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Estimating Sediment Flux for Coastal Inlets in the Northern Gulf of Mexico

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PURPOSE:

This Technical Note (TN) describes herein an approach to estimating the amount of sediment that passes through an estuary inlet in the Gulf of Mexico in terms of sediment yield per year. Estimated values for the Weeks Bay estuary and the approach taken to obtain the values are provided as guidance for other estuaries. The TN is in direct support of the Mississippi State University lead project "Modeling Mobile Bay Sediments and Pollutants with New Technologies", and is a continuation of the Sediment Budget Template, SBT (Sharp 2007).

INTRODUCTION AND OBJECTIVE:

With increases in urban development and frequent changes in watersheds; geomorphic and flow conditions are changing continually. Variation from the typical normality in both causes increases in sediment flux. One area requiring a simple straightforward approach to estimating such changes is estuary inlets. Flux through this part of the watershed was not addressed in the SBT.

The objective of this work is to create a method in the form of a VBA code that estimates the sediment flux through an inlet as a function of rating curves, daily high and low water levels, and inlet bathymetry. Sharp (2007) created the SBT, which is used to estimate sediment fluxes, and deposition/erosion rates. The first implementation of the SBT was at the Aberdeen Pool on the Tennessee-Tombigbee Waterway, an inland waterway with no tidal influences. However, for further use, the SBT is applied to demonstrate it in areas of tidal influence, i.e. Weeks Bay, Alabama. Tidally driven systems must account for both the ebb and flood tides in the sediment budget. With tidal accommodations comes a further addition to the SBT to account for a tidally driven sediment flux.

Two different methods for estimating the flow through the inlet are implemented and comparisons are made. First, the Jarrett's relationship based on curve fitting from inlets around the lower 48 States is implemented. Next an empirical relationship, Krishnamurthy's Equation, is used and comparisons are made between the two different approaches.

TIDAL DATA SORTING:

Initial analysis requires data sorting that extracts the high and low water levels from each day in the data set. The code is not limited to the time difference between each tidal measurement as long as the data captures the high and low water for the day. Therefore, it is recommended for a semidiurnal system that 3-min, 6-min, 1-hour, and 3-hour data be used. It is noted that this sorting process can be skipped if the recorded data already isolate the high and low water or the mean high water and mean low water. The code simply subdivides the data per day and by using a combination of "if" statements it extracts the maximum and minimum data values for each day. The selected data can then be used to evaluate the tidal prism.

IMPLEMENTATION OF JARRETT'S RELATIONSHIPS:

Jarrett (1976) used regression analysis to determine equations of best fit to estimate inlet area to tidal prism relationships. He divided the collected data into three main groups; all inlets, unjettied and single-jettied inlets, and inlets with two jetties. Further subdivision was done for locations of inlets; Atlantic coast, Gulf coast, and Pacific Coast. Jarrett implemented the equations to solve for the inlet area as a function of the tidal prism. Here his equations are rearranged to estimate the tidal prism in terms of the inlet area. Rearrangement of Jarrett's Equation is useful in locations where the tidal prism is unknown but the inlet cross-sectional area is more easily obtainable. Thereby, using Jarrett's equation the flow volume is established for the tidal influx based on inlet cross sectional area, tidal prism, and tidal stages.

The regressed empirical equations that Jarrett used were power curves. As previously mentioned Jarrett developed an extensive group of equations to cover the continental US. For work presented here for use in the Gulf Coast Region, two regression curves are implemented. One for all inlet types, both jettied and unjettied, see Equation 1 and the other for single or no jettied inlets, see Equation 1-A (Jarrett 1976).

$$\begin{aligned}&\text{All Inlets:}\\ &A = 5.02\times10^{-4}\times TP^{0.84}\end{aligned} \qquad \text{Equation 1}$$

$$\begin{aligned}&\text{Unjettied or Single:}\\ &A = 3.51\times10^{-4}\times TP^{0.86}\end{aligned} \qquad \text{Equation 1-A}$$

Where:

A = area of the inlet, ft^2
TP = tidal prism cft
$C_1 = 5.02 \times 10^{-4}$
$n_1 = 0.84$
$C_{1\text{-}A} = 3.51 \times 10^{-4}$
$n_{1\text{-}A} = 0.86$

Equations 1 and 1A are both applicable for Weeks Bay. For other locations around the country Jarrett gave a third equation for inlets with two jetties; however, in the Gulf Coast Region the data were insufficient for regression analysis of the two jetty equation (Jarrett 1976). Jarrett provides each equation with the 95 percent upper and lower confidence limits (see Table 1).

Table 1 Confidence limits for Jarrett's Equations

95% Confidence Limits			
Form of equation A = CxTP^n			
Term	**Limits**	**Equation 1**	**Equation 1-A**
C	Upper	5.39 E -4	4.16 E -4
	Lower	4.25 E -4	2.97 E -4
n	Upper	0.95	0.99
	Lower	0.73	0.73

Rearranging Equation 1 and 1-A and using Equation 2, a rough estimate is back-calculated for the tidal prism, see Equation 3 and 3-A.

$$A = \frac{A_{HW} + A_{LW}}{2} \qquad \text{Equation 2}$$

Where:

A = area at mean sea level
A_{HW} = area of inlet at high water
A_{LW} = area of inlet at low water

$$TP = \sqrt[0.84]{\frac{A_{HW} + A_{LW}}{1.004 \times 10^{-3}}} \qquad \text{Equation 3}$$

$$TP = \sqrt[0.86]{\frac{A_{HW} + A_{LW}}{7.02 \times 10^{-4}}} \qquad \text{Equation 3-A}$$

Where:

A_{HW} = cross sectional area at MHW = $H_T \times B + A$

Where:

H_T = elevation above MTL at high tide
B = inlet cross width (assumed unchanging)
A = area at mean tide level (MTL)
A_{LW} = cross sectional area at MLW = $L_T \times B + A$
L_T = elevation above/below MTL at low tide

The inlet area below mean low water is required to properly implement this approach. However, the inlet area above mean low water is assumed rectangular (see Figure 1).

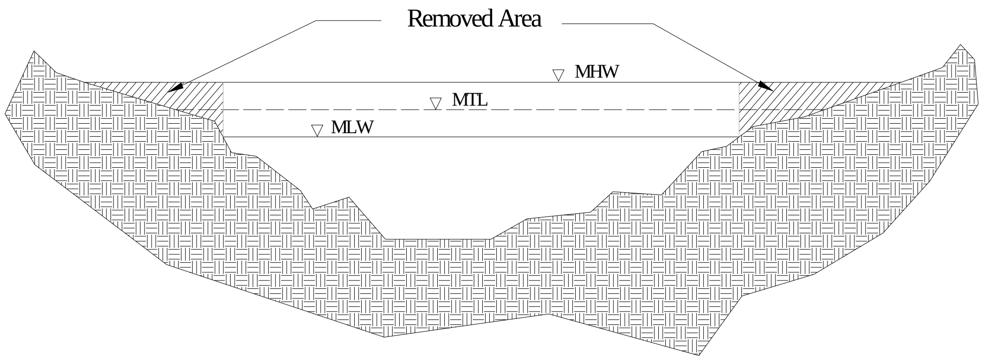

Figure 1 Typical inlet cross section

A rectangular assumption above mean low water is removing an area, the removed area, which falls outside the rectangle area. It is assumed that in the Gulf Coast region with a low tidal range the removed area from the inlet cross section results in minimum error since the tidal range for the region is relatively small. Therefore, having a minimum flow through the section not including the removed area has a negligible effect.

IMPLEMENTATION OF KRISHNAMURTHY RELATIONSHIPS:

Muthusamy Krishnamurthy (1977) derived a formula that computes the tidal prism of an inlet in equilibrium as a function of tidal period, tidal range, flow resistance, and size of bed material. Equation 4 is the derived equation. A detailed derivation of Krishnamurthy equation is found in his original journal paper and is not given here.

$$TP = 1.25 B y_o V_{fc} T \left(1 + \frac{2a_o}{\pi y_o}\right)\left(\ln \frac{10.93 y_o}{k}\right) \qquad \text{Equation 4}$$

Where:

TP = tidal prism
B = width of inlet
y_o = depth of flow at mean sea level
T = tidal period
a_o = amplitude of tide
k = roughness coefficient of flow

$$V_{fc} = \sqrt{\frac{\tau_c}{\rho}} \qquad \text{Equation 5}$$

Where:

τ_c = critical shear stress of the bed material
ρ = density of sea water

When selected in the code the Krishnamurthy equation is used in the place of Equation 3 or 3-A.

For the Weeks Bay inlet bathymetry from NOAA data is used. The bathymetry quantifies both the top width and cross sectional area at the inlet. Bed samples collect by University of Southern Alabama are used to select the appropriate critical shear stress. Samples collected at the inlet in 1998 showed that approximately 60% of the sample contains"medium sized sand" (Haywick 2004). Although not clearly defined in Haywick's report, Julien reports medium sand as greater than 0.25 mm and less than 0.5 mm (Julien 2002). For this range of particle sizes the critical shear stress is 0.022 to 0.032 pounds per square foot (Graf 1971).

The tides are diurnal resulting in a tidal period of 44712 seconds. The tidal amplitude is calculated from the low and high waters per day, and the roughness coefficient of flow is 0.25 (Krishnamurthy 1977). For the sediment behavior of the system rating curves developed from USGS data and GSA data are implemented. These sediment rating curves are in an unpublished report, by Sharp, for a sediment budget for Weeks Bay.

SEDIMENT CHARACTERISTICS:

Once estimates for flow through the inlet, either by one or both of the methods above, are established the sediment flux is estimated with a calculated concentration. Using the following equations the daily sediment concentration at the inlet is estimated.

$$Q_s = 0.0027 \times Q \times C \qquad \text{Equation 6}$$

Where:

Q_s = sediment flux, tons/year

Q = discharge at the inlet, cfs

C = sediment concentration, ppm

Equation 7 is the basic form of the sediment rating curves based on suspended sediment data in the contributing rivers.

$$Q_s = \mathrm{A} \times Q^B \qquad \text{Equation 7}$$

Where:

A & B = sediment rating curve coefficients

Combining Equations 6 and 7 produces an equation for estimating the suspended sediment concentration, see Equation 8.

$$C = \frac{A \times Q^B}{0.0027 \times Q} \qquad \text{Equation 8}$$

Where:

$Q = Q_{TP}$ = flow in ebb and flood tidal prism, cfs

The daily sediment flux is estimated using the recorded low and high water stages (see Equation 9).

$$Q_S\,(\text{Daily}) = (TP + \overline{Q_{River}})C - (TP)KC \qquad \text{Equation 9}$$

Where:

TP = tidal prism see Equation 2
K = empirical value based on field conditions from suspended sediment differential
$\overline{Q_{River}}$ = mean daily river flow

Equation 7 estimates the flood suspended sediment concentration as a fraction of the ebb suspended sediment concentration. A mean daily flow of 300 cfs is estimated for both the Fish and Magnolia Rivers, and is based on USGS flow data from Station 0237800, located on the Fish River, were an additional 25% of the mean flow is added to account for the Magnolia River.

EVALUATION OF THE EMPIRICAL COEFFICIENT K:

The coefficient K in Equation 9 dictates the sediment differential between the inner and outer portions of the estuary. A proper evaluation of K is required to adequately account for the flood tide suspended sediment. The coefficient, K, is a percentage of the effluent suspended sediment. In this report K is estimated using ADEM data that was integrated over the depth using the Rouse profile to describe the concentration with respect to the water column. For concentrations in the estuary two locations were available, one at the mouth of the Fish River and the other slightly upstream of the Estuary on the Magnolia River. A weighted average based on the percentage of total yearly flow, that estimates 75% from the Fish River and 25% from the Magnolia River, is used to estimate a suspended sediment concentration for Weeks Bay. From this estimate it is assumed that the suspended sediment concentration is 63 mg/l. Ideally, the sediment concentrations would be sampled over the entire tidal cycle at the mouth of the estuary producing a sediment concentration as a function of inlet discharge.

The outer portion, Mobile Bay near the mouth of Weeks Bay, was sampled by MSU researchers. The Rouse Curve was applied to the collected data and integrated over the depth to estimate a suspended sediment concentration. From the field data values K is estimated at 1.7. The large value of K, not typical with most K, is a direct result of the suspended sediment concentration in the Mobile Bay, 110 mg/l, being greater than what is in Weeks Bay. With a larger concentration of suspended sediment out of the Estuary then what is in the estuary, this allows for larger than normal influent sediment concentration into the Estuary.

COMPARISION OF METHODS FOR WEEKS BAY:

Table 2 is a comparison of all the values calculated using the described method. Further data analysis is recommended for an accurate evaluation of the below values. In the following remarks both engineering experience and statistical approaches are used to evaluate the calculated values.

Sediment flux were calculated from Jarrett's upper and lower 95% confidence limits coefficients and exponents, listed in Table 1, but produced widely varying results. Since the upper and lower limits varied those results are not reported in this Technical Note. The sediment flux values calculated from Jarrett's relationship (Equation 3 and 3A) are assumed to be at or near the mean in the distribution (see Table 2).

Table 2 Comparison of methods at Weeks Bay

Weeks Bay, Alabama			
	Total Flux, Tons/Year		
	Equation 3	**Equation 3-A**	**Equation 4**
USGS	-650,000	-620,000	-73,000
ADEM	-30,000	-29,000	-7,000
USGS & ADEM	-37,000	-36,000	-8,000
Random 1	-740,000	-700,000	-77,000
Random 2	-1,500,000	-1,400,000	-130,000
Random 3	-570,000	-540,000	-73,000
Average	-590,000	-550,000	-61,000

Estimating the tidal prism by multiplying the estuary inlet times the tidal range produces a tidal prism of 1.96 E 8 for Weeks Bay. Using this value as a gauge value the tidal prisms estimated by the two methods are evaluated.

Table 3 Tidal Prism Estimates for Weeks Bay

	Tidal Prism, cfs
Equation 3	2.3 E 8
Equation 3-A	2.2 E 8
Equation 4	7.04 E 7

From Table 3 it is shown that the tidal prism estimated from Equation 3 and 3-A is greater than that of both the above value and the value estimated from Equation 4. It can be safely assumed that if a conservative sediment flux is desired then Jarrett's Equation is recommended. However, for Weeks Bay it appears that rather than more sediment flowing out on the ebb tide then on the flood there is the reverse (see Table 2). The negative values in Table 2 indicate the reverse in typical estuary sediment behavior. This inversion is a direct result of larger amounts of sediment concentrations being found in the Mobile Bay, which result in more deposition in Weeks Bay.

Therefore, using the more conservative Jarrett's Equations will result in more deposition in Weeks Bay due to the greater inflowing sediment fluxes.

The author's engineering judgment suggests that, based on the USGS and GSA rating curves only and not on the Random curves and only using Equation 4 the sediment flux through the Weeks Bay inlet is approximately -32,000 tons/year i.e. 32k tons/yr into the Bay. The random curves where eliminated since these would skew the flux values. The combination of these curves was chosen, since the actual sediment concentration in Weeks Bay has not been sampled and is unknown. Therefore, by using the high river value concentrations of the USGS data and the relatively lower GSA upper bay and river concentrations, equilibrium in suspended sediment concentrations is more probable.

For a statistical approach the random curves are once again eliminated to minimize any bias and all values are rounded to the nearest thousand. All three Equations are used to properly account for any skewness in the data set. First, outliers are checked for using the interquartile range. It is determined from this statistical approach that the lower and upper limits are -139,000 and 37,000 tons/year respectively. Note that the upper limit is negative which only indicates the direction of flow. Therefore, the actual numerical variation in the upper and lower limits is actually 176,000. With these limits there are no upper outliers but there are two lower outliers, -650,000 and -620,000 tons/year which were removed from the data set. Using the remaining values the average flux per year is 32,000 tons. An additional approach for further statistical comparison is to use Jarrett's 95% confidence limits outlined in Table 1, but as stated previously these produced widely varying results and are not included.

CONCLUSION:

The process outlined in this TN provides a first approximation for the sediment flux through an inlet. Obviously both simplifications and assumptions exist in this process and further modeling is recommended. Further modeling should include numerical modeling along with extensive field sampling to adequately define sediment conditions in the system.

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