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Project Summary

Modeling Fine Sediment Transport in Estuaries

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A sediment transport model (SEDIMENT IIIA) was developed to assist in predicting the fate of chemical pollutants sorbed to cohesive sediments in rivers and estuaries. Laboratory experiments were conducted to upgrade an existing two-dimensional, depth-averaged, finite element, cohesive sediment transport model. The utility of SEDIMENT IIIA was demonstrated by laboratory resuspension and deposition tests and simulations of the sedimentation processes in a hypothetical canal. The effect of salinity in these simulations also was examined.

The model should enhance capabilities for predicting water quality impacts and for analyzing sedimentation management issues. The improved transport descriptions should be useful in making more reliable predictions of the fate of dissolved and sorbed pollutants discharged into an estuary or harbor by stormwater runoff or industry releases, thus assisting in the evaluation of water pollution control options. The enhanced descriptions should also be useful in predicting the movement of dredged material released in open marine waters, identifying harbor sites in estuaries and bays where shoaling is minimized, predicting changes in sedimentation that may occur as a result of proposed changes or developments of an estuary or harbor, and estimating shoaling rates and maintenance dredging requirements in areas of low flow.

This Project Summary was developed by EPA's Environmental Research Laboratory, Athens, GA, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Modeling the movement of cohesive sediments to predict the fate of pollutants introduced into an estuary is important because a significant fraction of many pollutants (e.g. heavy metals, radioactive elements, and organic substances) is typically transported sorbed to these sediments rather than in the non-sorbed state. Modeling the transport of cohesive sediments requires a knowledge of the geometry of an estuary; the flow and salinity fields; the coagulation, settling and depositional characteristics of the sediment; the structure (i.e. bed shear strength and bed density profiles) of the sediment bed at several different locations in the estuary; and the erosional characteristics of these beds when subjected to an excess bed shear stress.

None of the existing fine sediment transport models has the capability of determining the effect of salinity variation (e.g. in the mixing zone between fresh and sea water in estuaries) on the processes of erosion and deposition of cohesive sediments in a turbulent flow field. Empirical laws employed in existing models for these transport processes were derived with the use of empirical evidence from limited laboratory experiments conducted in natural or artificial sea water. In addition, the empirical laws of erosion and deposition cannot be considered to be the state-of-the-art even for sea water, because a considerable number of laboratory experimental tests have been conducted since these laws were proposed. Based on findings reported in the literature plus those derived from experiments conducted in this study, new evidence has been revealed about the erosional and depositional behavior of cohesive sediments.

This study had the following five primary objectives: (1) conduct a comprehensive review of the existing theory on the erosion and deposition of fine, cohesive sediments; (2) determine the effects of salinity on the rates of erosion of flow-deposited cohesive sediment beds under turbulent flows; (3) determine the effects of salinity on the deposition rates under turbulent flows; (4) upgrade an existing "state-of-the-art" two-dimensional, vertically integrated mathematical model of cohesive sediment transport by improving upon the capability of this model to predict the erosion and deposition of cohesive sediments in estuaries; and (5) demonstrate the utility of the improved transport model in simulating the erosion and deposition of cohesive sediments and the effect of salinity on these transport processes.

Research was directed towards obtaining an improved understanding and quantitative description of the erosion (resuspension) and deposition of fine sediments under turbulent flows. This was achieved by investigating the erosive behavior of flow-deposited (i.e. stratified) cohesive sediment beds and the effect of salinity on the rates of erosion and deposition. The results of these investigations, in the form of empirical erosion and deposition functions and an improved schematization of flow-deposited beds, were incorporated into the selected cohesive sediment transport model. The fifth objective given above was accomplished by using the modified model to simulate laboratory erosion and deposition experiments and to demonstrate the effect of salinity on the rates of erosion and deposition of cohesive sediments in both laboratory experiments and in a 10-km-long hypothetical canal.

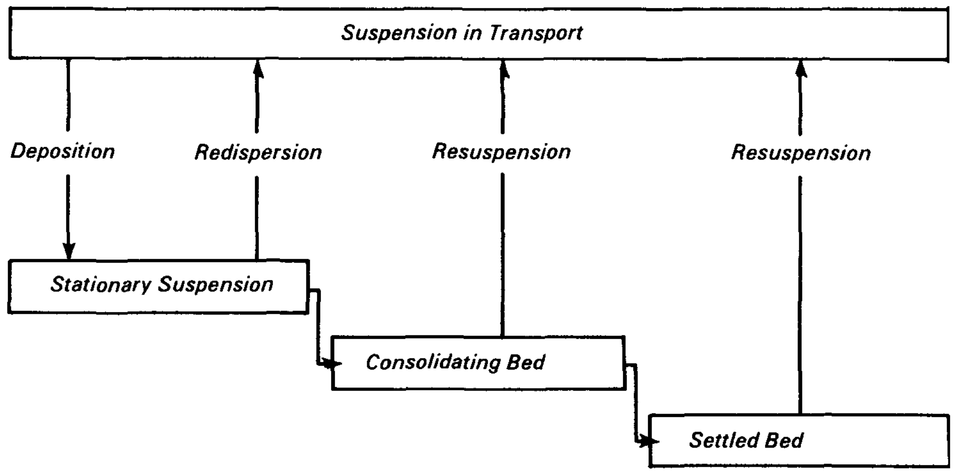

Figure 1. *Schematic of erosion-deposition phenomena handled in SEDIMENT IIIA.*

Model Description

The fine sediment transport model selected for modification was a time-varying, two-dimensional finite element model that is capable of predicting the horizontal and temporal variations in the depth-averaged suspended concentrations of cohesive sediments and bed surface elevations in an estuary, coastal waterway, or river. In addition, it can be used to predict the steady-state or unsteady transport of any conservative substance (e.g. salt) or nonconservative constituent, if the reaction rates are known. The model describes the advective and diffusive transport of suspended or dissolved constituents, the settling, deposition (i.e. sink) and erosion (i.e. source) of cohesive sediments to and from the bed, respectively, and the consolidation of the bed due to continuing deposition. Figure 1 is a schematic of the erosion-deposition phenomena handled by the model. According to this description, fine sediments can exist in four different physical states in a tidal estuary--a mobile suspension, a stationary suspension, a consolidating bed, and a settled bed.

The existing model was refined by incorporating a newly developed bed schematization model, as well as mass erosion, surface erosion, and deposition algorithms and the effect of salinity on the rates of surface erosion and deposition. The modified version, SEDIMENT IIIA, also includes modifications to the equation used for calculating kinematic viscosity, the use of nodal salinity values for evaluating the settling velocity and deposition rate, and the equation for calculating the density of the suspending fluid.

These refinements were based on recent developments reported in the literature and on the results of laboratory experiments conducted in this study. Experiments were carried out to determine: (1) the resuspension characteristics of partially consolidated, flow-deposited cohesive sediment beds under turbulent flows, (2) the effects of salinity on the rates of erosion of these beds, and (3) the effects of salinity on the rates of deposition and the settling velocity of suspended cohesive sediments under turbulent flows.

Resuspension tests were conducted in a rotating annular flume and in a straight recirculating flume at the University of Florida using kaolinite and a natural mud. These tests revealed that flow-deposited beds are stratified with respect to bed shear strength and density and can consist of unconsolidated stationary suspensions partially consolidated beds and settle fully consolidated beds. Both the cohesiv shear strength and the bed density ir crease with consolidation. When subjecte to an excess bed shear stress, stationar suspensions erode almost instantly, whil partially and fully consolidated beds ur dergo surface (aggregate-by-aggregate erosion. An empirical expression for th rate of surface erosion of partially cor solidated beds was derived that is ana ogous to the rate expression which result from a heuristic interpretation of the rat process theory of chemical reactions. Thi rate expression indicates that the rate c erosion varies exponentially with the ex cess bed shear stress. The rate of erosio of settled beds is linearly proportional t the excess shear stress.

A cohesive sediment bed algorithm an an erosion algorithm were developec Based on an interpretation of typicall observed Eulerian time-concentration rec ords in estuaries, erosion is considered t occur during accelerating flows. Likewise deposition is considered to occur durin decelerating flows. The erosion algorithr simulates mass erosion of stationary sus pensions and surface erosion of partiall consolidated and settled beds. The be schematization includes these three be sections and divides each section int discrete layers. The amount of sedimen eroded from the bed or deposited onto th bed in each element is determined, an the thickness and the structure of the be in that element are adjusted accordingly Consolidation of the bed due to over burden is accounted for by first filling u the top stationary suspension layers and then the partially consolidated layers as deposition occurs.

A refined deposition algorithm was also developed. This algorithm integrates the concepts proposed by various investigators and represents a unified model of this process. Deposition is predicted to occur when the bed shear stress is less than the maximum depositional shear stress. The rate of deposition depends, among other factors, on the bed shear stress and the settling velocity of the suspended sediment. The bed shear strength was found to vary with the salinity of the eroding fluid, for salinities less than 2 parts per thousand.

The rates of deposition of the natural mud were found to increase with increasing salinity. A power relationship between the settling velocity and salinity was determined from analysis of deposition tests conducted at different salinities and under varying bed shear stresses.

Model Performance Testing

Model simulations of erosion and deposition were conducted in laboratory experiments and sediment transport tests were conducted using a hypothetical prototype canal. The purpose was to show the capability of SEDIMENT IIIA in predicting cohesive sediment transport processes by comparing measured and predicted results and the effect of salinity on these same processes.

Simulation of various sediment problems using the model showed that the numerical scheme is stable for all conditions. The accuracy of the solution is affected when the Peclet number, which is the ratio of convection to diffusion, becomes too large (greater than 10^2) or too small (less than 10^{-3}).

The model was used to simulate a laboratory resuspension test and four laboratory deposition tests. Reasonably good agreement between the predicted and measured results was obtained in each of these cases (see Figure 2, for example). The effect of salinity on both the resuspension test and one of the deposition tests revealed that, as expected, the rates of resuspension and deposition decreased and increased, respectively, with increasing salinity. Sedimentation processes in a 10-km hypothetical canal in which both erosion and deposition of sediment occurred also were simulated at three different salinities to show the effect of salinity under typical prototype conditions. The effect of salinity in the simulation was less apparent than in the case of the laboratory tests because of the simultaneous occurrence of erosion, convection, diffusion and deposition along the canal.

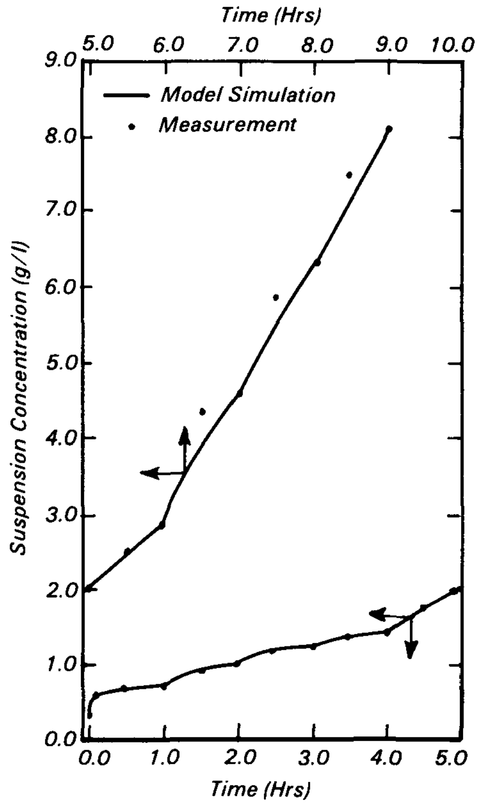

Figure 2. *Comparison of predicted and measured suspension concentrations versus time for a resuspension experiment.*

Limitations on Model Use and Application

A two-dimensional, vertically integrated model such as SEDIMENT IIIA can strictly be applied only to estuaries, harbors and basins (such as marinas) where the horizontal dimensions of the water body are at least one order of magnitude greater than the vertical dimension. Applications to partially mixed water bodies or especially to highly stratified water bodies should be made only when rough estimates of some sedimentation process (e.g. shoaling rate) are required.

Currently the model has the capability of simulating the movement of only one constituent (e.g. cohesive sediment, water temperature, or algae, provided that the source/sink expressions for a nonconservative constitutent are known). It is possible, however, to modify the model so that any number of constituents may be incorporated.

Probably the main "limitation" of a model arises from three sources: insufficient data, poor quality of data and limitations of hydrodynamic modeling. The first two sources are attributable to the fact that, owing mainly to time and cost considerations, all the bathymetric, hydraulic and sedimentary data required for use in such a model are rarely if ever measured and/or collected in the body of water being modeled. In addition, the quality of the data is often questionable. Data requirements and the field collection and laboratory testing programs required to obtain these data are briefly described in the report. The third source is often the result of the first two in addition to the technical deficiencies in the state of science in modeling estuarine hydrodynamics.

The sediment transport descriptions developed here, when incorporated into newly developed water quality models (e.g., TOXIWASP), should enhance the reliability of these models in making exposure predictions.

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The complete report, entitled "Modeling Fine Sediment Transport in Estuaries," (Order No. PB 83-223 362; Cost: $20.50, subject to change) will be available only from:

National Technical Information Service
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