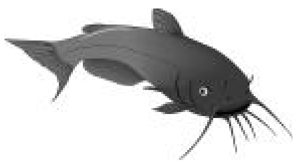
ENV Report 20

Interim Report For The Upper Mississippi River - Illinois Waterway System Navigation Study



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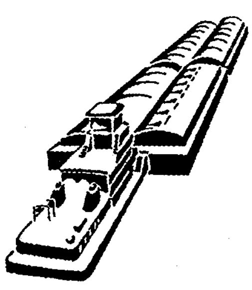

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Upper Mississippi River - Illinois Waterway System Navigation Study

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Wave-Induced Sediment Resuspension near the Shorelines of the Upper Mississippi River System

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Contents

Preface

The work reported herein was conducted as part of the Upper Mississippi River – Illinois Waterway (UMR-IWW) System Navigation Study. The information generated for this interim report will be considered as part of the plan formulation process for the System Navigation Study.

The UMR-IWW System Navigation Study is being conducted by the U.S. Army Engineer Districts, Rock Island, St. Louis, and St. Paul under the authority of Section 216 of the Flood Control Act of 1970. Commercial navigation traffic is increasing, and in consideration of existing system lock constraints, will result in traffic delays that will continue to grow in the future. The system navigation study scope is to examine the feasibility of navigation improvements to the Upper Mississippi River and Illinois Waterway to reduce delays to commercial navigation traffic. The study will determine the location and appropriate sequencing of potential navigation improvements on the system, prioritizing the improvements for the 50-year planning horizon from 2000 through 2050. The final product of the System Navigation Study is a Feasibility Report which is the decision document for processing to Congress.

Dr. Trimbak M. Parchure, Sedimentation Engineering and Dredging Group, Tidal Hydraulics Branch, Estuaries and Hydrosciences Division, Coastal and Hydraulics Laboratory (CHL), Vicksburg, MS, U.S. Army Engineer Research and Development Center (ERDC), was the principal investigator for the work described herein. Dr. William H. McAnally, Chief, Estuaries and Hydrosciences Division, and Mr. Allen Teeter, Chief, Sedimentation Engineering and Dredging Group, contributed to the development of the model, laboratory analysis, and preparation of this report. Dr. Parchure conducted the work under general supervision of Dr. Robert T. McAdory, Chief, Tidal Hydraulics Branch, Dr. McAnally, and Dr. James R. Houston, Director, CHL.

This report was edited and published by the Information Technology Laboratory, ERDC. Mr. Robert C. Gunkel, Jr., Environmental Laboratory (EL), ERDC, was responsible for coordinating the necessary activities leading to publication. Dr. John W. Keeley was Acting Director, EL.

At the time of publication of this report, Director of ERDC was Dr. James R. Houston. COL James S. Weller, EN, was Commander.

1 Introduction

Background

Estimation of environmental impacts caused by increased navigation on the Upper Mississippi River-Illinois Waterway (UMR-IWW) System is a part of the UMR-IWW Navigation Study. The study had two components: site-specific and system-wide impacts. Some of the potential site-specific impacts to be evaluated included the following:

a. Loss of benthic and riparian habitat in and adjacent to a construction site.

b. Changes in the lock and/or dam structure that could alter tailwater velocities, water quality, or substrate composition.

c. Changes in lock approach patterns that could cause towboats to increase bank erosion or benthic disturbance, or require dredging for new channel alignment.

d. Changes to terrestrial or shoreline habitat due to bankline excavation, borrow or staging area placement, or dredged material placement sites.

First, personnel of the Coastal and Hydraulics Laboratory (CHL), Vicksburg, MS, U.S. Army Engineer Research and Development Center (ERDC), determined the physical effects generated by navigation craft. These effects were then translated into impacts to biological resources of the system. It was considered necessary to investigate whether increased navigation would result in increased erosion in the nearshore areas, generally called the riverbanks. This was a matter of concern for two reasons:

a. Loss of bank sediment could result in the loss of propagules and aquatic plants.

b. An increase in the suspended sediment concentration as a result of bank erosion could impact the riparian habitat of fish and wildlife and cultural resources along the shoreline of the Mississippi River.

Maynord and Martin (1996) identify five dominant mechanisms of bank erosion in the context of the Upper Mississippi River System:

a. Piping caused by flood recharge of banks.

b. Slope failures.

c. Flow-induced scour.

d. Navigation effects.

e. Wind-generated waves.

While the erosion of riverbed and bank is caused primarily by the flow-induced shear stress at the sediment-water interface, the riverbanks are also eroded to a considerable extent by the action of waves. The waves may be generated either by local wind or by the vessels navigating along the river. Field observations have shown that small, high-speed pleasure craft and fishing boats plying in shallow water near the riverbanks cause significant bank erosion.

The navigation effects are schematically shown in Figure 1 (Maynord 1996). The following four components are significant in terms of sediment resuspension:

a. Vessel-induced waves.

b. Water level changes (drawdown).

c. Vessel-generated currents.

d. Propeller wash.

Maynord (1996) has studied the return velocity and drawdown in navigable waterways using physical models. Examples of field observations of drawdown measured along the Mississippi River are shown in Figures 2 and 3. The effect of vessel-induced waves on sediment erosion is considered in this report. The term erosion is used when sediment that has not been removed recently from the riverbed is brought into suspension. The term resuspension applies when bed sediment that was eroded earlier and subsequently deposited gets back into the water column either by current or waves.

Erosion/resuspension of sediment in the near-shore zones of rivers, bays, and estuaries has ecological significance due to its adverse effect on submerged aquatic vegetation (SAV) and the aquatic/benthic organisms (Parchure, Kim, and McAnally 1996). Bed-load transport of sediment may cause uprooting of plants and washing away of propagules before they establish themselves firmly in the bed for further growth. Suspended sediment may result in a substantial attenuation of sunlight and/or deposition on leaves, thus hindering plant growth.

Resuspension of fine clayey sediment may be particularly important because of three reasons:

a. Resuspension of a very thin layer, on the order of only a couple of millimeters thick, is enough to release millions of primary clay particles in water.

b. The fine sediment particles often remain in suspended stage over a very long period of time because of their low settling velocity.

c. The fine particles have a very large specific surface area; hence a very small amount by weight in suspension may significantly reduce light penetration to the bed.

Sediment deposition initiates or promotes germination and growth of aquatic plants. Aquatic plants slow down flow of water and dissipate wave energy, thus inducing more deposition of sediment. Adequate quantitative information on such complex interaction of sediment and aquatic vegetation is not available at the present stage. Hence a preliminary numerical model was developed for predicting the concentration of suspended sediment in the near-shore zone without the effect of vegetation. A procedure for estimating suspended sediment concentration resulting from currents is already available. Procedures for estimating beach erosion caused by wind-generated waves are also available; however, models for estimating sediment resuspension caused by navigation effects were not available in literature. Hence the present study involved developmental work. The model developed can be used by itself or it can be added to a comprehensive sediment model for a study of a river/estuary.

Scope of Report

Although several factors mentioned earlier have an impact on bank erosion, the scope of the present report is limited to development of a model and its application for estimating the impact of locally generated vessel-induced waves on the bank erosion and sediment suspension.

This study addresses the following issues:

a. Generalization of wave patterns for the event of vessel passage.

b. Estimation of maximum suspension concentration caused by individual events of vessel passage.

c. Deposition of suspended sediment.

d. Interference effect on the sediment suspension caused by the passage of another vessel before sediment from the previous event has deposited.

Literature Review

Camfield, Ray, and Eckert (1979) reviewed literature on the possible impact of vessel wakes on bank erosion. It was concluded that "no computational methods exist for linking a vessel with a chosen hull shape, traveling at a chosen speed in a channel of chosen depth and chosen cross-sectional area and shape with banks of chosen height and materials, to a predicted occurrence of erosion." Although a literature search was not successful in finding a procedure for predicting wave-induced resuspension, the following parameters involved in prediction were revealed:

a. Vessel-related:

(1) Size of vessel (draft, length, beam width, and tonnage).

(2) Speed of the vessel.

(3) Hull shape.

b. Channel-related:

(1) Size of channel (width, depth, and cross-sectional area).

(2) Bank height.

(3) Shape of channel.

c. Sediment-related:

(1) Type of sediment.

(2) Erodibility.

d. Wave-related:

(1) Wave height and period.

(2) Time series of occurrence.

(3) Time after passage of vessel.

(4) Distance from the vessel (wave decay).

Sorensen (1973) has given a literature review on water waves produced by ships. This review pertains to large vessels navigating in water depths of 38 to 42 m. Hence it is not relevant to the present study. Skafel and Bishop (1994) reported on the flume experiments related to erosion of till shores by waves. A series of 200 random waves was produced in 1-m water depth in a laboratory flume. This wave pattern does not match the ship-generated waves. Bishop, Skafel, and Nairn (1992) have described cohesive profile erosion by waves. The emphasis of the study was to determine the effect of sand on cohesive sediment erosion. Both these investigations deal with the bank erosion and do not include the effect of waves on resuspension of bottom sediment.

Maynord and Martin (1996) conducted a literature review on riverbank erosion. Their report describes navigation-related processes and provides numerous examples of bank erosion studies conducted throughout the world over the past several years. Regarding bank erosion models, "little modeling effort relating boating activity to bank recession was found. It is likely that a wind-wave bank recession model could be modified to address boat-wave-induced bank erosion. The ability of waves to downcut the foreshore slope must be considered in predicting long-term recession rates."

The effect of wave action on fine sediment beds has been studied only recently. Hwang and Wang (1982) have reported work on wave kinematics and sediment suspension at the wave breaking point. Maa (1986) conducted a laboratory study on the erosion of soft mud by waves. While studying constituent release at the mud-water interface due to waves, Li (1996) has provided information on wave-mud interaction. All these studies take into account several parameters and are very complex in nature.

A field study conducted by Halka, Sanford, and Ortt (1994) has shown that shoreline erosion makes a significant contribution to suspended sediment concentration. In a study of Chesapeake Bay, Ward (1985) noted that in water depths less than 6 m, resuspension of bottom sediment by wind provides a major source of suspended sediment. Response of different types of submerged aquatic vegetation to the varying nutrient loading scenarios and varying suspended sediment concentration is still not adequately understood.

2 Conditions in Nature

Sedimentary Processes

Grain size analysis of sediment along the length of a river typically shows a wide range of sediment types from gravel and coarse sand (noncohesive sediments) to fine sediments in the range of clays and silt (cohesive sediments). Sometimes the fine sediments may also contain organic matter. Mathematical expressions formulating the transport processes of the cohesive and the noncohesive processes are significantly different. Hence the two types of sediments need to be treated separately.

The primary parameters to be considered for the noncohesive sediments consist of particle size and density and critical shear stress for incipient motion, which may be used in the equations for bed load and suspended load.

For cohesive sediments, the processes of erosion, transport, deposition, and resuspension are quite different from those for the noncohesive sediments. In particular, the processes of erosion, deposition, and consolidation of the fine sediment take place in a cyclic order (Mehta et al. 1982). Because of time-varying magnitude and direction of flow under vessel-induced flows, the time available for the sediment consolidation process is relatively very small. Hence a very thin and easily erodible layer (on the order of a few centimeters thick), which participates in these processes, is formed at the surface. This thin layer between the water column and firm bed is in the form of fluid mud. Fluid mud is a suspension, which by definition is essentially fluid supported and does not have any effective shear strength.

Fine sediment beds are classified as (a) uniform, which has a constant shear strength over depth, (b) stratified, which has layers of varying shear strength, and (c) fluid mud. The erosional properties of these are quite different, requiring use of corresponding mathematical equations for each. The entrainment of sediment due to hydrodynamic instability at the interface resulting in the generation and breakup of sediment billows has been described in terms of the balance between production of turbulent kinetic energy, buoyancy work in entraining sediment, and viscous energy dissipation (Kranenburg 1994). Thus, this process is distinct from surface erosion of sediment flocs, which occurs over a consolidated cohesive sediment bed. It is therefore essential to determine the type of bed and select an appropriate mathematical formulation.

Several factors need to be considered when dealing with fine sediment processes. These are classified under the following categories: sediment-related, fluid-related and process-related. The major factors are as follows:

a. Sediment-related factors.

(1) Mineral composition.

(2) Organic content.

(3) Bulk density.

(4) Particle size distribution.

(5) Cation exchange capacity.

b. Fluid-related factors.

(1) Salinity/chemical composition.

(2) pH.

(3) Temperature.

c. Process-related factors.

(1) Dispersion.

(2) Biological processes.

(3) Settling process.

(4) Turbulence.

The combined effect of both waves and current is more complex than their individual effects. Research of this phenomenon in physical models has shown that when action of each factor is important enough to require simulation of both waves and current, physical modeling becomes more complex and the similitude laws related to each action are generally not compatible (Villaret and Latteux 1992). It is necessary to take into account combined action of waves and currents while developing numerical models to study the aspects of sediment resuspension. Wikramanayake and Madsen (1994) have suggested a method of calculating suspended sediment transport by combined wave-current flows. The treatment is limited to the case of nonbreaking waves over a horizontal bottom, and only noncohesive sediment is considered.

Sediment Characterization

Field observations of Sanford (1994) have shown that the estimated shear stress that resulted in the largest resuspension was about four times smaller than the estimated shear stress that produced a lower resuspension at the same site. This apparently contradictory result has been explained by the fact that the sediments were less erodible during the period of higher stress than they were during lower stress. Hence characterization of fine, cohesive sediment beds is more important than that of coarse, noncohesive sediment beds because of the large number of parameters that affect the sediment properties of cohesive sediments and hence their erosional and depositional behavior.

Parameters that have been identified as influencing the properties and behavior of fine sediments may be grouped under three categories (Cohesive Sediments Research Newsletter 1992):

a. Physicochemical properties of fluid.

b. Physicochemical properties of the mud.

c. Water-mud exchange processes.

For this study three sediment-related parameters were selected to characterize fine sediments: (a) particle size distribution, (b) organic content, and (c) bulk density.

Vessel-Generated Waves

Maynord and Martin (1996) have reported numerous examples and references on field studies and model studies conducted in Europe and the United States related to vessel-generated waves. The parameters used for prediction of vessel-generated wave height and wave period are listed earlier in this report.

Maynord and Martin (1997) have reported results of physical model studies conducted at CHL. Illustrations of model-recorded wave trains generated by a commercial barge-tug are given in Figures 4 and 5. Sometimes, a bimodal pattern is noticed as shown in Figures 6 and 7; however, this is not common and may be due to reflection effects. In Figures 4 through 7 all water level fluctuations with wave periods greater than 10 sec have been filtered out because they may be drawdown and do not represent vessel-induced waves. The following are main features of the vessel-generated waves:

a. The waves are not random; instead they have a specific pattern. From the background ripples on the water surface, wave height increases rapidly as a vessel passes by, followed by a slow decay with time and distance from the vessel.

b. Wave heights are small, ranging from about 3 cm to 20 cm. Occasionally, they may reach as high as 60 cm.

c. Wave periods are small, ranging from 2 to 5 sec.

d. Due to small wave height and relatively large water depth, wave breaking occurs very close to the banks.

e. Wave activity is associated with a fluctuation in water level near the vessel and also near the banks.

f. Vessel waves at a given bank location have a duration of occurrence on the order of 2 to 8 min.

3 Preparatory Works

Field Measurements and Laboratory Studies

CHL conducted field measurements for wave heights, current, and suspended sediment concentration at various sites for three different time periods, November 1995, July 1996, and September 1996 (Pratt and Fagerburg 1998). The wave heights were measured with a pressure sensor, currents with a current meter, and suspended sediment concentration with Optical Backscatter (OBS).

The effect of a passing vessel on sediment suspension and the interference effect caused by another vessel passing through the waterway within a short time after the passage of the previous vessel are shown through two examples in this report.

The first example pertains to Range 2 at LaGrange Pool. The OBS assembly deployed at this site is shown in Figure 8. This assembly was in a water depth of 2.6 m (8.5 ft) and was located about 24 to 30 m (80 to 100 ft) away from the center of the navigation channel. It had OBS sensors installed at depths of 0.46, 2.1, and 2.4 m (1.5, 7.0, and 8.0 ft), respectively, below water surface. The particle size distribution of a surface bed sample collected at this site is shown in Figure 9.

Figure 10 shows measured water level changes caused by passage of three boats on 9 September 1996. Boat 4 traveled upbound at 1308 hours, Boat 5 passed downbound at 1347 hours, and at 1350 hours Boat 6 passed upbound. Figure 11 shows that the background suspension concentration of about 90 mg/L at 0.46 m (1.5 ft) below surface jumped to 440 mg/L with the passage of the first boat. Before this high concentration dropped down to the initial value, the combined effect of passage of the second and third boats resulted in an increase from 115 mg/L to about 250 mg/L. Changes in concentration at 2.1 and 2.4 m (7 and 8 ft) below surface are shown in Figures 12 and 13, respectively, which also show an increase in suspension concentration with the passage of boats.

It may be noted that the increase in suspended sediment concentration is caused by sediment dislodged from the bed and dispersed vertically within the water column. The sediment may be dislodged by the following:

a. The action of propeller (commonly called the prop wash).

b. Vessel-induced waves.

c. Vessel-induced return current.

d. Drawdown of water surface.

e. Sediment advected with currents in the area, which may be parallel and/or perpendicular to the riverbank.

Field measurements give the total concentration, and the contribution of each of these factors in the total suspended sediment concentration is not easily isolated.

Figure 11 shows a time series of suspended sediment concentration measured at 0.46 m (1.5 ft) below water surface covering the event of passage of three vessels. The following points may be noted in connection with the event shown in the figure:

a. The first vessel (Boat 4) was upbound (against current) and hence was using more power to navigate than the second (Boat 5), which was downbound (moving in the same direction as the riverflow).

b. The first vessel was a tugboat with a draft of 2.7 m (9 ft), pushing a set of 13 loaded rock barges with an overall length of 335 m (1,100 ft) whereas the second was a single 12-m- (40-ft-) long yacht, which was much smaller and lighter. Boat 6 was also a yacht, 11 m (35 ft) long.

c. Information on the speeds of the three vessels is not available; however, a tugboat moving several barges always travels much slower than a small pleasure craft such as a yacht.

d. The increase in suspended sediment concentration was higher (440 mg/L) with the passage of the first vessel than with the passage of the next two vessels (170 mg/L and 240 mg/L, respectively).

A wave gauge was located close to the OBS assembly on a tripod for measuring changes in water level, i.e., waves as well as drawdown. The wave sensor was located about 2 m (6.5 ft) below surface. It is seen from Figure 10 that the maximum wave heights generated by the three vessels were 0.08, 0.31, and 0.03 m, respectively. The drawdown caused by the three vessels was 16 cm, 2 cm, and 2 cm, respectively. Comparing the corresponding values of maximum wave height, drawdown, and suspended sediment concentration gives the following conclusions:

a. Large vessels generate large variation in water level (drawdown) and small wave heights but a high suspended sediment concentration.

b. Small vessels such as a yacht generate small drawdown, large wave heights, and a substantial increase in suspended sediment concentration.

Figures 12 and 13 show suspended sediment concentration observed at 2.1 and 2.4 m (7 and 8 ft), respectively, below water surface at the same station. Although sediment initially dispersed over the water column, a rapid settling of sediment and a sustained accumulation at lower depths are clearly seen. There is a substantial reduction in the peak values with water depth and increased oscillations in the values of suspended sediment concentration due to sustained turbulence in the water column subsequent to the events. It may be noted that over the entire duration of time from 1247 hours to 1447 hours shown in the three figures (11, 12, and 13), the time-average concentration remained about the same at 135 mg/L.

Another example of water level changes due to passage of a towboat carrying several loaded barges was seen at Range 3 in LaGrange Pool. The OBS assembly was deployed in 1.5 m (5 ft) water depth at this location as shown in Figure 14. The OBS sensors were mounted at 0.45, 1.1, and 1.4 m (1.5, 3.5 and 4.5 ft) below water surface. Particle size distribution of surface bed samples from this location is shown in Figure 15. Measured wave heights are shown in Figure 16, and suspended sediment concentrations at 0.45, 1.1, and 1.4 m (1.5, 3.5, and 4.5 ft) below water surface are shown in Figures 17, 18, and 19, respectively. Boat 2 was a tug with eight barges with a total length of 335 m (1,100 ft). It passed Range 3 at 0935 hours. The observations and conclusions drawn earlier for the passage of large vessels are confirmed by these measurements.

Wave Data Analysis

Physical model studies were conducted at CHL (Maynord and Martin 1997) in a 21-m- (70-ft-) wide, 122-m- (400-ft-) long flume by towing scale models of barges at different speeds. The resulting currents and waves were measured at several places within the simulated channel cross section. Also field data on wave heights and suspended sediment concentration were collected for several events of vessel passing.

Both the laboratory and field data on vessel-induced waves were processed at CHL. All waves smaller in height than 20 percent of the height of the maximum wave were filtered out, and the following statistical parameters were determined for each vessel-generated wave train:

a. Total number of waves in each event.

b. Maximum wave height during the wave train.

c. Average of the highest three waves.

d. Average height of all the waves.

e. Average period of all the waves.

The conclusions of the wave data analysis were as follows:

a. The background value of ripples was 2 cm. All the vessel-induced waves were greater than 2 cm in height.

b. The average wave period of all the waves may be taken as 2 sec. Any deviations from this value were not significant.

c. Each event consisted of about 200 waves on an average. With an average wave period of 2 sec, the duration of each event was considered to last for 420 sec or 7 min.

d. The train of wave heights reached the maximum value H_{max} at the end of 25 waves.[1] This was followed by a rapid decrease in wave height from H_{max} to H_{L1}, where H_{L1} was 20 percent of H_{max} or 5 cm, whichever is greater. This was reached after 75 waves. During the next phase, wave height decreased further at a slower rate until it reached a value of H_{L2}. For the present study, the value of H_{L2} was assigned to be 2 cm. This pattern is shown schematically in Figure 20.

The physical model tests were very useful in supplementing available field data and in determining a schematic wave pattern generated by barges being towed in restricted waterways. This pattern was then used for prediction of wave-induced suspended sediment concentration.

Sediment Shear Strength

The shear strength of an erodible cohesive sediment bed needs to be determined experimentally either in the field or in a laboratory. Correlations such as that between the dry/bulk density and shear strength are sometimes established based on a large number of tests conducted on site-specific sediment samples. At present no analytical procedure is available for obtaining the following exact values:

a. The critical shear stress for erosion.

b. The rate of erosion as a function of bed shear stress.

c. The erosion rate constant for any sediment, even if values of some of its properties are available.

A commonly used form of erosion equation is

$$E = \sigma\left(\frac{\tau_b - \tau_e}{\tau_e}\right) \qquad (1)$$

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[1] For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix B).

where

E = erosion rate

s = erosion rate constant

τ_b = bed shear stress

τ_e = critical shear stress for erosion

The erosion rate constant is the proportionality constant in the erosion rate equation. It is a sediment-specific empirical coefficient, which needs to be determined through laboratory or field tests. The critical shear stress for erosion is a function of several parameters such as the clay mineral, chemistry of pore fluid and eroding fluid, percent organic contents, water content, and so on. Hence it needs to be determined experimentally.

It is essential to conduct laboratory tests at least on a few sediment samples to determine these parameters and then use the results for making estimates for other samples from the same site.

Algorithm Outline

The sediment suspension model, VESTUNS, uses a one-dimensional (vertical (1DV)) numerical solution of the convection diffusion equation to compute the vertical profile of sediment. It accounts for sediment settling and deposition plus erosion from the bed and upward diffusion by short-period waves and/or a superposed current. It considers the bed to be formed of mud with significant quantities of cohesive material. VESTUNS is based on the model VEST (Mehta and Li 1996).

Vertical transport

The model solves the 1DV equation

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left(K \frac{\partial C}{\partial z} + W_s C \right) \qquad (2)$$

where

C = sediment mass concentration

t = time

z = vertical dimension

K = diffusion coefficient

W_s = sediment settling velocity

with the latter two parameters calculated from the following expressions:

$$K = \frac{a_w H^2 \frac{\sinh^2(kz)}{2\sinh^2(kh)} + \kappa u_* z\left(1 - \frac{z}{h}\right)}{(1+\alpha_0 R_i)^{\beta_0}} \tag{3}$$

$$W_s = \begin{cases} W_{sf} & C < C_{sf} \\ \dfrac{a\,C^{m_1}}{\left(C^2 + b^2\right)^{m_2}} & C > C_{sf} \end{cases} \tag{4}$$

where

α_w	= wave diffusion constant
H	= wave height
σ	= wave frequency
k	= wave number
h	= water depth
κ	= von Karman coefficient, taken to be 0.4
u_*	= shear velocity
α_0, β_0	= empirical coefficients
W_{sf}	= free settling velocity of sediment, determined by experiment
C_{sf}	= upper concentration limit on free settling
a, b, m_1, m_2	= empirical coefficients
R_i	= gradient Richardson number, given by

$$R_i = \frac{-g\dfrac{\partial\rho}{\partial z}}{\rho\left(\dfrac{\partial u}{\partial z}\right)^2} \tag{5}$$

where

g = acceleration of gravity

ρ = fluid density

u = horizontal velocity (current plus wave)

Initial and boundary conditions

The user specifies the initial concentration profile. Boundary conditions are zero concentration flux at the water surface and erosion/deposition flux at the bed F_n given by

$$F_n = \begin{cases} -W_s\, C_{bed} \left(1 - \dfrac{\tau_b}{\tau_d}\right) & \tau_b \le \tau_d \\ 0 & \tau_d < \tau_b < \tau_e \\ +s\,(\tau_b - \tau_e) & \tau_b > \tau_e \end{cases} \tag{6}$$

where

C_{bed} = sediment concentration just above the bed

τ_d = critical shear stress for deposition, determined by experiment

s and τ_e are given by

$$s = s_{\max} e^{-a_r \tau_e^{b_r}} \tag{7}$$

$$\tau_e = \alpha_e (\phi - \phi_e)^{\beta_e} \tag{8}$$

where s_{max}, a_r, b_r, α_e, and β_e are empirical coefficients, and ϕ is the solids weight fraction, with ϕ_e the critical value below which the mud behaves like a fluid. The model allows for fluidization of the bed by waves, but that feature was not employed in this application.

The bed shear stress is calculated from

$$\tau_b = \begin{cases} \dfrac{f_w}{2}\, \rho\, u_b^2 & \text{wave motion} \\ \dfrac{f_c}{2}\, \rho\, U^2 & \text{current} \end{cases} \tag{9}$$

where

f_w = wave friction factor

u_b = wave orbital velocity amplitude at the bed

f_c = current friction factor

U = depth-averaged current velocity

The wave friction factor f_w is given by

$$\frac{1}{4\sqrt{f_w}} + \log \frac{1}{f_w} = -0.08 + \log \frac{A_{ab}}{K_s} \qquad (10)$$

where K_s is the Nikuradse roughness parameter.

The wave parameter A_{ab} is given by

$$A_{ab} = \frac{a \cosh kh}{\sinh kh} \qquad (11)$$

and

$$f_c = 2g \frac{n^2}{h^{1/3}} \qquad (12)$$

where n = Manning’s roughness coefficient.

Solution method

Equation 2 is solved by an implicit finite difference scheme.

Model verification

The model was verified by comparing results with field observations of suspended sediment concentrations (Figures 11-13 and 17-19). Initial values for the several empirical parameters were selected from the literature or determined through laboratory experiments.

Laboratory Testing of Field Sediment

Nine surface sediment samples collected from the nearshore region were subjected to laboratory tests. The locations of collection are shown in Figures 21 and 22. The sample locations were selected to ensure that they contained a high percentage of clay because only the cohesive sediments require laboratory testing for their erosion characteristics.

Particle size distribution was determined using a Coulter Counter model LS100Q instrument. Results of particle size analysis are given in Figures 23-31.

Erosion tests were conducted using the Particle Entrainment Simulator (PES) at CHL. The sediment samples brought from the site were placed in the PES cylinder and tap water was used as the eroding fluid. The PES (Figures 32, 33, and 34) consists of a perforated disc placed horizontally in a Plexiglas cylinder containing sediment sample. Shear stress is imparted at the sediment-water interface by moving the disc vertically up and down by an electric motor. Samples of sediment suspended within the water column are drawn periodically from the cylinder to determine the suspension concentration. These data are used to compute the rate of erosion. By plotting the values of erosion rate E as a function of fluid-induced bed shear stress, the values of critical shear stress for erosion and erosion rate constant are determined. Each test generally provides two values of both the parameters, one in the lower range of bed shear stresses and the other in the higher range. Such tests were conducted on nine bed samples sent by the project authorities. Results of erosion tests on eight of the bed samples are given in Figures 35-37. The samples were also analyzed to determine the total organic content and bulk density. The results of all the tests are summarized in Table 1.

Sediment Classification

Results of laboratory analysis of sediment samples showed that the three parameters particle size, total organic content, and bulk density selected for this study had a wide variation as would be expected because the sample locations are separated by several miles. For erosion estimates, all samples were first classified under three groups: Group1-Cohesive, Group2-Cohesive, and Noncohesive. Each sample under the Group1-Cohesive and Group2-Cohesive was then assigned one of three erodibility labels, soft, medium, or hard, based on criteria of bed density and percentage of organic matter. By definition, sediment bed labeled as soft is easier to erode than the bed labeled medium. Similarly, sediment bed labeled medium is easier to erode than the bed labeled hard. In other words, a soft bed has a lower critical shear strength for erosion than that for the medium bed, and a medium bed has a lower critical shear strength for erosion than that for the hard bed. For the present purpose, the use of these terms is indicative of only the relative erodibility of sediment.

In order to group and label each sample, the following three-step approach was adopted:

a. *Step 1.* The samples were first separated into three categories based on the relative percentages of clay, silt, and sand obtained from particle size distribution.

(1) *Group1-Cohesive.* When the sediment has 70 percent or more particles finer than 4 microns ($D_{70} \leq 4$ microns).

(2) *Group2-Cohesive.* When the sediment has 70 percent or more particles finer than 62 microns or when the sample has more than 16 percent clay ($D_{70} \leq 62$ microns or $D_{16} \leq 4$ microns).

(3) *Noncohesive.* When the sediment contains more than 30 percent sand ($D_{70} \geq 62$ microns and $D_{16} \geq 4$ microns).

b. *Step 2.* The sediments were next separated based on the percentage of total organic contents.

(1) Low: when the total organic content is less than 5 percent.

(2) Medium: when the total organic content is 5 to 10 percent.

(3) High: when the total organic content is more than 10 percent.

c. *Step 3.* The last separation was done based on the sediment bulk density.

The sediment classification procedure is explained in Figures 38, 39, and 40, respectively, for the Group1-Cohesive sediments, Group2-Cohesive sediments and for the noncohesive sediments. Based on the results of laboratory erosion tests conducted on the samples from field, these three types of beds were assigned values of bulk density, critical shear strength, and erosion rate constant. These are shown in Table 2.

Only limited samples were available for the present study. None of these could be classified under Group1-Cohesive. It is expected that more samples from different reaches of the river will be collected in the future and there will be a need to classify them. Hence the classification system has been made comprehensive to meet this future requirement.

The following trends reported in literature on the properties of sediments have been taken into account while preparing Figures 38, 39, and 40:

a. Shear strength of a cohesive sediment bed generally increases with increasing bulk density (Owen 1970).

b. Erosion rate constant generally decreases with increasing bulk density (Hwang 1989).

c. Settling velocity for cohesive sediments is a function of suspension concentration (Parchure and Long 1993) in addition to other factors.

The settling velocity increases with increasing concentration of sediment in suspension between the range from about 50 mg/L to about 5,000 mg/L. This increase could be up to two orders of magnitude. For concentrations higher than about 5,000 mg/L, the settling velocity decreases with increasing concentration (Hwang 1989).

d. Erosion rate constant decreases with increasing bed shear strength (Lee and Mehta 1994).

e. Decreasing organic content generally correlates with increasing bed density (Lee and Mehta 1994). In other words, higher organic content decreases bed density.

f. Clay particles are smaller than 4 microns and silt is finer than 62 microns (Selley 1982).

g. Erosion rate of cohesive sediments is a function of flow-induced/wave-induced bed shear stress (Equation 1) among other factors. Laboratory tests on erosion of cohesive sediments often indicate two ranges of erosion rates and erosion rate constants, one in the lower range of bed shear stress and the other for the higher bed shear stress. Hence the same sediment may have two values of these two parameters (Parchure 1980).

4 Model Results

Ranges of Variables

The following ranges of variables were chosen for the study:

a. Wave height: 10, 20, 30, 40, 50, and 60 cm.

b. Wave period: 2 sec, constant for all waves.

c. Water depth: 0.5, 1.0, and 1.5 m.

d. Sediment types: clay, silt, and sand.

e. Sediment beds: soft, medium, and hard (in terms of resistance to erosion).

f. Sediment settling velocity: variable, depending on the type of sediment, and a function of initial concentration in the case of cohesive sediments.

g. Initial suspension concentration: variable.

h. Time interval between consecutive events of vessel passage: variable.

Estimation of Maximum Concentration

As mentioned earlier, a defined pattern of variation of heights in each wave train was developed for each value of maximum wave height H_{max}. It was necessary to use this time series of waves as input for computation of suspension concentration. However, the physical processes require a certain time to erode the sediment and to entrain it vertically within the water column before accepting the next set of wave conditions. Several trials with respect to the smallest duration for changing the wave conditions indicated that a minimum duration of 6 sec for the wave interval was required. Since the wave period was 2 sec, arithmetic averaging of three consecutive wave heights was performed and a new series was generated for each of the maximum wave heights. This did not make any significant change in the wave input. This may be seen from the comparison of Figures 41 and 42, which show the wave time series for the actual wave train and the averaged wave train, respectively, for a maximum wave height of 10 cm. Similar plots are given in Figures 43 and 44 for the maximum wave height of 60 cm. The averaged time series of waves was used as input for the algorithm for computing suspension concentration as a function of time. Although the program calculates suspension concentration at several elevations over the bed, depth-averaged values were computed and used throughout this report in view of the comparatively small water depth.

Out of 54 combinations of parameters *a* through *h*, three are illustrated in Figures 45, 46, and 47. The three parameters are (a) type of bed, (b) maximum wave height H_{max}, and (c) water depth *D*. These figures show the time variation of suspension concentration resulting from 60-cm waves in 1.5-m water depth for soft, medium and hard beds, respectively. The time series of waves consists of an initial phase of increasing wave heights leading to the maximum, followed by wave decay. This trend is reflected in the concentration graphs. Results of all the runs are presented in Tables 3, 4 and 5 for soft, medium, and hard beds, respectively. These values show the maximum value of suspension concentration for each condition. These tables are recommended for use for estimation of the maximum suspension concentration under different conditions. Linear interpolation may be used for values other than those listed. It may be noted that an X in the tables indicates wave breaking due to shallow water. The simplified criterion of $d_b/H_b = 1.28$ was used, where d_b is the wave-breaking water depth and H_b is the breaking wave height. The algorithm used for this study does not offer a solution under these conditions.

Effect of Background Concentration

All the model runs described earlier were conducted for the condition of zero background concentration of sediment in suspension. This is rarely the case in any natural environment. OBS data collected along the Mississippi River shown in Figures 48 and 49 indicate background concentrations of the order of 18 and 110 mg/L, respectively. Changes in the magnitude of background concentration are due to several factors such as freshwater discharge, wind and wave action, or temporary disturbance caused by a passing vessel. Model runs were conducted for five different magnitudes of initial concentration (0, 30, 60, 90, and 120 mg/L) for a maximum wave height of 60 cm on a soft bed in 1.5-m water depth. The concentration versus time curve obtained for the condition of zero background concentration is given in Figure 50 and the effect of four other values is given in Figures 51-54. A comparison of the maximum values revealed that the maximum concentration in each case was the concentration for the corresponding wave height plus the initial concentration. Although such addition is not expected to provide accurate results in other situations, the reasons for the simple answer in the present case are likely to be as follows: the wave height increases very rapidly from 2 cm to the maximum value within less than a minute. This continually adds sediment to the suspension. Due to relatively high levels of turbulence, the suspended sediment does not deposit during the period of growth of wave heights; hence the magnitude of initial concentration gets added to the maximum value that would have been reached with zero background concentration.

Sediment Deposition

Figure 55 shows field measurements indicating that a background concentration of about 110 mg/L increased to 370 mg/L very rapidly when a vessel passed by. Then the concentration reduced rather slowly, requiring almost an hour to get back to the background level. This is typical of suspension of fine sediments because a relatively small level of turbulence is sufficient to prevent them from settling. On the other hand, a rapid deposition shown in Figure 56 is typical of noncohesive sediments.

When cohesive sediments are in suspension, flocculation of primary mineral particles leads to formation of aggregates. The formation rate, size, and density of these aggregates is a function of several factors such as water chemistry, type of clay mineral, level of turbulence, interparticle collision frequency, and the magnitude of suspension concentration. The rate of deposition of cohesive sediment is calculated by a rather complicated sediment deposition module of the algorithm (Mehta and Li 1996), which finally gives the magnitude of suspension concentration as a function of time. The algorithm was used to compute suspension concentration at the end of 1 hr starting with the following concentrations: 1,500, 1,300, 1,100, 800, 525, 430, 210, 110, 55, 27, 10, and 5.5 mg/L. The results are presented in Table 6.

At higher concentrations of suspension, the interparticle collision frequency is high, leading to larger flocs, which settle rapidly, and the suspension concentration reduces rapidly. This may be seen from Figure 57. The initial concentration of 1,500 mg/L reduced to 290 mg/L (reduction by 81 percent) at the end of 1 hr. At lower concentrations such as that shown in Figure 58, the concentration dropped from 430 to 190 mg/L (reduction by 56 percent). At very low concentrations, the particles settle separately, the drop is quite small, and the settling process is close to linear as may be seen from Figure 59. With an initial concentration of 27 mg/L, the concentration after 1 hr was 24 mg/L (reduction by 11 percent). An approximate correlation between the initial concentration and the concentration after 1 hr was established by plotting the tabulated values in the form of a graph, which is shown in Figure 60. A simplified version of the same two parameters is given in Figure A4 (Appendix A).

Model Verification

Field data on total suspended solids (TSS) and on the vessel-induced wave heights were collected at the site by the CHL team. These data were available predominantly for deep-water locations. One of the few shallow-water locations was at Range 3, LaGrange Pool, where the measurements were taken in a water depth of 1.5 m (5 ft). These measurements showed that for a vessel-induced maximum wave height of 30 cm, the maximum suspension concentration at an elevation of 1.1 m (3.5 ft) above the bed changed from the ambient magnitude of 125 mg/L to 150 mg/L, thus giving an increase of 25 mg/L. Measurements taken at 0.2 m (0.5 ft) and 0.46 m (1.5 ft) above the bed were somewhat ambiguous in demarking vessel impact. The corresponding computed value using the algorithm was 51 mg/L, which was considered satisfactory for the purposes of this investigation.

A better comparison in the form of a time series of suspension values was not expected to be achieved because of the following possible reasons for deviation between the two data sets:

a. The actual time series of waves in the field is somewhat different from the synthesized wave series used for the model for a value of maximum wave height.

b. The average erosional properties assigned to the model bed are somewhat different from the properties of a site-specific sediment.

c. The presence of suspended organic particulates in water influences the settling rate.

Applications

The following fundamental questions need to be answered:

a. Is the sediment at any given location susceptible to erosion as a result of vessel-induced waves?

b. If it is erodible, what is the expected value of maximum sediment concentration in suspension?

c. How long will the sediment remain in suspension?

The present study helps in providing answers to all of these questions. The possible impact on vegetation or benthic organisms could then be evaluated separately. A procedure for answering the following issues has been explained in Appendix A through solved examples.

Classification of a bed sediment sample based on its relative erodibility

The present study is related to a very large area along the Mississippi River. As would be expected, the sediment in different reaches of the river shows considerable variation. Standard classification procedures available in literature could not be applied for two reasons: (a) they are based predominantly on particle size distribution and provide about 10 to 15 nomenclatures with a finer level of subdivisions; and (b) the standard classification system does not include the aspect of relative erodibility and the effect of related parameters such as organic content and bed density.

Under this project, a major task consisted of placing all the crucial data and information related to the Mississippi River into a Geographical Information System (GIS). This included hydrological, biological, and geographical information, which will be immensely useful for numerical modeling at a later date. Type of sediment along the banks of the river was required to be included in the GIS database using the limited field data on bed sample analysis. This classification was required to be oriented to the erodibility of near-bank sediment. Hence a customized classification procedure has been developed in this study.

Estimation of vessel-induced wave height

Passage of a vessel through a waterway generates a time series of waves. The pattern and magnitude of such waves are functions of a large number of parameters including the type of vessel, type of bow, vessel speed, water depth, keel clearance, physical dimensions of vessel, waterway geometry, fraction of waterway area occupied by the vessel, and distance of the vessel from bank line. A simple procedure for estimating the maximum wave height has been offered by Knight (1999). A generalized pattern based on the wave data analysis is given in this report. Under this procedure, the requirement of using the entire variable wave train has been eliminated by correlating it to a single parameter, the value of maximum wave height.

Estimation of maximum suspended sediment concentration

Wave action generates bed shear stress, which in turn may or may not result in sediment suspension depending upon the relative magnitudes of wave-induced bed shear stress and the bed shear strength. The relationship between wave height and bed shear stress is nonlinear. The sediment classification procedure proposed in this study takes care of providing an appropriate value of the bed shear strength. Once the magnitude of the maximum wave height is estimated, look-up tables are used to estimate maximum suspension concentration.

Effect of background (ambient) suspension concentration

The amount of sediment remaining in suspended form within a water column depends on the net result of sediment erosion and sediment deposition. The rate of deposition of cohesive sediment depends upon the suspension concentration. Since the background concentration influences the sediment deposition rate, its impact has been assessed.

Estimation of decrease in suspension concentration resulting from deposition without waves

A graph constructed with the results of model runs provides an easy way to estimate the decrease in suspension concentration after any variable duration starting with a known concentration.

Estimation of time needed for the suspension concentration to drop back to the background magnitude of concentration

Instead of estimating the magnitude of concentration after a given time, the time required for the initial concentration to drop to a given value such as the background concentration can also be easily determined with the use of a graph provided in the report.

Effect of passage of next vessel before the suspended sediment resulting from the previous vessel drops down to background value

A variety of vessels will navigate the waterway in a random sequence, and the time interval between consecutive passages of vessels will also be variable. In other words, the magnitudes of maximum wave heights as well as the duration of zero wave condition will be variable. Running the algorithm for given sets of conditions is of course one way of providing the required answer; however, it is time-consuming, expert oriented, and tedious. Hence, a simpler procedure is offered to handle this problem.

Entrainment of noncohesive sediment and time required for settling

The present study is oriented mainly to the aspect of the environmental impact of suspended sediment. Hence fine sediments are the main concern. Coarse or noncohesive sediment may not be of primary concern because of two reasons:

a. They require a higher bed shear stress to place bed sediment in suspension, and most of the small, vessel-induced waves may not have adequate energy to suspend them.

b. Even if they are suspended, they deposit back to the bed quickly, do not form flocs, and do not block sunlight to the same extent as the fine sediments due to their low specific surface area.

However, to be able to evaluate the possibility of suspension and the duration of stay in suspension of noncohesive sediments, diagrams have been provided from which values can be read easily.

Effect of multiple parameters

The present model is very versatile in its use. Effects of several relevant parameters such as wave height, wave period, time interval between consecutive vessels, water depth, type of vessel, characteristics of vessel, or sediment properties can be evaluated from the use of this model. For example, evaluation of the effect of boat type and frequency of passage is described in the following paragraphs.

The towboat traffic in the Mississippi River has a relatively very low frequency. On the other hand, in certain reaches of the river very popular for recreation, the number of recreational boats in the area on popular summer holidays can be very high. Although the recreational boats are small in size, their higher speed and higher frequency of occurrence can result in an impact that may be more severe than that of the towboats.

The frequency of boats (or the time interval between passage of consecutive boats) has a profound impact on the sediment suspension concentration because the sediment already in suspension starts depositing as soon as the wave height becomes near zero. The deposition continues until the commencement of the next series of waves. The longer the time interval between the consecutive vessel-generated waves, the greater the amount of sediment deposition. Thus the effect of a wave series is to generate cycles of erosion and deposition of sediment. The computer-generated results show that this cyclic phenomenon with a fixed periodicity results in maintaining a time-averaged equilibrium concentration in suspension, which is the most significant in the context of the present study.

The resuspension model presented here has been used for estimating suspension concentration resulting from passage of a single barge as well as from the passage of multiple recreational vessels. The effect of a single event consisting of a barge-generated maximum wave height of 60 cm is shown in Figure 61. The effect of multiple recreational boats, each generating a 40-cm wave height, is shown in Figure 62.

5 Conclusions

Existing methods for predicting wave-sediment interaction for cohesive sediment are complex. A simple approach should suffice for a preliminary estimation needed in the context of near-bank erosion of the Mississippi River.

Existing methods used for predicting transport of noncohesive sediment under wind-generated waves are not directly applicable for predicting sediment transport under vessel-generated waves. A revised approach is provided for this purpose.

This report presents the basic mathematical expressions and a recommended approach for estimating sediment resuspension under vessel-generated waves.

The proposed approach can be used for a reasonable prediction of wave-induced near-bank erosion with cohesive or noncohesive sediments without the effect of vegetation on the banks. Due to the complexity of real-life situations and necessary simplification of the physical phenomena, the model may not give exact answers for a given site. However, it does provide consistent and reasonable estimates of suspension concentration values for evaluation of environmental impacts over large reaches of the river.

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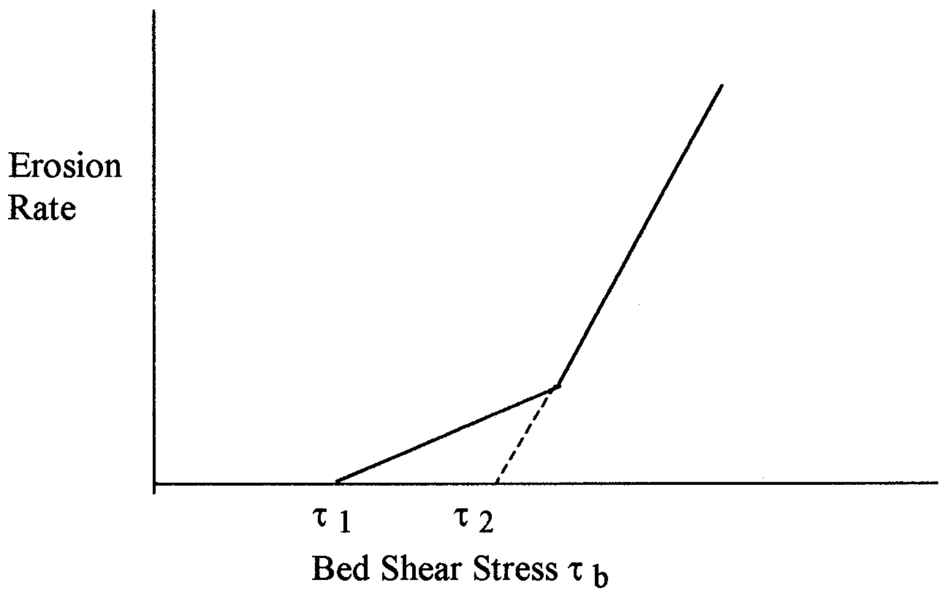
Explanation of Laboratory Results Reported in Table 1

A commonly used form of erosion equation is

$$E = s\left(\frac{\tau_b - \tau_e}{\tau_e}\right) \tag{1}$$

In this equation E is the erosion rate, s is the erosion rate constant, τ_b is the bed shear stress, and τ_e is the critical shear stress for erosion. The erosion rate constant s is the proportionality constant in the erosion rate equation. Typical results of laboratory tests are shown in the figure below.



τ_1 and τ_2 show the two values of critical shear stress. s_1 and s_2 represent the two values of Erosion Rate Constant associated with each of these. Table 1 gives the results of laboratory tests giving values of τ and s for the samples tested.

Table 1
Erosion Rate Parameters of Bed Samples Obtained from Laboratory Measurements

Sample Number	Bulk Density kg/m^3	Organic Content %	% by Weight Finer Than 4 Microns	% by Weight Finer Than 62 Microns	Critical Shear Stress P_a τ_1	Erosion Rate Constant m_1, g/m^2/min	Critical Shear Stress P_a τ_2	Erosion Rate Constant m_2, g/m^2/min
6606	1873	3.18	20.85	77.2	> 0.6	No erosion at 0.6 Pa	> 0.6	No erosion at 0.6 Pa
6701	1840	2.60	13.18	53.5	< 0.10	0.1	> 0.5	N.A.
6702	1731	4.25	25.97	81.3	< 0.10	0.2	0.38	4.46
6932	1966	1.71	6.19	24.7	< 0.20	0.1	0.39	1.87
6759	1638	3.36	12.82	52.4	< 0.20	0.2	0.37	1.22
6876	1625	3.54	8.09	40.6	< 0.3	0.2	0.38	5.89
6556	1492	4.03	21.46	79.3	0.16	1.0	N.A.	N.A.
6704	1807	3.12	21.63	61.8	< 0.10	0.03	0.48	1.49
6964	1802	3.91	24.71	80.2	< 0.20	0.1	0.36	1.33

Note: Equation 1 was used to calculate erosion rate.

Table 2
Values Assigned to Bed Parameters

Erodibility Label	Bulk Density, kg/m^3	Critical Shear Stress P_a τ	Erosion Rate Constant S, g/m^2/min
Soft	1600	0.021	6.27
Medium	1900	0.147	2.06
Hard	2000	0.458	0.53

Table 3
Estimated Depth-Averaged Maximum Suspension Concentration, mg/L, for Soft Soil

Water Depth m	Maximum Wave Height H_{max}, cm					
	10	**20**	**30**	**40**	**50**	**60**
0.5	241	700	1463	**X**	**X**	**X**
1.0	13	102	218	384	610	890
1.5	0	17	51	95	151	217

Note: **X** = wave breaking due to shallow water.

Table 4
Estimated Depth-Averaged Maximum Suspension Concentration, mg/L, for Medium Soil

Water Depth m	Maximum Wave Height H_{max}, cm					
	10	**20**	**30**	**40**	**50**	**60**
0.5	4	23	56	**X**	**X**	**X**
1.0	0	2	7	14	24	36
1.5	0	0	1	2.4	5	8

Note: **X** = wave breaking due to shallow water.

Table 5
Estimated Depth-Averaged Maximum Suspension Concentration, mg/L, for Hard Soil

Water Depth m	Maximum Wave Height H_{max}, cm					
	10	20	30	40	50	60
0.5	0	1	4	**X**	**X**	**X**
1.0	0	0	1	1	2	3
1.5	0	0	0	1	1	1

Note: **X** = wave breaking due to shallow water.

Table 6
Initial Suspension Concentration and Concentration after 1 hr of Sediment Deposition

Initial Concentration mg/L	Concentration after 1 hr mg/L
0	0
5.5	5
10	9
27	24
55	47
110	90
210	148
430	190
525	243
800	252
1,100	310
1,300	280
1,500	290

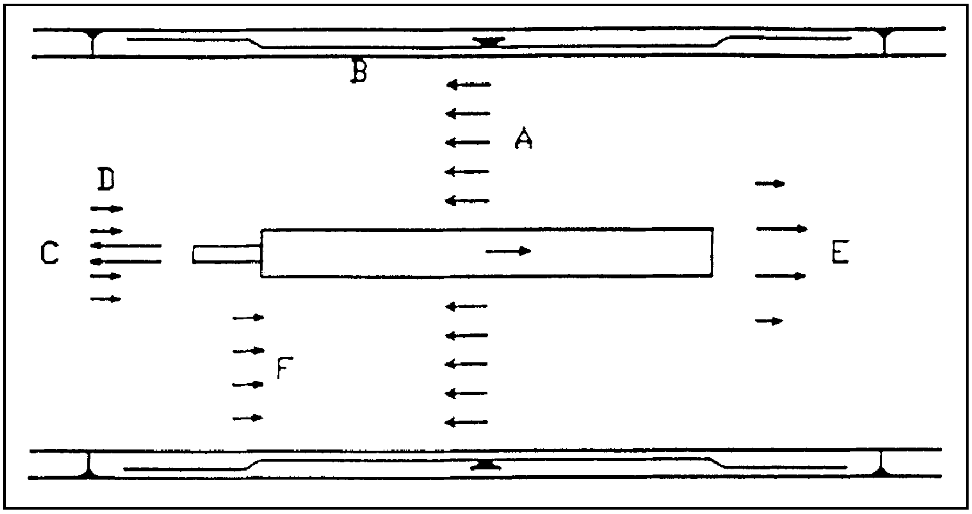


Figure 1. Navigation effects: *A* = return velocity; *B* = drawdown; *C* = propeller jet; *D* = wake flow; *E* = bow wave; and *F* = slope supply flow (from Maynord 1996)

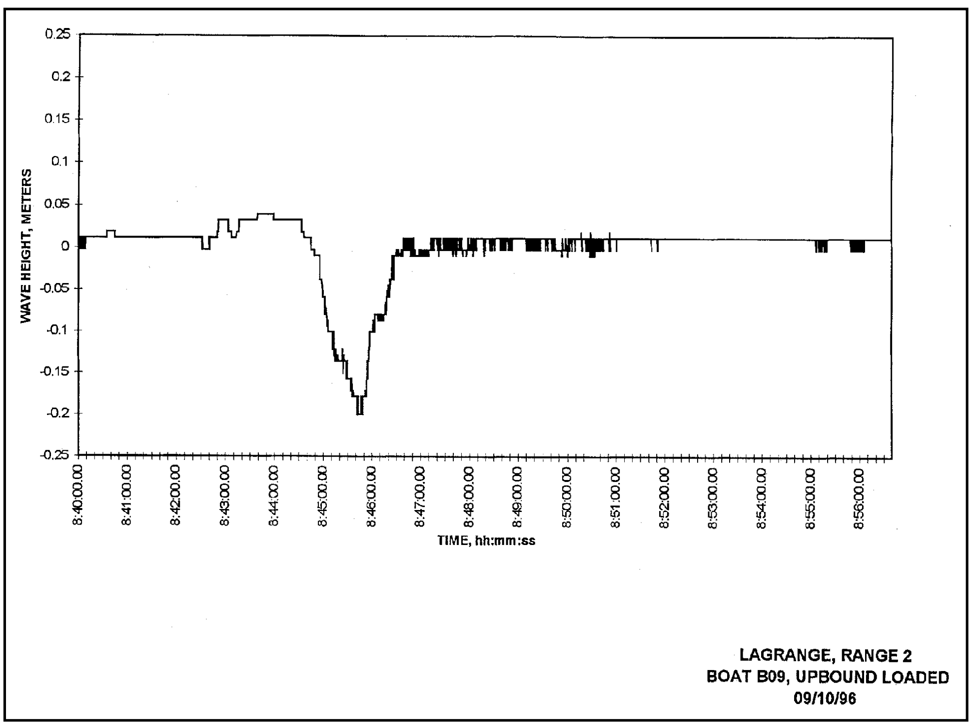


Figure 2. Drawdown due to passage of vessel, Illustration 1

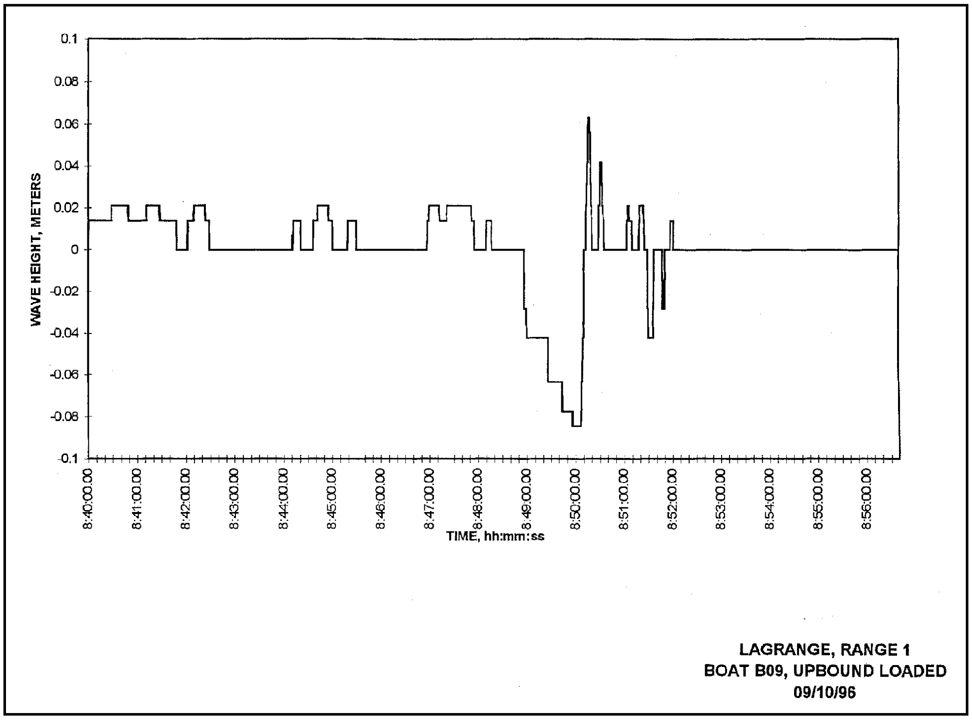


Figure 3. Drawdown due to passage of vessel, Illustration 2

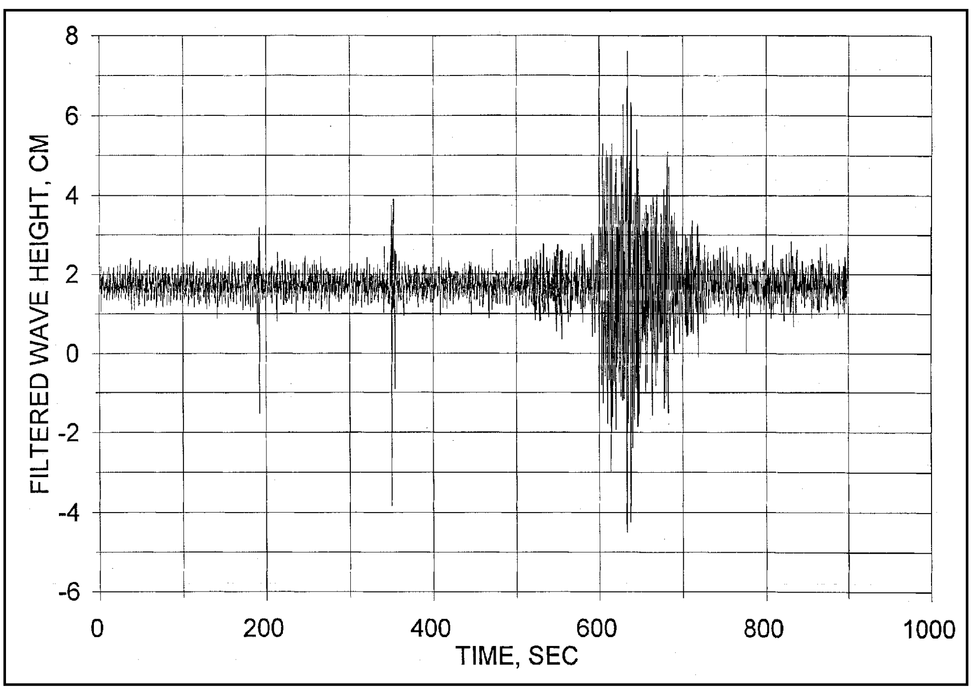


Figure 4. Vessel-generated waves, Illustration 1. (Water level fluctuations with period greater than 10 sec were filtered out)

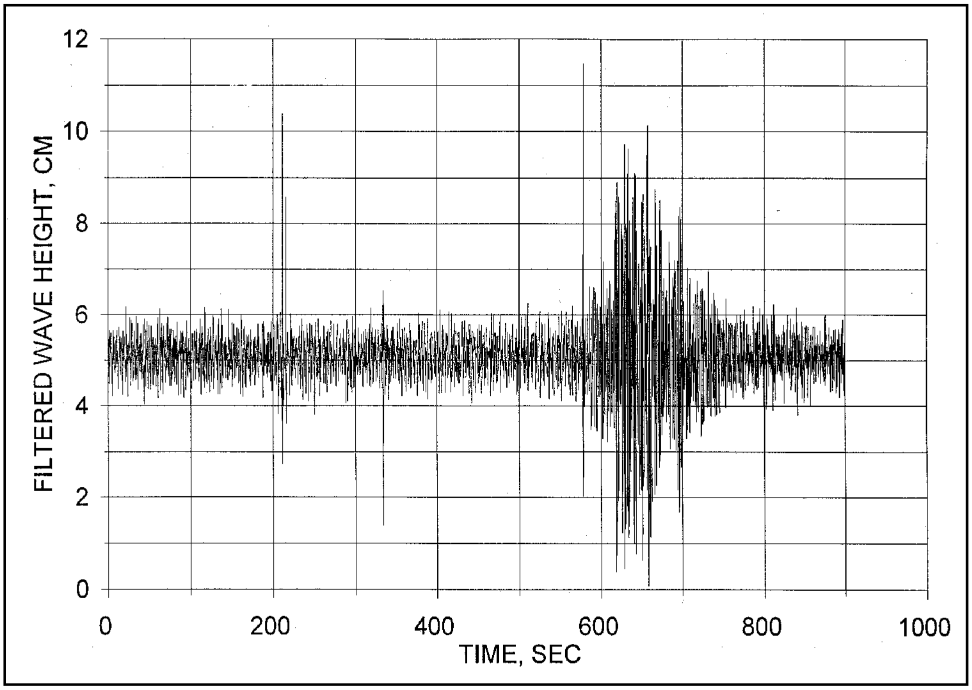


Figure 5. Vessel-generated waves, Illustration 2. (Water level fluctuations with period greater than 10 sec were filtered out)

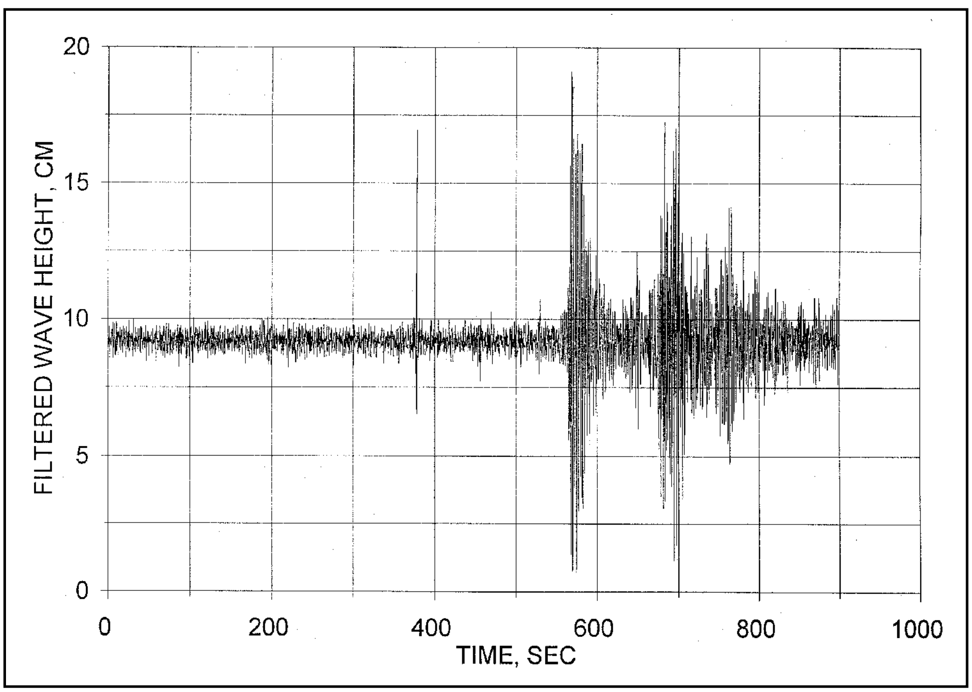


Figure 6. Vessel-generated waves, Illustration 3. (Water level fluctuations with period greater than 10 sec were filtered out)

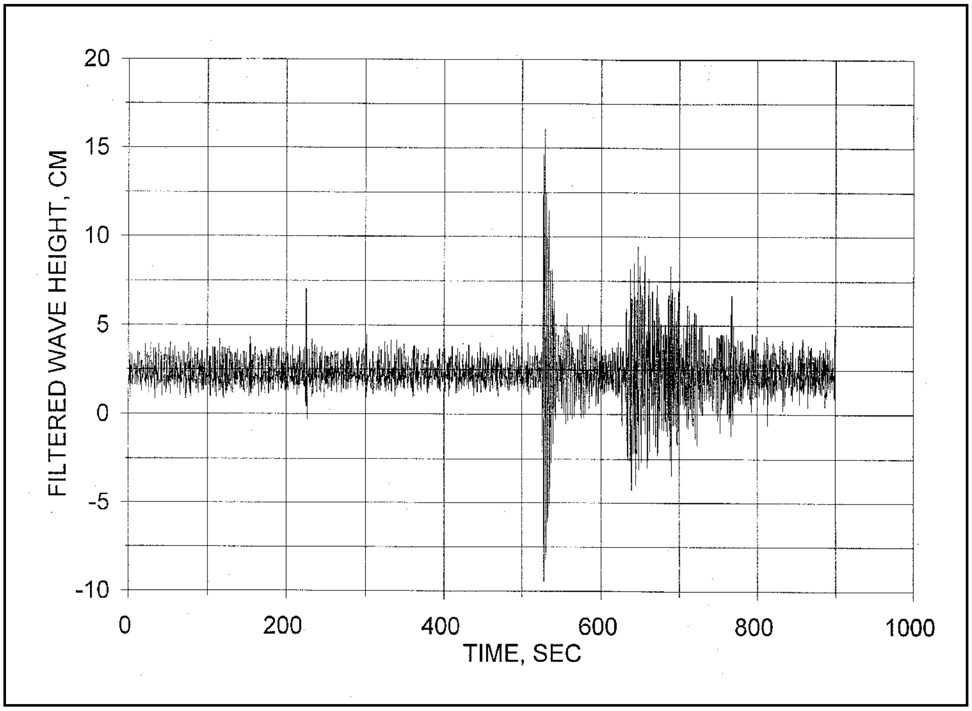


Figure 7. Vessel-generated waves, Illustration 4. (Water level fluctuations with period greater than 10 sec were filtered out)

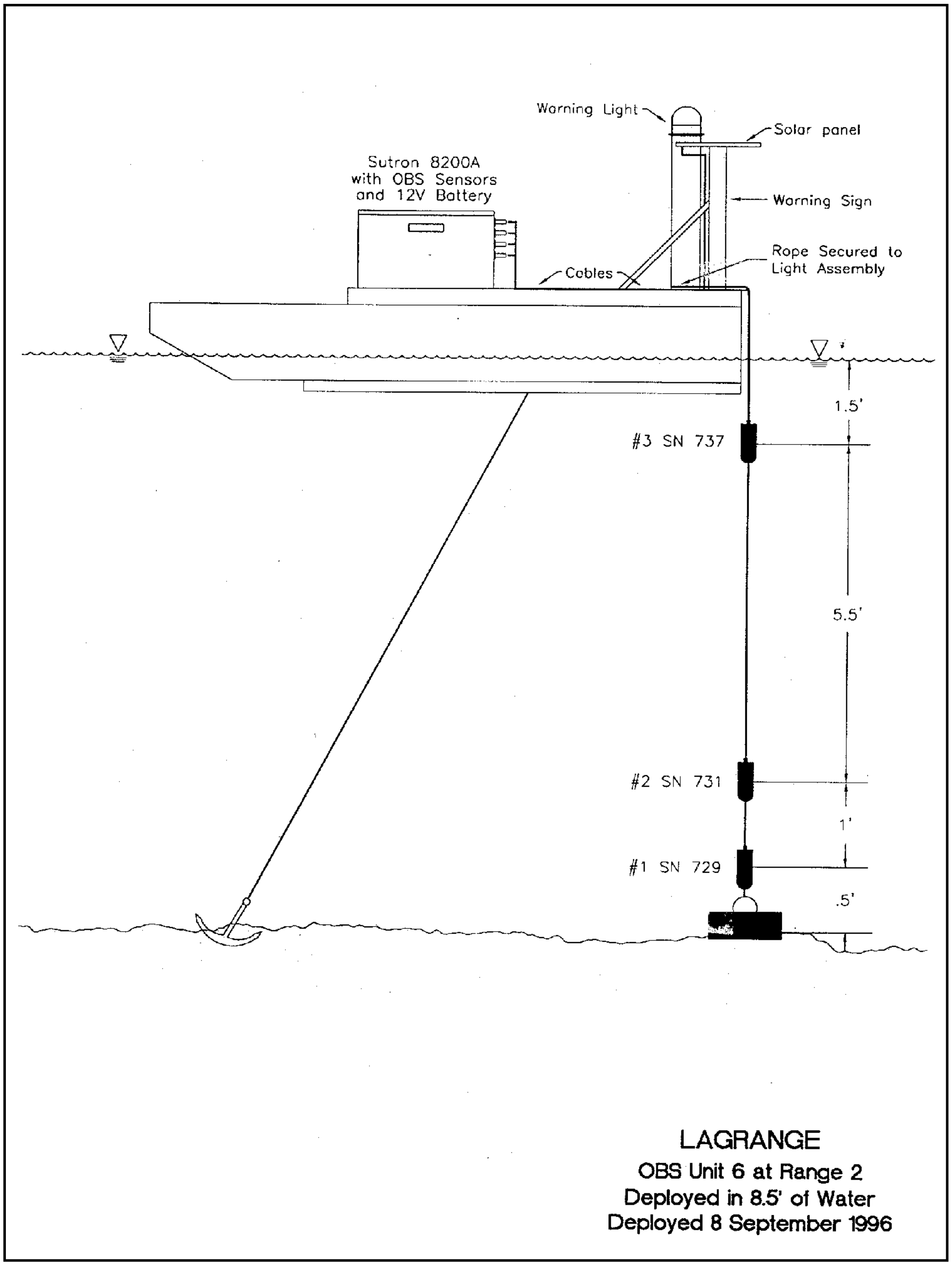


Figure 8. Field mooring at Range 2, LaGrange Pool (from Pratt and Fagerburg 1998)

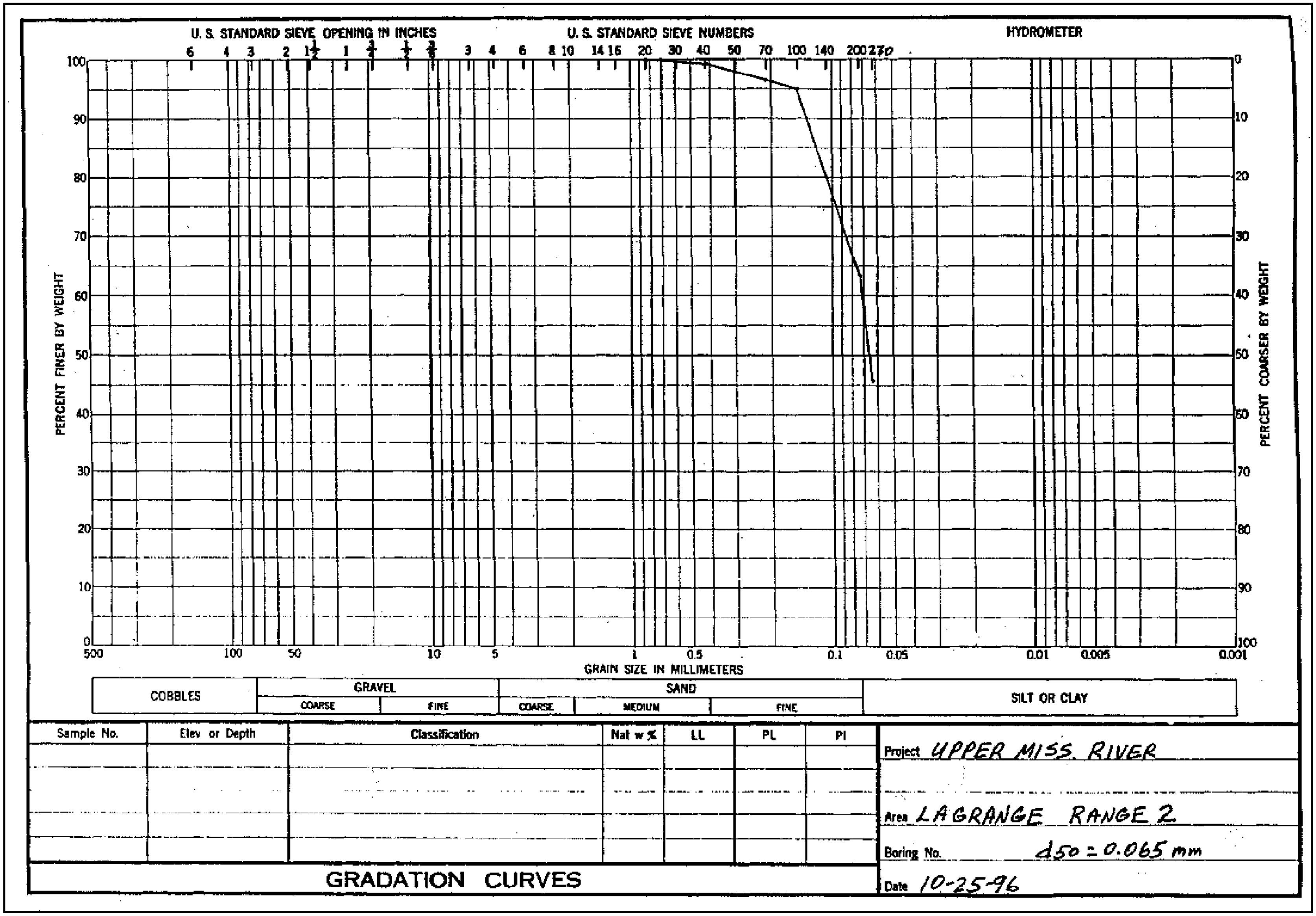


Figure 9. Particle size distribution of sediment sample collected at Range 2, LaGrange Pool

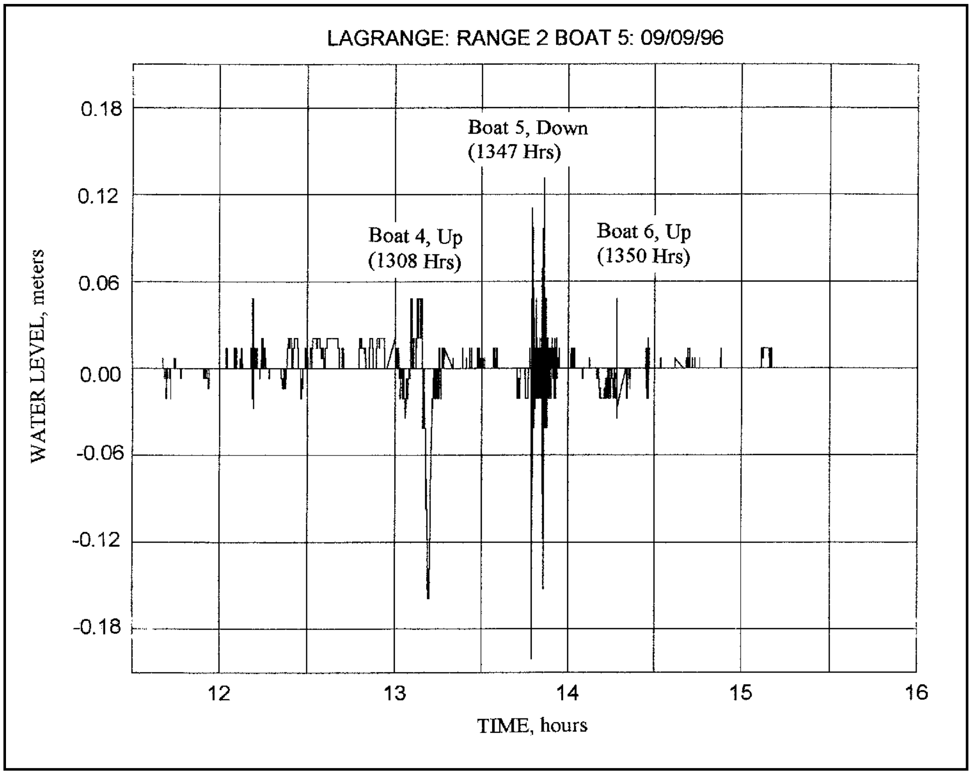


Figure 10. Changes in water level caused by passage of vessel at Range 2, LaGrange Pool (after Pratt and Fagerburg 1998)

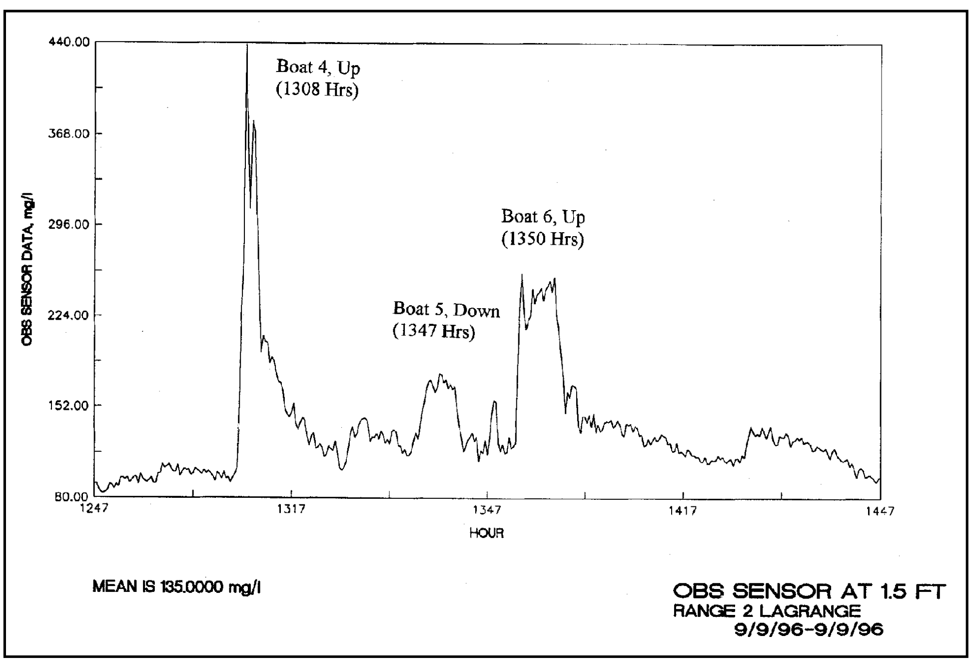


Figure 11. Suspended sediment concentration at 0.46 m (1.5 ft) below water surface at Range 2, LaGrange Pool (after Pratt and Fagerburg 1998)

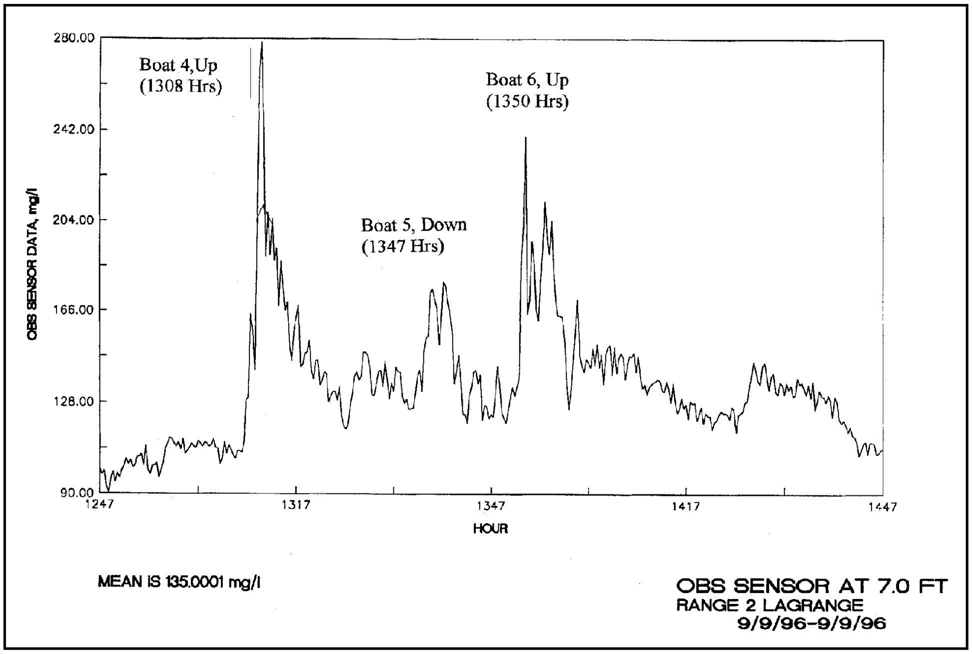


Figure 12. Suspended sediment concentration at 2.1 m (7.0 ft) below water surface at Range 2, LaGrange Pool (after Pratt and Fagerburg 1998)

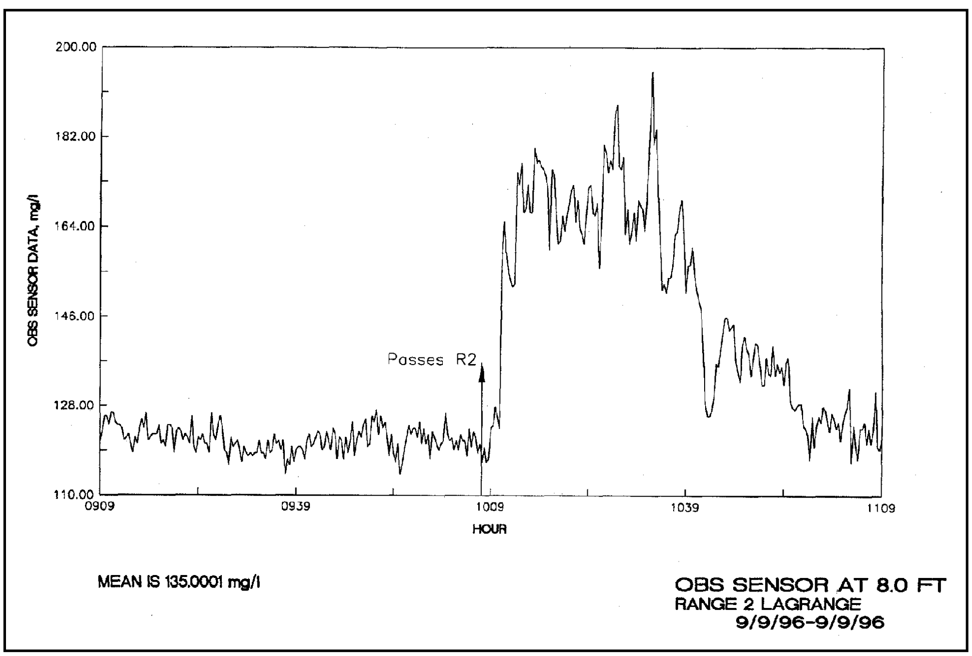


Figure 13. Suspended sediment concentration at 2.4 m (8.0 ft) below water surface at Range 2, LaGrange Pool (from Pratt and Fagerburg 1998)

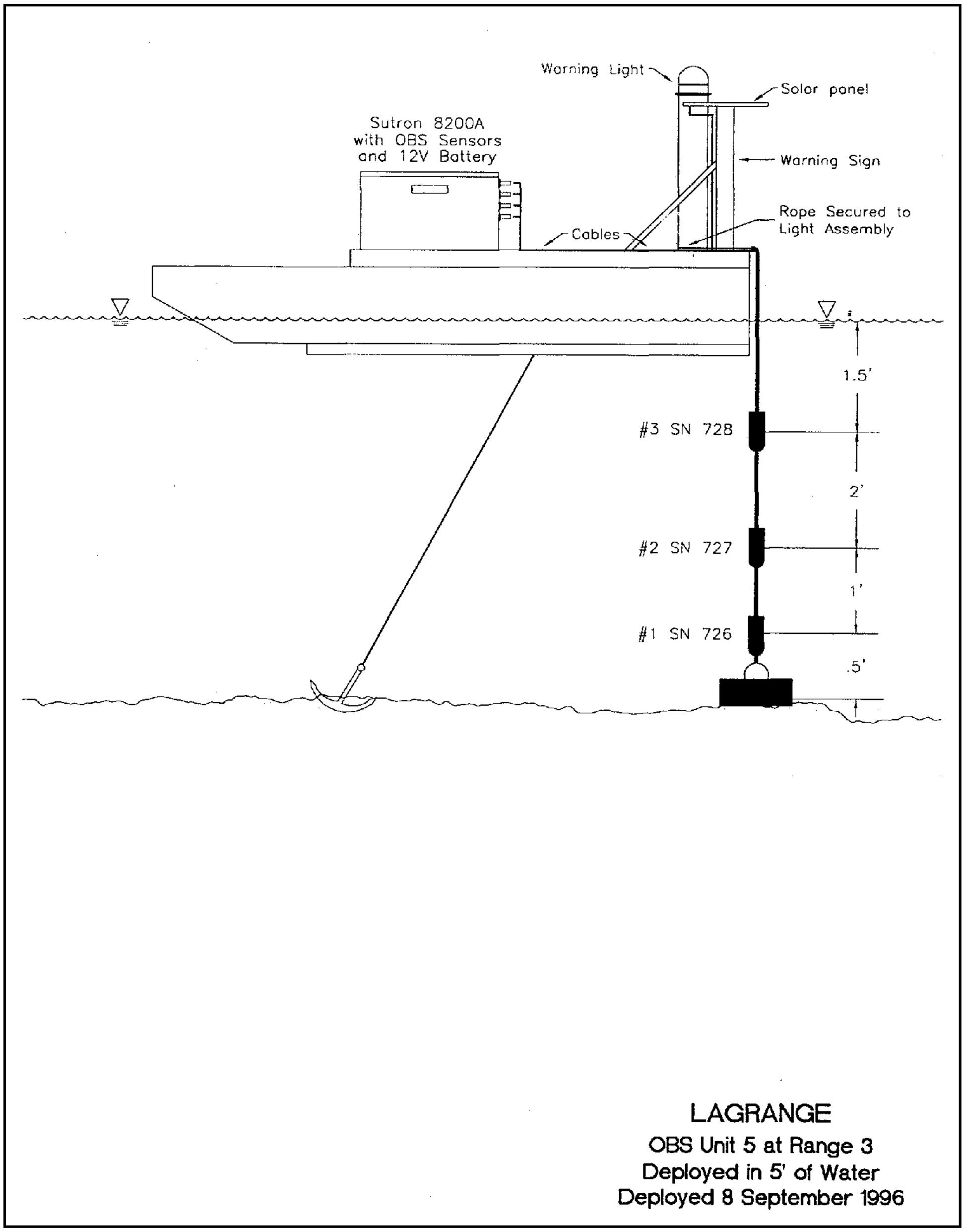


Figure 14. Field mooring at Range 3, LaGrange Pool

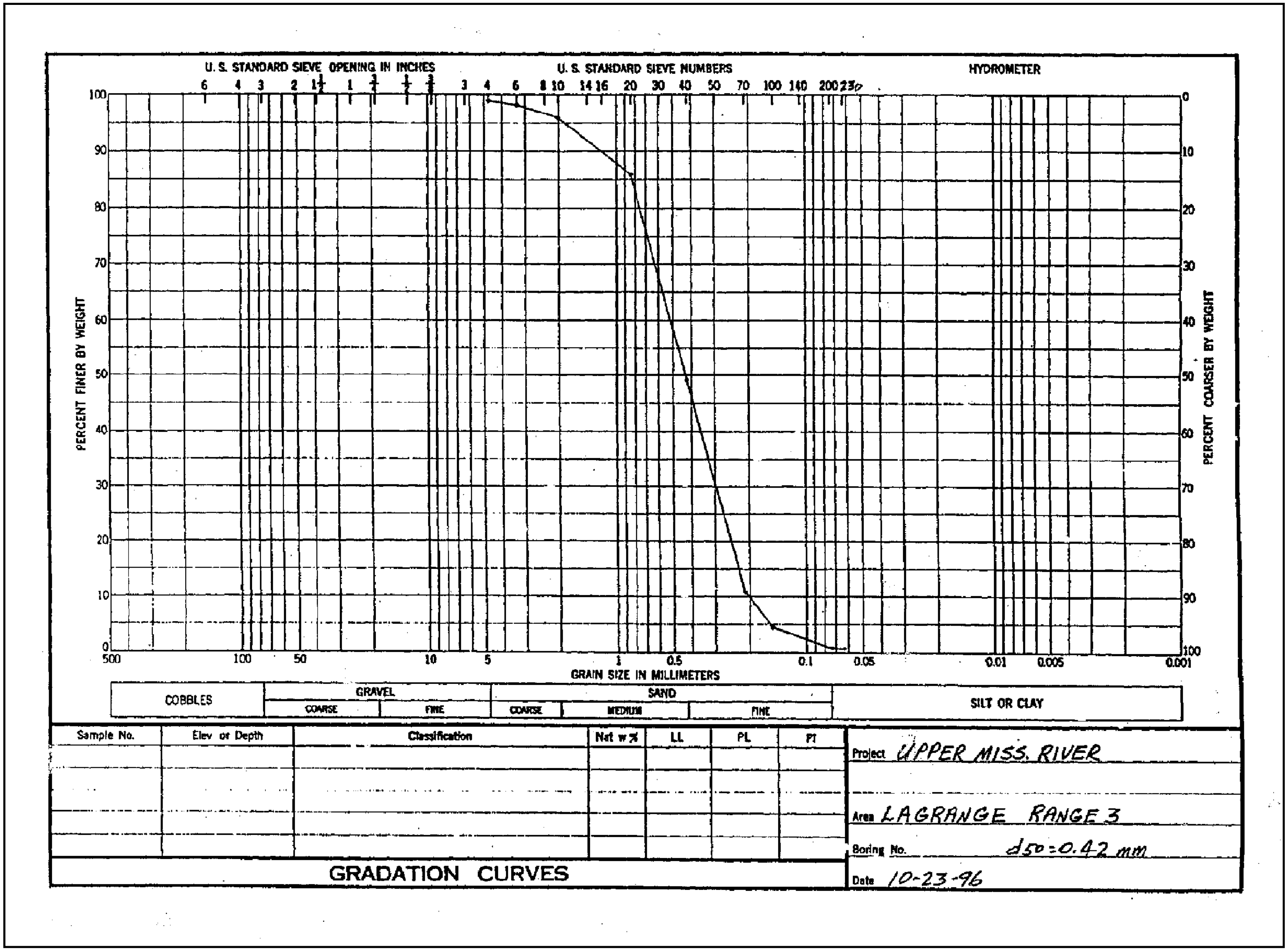


Figure 15. Particle size distribution of sediment sample collected at Range 3, LaGrange Pool

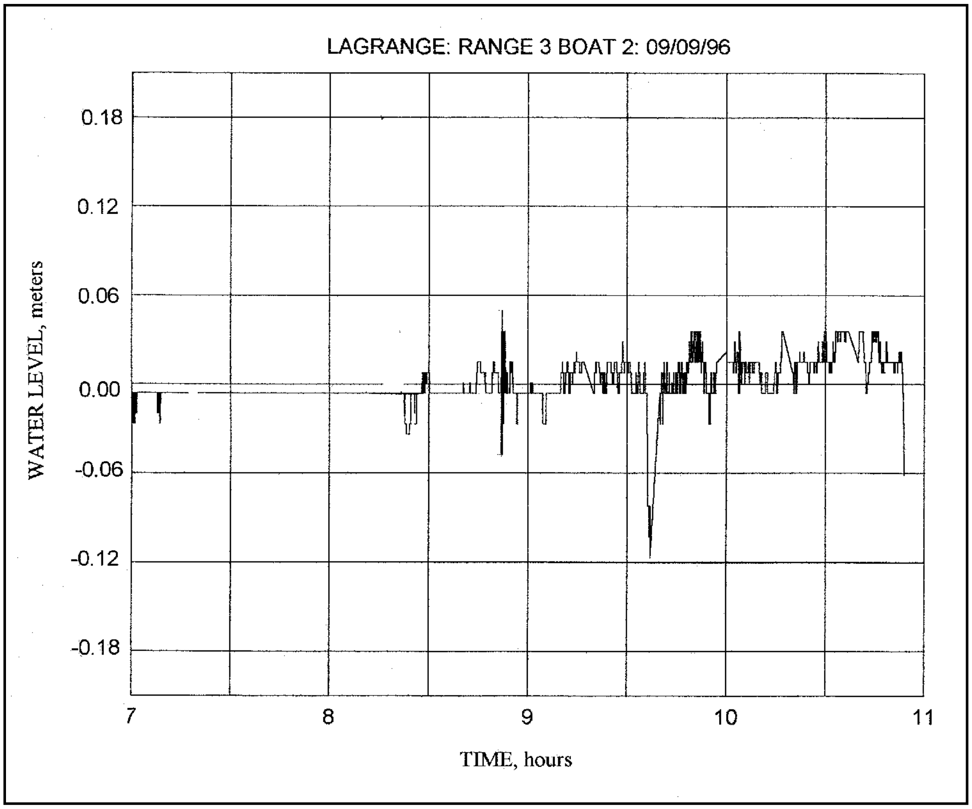


Figure 16. Changes in water level caused by passage of vessel at Range 3, LaGrange Pool

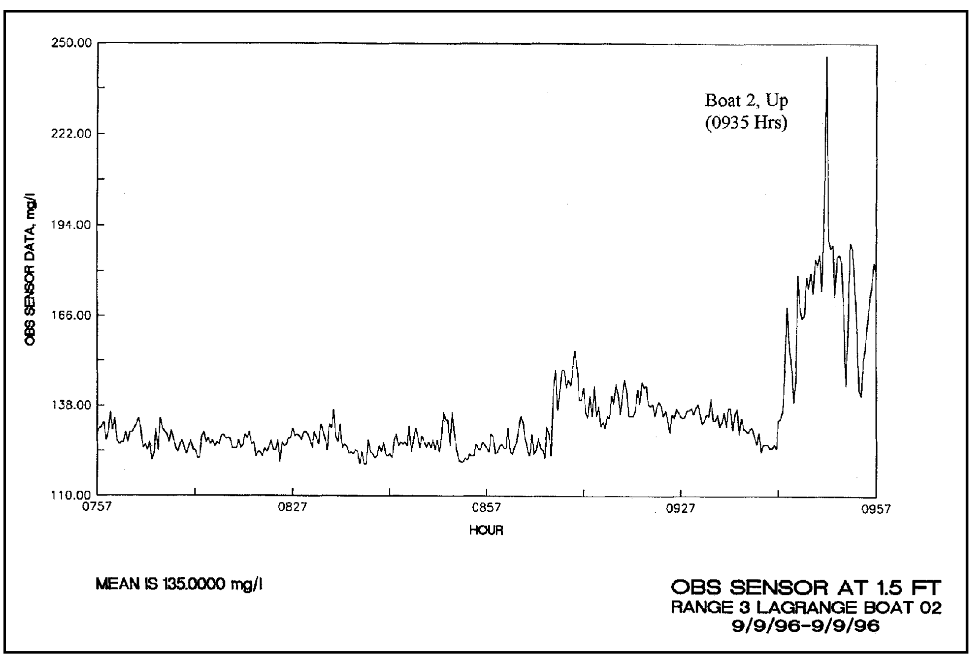


Figure 17. Suspended sediment concentration at 0.45 m (1.5 ft) below water surface at Range 3, LaGrange Pool

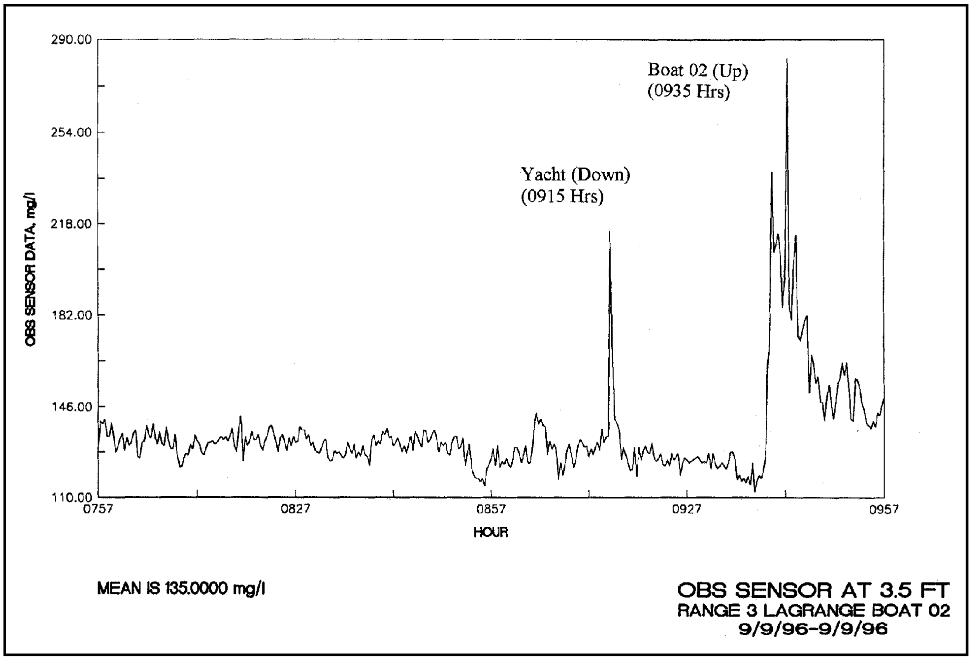


Figure 18. Suspended sediment concentration at 1.1 m (3.5 ft) below water surface at Range 3, LaGrange Pool

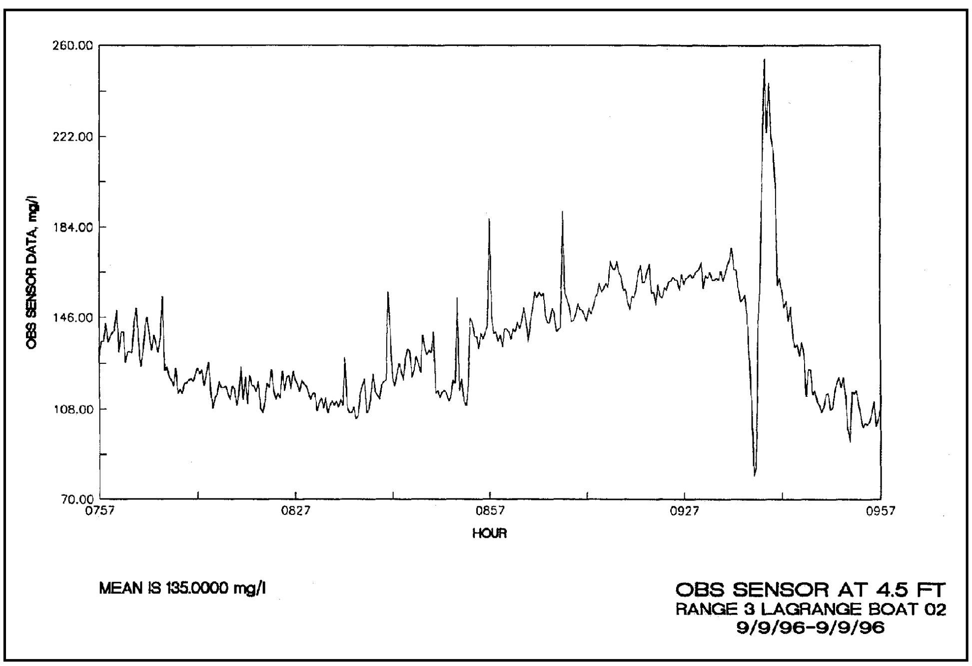


Figure 19. Suspended sediment concentration at 1.4 m (4.5 ft) below water surface at Range 3, LaGrange Pool

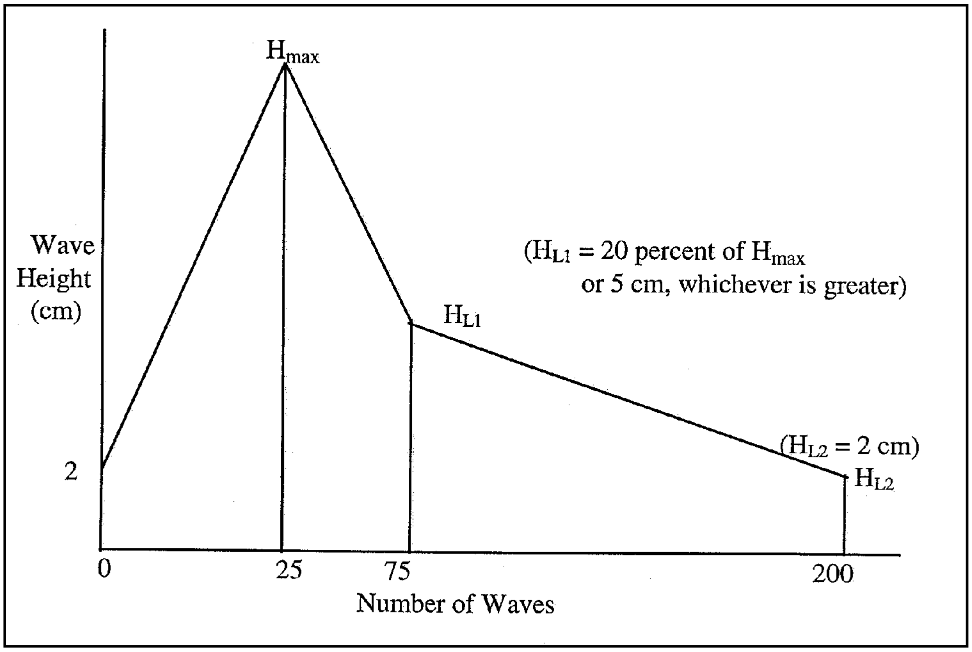


Figure 20. Schematic drawing showing growth and decay of vessel-generated waves

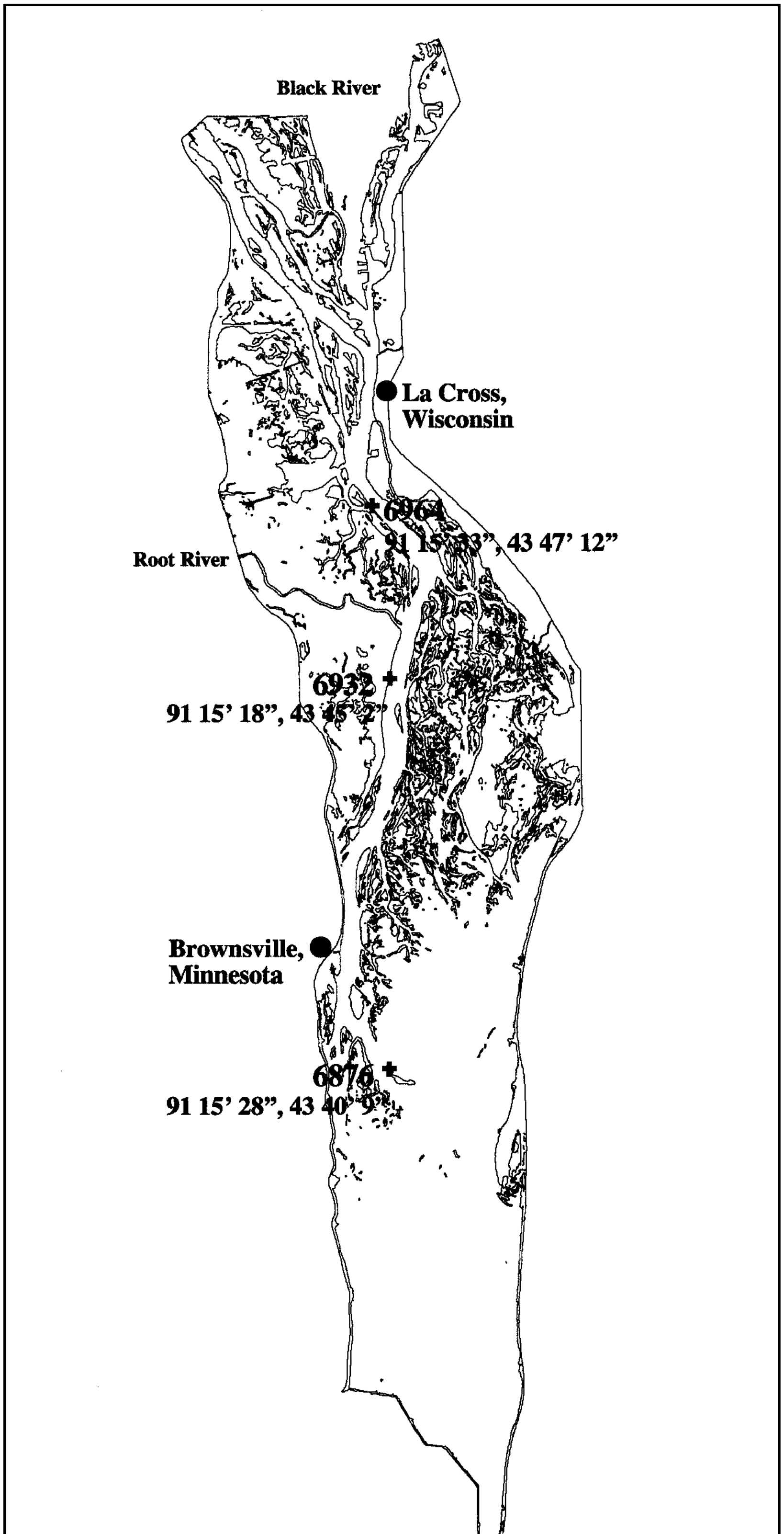


Figure 21. Locations of sediment samples (6964, 6932, 6876) in Pool 8

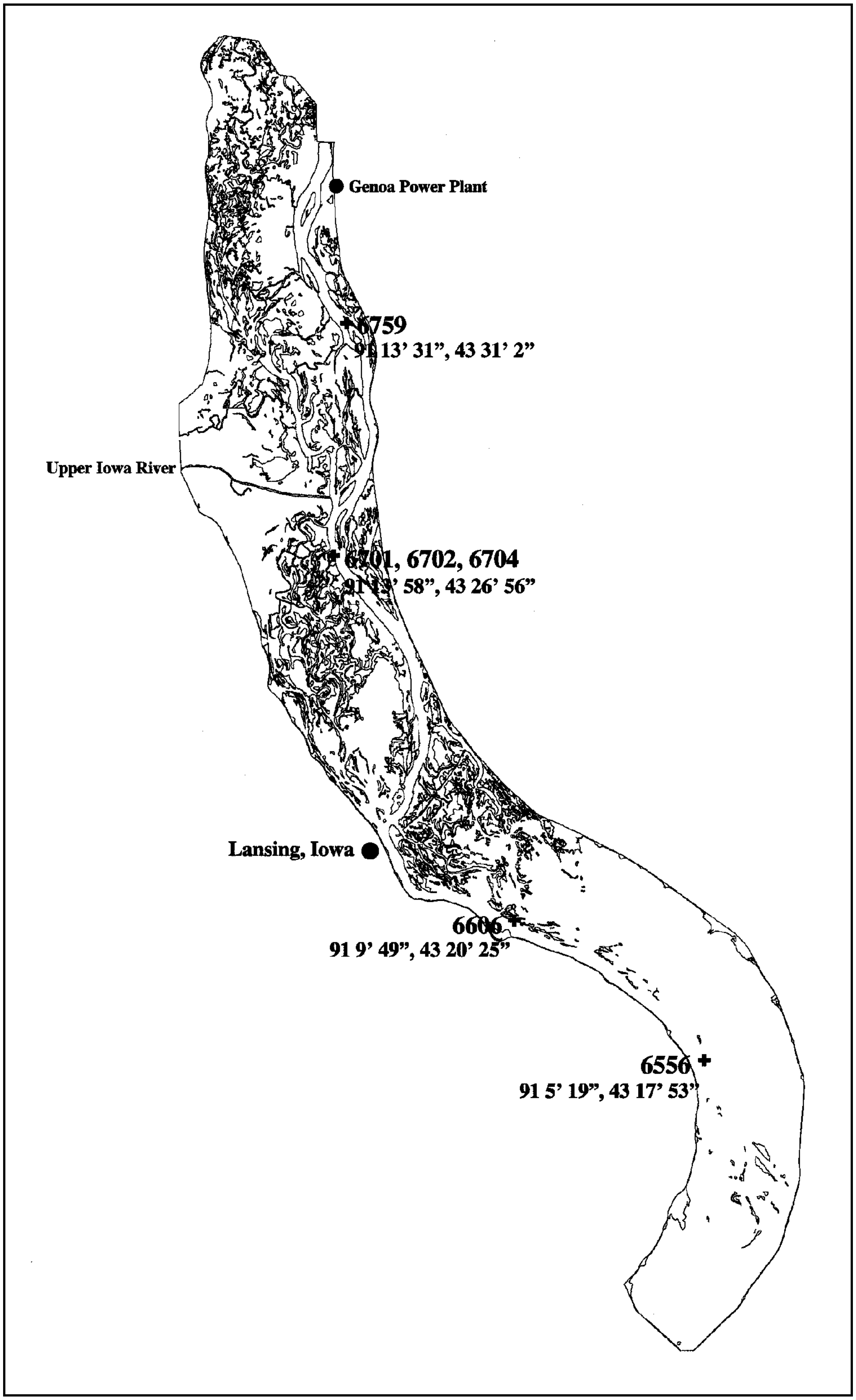


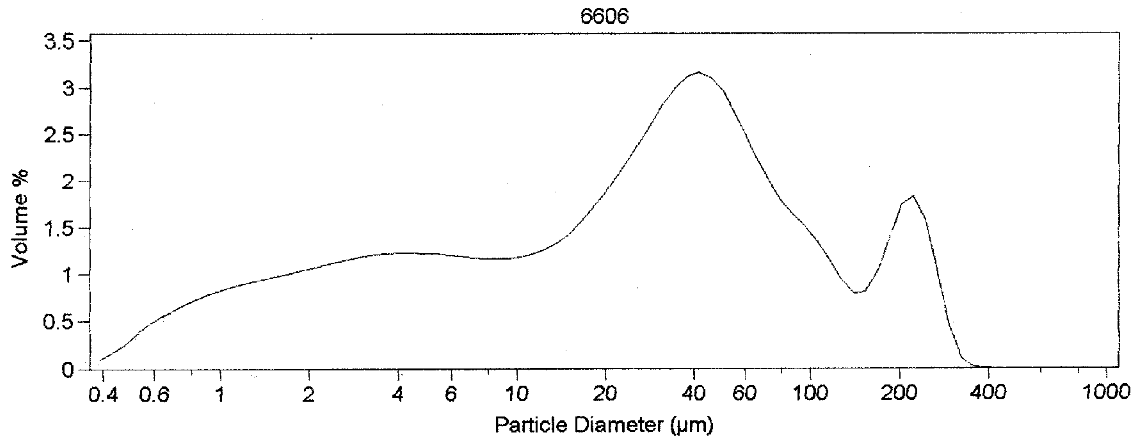
Figure 22. Locations of sediment samples (6759, 6701, 6702, 6704, 6606, 6556) in Pool 9

COULTER® LS Particle Size Analyzer

19 Dec 1997

HYDRAULICS SEDIMENTATION LABORATORY

File name:	ums6606.$01	Group ID:	UMS6606
Sample ID:	6606		
Operator:	CRL	Run number:	1
Comments:	Used distilled water on wash #2, used bicarb wash for wash #1 & #2. Medium brown sandy clay. Added Calgon to chamber		
Optical model:	Fraunhofer		
LS 100Q	Fluid Module		



Volume Statistics (Arithmetic) ums6606.$01

Calculations from 0.375 µm to 948 µm

Volume	100.0%		
Mean:	49.44 µm	S.D.:	64.2 µm
Median:	26.78 µm	C.V.:	130%
D(3,2):	5.130 µm	Skewness:	1.96 Right skewed
Mode:	41.67 µm	Kurtosis:	3.32 Leptokurtic

% <	10	25	50	75	90
Size µm	1.643	5.484	26.78	59.65	146.3

ums6606.$01

Particle Diameter µm	Volume % <
4.000	20.85
15.60	38.78
44.00	65.59
74.00	80.17
125.0	88.55
250.0	97.97
500.0	100.00
1.000	100.00

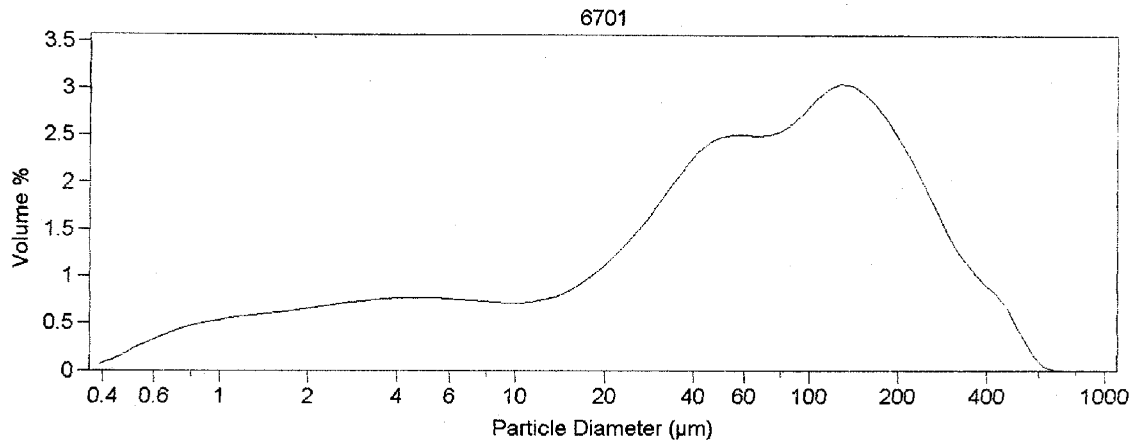
Figure 23. Particle size distribution for dispersed sample 6606

COULTER® LS Particle Size Analyzer

19 Dec 1997

HYDRAULICS SEDIMENTATION LABORATORY

File name:	6701.$01	Group ID:	6701
Sample ID:	6701		
Operator:	CRL	Run number:	1
Comments:	Used distilled water on wash #2, used bicarb wash for wash #1 & #2. Medium brown sandy clay. Added Calgon to chamber		
Optical model:	Fraunhofer		
LS 100Q	Fluid Module		



Volume Statistics (Arithmetic) 6701.$01

Calculations from 0.375 µm to 948 µm

Volume	100.0%		
Mean:	96.52 µm	S.D.:	105 µm
Median:	60.44 µm	C.V.:	109%
D(3,2):	7.851 µm	Skewness:	1.65 Right skewed
Mode:	127.6 µm	Kurtosis:	2.85 Leptokurtic

% <	10	25	50	75	90
Size µm	2.694	16.90	60.44	141.3	240.6

6701.$01

Particle Diameter µm	Volume % <
4.000	13.18
15.60	24.22
44.00	41.57
74.00	55.46
125.0	71.02
250.0	90.85
500.0	99.43
1,000	100.00

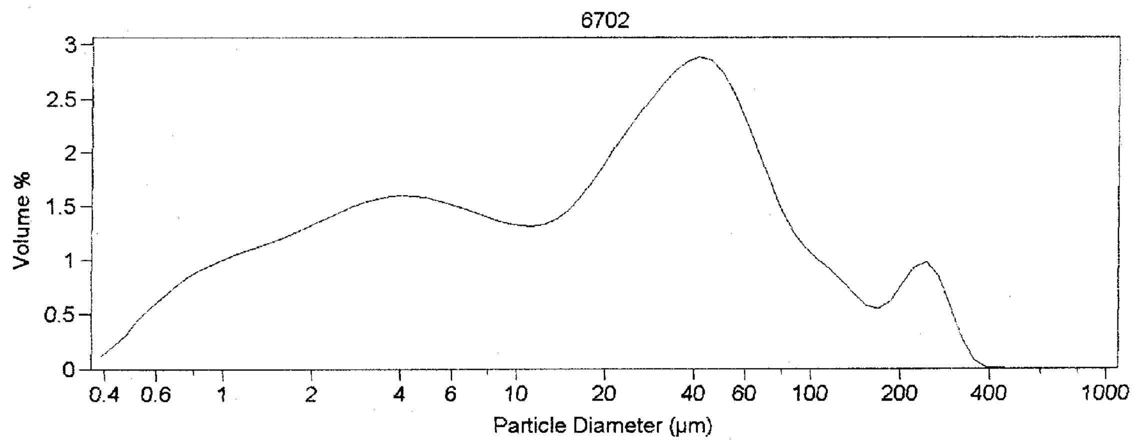
Figure 24. Particle size distribution for dispersed sample 6701

COULTER® LS Particle Size Analyzer

19 Dec 1997

HYDRAULICS SEDIMENTATION LABORATORY

File name:	6702.$01	Group ID:	6702
Sample ID:	6702		
Operator:	CRL	Run number:	1
Comments:	Used distilled water on wash #2, used bicarb wash for wash #1 & #2. Medium brown sandy clay. Added Calgon to chamber		
Optical model:	Fraunhofer		
LS 100Q	Fluid Module		



Volume Statistics (Arithmetic) 6702.$01

Calculations from 0.375 µm to 948 µm

Volume	100.0%		
Mean:	39.10 µm	S.D.:	57.8 µm
Median:	18.52 µm	C.V.:	148%
D(3,2):	4.248 µm	Skewness:	2.65 Right skewed
Mode:	41.67 µm	Kurtosis:	7.49 Leptokurtic

% <	10	25	50	75	90
Size µm	1.384	3.781	18.52	47.38	97.26

6702.$01

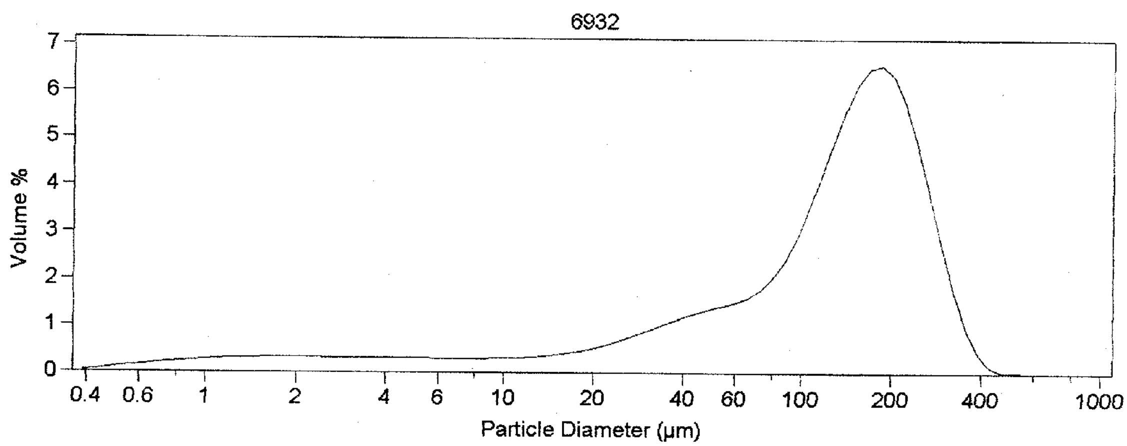
Particle Diameter µm	Volume % <
4.000	25.97
15.60	47.01
44.00	72.74
74.00	86.10
125.0	92.59
250.0	97.95
500.0	100.00
1,000	100.00

Figure 25. Particle size distribution for dispersed sample 6702

COULTER® LS Particle Size Analyzer

HYDRAULICS SEDIMENTATION LABORATORY 19 Dec 1997

File name:	6932.$01	Group ID:	6932
Sample ID:	6932		
Operator:	CRL	Run number:	1
Comments:	Used distilled water on wash #2, used bicarb wash for wash #1 & #3. Medium brown sandy clay. Added Calgon to chamber		
Optical model:	Fraunhofer		
LS 100Q	Fluid Module		



Volume Statistics (Arithmetic) 6932.$01

Calculations from 0.375 µm to 948 µm

Volume	100.0%		
Mean:	137.7 µm	S.D.:	89.2 µm
Median:	137.6 µm	C.V.:	64.7%
D(3,2):	15.77 µm	Skewness:	0.297 Right skewed
Mode:	185.3 µm	Kurtosis:	-0.494 Platykurtic

% <	10	25	50	75	90
Size µm	13.03	63.51	137.6	199.5	255.7

6932.$01

Particle Diameter µm	Volume % <
4.000	6.19
15.60	10.70
44.00	19.39
74.00	27.77
125.0	44.80
250.0	88.82
500.0	100.00
1,000	100.00

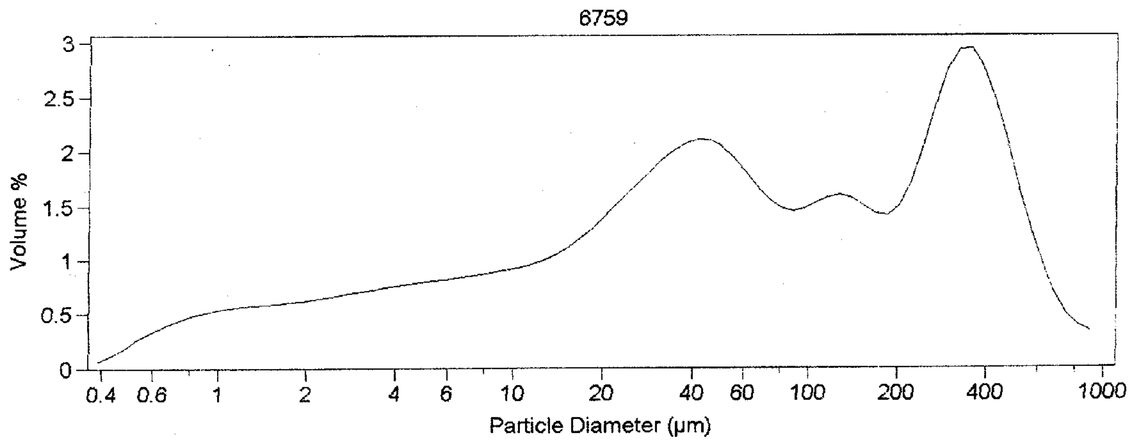
Figure 26. Particle size distribution for dispersed sample 6932

COULTER® LS Particle Size Analyzer

19 Dec 1997

HYDRAULICS SEDIMENTATION LABORATORY

File name:	6759.$02	Group ID:	6759
Sample ID:	6759		
Operator:	crl	Run number:	2
Comments:	Used distilled water on wash #2, bicarb. soln for washes # 1 & #3 Medium brown sandy clay. 0.5% calgon in chamber.		
Optical model:	Fraunhofer		
LS 100Q	Fluid Module		



Volume Statistics (Arithmetic) 6759.$02

Calculations from 0.375 µm to 948 µm

Volume	100.0%		
Mean:	146.2 µm	S.D.:	180 µm
Median:	56.69 µm	C.V.:	123%
D(3,2):	7.855 µm	*Skewness:*	1.5 Right skewed
Mode:	356.1 µm	Kurtosis:	1.83 Leptokurtic

% <	10	25	50	75	90
Size µm	2.776	14.67	56.69	247.6	415.1

6759.$02

Particle Diameter µm	Volume % <
4.000	12.82
15.60	25.74
44.00	44.49
74.00	54.93
125.0	63.46
250.0	75.23
500.0	94.45
1,000	100.00

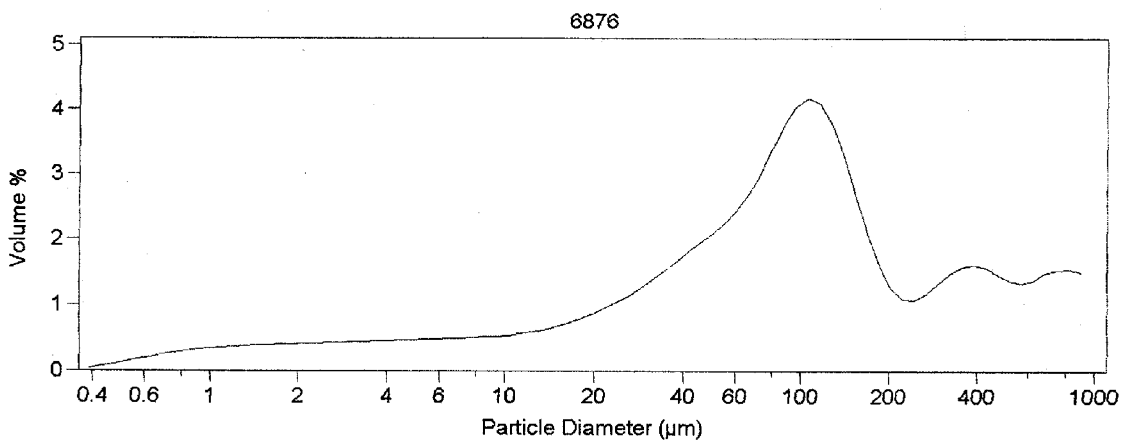
Figure 27. Particle size distribution for dispersed sample 6759

COULTER® LS Particle Size Analyzer

19 Dec 1997

HYDRAULICS SEDIMENTATION LABORATORY

File name:	6876.$01	Group ID:	6876
Sample ID:	6876		
Operator:	CRL	Run number:	1
Comments:	Used distilled water on wash #2, used bicarb wash for wash #1 & #3. Medium brown sandy clay. Added Calgon to chamber		
Optical model:	Fraunhofer		
LS 100Q	Fluid Module		



Volume Statistics (Arithmetic) 6876.$01

Calculations from 0.375 µm to 948 µm

Volume	100.0%		
Mean:	168.6 µm	S.D.:	211 µm
Median:	91.09 µm	C.V.:	125%
D(3,2):	12.14 µm	Skewness:	1.89 Right skewed
Mode:	105.9 µm	Kurtosis:	2.85 Leptokurtic

% <	10	25	50	75	90
Size µm	5.834	35.37	91.09	180.2	497.5

6876.$01

Particle Diameter µm	Volume % <
4.000	8.09
15.60	15.78
44.00	29.04
74.00	42.24
125.0	63.87
250.0	79.41
500.0	90.08
1,000	100.00

Figure 28. Particle size distribution for dispersed sample 6876

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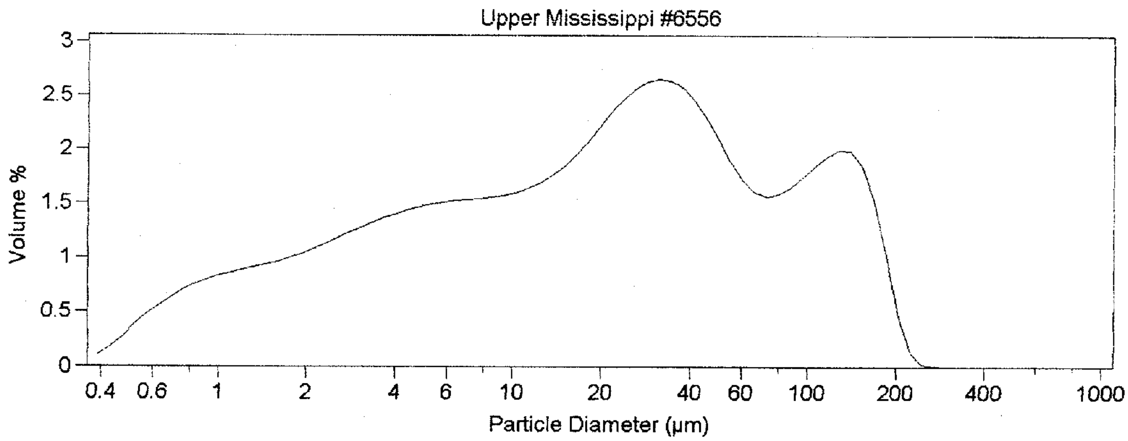
19 Dec 1997

HYDRAULICS SEDIMENTATION LABORATORY

File name: 6556.$01 Group ID: 6556
Sample ID: Upper Mississippi #6556
Operator: CRL Run number: 1
Comments: Brown clay, no or little sand. Calgon in chamber.
Only 1 carb-bicarb wash, 2nd wash was distilled water, was suspended
Optical model: Fraunhofer
LS 100Q Fluid Module



Volume Statistics (Arithmetic) 6556.$01

Calculations from 0.375 µm to 948 µm

Volume	100.0%		
Mean:	38.87 µm	S.D.:	46.9 µm
Median:	20.11 µm	C.V.:	121%
D(3,2):	4.879 µm	Skewness:	1.6 Right skewed
Mode:	31.50 µm	Kurtosis:	1.83 Leptokurtic

% <	10	25	50	75	90
Size µm	1.625	5.032	20.11	51.71	116.5

6556.$01

Particle Diameter µm	Volume % <
4.000	21.46
15.60	44.44
44.00	71.22
74.00	81.64
125.0	91.49
250.0	99.99
500.0	100.00
1,000	100.00

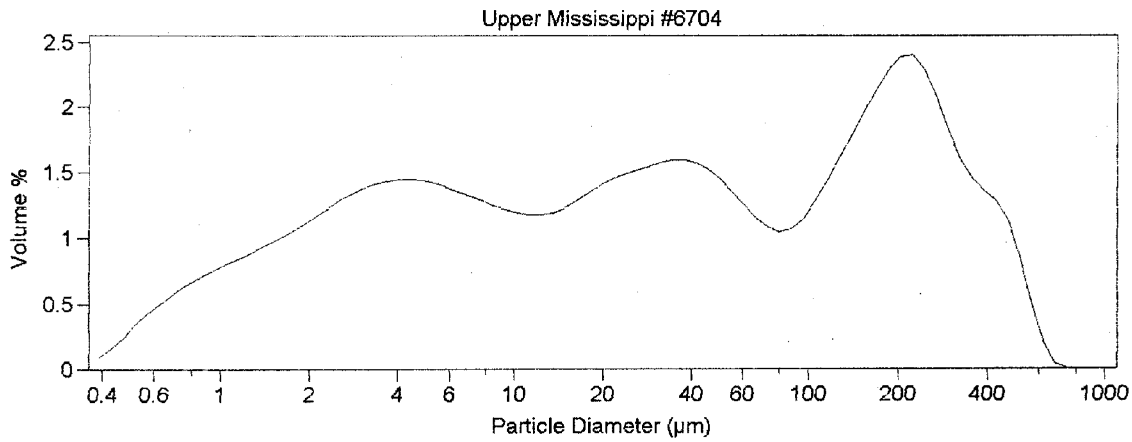
Figure 29. Particle size distribution for dispersed sample 6556

COULTER® LS Particle Size Analyzer

19 Dec 1997

HYDRAULICS SEDIMENTATION LABORATORY

File name:	6704.$01	Group ID:	6704
Sample ID:	Upper Mississippi #6704		
Operator:	CRL	Run number:	1
Comments:	Calgon in chamber. At least 2 washes w/ carb-bicarg soln. Brown sandy clay with some black pebbles.		
Optical model:	Fraunhofer		
LS 100Q	Fluid Module		



Volume Statistics (Arithmetic) 6704.$01

Calculations from 0.375 μm to 948 μm

Volume	100.0%		
Mean:	94.53 μm	S.D.:	129 μm
Median:	28.95 μm	C.V.:	136%
D(3,2):	5.236 μm	Skewness:	1.66 Right skewed
Mode:	223.4 μm	Kurtosis:	2.23 Leptokurtic

% <	10	25	50	75	90
Size μm	1.716	4.979	28.95	152.6	285.8

6704.$01

Particle Diameter μm	Volume % <
4.000	21.63
15.60	40.57
44.00	57.09
74.00	64.42
125.0	71.26
250.0	87.01
500.0	98.53
1,000	100.00

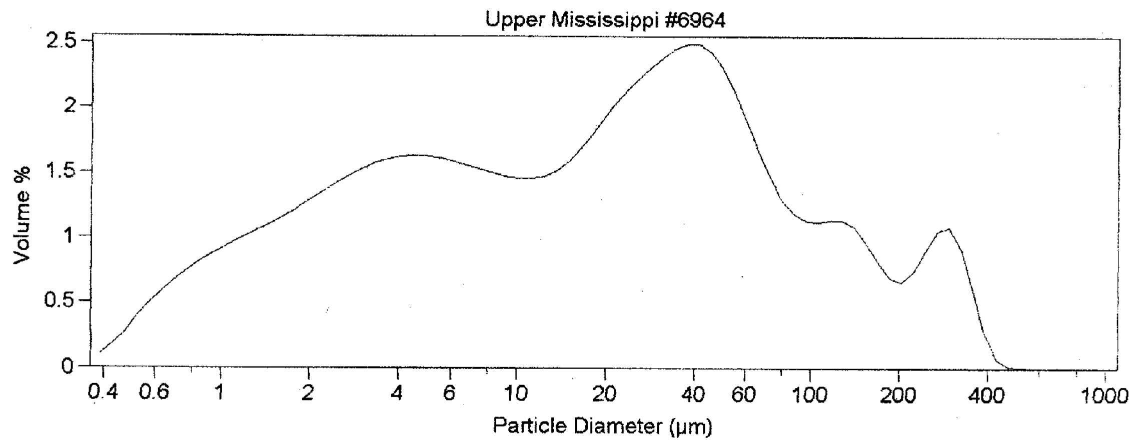
Figure 30. Particle size distribution for dispersed sample 6704

COULTER® LS Particle Size Analyzer

19 Dec 1997

HYDRAULICS SEDIMENTATION LABORATORY

File name:	6964.$01	Group ID:	6964
Sample ID:	Upper Mississippi #6964		
Operator:	CRL	Run number:	1
Comments:	Calgon in chamber. At least 2 washes w/ carb-bicarg soln. Brown sandy clay with some black pebbles.		
Optical model:	Fraunhofer		
LS 100Q	Fluid Module		



Volume Statistics (Arithmetic) 6964.$01

Calculations from 0.375 µm to 948 µm

Volume	100.0%		
Mean:	46.45 µm	S.D.:	72.7 µm
Median:	18.18 µm	C.V.:	157%
D(3,2):	4.509 µm	Skewness:	2.55 Right skewed
Mode:	37.96 µm	Kurtosis:	6.52 Leptokurtic

% <	10	25	50	75	90
Size µm	1.505	4.072	18.18	50.64	132.2

6964.$01

Particle Diameter µm	Volume % <
4.000	24.71
15.60	47.19
44.00	71.44
74.00	82.62
125.0	89.32
250.0	95.74
500.0	100.00
1,000	100.00

Figure 31. Particle size distribution for dispersed sample 6964

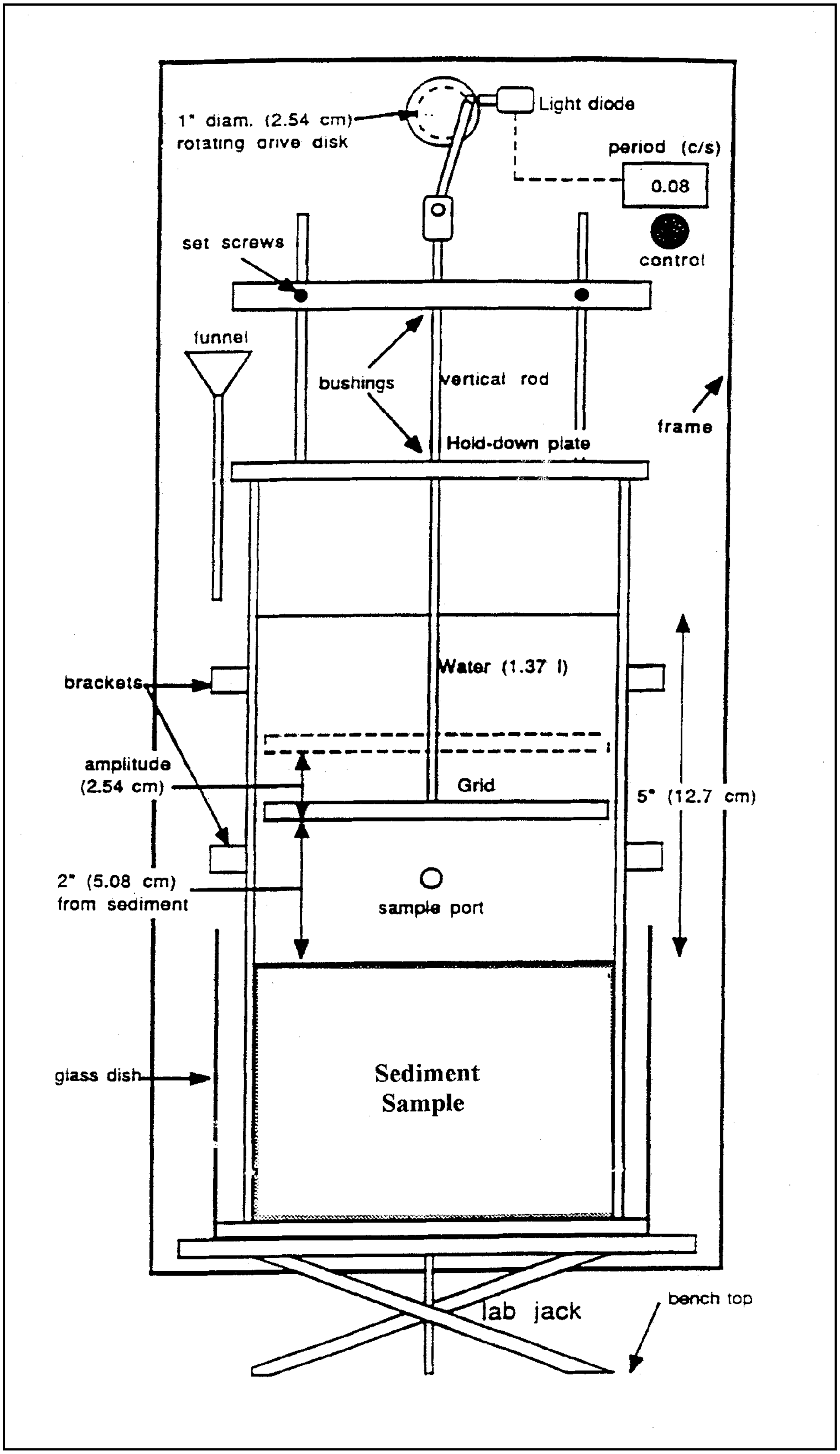


Figure 32. Schematic drawing of PES

Figure 33. Particle Entrainment Simulator (PES)

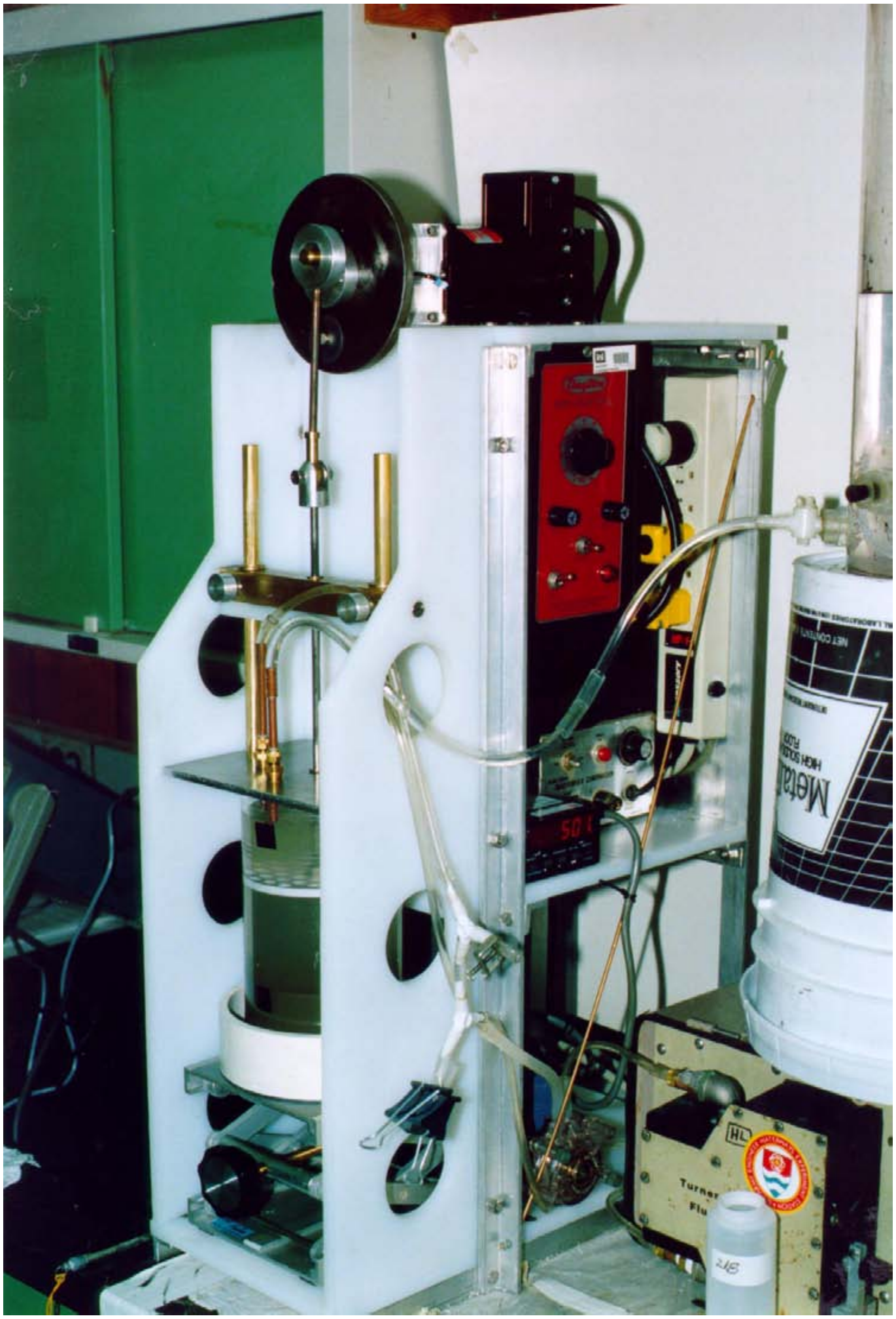


Figure 34. Vertically oscillating perforated disc and sediment sampling tubes of PES

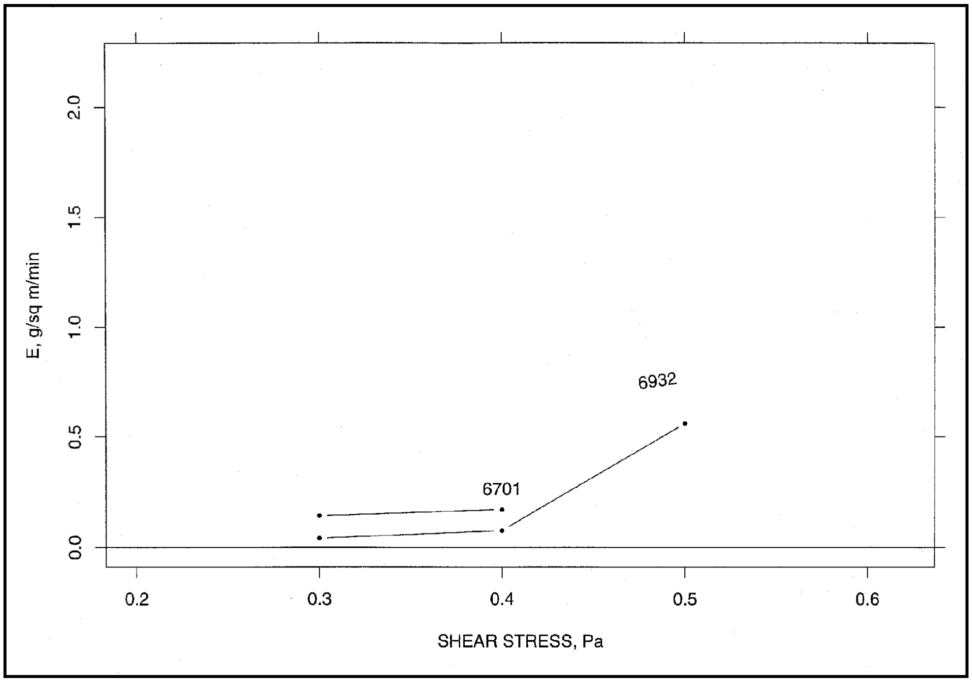


Figure 35. Results of erosion tests on samples 6932, 6701

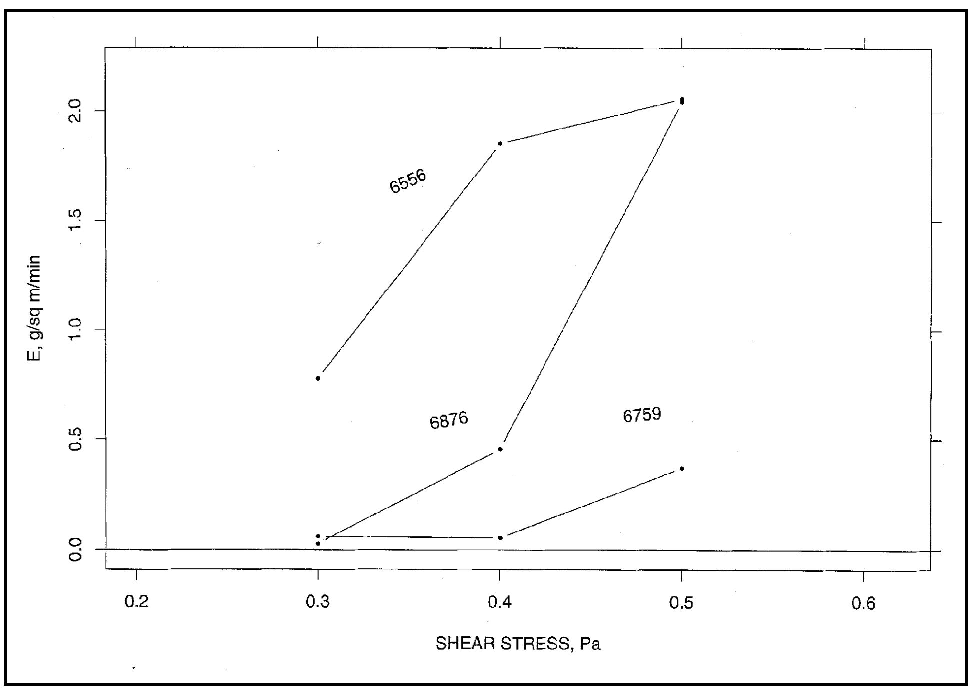


Figure 36. Results of erosion tests on samples 6556, 6876, 6759

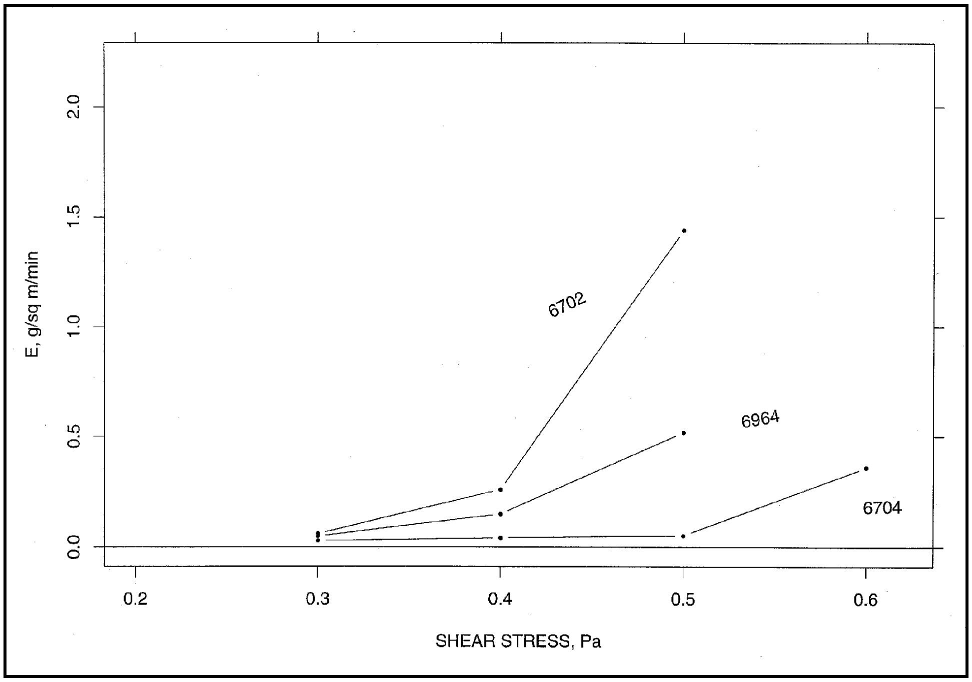


Figure 37. Results of erosion tests on samples 6702, 6964, 6704

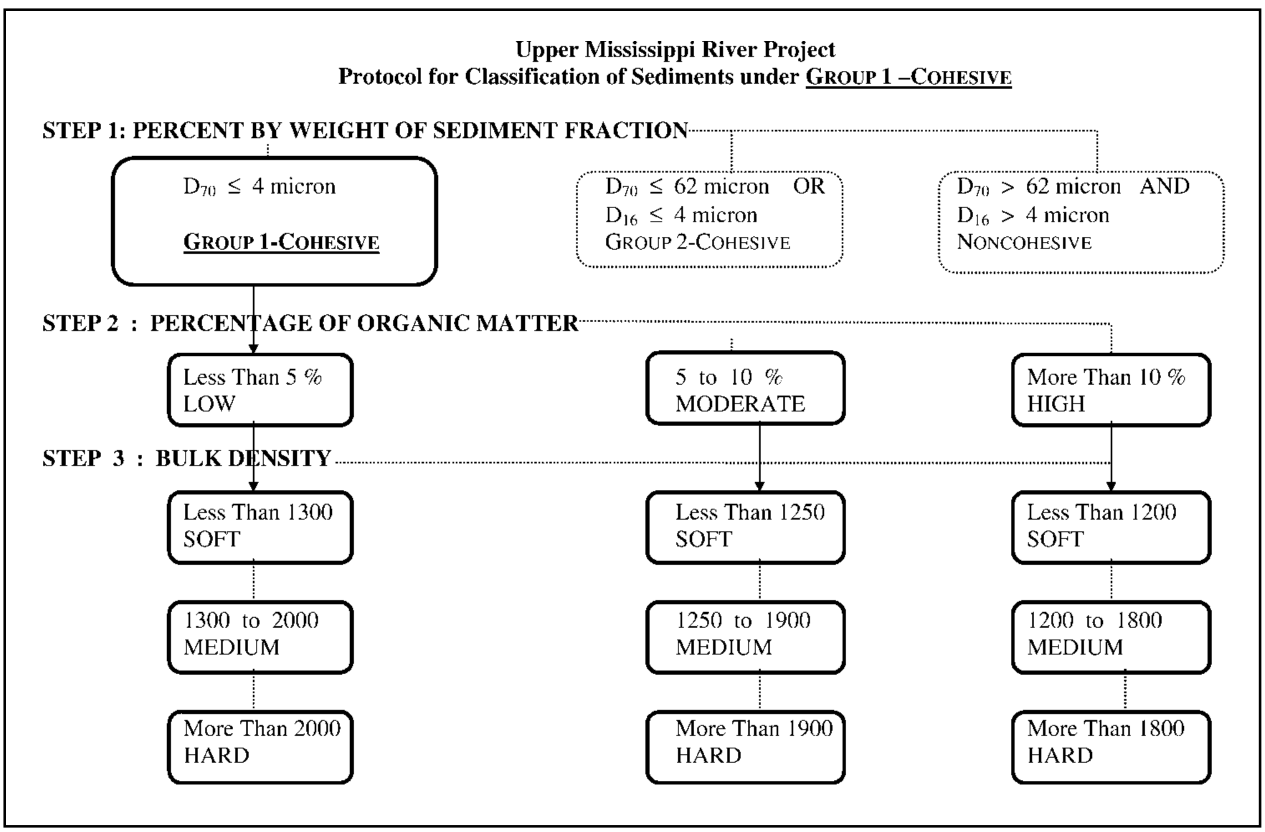


Figure 38. Protocol for classification of sediments under Group1-Cohesive

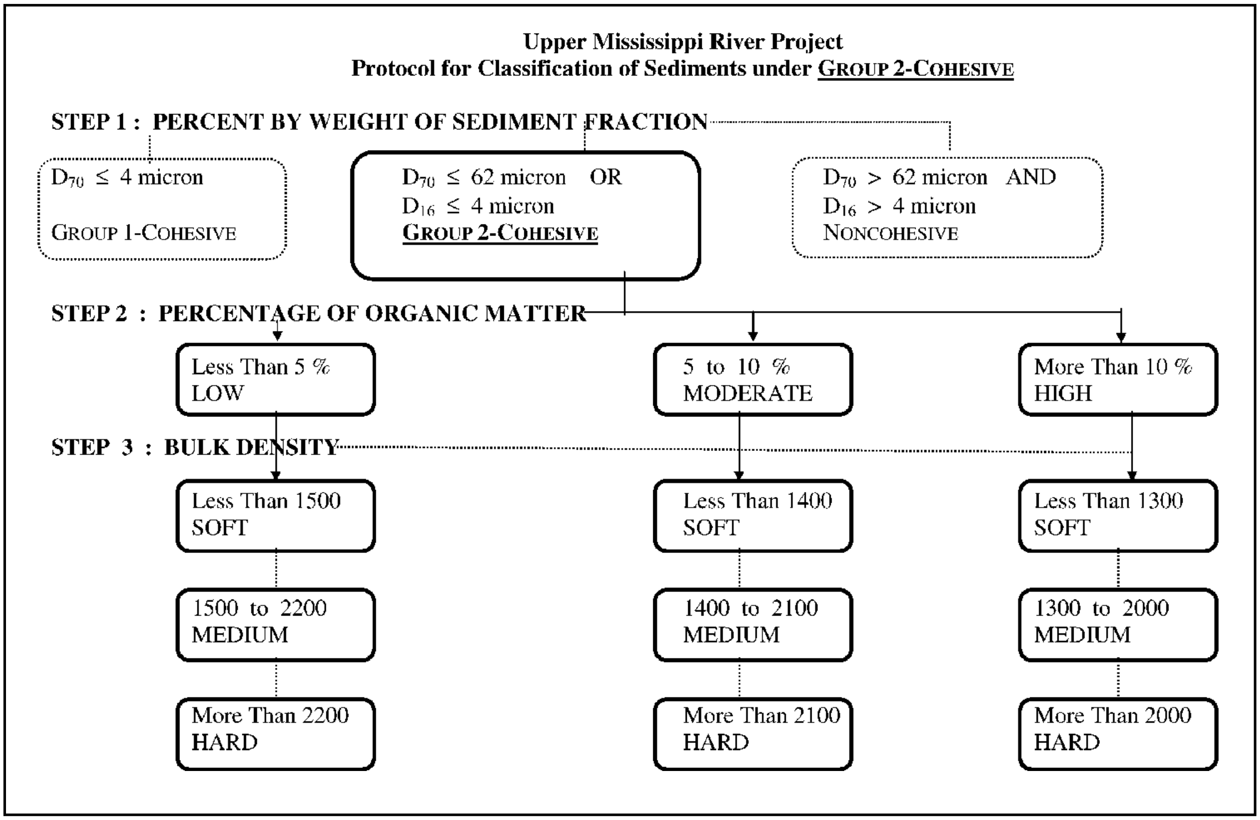
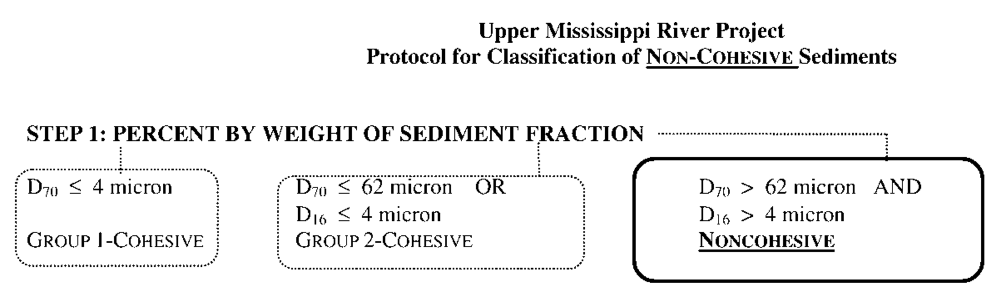


Figure 39. Protocol for classification of sediments under Group2-Cohesive



The only parameter that needs to be considered for treatment of "Noncohesive" sediments is the particle size. The other two parameters, "Percentage of Total Organic Matter" and "Wet Bulk Density," may not be significant unless the sand mixture contains more than 10 percent of organic matter.

STEP 1: PARTICLE SIZE SELECTION

Select a representative single value of grain diameter for a bed sample, e.g., D_{50} from the particle size distribution graph. If necessary, several sizes may be selected to represent different size classes.

STEP 2: ENTRAINMENT AND DEPOSITION

Use Figures A5 and A9 for entrainment and deposition of noncohesive sediments.

Figure 40. Protocol for classification of noncohesive sediments

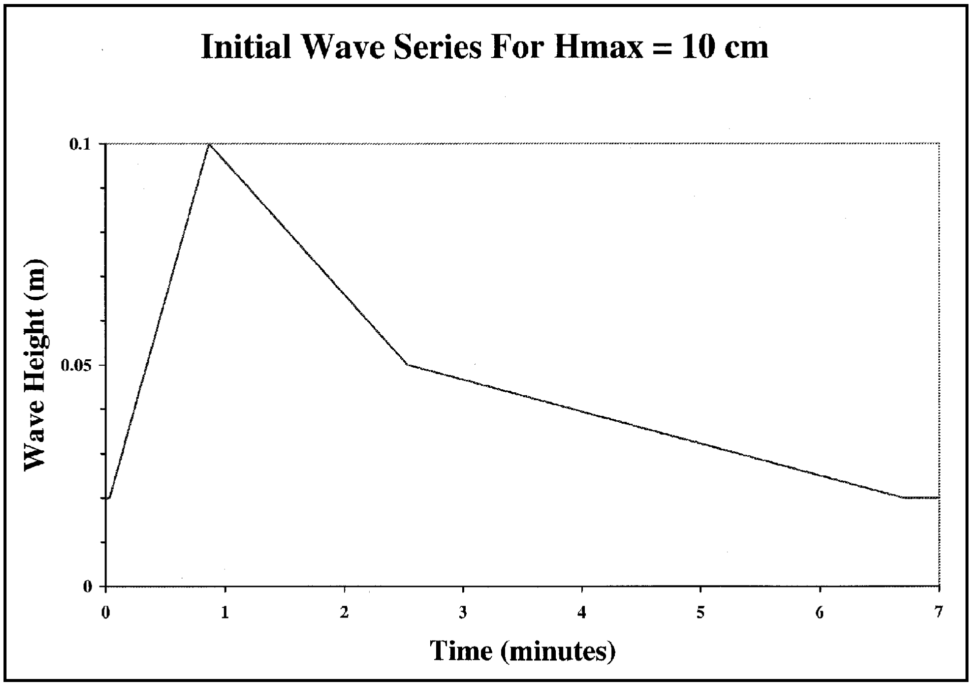


Figure 41. Original wave series for H_{max} = 10 cm

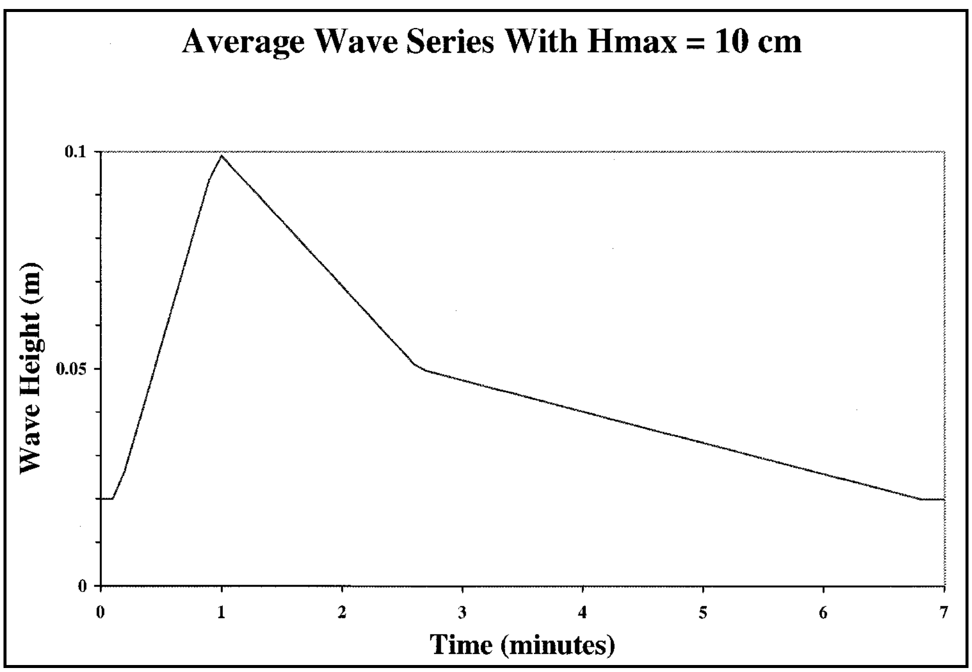


Figure 42. Average wave series for H_{max} = 10 cm

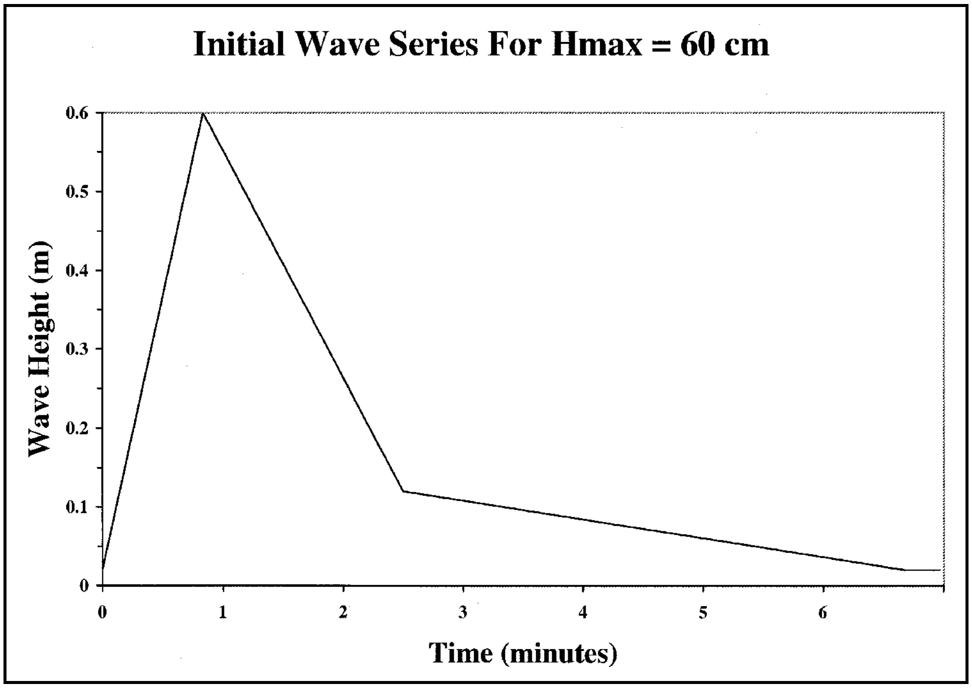


Figure 43. Original wave series for H_{max} = 60 cm

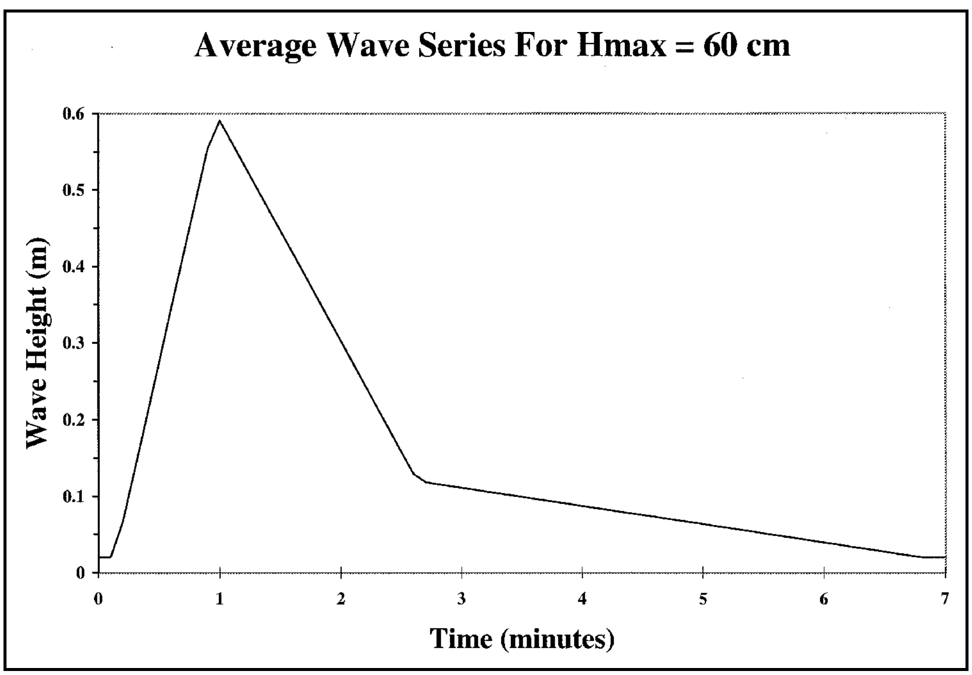


Figure 44. Average wave series for H_{max} = 60 cm

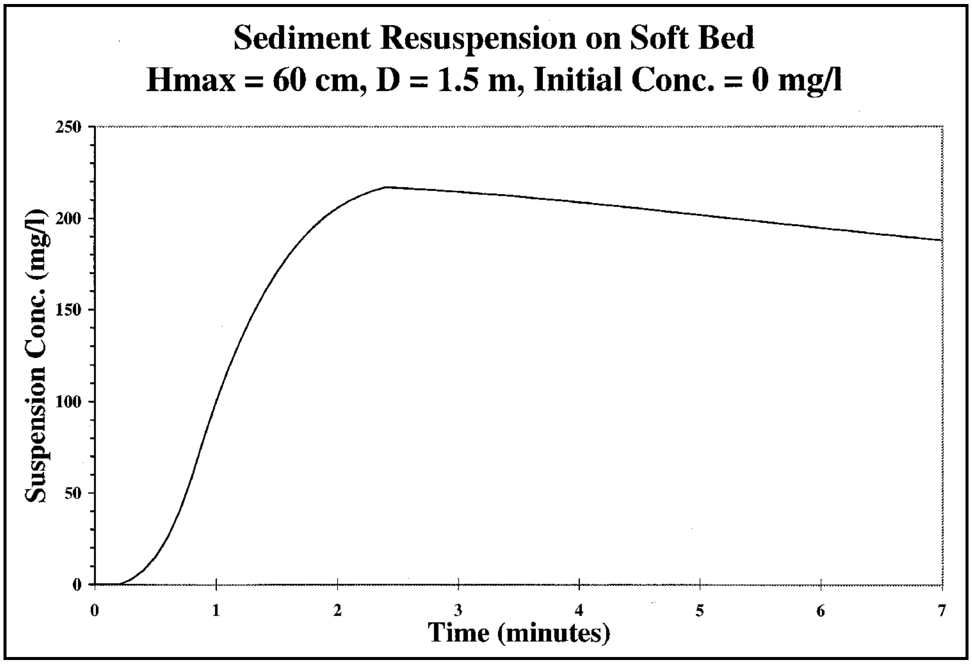


Figure 45. Sediment resuspension on soft bed, H_{max} = 60 cm, D = 1.5 m

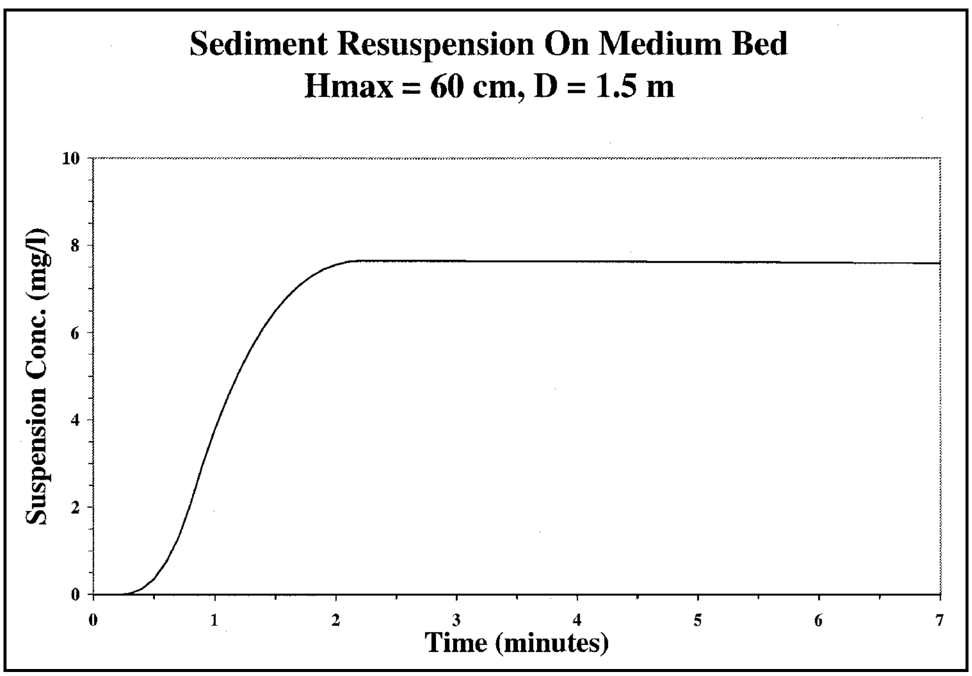


Figure 46. Sediment resuspension on medium bed, H_{max} = 60 cm, D = 1.5 m

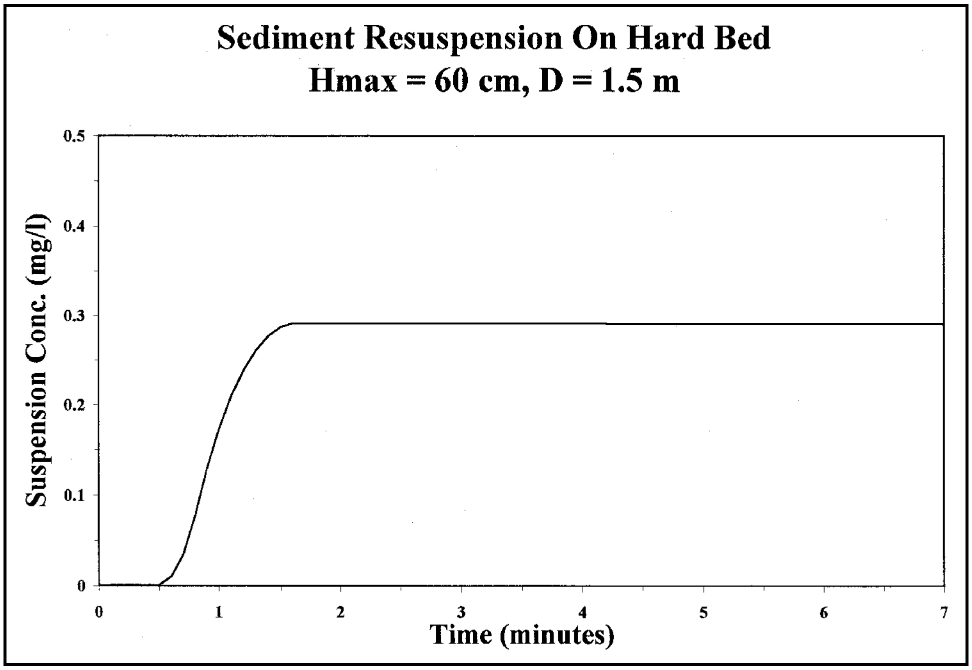


Figure 47. Sediment resuspension on hard bed, H_{max} = 60 cm, D = 1.5 m

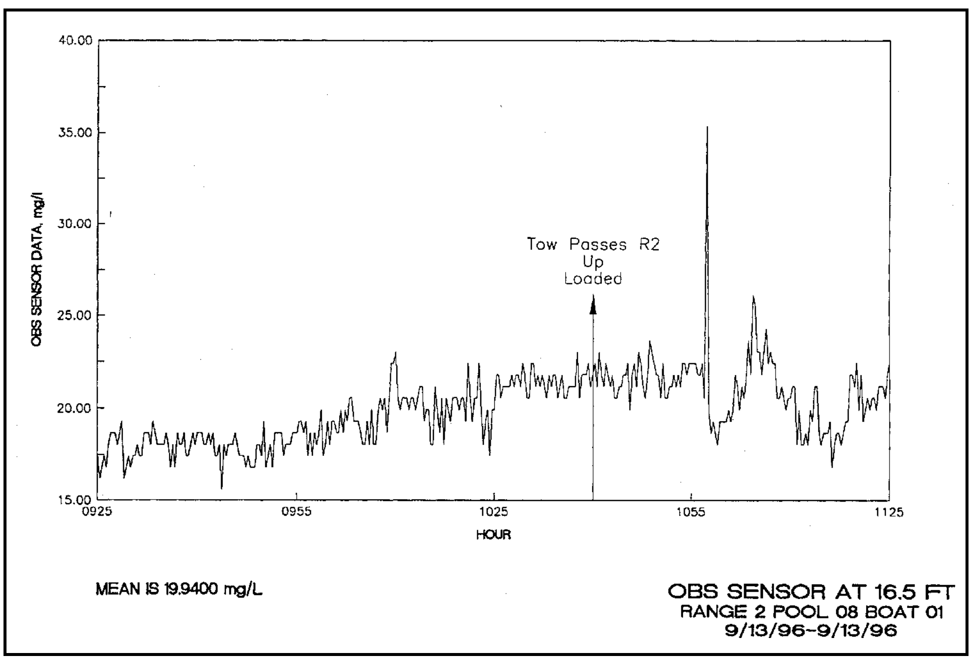


Figure 48. Observed sediment suspension at Range 2, Pool 08, Boat 03

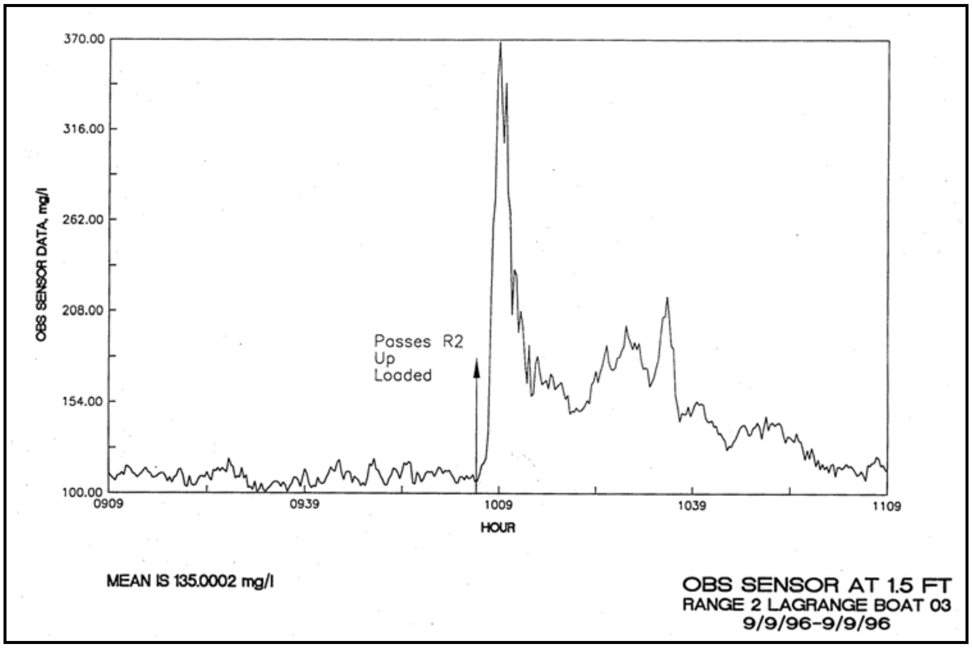


Figure 49. Observed sediment suspension at Range 2, LaGrange Pool, Boat 03

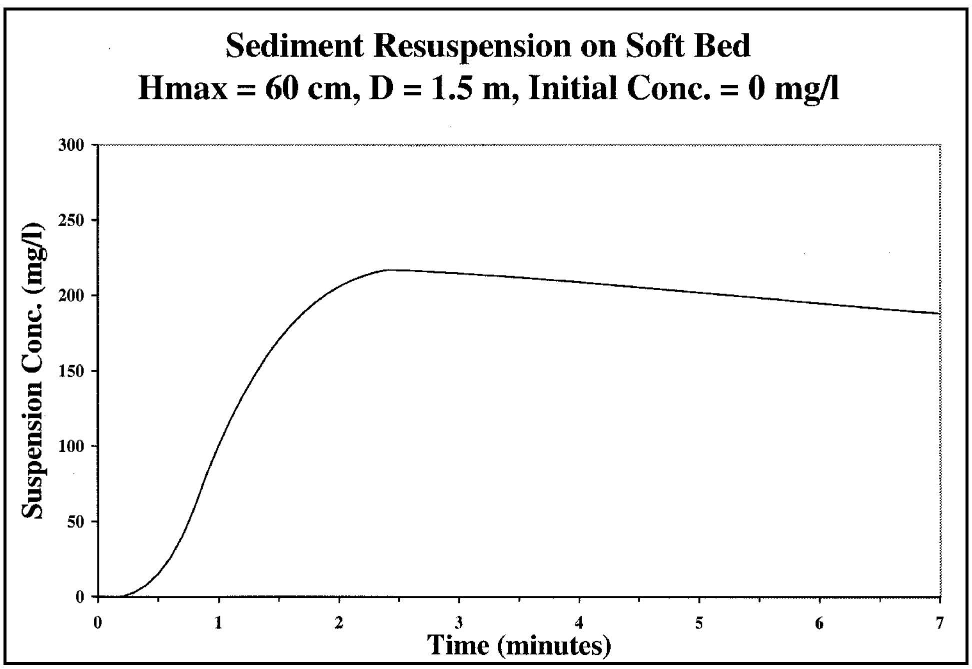


Figure 50. Computed time series of suspension concentration, initial concentration = 0 mg/L

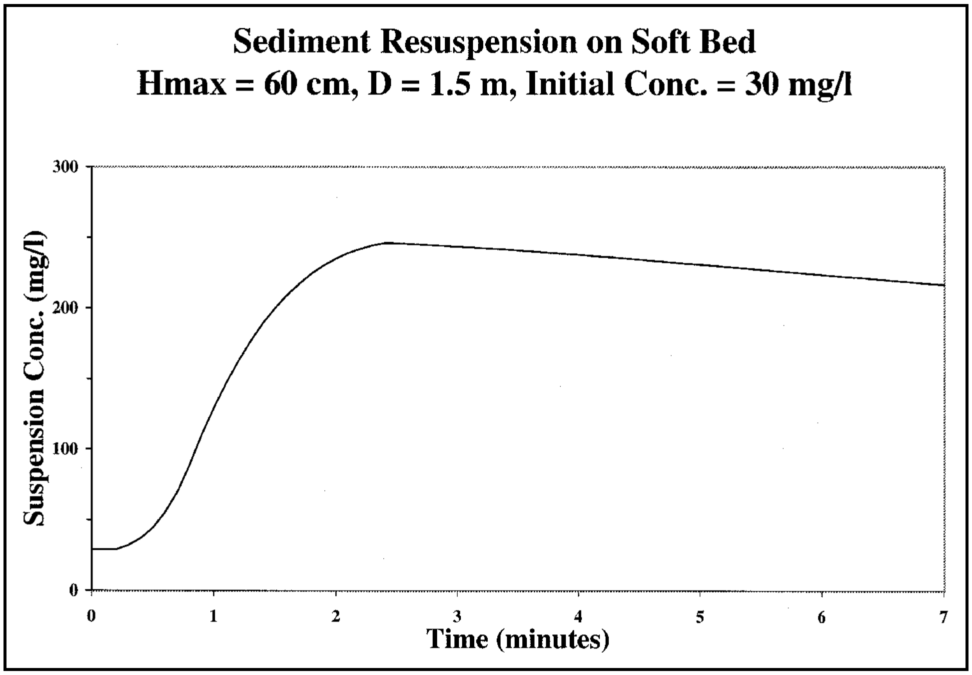


Figure 51. Computed time series of suspension concentration, initial concentration = 30 mg/L

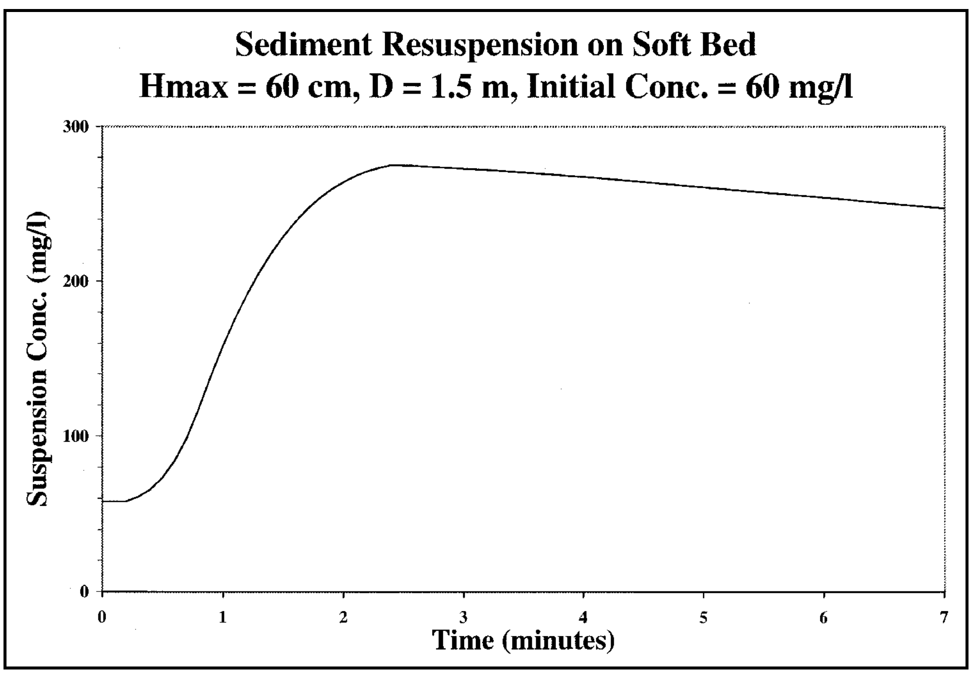


Figure 52. Computed time series of suspension concentration, initial concentration = 60 mg/L

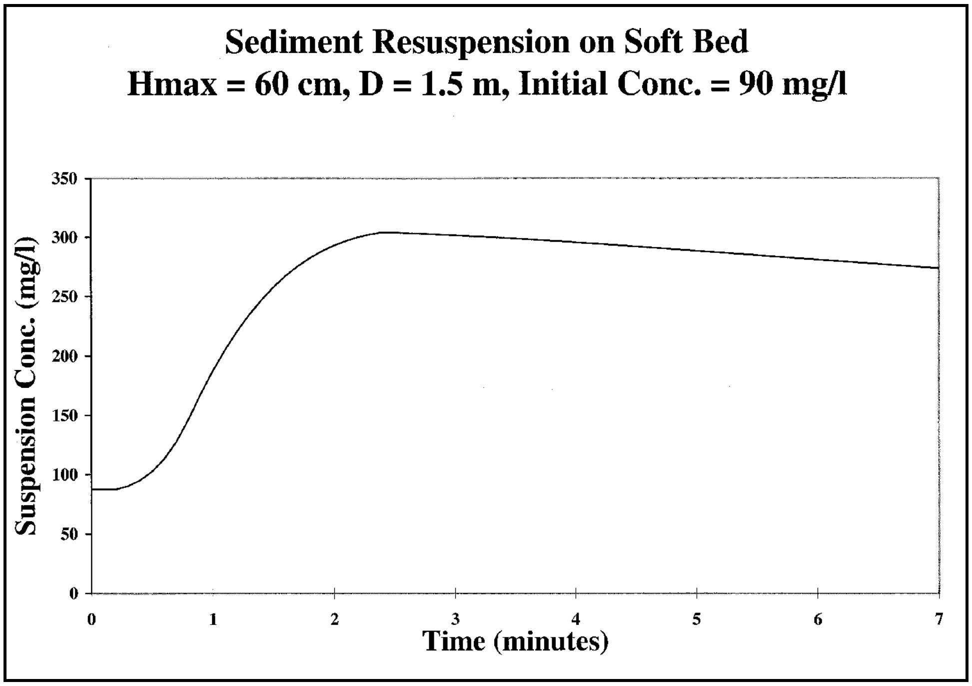


Figure 53. Computed time series of suspension concentration, initial concentration = 90 mg/L

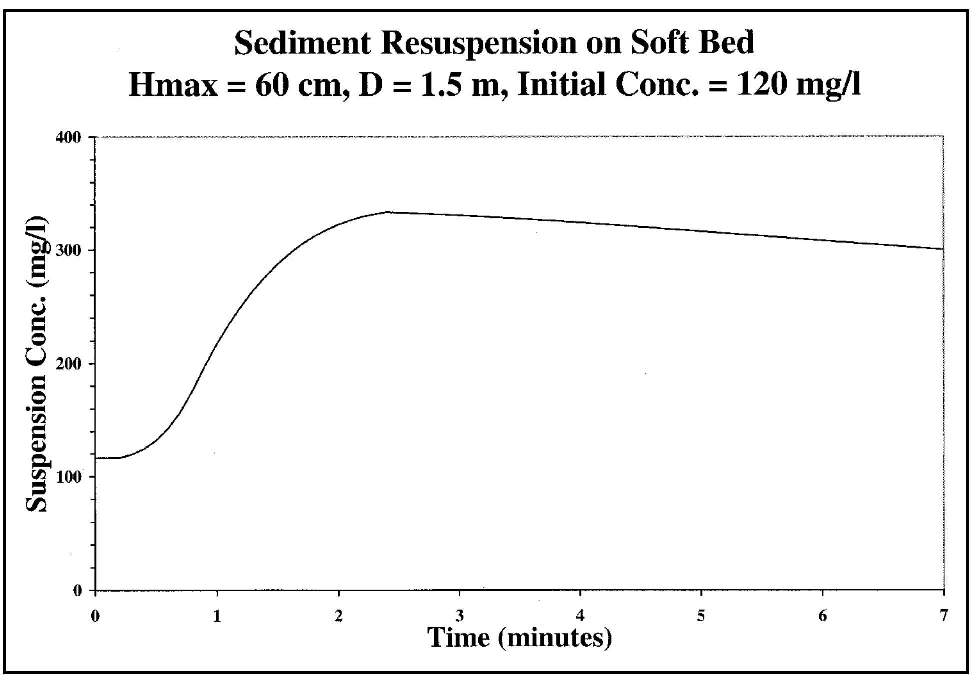


Figure 54. Computed time series of suspension concentration, initial concentration = 120 mg/L

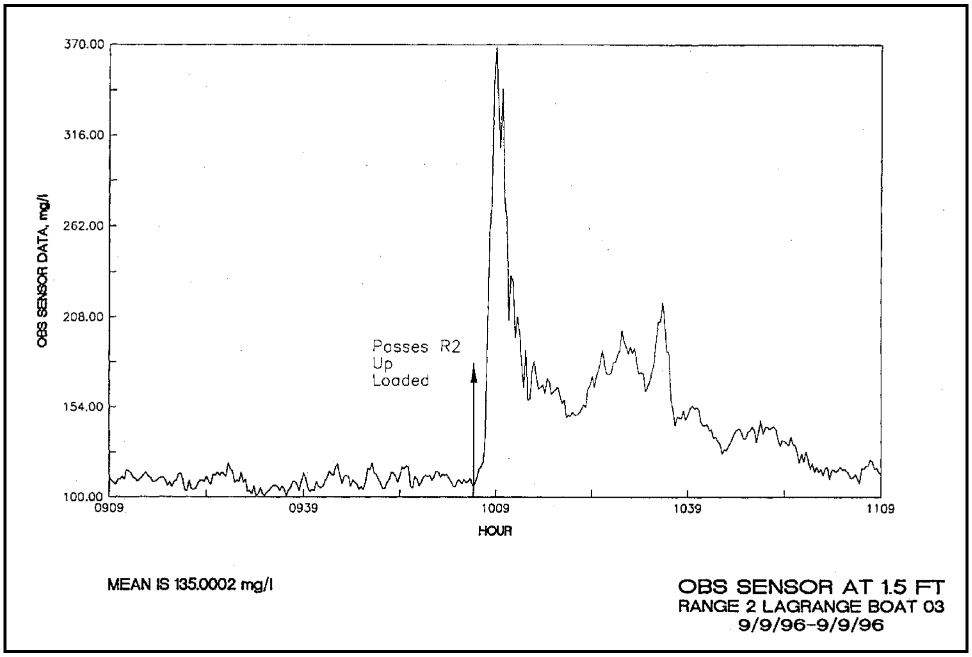


Figure 55. Observed sediment suspension at Range 2, LaGrange Pool, Boat 03

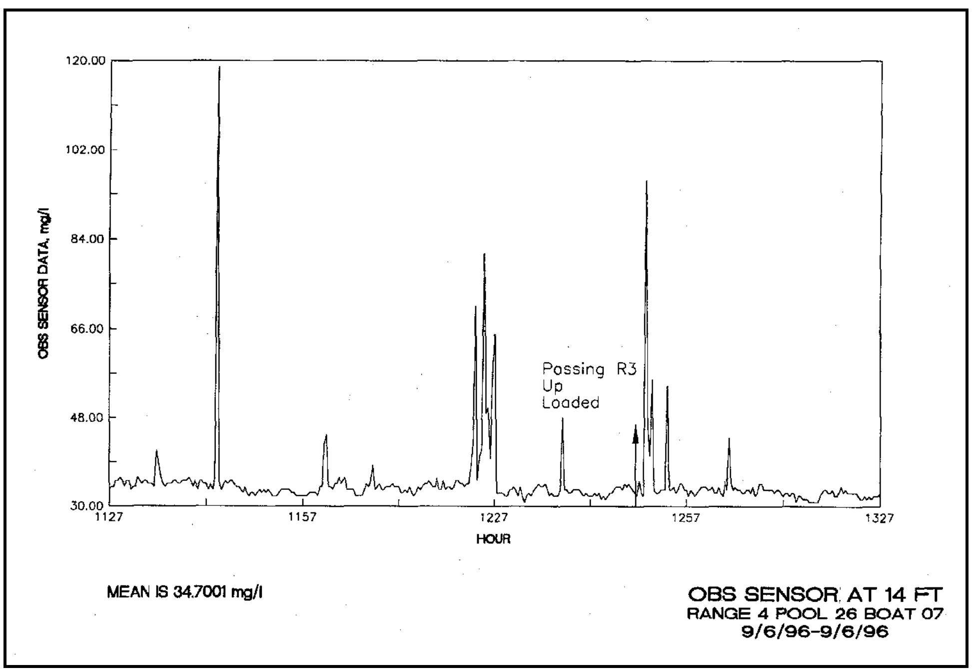


Figure 56. Observed sediment suspension at Range 4, Pool 26, Boat 07

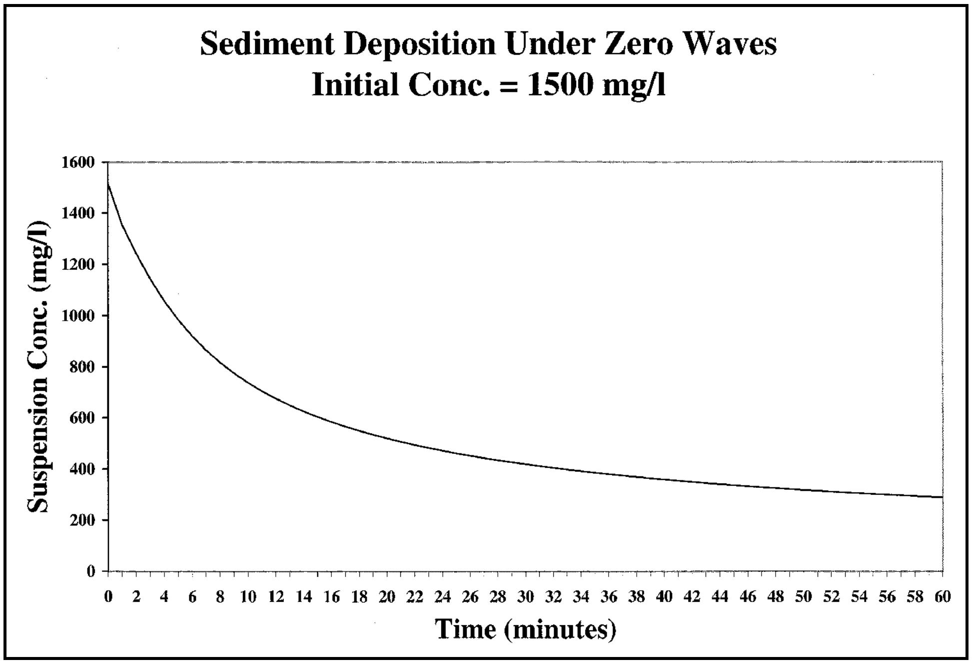


Figure 57. Sediment deposition under no waves, initial concentration = 1,500 mg/L

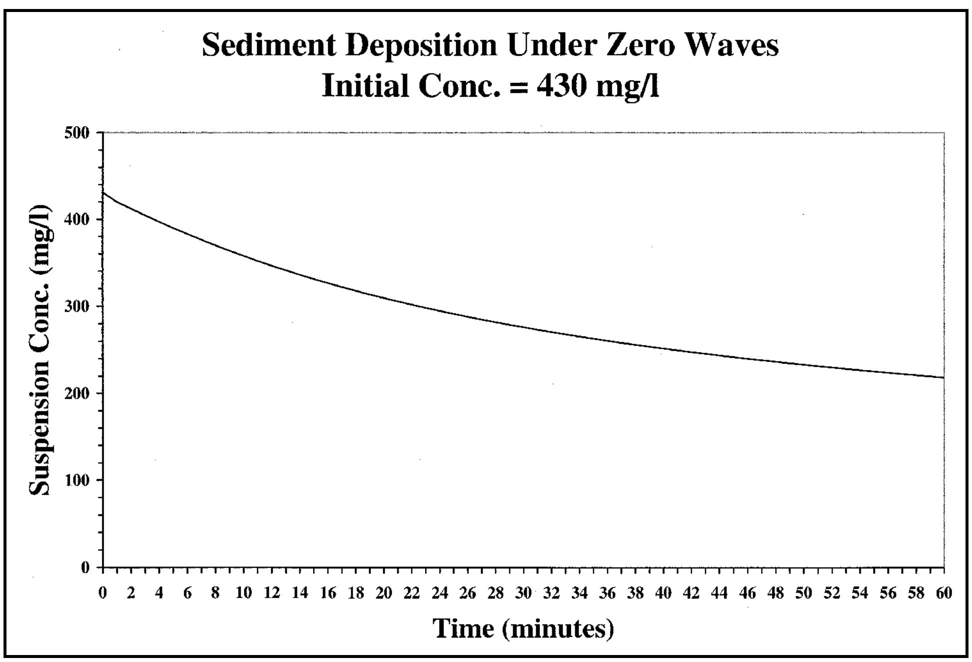


Figure 58. Sediment deposition under no waves, initial concentration = 430 mg/L

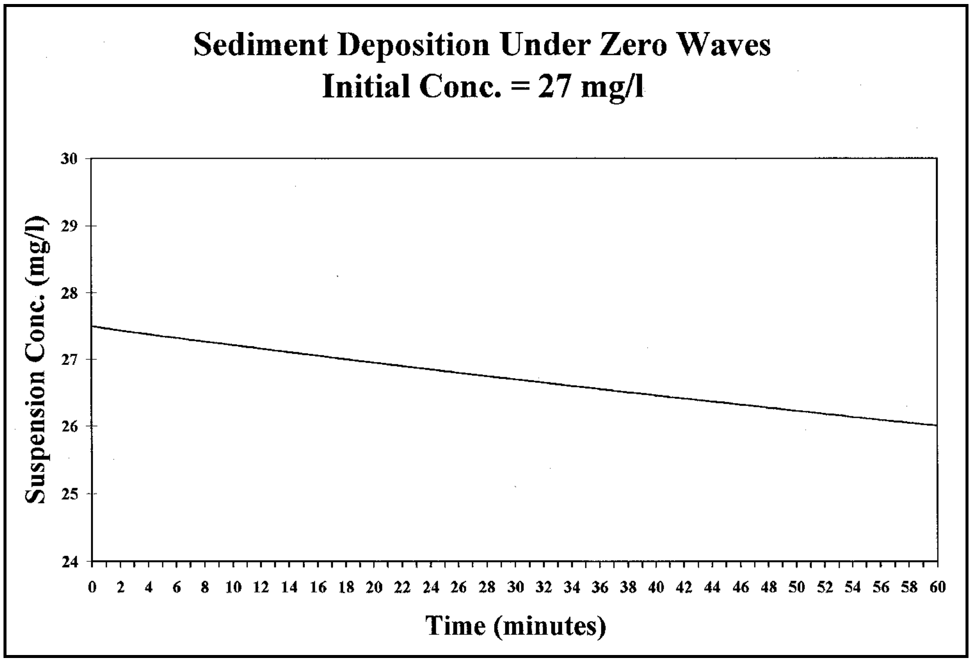


Figure 59. Sediment deposition under no waves, initial concentration = 27 mg/L

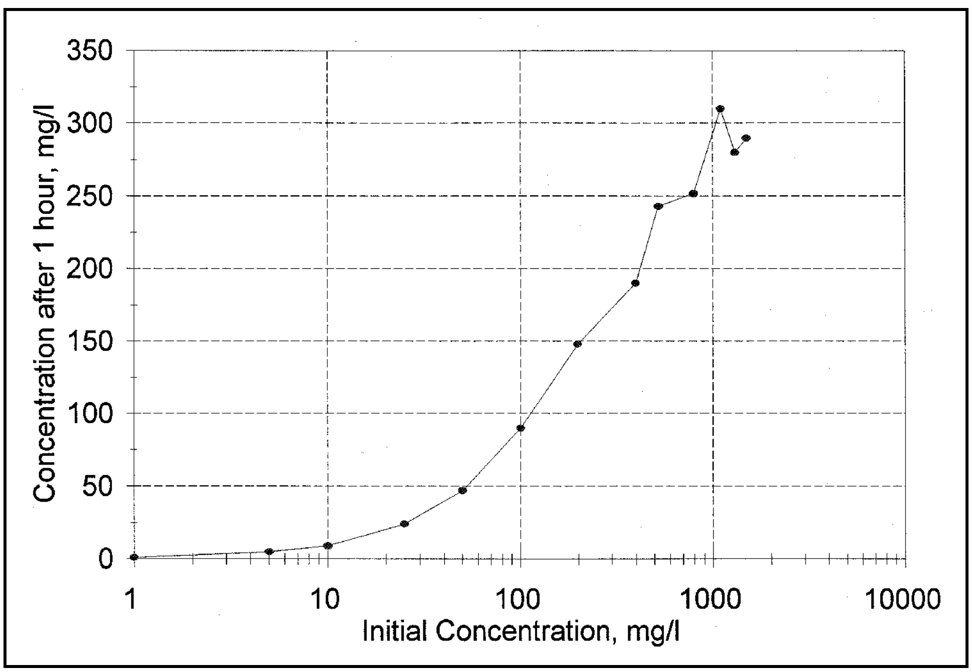


Figure 60. Concentration after 1 hr of deposition versus initial concentration

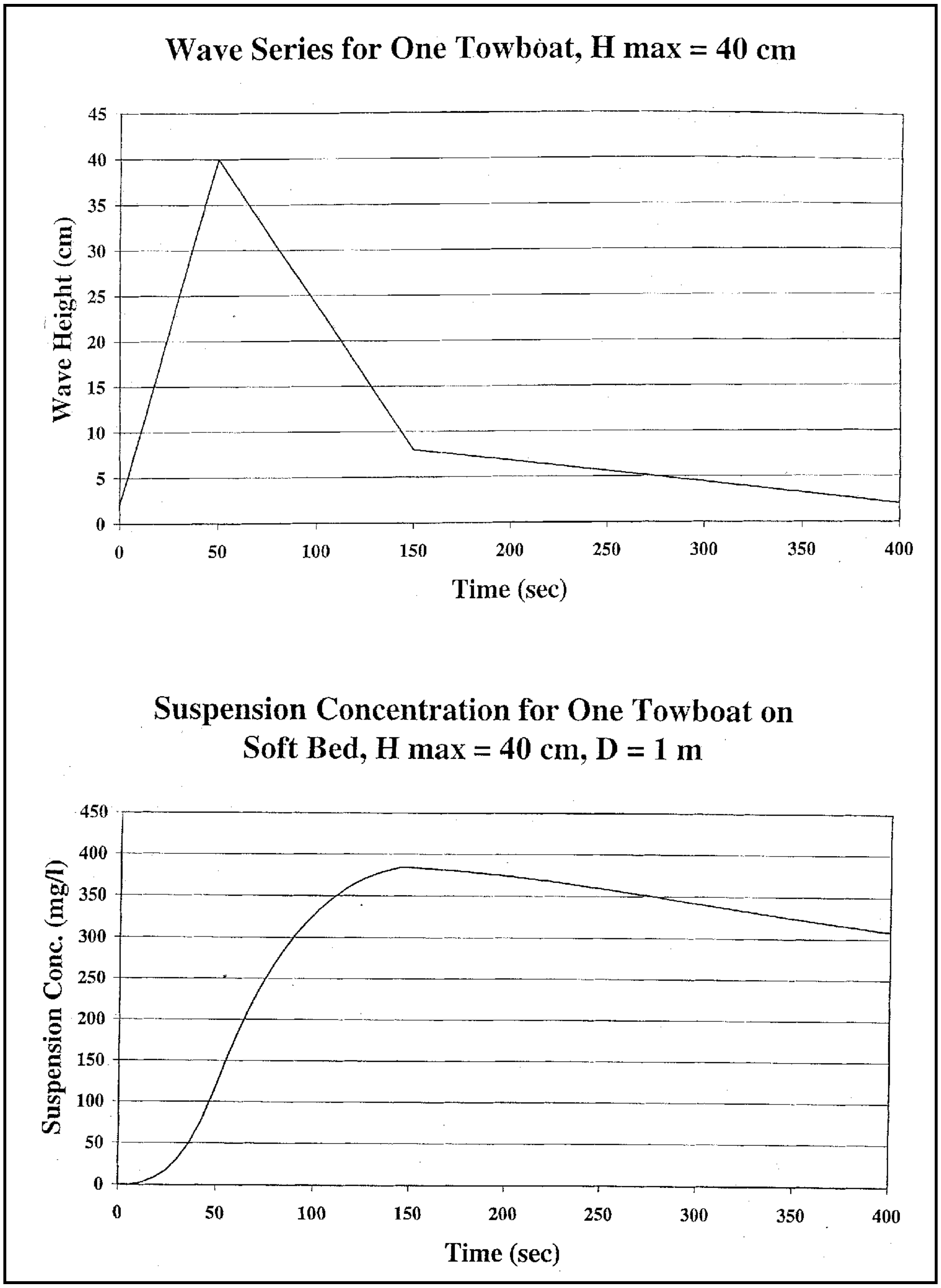


Figure 61. Suspension concentration resulting from passage of a single towboat generating a maximum wave height of 60 cm

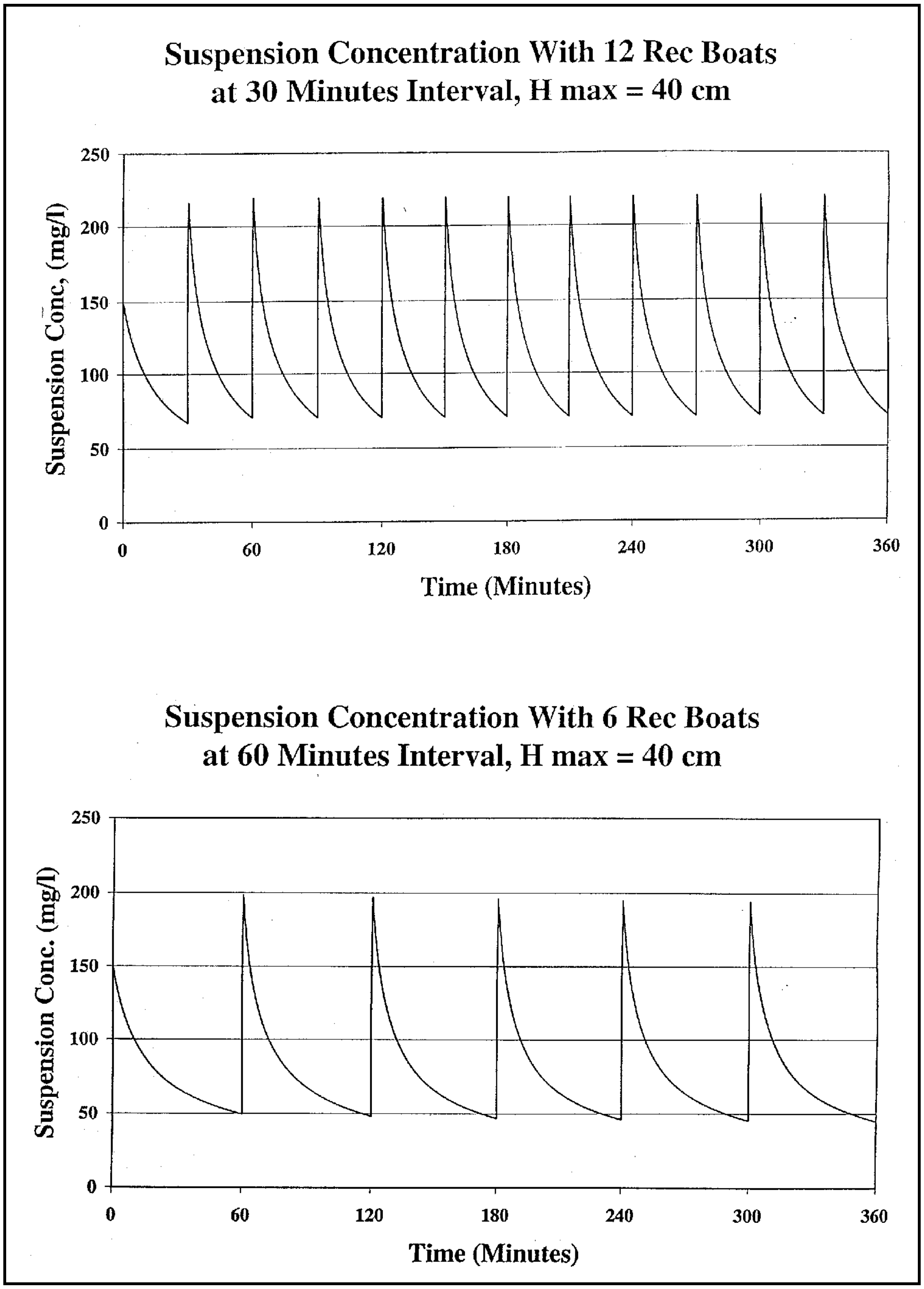


Figure 62. Suspension concentration resulting from passage of a series of recreational boats, each generating a maximum wave height of 40 cm every 30 min

Appendix A
Procedure Demonstration

The sediment classification and procedures described in this appendix were developed specifically for the Upper Mississippi River project where preliminary estimates of wave-induced sediment resuspension were urgently needed in spite of limitations on the size and analysis of field and laboratory database relative to the total project area. The results were expected to be used for (a) assessment of relative impact of increased barge traffic in the river and (b) identification of potential areas along the riverbanks that are likely to be sensitive from the point of view of environmental considerations, and may need further evaluations. Use of these procedures outside the Upper Mississippi River project will require a separate evaluation of applicability.

Part 1: Classification of Bed Sediment Sample Based on its Relative Erodibility

Step 1: Classification based on particle size distribution

Need measured values of the following three bed sample parameters:

a. Particle size distribution curve, particularly percentage of sediment finer than 4 microns and percentage of sediment finer than 62 microns, or values of D_{70} and D_{16} .

b. Percentage of total organic matter.

c. Wet bulk density.

If the sample contains 70 percent or more particles finer than 4 microns (i.e., $D_{70} < 4$ microns), it is classified as Group1-Cohesive. Such samples contain 70 percent or more clay and less than 30 percent silt plus sand. Follow steps in Figure 38 for labeling.

If the sample does not fall in Group1-Cohesive and contains more than 70 percent sediment finer than 62 microns (i.e., $D_{70} < 62$ microns), or if it contains more than 16 percent sediment finer than 4 microns (i.e., $D_{16} >$ 4 microns), it is classified as Group2-Cohesive. Such samples contain 70 percent or more silt plus clay. Follow steps in Figure 39 for labeling.

If the sample contains 30 percent or more sediment coarser than 62 microns, and less than 16 percent of sediment finer than 4 microns (i.e., $D_{70} > 62$ microns and $D_{16} > 4$ microns), it is classified as Noncohesive. Follow steps in Figure 40 for labeling.

Use format suggested in Figure A1 to record the classification based on Step 1. Samples under Group1-Cohesive and Group2-Cohesive are given further *Erodibility Labels* to indicate their relative resistance to erosion.

Step 2: Classification based on percentage of total organic matter

Determine the value of percentage of total organic matter.

a. If it is less than 5 percent, classify it as low.

b. If it is between 5 and 10 percent, classify it as moderate.

c. If it is more than 10 percent, classify it as high.

Use format suggested in Figure A1 to record the classification based on Step 2.

Step 3: Classification based on wet bulk density

Determine the value of wet bulk density.

a. If the sample is classified as Group1-Cohesive, look up Step 3 under Figure 38.

b. If the sample is classified as Group2-Cohesive, look up Step 3 under Figure 39.

Use format suggested in Figure A1 to record the erodibility label of soft, medium, or hard assigned under the column labeled Step 3.

<u>NOTE</u>: After following these three steps, each bed sample initially classified as Group1-Cohesive or Group2-Cohesive will ultimately be classified in Figure A1 under three erodibility labels, soft, medium, or hard. These labels refer only to the relative erosional resistance of the sediment sample.

Part 2: Estimation of Vessel-Induced Wave Height

Using the procedure recommended in Chapter 4 of the main text, determine the estimated maximum wave height generated by the passage of a vessel at the location of interest. The estimated maximum wave height H_{max} has to be in a water depth of 1.5 m.

Sample #	% Weight Finer Than 4 microns	% Weight Finer Than 62 microns	% Weight Coarser Than 62 microns	Step 1 Classification	Organic Content %	Step 2 Classification	Bulk Density kg / m^3	Step 3 Classification
6001	21	80	20	Silt Mixture	3.18	Low	1873	Medium

Figure A1. Format for recording sediment classification based on three measured parameters of bed samples

Part 3: Estimation of the Maximum Suspended Sediment Concentration

Select one of the three soil types, soft, medium, or hard, from Tables 3, 4, and 5, respectively, in the main text compatible with the sample classified in Figure A1 under the same categories.

Read the value of maximum suspension concentration from the selected table for the required values of water depth and the maximum wave height H_{max}. For example, a 60-cm wave height in 1.0-m water depth on a soft bed will produce a maximum suspension concentration of 217 mg/L (from Table 3). An “X” in Tables 3-5 indicates wave breaking due to shallow water. The algorithm used for this study does not offer a solution under these conditions.

Boat-induced waves consist of a time series of waves, which rapidly increase in height initially and then gradually decrease in height. For convenience and consistency, all waves are assumed to have a 2-sec period and the average total duration of each event is assumed to be 7 min. These assumptions are based on an extensive analysis of actual observations. Deviations from these assumptions are minor, and they do not affect the results significantly. This wave train pattern has been simulated with the sediment model. Hence the suspension concentration also has a pattern that consists of a rapid increase in suspension concentration followed by a gradual decrease, as shown in Figure 45 of the main text as an illustration. The value of C_{max} obtained earlier (217 mg/L) is the highest value under the time series of suspension concentration for a 60-cm wave in 1-m water depth on a soft bed.

Part 4: Effect of Background (Ambient) Suspension Concentration

For conditions under the present study, the bed shear stress increases very rapidly from zero to maximum within a duration of less than 3 min. Due to high levels of turbulence during this phase, the suspended fine sediment does not settle. Several runs of the sediment model were conducted to assess the effect of background concentration on the final concentration resulting from the wave train conditions selected for this work. It is concluded that the final value of suspension concentration may be obtained by adding the background (ambient) concentration to the value of C_{max} determined for the zero initial concentration. For example, a wave train with a maximum wave height of 60 cm in 1.0-m water depth would produce a maximum concentration of 217 mg/L with zero initial concentration. If the ambient concentration is 50 mg/L, the maximum concentration would be 217 + 50 = 267 mg/L.

Part 5: Estimation of 1-hr Decrease in Suspension Concentration in 1 Year Resulting from Deposition Without Waves

After the 7-min event of waves, the wave activity dies down to zero. Deposition of suspended sediment commences after the wave heights decrease during the wave decay period. With no waves, sediment deposition takes place at a faster rate. The fall velocity of cohesive sediments and mixtures of clay and fine silt is a function of suspended sediment concentration. For the present case, the process is shown in Figure A2. The results shown in this figure were obtained by using the sediment deposition algorithm. An average value from the graph may be used.

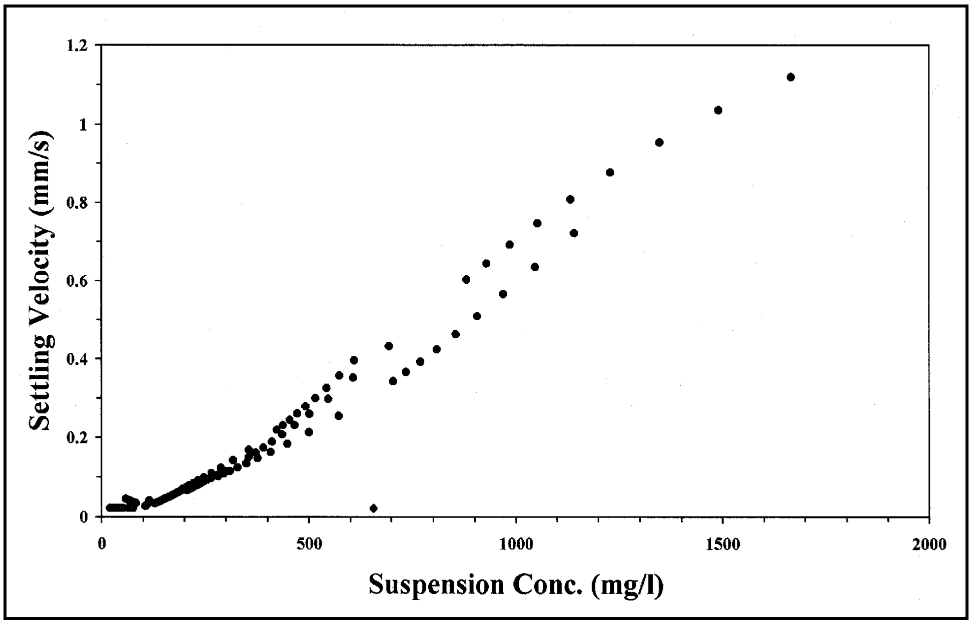


Figure A2. Settling velocity versus suspension concentration

Suspended sediment concentration decreases when the wave height decreases. For the case shown in Figure 45, the suspension concentration dropped from the maximum of 217 mg/L to 190 mg/L in less than 5 min.

The subsequent decrease in sediment concentration takes place asymptotically as illustrated in Figure A3**.** In this case, the initial concentration of 210 mg/L dropped to 157 mg/L within the next hour.

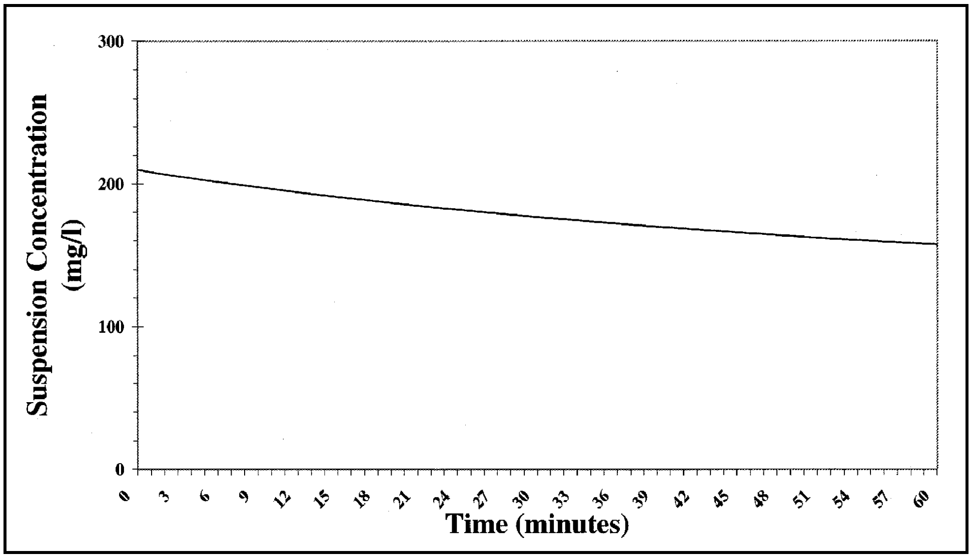


Figure A3. Sediment deposition under zero waves, initial concentration = 210 mg/L

Part 6: Estimation of Time Needed for the Suspension Concentration to Drop Back to the Background Magnitude of Concentration

A series of curves similar to that shown in Figure A3 were plotted for a range of initial concentration values. The data on initial concentration versus concentration after 1 hr of sediment deposition are plotted as a graph shown in Figure A4.

This graph can be used to answer the following questions:

a. What will be the suspension concentration after a deposition time of, say, "T1"?

b. How much time will be needed for the suspension concentration to drop to the ambient concentration C_{bak}?

Example a: Take the concentration at the end of a 7-min event of vessel passage as 400 mg/L and time T1 = 1 hr and 40 min

From Figure A4, line *a*, the initial suspension concentration of 400 mg/L will drop to 190 mg/L after 60 min.

Now consider 190 mg/L as the initial concentration. From Figure A4, line *b*, the 190 mg/L will reduce to 140 mg/L after the next 60 min.

Thus

C = 400 mg/L at time = zero

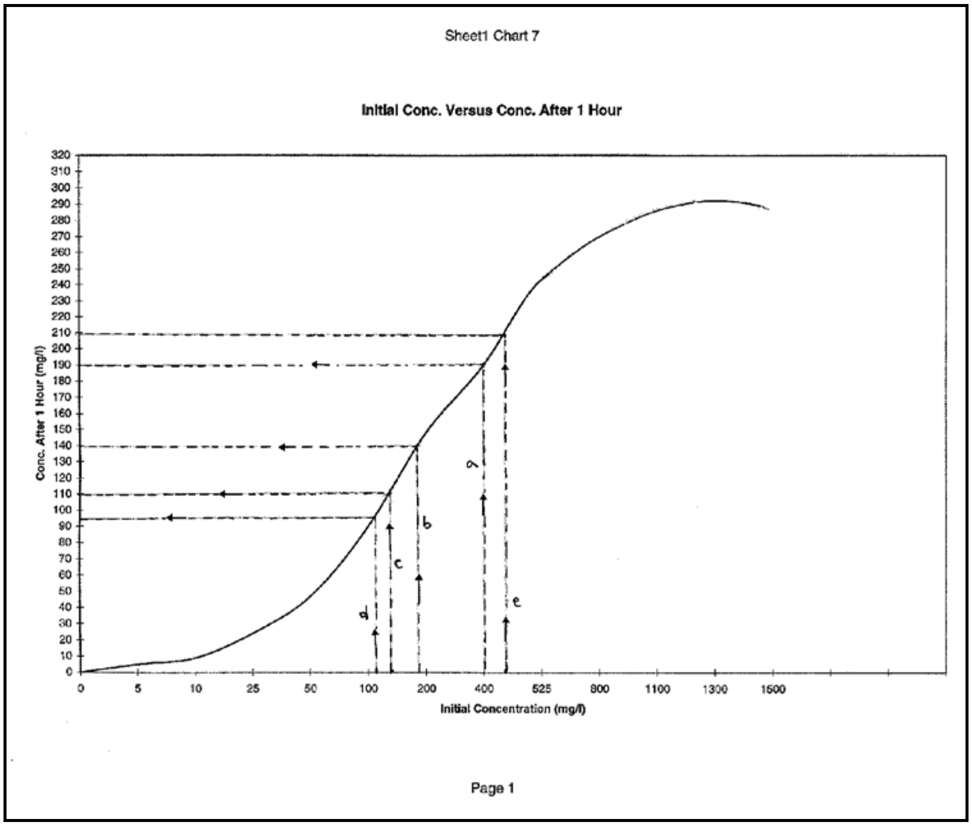


Figure A4. Initial concentration versus concentration after 1 hr

C = 190 mg/L at time = 1 hr

C = 140 mg/L at time = 2 hr

A linear interpolation between the last two values gives C = 157 mg/L at the end of 1 hr and 40 min.

Example b: Let C_{bak} be equal to 100 mg/L

Repeating this procedure gives

C = 110 mg/L at time = 3 hr (*c* in Figure A4)

C = 95 mg/L at time = 4 hr (*d* in Figure A4)

Linear interpolation gives that the concentration will be 100 mg/L at time = 3 hr and 40 min.

Part 7: Effect of Passage of Next Vessel

To determine the effect of passage of the next vessel before the suspended sediment resulting from the previous vessel passing drops down to background value:

Example: Background concentration C_{bak} = 50 mg/L

Type of sediment: soft
Maximum wave height during the first event of vessel passing = 40 cm
Water depth = 1.0 m, wave period = 2 sec
Time interval between the two successive events of boat passing = 40 min
Maximum wave height during the second event of vessel passing = 30 cm

From Table 3 for soft sediment, H_{max} = 40 cm, and D = 1.0 m

C_{max} = 384 mg/L
Add background concentration of 50 mg/L
Actual C_{max} = 434 mg/L

From Figure A4, line *e*,

C = 210 at time = 60 min
Rate of decrease = (434 - 210) / 60 = 3.73 mg/L per minute
Hence, C = 434 - (3.73 × 40) = 285 mg/L at time = 40 min

The next event has H_{max} = 30 cm.

From Table 3, H_{max} = 30 cm, D = 1.0 m, C_{max} = 218 mg/L

Add concentration from the previous event at the end of 40 min, i.e., 285 mg/L.
Hence maximum concentration at the end of second event = 285 + 218 = 503 mg/L.

Part 8: Entrainment of Noncohesive Sediment

When the sediment sample contains 30 percent or more particles coarser than 62 microns, the sediment is termed Noncohesive for the present project.

Use Figure A5 to determine critical shear stress for erosion of particles of any size between 100 and 4,000 microns (0.1 mm to 4.0 mm). For example, a sand particle of 500 microns (0.5 mm) in diameter has a critical shear stress of 0.287 Pascal. (One Pascal, denoted as Pa, is equal to 1 N/m^2.)

A parameter R_* appears in Figure A5. This is called the Boundary Reynolds Number and is given by

$$R_* = (u_* d_s) / \nu$$

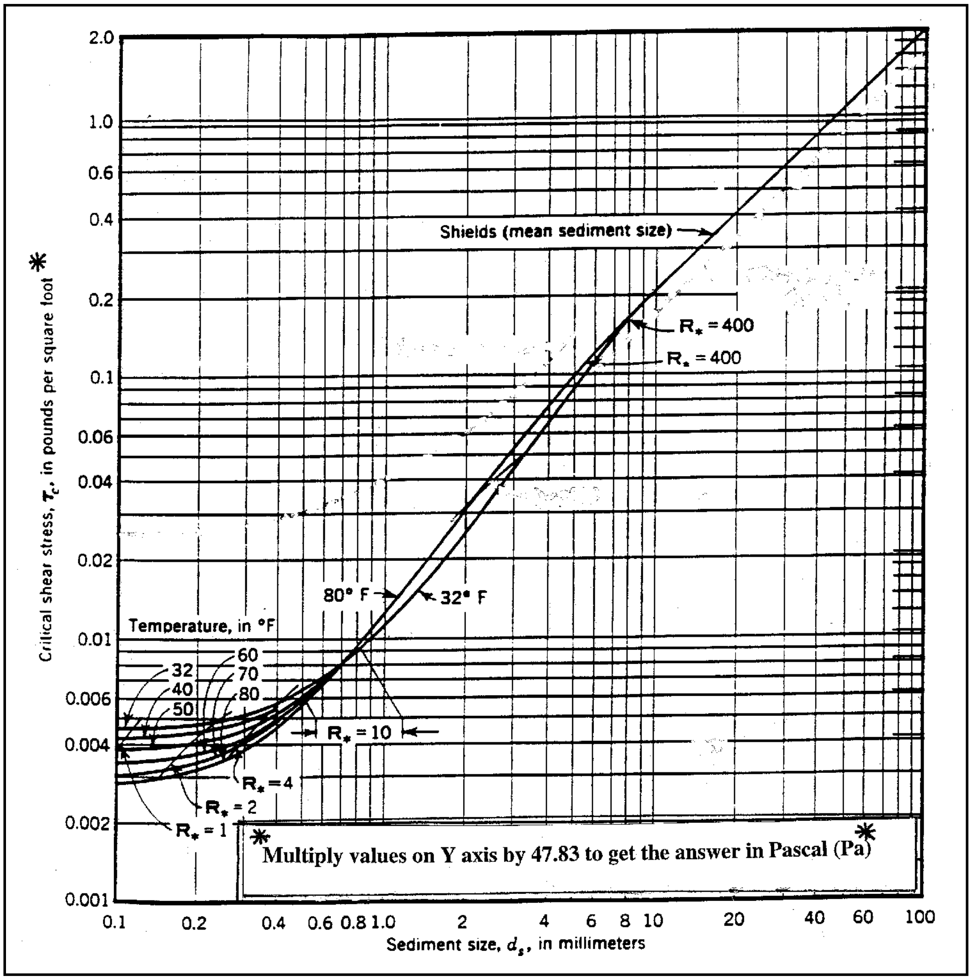


Figure A5. Critical shear stress for sand particles in water for different grain diameters (from V. A. Vanoni, ed. (1975). *Sedimentation engineering.* American Society of Civil Engineers, New York, reproduced with permission from ASCE)

where

$u*$ = shear velocity defined by $u* = \sqrt{(\tau_0/\rho)}$

τ_0 = bed shear stress

ρ = density of water

d_s = particle diameter

ν = kinematic viscosity of water

The parameter $R*$ needs to be calculated when the particle size is smaller than 0.5 mm.

Wave-induced bed shear stresses are given in Figures A6, A7, and A8 for water depths of 1.5 m, 1.0 m, and 0.5 m, respectively, for wave heights ranging from 10 to 60 cm with a wave period of 2 sec.

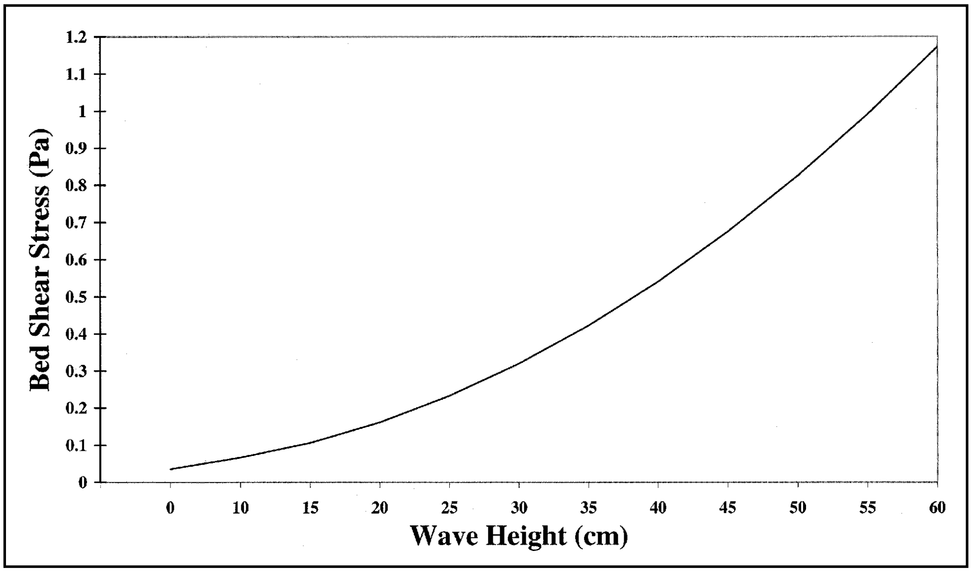


Figure A6. Wave-induced bed shear stress, D = 1.5 m

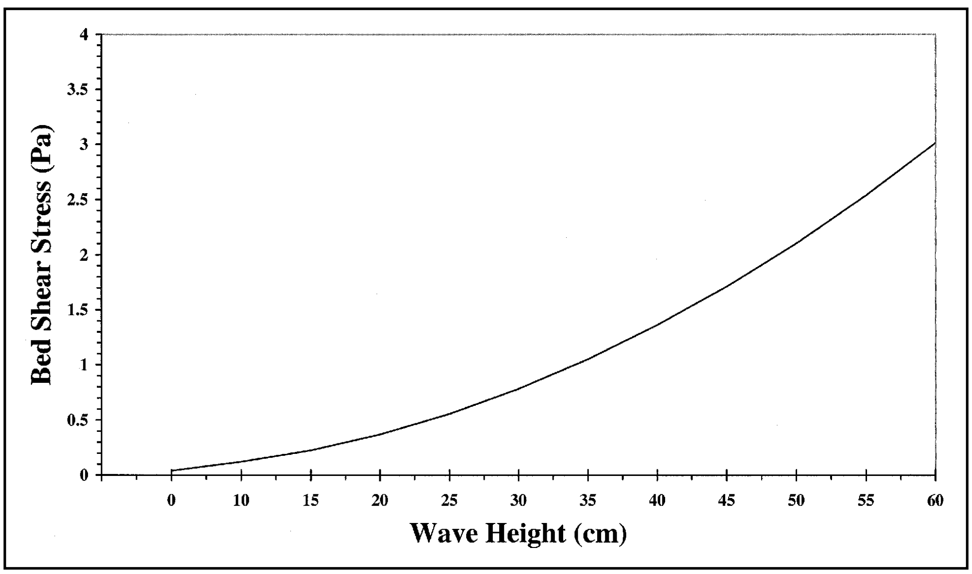


Figure A7. Wave-induced bed shear stress, D = 1.0 m

Example: Consider a wave height of 40 cm in 1.0-m depth. From Figure A7, the wave-induced bed shear stress would be 1.4 Pa. Since this is larger than the critical shear stress of 0.287 Pa needed to move the sediment, sand particles of 0.5-mm diameter (and smaller) will be entrained.

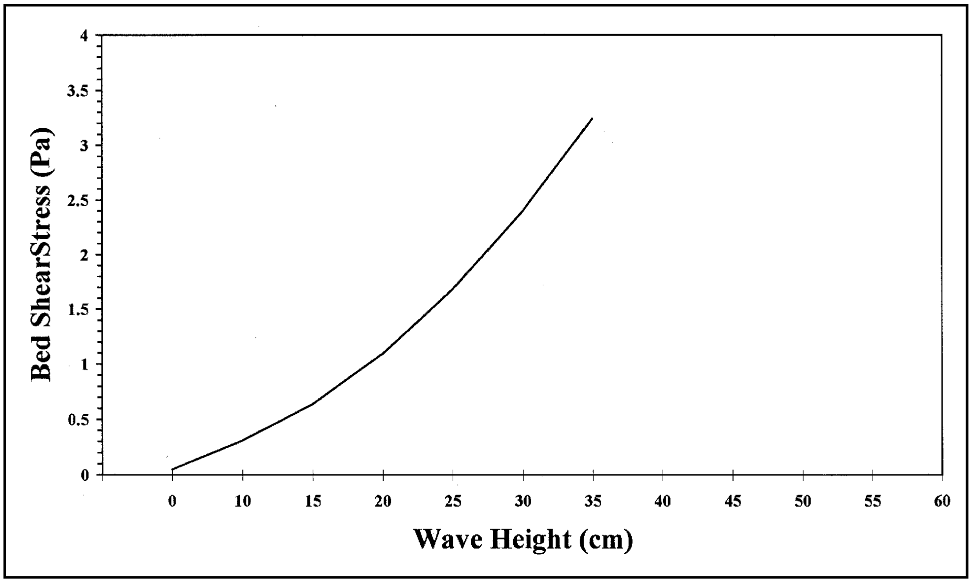


Figure A8. Wave-induced bed shear stress, $D = 0.5$ m

It may be seen from Figure A7 that waves greater than 18 cm in 1.0-m depth have critical shear stress of 0.287 Pa or more. Hence these waves will dislodge sand particles smaller than 0.5 mm from the bed.

Part 9: Time Required to Settle Sand Particles

Use Figure A9 to determine time required to settle sand particles. For instance, a sand particle of 0.2-mm diameter and shape factor of 0.5 has a fall velocity of about 2.5 cm/s at water temperature of 30 ºC. Hence in the absence of river current, it will take only 60 sec to redeposit on the bed in 1.5-m water depth.

The shape factor is given by $SF = c / \left(\sqrt{ab}\right)$, where *a, b,* and *c,* respectively, are the lengths of the largest, intermediate, and shortest mutually perpendicular axes of the particle.

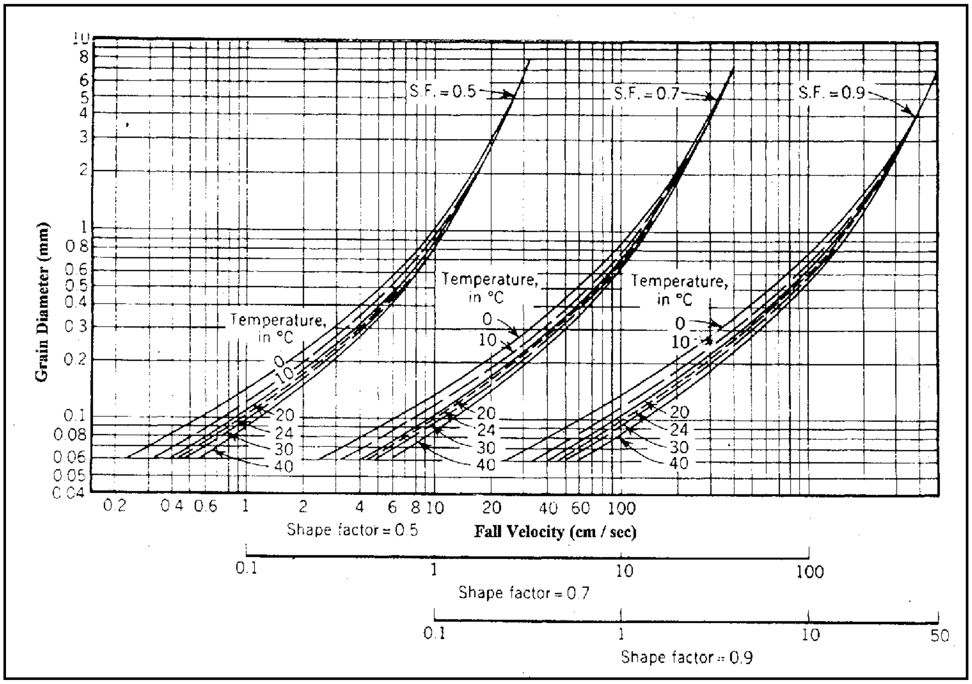


Figure A9. Fall velocity as a function of grain diameter, shape factor, and temperature (from V. A. Vanoni, ed. (1975). *Sedimentation engineering.* American Society of Civil Engineers, New York, reproduced with permission from ASCE)

Appendix B
Notation

A_{ab}	Wave parameter
a	Empirical coefficient
a_r	Empirical coefficient
b	Empirical coefficient
b_r	Empirical coefficient
C	Sediment mass concentration
C_{bed}	Sediment concentration just above the bed
C_{sf}	Upper concentration limit on free settling
d_b	Wave-breaking water depth
E	Erosion rate
f_c	Current friction factor
f_w	Wave friction factor
F_n	Erosion/deposition flux at the bed
g	Acceleration of gravity
h	Water depth
H	Wave height
H_b	Breaking wave height
H_{L1}	20 percent of H_{max} or 5 cm, whichever is greater
H_{max}	Maximum value of wave height
k	Wave number

K Diffusion coefficient

K_s Nikuradse roughness parameter

m_1 Empirical coefficient

m_2 Empirical coefficient

n Manning's roughness coefficient

R_i Gradient Richardson number

R_* Boundary Reynolds number

s Erosion rate constant

s_{max} Empirical coefficient

t Time

u Horizontal velocity (current plus wave)

u_b Wave orbital velocity amplitude at the bed

u_* Shear velocity

U Depth-averaged current velocity

W_s Sediment settling velocity

W_{sf} Free settling velocity of sediment, determined by experiment

z Vertical dimension

α_e Empirical coefficient

α_w Wave diffusion constant

α_0 Empirical coefficient

β_e Empirical coefficient

β_0 Empirical coefficient

ϕ Solids weight fraction

ϕ_e Critical value below which the mud behaves like a fluid

κ von Karman coefficient, taken to be 0.4

ρ Fluid density

σ Wave frequency

τ_b Bed shear stress

τ_d Critical shear stress for deposition, determined by experiment

τ_e Critical shear stress for erosion

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13. ABSTRACT ***(Maximum 200 words)***

Part of the Upper Mississippi River-Illinois Waterway System Navigation Study deals with estimation of environmental impacts caused by an increase in navigation traffic. Resuspension and deposition of fine clayey sediment have a significant impact on aquatic plants and animals. The objective of the study described in this report was to estimate the sediment resuspension resulting from waves generated by towboats and recreational craft. The scope of this study was limited to (a) generalization of wave patterns for the event of vessel passage, (b) estimation of maximum suspension concentration caused by individual events of vessel passage, (c) deposition of suspended sediment, and (d) interference effect on the suspended sediment concentration caused by the passage of another vessel.

The Coastal and Hydraulics Laboratory, Vicksburg, MS, U.S. Army Engineer Research and Development Center, conducted field measurements for wave heights, current, and suspended sediment concentration at various sites during November 1995, July 1996, and September 1996. The wave heights were measured with a pressure sensor, currents with a current meter, and suspended sediment concentration with Optical Backscatter (OBS) sensors. The

(*Continued*)

14. SUBJECT TERMS

Boat traffic in Mississippi River	Towboat traffic
Fine sediment resuspension	Upper Mississippi River System
Recreational vessel	Vessel-generated waves
Sediment resuspension	Wave-induced sediment resuspension

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following conclusions are drawn: (a) large vessels generate large drawdown and small wave heights but a high suspended sediment concentration, and (b) small vessels such as a yacht generate small drawdown and large wave heights. At high speed, small vessels also cause a substantial increase in suspended sediment concentration.

The laboratory and field data on vessel-induced waves were analyzed to determine various statistical parameters for each vessel-generated wave train, and generalized patterns were evolved for conducting model runs.

Surface sediment samples collected from the nearshore region were subjected to laboratory determination of particle size distribution using a Coulter counter. Erosion tests were conducted using the Particle Entrainment Simulator (PES) to compute the rate of erosion and to determine the critical shear strength of the bed material. The sediment samples were also analyzed to determine the total organic content and bulk density.

A new system of sediment classification was evolved based on particle size, total organic content, and bulk density. A protocol was developed for assigning one of three erodibility labels, such as soft, medium, and hard, based on these three sediment properties. With this procedure, the sediment bed labeled as soft is easier to erode than the bed labeled medium. Similarly, the sediment bed labeled as medium is easier to erode than the bed labeled as hard.

A new numerical sediment resuspension model, VESTUNS, was developed for predicting the concentration of suspended sediment in the nearshore zone. It uses a one-dimensional (vertical, 1DV) numerical solution of the convection diffusion equation to compute the vertical profile of sediment. It accounts for sediment settling and deposition plus erosion from the bed and upward diffusion by short-period waves and/or a superposed current. It considers the bed to be formed of mud with significant quantities of cohesive material. The model was verified using field and laboratory data. The model is very versatile. Effects of several relevant parameters such as wave height, wave period, time interval between consecutive vessels, water depth, type of vessel, characteristics of vessel, and sediment properties were evaluated from the use of this model. Effects of background concentration and sediment deposition were also evaluated. Model applications provided answers to the following: (a) whether the sediment at any given location is susceptible to erosion or not as a result of vessel-induced waves; (b) if it is erodible, the expected value of maximum sediment concentration in suspension, and (c) how long the sediment will remain in suspension.

The conclusions of the study are as follows: (a) a simple approach reported in this study should suffice for a preliminary estimation needed in the context of near-bank erosion of the Mississippi River; (b) a simplified approach is provided for classifying sediments based on their erodibility; (c) the report presents basic mathematical expressions and a recommended approach for estimating sediment resuspension under vessel-generated waves; (d) the proposed approach can be used for a reasonable prediction of wave-induced near-bank erosion with cohesive or noncohesive sediments without the effect of vegetation on the banks; (e) due to the complexity of real-life situations combined with the assumed simplification of the physical phenomena, the model may not give exact answers for a given site; however, it does provide consistent and reasonable estimates of suspension concentration values for evaluation of environmental impacts over large reaches of the river.