

Gross Transport Effects and Sand Management Strategy at Inlets

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ABSTRACT



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Particularly for inlets which act as sediment sinks, the components of the *gross* longshore sediment transport rate (vs. *net* transport) are demonstrated to be effective indicators of an inlet's sediment budget, sediment transport pathways, and transport effect upon adjacent shorelines. Using the example of Port Canaveral Entrance, Florida, it is shown that the inlet's impact on downdrift beaches may likely extend up to 30 to 42 km. Engineering methods for improving sand-bypassing across inlets are also discussed from the standpoints of: improved attention to annual sediment transport variability, distribution of transport across the surf zone, the importance of crater-shoaling rates (versus pump productivity), and the integration of engineering solutions for navigation and beach-erosion problems.

ADDITIONAL INDEX WORDS: *Canaveral Harbor, coastal engineering, inlet management, littoral drift, longshore sediment transport, sand bypassing, South Lake Worth Inlet, swash zone.*

INTRODUCTION

This paper is concerned with how those charged with inlet management perceive sediment transport patterns at an inlet. Specifically, the paper discusses the appropriateness of commonly accepted notions of inlet impacts to littoral drift and the appropriateness of technology to move sand around the inlet. Central to the paper, therefore, are three aspects of inlet management: (1) quantifying an inlet's sediment budget, (2) identifying where, how and when the sand is moving, and (3) developing and implementing strategies to reduce an inlet's littoral impacts so as not to adversely impact navigation. Several prototype examples, including Port Canaveral Entrance and South Lake Worth Inlet in Florida,

are presented to highlight the paper's discussion.

GROSS TRANSPORT AND SEDIMENT BUDGETS

A cursory review of the literature, especially the non-refereed portion, reveals that an inlet's littoral impact is increasingly expressed in terms of its "*interruption of the average annual net transport rate.*" This is a useful concept to help explain inlet impacts to laymen; however, it is a significant simplification of littoral processes. One who chooses to view an inlet solely in terms of *average, net* transport rates risks underestimating the inlet's littoral impacts and misunderstanding the inlet's sediment transport paths. In the end, after all, it is the inlet's littoral impacts

and transport paths which determine the design volumes and technologies appropriate for sand management at the inlet.

Net vs. Gross Transport

Looking seaward across a beach, longshore sediment transport can occur in two directions: to the right and to the left. The sum and difference of these oppositely-directed components represent the *gross* and *net* longshore transport rates, respectively.

The present paper is concerned with the components of transport rather than the net transport. For convenience, the term "gross transport" will not only describe the sum of the components, but will also refer formally to the individual transport components.

It is recognized that a perturbation placed along a shoreline with negligible *net* longshore transport can induce a net shoreline response. That is, many coastlines with negligible net drift rates feature equally-valued and oppositely-directed component drift rates; i.e., a large-valued *gross* drift. A perturbation built upon such a beach will interrupt the gross drift components, and thereby alter the beach. The degree to which the beach is net erosional or accretional on each side of the perturbation may depend upon the state of the transport regime at the time at which the perturbation is introduced. Hence it is recognized that *gross* (not *net*) transport processes can be central to understanding littoral impacts of a shoreline structure.

Likewise, an inlet (natural or improved) is a shoreline perturbation; and in particular, it is often a sediment sink in response to gross transport processes (e.g., BRUUN and BATTJES, 1963; DEAN and WALTON, 1975; WALTON and ADAMS, 1976). Figure 1a illustrates an example where a natural inlet bypasses component drift rates of +100 and -20 units, yielding a net drift rate of +80 units. In Figure 1b, the inlet is stabilized and becomes a complete littoral barrier. The inlet's net downdrift impact is *not* necessarily limited to the net drift rate of 80 units. If, for example, all or part of the transport directed towards the inlet on its downdrift side leaks into the inlet channel, then the net

downdrift erosion stress could be as much as 100 units -- not 80. Similarly, if all or part of the transport directed towards the inlet's updrift side is sunk to the channel or permanently impounded, there will be up to 20 units of localized erosion well updrift of the inlet. Thus the inlet's potential impacts are seen to be as great as the gross drift rate -- not the net drift rate.

A prototype example of this effect is Port Canaveral Entrance, south of Cape Canaveral, Florida, on the southeast U.S. Atlantic coastline. This inlet was cut into a regular, sandy barrier island in 1950-52 as part of the Canaveral Harbor Federal Navigation Project. There are no tidal shoal fields at the inlet because the inlet and port have always been hydraulically isolated from the inland waters by a navigation lock or causeway, and the inlet's tidal currents are very small. The entrance channel, presently maintained to -14 m MLW, is thought to be a complete littoral barrier. Rock jetties which extend about 220 m and 70 m seaward of the pre-inlet MHWL bound the channel entrance to the north and south, respectively.

BODGE (1992) prepared a comprehensive sediment budget for pre- and post-inlet conditions at Port Canaveral as part of the State of Florida's Inlet Management Plan program. The results, shown in Figure 2, are based solely upon interpretation of (i) measured shoreline changes north and south of the inlet, (ii) maintenance dredging records, and (iii) assumed values of the gross southerly and northerly transport rates incident to the inlet (268,000 and 54,000 m³/yr, respectively). The selection of these latter two drift rates was guided by wave refraction and GENESIS modeling results, and early studies of shoaling patterns at the newly cut inlet (USACE, 1961; BODGE, 1989a; USACE, 1992). It was also assumed that these incident drift rates were unaffected by the inlet's construction and thus were identical for pre- and post-inlet conditions. The maintenance dredging records were interpreted to account for only the *sandy* fraction of the dredged material, and to neglect the silt and clay fractions which dominate the inlet's maintenance requirements. The effects of beach nourishment were also removed from the data.

To convert shoreline changes to volumetric

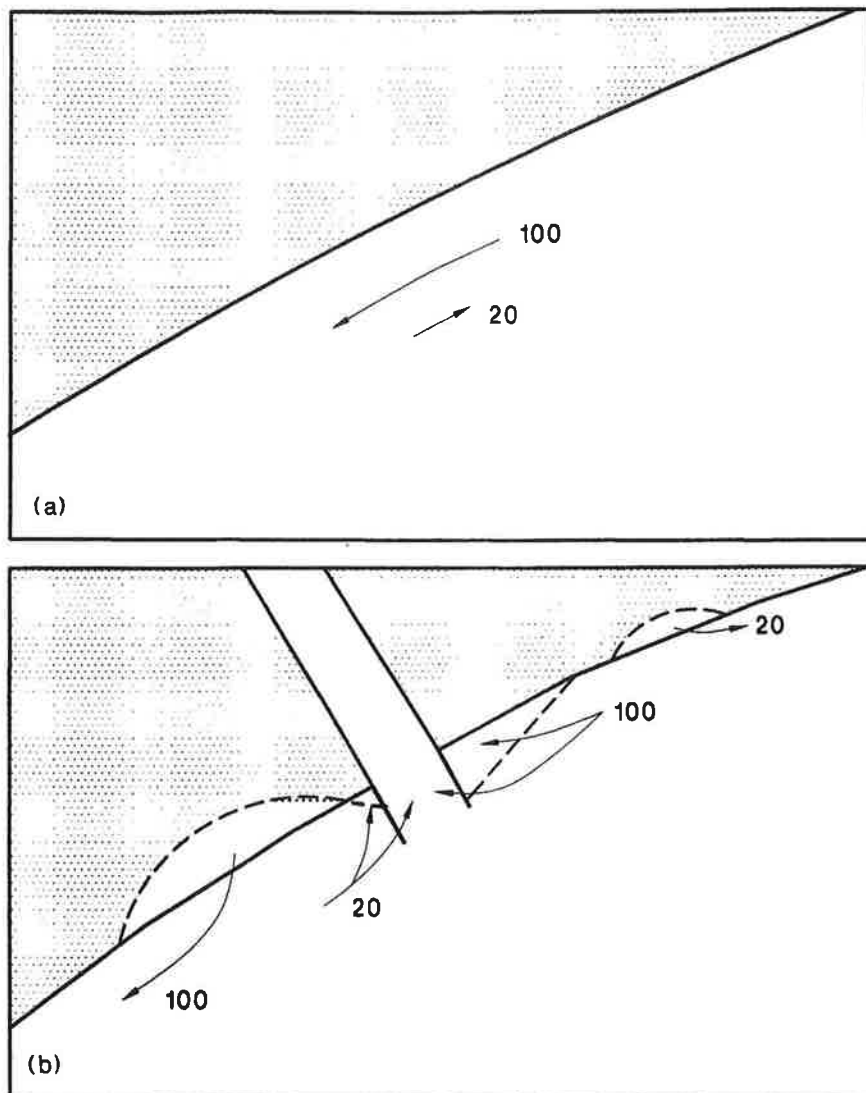


Figure 1. Example effect of a shore-perpendicular perturbation: (a) initial condition with gross and net drift rates of 120 and 80 units, respectively, and a stable shoreline; (b) perturbation condition with a sediment sink (e.g., inlet). By introducing the perturbation, the potential downdrift and updrift erosional impacts are 100 units and 20 units, respectively. Consideration of only the net drift rate leads to the erroneous conclusion that erosional impacts are limited to 80 units on the downdrift side.

changes, measured MHWL changes were correlated with sectional volume changes, where data were available, north and south of the inlet. The respective correlation results were 3.3 and 1.8 m^3/m (per unit shorefront distance). The former value was conservatively reduced to 2.5 m^3/m so as not to overestimate volumetric accretion north of the inlet. The large difference between correlation values north and south of the inlet appears

to be related to the highly accretional and erosional natures of the respective shorelines.

In pre-inlet conditions, it is estimated that strong southerly drift from Cape Canaveral rapidly decelerated across the inlet, depositing 38,000 and 15,000 m^3/yr along 3.3 km of shoreline north and south of the future inlet location, respectively. The drift incident from south of the inlet was relatively weak, and slightly decelerated

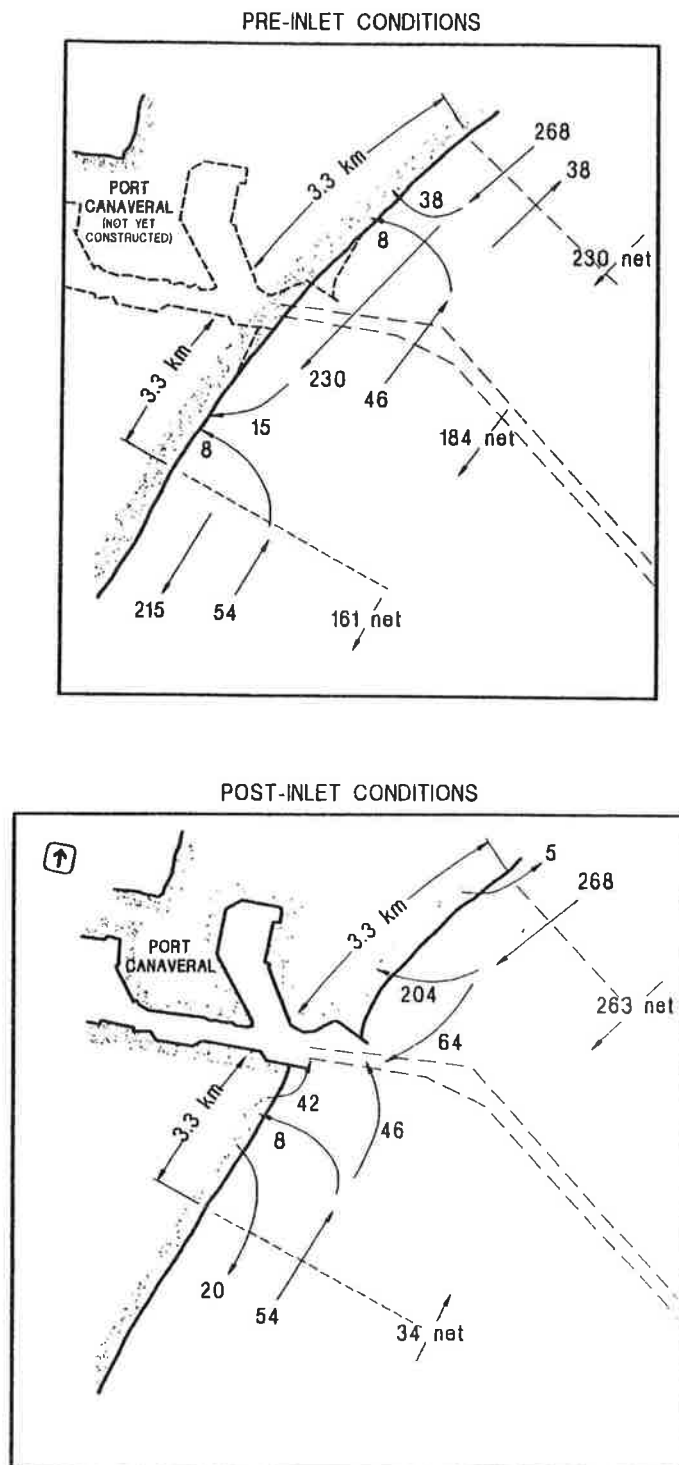


Figure 2. Gross sediment budget computed for Port Canaveral Entrance. The arrows and values represent longshore sediment transport rate in thousands of m^3/yr .

in a northerly direction across the inlet, depositing another 8,000 m³/yr on each side of the inlet location. The shoreline along 3.3 km north and south of the future inlet thus accreted by 46,000 and 23,000 m³/yr, respectively. Net transport across the pre-inlet location is estimated to have been 184,000 m³/yr to the south.

Since inlet construction, the shorelines along 3.3 km north and south of the inlet have accreted by 199,000 ($\pm 38,000$) m³/yr and eroded by 54,000 m³/yr, respectively. Relative to pre-inlet conditions, this equates to 153,000 ($\pm 38,000$) cy/yr of inlet-related accretion within 3.3 km north of the inlet, and 77,000 m³/yr of inlet-related erosion within 3.3 km south of the inlet. Over its 40 year history, the inlet's volumetric impact is estimated to be 12.1 (± 1.5) MCM, of which 6.0 MCM is associated with maintenance dredging and offshore disposal of beach-quality sand, and of which 6.1 (± 1.5) MCM is associated with updrift impoundment.

Concluding that the littoral impact of the Canaveral Harbor Federal Navigation Project is equal to its interruption of the local *net* transport rate is erroneous. Such a conclusion underestimates the project's actual impacts by 40 percent. That is, a 40-year interruption of the pre-inlet net drift rate of 184,000 m³/yr yields an estimated impact of 7.4 MCM. However, as noted above and summarized in Figure 3, the actual impact over 40 years is computed to be 12.1 (± 1.5) MCM, or 304,000 ($\pm 38,000$) m³/yr.

Why the difference? Consideration of only the interruption of net bypassing neglects the inlet's sink effect to the component, or "gross", transport. Specifically, in the case of Port Canaveral, considering only impacts to *net* transport neglects the loss of 46,000 m³/yr of incident northerly drift into the channel, and the loss of another 42,000 m³/yr from the south beach into the channel. (The latter is presumably linked to the leaky south jetty). It neglects another 8,000 m³/yr of erosion from the south beach which, in pre-inlet conditions, accreted from northerly-drift deposition. And, it neglects the loss of another 33,000 m³/yr of gross northerly drift updrift of the inlet (presumably due to updrift impoundment and loss of incident drift through the leaky north jetty).

Paths of Sediment Loss

Consideration of gross littoral transport patterns -- versus net patterns -- also yields additional insight to the paths by which the littoral drift is "captured" by the inlet. In the case of Port Canaveral, the gross transport patterns clearly reveal the severity of sediment losses through the leaky jetties. In fact, it suggests that channel shoaling is more severe from the *downdrift* side than from the updrift side. It also reveals the possibility of an updrift deficit beyond the inlet's impoundment fillit. An apparent downdrift reversal is also suggested because of the inlet's simultaneous sink effect to the gross northerly transport and interruption of the southerly (bypassed) transport.

Extent of Downdrift Impacts

The theory of PELNARD-CONSIDERE (1956), as well as model results of PERLIN and DEAN (1978) among others, suggest that the ultimate downdrift impact of a littoral barrier extends to infinity. Nonetheless, common thought appears to suggest that barrier-induced downdrift erosion is realized along the first sediment rich shoreline immediately downdrift of the barrier's wave shadow. As a rule of thumb, the wave shadow is generally between 1 and 5 times the shore-perpendicular length of the barrier. Hence, it is generally envisioned that inlet-induced erosion is realized within, say, about 1.5 to 7.5 km downdrift of inlets with jetties which are about 300 to 1500 m in length. However, this view seems patterned after the vision that the barrier, or shoreline-perturbation, interrupts the "river-like" net drift of sand. But as shown above, the perturbation actually interrupts the component, or gross, transport of sand. Further, to the author's knowledge, there is no evidence that all of the sand which is "interrupted" by the perturbation must be "restored" to the sediment transport pathways *immediately* beyond the perturbation's wave shadow.

In the case of Port Canaveral Entrance, 12.1 MCM (± 1.5 MCM) of sand is estimated to have been removed from the littoral system due to the inlet's presence. Of this total, only 3.0 MCM of

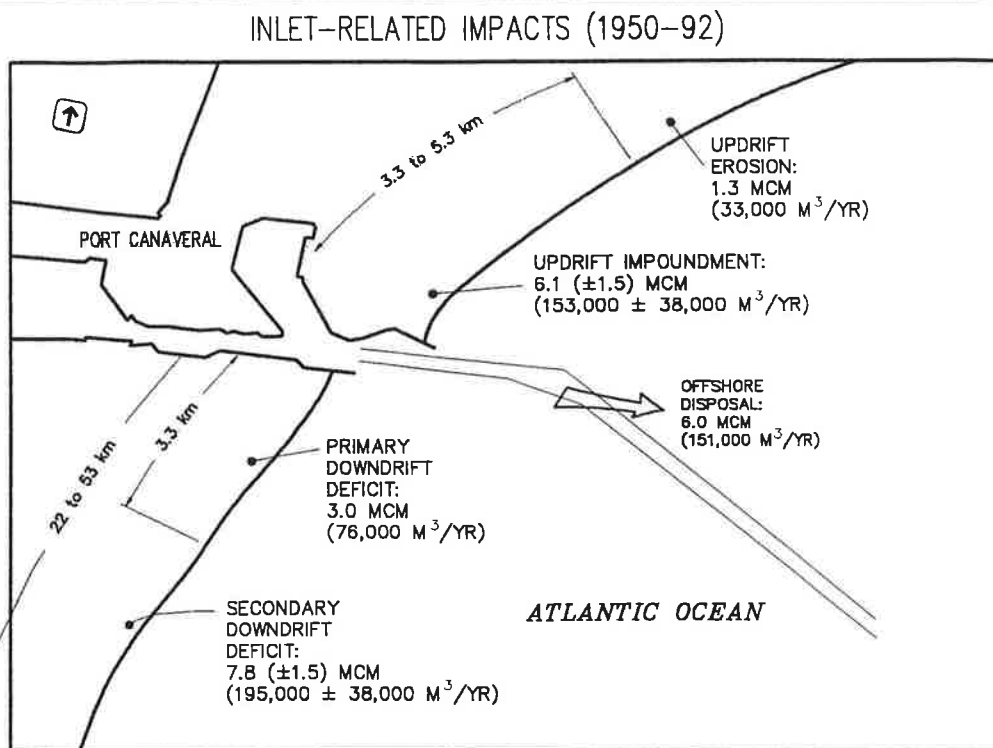


Figure 3. Summary of inlet-related littoral impacts estimated since the construction of Port Canaveral Entrance in about 1950-52.

erosion is evident immediately downdrift of the inlet (i.e., within 3.3 km south of the entrance jetties). Another 1.3 MCM of erosion well updrift of the inlet may also be attributed to the inlet's presence (see Figure 3). These two features comprise only 4.3 MCM of impact. This leaves 7.8 (± 1.5) MCM of impact unaccounted for. Because there are no major shoals at the inlet, and because further updrift impacts are improbable, one is led to conclude that this remaining 7.8 MCM of erosion has occurred beyond 3.3 km south of the inlet. That is, the total downdrift impact of the inlet is 10.8 (± 1.5) million cubic meters.

The cumulative change in beach volume south of the inlet -- since the inlet's construction -- is depicted in Figure 4. The upper pair of curves is an estimate of the "observed" change since 1952 neglecting the area's pre-inlet history of accretion; that is, this is the volume of sand thought to have eroded from the 1952 beach condition during the 40 years since the inlet was construct-

ed. The lower pair of curves is an estimate of the volume change relative to the area's pre-inlet, accretive conditions; i.e., the volume of sand which has theoretically been deprived from the beach relative to a no-inlet condition. The range of values shown for each pair of curves reflects the uncertainty (error bars) associated with converting shoreline change data to volumetric data along Brevard County -- where it is known that the two are sometimes poorly correlated well south of Port Canaveral (SAVAGE, 1990; BODGE and SAVAGE, 1992).

A volume change of 10.8 MCM relative to pre-inlet conditions (consistent with the inlet-impact analysis) is noted between 30 and 42 km south of the inlet. This distance is the possible downdrift extent of the inlet's historical impact. The ± 1.5 MCY margin-of-error widens the predicted range of downdrift impact to between 22 and 53 km. Over this total range, the beaches have exhibited a net loss of 4.6 to 11.5 MCM, neglecting pre-inlet trends, since about 1952.

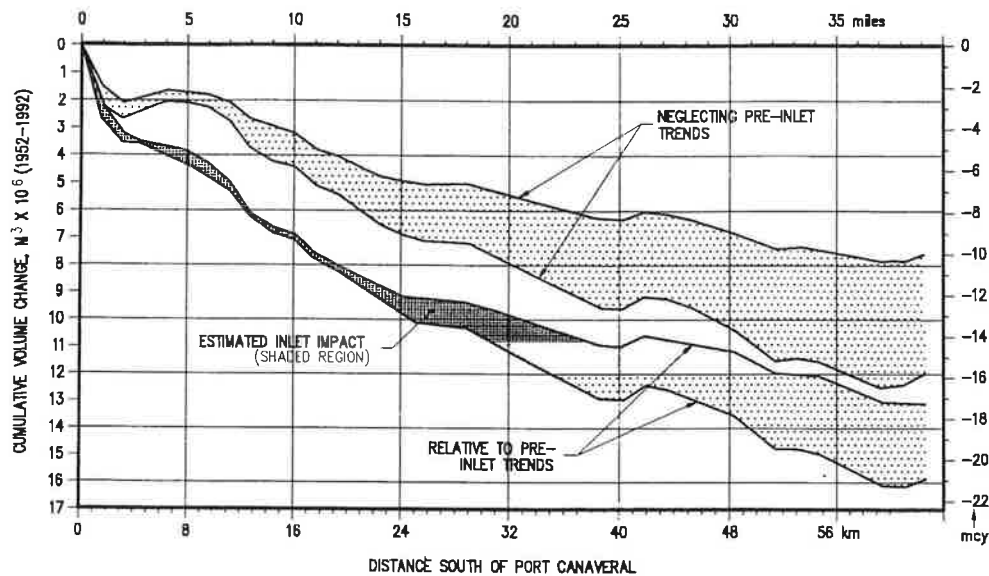


Figure 4. Cumulative, volumetric beach erosion estimated as a function of downdrift distance from Port Canaveral Entrance. The upper pair of curves refers to "observed" changes since the inlet's construction. The lower pair refers to changes since the inlet's construction -- relative to the area's pre-inlet accretion trend. The range between the curves in each pair reflects error bars associated with transforming shoreline change data to volumetric estimates.

Figure 5 depicts the estimated distribution of the inlet's downdrift impacts -- computed relative to pre-inlet conditions. The impact is seen to decrease exponentially away from the inlet.

The shoreline between 3.3 and 8 km south of the inlet has continued to accrete even after the inlet was constructed. This has led many to conclude that the inlet's downdrift impact does not extend beyond about 3.3 km. However, this area is eroding relative to pre-inlet conditions. That is, the local accretion decreased from at least 32,000 m³/yr in pre-inlet conditions to 10,700 m³/yr in post-inlet conditions. The continued accretion along this area can be theoretically shown to be due to the northerly component of the gross transport which is incident from the south beaches. This component should be unchanged by the inlet's presence. Viewed relative to pre-inlet conditions, then, the inlet's downdrift impacts are seen to extend far greater than previously thought (in this case, up to perhaps 53 km); and, the impact decreases exponentially with distance from the inlet.

Average Conditions

The previous discussion is partly presented in terms of equivalent "average annual" conditions. While this expression is convenient, its chronic use increasingly masks the random nature of coastal processes. Just as a wise farmer knows that a year of "average rainfall" is only an abstraction, coastal engineers and scientists are wise to recognize and plan for the variable, episodic nature of real-world coastal processes. The variable nature of sediment transport rates argues strongly for the wider adoption of *stochastic* engineering approaches to coastal sediment transport problems and operational schemes to manage sand transfer at inlets.

As an example, Figure 6 illustrates the annual variation in the longshore sediment transport rate computed from 20 years of [revised] Wave Information Study (WIS) hindcast wave data (JENSEN, 1983) near Palm Beach County, Florida. The rates are computed using Phase II, offshore wave data and the "offshore version" of the CERC Formula (Eq. 4-45; USACE, 1984).

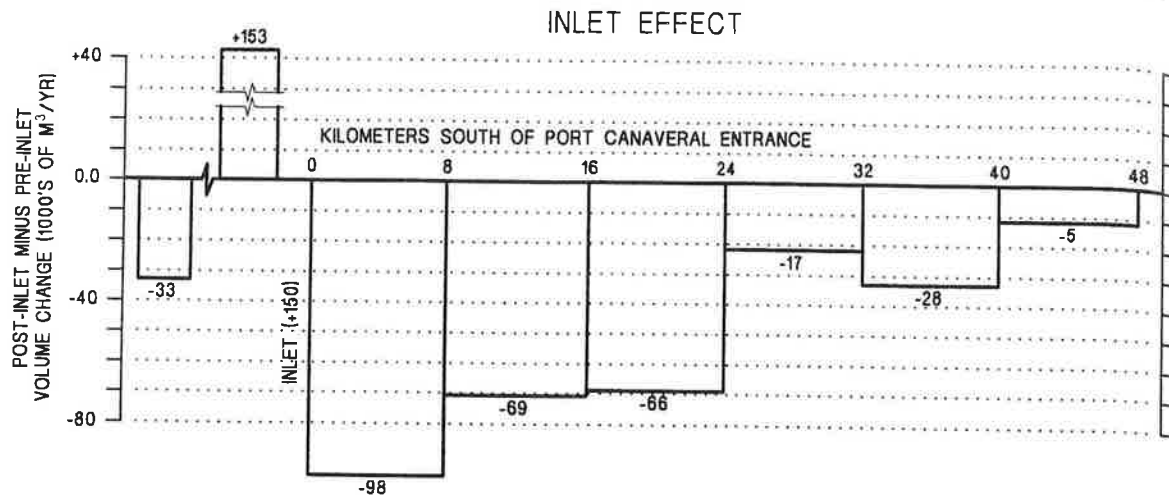


Figure 5. Distribution of inlet impacts downdrift of Port Canaveral Entrance -- estimated by comparing pre- and post-inlet beach volume changes along 5-mile reaches of shoreline.

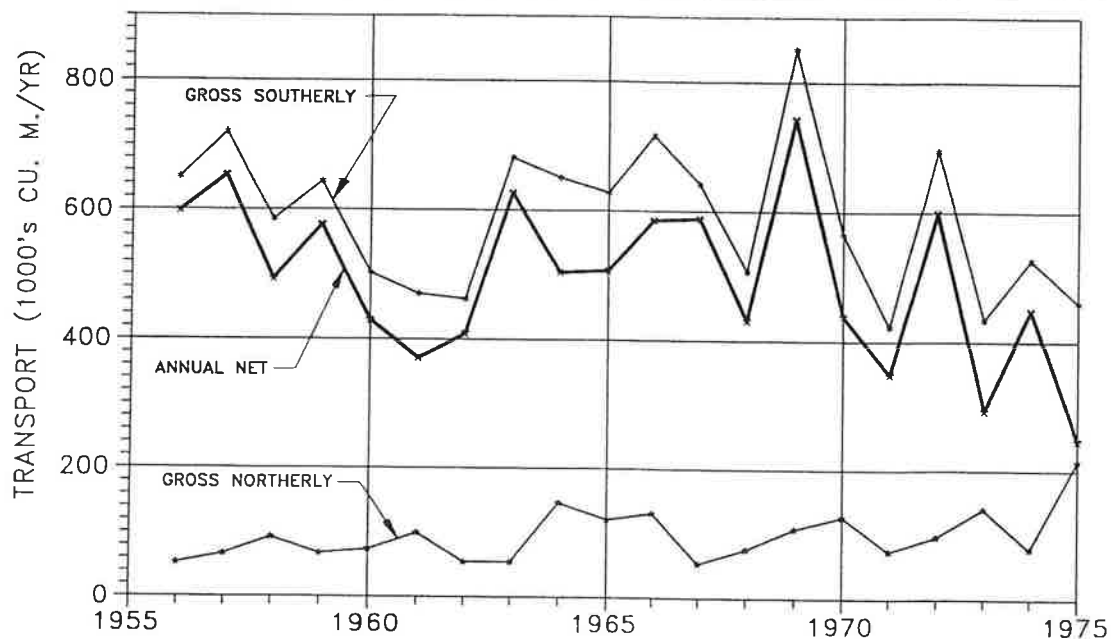


Figure 6. Yearly variations in the predicted gross and net longshore sediment transport rates at WIS Station RA2-11 near Palm Beach, Florida; 1956-75.

The normalized standard deviations of the annual net and gross southerly transport values, relative to the mean values, are 26% and 42%, respectively.

INTERCEPTING SAND FOR INLET BYPASSING

Successful design of engineering works to improve sand management at inlets depends, in

part, upon accurate recognition of (1) the locations at which sediment transport occurs, and (2) the physical processes required to move sand towards (or keep sand away from) the devices intended to bypass (or block) sediment transport. Improper consideration -- or a lack of consideration -- for either of these issues may result in a bypassing system or other inlet structure which is unexpectedly limited in effectiveness.

Swash Zone Transport

For example, it would appear that the KOMAR (1977) model of the distribution of longshore transport across the surf zone remains fixed in many investigators' minds. In this classical model, the transport peak is said to occur about seven-tenths of the distance to the breakpoint, with negligible transport at the shoreline. However, the literature demonstrates that the cross-shore distribution of longshore transport is as likely bimodal; that is, with a peak near the breakpoint and at the swash zone (BODGE, 1989). The significance of this observation to inlet management is clear: it is as critical to intercept littoral drift at the shoreline and within the swash zone as it is near the breakpoint.

Prototype examples of the significance of intercepting longshore transport at inlets' swash -- or intertidal -- zones are numerous. For instance, the record of operating hours for the jet pumps at the Nerang River sand bypassing plant in Queensland, Australia, illustrated in Figure 7, are significantly greater for the nearshore pumps than for the offshore pumps (CLAUSNER, 1980; COUGHLAN and ROBINSON, 1990). This distribution of operating hours (reinforced by the operators' comments) implies that the most effective bypassing is achieved by the pumps closest to the shoreline and swash zone.

Likewise, the recent experience of the Indian River Inlet mobile bypassing plant -- which creates a dredge pit at the shoreline -- attests for the effectiveness of bypassing from the swash zone (GEBERT *et al.*, 1991). Lastly, it is noted that the productivity of the fixed sand bypassing plant at South Lake Worth Inlet, Florida, did *not* increase when the plant was moved in 1967 from its shoreline location to its present site in the

mid- to outer surf zone. This is despite the fact that the sand thickness above the underlying rock strata (which limits the size of the bypassing crater) is about the same at both the plant's present and previous locations. Each of these three examples point to the importance and benefit of: (1) intercepting littoral drift at the intertidal area; and (2) ensuring that jetty structures are sand-tight at the intertidal area.

Limits of Sand Interception

Attention to the swash zone can improve sand interception and bypassing at inlets, but it is obviously not a cure-all. That is, building a bigger trap won't necessarily catch a bigger mouse; i.e., oversizing a single-point bypass system will not necessarily increase productivity.

For the case of the fixed sand bypassing plant at South Lake Worth Inlet, for example, the present plant appears to bypass as much sand as possible for its given location (OLSEN ASSOCIATES, INC., 1990). Its performance is limited by crater-infilling rates. The plant falls short of bypassing all available sand only during energetic northeasterly wave conditions (when the crater fills as fast or faster than it can be pumped). On average, the plant operates about 76 days per year. The frequency and duration of the plant's operations is mostly dictated by the amount of sand which has filled the crater.

A simplistic estimate of the average shoaling rate at the South Lake Worth Inlet sand bypassing pit was developed through examination of the plant's daily production records. For each day during which the plant was operated, the volume of sand excavated from the pit was divided by the number of non-pumping hours which preceded the excavation. For example, if 460 m³ were excavated beginning Wednesday at 0600 and the previous pumping event ended at 1200 on Monday, the average shoaling rate was estimated to be 460 m³ per 42 hrs, or 10.95 m³/hr.

Figure 8 depicts the distribution of shoaling rates computed in this manner for the years 1986, 1988, and 1989. (The year 1987 was excluded because of unreliable volumetric pumping data.) Figure 8 also depicts the distribution

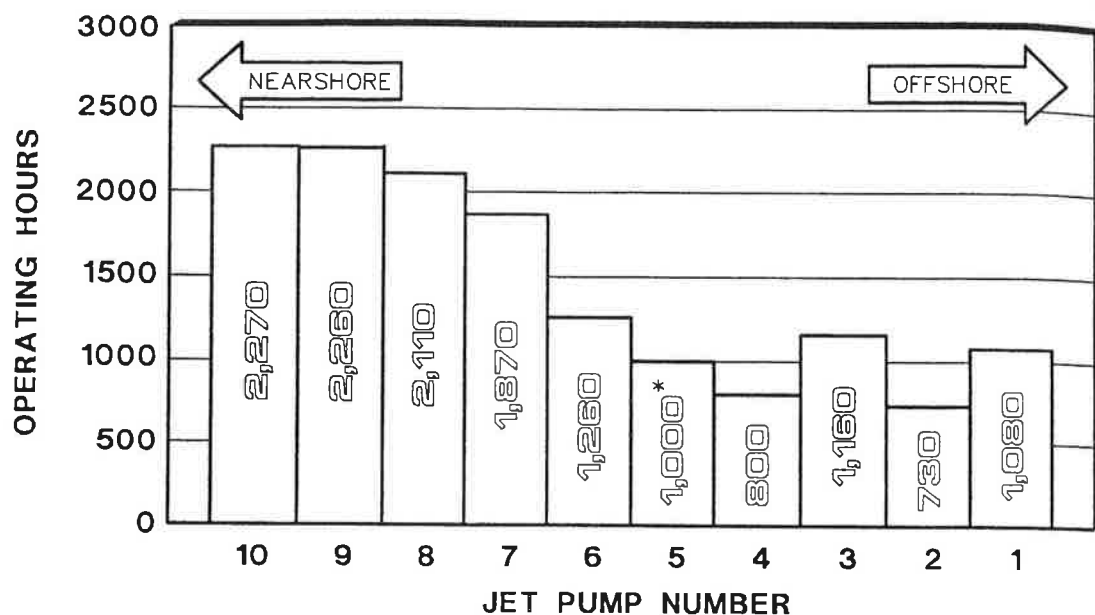


Figure 7. Jet pump operating hours from May, 1986 to February, 1988; Nerang River bypassing plant, Queensland, Australia (data from Clausner, 1988). The hours for pump #5 are estimated.

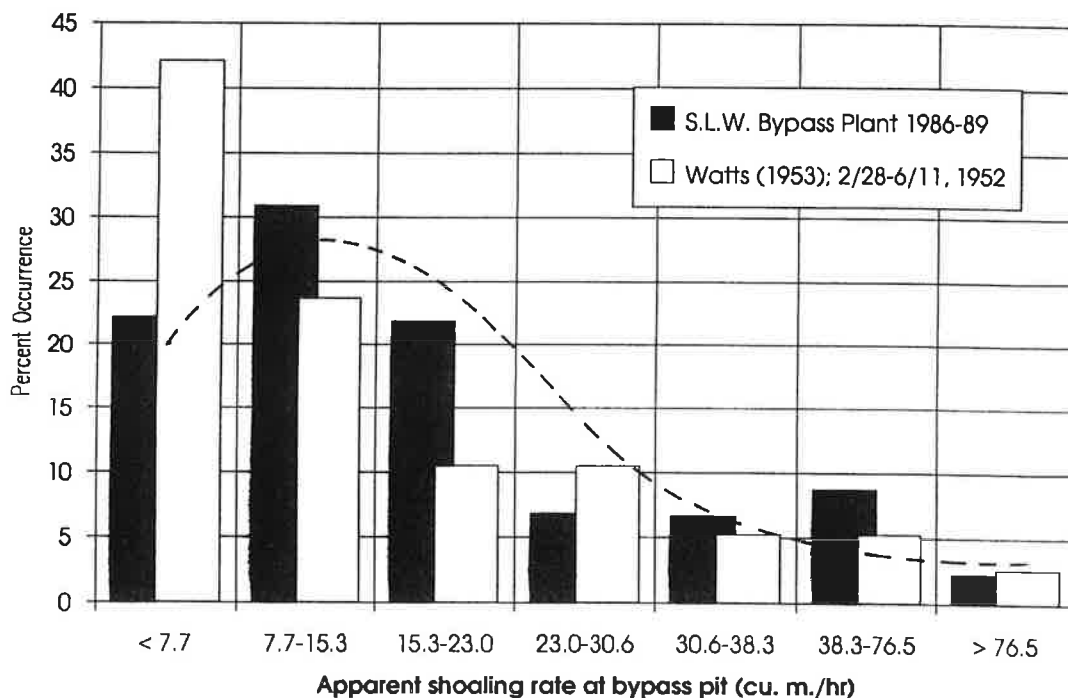


Figure 8. Crater shoaling rates hindcast from (a) 1986, 1988, and 1989 operating records of the fixed-plant sand transfer facility, and (b) a 4-month experiment in 1952 at South Lake Worth Inlet, Florida. The dashed line represents a Rayleigh distribution about the mean of the 1986-89 dataset.

of shoaling rates computed in the same manner using data from a temporary bypassing experiment conducted at South Lake Worth Inlet between Feb. 28 and June 11, 1952 (WATTS, 1953). The average values of the 1986-89 and 1952 datasets are 19.9 and 15.7 m³/hr, respectively. The former data are suggestive of a Rayleigh distribution.

The distribution of crater shoaling rates shown in Figure 8 may be used to investigate the limitations of the existing bypassing plant -- or the potential effectiveness of plant improvements. That is, a plant is typically limited by its maximum crater volume, V , and/or its effective net productivity, P , where the latter is expressed as volume/time and includes operational limitations. The time T_p required to excavate the maximum crater volume is

$$T_p = \frac{(V + S T_p)}{P} \quad (1)$$

where a quasi-steady shoaling rate, S , is assumed. The time T_s required for the crater to refill is

$$T_s = \frac{V}{S} \quad (2)$$

If the crater is not completely refilled by the start of the next bypassing event, then the bypassing plant has sufficient capacity to "keep up" with the shoaling rate. On the other hand, if the crater is completely refilled prior to the start of the next bypassing event, then an increase of the plant's capacity will increase net bypassing production -- at least for that particular shoaling event. If, for example, a plant's *daily* productivity potential is of interest, then for those instances where

$$T_p + T_s < 24 \text{ hrs} \quad (3)$$

the plant cannot "keep up" with the shoaling rate and the plant would benefit from increased crater volume or productivity. By combining Eqs. 1 through 3, one concludes that this condition will occur when

$$S > \frac{1}{2} \left(P - \sqrt{P^2 - \frac{VP}{6}} \right) \quad (4)$$

for S , P , and V expressed in units of volume per hour. (More generally, where E hours are to occur between the start of subsequent dredging events, the "6" in the denominator of Eq. 4 is replaced by $E/4$, and consistent units of volume and time are used for S , P , V , and E .)

For the case of the existing sand bypass plant at South Lake Worth Inlet, the maximum crater volume is limited to about 460 m³ by underlying rock strata, crane geometry, and typical seabed depths. The plant's productivity is such that the 460 m³ crater volume can be typically excavated in about 4 hrs; i.e., a rate of about 115 m³/hr. Hence, from Eq. 4, for $V = 460$ m³ and $P = 115$ m³/hr, the plant cannot "keep up" with crater shoaling rates in excess of 24.3 m³/hr during typical daily production; i.e., where $E = 24$ hrs. From Figure 8, this condition occurred about 23% -- or about one-quarter -- of the time during which bypassing operations were undertaken in 1986-89. This implies that an increase of the existing plant's crater size or mechanical productivity would be of value for only about one-quarter of the days for which the plant was operated. For example, increasing the plant's boom length from 10.7 m to 15.2 m would increase the potential crater volume by 43%. However, the effective increase in annual productivity would be only one-quarter as great -- or 11%. In the case of South Lake Worth Inlet, then, where a 40%-plus increase in sand bypassing is required to restore the pre-inlet transport regime, it may be necessary to broaden the zone of sand interception (i.e., by adding another bypass plant) rather than to just modify the existing plant.

Data which describe the distribution data of crater shoaling rates, such as are shown in Figure 8, are not commonly available. For these instances, it is suggested that a Rayleigh distribution be assumed about the site's mean shoaling rate. The latter might be estimated as the annual gross drift rate at the crater location minus the rate of natural (or other) bypassing around the crater's location. Such rates are typically determined through a sediment budget analysis.

As a convenient example, consider again South Lake Worth Inlet. The gross longshore transport rate is estimated as about 230,000 m³/yr

(BRUUN *et al.*, 1966) and the natural bar-bypassing rate is estimated as about 68,000 m³/yr (OLSEN ASSOCIATES, INC., 1990). Hence the mean shoaling rate may be about 162,000 m³/yr, or 18.5 m³/hr. This value agrees fairly well with the "observed" 1986-89 value of 19.9 m³/hr. If it is desired that the bypassing plant be fully capable of handling, say, 90% of all shoaling events in daily operation, and a Rayleigh distribution centered about 18.5 m³/hr is assumed, then the plant should be designed for a crater shoaling rate of about 29 m³/hr. For example, from Eq. 4 and using $S = 29.0 \text{ m}^3/\text{hr}$, a nominal crater volume of 520 m³ would be required for a given production rate of 115 m³/hr.

IMPLEMENTING INLET MANAGEMENT STRATEGIES

Identifying the quantities and pathways of an inlet's littoral impacts is of little value unless the engineering solutions for these problems are implemented. Communication between and participation of the relevant design professionals throughout the design, contracting, award, and supervision phases of the project is central to the successful implementation of a beach- or inlet-related project. Additionally, it is essential that all parties involved keep an open mind to alternative methods by which the inlet can be managed, recognizing that the most forward-looking solution is as likely to require conventional technology as it is new technology.

Conventional Technologies

Using Port Canaveral again as an example, a new dredge disposal solution there -- using older technology -- enabled the Corps to retain 122,000 m³ of sand within the littoral system which would otherwise have been disposed of at sea (OLSEN, 1992). Forced to abandon hopper dredging for maintenance of the Port's entrance channel (so as to minimize impacts to sea turtles), the Jacksonville District, Corps of Engineers, returned to clamshell dredging. This, in turn, enabled the Contractor to dredge sand-rich shoals separately from the silt and clay bottom within the channel, and to subsequently dispose

of the sandy material to a nearshore berm downdrift of the inlet. The pilot project was conducted with the financial support of the Canaveral Port Authority in 1992. The project will be continued as a regular part of the Canaveral Harbor federal maintenance program -- as a least-cost alternative. The use of shallow scows and dredges such as the *Currituck* developed decades ago may enable cost-effective dredge disposal in the outer surf zone -- increasing the rate of littoral recovery while simultaneously providing recreational enhancements.

Economic Analysis

Alternative economic analysis of a broader scope is likewise required for improved inlet management. The "least-cost" method to execute one authorized task may increase the cost of some other task; thus resulting in an overall economic inefficiency. A historical example of this in the United States is the separation of most Federal navigation works from *beach erosion control* works.

Many *interim* works to improve an inlet can be shown to be economically justified -- even though the works appear very small or "temporary" relative to typical inlet improvements. Moreover, the requisite economic analysis need not be complicated. Employing Port Canaveral yet again as an example, it is known that the Port's south jetty leaks sand (USACE, 1992; BODGE, 1992). From the inlet's sediment budget, about 48,000 m³ of sand enters the channel each year over/through the landward end of the south jetty. The earliest that permanent sand-tightening of the south jetty will be undertaken is 18 months from this writing. During this time, 72,000 m³ will be lost from the south beach and deposited into the channel through the landward end of the jetty. An *interim* sand-tightening solution would be a sand-filled geotextile tube placed parallel to and along the south jetty to temporarily sand-tighten it.

If, over 18 months, the tube reduced the sand flow over the landward half of the south jetty by 80% (i.e., by 57,600 m³), then a maintenance-dredging savings of about U.S.\$ 320,000 would be realized. Also, the 57,500 m³ of sand retained

upon the beach would lessen subsequent beach nourishment requirements by the same volume -- thus potentially saving another U.S.\$ 300,000.

Construction-cost estimates for this interim solution are about U.S. \$180,000 for a tube placed along the landward half (150 m) of the jetty. Considering only the navigation (maintenance) benefit, the tube's Benefit/Cost ratio is 1.8:1. Including beach erosion benefits, the B/C ratio is at least 3.4:1. The robust value of these B/C ratios means that the estimates of the tube's effectiveness can be off by a factor of almost 2 or more, and the project would be still cost-effective. Overall, then, an otherwise insipid, temporary jetty project is shown to be a very economically-favorable means by which to jointly improve navigation and beach erosion control.

CONCLUSION

Four major observations have been presented which may aid the development and implementation of successful sand management strategies at inlets:

1.) Over-simplification of littoral processes potentially biases the quantification of sediment transport paths. Specifically, inlet impacts are not necessarily limited to the interruption of the net drift rate -- but are a function of the component, or gross, transport processes. The increasing use of the average annual net drift rate to describe inlet dynamics obscures both the gross transport processes and the variable nature of sediment transport quantities. This is detrimental to both the determination of an inlet's actual littoral impact and the development of solutions to reduce the impact.

2.) The erosive impact of an inlet may extend significantly further downdrift than is conventionally thought. In the case of Port Canaveral Entrance -- a man-made inlet created in about 1952 -- the downdrift impact may extend between 30 and 42 km south of the inlet, decreasing exponentially with distance from the inlet.

3.) Traditional concepts regarding sand interception may limit the effectiveness of sand bypassing operations. Intercepting longshore transport across the intertidal (swash) zone is probably as -- or maybe more -- important than

it is across the outer surf zone. Also, increasing the zone(s) at which sand is intercepted can be more important to bypassing productivity than is expansion of the plant's pumping capacity.

4.) Development of inlet management strategies which address both navigation and beaches requires active cooperation between all involved parties. Specifically, all parties should be open to the consideration of new ideas and modifications of existing operations. Some *new* ideas may utilize *old* equipment. Some very sensible, cost-effective inlet improvements can be made with small-scale, temporary works. Economic analysis of improvements should be broadened to consider all relevant costs and benefits of the work.

In closing, it is now recognized that navigation and beach erosion are coupled through inlets. Therefore, to be successful, inlet management can not de-couple navigation planning and beach planning. After all, strategic resource recovery for the beaches (i.e., sand) can positively affect navigation.

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LITERATURE CITED

- BODGE, K.R., 1989a. Wave refraction and littoral drift along Brevard County, Florida. *Report*, Jacksonville, Florida: Olsen Associates, Inc., 270p.
 BODGE, K.R., 1989b. A literature review of the distribution of longshore sediment transport across the surf zone. *Journal of Coastal Research*, 5(2), 307-328.

- BODGE, K.R., 1992. Inlet management plan; Port Canaveral, Florida. *Draft Report*, Jacksonville, Florida: Olsen Associates, Inc., 335p.
- BODGE, K.R. and SAVAGE, R.J., 1992. Inopportune timing of oceanfront structures. *Proceedings, Beach Preservation Technology '92*; Florida Shore and Beach Preservation Association, Tallahassee, Florida, 55-67.
- BRUUN, P. and BATTJES, J.A., 1963. Tidal inlets and littoral drift. *Proceedings of the International Association for Hydraulic Research*, 4(1.17), 123-36.
- BRUUN, P.M.; BATTJES, J.A.; CHIU, T.Y., and PURPURA, J.A., 1966. Coastal engineering model studies of three Florida coastal inlets. *Engineering Progress at the University of Florida*, 20(6), 72p.
- CLAUSNER, J.E., 1988. Jet pump sand bypassing at the Nerang River Entrance, Queensland, Australia. *Proceedings, Beach Preservation Technology '88*, Florida Shore and Beach Preservation Assoc., Tallahassee, Florida, 345-355.
- COUGHLAN, P.M. and ROBINSON, D.A., 1990. The Gold Coast Seaway, Queensland, Australia. *Shore and Beach*, 58(1), 9-16.
- DEAN, R.G. and WALTON, T.L., 1975. Sediment transport processes in the vicinity of inlets with special reference to sand trapping. In: L.E. Cronin (ed.), *Estuarine Research*. New York: Academic Press, pp. 129-150.
- GEBERT, J.A.; WATSON, K.D., and RAMBO, A.T., 1992. 57 years of coastal engineering practice at a problem inlet; Indian River Inlet, Delaware. *Proceedings, Coastal Engineering Practice '92* (ASCE), 503-519.
- JENSEN, R.E., 1983. Methodology for the calculation of a shallow water wave climate. *WIS Report #8*, Coastal Engineering Research Center, Vicksburg, Mississippi, pp. 3-48. [Data revised 1992, provided by U.S. Army Corps of Engineers, Jacksonville District, personal communication.]
- KOMAR, P.D., 1977. Beach sand transport: distribution and total drift. *Journal of the Waterway, Port, Coastal, and Ocean Division* (ASCE), 103(2), 225-239.
- OLSEN ASSOCIATES, INC., 1990. South Lake Worth Inlet sand management plan. Jacksonville, Florida: Olsen Associates, Inc., 270p.
- OLSEN, E.J., 1992. Canaveral Harbor nearshore disposal project; post-project assessment. *Report*, Jacksonville, Florida: Olsen Associates, Inc., 69p.
- PELNARD-CONSIDÈRE R., 1956. Essai de théorie de l'évolution des forms de rivage en plage de sable et de galets. *4th Journées de l'Hydraulique: Les Énergies de la Mer*, Question III, No. 1; 289-300.
- PERLIN, M. and DEAN, R.G., 1978. Prediction of beach planforms with littoral controls. *Proceedings Sixteenth International Conference on Coastal Engineering* (ASCE), 1818-1838.
- SAVAGE, R.J., 1990. A comparison of mean high water shoreline change and bluff movement. *Proceedings, 1990 National Conference on Beach Preservation Technology*, Florida Shore and Beach Preservation Association, Tallahassee, Florida, 324-338.
- USACE, 1961. Survey Review Report on Canaveral Harbor, FL. *Serial No. 106*. Jacksonville, Florida: U.S. Army Corps of Engineers, Jacksonville District. Became U.S. Senate Doc. 140/87/2 in 1962, variously paginated.
- USACE, 1984. Shore Protection Manual. Vicksburg, Mississippi: U.S. Army Corps of Engineers, Coastal Engineering Research Center, Vol. 1, pp. 4-94.
- USACE, 1992. Canaveral Harbor, Florida - sand bypass system. *General Re-Evaluation Report with Environmental Assessment*. Jacksonville, Florida: U.S. Army Corps of Engineers, Jacksonville District, variously paginated.
- WALTON, T.L. and ADAMS, W.D., 1976. Capacity of inlet outer bars to store sand. *Proceedings Fifteenth International Conference on Coastal Engineering* (Honolulu, Hawaii) (ASCE), 1919-1937.
- WATTS, G.M., 1953. Study of sand movement at South Lake Worth Inlet, Florida. *Technical Memorandum No. 42*, Washington, DC: U.S. Army Beach Erosion Board, 24p.