

## INLET IMPACTS AND FAMILIES OF SOLUTIONS FOR INLET SEDIMENT BUDGETS

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**Abstract:** The paper presents an algebraic method by which a “Family of Solutions” can be developed to numerically bound and describe the sediment transport pathways integral to an inlet’s sediment budget. The method considers inlet-directed transport from both adjacent shorelines (i.e., gross transport vs. net), as well as localized transport induced by inlet shoals or other perturbations. The method likewise accounts for jetty permeability, natural sand bypassing, riverine input, the effects of dredging and sand bypass, and out-of-system dredge disposal. The paper additionally describes methods to assess the littoral impact of the inlet upon adjacent shorelines.

### INTRODUCTION

This paper presents an analytic method to quantitatively evaluate (1) the extent of the inlet’s littoral impact upon the adjacent shorelines, and (2) the magnitude and direction of a tidal inlet’s sediment transport pathways. The method utilizes measured (or estimated) volume changes within and updrift of the inlet, estimates of historical dredging volumes, and broad estimates of the probable local littoral drift, the extent to which the inlet’s presence influences the littoral drift, and the inlet jetties’ permeability. *A priori* knowledge or certainty of any of these factors is not assumed. Instead, inherent uncertainties in any or all of these factors are accommodated by specifying a *range* of input values (minima and maxima) for each. This bounds the resulting computations to a *family of solutions* that can describe (quantify) the inlet’s sediment transport pathways and sediment budget. This *family*, in turn, yields useful bounds on the transport values of the individual sediment pathways. That is, for given ranges of physically reasonable inlet parameters (e.g., jetty permeability, ratio of right- and left-directed littoral drift, historical shoaling rates, etc.), a family of solutions is developed which ultimately narrows the range of possible values for each transport parameter in order that the overall inlet sediment budget can be

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solved. Ultimately, inspection of this "family of solutions" yields insight to the most probable, discrete solutions for the inlet's natural bypassing rate, jetty permeabilities, and other sediment transport pathways. In developing the methodology, a rational means by which to assess the inlet's total volumetric impact upon the adjacent beaches is presented.

The approach developed here is an extension of those described by Bruun (1966), Weggel (1981), the Shore Protection Manual (USACE, 1984), Jarrett (1991), Kana and Stevens (1992), as well as early case studies by Johnson (1959), Jarrett (1977), among others; and more recent case studies such as by Dolan et al. (1987), Headland et al. (1987), Olsen (1990), CP&E (1992), among others. The paper's approach likewise recognizes the significant influence of the gross littoral drift — versus simply the net drift (Bruun and Battjes, 1963; Dean and Walton, 1975; Walton and Adams, 1976; Bodge, 1993), as well as the potential significance of inlet shoaling and adjacent beach erosion that results from both up- and downdrift jetty permeability (Wang and Lin, 1992; Dean and Work, 1993). The sediment budget results developed by the present method can provide a useful starting point for more detailed analyses, including uncertainty valuations, such as those described in Rosati and Kraus (1998) and Kraus and Rosati (1998).

## INLET IMPACT UPON ADJACENT SHORELINES

An inlet — particularly an improved inlet — typically diverts littoral material (hereafter referred to as "sand", for brevity) from the adjacent littoral system by (1) impoundment, (2) net increases in shoal volume (beyond that associated with the pre-improvement condition), and (3) maintenance dredging and out-of-system disposal of littoral material. The sum of these three factors represents the inlet's potential volumetric impact to the adjacent beaches.

Most investigators have conventionally attempted to assess an inlet's littoral impacts by evaluating the extent of erosion along the adjacent beaches, particularly the net downdrift beach. This approach can be typically difficult, inconclusive, or prone to underestimation because (1) the downdrift extent of the inlet's impact (and therefore the limits of the study area) are not known at the outset, and (2) condition surveys of the downdrift beach are either incomplete or contain obfuscating (and often irreconcilable) influences from shoreline armoring and/or beach nourishment. The latter is particularly likely where downdrift erosion has been severe and significant, such that artificial manipulation of the shoreline has been necessary.

An alternative, and potentially less ambiguous, approach is to first evaluate the volume of sand that has been removed from the littoral system by the inlet; i.e., the sum of impoundment, net increases in inlet shoal volumes, and maintenance dredging and out-of-system disposal, as noted above. Then, shoreline (volume) changes along the adjacent beaches are examined to discern the alongshore extent to which this inlet-impact volume is manifest. Means by which to assess the inlet's volumetric impact upon the littoral system are described below.

Impoundment. Historical changes in inlet-adjacent beach volume are cumulated (integrated) along the shoreline beginning at the inlet and moving therefrom, and the results are plotted. Changes in shoreline position can be approximately converted to volume change by a locally calibrated correlation factor, or, for example, by a form of the "Bruun Rule" whereby

$$\Delta V = \Delta x (h^* + B) \quad (1)$$

where  $\Delta V$  is the volumetric change per unit distance alongshore,  $\Delta x$  is the local shoreline change, and  $(h^* + B)$  is the vertical height of the active beach profile; i.e., where  $h^*$  is the depth of closure

and B is the berm elevation. The alongshore extent of the inlet-adjacent impoundment signal is typically evidenced by a break in slope (flattening or decline) of the plotted, cumulative curve. See Figure 1. The integrated volume change at this point potentially represents the impoundment volume along the shoreline. The “background” volume change can be, or should be, removed from this value by subtracting the corresponding, cumulative volume change from along the same shoreline reach for the pre-inlet (or pre-improvement) condition. Such “background” changes might be estimated by examining shoreline behavior outside the range of the apparent impoundment effect.

In the example of Figure 1, below, the updrift shoreline’s background change is presumed to be the quasi-uniform accretion observed beyond 3- to 4-km updrift of the inlet. After subtracting this effect from the total observed (measured) cumulative volume change, the example inlet’s apparent impoundment effect is about 2.3 million cubic meters (mcm), extending to about 3.5 km updrift of the inlet. Cumulating – or integrating -- the measured volume changes in this way acts to smooth the noise of volume changes along the shoreline. This improves one’s ability to discern trends, or “breaks”, in the data, relative to plots of discrete volume changes alongshore.

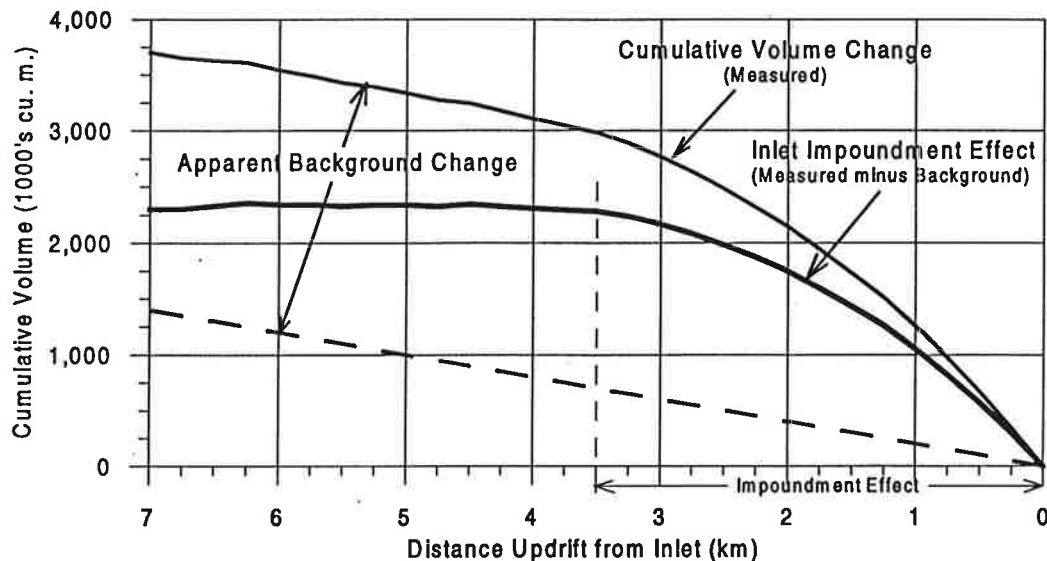


Figure 1. Updrift impoundment effect discerned from cumulative alongshore volume change.

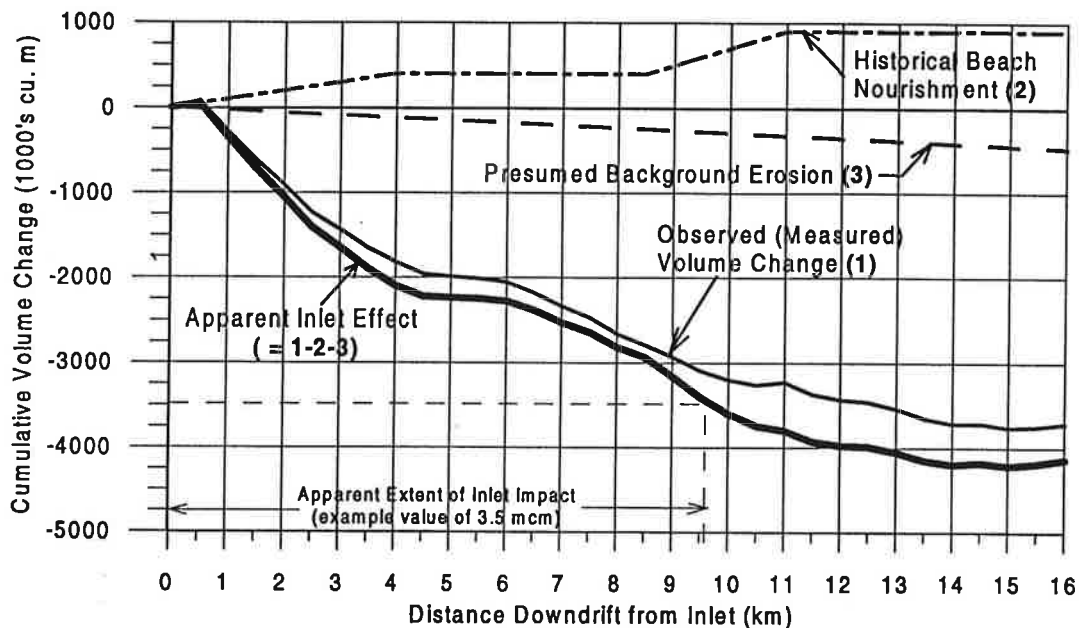
Impoundment is most often manifest along the net updrift shoreline, but can also occur along the downdrift shoreline. In this instance, the impoundment fillet represents a “dead storage” of sand that has been made unavailable for transport to the adjacent, downdrift beach — most typically because of wave “shadow” effects related to the inlet’s jetties or ebb shoal platform. This downdrift impoundment volume thus contributes to the inlet’s diversion of sand from the littoral system, and is added to the sum total of the inlet’s volumetric impact.

**Inlet Shoal Volumes.** Typically, historical bathymetric surveys are compared to estimate the net change in ebb, flood, and inlet-throat shoals over a given period. In the case of a new inlet for which pre-inlet surveys are unavailable, the shoal volumes are compared to theoretical “straight & parallel depth contours” presumed to represent the pre-inlet seabed (Walton and Adams, 1976; Marino and Mehta, 1986). In contrasting historical bathymetric surveys, it is important to account

for the effects of survey-datum changes and dredging, and to exclude those volume changes likely associated with non-littoral sediments or episodic, fluvial sediments. Failure to account for new-work dredging (channel expansions), or historical mining of inlet shoals for upland reclamation, for example, can lead to an erroneously deflated estimates of shoal growth. Comparison of long-term surveys referenced to tidal datums (not fixed geodetic datums) can likewise result in deflated or inflated values for sites with pronounced sea level rise or fall, respectively.

Maintenance Dredging. Records that indicate the volumes and fate of maintenance dredging are used to estimate out-of-system sand disposal. Only that fraction of the dredged material that is of suspected littoral origin or quality is considered. Such information can be gleaned from sediment records or from examination of channel surveys that reveal typical pre-dredge shoaling volumes in those locations of probable littoral influx (e.g., adjacent to jetties, etc.).

Downdrift Extent of Inlet Influence. The inlet's potential volumetric diversion of sand from the littoral system is the sum of the three constituents noted above. Particularly in the "classical" case where inlet-adjacent beach erosion is principally manifest along the net downdrift shoreline, the alongshore extent of the inlet's littoral influence can be examined by comparing this inlet-volumetric impact with the observed volumetric change along the downdrift beaches. As noted, this is often confounded by incomplete or "noisy" survey data along the downdrift shoreline; however, an order-of-magnitude estimate (or range of estimates) may be achievable. In this approach, the measured or estimated beach volume changes, for a given period of interest, are cumulated (integrated) along the downdrift shoreline commencing at the inlet and proceeding therefrom — as was done for estimation of the impoundment signal. See Figure 2. Background (no-inlet or pre-inlet) changes are subtracted, as possible, along with the volumes of nourishment sand placed from out-of-system sources. Most simply, the lineal extent of the inlet's impact is the alongshore location at which the observed downdrift volume change equals the volume of sand



**Figure 2:** The inlet's littoral impact is compared to the cumulative volume change downdrift of the inlet. The inlet's effect is the measured volume change minus sand nourishment (sourced from outside of the inlet) minus background (non-inlet-related) changes.

diverted from the inlet over the given period of interest. The way in which natural variations in the longshore transport rate, from one side of an inlet to another, alter the inlet's impact to the adjacent beaches is described in the next section.

In the example of Figure 2, a total of 0.9 mcm of historical beach nourishment (from offshore and upland sources) is subtracted from the measured downdrift volume change. Likewise, non-inlet erosion – ascribed to, say, sea level rise – is subtracted. The result (bold line) is the apparent inlet-related volume change. In the example, if the sum of the inlet's volumetric diversion of sand was computed to be 3.5 mcm, and none of this was accounted for by updrift erosion, then the inlet's apparent downdrift impact is on the order of about 9.5 km.

To-date, prototype application of this approach for at least five inlets (Bodge, 1994; Raichle et al., 1997; Olsen, 1998; Olsen/CPE, 1998; Browder, 1999) has resulted in estimates of downdrift erosion influence that are significantly larger (longer) than previous investigators concluded for the same inlets -- even when the approach's results are interpreted conservatively. In these cases, prior studies estimated the downdrift inlet impacts by examining the shoreline changes along a pre-determined, finite length of the downdrift beach. For example, the littoral impact of Port Everglades Entrance is computed to be about 4.5 to 5.2 mcm since the inlet's construction in 1926 (Olsen/CPE, 1998). Downdrift erosion within the first 5 km of the inlet (John U. Lloyd Park, etc.) accounts for only about 64% of this total. The inlet's littoral impacts have traditionally been thought to be limited to this reach because of the area's obvious erosional signature. The remaining 36% of the inlet's volumetric erosion appears to extend another 8 km further downdrift -- a total of 13 km. In each study to-date, the inlet's signature along the downdrift shoreline, computed in this manner, supports the notion of "near-field" and "far-field" inlet-induced erosion described by Bruun (1995), among others.

## INLET SEDIMENT BUDGET FORMULATION

Figure 3 illustrates the sediment transport pathways at an idealized inlet for (a) right- and left-directed incident transport, and (b) mechanical transport (dredging and bypassing). Except as noted, all right-directed transport is positive-valued. All left-directed transport is negative-valued. Right- and left-directions are based upon an observer standing at the inlet, facing seaward. The study area boundaries are selected as locations outside of the inlet's direct influence on wave refraction and tidal currents. In Figure 3(a), each transport component is defined as a fraction or multiple of the right- and left-directed longshore transport rates at the boundaries. The subscript "1" refers to transport directed rightward from the left shore, and the subscript "2" refers to transport directed leftward from the right shore. In Figure 3, the terms illustrated in the sediment transport pathways are as follows:

- $R, L$  = rightward- and leftward-directed incident transport values at the study area's boundaries;
- $j_1, j_2$  = fraction of incident transport ( $R$  or  $L$ ) impounded by the inlet's jetties ( $j_1$  = left jetty;  $j_2$  = right jetty; 0.0 = transparent jetty; 1.0 = impermeable jetty );
- $p_1, p_2$  = fraction of incident transport ( $R$  or  $L$ ) naturally bypassed across the inlet ( $p_1$  = from the left,  $p_2$  = from the right; 0.0 = no bypassing; 1.0 = perfect bypassing );
- $m_1$  = local inlet-induced transport from the *left* shoreline into the inlet (expressed as a fraction or multiple of the right-directed incident transport,  $R_1$ );
- $m_2$  = local inlet-induced transport from the *right* shoreline into the inlet (expressed as a fraction or multiple of the left-directed incident transport,  $L_2$ );
- $S_u$  = transport of littoral material into the inlet from upland sources (positive value);

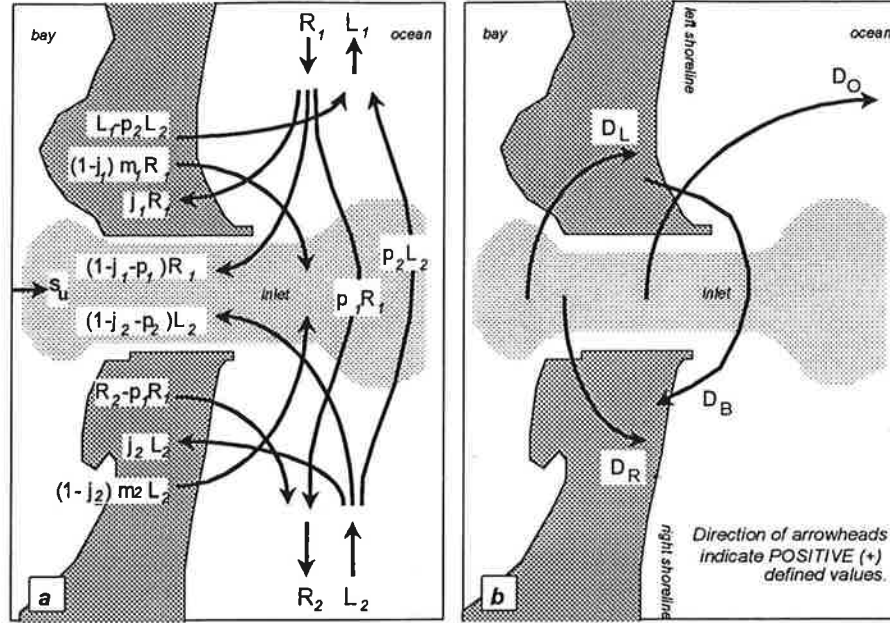


Figure 3: Sediment budget pathways (definition sketch).

- $D_L, D_R$  = mechanical transfer of sand from the inlet to the left & right shorelines, respectively;
- $D_B$  = mechanical transfer of sand from the left shoreline to the right shoreline (defined as positive from left to right; negative from right to left); and
- $D_O$  = maintenance dredging and out-of-system disposal from the inlet (positive-valued; includes only material of littoral origin; includes deep-water (offshore) and upland disposal; excludes new work).

The transport terms ( $R, L, Q, S_w, D_L, D_R, D_O$ ) can be expressed as either volume quantities or volumetric rates, so long as the units of each term are consistent with one another. The ratio of left- to right-directed transport magnitude at the study area's boundaries is defined as

$$r_1 = -L_1 / R_1 \quad \text{and} \quad r_2 = -L_2 / R_2 \quad (2)$$

By definition,

$$\begin{aligned} 0 \leq j_1 \leq 1 & & 0 \leq j_2 \leq 1 \\ 0 \leq p_1 \leq 1 & & 0 \leq p_2 \leq 1 \\ 0 \leq p_1 + j_1 \leq 1 & & 0 \leq p_2 + j_2 \leq 1 \\ m_1 \geq 0 & & m_2 \geq 0 \end{aligned} \quad (3)$$

The net volume changes of the left and right shorelines are, respectively,

$$\Delta V_L = (j_1 + j_1 m_1 - m_1) R_1 + L_1 - p_2 L_2 - D_B + D_L \quad (4)$$

$$\Delta V_R = (m_2 - j_2 m_2 - j_2) L_2 - R_2 + p_1 R_1 + D_B + D_R \quad (5)$$

where positive  $\Delta V$  values imply net accretion and negative values imply net erosion. The gross volume of sand that enters the inlet, prior to maintenance dredging, is

$$\Delta V_G = (1 - j_1 - p_1 + m_1 - j_1 m_1) R_1 - (1 - j_2 - p_2 + m_2 - j_2 m_2) L_2 \quad (6)$$

The inlet's net volume change after dredging, and neglecting upland/offshore input, is

$$\begin{aligned}\Delta V_N &= \Delta V_G - D_L - D_R - D_O - S_U \\ &= (1 - j_1 - p_1 + m_1 - j_1 m_1) R_1 - (1 - j_2 - p_2 + m_2 - j_2 m_2) L_2 - D_L - D_R - D_O - S_U\end{aligned}\quad (7)$$

Combining Eqs. (4) through (7) yields:

$$\Delta V_L = -(\Delta V_R + D_O + (\Delta V_N - S_U)) + \Delta R + \Delta L \quad (8)$$

$$\Delta V_R = -(\Delta V_L + D_O + (\Delta V_N - S_U)) + \Delta R + \Delta L \quad (9)$$

where  $\Delta R = R_1 - R_1$  and  $\Delta L = L_1 - L_2$ .

Physically, if the incident transport rates are identical on both sides of the inlet (that is,  $\Delta R = \Delta L = 0$ ), Eqs. (8) and (9) demonstrate that the net volume change of an inlet-adjacent shoreline is the negative sum of (i) the other shoreline's net volume change (e.g., impoundment), (ii) the volume of sand removed from the inlet by maintenance dredging and out-of-system disposal, and (iii) the net growth of the inlet shoal volumes (minus upland/offshore input). This simple and significant result corroborates the method presented above for computing the inlet's impacts upon adjacent shorelines. That is, it states that an inlet's net volumetric effect to the downdrift shoreline is the sum of (1) the updrift impoundment, (2) maintenance dredging and out-of-system disposal, and (3) net shoal growth beyond that attributed to upland input. In this way, the global volumetric impact of the inlet to the downdrift shoreline (minus any impoundment fillet, or "dead storage" on the downdrift side) can be computed without reference to, or assumption of, measured downdrift shoreline changes, ambient longshore transport rates, or detailed mechanics of the inlet's transport pathways. While these data are ultimately useful, Eqs. (8) and (9) demonstrate that such data are not fundamentally required to assess the inlet's downdrift, volumetric impact, at least so long as differences in the ambient transport potential across the inlet are small or known.

Eqs. (4) through (6) can be solved for  $p_1$  and  $p_2$  and combined to yield two coupled equations containing the volume change terms  $\Delta V_L$ ,  $\Delta V_R$ , or  $\Delta V_G$ . In practice, as noted above, the net volume change of the downdrift beach is often most uncertain or suspect because of the effects of armoring or beach nourishment, or because the length of shoreline to consider is not known *a priori*. Accordingly, it is advantageous to remove the downdrift volume change term from the coupled equations, and to solve in terms of the volume changes of the updrift beach and the inlet.

If the RIGHT shoreline is downdrift (or of less certain volume change), then from (4, 5, 6):

$$p_1 = 1 - j_1 (1 + m_1) + m_1 - (L_2/R_1)(1 - j_2 (1 + m_2) + m_2 - p_2) - \Delta V_G/R_1 \quad (10a)$$

$$p_2 = [ (j_1 (1 + m_1) - m_1) R_1 + L_1 - \Delta V_L + D_L - D_B ] / L_2 \quad (10b)$$

and the corresponding, computed volume change of the right shoreline is:

$$\Delta V_R = (m_2 - j_2 m_2 - j_2) L_2 + p_1 R_1 - R_2 + D_R + D_B \quad (11)$$

If the LEFT shoreline is downdrift (or of less certain volume change), then from (4, 5, 6):

$$p_1 = [ (j_2 (1 + m_2) - m_2) L_2 + R_2 + \Delta V_R - D_R - D_B ] / R_1 \quad (12a)$$

$$p_2 = 1 - j_2 (1 + m_2) + m_2 - (R_1/L_2) (1 - j_1 (1 + m_1) + m_1 - p_1) + \Delta V_G/L_2 \quad (12b)$$

and the corresponding, computed volume change of the left shoreline is:

$$\Delta V_L = (j_1 - m_1 + j_1 m_1) R_1 + L_1 - p_2 L_2 + D_L - D_B \quad (13)$$

To solve for the inlet sediment budget, a family of solutions is developed from either (10) or (12). Specifically, input values are identified for the updrift volume change ( $\Delta V_L$  or  $\Delta V_R$ ) and the gross inlet volume change ( $\Delta V_G$ ) and for the dredging/bypassing quantities ( $D_O$ ,  $D_L$ ,  $D_R$ ,  $D_B$ ) and for upland/offshore inlet volume influx ( $S_U$ ). A range of physically plausible values for the other transport parameters are additionally identified; i.e., the jetties' impermeability ( $j_1$ ,  $j_2$  (between 0 and 1)), the local inlet-induced transport ( $m_1$ ,  $m_2$ ), the tendency for natural bypassing ( $p_1$  and  $p_2$  (between 0 and 1)), and the incident transport components ( $R$  and  $L$ ). In application, input of 3 incident transport components are required:  $R_1$ ,  $R_2$ , and  $L_1$  for (10), and  $L_1$ ,  $L_2$ , and  $R_1$  for (12).

Candidate values for the various parameters, within their identified plausible ranges, are input to Eqs. (10) or (12). Those combinations of parameters that yield values of  $p_1$  and  $p_2$  within the allowed range of  $p_1$  and  $p_2$  (or, at least, values between 0 and 1), and which likewise satisfy

$$0 \leq j_1 + p_1 \leq 1 \quad \text{and} \quad 0 \leq j_2 + p_2 \leq 1 \quad (14)$$

are retained as viable discrete solutions of the sediment budget. The set of all such viable, discrete solutions represents the sediment budget's *family of solutions*.

The family of solutions can be conveniently plotted and inspected in the following way. For each discrete solution, values are computed for the incident [updrift] net transport  $Q$ , the natural net bypassing  $P$ , and the gross volume that shoals the inlet from the left and right shorelines,  $S_{LEFT}$  and  $S_{RIGHT}$ , respectively. If Eq. (10) is used, where the RIGHT shoreline is downdrift, then

$$Q = Q_1 = R_1 + L_1 \quad (15a)$$

or if Eq. (12) is used, where the LEFT shoreline is downdrift, then

$$Q = Q_2 = R_2 + L_2 \quad (15b)$$

The net natural bypassing and left- and right- gross inlet shoaling volumes are, respectively,

$$P = p_1 R_1 + p_2 L_2 \quad (16a)$$

$$S_{LEFT} = \Delta V_G - S_U - S_{RIGHT} = (1 - j_1 - p_1 + m_1 - j_1 m_1) R_1 \quad (16b)$$

$$S_{RIGHT} = \Delta V_G - S_U - S_{LEFT} = -(1 - j_2 - p_2 + m_2 - j_2 m_2) L_2 \quad (16c)$$

An example is illustrated in Figure 5, below. The family of solutions can be *narrowed* by imposing additional constraints; e.g., requiring that the direction of any net natural bypassing,  $P$ , be coincident with the incident net transport rate,  $Q$ ; or, that the jetties' impermeability values ( $j_1$  and  $j_2$ ) be similar to one another; or, that the shoaling from one side or the other be a minimum percentage of the inlet's total shoaling rate; etc. Or, families of solutions from different time periods can be overlaid, retaining only those subsets of solutions for which the incident transport,  $Q$ , solves the sediment budget for both time periods, etc.

Methods to identify the sediment budget's parameters include the following. The volume change of the updrift shoreline ( $\Delta V_L$  or  $\Delta V_R$ ) can be estimated from the cumulative volume change updrift of the inlet as in Figure 1, where background changes are retained. The gross volume change of the inlet ( $\Delta V_G$ ) can be estimated from surveys and dredging histories, where care is taken to exclude changes due to new-work dredging, datum shifts, etc. The dredging and mechanical bypassing terms ( $D_R$ ,  $D_L$ ,  $D_O$ ,  $D_B$ ) are estimated from dredging records. The volume influx from upland or offshore sources ( $S_U$ ) requires some insight as to the inlet's overall geology and/or the influence of, for example, episodic fluvial input, but in many cases can be neglected.



A convenient method to identify ranges of values for the incident transport ( $R$  and  $L$ ) is to consider the right- and left-directed transport potential from offshore [hindcast, etc.] wave data. The computed transport rates can be used directly (with ranges bound by some percentage or by standard deviation, etc.). It is additionally useful to compute the ratio of left- to right-directed transport,  $r$ , from Eq. (2). In solving the sediment budget equations, this ratio can be held constant, so that the value of  $L$  remains a computed, fixed fraction of specified values of  $R$  that will be considered. The values of  $R$  to be considered should be such that the net incident transport,  $Q = R + L$ , or  $Q = (1-r)R$ , are within a range of physically plausible values -- perhaps defined by the range of values of  $Q$  for the inlet suggested by prior investigators.

Plausible values for the jetties' impermeabilities ( $j_1$  and  $j_2$ ) are made from aerial photography, surveyed shoaling patterns, and physical inspection; or, in the limit, can be left to the default uncertainty range of 0 (permeable) to 1 (impermeable). Values for the inlet's net natural bypassing tendency ( $p_1$  and  $p_2$ ) are typically most uncertain and can be left to the default range of 0 (no bypassing) to 1 (full bypassing). In many cases, however, it might be accepted that an improved inlet is an imperfect bypassing system ( $p < 1$ ) or a complete littoral barrier ( $p=0$ ), etc.

Values for the local, inlet-induced transport ( $m_1$  and  $m_2$ ) can be estimated from inspection of computed increases in the inlet-directed longshore transport potential near the inlet mouth. This can be discerned from wave refraction investigation whereby the longshore transport potential is computed from incipient breaking conditions along the shoreline developed for each of several representative offshore wave cases. The transport potential can be computed by, say, the CERC formula with arbitrary coefficient. For example, an increase in the transport potential,  $R_1$ , from say 0.5 to 0.7 (arbitrary units) -- induced by refraction across the inlet's ebb shoal -- represents a 40% inlet-induced increase in local right-directed transport, suggesting a value of  $m_1 = 0.4$ . Additionally, the parameters  $m_1$  and  $m_2$  can be used to account for inlet-directed transport from the adjacent shorelines induced by tidal currents.

## EXAMPLE APPLICATION

To illustrate the method's application and utility, an example application at St. Lucie Inlet, Florida, is presented. St. Lucie Inlet is located on Florida's south-central east coast, on the Atlantic Ocean. The inlet was artificially opened in the 1920's, and jetties were later constructed on the north (left) and south (right) shorelines. The north jetty extends across most of the typical surf zone, but is low and permeable. The south jetty is sand-tight, but is very short, and sand is known to be transported around its seaward end. The net incident drift is acknowledged to be from north to south, and is plausibly between 40,000 and 260,000 m<sup>3</sup>/yr (50K to 340K cy/yr). The downdrift (south, or right) shoreline has experienced chronic erosion along a great distance (10's of km), and it is generally acknowledged that the inlet exhibits some, but far less than perfect, natural sand bypassing.

Values of volume changes and typical dredging practices were identified over a period of 6 to 10 years in the late 1980's, and converted to equivalent annual rates (ATM, 1995; USACE, 1999). These included an updrift (left) shoreline change of  $\Delta V_L = -16,000$  m<sup>3</sup>/yr [net erosion]; gross inlet shoaling of  $\Delta V_G = 156,000$  m<sup>3</sup>/yr; maintenance dredging and out-of-system disposal of  $D_O = 33,000$  m<sup>3</sup>/yr; and maintenance dredging and placement to the downdrift (right) shoreline or nearshore of  $D_R = 60,000$  m<sup>3</sup>/yr. Upland/offshore influx to the inlet shoals is assumed to be negligible; i.e.,  $S_U = 0$ . From (7), the net inlet shoaling rate is  $\Delta V_N = 63,000$  m<sup>3</sup>/yr, representing the estimated net rate of accretion across the inlet's ebb and flood shoals and/or losses to the offshore.

Relevant results of a wave refraction and littoral transport analysis at the inlet (Browder, 1996, conducted for USACE, 1999) are illustrated in Figure 4. Representative wave conditions from various offshore directions were refracted/diffracted to the point of incipient breaking, from which the longshore transport potential was computed. The results were weighted by each wave condition's hindcast occurrence and summed to develop an alongshore estimate of the right- and left-directed transport potential. The values in the figure are normalized by the maximum value of the computed transport potential. Source wave data were WIS Phase II hindcast, 1956-95.

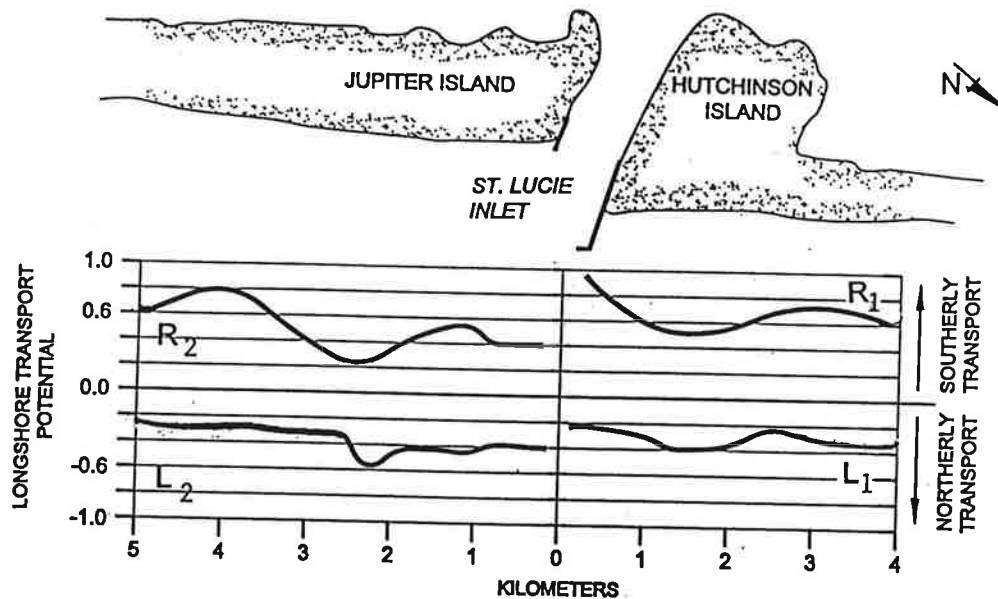


Figure 4. Longshore transport potential computed adjacent to St. Lucie Inlet (after Browder, 1996).

From Figure 4, the ratio of left-to-right-directed transport at the updrift (left) boundary is about  $r = -L/R = 0.45$ . For an assumed range of net incident transport,  $Q = 40,000$  to  $260,000$   $\text{m}^3/\text{yr}$ , this implies a range of considered values for the incident, right-directed transport of

$$R_1 = Q/(1-r) = (40,000)/(1-0.45) \text{ to } (260,000)/(1-0.45) = 72,700 \text{ to } 472,700 \text{ m}^3/\text{yr}$$

and corresponding incident, left-directed transport of

$$L_1 = -r R_1 = (-0.45)(72,700) \text{ to } (-0.45)(472,700) = 32,700 \text{ to } 212,700 \text{ m}^3/\text{yr}.$$

Left-directed transport at the downdrift (right) boundary is approximately 90% that at the updrift (left) boundary; hence, it will be presumed that  $L_2 = 0.9 L_1$ . Due particularly to shoal and reef features near the inlet mouth, the transport potential directed toward the inlet is computed to increase by about 30 to 50% in the immediate vicinity of the inlet. Local transport directed toward the inlet is likewise augmented by tidal (flood) currents, the contributions of which are not included in the figure. It is thus reasonably assumed that the local, inlet-induced increases in right- and left-directed transport,  $m_1$  and  $m_2$ , are each in the range of at least 0.3 to 0.5, more or less.

For the sake of generality, no presumptions will be made regarding the jetties' impermeability values ( $j_1$  and  $j_2$ ) or the natural bypassing tendency ( $p_1$  and  $p_2$ ). These values, at least initially, will be allowed to range from 0 to 1.

As the right shoreline is downdrift (and of uncertain volume change), Eqs. (10a) and (10b) are solved for  $p_1$  and  $p_2$  for the ranges of values described above; viz.,

$$p_1 = 1 - j_1 (1 + m_1) + m_1 - (L_2/R_1)(1 - j_2(1+m_2) + m_2 - p_2) - (156000)/R_1$$

$$p_2 = [ (j_1 (1 + m_1) - m_1) R_1 + L_1 - (-16000) + 0 - 0 ] / L_2$$

where  $0 \leq j_1 \leq 1$ ;  $0 \leq j_2 \leq 1$ ;  $0.3 \leq m_1 \leq 0.5$ ;  $0.3 \leq m_2 \leq 0.5$ ;  $72700 \leq R_1 \leq 472,700$ ; and,  $L_1 = 0.45 R_1$ ; and  $L_2 = L_1$ . Only those combinations of values for which  $0 \leq p_1 \leq 1$  and  $0 \leq p_2 \leq 1$ , and for which  $0 \leq p_1 + j_1 \leq 1$  and  $0 \leq p_2 + j_2 \leq 1$ , are retained as viable solutions. For each of these, the net incident transport, shoaling volume from the left and right shorelines, and the net bypassing volume, are computed from Eqs. (15a), (16a), (16b), and (16c), respectively.

Figure 5 illustrates the results of these computations; i.e., the general family of solutions. Any point within this family (the shaded area) can solve the sediment budget. The solutions lie along lines of constant net incident transport value ( $Q_1$ ). The size of the solution family decreases as the local inlet-induced transport term ( $m_1, m_2$ ) increases. This is indicated by the truncation of the family along its lower right-hand side as  $m_1$  and  $m_2$  increase from 0.3 to 0.5.

From Figure 5, it is noted that the minimum net incident transport ( $Q_1$ ) is about 80,000  $m^3/yr$  in order to solve the sediment budget. A numeric scan of the results demonstrates that the updrift jetty must be at least 25% impermeable but not more than 60% impermeable ( $0.25 < j_1 < 0.6$ ) to solve the sediment budget; and that the modal impermeability value is about 46% ( $j_1 = 0.46$ ). Values for the downdrift jetty's impermeability ranged from 0 to 1, though 90% of the values

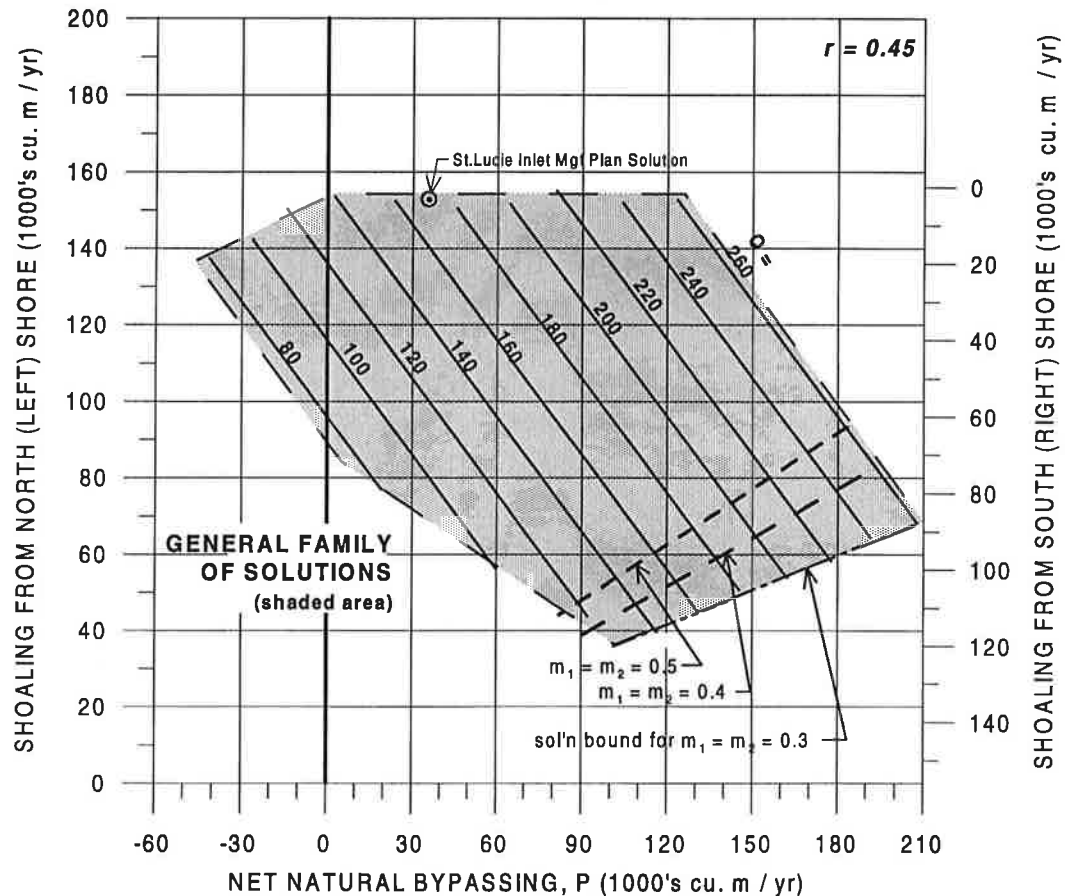


Figure 5. General family of solution for St. Lucie Inlet, FL inlet sediment budget.

were less than 0.7. Likewise, natural bypassing of the right-directed transport must be less than 69% ( $p_1 < 0.69$ ) to solve the sediment budget. A solution proposed in the St. Lucie Inlet Management Plan, prepared for the State of Florida, plots at the top edge of the family. While mathematically viable, it appears as an “outlier” relative to the bulk of the solution, and was ultimately not adopted by the State.

The family of solutions can be readily *narrowed* by imposing additional physical constraints, developed through observation of the inlet. For illustration, these shall include:

1. Direction of any net natural bypassing to coincide with the net drift ( $P > 0$ )
2. Net natural bypassing is not greater than 2/3rds the net incident, drift ( $P < 0.67 Q_1$ )
3. Shoaling from the right comprises at least 1/3rd of the total inlet shoaling ( $S_{\text{RIGHT}} > 0.33 \Delta V_G$ ).
4. The downdrift, right jetty is not more than 70% impermeable ( $j_2 \leq 0.7$ ).

The resulting, narrowed family is plotted in Figure 6, below. Requirements #1, 2, and 3 respectively truncated the general solution's left, right, and top boundaries; while #4 had little effect in this case, as expected, given that 90% of  $j_2$ 's values were naturally less than 0.7. The bounds of this narrowed family are identical for values of  $m_1$  and  $m_2$  from 0.3 to 0.5. The maximum net, incident transport rate must be less than 250,000  $\text{m}^3/\text{yr}$  in order to solve the sediment budget.

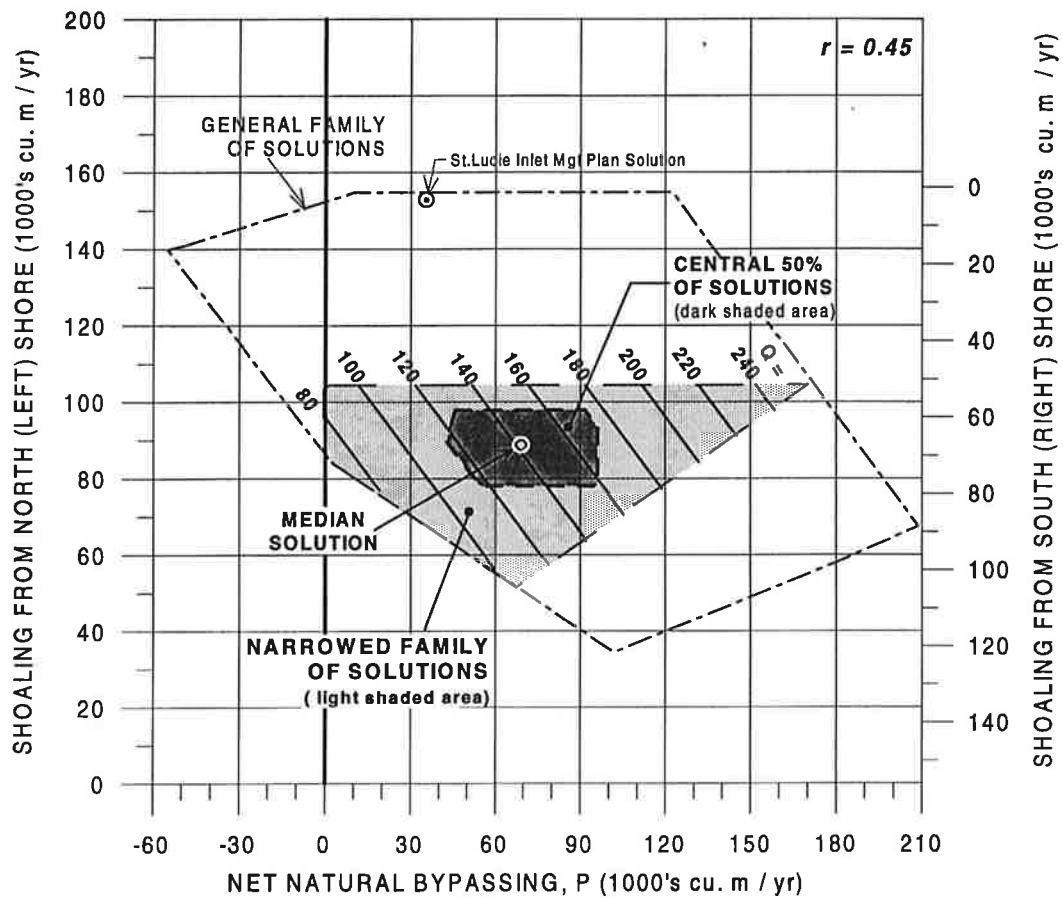


Figure 6. Narrowed family of solutions, per requirements #1 - #4, above.

A numeric scan of the narrowed family's results reveals the frequency with which values of the various transport parameters can solve the sediment budget for fixed increments of the input values  $j_1$ ,  $j_2$ , and  $R_1$  (or  $Q_1$ ). For example, the modal (most frequent) value of shoaling from the left shore is 88,600 m<sup>3</sup>/yr -- or 56% of the total gross shoaling rate -- with half of all of the solutions falling within values of 44,000 m<sup>3</sup>/yr (28% of gross shoaling) to 96,000 m<sup>3</sup>/yr (62%). The modal value of the net incident transport rate is  $Q_1 = 147,000$  m<sup>3</sup>/yr, with half of all of the solutions defined by values between about 120,000 and 170,000 m<sup>3</sup>/yr. The modal value of the updrift jetty impermeability is  $j_1 = 0.47$ , with half of all solutions described by  $j_1 = 0.43$  to 0.53. The modal value of the downdrift jetty impermeability is  $j_1 = 0.26$ , with half of all solutions described by  $j_1 = 0.13$  to 0.43. This suggests that the updrift jetty is about twice as impermeable as the downdrift jetty -- a notion that is physically reasonable.

The dark shaded area in Figure 6 is a subset of solutions that represents the central 50% of the narrowed family. That is, it comprises those 50% of the solutions distributed about the inlet-parameter values that most frequently solve the sediment budget. Formally, it represents that half of the viable inlet solutions that occur "most frequently". The "modal solution" in the middle indicates the narrowed solutions' weighted average value of computed net bypassing,  $P$ , and shoaling,  $S_{LEFT}$  and  $S_{RIGHT}$ .

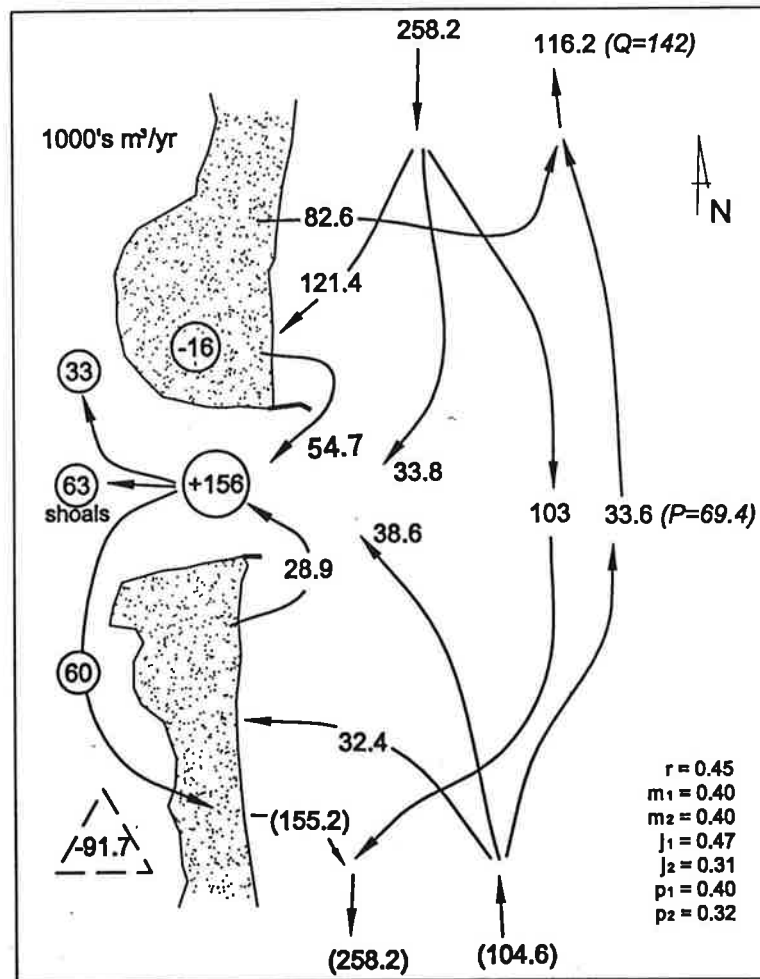
Below, an example, discrete solution is selected from the family and "exploded" to develop the corresponding sediment transport pathways. The "modal solution" is chosen as an illustration, where the most frequently occurring values of the transport parameters are selected as a discrete solution; viz.,  $Q_1 = 142,000$  m<sup>3</sup>/yr ( $R = 258,200$  m<sup>3</sup>/yr, and  $L = -116,200$  m<sup>3</sup>/yr);  $P = 69,400$  m<sup>3</sup>/yr,  $S_{LEFT} = 88,600$  m<sup>3</sup>/yr, and  $j_1 = 0.47$ . The family of solutions is scanned for these discrete conditions (or, a discrete solution can be computed directly for these values). For nominal values of  $m_1 = m_2 = 0.4$ , the parameters that correspond to these conditions are  $j_2 = 0.31$ ,  $p_1 = 0.40$ , and  $p_2 = 0.32$ . For each of these values, and recalling that  $L_2 = 0.9 L_1$ , the transport pathways attendant to the inlet are computed with reference to the definition sketch, Figure 3. The results are plotted in Figure 7.

From Eq. (11), the volume change of the downdrift shoreline is also computed. This requires presumption of the rightward transport,  $R_2$ , directed away from the inlet on the downdrift side -- not otherwise needed up to this point. In the present example, and by reference to Figure 3, it is presumed that  $R_1 = R_2 = 258,200$  m<sup>3</sup>/yr. This suggests that the downdrift shoreline exhibits an erosion potential of 91,700 m<sup>3</sup>/yr. From (11), this is the sum of net inlet shoaling (63,000 m<sup>3</sup>/yr) and out-of-system dredge disposal (33,000 m<sup>3</sup>/yr) minus net change of the updrift shoreline (-15,900 m<sup>3</sup>/yr, computed), and accounting for a presumed decrease in the left-directed transport potential across the inlet (11,600 m<sup>3</sup>/yr).

Measurements of net downdrift volume change vary widely -- particularly because of fairly frequent beach nourishment and nearshore (dredge) sand placement of uncertain success. With sand placement to the downdrift shoreline, the observed net volume change is between +67,000 m<sup>3</sup>/yr to -139,000 m<sup>3</sup>/yr. [These are the values to which to compare the computed net downdrift volume change, above,  $\Delta V_R = -91,700$  m<sup>3</sup>/yr.] After subtracting sand placement, net downdrift erosion is reported on the order of 160,000 to 367,000 m<sup>3</sup>/yr along 9 km south of the inlet (USACE, 1999). The great uncertainty in these values is not atypical for downdrift shorelines.

The "modal" solution depicted above presumes a net incident transport rate of 142,000 m<sup>3</sup>/yr. Prior studies by the Corps estimate this value as about 175,000 m<sup>3</sup>/yr (USACE, 1999). The

**Figure 7.**  
Sediment transport  
pathways computed  
for the “modal solu-  
tion” point in Figure  
6. Values represent  
1000's m<sup>3</sup>/yr. St.  
Lucie Inlet, FL.



#### ST. LUCIE INLET, FL.

solution, above, suggests that the transport rate into the inlet from the north and south shorelines are about 88,500 and 67,500 m<sup>3</sup>/yr, respectively. Corresponding values estimated in USACE (1999) are about 103,000 and 56,000 m<sup>3</sup>/yr, more or less.

Many other discrete solutions can, of course, be developed from the family of solutions presented in Figures 5 and 6. Those from the latter, narrowed family are more physically plausible -- based upon general examination of the inlet. Although even this narrowed family appears broad, one will find that there are not extraordinarily significant differences between discrete solutions within the family, particularly after plotting the results as shown in Figure 7, above. In particular, there are very modest differences between those solutions that define the central 50% of the narrowed family as a whole; i.e., the dark-shaded area in Figure 6.

#### SUMMARY

The methodology described above allows the coastal engineer a framework by which to (1) investigate the volumetric and lineal extent of an inlet's impact upon adjacent shorelines; and, (2) to develop a framework for a conceptual inlet sediment budget based upon ranges of physically plausible input values. The latter results in a “family of solutions” which bounds those solutions

that can mathematically and reasonably solve an inlet sediment budget. This "family of solutions" inherently accounts for the under-constrained nature of an inlet sediment budget calculation; i.e., where there are more variables than known values. While it allows flexibility of solutions, it provides useful boundaries to the solution. These boundaries can be narrowed, or studied, to the degree that the investigator wishes to prescribe physical constraints to the inlet's transport patterns. The statistics of the values within the family of solutions can be examined to discern the occurrence with which various values of the inlet's transport parameters can solve the sediment budget. This can help to establish the degree to which a given discrete solution lies within the "central" or "outer" parts of the "most likely" (or at least, modal) solutions.

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