

CHAPTER 122

SEDIMENT TRANSPORTATION AND DEPOSITION MODELS FOR MOBILE BAY, ALABAMA

by

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ABSTRACT

The objective of this study is the application of hydrodynamic and material transport mathematical models for Mobile Bay in predicting sediment transport and deposition profiles within the bay system. Of particular importance are the seasonal variations of sediment distribution which are critically influenced by current patterns within the estuary. Both point and non-point sources of sediment will be included in the analysis.

Results will be presented in two ways. The first or long term variations in sediment distribution will be assessed by correlation with tidal cycle average velocities at various locations within the bay. Calculated distribution patterns will be compared with observed bathymetric data over the past century. The net effect of the construction of the Mobile ship channel on deposition patterns within the bay will also be evaluated. Secondly, short term variations in sediment transport and deposition resulting from man-made and natural disturbances will be analysed using a sediment transport model. This model will include deposition, bulk fluid transport and resuspension characteristics and will be capable of predicting localized, short term sediment patterns from maintenance dredging operations within the bay. Model trend results will be compared with field data collected during recent dredging activities and high altitude photographic data obtained for the bay area.

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INTRODUCTION

There is a growing awareness that the natural resources of the world are limited. This fact gives credence and a sense of immediacy to those who are trying to better understand and describe those processes which affect the amount and the quality of these resources. One of the most abundant and most taken-for-granted natural gifts is water. The waters adjacent to coastal regions are some of the most often studied because of their importance to man.

The coastal environment is a vital part of man's daily activity - providing food, recreation, jobs and habitats. Thus the already complex, dynamic natural processes which maintain a balance between fresh water and saline water is further confounded by man-made impacts. To minimize adverse events on these areas, a clear understanding of the properties and behavior of these systems must be established. Plans formulated with technically sound data are far more likely to produce results which are both environmentally and economically sound.

In recent years, studies have been accelerated to better characterize the coastal waters and to better describe the processes which take place in these areas. Studies have included models - both mathematical and physical - as well as the more traditional investigations involving data acquisition - both field oriented and remotely sensed. The interaction of these methods provide techniques for the rapid prediction of changes in the system and the impact that these changes have on water quality and behavior.

This paper summarizes some of the interactive methods used to characterize sediment transport patterns within the Mobile Bay estuary along the coastline of the northeastern Gulf of Mexico. The methods described are part of a continuing effort to develop compatibility between model, ground truth and remotely sensed information for the rapid estimation of estuarine behavior as governed by man-made and natural events.

MOBILE BAY SYSTEM

Mobile Bay receives the discharge of the fourth largest river system in the United States (Figure 1). An average of 5×10^9 kilograms of suspended sediment are transported into the estuary each year. Circulation patterns within the bay are governed by these river discharges, tidal influence from the Gulf of Mexico, wind influence and bay geometry. Seasonal variations due to meteorologic conditions, and shorter term variations due to the diurnal tidal state, result in hydrodynamic and material transport behavior which is complex.

The bay experiences seasonal variations in rainfall, runoff and sediment loading which can be broadly classified as low, medium and high in the following way (Table 1).

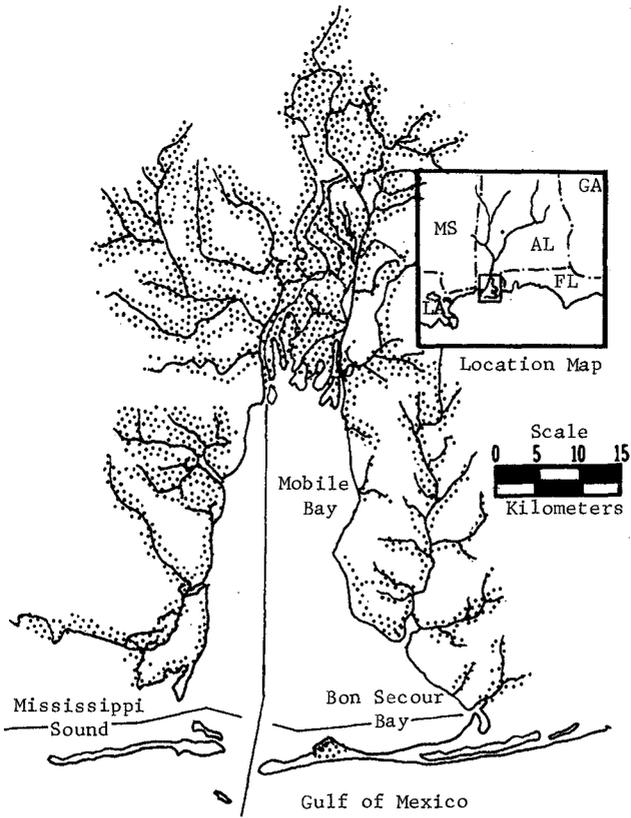


Figure 1.--Mobile Bay Estuarine System.

Table 1. -- Seasonal Average River Flow Rates and Sediment Load for the Mobile Bay System; 1952-1963 (U.S. Corps of Engineers, 1974).

River Flow Rate Classification	Period Covered	Average Flow Rate m ³ /sec	Flow Rate (Range) m ³ /sec	Average Sedi- ment Load Kilograms x 10 ⁻⁶	Sediment Load (Range) Kilograms x 10 ⁻⁶
Low	August-November	531	447-700	68	50-107
Medium	May-July	1090	801-1609	215	145-353
High	December-April	2978	1609-3849	673	343-937
	Annual Averages	1609		357	

During the heavy runoff period the bay receiving waters are dominated by the high river flows to the extent that salinity intrusion within the bay is suppressed to the mid and lower sections of the estuary. This condition also results in the most pronounced transportation of sediment within the bay. Conversely, during periods of reduced river flow and sediment loading, bay currents are dominated by the tidal influence. This results in a greater potential to deposit sediment although the total volume is significantly reduced because of the decrease in solids loading during these periods.

Shoaling in the bay has averaged about 0.6m per century. However, there are portions of the bay which are highly stable and other regions which have rates of nearly 3.0m per century. These wide variations are a result of the complex, natural circulation patterns and man-made influences such as channel construction and maintenance dredging activities which exist in the bay (Ryan, 1969). Nearly 1.6×10^9 kilograms of suspended sediment bypass the bay annually. This material discharges into the Gulf through two natural passes in the southwestern area of the estuary. During tidal dominant periods (especially during flood tide cycles) solids can be introduced into the bay from the Gulf. These materials are transported to the bay mouth by the predominantly east to west littoral current which occurs in the northeastern Gulf of Mexico.

The influence of these variations in sediment transport and deposition patterns is analysed in this paper by considering the hydrodynamic behavior of the bay using mathematical modeling methods (Hill and April, 1974; Liu and April, 1975).

MODEL DESCRIPTION

Several mathematical models based on the laws of conservation of mass and momentum have been formulated for Mobile Bay (Table 2). These include two dimensional (depth averaged) models describing the hydrodynamic, conservative and non-conservative species transport behavior within the bay. Solution of the model equations is achieved using finite difference methods on a UNIVAC 1110 digital computer. These models have been used to study the influence of river discharge rate, wind direction and speed and tidal conditions on bay circulation and material transportation. Utilization of these models to investigate long term and short term trends resulting from natural and man-made disturbances on the system is part of an on-going research effort.

MODEL APPLICATION

Examples of methods used to assess sediment behavior are presented for a series of different conditions as dictated by the time frame over which information is being sought. These periods are broadly classified into long range or seasonal events and short range or within tidal cycle events for convenience. Each type will be discussed separately in subsequent sections.

The Effect of Seasonal Variations on Sediment Transport in Mobile Bay

Just as there are settling and scouring events within tidal cycles, there also exist seasonal variations which influence the sediment transportation and deposition characteristics within the bay. The effect of these seasonal events are studied by considering the hydrodynamic behavior of the bay using mathematical modeling methods. In particular, for the purpose of this paper, correlation of the hydrodynamic and sediment transport behavior is made using a tidal cycle average current generated for seasonal average flow conditions. This technique is a convenient method of lumping variables which are difficult to interpret and impossible to obtain over long term periods. The method provides a rapid assessment of those regions more susceptible to high transport and/or deposition of sediment. For Mobile Bay, a value of 0.06 m/sec correlates well with observed long term sediment transportation and deposition trends (i.e. a value < 0.06 m/sec indicates a region of low transportation; a value > 0.06 m/sec indicates a region of high transportation). Areas which have a high transportation potential regardless of river flow rate are indicated by the closed regions (Figure 2). These include the Bay areas adjacent to passes and waters near the Mobile and Tensaw Rivers in the north.

Table 2.--Mathematical Representation and Operational Modes of the Mobile Bay Models (Hill and April, 1974; Liu and April, 1975).

Name	Equation Form	Results	Modes
Continuity	$\frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} + \frac{\partial H}{\partial t} = -(R + E)$	Tidal Height	Tidal Cycle Daily Avg Monthly Avg Seasonal
Momentum x-Component	$\frac{\partial Q_x}{\partial t} + gD \frac{\partial H}{\partial x} = KV^2 \cos \psi - fQQ_x D^{-2} + Q_x (2Ws \sin \phi)$	x-Component of Surface Current	Tidal Cycle Daily Avg Monthly Avg Seasonal
y-Component	$\frac{\partial Q_y}{\partial t} + gD \frac{\partial H}{\partial y} = KV^2 \sin \psi - fQQ_y D^{-2} + Q_y (2Ws \sin \phi)$	y-Component of Surface Current	Tidal Cycle Daily Avg Monthly Avg Seasonal
Species Continuity	$\frac{\partial C}{\partial t} + v_x \frac{\partial C}{\partial x} + v_y \frac{\partial C}{\partial y} = E \left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} \right) + \frac{E}{D} \left(\frac{\partial C}{\partial z} (z_s) - \frac{\partial C}{\partial z} (z_b) \right) - \frac{1}{D} (Cv_z (z_s) - Cv_z (z_b)) + R_o$	Concentration of Species	
Salinity	$R_o = 0$	Salinity Concentration	Daily Avg Seasonal
Coliform	$R_o = KC$; where $K = f(\theta)$	Coliform Bacteria Concentration	Monthly Avg Seasonal
Sediment	$R_o = K_1 f(v_s) + K_2 f(E) - K_3 f(v_r)$	Suspended Sediment Concentration	Seasonal Tidal Cycle

Note: f in the last equation is a functional representation for those terms listed. For example a modified form of Stokes' Law might be represented by the term $f(v_s)$.

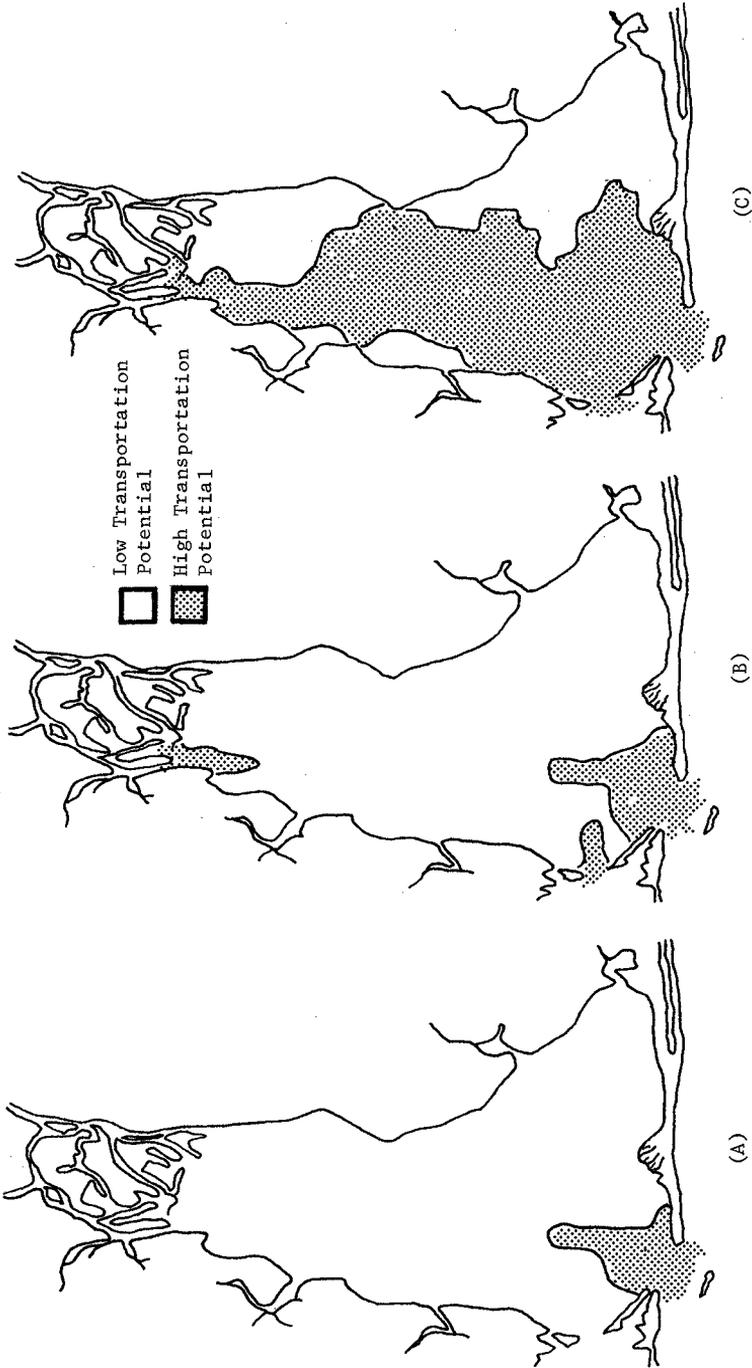


Figure 2.--Schematic Diagram Illustrating the Areas of High Transportation Potential at (A) Low, (B) Medium, and (C) High River Flow Conditions.

The open areas represent regions of low sediment transportation. These areas include the head waters between the Mobile and Tensaw Rivers, the Bon Secour Bay area and regions along the western shoreline. The seasonal variations can be observed by following the progression of the high transportation potential areas from high to low river flow conditions. It is likely that materials deposited during low river flow conditions become re-suspended during high river flow periods. This phenomenon can be traced using the hydrodynamic and material transport model for the bay. Included in this method of analysis are allowances for turbulence as estimated by local dispersion coefficients.

The Impact of Channelization on Long Term Sediment Transport in the Bay

In order to assess the possible long term impact that the Mobile ship channel has had on bay circulation and sediment transportation patterns, the hydrodynamic model was run under two conditions. The first set of conditions was derived from the 1847-1851 bay contour diagram from which bay depths were used as input to the model (Ryan, 1969). The second set of conditions were those including the ship channel in which bay depths and model parameters were adjusted to simulate this modification to the natural system. Both cases were run for a river flow rate of $3510 \text{ m}^3/\text{s}$. Transportation patterns were again determined using the tidal cycle average velocity criteria discussed earlier (Figure 3). A more even transportation pattern is observed over the lower two-thirds of the bay for conditions in which the ship channel is excluded. This condition can be explained by the higher volumetric throughput that occurs as a result of channelization along the west-central bay. A comparison of these results with deposition maps for the periods 1852-1920 and 1920-1973 prepared from bathymetric data supports the general patterns projected by the hydrodynamic model (Figure 4).

Within Tidal Cycle Variations in Mobile Bay Sediment Transport

Short term variations in sediment transportation patterns within the bay are of two varieties; man-made sediment disturbances resulting from maintenance dredging activities, and, naturally occurring sediment disturbances caused by high river flow rates, runoff and wind conditions. The latter cases are of particular interest in that it provides a means of interacting the hydrodynamic model with satellite and high altitude photographic data (remotely sensed) obtained during high sediment load conditions.

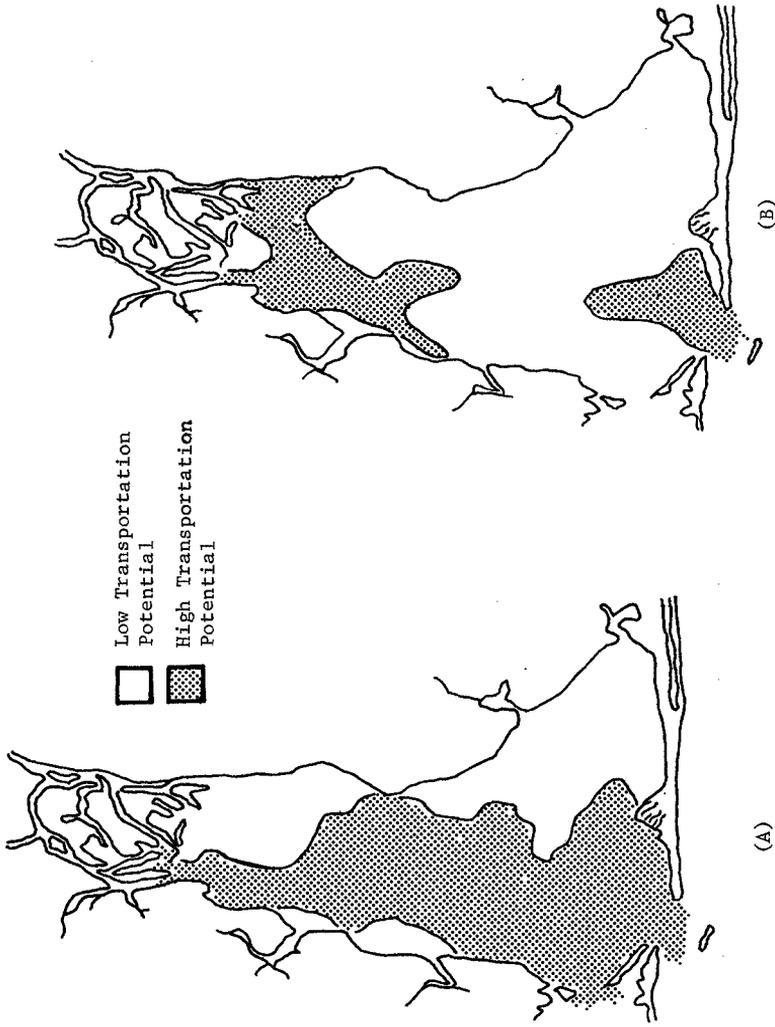


Figure 3.--Schematic Diagram Illustrating the Impact of Channel Construction on Bay Transportation Potential at High River Flow Conditions; (A) No Channel, (B) Channel.

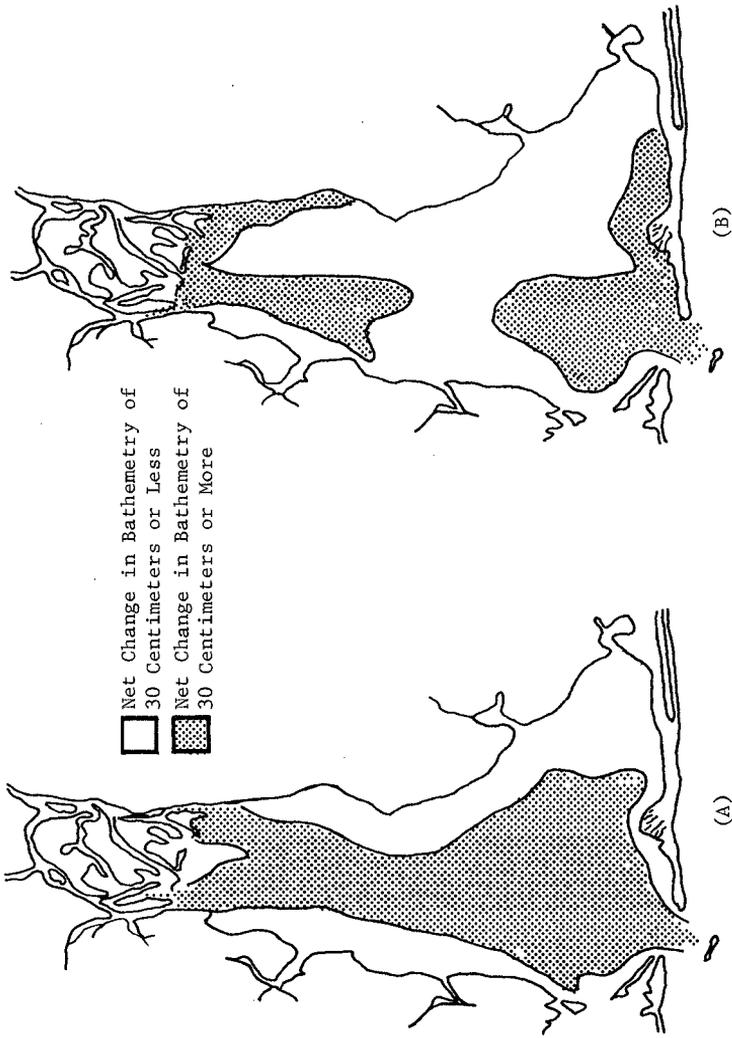


Figure 4.--Sediment Deposition Trends as Reflected by Bay Bathymetric Data for the Periods (A) 1852-1920 and (B) 1920-1973 (Sapp, 1975).

Sediment Transportation Resulting from Maintenance Dredging

Disturbances to the bay system resulting from maintenance dredging activities in areas adjacent to the Mobile ship channel account for the relocation of approximately 7.6×10^6 cubic meters of sediment. Hence, it becomes important to assess the impact that these dredged materials have on bay sediment transport and resettling behavior and the areas affected.

Such an analysis was made using the hydrodynamic model of the bay as a source of current direction and speed, and dispersion coefficient data as a function of tidal state. Subsequently, the material transport model was used for a subsystem (i.e. cell grid dimensions of 0.5 km; reduced from the two km hydrodynamic grid size) defined by the location affected by the dredging operation.

Field data collected in an independent study (Brett, 1975) were used to verify the model results. The field data were collected in May 1972 for the purpose of measuring the extent of sediment transport and deposition adjacent to a dredge discharge line. The dredge location was in the central bay (Figure 5). Comparison of suspended sediment concentrations as a function of distance from the dredge discharge indicates good agreement between the model predicted results and actual field data (Figure 6). There was no noticeable level of sediment in the water column beyond station 5; a distance of 1525 meters from the dredge discharge in a north-northeasterly direction. This is attributed to a change in the bay current pattern from near flood tide to near high water slack in which current velocities decrease rapidly to levels less than 0.06 m/sec. Similar conclusions can be derived by considering the thickness of deposited material along the north-south sampling transect (Figure 6).

As the tide enters high water slack, the sediment transport was shifted from a north-northeasterly direction to a more easterly direction. Similar patterns were observed as those discussed during the flood tide condition. However, because of the low current velocities, the dredging discharge rate becomes an important source of energy for transportation during this period. Thus the nature of the deposition patterns was such that this material was deposited over a shorter distance (Figure 6). These observations are consistent with the lower velocities and shorter period of time that occur during the slack water condition.

Similar patterns to those experienced during flood tide and high water slack conditions were postulated for ebb tide and low water slack. More material will be transported over a longer distance as a consequence of the longer period of high current velocities in the ebb flow direction. During seasonal periods when river flow rates are smaller than the value investigated in this study, a smaller area will be affected as a result of the more uniform ebb/flood tidal relationship. Because of the river inputs, the ebb tide condition is always greater than the flood conditions except during unusual periods.

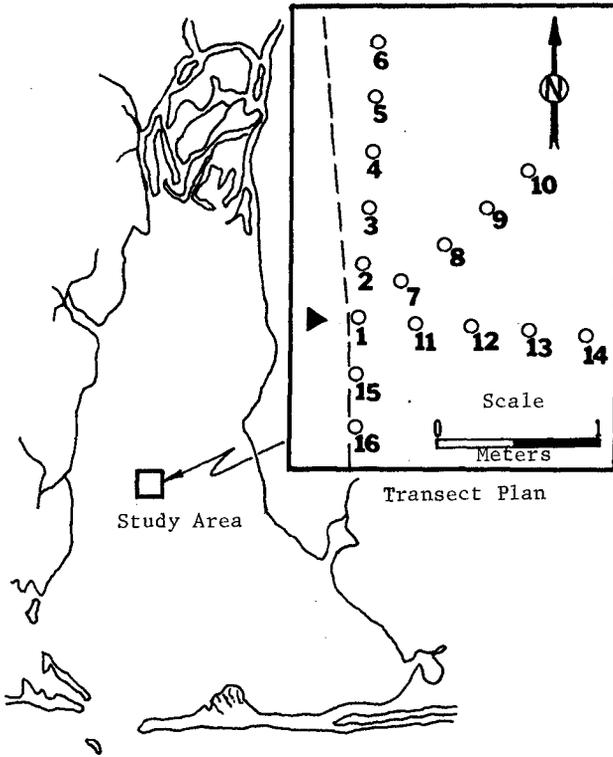


Figure 5.--Location Map and Transect Plan for Maintenance Dredging Program (Brett, 1975).

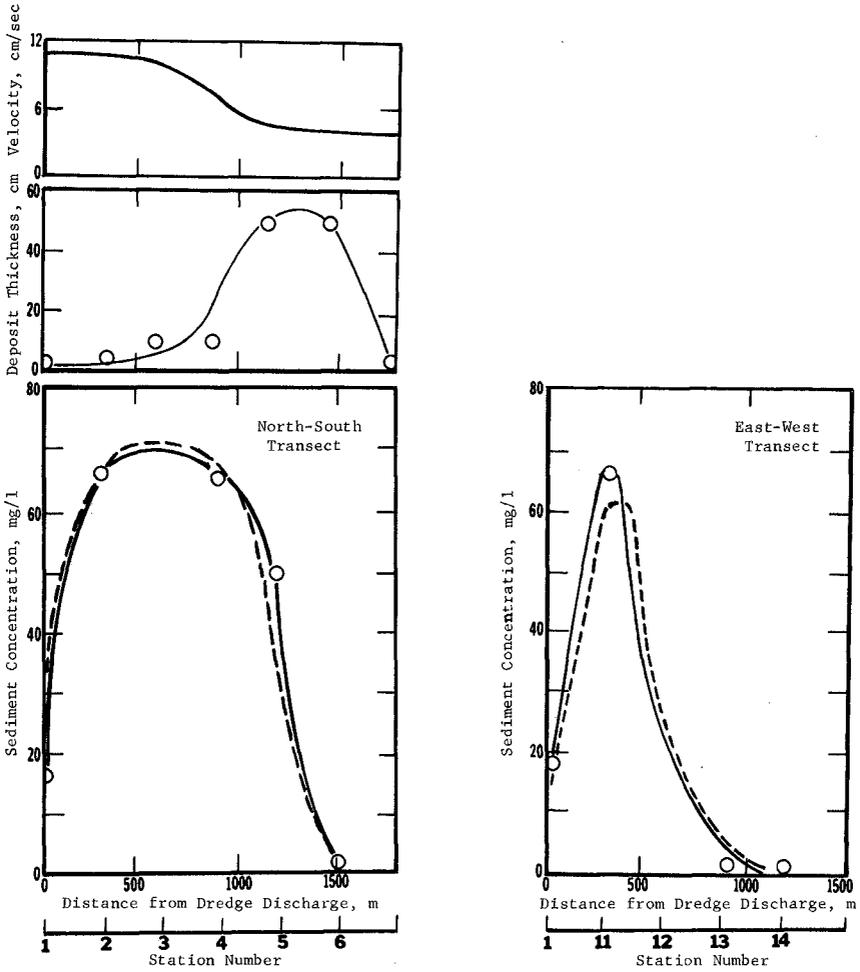


Figure 6.--Comparison of Model Calculated (Dash) and Field Measured (Solid) Results for Maintenance Dredging Program (Brett, 1975).

Naturally Occurring Sediment Transportation Events

The relationship of sediment transportation patterns to the hydrodynamic properties of Mobile Bay is shown by comparing model predicted velocity profiles with satellite photographs (Figure 7). In the case shown the hydrodynamic model was run at the local conditions observed during the photographic mission over the bay. The resulting velocity vectors were then reduced by a density slicing method where the following criteria were applied:

Category	1	2	3	4	5
Velocity Range m/sec	0-0.13	0.13-0.25	0.25-0.45	0.45-0.90	0.90-1.25

It should be noted that this method is highly acceptable when there is high sediment loads within the bay in which hydrodynamic factors constitute the primary driving force. Studies are in progress to better identify and account for those conditions which produce wind and/or bay bottom sediment disturbances.

The comparison shown indicates a first attempt at using remotely sensed data to complement mathematical modeling efforts. It also provides better coverage of bay behavior than what is currently available by either sporadic field data programs and photographic missions, the success of which is dependent on good meteorological conditions.

CONCLUSIONS

The above discussion of ongoing work related to the characterization of natural and man-made disturbances and the impact that they have on bay behavior is intended as a review of methods currently used. Because of the interrelationship of material transport (sediment) and hydrodynamic behavior (current), the use of mathematical modeling methods to predict change and assess impacts on the bay quality and material transport can be made. As seen the techniques can be rather crude such as those long range variations in sediment depositional potential or more refined analyses involving local, within tidal distribution of dredge materials. In either case, the dependency on data to calibrate and verify the results forms the critical step in the method. Once calibrated, however, the model results can be used to supplement data collection programs and provide a broader, more complete coverage than what is currently available. Some success has been shown for high sediment load conditions which are river oriented. Continued efforts to predict disturbances which are wind driven or which result from local bay bottom scouring is important to complete this area of investigation.



(A) (B)
Figure 7.---Comparison of Sediment Transportation Patterns Predicted by the Hydrodynamic Model (A) and Skylab IV photograph taken January 21, 1974 (B).

The knowledge gained from these studies have allowed, in many cases, quantification of results previously considered only in a qualitative sense. Although far from analytical in all cases, these methods provides a basis for assessing trends in behavior caused by natural and man-made disturbances. These methods also point out the need for continued investigations aimed at better descriptions of these complex systems which are vital to man's future.

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NOMENCLATURE

C	Concentration of Species in the Water Column, M/L^3
D	Depth of Water in the Bay, L
E	Rate of Mass Transfer by Evaporation, L/T
	Dispersion Coefficient, L^2/T
f	Bay Bottom Friction Factor
	Functional Representation
g	Gravitational Acceleration, L/T^2
H	Height of Water Above a Cell Datum, L
K	Constants
Q	Discharge Rate, L^3/T
R	Rate of Mass Transfer by Rainfall, L/T
	Rate of Disappearance or Appearance of Mass, M/L^3T
t	Time, T
V	Resultant of the Velocity Vector, L/T
v	Local Grid Velocity, L/T
W	Wind Velocity, L/T
x	Distance in the East-West Direction, L
y	Distance in the North-South Direction, L
z	Distance in the Depth Direction, L
∂	Differential Operator
θ	Temperature
ϕ	Wind Direction
ψ	Angle Measurement in the Coriolis Term

SUBSCRIPTS

b	Bottom
o	Source or Sink Term
r	Resuspension
s	Settling
	Surface
x	East-West Direction
y	North-South Direction
z	Depth Direction