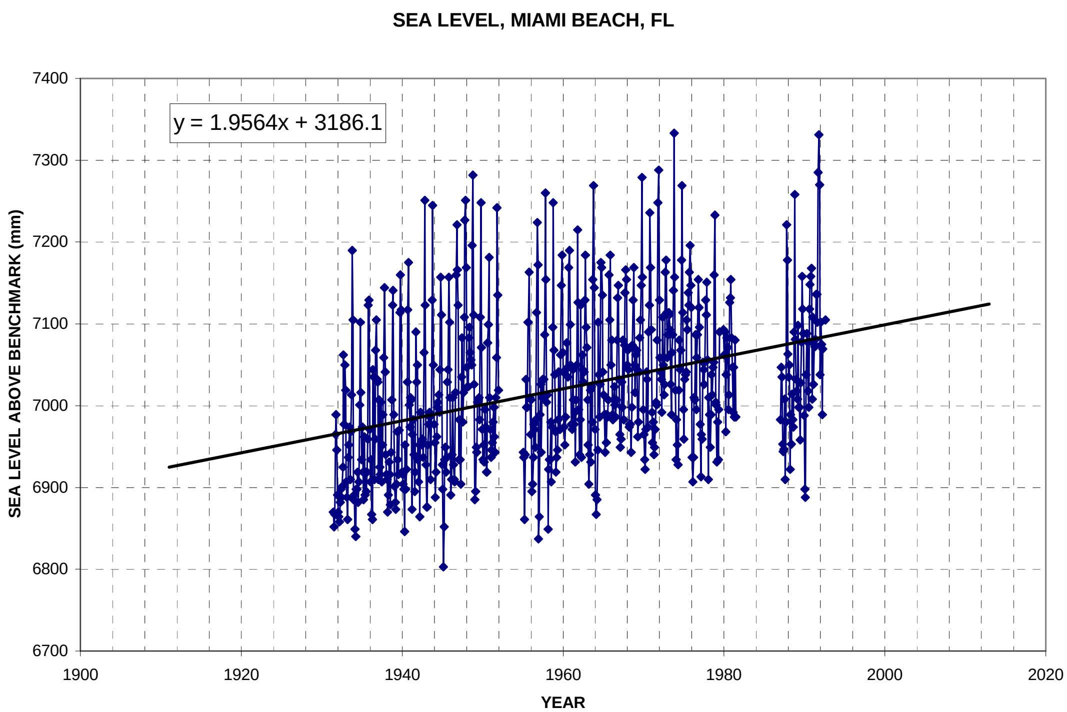


Figure I.2 Mean Monthly Sea Levels at Miami Beach and Haulover Pass, Florida.

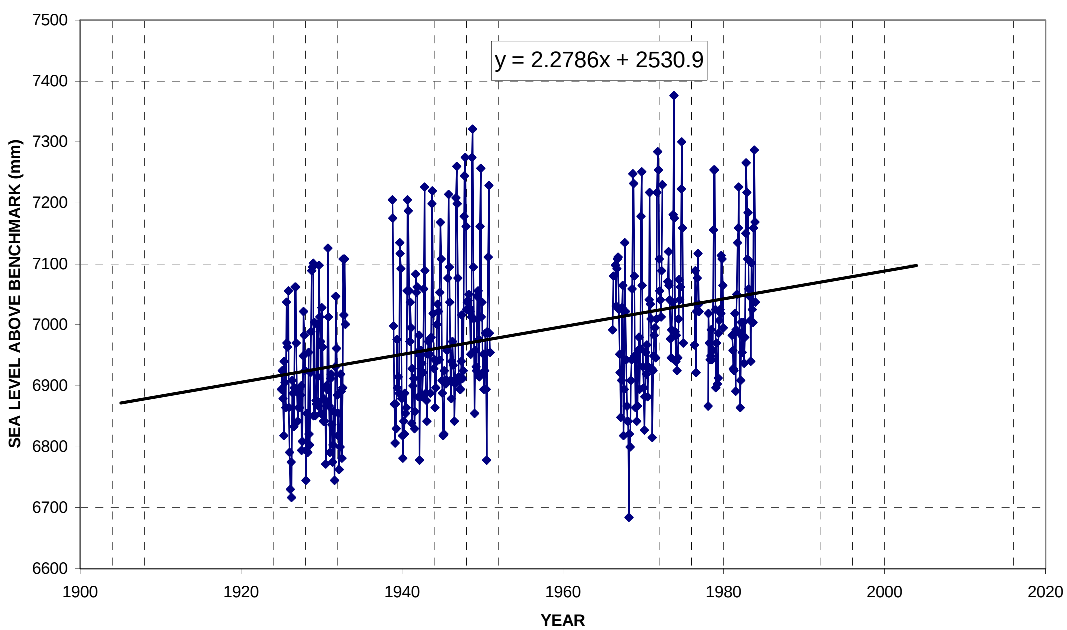


Figure I.3 Mean Monthly Sea Levels at Daytona Beach and Daytona Shores, Florida.

The impact of this sea level rise can be translated into shoreline recession using the Bruun Rule. The Bruun Rule states that, in response to sea level rise, a beach profile will simultaneously rise an amount equal to the increase in sea level, and retreat landward by an amount sufficient to balance offshore sand deposition required to raise the beach profile. These changes occur over a vertical distance from the top of the active beach (beach berm or dune toe elevation) to the depth of closure. They also occur over a horizontal distance from the due toe to the closure depth contour.

Assuming that the closure depth is approximately 20 feet and using the 1972 survey profiles to define the width of the active beach profiles along Brevard County, the cumulative annual offshore losses and shoreline recession rates shown in Figure I.4 are found through application of the Bruun Rule. The average annual shoreline recession rate along the 25 mile reach south of the inlet is about 0.5 ft/yr with a volume loss of about 12 ft^3/ft/yr.

The observed rate of shoreline erosion for the North Reach of the Shore Protection Project far exceeds the erosion rate due to sea level rise, suggesting that other mechanisms, i.e. the inlet, are responsible for the observed erosion. Erosion rates observed in the South Reach are, however, comparable that predicted by sea level rise effects. This, along with other data presented in this report, suggests that the South Reach is not impacted by inlet effects.

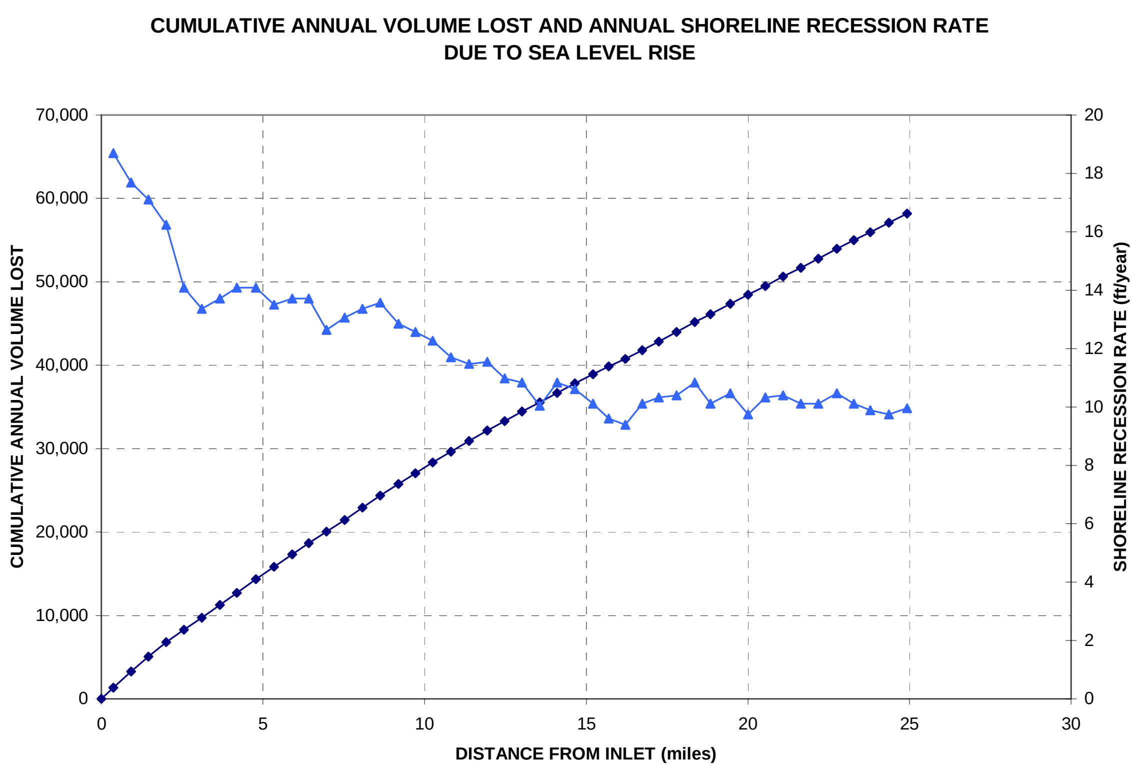


Figure H.3 Annual Shoreline Recession Rates and Cumulative Volume Losses due to Sea Level Rise.