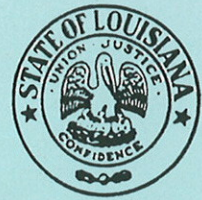
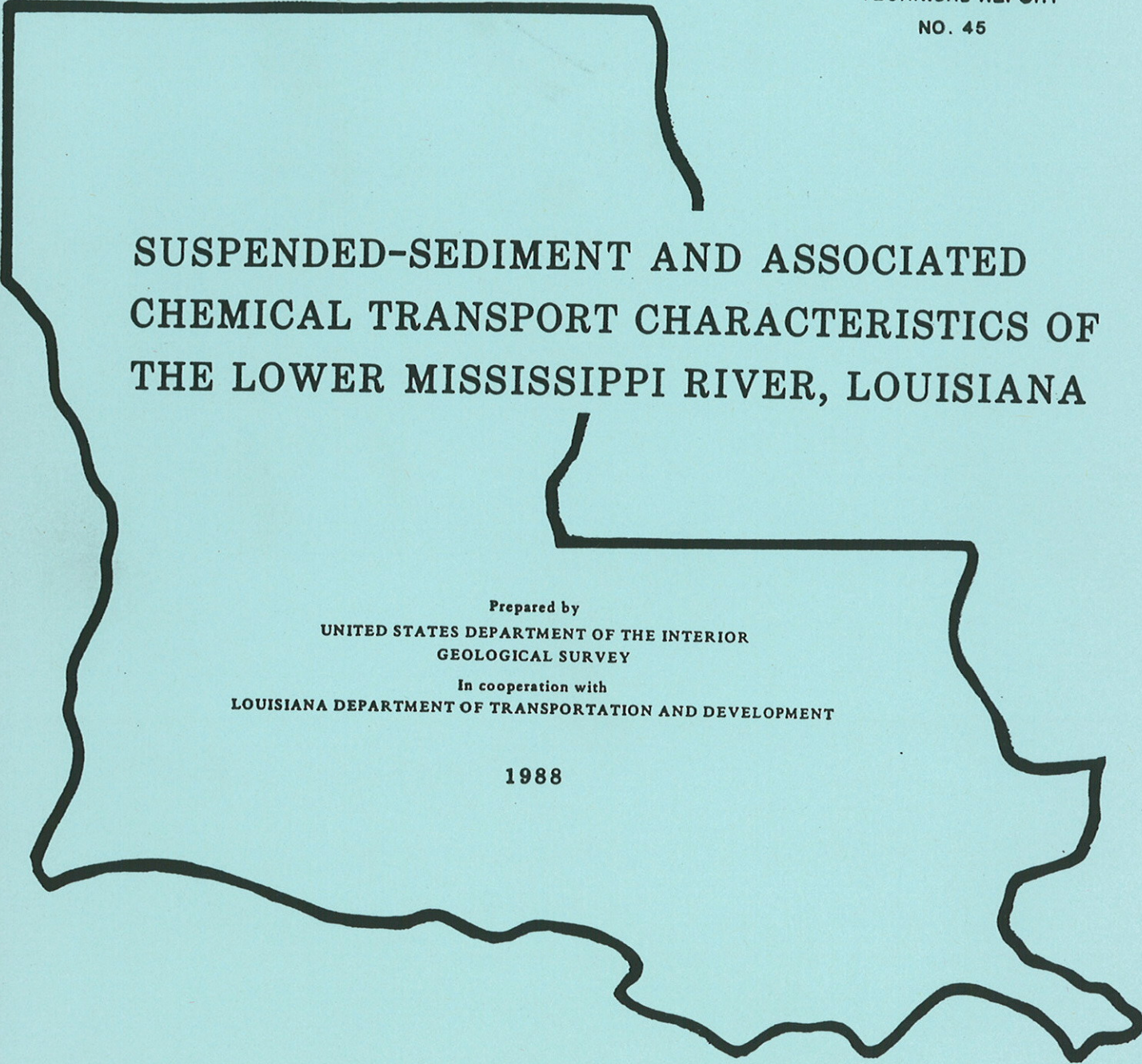




STATE OF LOUISIANA
DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT



WATER RESOURCES
TECHNICAL REPORT
NO. 45



SUSPENDED-SEDIMENT AND ASSOCIATED
CHEMICAL TRANSPORT CHARACTERISTICS OF
THE LOWER MISSISSIPPI RIVER, LOUISIANA

Prepared by
UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
In cooperation with
LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT

1988

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DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT

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CHARACTERISTICS OF THE LOWER MISSISSIPPI RIVER,
LOUISIANA

By
Charles R. Demas and Philip B. Curwick
U.S. Geological Survey

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CONVERSION FACTORS AND ABBREVIATIONS

For the convenience of readers who prefer to use metric (International System) units rather than the inch-pound units used in this report, values may be converted by using the following factors:

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square inch (in ²)	6.452	square centimeter (cm ²)
square foot (ft ²)	929.0	square meter (m ²)
square mile (mi ²)	0.0929	square kilometer (km ²)
ounce, fluid (fl. oz)	2.590	liter (L)
pint (pt)	0.02957	liter (L)
quart (qt)	0.4732	liter (L)
gallon (gal)	0.9464	liter (L)
	3.785	liter (L)
	0.003785	cubic meter (m ³)
cubic foot (ft ³)	0.02832	cubic meter (m ³)
foot per second (ft/s)	0.3048	meter per second (m/s)
ton, short, per day (ton/d)	0.9072	metric ton per day (ton/d)
ton, short	0.9072	megagram (Mg)
ounce (oz)	28.35	gram (g)
pound (lb)	453.6	gram (g)

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows: °F = 1.8 X °C + 32.

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level of 1929."

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SUSPENDED-SEDIMENT AND ASSOCIATED CHEMICAL TRANSPORT CHARACTERISTICS OF THE
LOWER MISSISSIPPI RIVER, LOUISIANA

By Charles R. Demas and Philip B. Curwick

ABSTRACT

The most efficient use of the Mississippi River for navigation and its manipulation for land accretion requires an understanding of suspended-sediment transport and deposition in the river system. The concentration of chemical constituents carried by suspended sediments is of comparable importance in selecting land accretion strategies because the sediment represents a significant reservoir of possible hazardous and toxic substances that could be released to the environment.

Suspended-sediment and associated chemical characteristics were determined for a 295.6 mile reach of the lower Mississippi River extending from Tarbert Landing, Mississippi, to Venice, Louisiana. The concentration of suspended sediment decreases in a downstream direction during steady flow conditions of less than 500,000 ft³/s (cubic feet per second) and increase in a downstream direction during steady flow conditions greater than 700,000 ft³/s. Observed variations of suspended-sediment concentration were caused by fluctuations in the silt and clay concentration rather than in the sand concentration. Data indicate that the bed of the lower Mississippi River in the study reach serves as a sink and reservoir for suspended sediment during flows less than 500,000 ft³/s and conversely a source of sediment for suspension during flows greater than 500,000 ft³/s.

Chemical analysis of unfiltered-water samples showed strong linear correlations ($r > 0.7$) between concentrations of fines and total-recoverable and suspended manganese, iron, and cobalt. Chemical analysis of three suspended-sediment size classes showed increasing minor-element concentrations with the two smaller sediment-particle sizes. Data indicate that manganese and iron oxide coatings and suspended sediment in the fines size range (< 0.063 millimeters) play a major role in the transport of minor elements in the lower Mississippi River. No correlations were found between semivolatile organic compounds and suspended sediment, indicating little transport of these compounds associated with suspended sediment within the study area.

Suspended-sediment data from six steady-streamflow events were simulated using a Lagrangian transport model. Model results compared favorably with observed data for sand and fines size classes, demonstrating the effectiveness of the model in predicting short-term suspended-sediment transport in the lower Mississippi River.

INTRODUCTION

The Mississippi River is the major commercial inland waterway in the United States and the seventh largest river in the world in terms of discharge. In terms of volume, the ports of New Orleans and Baton Rouge are the number one and number five ports in the Nation, respectively. They handle a combined cargo of approximately 250 million tons per year carried by ocean-going vessels and inland barges. The large amount of ship traffic and size of the Mississippi River make data collection difficult and require innovative techniques in data collection and analyses. Consequently, much remains to be learned about the Mississippi River.

Sedimentation and channel bed movement in the lower Mississippi River are constant threats to navigation and require continuous monitoring. Because of the commercial value of shipping, millions of dollars are spent each year on dredging and navigation projects. The success of a proposed channel deepening from 40 to 45 ft from the mouth of the Mississippi River at Southwest Pass to Baton Rouge will be greatly influenced by the manner in which suspended sediment is transported through this river reach. The chemical constituents associated with these sediments will also, at least in part, affect decisions such as where the dredge spoils will ultimately be deposited and how they will be used.

Additionally, the coast of Louisiana is losing approximately 50 mi²/yr of wetlands (S.M. Gagliano, Coastal Environments, Inc., oral commun., 1984). The causes of this coastal-land loss can probably be traced to man's levee construction along the lower Mississippi River and damming of its major tributaries. Maintenance of a highly productive estuarine, coastal, and marsh habitat requires that this progressive loss be reduced or eliminated, and that saltwater intrusion be minimized. It has been suggested that land accretion to offset coastal-land loss could be accomplished by diverting Mississippi River water below New Orleans, La., into the shallow water areas adjacent to the river, resulting in the availability of new sources of sediment and freshwater to the shallow coastal areas.

The most efficient use of the Mississippi River for transportation and for land accretion requires a thorough understanding of suspended-sediment transport and deposition in the river system. The chemical constituents carried by these sediments is of comparable importance in selecting land accretion strategies, because they could represent a significant reservoir of hazardous or toxic substances or both that could be released to the environment.

Water quality and suspended sediment in the lower Mississippi River have been studied by Everett (1971), Robbins (1976), Meade (1985), Wells (1980), and Grayman (1985). However, a number of questions still remain to be answered: (1) What are the suspended-sediment transport characteristics relative to river hydraulics? (2) What are the sources of suspended sediment in relation to river hydraulics? (3) What are the chemical characteristics, including trace metals and organic compounds, of suspended sediment?

In an effort to answer these questions and better understand movement of minor elements, organic compounds, and suspended sediment in the lower Mississippi River, an intensive sediment-chemical data collection and transport modeling study was initiated in December 1982 and continued through February 1985. This study was jointly funded by the U.S. Geological Survey and the Louisiana Department of Transportation.

Purpose and Scope

The purpose of this report is to describe the physical and chemical characteristics of the suspended and bed sediments in the lower Mississippi River, show how the sediment is transported through the river system, and discuss results of simulation of suspended-sediment transport in the river.

The physical and chemical characteristics of sediment were determined for a 295.6 mile reach of the lower Mississippi River extending from Tarbert Landing, Mississippi, to Venice, Louisiana (pl. 1). Water and sediment samples were collected on a monthly basis. Data collected during the study were used in calibration and verification of the Lagrangian suspended-sediment transport model. Simulations of six steady-streamflow events were made using three particle size fractions: sand (2 to 0.062 mm), silt (0.062 to 0.004 mm), and clay (<0.004 mm). All data collected as part of this study are published in Demas and Curwick (1987).

DESCRIPTION OF STUDY REACH

The lower Mississippi River study reach is leveed for the entire length. Also, there are no tributaries or distributaries of any significance that enter or leave this reach. Cross-sectional widths range from approximately 4,400 ft (Tarbert Landing) at flood stage to approximately 2,000 ft (Belle Chasse) at low flow. Navigation channel depths are maintained at 12 ft from Tarbert Landing, Miss., to Baton Rouge, La., and 40 ft from Baton Rouge, La., to Venice, La. Depths exceeding 100 ft are common along many of the bends throughout the entire study reach. Stream velocities range from less than 2 ft/s to greater than 8 ft/s depending on stage and location.

The flow pattern in the lower Mississippi River is usually unidirectional, turbulent, and pulsating. Exceptions to this flow pattern occur during long periods of extreme low flow and during hurricane surges, when a significant length of the lower study reach is affected by bidirectional flow patterns. Because the thalweg of the lower Mississippi River is below sea level, saltwater intrudes some distance upstream during periods of low flow. The extent of saltwater intrusion depends primarily on river discharge; however, flow duration, wind velocity, tides, and river-bed conditions also influence the upstream intrusion of saltwater (Wells, 1980). For flows above 200,000 ft³/s, saltwater intrusion is not significant and was not included in the modeling.

Turbulent flow is always characterized by local eddying which results in pulsations in the velocity at a fixed point. Figure 1 shows the pulsations observed at a fixed point in the lower Mississippi River at Baton Rouge, La. The discharge was approximately 400,000 ft³/s. Velocities are shown to vary plus or minus 20 percent about the mean in as little as 15 minutes. Despite these temporal variations, flow is nearly uniformly distributed laterally at most locations and for all flow regimes. An example of the lateral-flow distribution is shown in figure 2.

River stage changes vary little from day to day, although it can change as much as eightfold during a major flood. A major flood can last from 2 to 5 months. Discharge behaves similarly to stage in terms of day to day fluctuations but can change ninefold during a major flood. No constant, linear rating between stage and discharge exists for the river. The rating is complicated by combined effects of unsteady flow, sediment load, changing bed forms, and backwater (tide in lower reaches).

MATERIALS AND METHODS

Suspended sediment was collected monthly at eight fixed sites on the lower Mississippi River (pl. 1): Tarbert Landing, Miss. (07295100); St. Francisville, La. (07373420); Plaquemine, La. (07374120); Union, La. (07374220); Luling, La. (07374400); Belle Chasse, La. (07374525); West Pointe a la Hache, La. (07374530); and Venice, La. (07374550). All sites except Tarbert Landing, Miss., and West Pointe a la Hache, La., were also sampled on a monthly basis for selected total-recoverable and dissolved minor elements in the water column. All of the fixed sites were sampled periodically for minor elements in separate particle-size fractions of suspended sediment and bottom material, and trace-organic compounds in unfiltered water, filtered water, and bottom material.

Suspended sediment was sampled intensively during six steady-flow conditions. Suspended-sediment samples were collected every 5 to 10 river miles along the lower Mississippi River, extending from Tarbert Landing, Miss., to Venice, La. Suspended-sediment samples were never collected at any site (monthly or intensive) when saltwater was present at that site; the presence of saltwater at a site was determined from specific conductance profiles. This procedure was followed because of the flow reversal that takes place below the freshwater-saltwater interface and the inability to determine if the sampler was oriented properly to the direction of flow.

Discharge was measured monthly at Tarbert Landing, Miss., and Belle Chasse, La., during the study period. Discharge measurements were made at Tarbert Landing, Miss.; Belle Chasse, La.; and West Pointe a la Hache, La., and intermittently at St. Francisville, La.; Plaquemine, La.; and Union, La., during the intensive suspended-sediment surveys. Measurements were made using the moving boat technique according to methods reported by Smoot and Novak (1969). Figure 3 shows the stage hydrograph at Red River Landing, La. (07373290), and dates of sample collection.

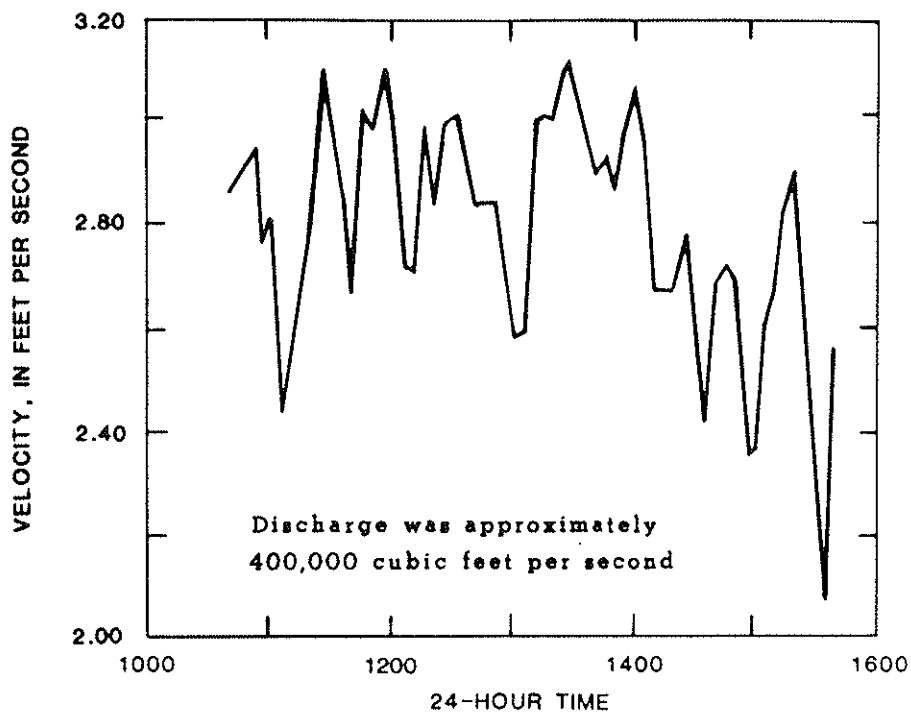


Figure 1.--Velocity fluctuations measured on the Mississippi River at Baton Rouge, Louisiana, September 17, 1974.

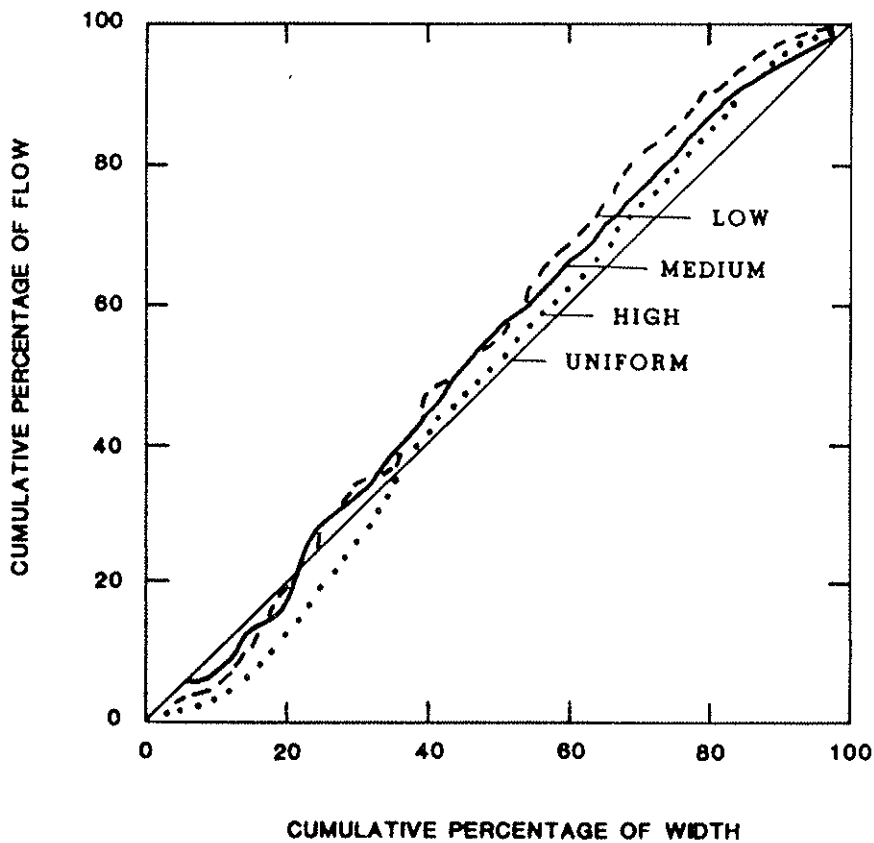


Figure 2.--Lateral flow distribution at low, medium, and high discharges of the Mississippi River at Belle Chasse, Louisiana.

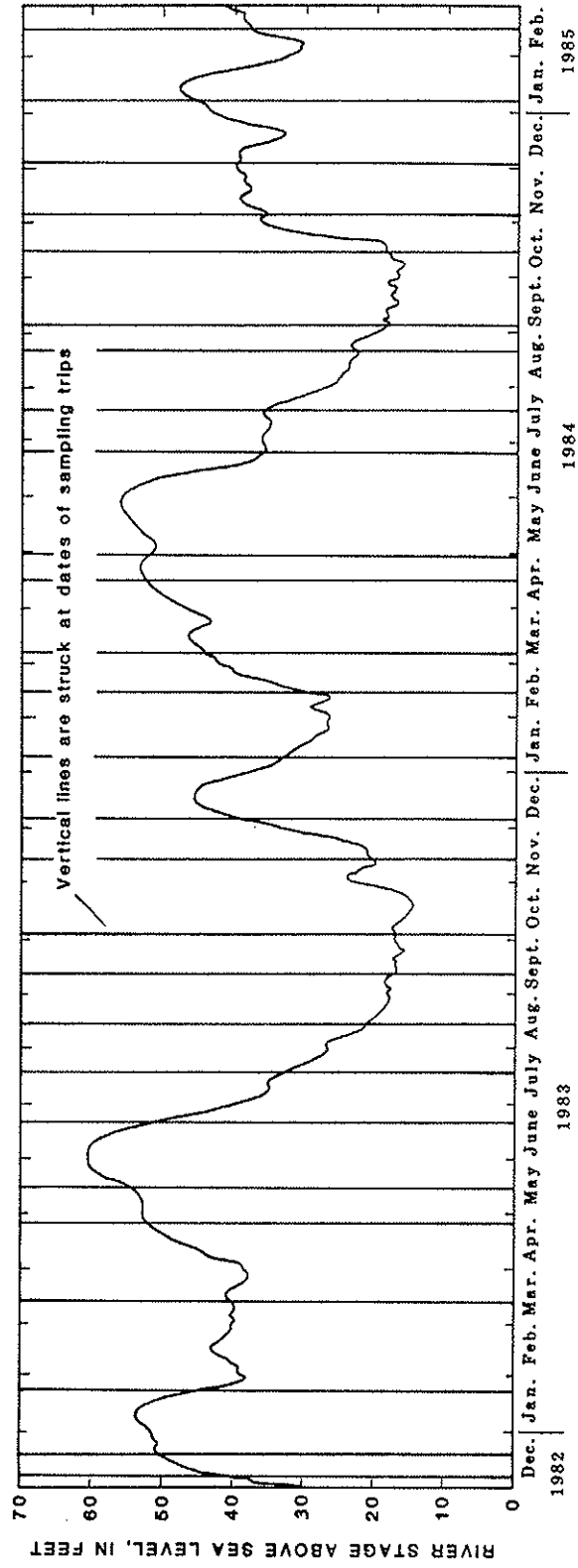


Figure 3.--Daily stage of the Lower Mississippi River at Red River Landing, Louisiana, during the study.

Specialized Sampling Equipment and Field Procedures

A 23-foot, deep v-hull work boat powered by twin 200-horsepower outboard engines was used as the data-collection platform on the lower Mississippi River. This boat (fig. 4) is equipped with a portable aluminum boom, originally designed by C.C. Cranston of the Washington District of the U.S. Geological Survey and slightly modified for our application. Attached to the boom is a standard E-reel powered by a variable-speed hydraulic winch system, developed at the Survey's Hydrologic Instrumentation Facility (W. Rodman and J.T. Wheat, U.S. Geological Survey, written commun., 1985). It allows collection of depth-integrated samples in the water column at constant transit rates in both directions (down and up) at any lateral position in the cross section.

Depth-integrated suspended-sediment and inorganic water-quality samples were collected using an 8-liter collapsible-bag sampler (fig. 5) attached to a 300 lb sounding weight. The field collection procedure was similar to techniques described by Nordin and others (1983). A Price AA current meter was secured to a hanger bar and positioned 1.5 ft above the collapsible-bag sampler. Current meter readings were used to determine the depth-averaged velocity at the vertical. The sampler-nozzle efficiency, E , was calculated at each vertical as:

$$E = \frac{V_{noz}}{V_{stm}} \quad (1)$$

where V_{noz} is the nozzle velocity and V_{stm} is the stream velocity, both in feet per second. The stream velocity was calculated from the standard rating as:

$$V_{stm} = \frac{2.17R}{t_s} + 0.030 \quad (2)$$

and the nozzle velocity was calculated from continuity considerations as:

$$V_{noz} = \frac{VOL}{A_n t_s} \times \frac{1}{30.48} \quad (3)$$

where R is the total number of revolutions recorded from the Price AA current meter; t_s is the total sampling time, in seconds; VOL is the total volume of sample collected, in cubic centimeters; A_n is the cross-sectional area of the sampler nozzle, in square centimeters; 0.030 is a constant; and 30.48 is a conversion factor. It was assumed in these computations that errors associated with the action of lowering and raising a current meter through the water column would be small in comparison to the mean stream velocity. Sampler efficiency was calculated to assure the use of correct sampling techniques and the collection of a representative sample. Adjustments to nozzle size and sampler transit rate were made when sampling efficiency fell outside the desired range, 85-105 percent.



Figure 4.--Work boat used as a data collection platform.

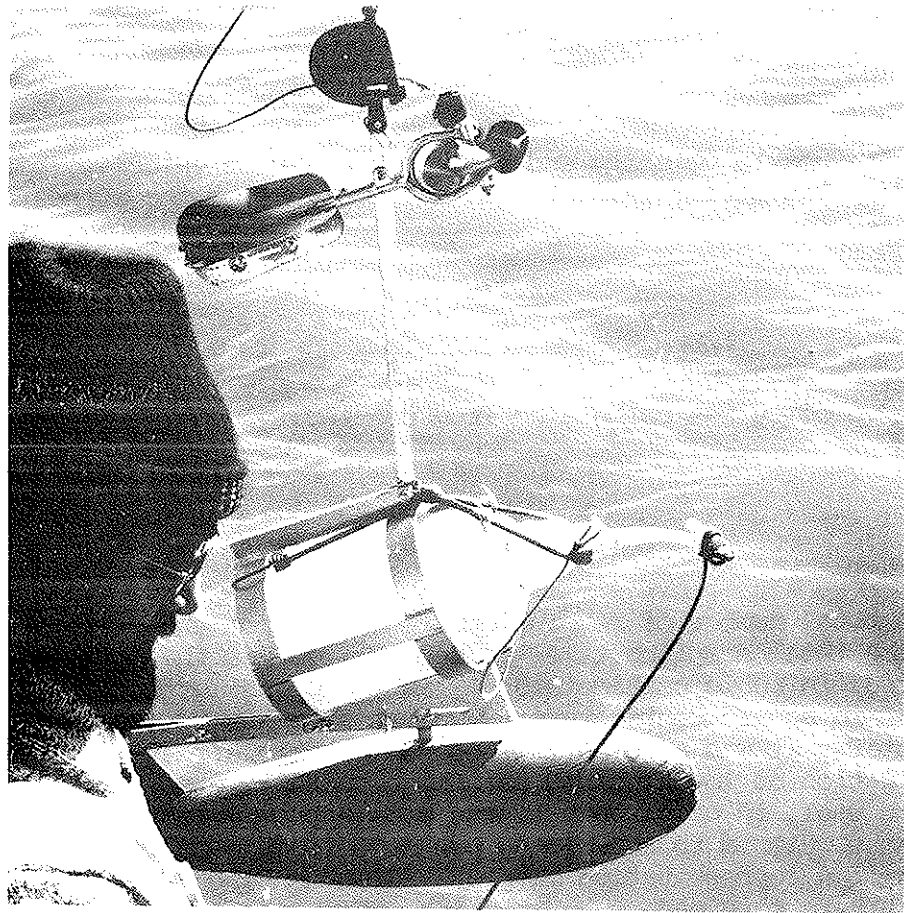


Figure 5.--Collapsible-bag suspended-sediment sampler.

The field sampling procedure was determined only after repeated site visits. Each cross section was sounded and divided into three to five equal-width increments. Lateral positions of verticals at the centroid of each subsection were determined. These positions almost always coincided with equal-discharge increments because lateral-flow distributions were nearly uniform. At each vertical, the work boat was held stationary by throttle adjustments of the outboard motors. The sounding weight, with current meter and sampler, was moved from the water surface to the bed and back to the water surface at a constant transit rate. The constant transit rate was fast enough so the sample container was not completely filled and did not exceed 40 percent of the stream velocity. The accumulated count from the current meter, the total transit time (down and up), and sample volume were recorded. These data were then used to compute the nozzle velocity and nozzle efficiency.

The collapsible-bag sampler allows collection of depth-integrated samples to great depths, whereas conventional depth-integrating suspended-sediment samplers are limited to depths less than 20 ft. Also, its large volume, up to 6.6 L, minimizes time of collection of water-quality samples requiring large sample sizes. Large sample volumes minimize potential analytical errors when suspended-sediment concentrations are low (especially when doing particle-size distribution analyses).

Water Column

The collapsible-bag sampler (Nordin and others, 1983; Stevens and others, 1980) was used to collect depth-integrated water samples for minor-element and inorganic-chemical constituent analyses. Samples were collected at equal-discharge increments across the cross section and composited in a 14-liter churn splitter. Composited samples were immediately processed and treated in the field in one of the Louisiana District mobile laboratories according to methods listed by Brown and others (1970). Processed samples were shipped as soon as possible and analyzed at the U.S. Geological Survey, Central Laboratory, Atlanta, Ga., according to methods listed by Skougstad and others (1979).

Additional suspended-sediment and water-quality samples were collected using a US P-63 suspended-sediment sampler (Guy and Norman, 1970). This sampler (fig. 6) was used to collect suspended-sediment samples at points of different depths in the vertical. The major drawbacks for use of the US P-63 as a suspended-sediment sampler on the lower Mississippi River were its relatively light weight of 200 lb and its relatively small sample size (a maximum of approximately 1 L).

The US P-63 sampler was used primarily for the collection of water samples for analysis of organic compounds because it reduced the chances of possible sample contamination. The sampler is constructed of brass; coated with epoxy; and equipped with a brass nozzle, a stainless-steel valve, and Teflon gaskets. It also accommodates a 1-liter bottle pretreated for collection of organic compounds in water. In contrast, the collapsible-bag sampler is constructed of plastic and uses bags constructed of polypropylene or nylon, both of which have been reported to bleed organic carbon into water (M.E. Thurman, U.S. Geological Survey, written commun., 1984).

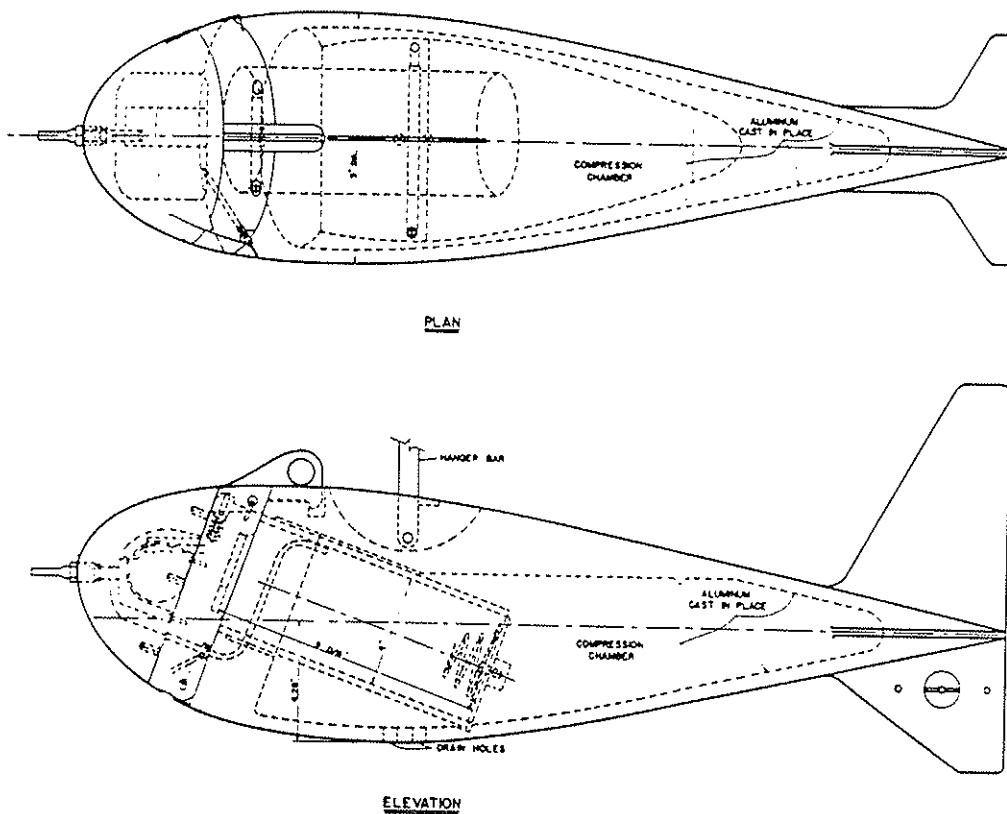


Figure 6.--Point integrated suspended-sediment sampler, US P-63.

All water samples collected for organic-compound analysis (phenols, acid and base-neutral extractable compounds, herbicides, and insecticides) were performed at the U.S. Geological Survey, Central Laboratory, Atlanta, Ga., using methods listed in Wershaw and others (1983).

Water samples for volatile organic-compound analysis were collected using a standard stainless steel sewage sampler. This sampler was selected because it does not aerate samples, flushes sample bottles a minimum of three times, and can easily be cleaned, thereby, minimizing possible sample contamination.

Suspended Sediment

Concentration and Particle-Size Distribution

Suspended-sediment samples were collected using the collapsible-bag sampler and were split into sand (particles >0.0625 mm in diameter) and fines (particles <0.0625 mm in diameter) in the field using an 8-inch brass U.S. Standard No. 230 sieve. Total sample volume was determined in the field using a 4-liter graduated cylinder. For determination of the sand, sand particles were rinsed off the sieve with de-ionized water from a pressurized garden

sprayer and passed through a funnel into a 500-milliliter glass milk bottle. The split containing the fines was poured into an 8-liter churn splitter, mixed, and churned into a 4-liter plastic bottle for particle-size analysis and a 500-milliliter glass milk bottle for total-fines concentration analysis. All bottles were labeled with cross-sectional location, date, time, total depth, and total sample volume. Sediment samples in glass milk bottles and 4-liter bottles were treated with 1 and 2 mL of household bleach, respectively, for prevention of algal growth, and stored for later analysis. All sampling equipment was rinsed with de-ionized water before and after each use.

Suspended-sediment concentration and particle-size distribution were determined at the U.S. Geological Survey, Louisiana District Sediment Laboratory according to methods listed in Guy (1969). The filtration method was used for analysis of concentration of both the sand and fines fractions. The dry-sieve method was used for particle-size analysis of the sand fraction, and the bottom-withdrawal tube method was used for particle-size analysis of the fines fraction.

Suspended-sediment samples were also collected as frequently as every 5 to 10 river miles from Tarbert Landing, Miss., to Venice, La., during six steady-flow conditions. These samples were only analyzed for sand and fines concentration. Sampling at each site consisted of three depth-integrated samples collected at the 0.17, 0.5, and 0.83 centroid of flow.

Associated Chemicals

Suspended sediment was collected for minor-element analysis on three occasions. A wet-sieve procedure was used to dewater and separate the suspended sediment into three particle size ranges (based on sieve-mesh diameter, d : $d > 0.0625$ mm, $d < 0.0625$ mm to $d > 0.030$ mm, and $d < 0.030$ mm) using acid-rinsed, 8-inch PVC U.S. Standard Nos. 230 and 500 Nitex sieves. Suspended sediment retained on each sieve was carefully washed with de-ionized water into freezer cartons and stored for later processing. The water-sediment mixture ($d < 0.030$ mm) that passed through the sieves was collected in 9.5-liter plastic jugs and stored at 4°C for later dewatering. Unfiltered water, that is unsieved, was collected at the same time in 9.5-liter plastic jugs and stored at 4°C for later dewatering. The unfiltered water and the $d < 0.030$ mm sediment-water mixture samples were dewatered by centrifugation at the Louisiana District Sediment Laboratory using a high-speed centrifuge. The centrifugate was washed from the centrifuge bottles (prerinsed, disposable 500-milliliter plastic bottles) into freezer cartons using de-ionized water. The sieved suspended-sediment samples and centrifugate were air dried and sent to the U.S. Geological Survey, Central Laboratory, Atlanta, Ga., for minor-element analysis according to methods listed in Skougstad and others (1979).

Bottom Material

Particle-Size Distribution

Bottom-sediment samples used for particle-size analysis were collected using a Teflon-coated Shipek grab sampler (fig. 7). The sampler consists of a

semicylindrical bucket which is lowered to the streambed with its openside downward. A powerful spring mechanism must be cocked and set to hold the sampler open before it is lowered to the streambed. As it strikes the bottom, the spring is activated causing the bucket to rotate into the bed. A sample is taken from approximately the top 6 in. of the streambed and is held tightly enclosed in such a way that it cannot be washed out when the sampler is recovered at retrieval rates less than 10.9 ft/s. The grab sampler, because of its weight (130 lb) and design, effectively sampled the full spectrum of bottom-material grain-sizes encountered in the study reach.

Particle-size distributions were determined in the Louisiana District Sediment Laboratory. Mechanical dry-sieve analysis, using standard methods reported in Guy (1969), was used for the samples containing mostly sand. Hydrometer analysis, using methods developed by the U.S. Army Corps of Engineers (1970), was used for the samples containing mostly fines. The particle-size distribution of samples containing both sand and fines was determined by combined sieve and hydrometer analyses.

Associated Chemicals

Bottom material was collected for minor element and pesticide analyses during the rising, peak, and falling stages of a major flood from December 1982 to January 1983. Samples were collected using the same methods as previously described for the collection of samples which were used for particle-size analyses. Each cross section was sounded and divided into three to five

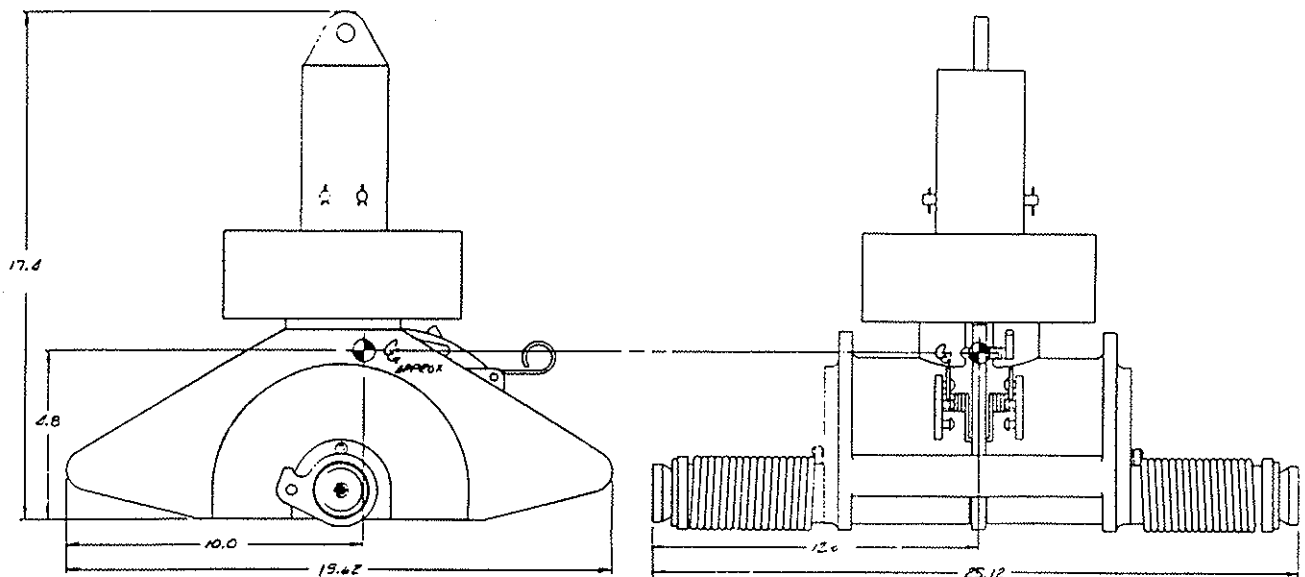


Figure 7.--Bottom-material grab sampler, Shipek Model 860.

equal-discharge increments, and samples were taken from the bottom at each subsection of flow. Bottom material from each subsection was placed in plastic trays, mixed using a Teflon spoon, and placed in freezer cartons for storage and transportation to the laboratory. Each sample represents a separate subsection of flow and was analyzed to provide some insight on cross-sectional and storm induced sample variability.

Bottom material, separated by size, was collected for organic analysis on one occasion. A wet-sieve method was used to dewater and separate samples into three particle size fractions (based on sieve-mesh diameter: $d > 0.0625$ mm, $d < 0.0625$ mm to $d > 0.030$ mm, and $d < 0.030$ mm) using an 8-inch brass U.S. Standard No. 230 sieve and an 8-inch PVC U.S. Standard No. 500 Nitex sieve. Samples were collected with the grab sampler at three to five equal-discharge increments and composited. Bottom material was selected rather than suspended sediment for organic analysis of acid and base-neutral extractable compounds and insecticides because of the relatively large sample size (25 g) required by the laboratory. All bottom-material samples were wet sieved in stainless steel pans, and transferred to pretreated glass bottles for storage at 4°C until analysis. Unfiltered and filtered water samples were collected at the same time as the bottom material and analyzed for total and dissolved acid and base-neutral extractable organic compounds. All water and bottom-material samples for acid and base-neutral extractable organic compounds were extracted with methylene chloride. Compounds present in samples were identified and quantified using GC-MS (gas chromatography and mass spectrometry) methods according to methods listed in Wershaw and others (1983).

Duplicate bottom-material and water samples also were analyzed for methylene-chloride extractable organic compounds using GC-FID (gas chromatography and flame ionization detector) methods. Individual compounds are not identified by the GC-FID method, but their presence is indicated as a peak having a unique retention time on the chromatograph if they are present above a detection limit of about 0.1 µg/L. This screening method will indicate the presence of most of the organic compounds listed by the U.S. Environmental Protection Agency as priority pollutants and thousands of other organic compounds. The GC-FID chromatographs are not published in this report because identifiable concentrations of organic compounds were not found in any of the samples.

DOWNSTREAM VARIATION OF SUSPENDED SEDIMENT

Earlier studies by Everett (1971) and Wells (1980) indicated suspended-sediment concentrations decreased in a downstream direction in the lower Mississippi River at steady-state flows less than 600,000 ft³/s and increased in a downstream direction during steady-state flows exceeding 600,000 ft³/s. Both investigators also found that suspended-sediment concentrations remained unchanged in a downstream direction at steady-state flows around 600,000 ft³/s. Unfortunately, Wells (1980) had no information on suspended sediment transported at discharges greater than 600,000 ft³/s and observations in both previous studies were based on a minimum number of samples. In an attempt to

supplement the data of the earlier studies and verify Everett's original observations, suspended sediment was sampled intensively during six steady flow conditions from November 1983 to February 1985.

Results of these six sampling trips are expressed in the downstream variations for the sediment concentrations of suspended sand, suspended fines, and the combined suspended sand and fines for three ranges in flow conditions as shown in figures 8 through 10. Flow of the lower Mississippi River was divided into low flow conditions ($<500,000 \text{ ft}^3/\text{s}$), medium flow conditions ($500,000\text{-}700,000 \text{ ft}^3/\text{s}$), and high flow conditions ($>700,000 \text{ ft}^3/\text{s}$) based on the discharge-duration curve presented by Wells (1980).

Suspended-sediment concentrations decreased significantly in a downstream direction at steady-flows less than $500,000 \text{ ft}^3/\text{s}$ in the lower Mississippi River (fig. 8). For example, suspended-sediment concentrations decreased in a downstream direction by 79 and 85 percent at flows of $267,000$ and $260,000 \text{ ft}^3/\text{s}$, respectively. This shows that $63,439$ and $92,664$ tons/d of suspended sediment were deposited between Tarbert Landing and West Pointe a la Hache during these two low flow conditions in the lower Mississippi River.

Suspended-sediment concentrations in the lower Mississippi River increased slightly in a downstream direction during medium flow conditions (fig. 8). An increase in suspended-sediment concentration of 9.1 and 9.2 percent was observed during flows of $532,000$ and $678,000 \text{ ft}^3/\text{s}$, respectively, between Tarbert Landing and Venice. However, such variations in concentration may be caused by sampling or analysis errors. More samples and analysis are needed to definitively state if any trend exists.

At high flows suspended-sediment concentrations increased significantly in a downstream direction in the lower Mississippi River (fig. 8). Concentrations increased between Tarbert Landing and Venice by 17 and 44 percent at flows of $899,000$ and $991,000 \text{ ft}^3/\text{s}$, respectively. Scour and resuspension of sediment in the study reach occurred at a rate of $138,356$ and $184,623$ tons/d during these two high flows.

Table 1 lists the net change in suspended-sediment concentrations observed during the six steady-flow conditions sampled on the lower Mississippi River (figs. 8-10). Variations in suspended-fines concentrations were responsible for the major changes observed in suspended-sediment concentrations that occurred in the entire study reach. At high flows net differences in suspended-fines concentration were responsible for 98 percent ($899,000 \text{ ft}^3/\text{s}$) and 96 percent ($991,000 \text{ ft}^3/\text{s}$) of the net downstream change in total suspended-sediment concentrations observed. Changes in suspended-fines concentrations accounted for 60 percent ($678,000 \text{ ft}^3/\text{s}$) and 62 percent ($532,000 \text{ ft}^3/\text{s}$) of the net downstream change in suspended-sediment concentrations observed during medium flow and 88 percent ($260,000 \text{ ft}^3/\text{s}$) and 64 percent ($267,000 \text{ ft}^3/\text{s}$) of the net downstream change in suspended-sediment concentrations observed during low flow. It should be noted, however, that sand in the unsampled zone (the column of water between the bottom of the sampler nozzle and the stream bed) was not considered in the above conclusions.

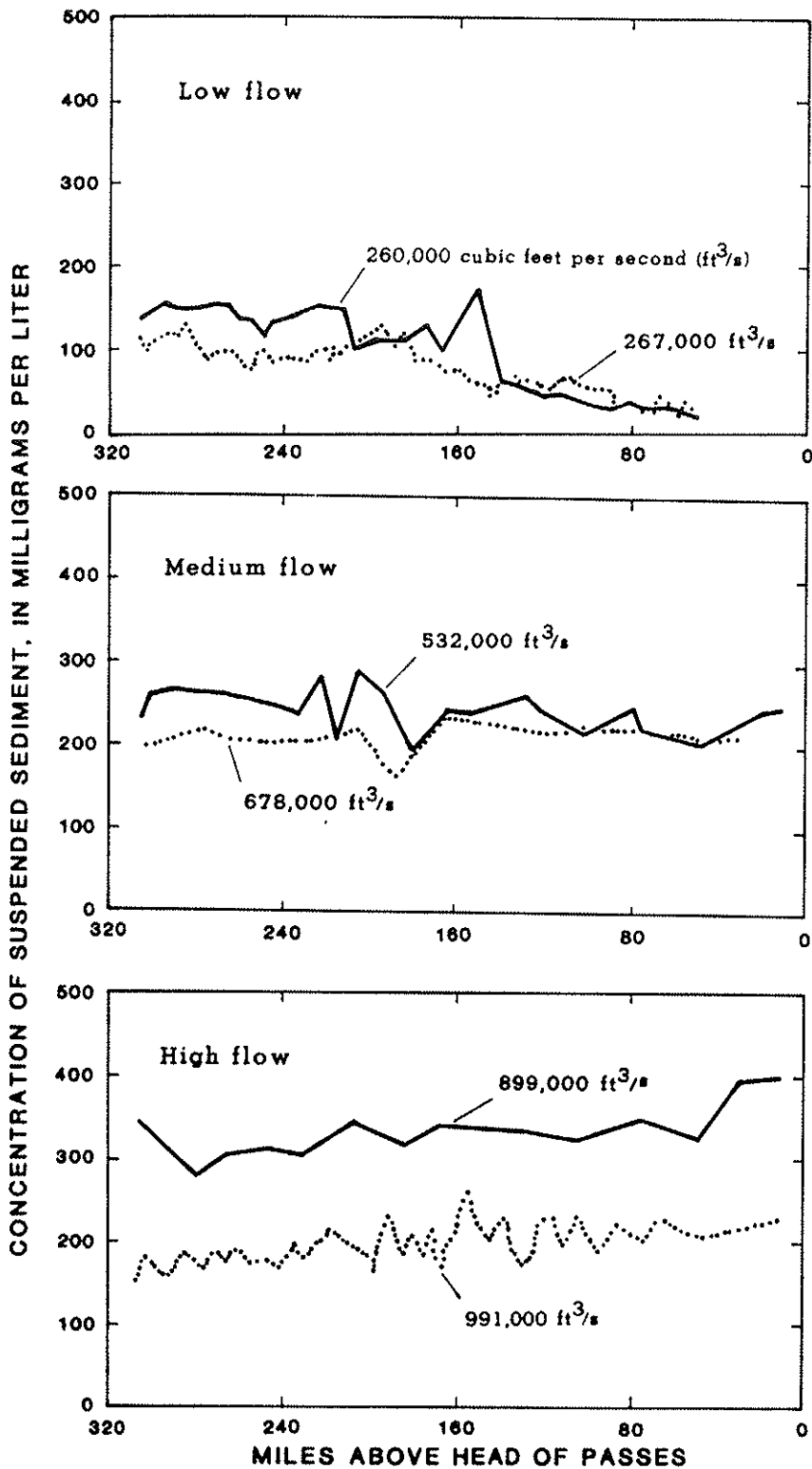


Figure 8.--The downstream variation of the concentration of suspended sediment at low, medium, and high steady-state flows in the lower Mississippi River, Louisiana.

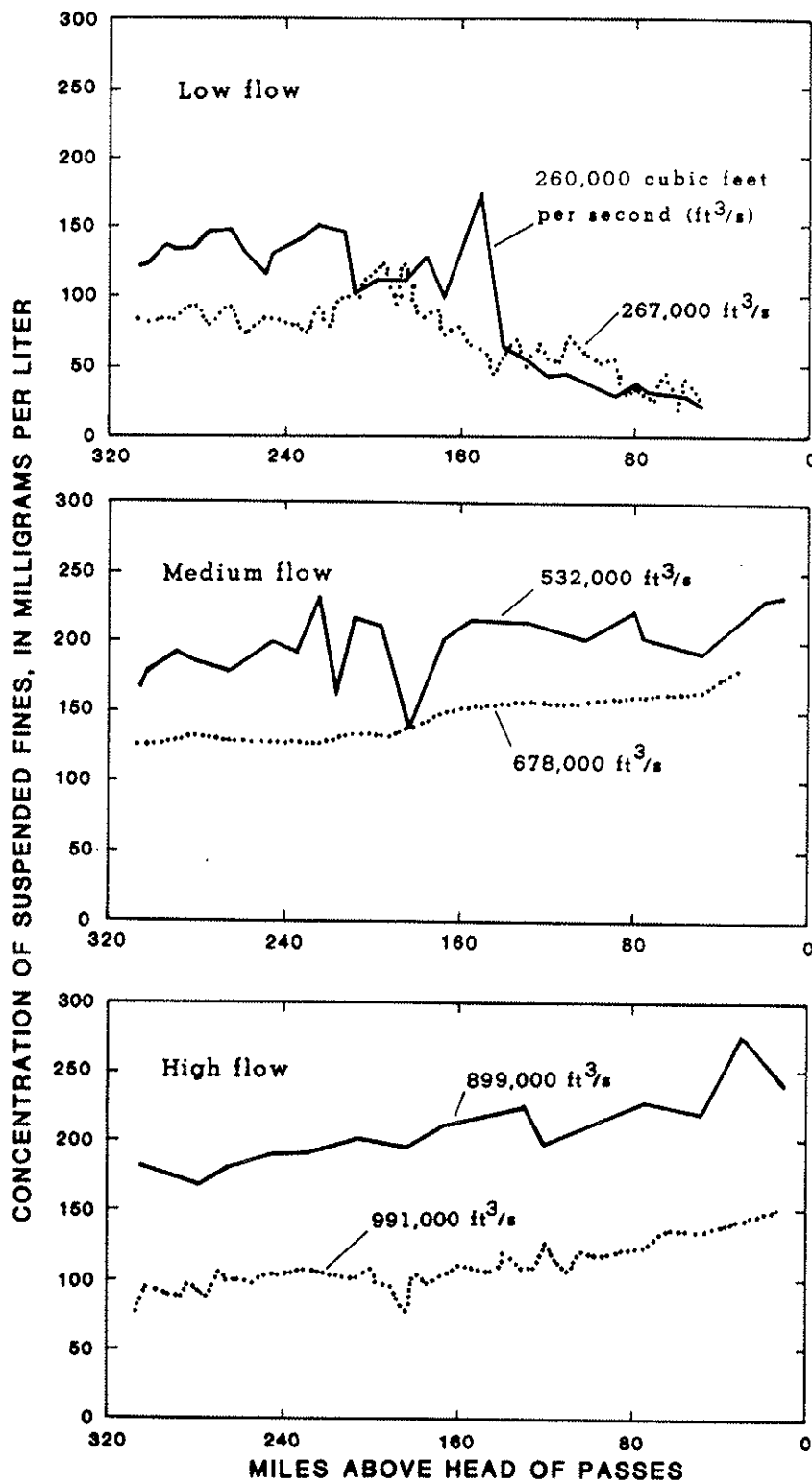


Figure 9.--The downstream variation of the concentration of suspended fines (<0.063 millimeters) at low, medium, and high steady-state flows in the lower Mississippi River, Louisiana.

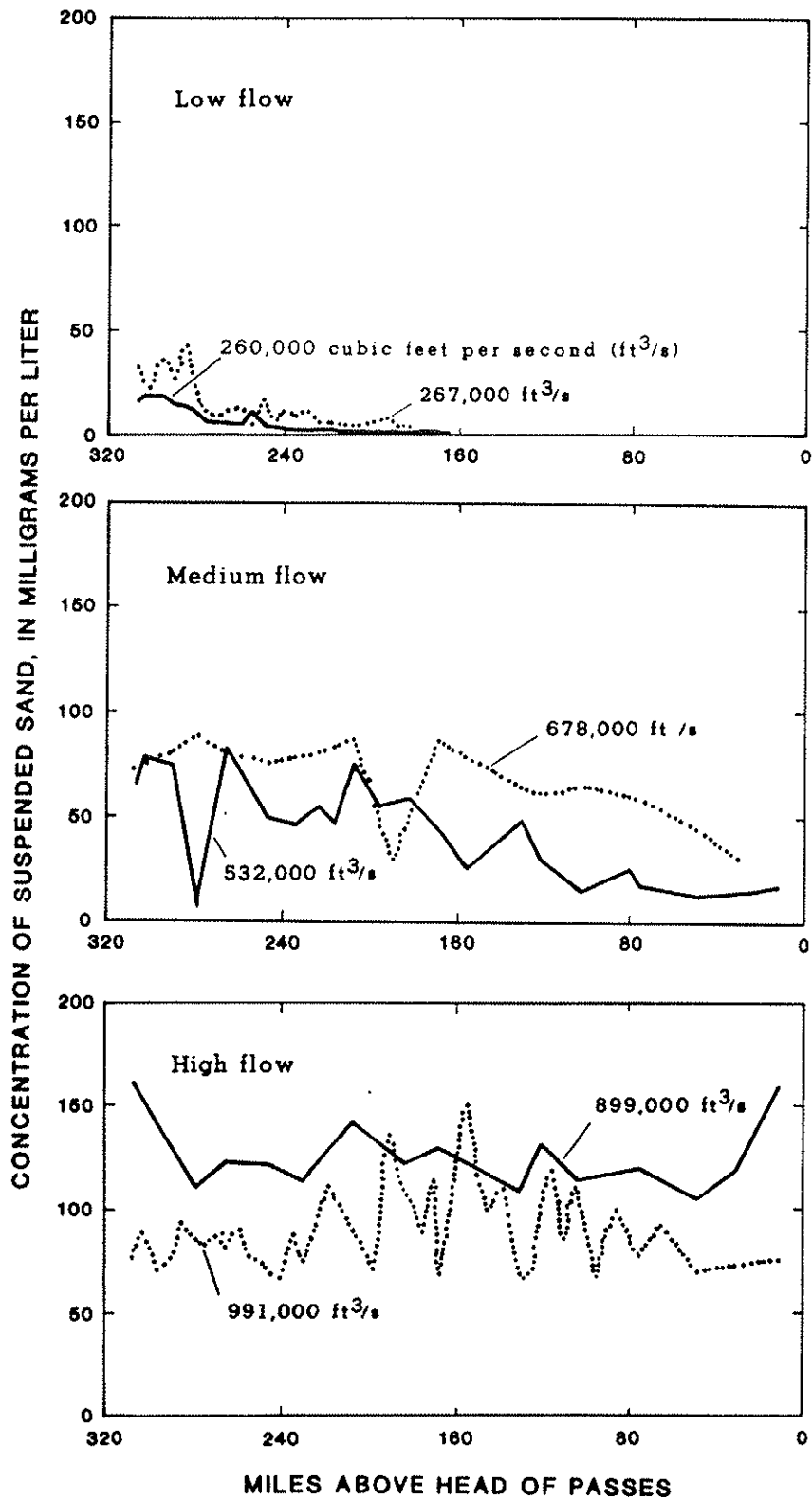


Figure 10.--The downstream variation of the concentration of suspended sand (>0.063 millimeters) at low, medium, and high steady-state flows in the lower Mississippi River, Louisiana.

Table 1.--Net downstream change in suspended-sediment concentrations observed during six steady-flow conditions on the lower Mississippi River, Louisiana

[Minus sign (-) equals a net loss in suspended sediment. Plus sign (+) equals a net gain in suspended sediment]

Date	Discharge (cubic feet per second)	Number of samples	Net change in suspended concentration of		
			sand	finest	sediment
(milligrams per liter)					
Low flow					
11-83	267,000	50	-32	-38	-70
10-84	260,000	30	-16	-116	-132
Medium flow					
11-84	532,000	22	-47	+78	+31
12-84	678,000	14	-40	+58	+18
High flow					
5-84	991,000	42	-3	+72	+69
1-85	899,000	15	-1	+58	+57

Suspended-fines concentrations decreased in a downstream direction during low flows and increased during medium and high flows (fig. 9). For example, the concentration of suspended fines decreased during the flow of 267,000 ft³/s from 91 mg/L at river mile 280.5 to 24 mg/L at West Pointe a la Hache. Net decrease was 38 mg/L in suspended-fines concentrations for the entire study reach (table 1).

Suspended-fines increased in a downstream direction during the medium flow of 532,000 ft³/s from 165 mg/L at Tarbert Landing to 233 mg/L at Venice. This was also observed at the high flow of 899,000 ft³/s when suspended-fines concentrations increased from 182 mg/L at Tarbert Landing to 240 mg/L at Venice. Net increases of 78 and 58 mg/L in the concentration of suspended fines were observed for the entire study reach during these medium and high flows.

Median particle size, d₅₀, of suspended fines (table 2) decreased in a downstream direction during low flows and remained relatively constant during medium and high flows. The d₅₀ of suspended fines ranged from a 0.004 mm at St. Francisville to a minimum of 0.001 mm at West Pointe a la Hache with an average of 0.002 and 0.003 mm during flows of 267,000 and 260,000 ft³/s. D₅₀ of suspended fines during medium flows ranged from 0.007 mm at Union to 0.003 mm at Luling with averages of 0.006 and 0.004 mm during flows of 532,000 and 678,000 ft³/s, respectively. During high flows d₅₀ of suspended fines ranged

Table 2.--Observed median particle size for the sand (>0.063 mm) and fine (<0.063 mm) fractions of suspended-sediment samples collected during six steady-flow conditions on the lower Mississippi River, Louisiana

Site	Discharge (cubic feet per second)	Median particle size		Discharge (cubic feet per second)	Median particle size	
		Sand (millimeters)	Fines		Sand (millimeters)	Fines
Low flow						
Tarbert Landing, Miss---		0.152	0.00299		0.160	0.00347
St. Francisville, La----	267,000	.0963	.00358	260,000	.111	.00426
Plaquemine, La-----		.0945	.00350		.152	.00271
Union, La-----		.132	.00281		.157	.00179
Luling, La-----		.113	.00122		.156	-----
Belle Chasse, La-----		.142	.00116		.117	.00114
West Pointe a la Hache, La.		-----	.00100		.103	-----
Average-----		0.122	0.00232		0.137	0.00267
Medium flow						
Tarbert Landing, Miss---		0.138	0.0110		0.141	.00260
St. Francisville, La----	532,000	.130	.00544	678,000	.157	.00302
Plaquemine, La-----		.127	.00643		.157	.00339
Union, La-----		.138	.00664		.141	.00416
Luling, La-----		.124	-----		.134	.00344
Belle Chasse, La-----		.119	.00568		.127	.00376
West Pointe a la Hache, La.		.116	.00549		.120	.00475
Venice, La-----		.102	-----		-----	-----
Average-----		0.124	0.00628		0.140	0.00359
High flow						
Tarbert Landing, Miss---		0.177	0.00114		-----	-----
St. Francisville, La----	991,000	.161	-----	899,000	0.144	0.00366
Plaquemine, La-----		.143	-----		.129	.00654
Union, La-----		.128	.00192		.115	.00521
Luling, La-----		.148	.00268		.119	.00425
Belle Chasse, La-----		.107	.00150		.108	.00418
West Pointe a la Hache, La.		.105	.00213		.109	.00476
Venice, La-----		.108	.00229		.103	.00555
Average-----		0.135	0.00194		0.118	0.00488

from a maximum of 0.007 mm at Plaquemine to 0.001 mm at Tarbert Landing with an average of 0.002 and 0.005 mm during flows of 991,000 and 899,000 ft³/s, respectively. It is apparent from these data that there is very little downstream variation in median particle-size of suspended fines transported by the lower Mississippi River in Louisiana.

Suspended sands (table 1) never showed a net increase in concentration or median particle size in the downstream direction for the entire study reach during any of the steady-flow conditions sampled.

Concentrations of suspended sands dropped by 100 percent between Tarbert Landing and West Pointe a la Hache during flows of 260,000 and 267,000 ft³/s (fig. 10). A net loss of 16 and 32 mg/L of suspended sand from the water column was observed during flows of 260,000 and 267,000 ft³/s, respectively. Initial suspended-sand concentrations were 16 and 33 mg/L during these two low flows. Significantly, 64 percent of the sand in suspension at Tarbert Landing had settled out in the reach between Tarbert Landing and St. Francisville (a distance of 40.9 river miles) and 88 percent in the reach between Tarbert Landing and Plaquemine (a distance of 98.3 river miles). This converts to 15,140 and 20,906 tons/d of suspended sand being deposited between Tarbert Landing and St. Francisville, and Tarbert Landing and Plaquemine, respectively. Suspended-sand concentrations never exceeded 2 mg/L in any samples collected downstream from river mile 175.4 (initial suspended-sand concentration was 33 mg/L at Tarbert Landing) and averaged 1.1 mg/L downstream from this location. Similar percent losses in suspended-sand concentrations also were observed between Tarbert Landing and St. Francisville, and Tarbert Landing and Plaquemine during the flow of 260,000 ft³/s.

Median particle size of suspended sands (table 2) also decreased in the downstream direction during these two low flow conditions. The d₅₀ of suspended sand decreased from 0.160 mm at Tarbert Landing to 0.103 mm at West Pointe a la Hache during the flow of 260,000 ft³/s. Similar decreases in d₅₀ of suspended sand were observed during the flow of 267,000 ft³/s. Average d₅₀ of suspended sand was 0.137 and 0.122 mm for the flows of 260,000 and 267,000 ft³/s, respectively (table 2).

Suspended-sand concentrations decreased by 72 and 56 percent between Tarbert Landing and Venice during the flows of 532,000 and 678,000 ft³/s, respectively. Sand stayed in suspension much longer during these flows. During the flow of 532,000 ft³/s, there was no significant decrease in suspended-sand concentrations until river mile 120.6 when a decrease of 54 percent occurred. During the flow of 678,000 ft³/s, a similar decrease in suspended-sand concentration was not observed until river mile 30. In both instances, no decrease in suspended-sand concentration was observed at either St. Francisville or Plaquemine. Suspended-sand concentrations ranged from 78 mg/L at river mile 302.4 to 13 mg/L at river mile 48.7 during the flow of 532,000 ft³/s and from 88 mg/L at river mile 278.4 to 31 mg/L at river mile 30.0 during the flow of 678,000 ft³/s.

The d_{50} of suspended sand decreased in a downstream direction during both medium flows (table 2); however, major differences in d_{50} were not observed until river mile 75.3. The d_{50} for suspended sand ranged from 0.138 mm at Tarbert Landing to 0.102 mm at Venice during the flow of 532,000 ft³/s and from 0.157 mm at St. Francisville to 0.120 mm at West Pointe a la Hache for the flow of 678,000 ft³/s. Average d_{50} for suspended sand were 0.124 and 0.140 mm for the flows of 532,000 and 678,000 ft³/s, respectively.

Net changes in suspended-sand concentrations were small during the two high flows. Net decreases of only 1 and 3 mg/L were observed for the entire study reach at flows of 899,000 and 991,000 ft³/s, respectively. Suspended-sand concentrations ranged from 161 mg/L at Tarbert Landing to 105 mg/L at river mile 48.7 during the flow of 899,000 ft³/s and from 137 mg/L at river mile 191.5 to 65 mg/L at river mile 130 during the flow of 991,000 ft³/s.

The d_{50} of suspended sand decreased steadily over the entire study reach at both high flow conditions sampled (table 2). The d_{50} of suspended sand ranged from 0.144 mm at St. Francisville to 0.103 mm at Venice during the flow of 899,000 ft³/s and from 0.177 mm at Tarbert Landing to 0.105 mm at West Pointe a la Hache during the flow of 991,000 ft³/s. Average d_{50} for suspended sand were 0.118 and 0.135 mm for the flows of 899,000 and 991,000 ft³/s, respectively.

No relation was observed between average particle-size distributions of suspended sediment and different flow conditions. The d_{50} of both suspended sand and fines were often observed to be larger during low flow than high flow (table 2). For example, the average d_{50} of suspended sand samples collected during the flow of 260,000 ft³/s (0.137 mm) was much greater than the average d_{50} of suspended sand samples collected during the medium flow of 532,000 ft³/s (0.124 mm) and the high flow of 899,000 ft³/s (0.118 mm). The reason for this lack of relation between increasing discharge and average particle size is probably related to antecedent hydrologic conditions which determine the source and the size of the material transported.

Downstream changes in suspended-sediment concentrations indicate that the bed of the lower Mississippi River, serves as a sink and reservoir for sediments during low flows and as a source of sediments during the medium and high flows. For example, during low flow, decreases in suspended-sediment concentrations in a downstream direction amounted to a deposition of 92,664 tons/d of sediment. In contrast, high flows resulted in as much as 184,623 tons/d of sediment being resuspended from the river bed. Resuspension of sediment from the river bed is the only possible source of this material because: (1) the river is leveed the entire study reach, thereby excluding sediment contributions by overland runoff, and (2) no significant tributaries enter the river in the study reach to contribute additional sediment loads from other watersheds.

SEDIMENT-CHEMICAL CHARACTERISTICS

Current literature has increasingly stressed the importance of sediment-chemical relations in the transport of minor elements and organic compounds by riverine systems. Work by Gibbs (1977), Rinella and McKenzie (1982), deGroot and others (1982), and Horowitz (1984) have documented relations between sediment particle size and chemical transport in South American and European rivers, storm runoff, and estuarine areas. The majority of previous work indicates that minor element and organic chemical concentrations increase with decreasing sediment particle size. Previous to this study, nothing similar to the above work had been attempted on the lower Mississippi River. This lack of knowledge, combined with increased interest in using the lower Mississippi River as a source of sediment and freshwater to help mitigate coastal erosion, points out the importance of such a study on the role of suspended sediment in the transport of minor elements and organic compounds. The potential impact of these sediment-associated chemicals on near-shore fishery and wildlife resources in areas of lower Mississippi River water diversion cannot be properly evaluated and managed until these mechanisms are better understood.

In an effort to better understand movement of minor elements and organic compounds through the lower Mississippi River, two sets of data were collected for physical and chemical analyses in this study. The first set of data was obtained from water and bottom material samples that were collected and analyzed separately each month. Physical analyses, including concentration determinations and particle-size distributions, were also performed on both the water and bottom material samples. The second set of data was obtained from samples of the water column and bed material that were physically separated into distinct size fractions prior to chemical analyses. Chemical analyses were performed on sediment from each size fraction.

Multiple correlation and factor analyses were performed on total-recoverable and suspended (total-recoverable minus dissolved) chemical data and suspended-sediment data (concentration and size distribution) from the first data set prior to actual chemical analysis of the three distinct suspended-sediment particle-size classes. These statistical comparisons between unfiltered-water chemical concentrations and suspended-sediment particle-size distributions were used as a screening tool to select actual suspended-sediment particle-size classes to be analyzed. Minor elements and suspended-sediment particle-size distributions compared were: total-recoverable and suspended arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, iron, lead, manganese, mercury, selenium, silver, and zinc with concentrations of sand, fines, and total sediment. The percent of suspended sediment finer by weight than 0.125, 0.063, 0.030, 0.016, 0.007, 0.004, and 0.002 mm also was determined in relation to minor elements. Minor elements and total organic carbon also were compared.

Minor Elements

Statistical analyses showed correlations ($r > 0.7$) between total recoverable and suspended iron, manganese, barium, cobalt, and concentration of

finer. Manganese (fig. 11) showed the best linear correlation with fines ($r=0.96$). Manganese correlated better with many of the minor elements tested than did any of the suspended-sediment particle-size fractions tested. Manganese correlated strongly with iron (fig. 12, $r=0.93$) and cadmium (fig. 13, $r=0.86$). Manganese also correlated with cobalt ($r=0.72$) and zinc ($r=0.71$) but not as strongly. Iron showed a good linear correlation with fines (fig. 14, $r=0.84$) and also correlated well with total-recoverable cadmium ($r=0.76$).

No significant linear correlations were observed between most minor elements and the sediment particle size ranges of >0.063 , <0.004 , and <0.002 mm. There also were no correlations greater than 0.5 between total organic carbon and any of the minor elements tested. Trefry and Shokes (1981) reported that Mississippi River particulate metals were predominantly in the oxide phases and Trefry and Presley (1982) reported that oxide coatings dominate manganese chemistry of the Mississippi River particulates and that total-manganese load is dominated by the particulate flux. This study's results support the previous findings and suggest minor-element transport in the lower Mississippi River may be associated with manganese- and iron-oxide sediment coatings, which are associated with fines-sediment concentration.

Minor element analyses of three distinct suspended-sediment particle-size classes, $d>0.063$ mm, $d<0.063$ mm to >0.030 mm, and $d<0.030$ mm, showed increasing minor-element concentrations with decreasing suspended-sediment particle-size classes. Figure 15 shows typical relations for aluminum, copper, manganese, and zinc. The solid line represents the average concentration of the minor element present in samples at five sites on the lower Mississippi River in February 1985. The range in the data is represented by the solid lines. Table 3 shows mean percentage contribution of these suspended-sediment particle-size classes to the total-particulate minor-element concentrations. The <0.063 to >0.030 mm particle-size class and <0.030 mm particle-size class contributions were added to give <0.063 mm particle-size class in table 3. In all instances, the <0.063 mm particle-size class contributed the highest percentage to the total-particulate minor-element concentrations. For nickel, the <0.063 mm particle-size class contributed 90 percent of the total-particulate nickel concentration. This was the highest contribution of all the minor elements analyzed; however, it should be noted that in 4 of 13 samples, nickel occurred below levels of detection in all size classes. Manganese occurred in all samples analyzed, and the <0.063 mm particle-size classes accounted for 89 percent of all manganese found in the particulate phase.

This agrees quite well with the statistical analyses of unfiltered-water and bulk suspended-sediment data. Chromium, aluminum, cadmium, copper, iron, lead, and mercury followed, respectively, in decreasing order of percent contribution of the <0.063 mm particle-size class to the total particulate minor-element concentration. Cadmium, copper, lead, and mercury occurred in such low concentrations (at or near levels of detection) in unfiltered-water samples that no conclusions could be drawn from the statistical comparison with bulk suspended-sediment particle-size fraction data. In contrast, concentrations of these minor elements were high enough on the suspended-sediment particle-size classes that relations between these different minor elements and suspended-sediment particle sizes could be determined.

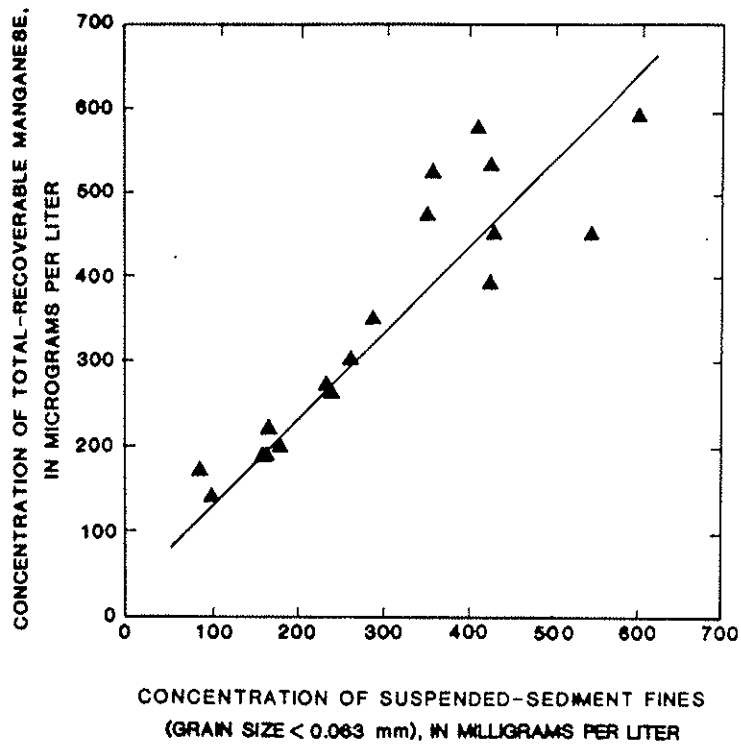


Figure 11.--Relation between concentration of suspended-sediment fines (<0.063 millimeters) and total-recoverable manganese in the lower Mississippi River, Louisiana.

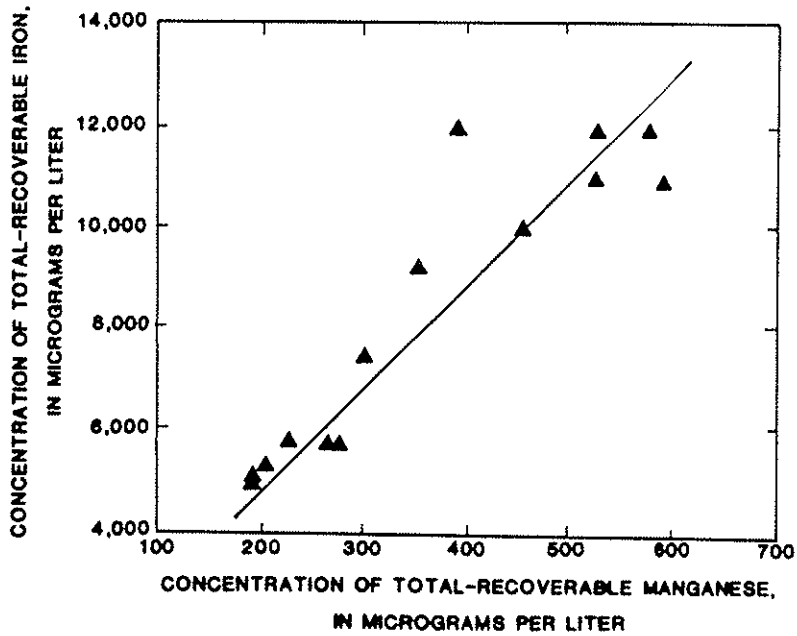


Figure 12.--Relation between concentration of total-recoverable manganese and total-recoverable iron in the lower Mississippi River, Louisiana.

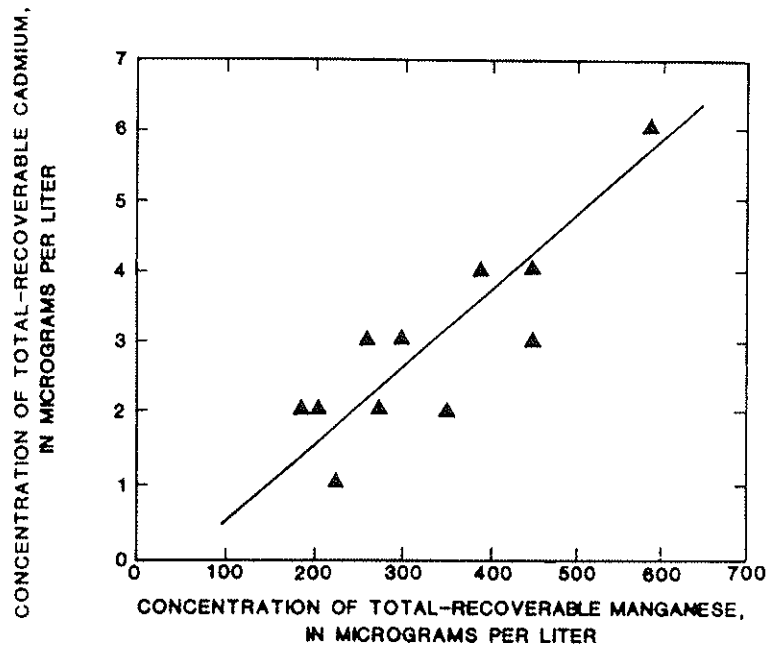


Figure 13.--Relation between concentration of total-recoverable manganese and total-recoverable cadmium in the lower Mississippi River, Louisiana.

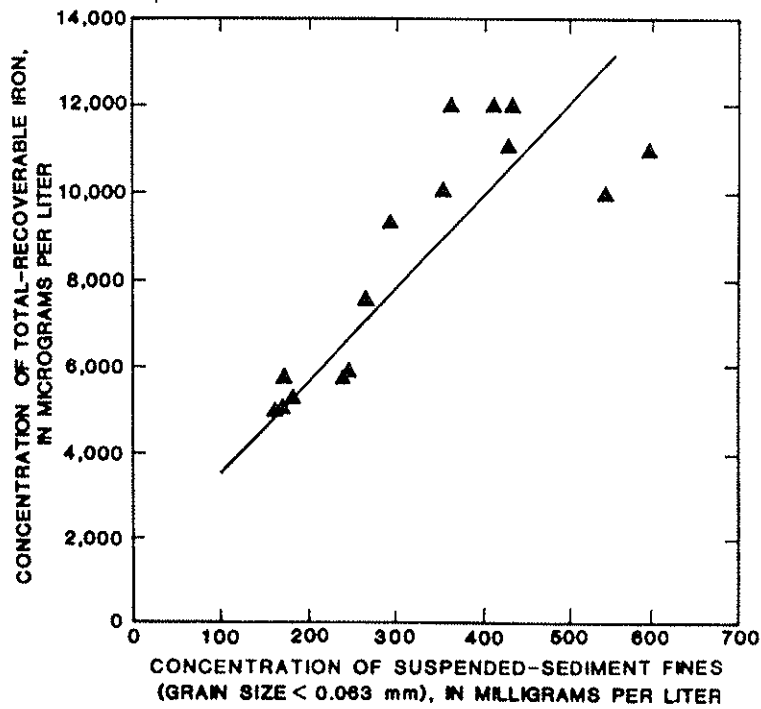


Figure 14.--Relation between concentration of suspended-sediment fines (<0.063 millimeters) and total-recoverable iron in the lower Mississippi River, Louisiana.

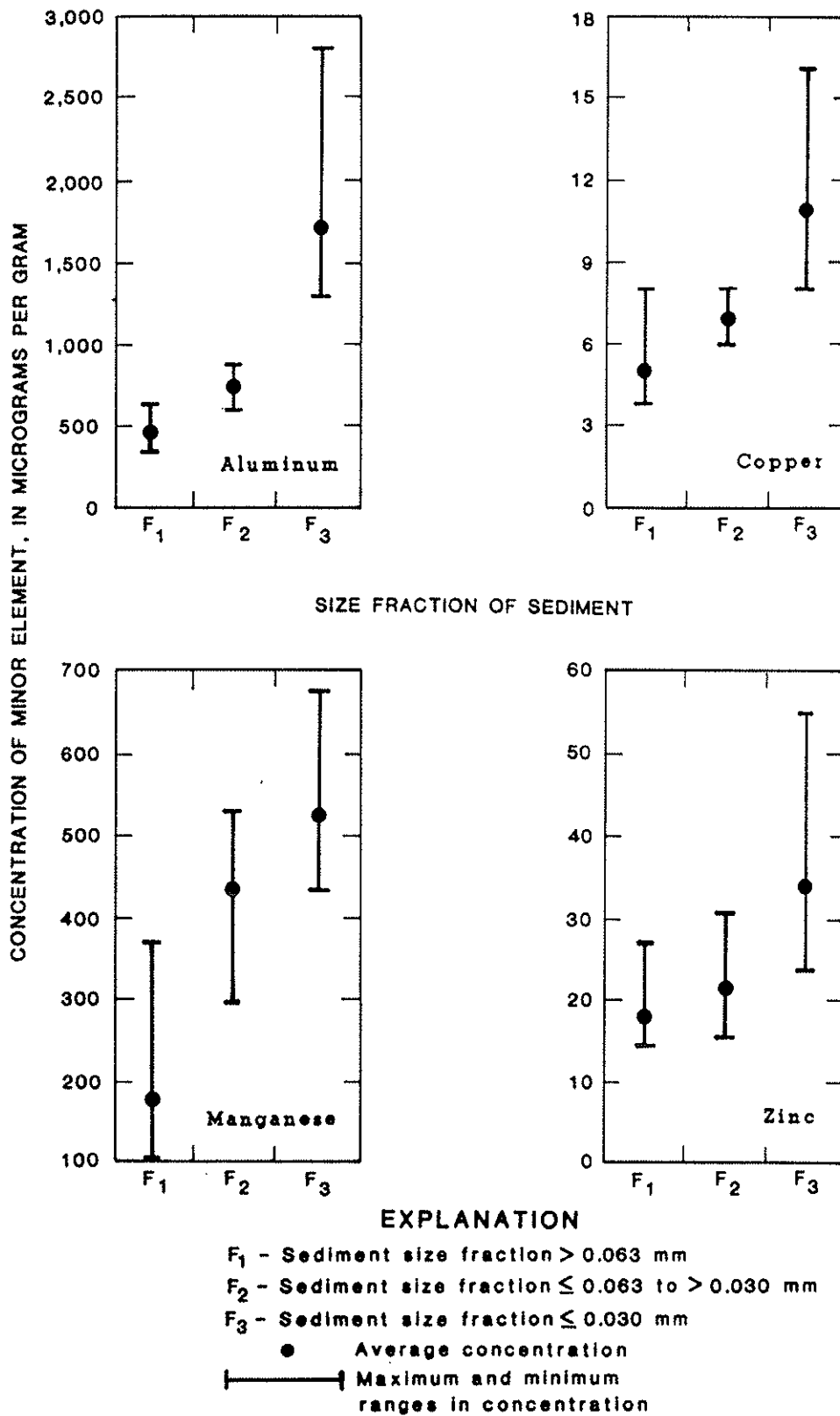


Figure 15.--Relation of selected minor elements to particle size in the lower Mississippi River, Louisiana, February 1985.

Table 3.--Percentage of total-recoverable particulate minor-element concentration contributed by three suspended-sediment particle-size ranges, in the lower Mississippi River, Louisiana

[Suspended-sediment particle-size fractions in millimeters]

Minor element	>0.063	≤0.063 ^a	≤0.063 to >0.030	≤0.030
Nickel-----	10	90	18	72
Manganese-----	11	89	35	54
Chromium-----	13	87	29	58
Aluminum-----	16	84	29	55
Cadmium-----	17	83	30	53
Copper-----	17	83	41	42
Iron-----	19	81	30	51
Zinc-----	21	79	33	46
Lead-----	27	73	26	47
Mercury-----	32	68	33	35
Arsenic-----	(b)	(b)	(b)	(b)

^a Column 2 = column 3 + column 4.

^b All samples below levels of detection.

Data from previous suspended-sediment studies (Everett, 1971; Wells, 1980), and the more recent studies, have shown that suspended-sediment concentrations in the lower Mississippi River reach precede peak streamflow. Therefore, the impact of minor elements on wetlands can be minimized by diverting Mississippi River water into the wetlands after peak flows when suspended-sediment concentrations are decreasing and associated minor elements are most dilute. Another strategy would be to restrict flow into wetlands during rising stage when suspended sediment, including fines, occurs at relatively higher concentrations and associated minor elements are most concentrated.

Organic Compounds

None of the semivolatile, acid and base-neutral extractable organic compounds listed in table 4 were detected in unfiltered- or filtered-water samples. Bis (2-ethylhexyl) phthalate and diethyl phthalate, however, were found in the ≤0.063 mm particle-size samples of bottom material at the St. Francisville site. These two compounds were not detected in the bulk or the >0.063 mm particle-size samples of bottom material at St. Francisville nor at any other site. None of the other compounds listed in table 4 were detected in any of the bottom samples.

The lack of detection of bis (2-ethylhexyl) phthalate and diethyl phthalate in any of the other samples at the St. Francisville site (in a non-industrialized area of the study reach) indicates that their presence was probably due to sample contamination during field collection, particle-size separation, or laboratory analysis.

Table 4.--List of organic compounds analyzed in water and bottom material from the lower Mississippi River, Louisiana

Acenaphthene	Dibenzo (a,h) anthracene
Acenaphthylene	2,4-Dichlorophenol
Aldrin	Dieldrin
Anthracene	Diethyl phthalate
bis (2-Chloroisopropyl) ether	2,4-Dimethylphenol
bis (2-Chloroethoxy) methane	Dimethyl phthalate
bis (2-Chloroethyl) ether	4,6-Dinitro-2-methylphenol
bis (2-Ethylhexyl) phthalate	2,4-Dinitrophenol
Benzidine	Di-n-butyl phthalate
Benzo (a) anthracene	Ethion
Benzo (b) fluoranthene	Fluoranthene
Benzo (k) fluoranthene	Fluorene
Benzo (g,h,i) perylene	Gross polychlorinated biphenyls
Benzo (a) pyrene	Gross polychlorinated naphthalenes
4-Bromophenyl phenyl ether	Heptachlor epoxide
Butyl benzyl phthalate	Heptachlor
Parachlorometacresol	Hexachlorobenzene
2-Chlorophenol	Hexachlorobutadiene
Chlordane	Hexachloroethane
2-Chloronaphthalene	Hexachlorocyclopentadiene
4-Chlorophenyl phenyl ether	Indeno (1,2,3-cd) pyrene
Chrysene	Isophorone
DDD	Lindane
DDE	Malathion
DDT	Methoxychlor
Di-n-octylphthalate	Methyl trithion
Diazinon	Methyl parathion
Mirex	Naphthalene
n-Nitrosodimethylamine	n-Nitrosodiphenylamine
n-Nitrosodi-n-propylamine	Nitrobenzene
Parathion	Pentachlorophenol
Perthane	Phenanthrene
Phenol	Pyrene
2,3,7,8-Tetrachlorodibenzo-p-dioxin	Toxaphene
2,4,6-Trichlorophenol	1,2,4-Trichlorobenze
Trithion	1,2-Dichlorobenzene
1,3-Dichlorobenzene	1,4-Dichlorobenzene
2-Nitrophenol	2,4-Dinitrotoluene
Endosulfan	Endrin
2,6-Dinitrotoluene	3,3-Dichlorobenzidine
4-Nitrophenol	

Duplicate bottom-material and water samples analyzed using GC-FID methodology confirmed the findings of the GC-MS analyses--no detectable concentrations of organic compounds. The GC-FID analyses of two samples, a bottom-material sample from the Mississippi River near Belle Chasse and a unfiltered-water sample from the Mississippi River near St. Francisville, indicated the presence of organic compounds; however, these compounds had concentrations too low to identify and quantify using GC/MS techniques and indicate possible sample contamination.

The lack of occurrence of organic compounds in both water and bottom-material samples make it impossible to say what relation the different sediment size fractions play in the transport of organic compounds in the lower Mississippi River.

SIMULATION OF SUSPENDED-SEDIMENT TRANSPORT

Practical engineering solutions to many problems in rivers with alluvial channels can be attained only with a knowledge of the suspended-sediment loads that can and actually are being carried by rivers. Knowledge of suspended-sediment loading characteristics is especially needed to identify pathways of toxic contaminants that are transported by sediment in the aquatic environment. However, predicting the diffusion and settling of suspended sediment in a river is one of the most difficult and uncertain aspects of water-quality modeling. Much of the existing information pertains to the larger particles which control the configuration of the bed and channel rather than the small suspended particles which are likely to adsorb toxic pollutants. The applicability of a recently developed suspended-sediment transport model is demonstrated in the following sections of the report.

Lagrangian Transport Model

The transport model documented by Jobson (1980) was used in this study. Diffusion and settling processes presented herein were programmed as the source/sink term of the transport equation solved in the model. The convective-diffusion equation is formulated using a coordinate system whose origin moves at the mean flow velocity (a Lagrangian reference frame). The equation is considerably simplified by the coordinate transformation because the term containing the mean convective velocity does not appear. The model follows an individual fluid parcel as it moves downstream while keeping track of all factors which act to change its concentration. The continuity of mass equation for a specific fluid parcel, in a Lagrangian reference frame is

$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial \xi} (D \frac{\partial C}{\partial \xi}) = \Sigma s \quad (4)$$

in which C is the cross-sectional mean concentration of suspended sediment, t is the time, D is the longitudinal dispersion coefficient, ξ is the distance from the parcel, and Σs is the sum of source and sink terms. The Lagrangian distance coordinate, ξ , is given by

$$\xi = x - x_0 - t_0 \int_0^t U dt' \quad (5)$$

in which, x is the Eulerian distance coordinate along the river, U is the cross-sectional mean flow velocity, t' is a dummy variable of integration, and x_0 is the location of the parcel at time, t_0 . By setting $\xi=0$ for a particular parcel at any time, the movement of a parcel can be tracked in the Eulerian distance coordinate system.

Integrating equation 4 gives

$$C = C_0 - t_0 \int_0^t \frac{\partial}{\partial \xi} \left(D \frac{\partial C}{\partial \xi} dt' \right) + t_0 \int_0^t \Sigma s dt' \quad (6)$$

in which C_0 is the suspended-sediment concentration of the parcel at time t_0 , and C is the concentration after a time lapse of t . The formulation is completed by approximating the distance between parcels, $d\xi$, as the velocity times the time-step size, Δt , and expressing the integral of the dispersion term as an explicit finite-difference.

The finite-difference solution is constructed by adding a new parcel with a known concentration at the upstream boundary at each time step. The parcels are numbered consecutively in the downstream direction and tracked as they traverse the system.

In natural channels there is usually a wide gradation of sediment sizes. Although the finer particles comprise the bulk of the load, the channel evolution is controlled by the coarser particles. Moreover, it is obvious that, different sizes are transported at different rates. It is, thus, important to predict the movement of the individual particle sizes encountered in the channel. In the present model, one can divide the size range into a suitable number (1-10) of size fractions and use equations 5 and 6 to track the movement of each fraction.

Dispersion calculated by the model is based on an exchange-flow concept. Inter-parcel mixing is related to a ratio of inter-parcel discharge to total discharge. The dispersion coefficient is related to this ratio as

$$D_f = \frac{D}{U^2 \Delta t} \quad (7)$$

Dispersion factors, D_f , for the lower Mississippi River were determined by calibrating the Lagrangian transport model with data from two previous time-of-travel dye studies (Stewart, 1967; Martens and others, 1974). A dispersion factor of 0.2 for a half-hour time step was found to adequately reproduce the observed longitudinal-dispersion characteristics of the entire study reach. The same dispersion factor was used for the suspended-sediment transport modeling.

The source/sink terms on the right side of equation 4 represent rates of increase (or decrease) of suspended-sediment concentration due to the physical sedimentation processes occurring within a parcel as it traverses the riverine system. These processes exclude convection and dispersion which have already been taken into account. At the channel bed, a source (increase) of suspended sediment would be entrainment and resuspension of sediment stored on the bed. A sink (decrease) of suspended sediment would be deposition of sediment on the bed. At an arbitrary level above the bed, diffusion and settling mechanisms are postulated to regulate suspended-sediment concentrations. The functional forms of the processes are not well understood. An approach that is used to simulate these processes is described in the following section.

Diffusion and Settling

The approach for simulating sedimentation processes for suspended-sediment transport modeling is derived from river mechanics. Theoretical developments reported by Bennett and Nordin (1977) are modified for use in this study. The basic concept consists of transport in two layers, a suspended-load and bed-load layer (fig. 16). Mass transfer between the two layers occurs with no resistance at the interface separating them, line B-B' of figure 16. Transfer between the layers is assumed to be linearly proportional to the concentration difference between them.

To define the source/sink term of equation 4, it is hypothesized that an instantaneous change in sediment-transport capacity induces a concentration difference between the bed-load layer and suspended-load layer across the line B-B' of figure 16. It is further hypothesized that, this concentration difference causes a flux from the higher to the lower concentration, which is assumed linearly proportional to the magnitude of this difference. The source/sink term is approximated as

$$s = K(C_1 - C_b) \quad (8)$$

where K is a mass transfer coefficient for sediment, C_1 is the concentration of sediment in the bed-load layer of thickness a' , and C_b is the concentration of sediment at the lower edge of the suspended-load layer at a depth of H .

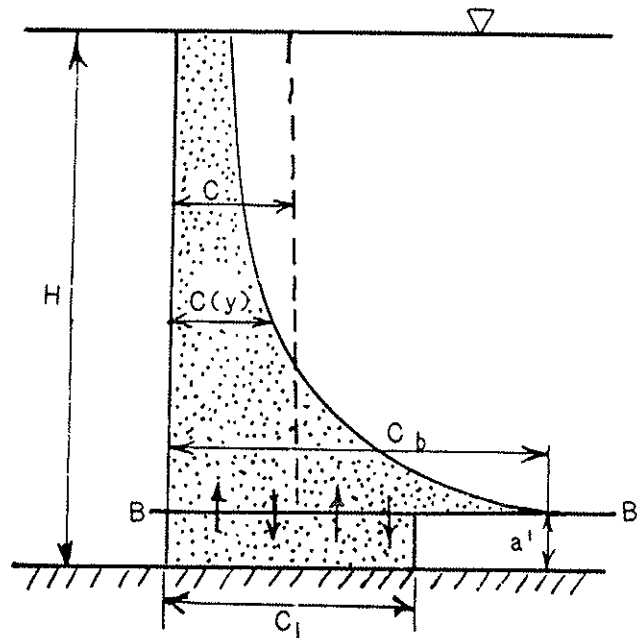
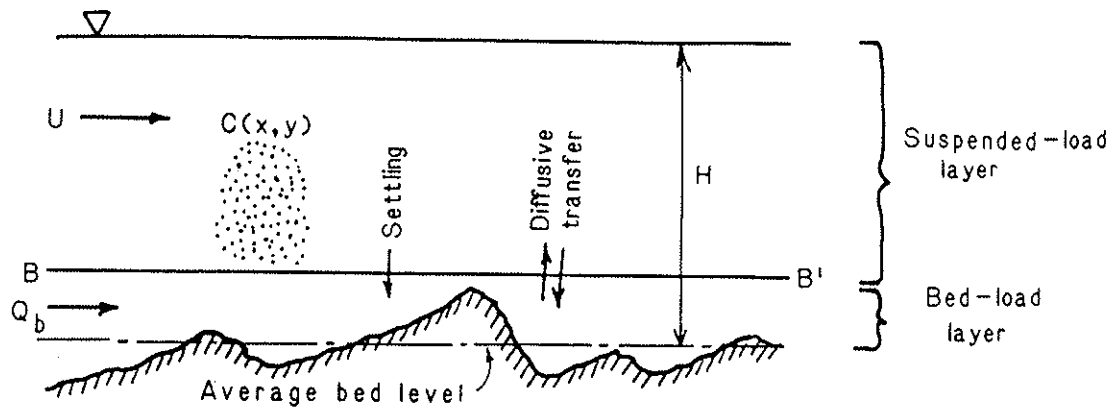
The mass transfer coefficient can be interpreted from practical considerations. Referring to figure 16, for the instance when the bed load, flux $Q_b=0$ (for example, flow over a coarse bed) and assuming a vertical eddy diffusivity of zero at the level a' , a mass balance in the bed-load layer shows the downward flux at B-B' to be $V_s C_b W/A$; where V_s is the sediment settling velocity, W is the width of the bed, and A is the cross-sectional area. If

$Q_b > 0$, then the concentration in the bed-load layer is $Q_b/Wa'U$. Assuming the flux is linearly proportional to the concentration deficit, the term S becomes

$$S = V_s \frac{W}{A} (C_1 - C_b) \quad (9)$$

The mechanics of the vertical distribution of suspended sediment in equilibrium and at steady state (Graf, 1971, p. 167) were used to approximate the concentration C_b at the lower edge of the suspended-load layer. In terms of the depth-averaged suspended-sediment concentration, C , C_b is approximated as

$$C_b = C \frac{V_s H}{\epsilon_s} \left[\frac{1}{1 - \exp\left(\frac{-V_s H}{\epsilon_s}\right)} \right] \quad (10)$$



EXPLANATION

- U —Average stream velocity
- H —Average stream depth
- Q_b —Sediment discharged in bed-load layer
- $B-B'$ —Hypothetical plane separating bed-load layer from suspended-load layer
- x —Distance in the longitudinal direction
- y —Depth from the water surface
- C —Suspended-sediment concentration
- C_1 —Sediment concentration in bed-load layer
- C_b —Sediment concentration at bottom of suspended-load layer
- a' —Depth of bed-load layer

Figure 16.--Vertical transport processes.

where ϵ_s is the eddy diffusivity for sediment, here assumed to be constant over depth, and H is taken as the flow depth. A depth-average value of the eddy diffusivity (Graf, 1971, p. 189) is used

$$\epsilon_s = \frac{1}{15} U^* H \quad (11)$$

where U^* is the shear velocity and will be defined subsequently.

Evaluation of the concentration of sediment in the bed-load layer is necessary to complete the model even though it could not be measured. An equilibrium concentration is computed from the bed-load transport rate as described by two dimensionless parameters (van Rijn, 1984). The two dimensionless parameters are a dimensionless particle parameter, D^* , and a transport-stage parameter, T . The particle and transport-stage parameters are defined as

$$D^* = d_{50} \left[\frac{(S - 1.00)g}{\nu^2} \right]^{1/3} \quad (12)$$

where d_{50} is the particle size for which 50 percent of the sediment is finer by weight, S is specific density, g is acceleration of gravity, and ν is kinematic viscosity; and

$$T = \frac{(U^{*'})^2 - (U^*_{cr})^2}{(U^*_{cr})^2} \quad (13)$$

where $U^{*'}$ is the bed-shear velocity related to grains and will be defined subsequently, and U^*_{cr} is the critical bed-shear velocity. The critical bed-shear velocity being the threshold bed-shear velocity at which bed load is impending transport. Above and at the critical bed-shear velocity, bed-load transport will occur; below the critical bed-shear velocity, bed-load transport does not occur. The concentration, C_1 is expressed as

$$C_1 = \alpha \frac{d_{50}}{a'} \left[\frac{T^{1.5}}{D^{*0.3}} \right] \quad (14)$$

where a' is the thickness of the bed-load layer and α is treated as basically a calibration parameter. Using selected flume and field data, van Rijn (1984) found a calibration parameter to be 1.25×10^{-3} .

Simulations at Steady Flow

The suspended-sediment transport model was run at steady flow with constant upstream boundary conditions. A half-hour time step was used for the computations. The model was run until the first parcel exited the reach, which occurs when the solution converges to steady state. Results were

printed at the last time step and compared to observed data. Simulations were made using three size fractions: sand, silt, and clay. Sand concentrations were directly obtained from the field techniques and laboratory analysis. Silt and clay concentrations were obtained from the particle-size distributions of the fine fraction collected in the field. However, since particle-size distributions were determined at only eight sites on the river, the results of simulations of the silt and clay fractions were summed to give a total fine fraction and compared with observed data at all sites.

A split-sample technique was used for calibration and verification analyses. Data collected at below-average, average, and above-average flow conditions were used to test and calibrate the suspended-sediment transport model. Calibration was achieved by visually fitting the simulation results to the observed data. Additional data at flow conditions similar to those used for calibration were used for verification. Discharge and sediment data used for model input are summarized in table 5.

Table 5.--Summary of data used for suspended-sediment transport simulations

[d_{90} is the diameter of which 90 percent of the sediment by weight is finer.
 d_{50} is the diameter of which 50 percent of the sediment by weight is finer]

Date	Discharge (cubic feet per second)	Temperature (degrees Celsius)	Sand		Silt		Clay	
			d_{90}	d_{50}	d_{90}	d_{50}	d_{90}	d_{50}
millimeters								
Calibration								
11-83	267,000	15.0	0.22	0.13	0.045	0.016	0.0025	0.0010
11-84	532,000	18.5	.25	.12	.050	.021	.0025	.0010
5-84	991,000	16.0	.25	.13	.050	.019	.0023	.0010
Verification								
10-84	260,000	22.0	0.25	0.13	0.040	0.013	0.0024	0.0010
12-84	678,000	9.5	.22	.12	.050	.021	.0022	.0010
1-85	899,000	9.0	.22	.11	.052	.020	.0029	.0011

Hydraulic data necessary for the transport computations were provided by a numerical streamflow model. The 295-mile reach was discretized using 35 grid points representing longitudinally-averaged cross sections. The flow model produced a data file containing velocity, cross-sectional area, top

width, and water-surface slope at each grid point. Hydraulic computations were performed uncoupled or independent of sediment computations. The fine sediments transported were assumed not to control the configuration of the bed and, thus, the hydraulics.

Other than hydraulic data, the only other data necessary for model simulations are the d_{50} and d_{90} of each size fraction to be modeled. Particle-size distributions measured at eight sites were averaged and the d_{50} and d_{90} were interpolated from these distributions for model input. The upstream-boundary conditions were the measured concentrations of sand, silt, and clay at Tarbert Landing, Miss. Settling velocities were determined using Stokes equation (Graf, 1971, p. 43). The bed-shear velocity was approximated using uniform flow theory for a wide channel as $U^* = (gRS)^{0.5}$ where $R = A/W$ and $S =$ water-surface slope. The bed-shear velocity due to grain roughness was calculated according to van Rijn (1984) as $U^{*'} = (g/C') U$, where C' is the Chézy coefficient due to grain roughness. C' was calculated as $C' = 18 \log (12.21 H/3d_{90})$. The critical bed-shear velocity was determined according to Shields diagram (Graf, 1971, p. 96). The height of the bed-load layer was estimated as $a' = 0.01H$ for lack of measurements of actual bed-form dimensions.

Comparisons of predicted and observed suspended-sediment concentrations used for calibration are presented in figures 17 and 18. In these figures, the solid curves represent the predicted concentrations and the symbols represent the observed concentrations. The only parameter free to fit is α . A value of $\alpha = 3.75 \times 10^{-3}$, was used to calibrate the model. The same value was used for all flow conditions. In his study van Rijn (1984) used a value of $\alpha = 1.25 \times 10^{-3}$ to fit observed suspended-sediment profiles from flume and river data. Discrepancies in the two values of α may exist because the height of bed forms were not available in either study so thickness of the bed-load layer is not comparable.

The results predicted by the model generally match the trends observed in the data with the exception of the May 1984 sand and November 1984 fines simulations. Velocity in the main channel of the upper reaches may be too high during the May simulation because no overbank flow was simulated in the flow model. Errors in the hydraulic computations probably have an adverse compound-effect on transport computations. Additional processes not accounted for in the diffusion and settling model most likely account for the discrepancies in the November 1984 fines simulations. Despite these discrepancies, the model is reasonable and can be calibrated with data from the lower Mississippi River.

Comparisons of predicted and observed suspended-sediment concentrations used for verification are presented in figures 19 and 20. The observed data are matched reasonably well with the possible exception of the highest flow event. The model appears to be valid but should be used with caution at high discharges. Additional calibration effort with a longitudinally varying coefficient may remedy this situation.

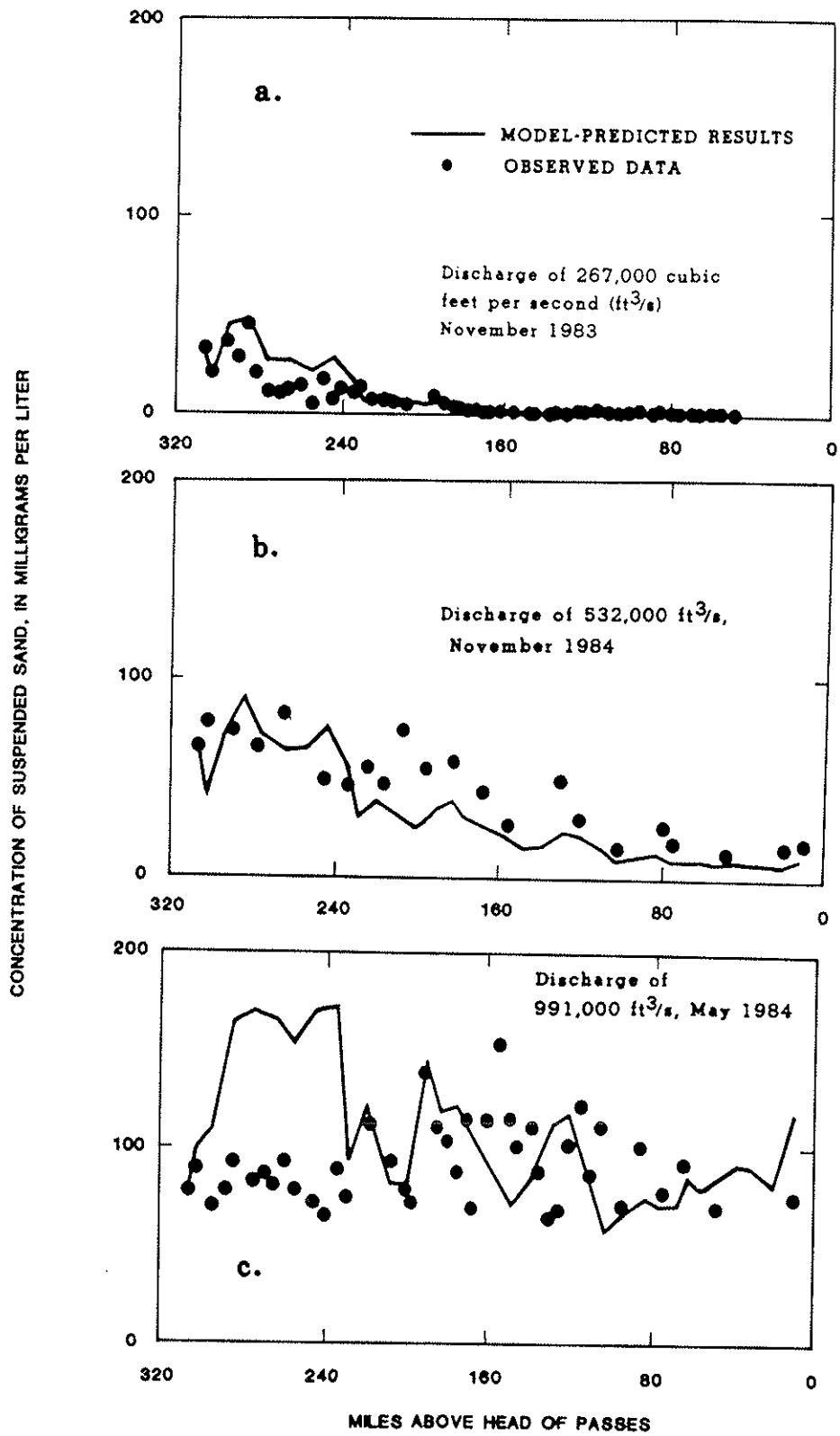


Figure 17.--Comparison of computed and observed concentrations of suspended sand used for model calibration of the lower Mississippi River, Louisiana.

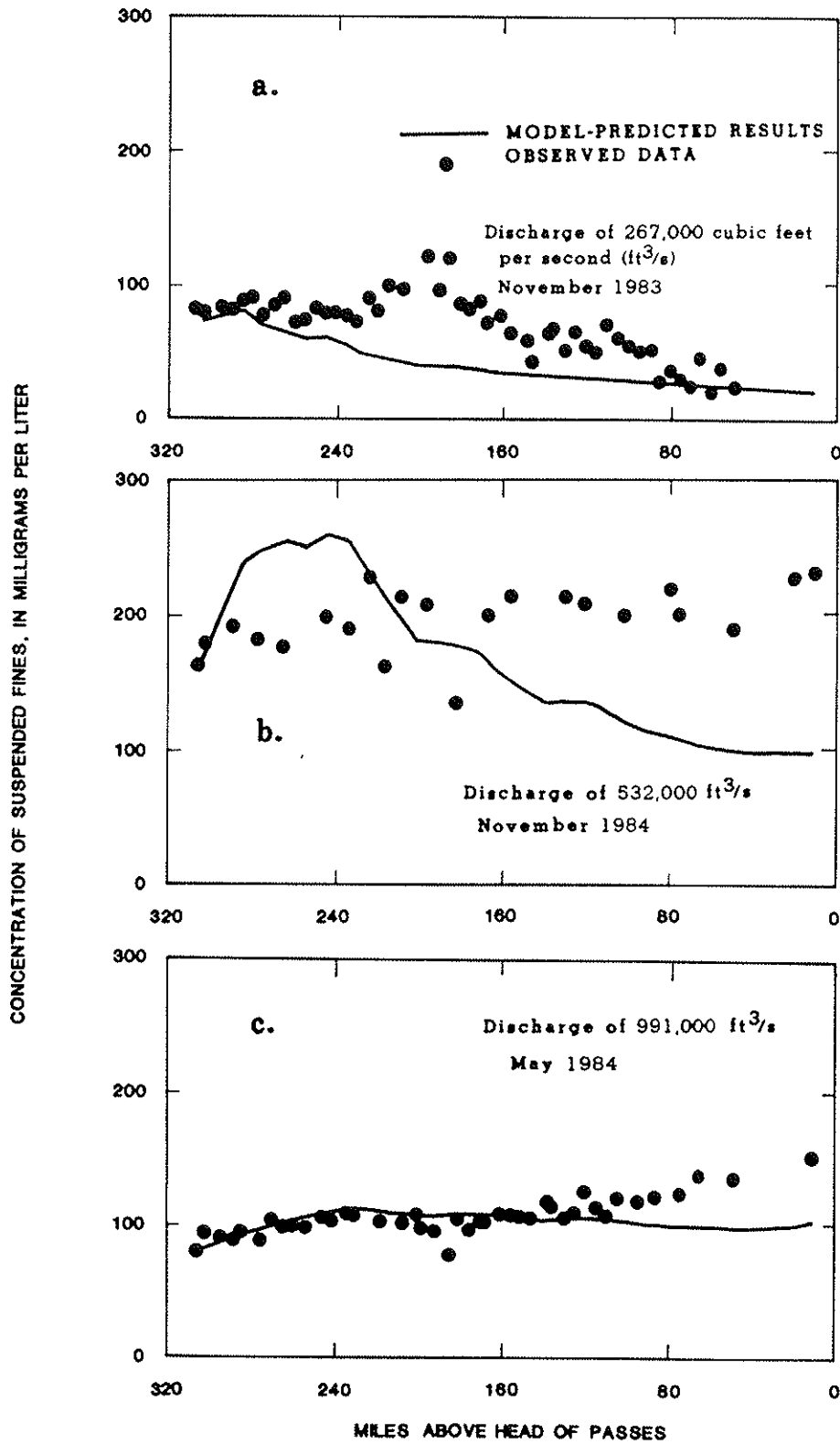


Figure 18.--Comparison of computed and observed concentrations of suspended fines used for model calibration of the lower Mississippi River, Louisiana.

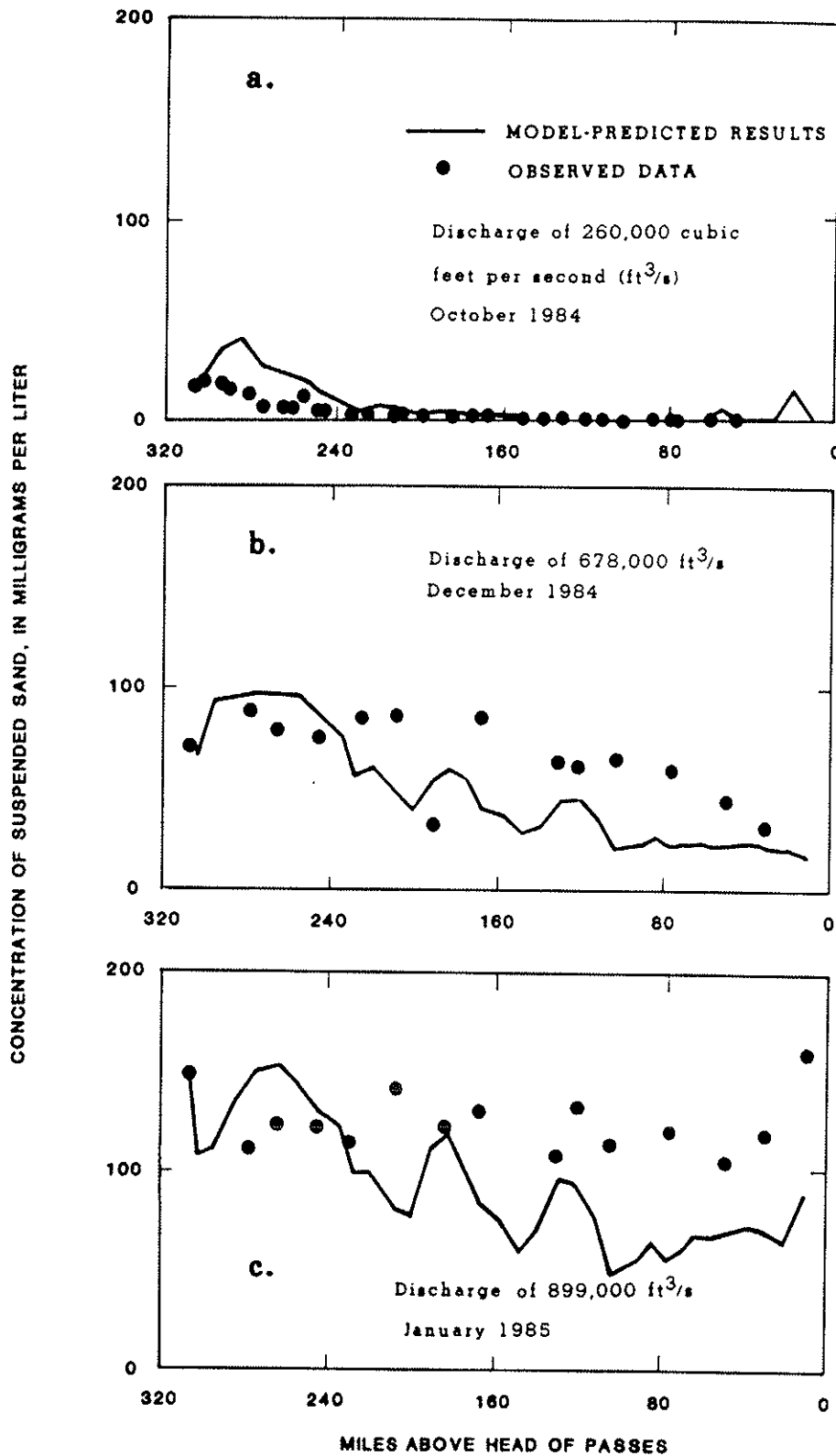


Figure 19.--Comparison of computed and observed concentrations of suspended sand used for model verification of the lower Mississippi River, Louisiana.

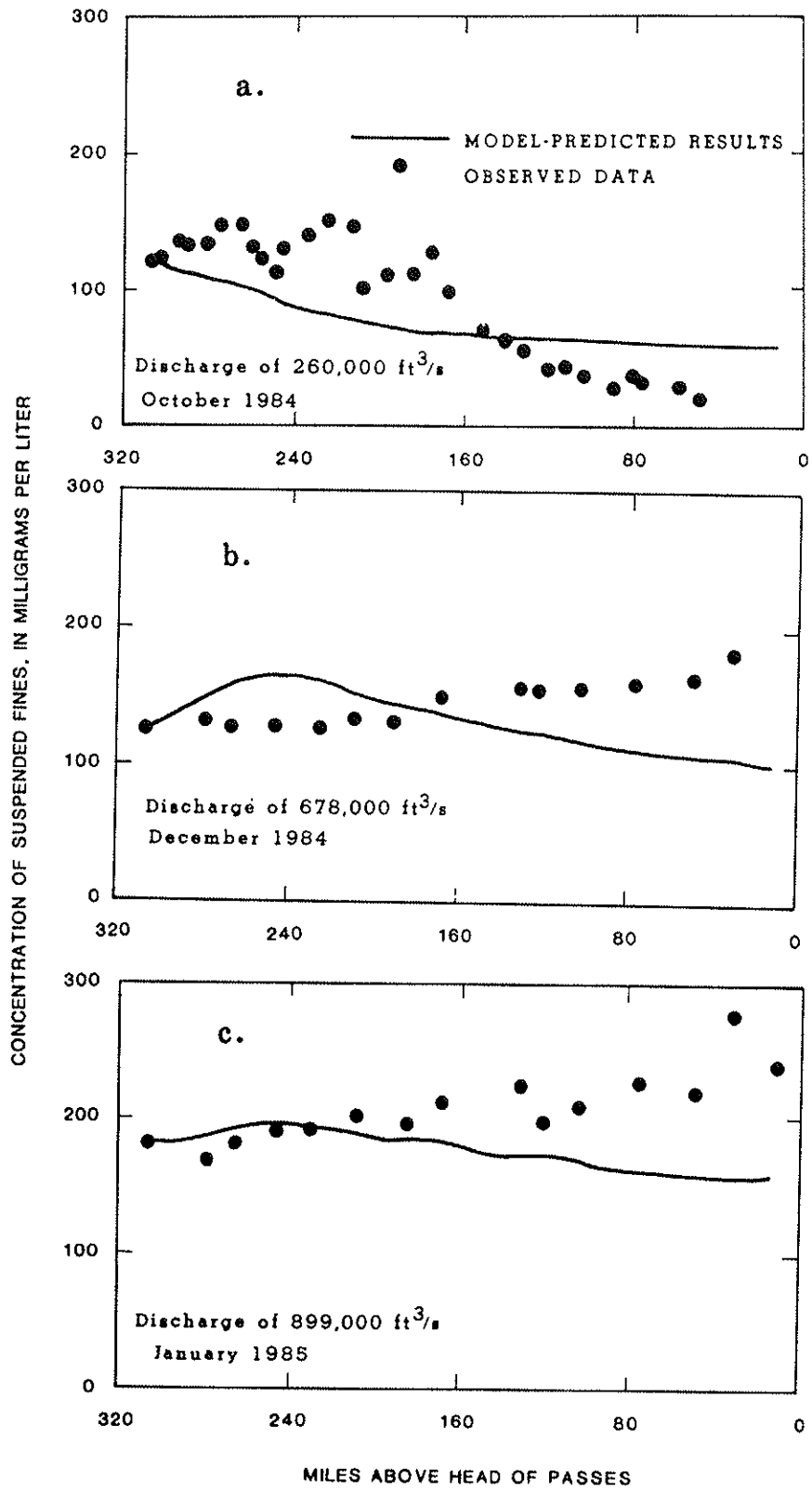


Figure 20.--Comparison of computed and observed concentrations of suspended fines used for model verification of the lower Mississippi River, Louisiana.

Results

Modeling suspended sediment using the approach presented is physically realistic. This is especially true for sand-sized sediments. For the silt- and clay-sized sediments, several processes not explicitly accounted for in this model may dominate their behavior. These processes are most likely attributable to the cohesiveness of the fines. The behavior of cohesive sediments differs from that of noncohesive sediments in several important ways.

In suspension of noncohesive material, the basic settling unit is the individual grain. Particle interactions are strictly mechanical. Noncohesive-sediment beds resist erosion by the submerged weight of the individual grains.

Cohesive sediments consists of particles small enough, with a surface-to-mass ratio large enough, that their surface physico-chemical forces may become much more important than their weight. These forces may include (a) van der Waals forces, (b) surface-electric charges, (c) chemical bonds, and (d) interactions of the double layer (Partheniades, 1965). These forces are only partially understood and may vary with environmental conditions (such as temperature, conductivity, and pH).

For clay-size particles in distilled water the net effect of these forces may be repulsion. However, even small amounts of dissolved salt will bring about particle attraction (through double layer compression), resulting in aggregation of colliding particles into flocs having size and fall velocity much larger than those of the individual particles. The basic settling unit, thus, becomes the floc. Cohesiveness also provides bed sediments with additional shear strength to resist erosion.

Results computed by the model show the clay-sized particles to be conservative; whereas, the observed data show these particles acting nonconservatively. Fall velocities based on individual clay-sized particles are so minute; practically no deposition is ever predicted. An effective fall velocity concept could be used to calibrate the model but was not done in this instance in order to minimize calibration parameters. The indirect estimation of an effective fall velocity may be difficult in many practical situations. If hydraulic and water-quality conditions vary along the length of the river, then the fall velocity may also vary. Normal scatter in the suspended-sediment data may make the identification of an effective fall velocity ambiguous. Nevertheless, this approach was used by Schoellhamer and Curwick (1986) and found to be successful using the same data set.

CONCLUSIONS

1. Suspended-sediment concentrations decreased by as much as 85 percent in a downstream direction during steady flow conditions less than 500,000 ft³/s and increased by as much as 44 percent in a downstream direction during steady flow conditions greater than 700,000 ft³/s.

2. Major fluctuations observed in concentration of total suspended sediment in a downstream direction were caused by fluctuations in concentrations of fines.
3. Suspended-sand concentrations never increased in a downstream direction during any of the steady flow conditions sampled.
4. Particle-size distributions of the suspended sediment showed no apparent relation to discharge and are probably determined by antecedent hydrologic conditions which determines the source of the material available.
5. Data indicate that the bed of the lower Mississippi River in the study reach serves as a sink and reservoir for suspended sediment during flows less than 500,000 ft³/s and a source of suspended sediment during flows greater than 500,000 ft³/s.
6. Findings show a correlation ($r > 0.7$) between concentration of fines and total-recoverable and suspended manganese, iron, and cobalt in unfiltered-water samples.
7. Analyses of three distinct suspended-sediment particle-size classes showed increasing minor-element concentration with the two smaller suspended-sediment particle size ranges for manganese, iron, cobalt, aluminum, chromium, copper, cadmium, nickel, and zinc. Highest concentrations were associated with the fines particle-size class, indicating fines play a major role in minor element transport in the lower Mississippi River.
8. Statistical results suggest that manganese and iron oxide coatings may be a significant factor in the transport of minor elements and that fine sediments play a significant role in the transport of minor elements in the lower Mississippi River.
9. No selected organic compounds were found on different bottom-material particle-size classes, probably because of little transport of these compounds within the study area.
10. A Lagrangian suspended-sediment transport model was successfully applied to the study reach of the lower Mississippi River. Simulated model results compared favorably with observed data for sand and fines fractions, demonstrating the effectiveness of the model in predicting short-term suspended-sediment transport in the river.

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