CURRENT AND HISTORICAL SEDIMENT LOADS IN THE LOWER MISSISSIPPI RIVER

Final Report

by

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July 2008

to

United States Army

EUROPEAN RESEARCH OFFICE OF THE U.S. ARMY
London, England

under

CONTRACT NUMBER 1106-EN-01

from

School of Geography, University of Nottingham
University Park Nottingham NG7 2RD

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*: 30 JULY 2008

2. REPORT TYPE: FINAL REPORT

3. DATES COVERED *(From - To)*: FEBRUARY 2007 - JULY 2008

4. TITLE AND SUBTITLE

CURRENT AND HISTORICAL SEDIMENT LOADS IN THE LOWER MISSISSIPPI RIVER

5a. CONTRACT NUMBER: N62558-07-C-004

5b. GRANT NUMBER: 1106-EN-01

5c. PROGRAM ELEMENT NUMBER: NOT APPLICABLE

6. AUTHOR(S)

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5d. PROJECT NUMBER: RK1526

5e. TASK NUMBER: NOT APPLICABLE

5f. WORK UNIT NUMBER: NOT APPLICABLE

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

UNIVERSITY OF NOTTINGHAM,
UNIVERSITY PARK, NOTTINGHAM,
NG7 2RD, UNITED KINGDOM

8. PERFORMING ORGANIZATION REPORT NUMBER: RK1526 (FINAL)

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

ERDC EUROPEAN RESEARCH OFFICE
EDISON HOUSE, 223 MARYLEBONE
ROAD, LONDON NW1 5TH, UK

10. SPONSOR/MONITOR'S ACRONYM(S): ERDC-ERO

11. SPONSOR/MONITOR'S REPORT NUMBER(S): NONE

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION UNLIMITED

13. SUPPLEMENTARY NOTES

NONE

14. ABSTRACT

Questions concerning past, present and future temporal trends in the sediment load of the Lower Mississippi River are relevant to the redistribution of available Mississippi River sediment as part of efforts to reduce loss and restore coastal lands in Louisiana. This project compiled a comprehensive data base on measured loads in the Lower Mississippi River and collected information on the behavior of sediment at diversions. Statistical techniques were used to analyze database records from selected hydrometric stations (especially Tarbet Landing) to establish how sediment loads have changed historically and examine how they vary seasonally, annually and decadally. Records of measured loads and dredging are used to assess the availability of sediment in the Mississippi River. The results of this research may inform plans to divert water and sediment out of the river to support coastal wetland enhancement and rehabilitation in the delta.

15. SUBJECT TERMS

MISSISSIPPI RIVER MEASURED LOAD SEDIMENT LOAD
REGIONAL SEDIMENT MANAGEMENT RIVER WETLAND RESTORATION

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)*

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Executive Summary

Questions concerning past, present, and future temporal trends in the sediment load of the Lower Mississippi River are of great importance because the redistribution of available Mississippi River sediment is vital to on-going efforts to reduce land loss and restore coastal marshes and wetlands in Louisiana. This document reports the results of a 1-yr study performed by Nottingham University, Halcrow and the Biedenharn Group in collaboration with the Waterways Experiment Station, Engineer Research Development Center (ERDC), Vicksburg, Mississippi, that was aimed at assembling available data on sediment loads in the river, assessing its reliability and temporal variability, and exploring the implications for sediment diversions.

The lower Mississippi River, extending from Cairo, Illinois, to the Gulf of Mexico, currently transports approximately 150 million tons of sediment annually. Historically, the quantity and caliber of sediment derived from catchment erosion have been affected by changes in land-use and river management; increasing in the 19th and early-20th Centuries, before decreasing due to soil conservation and improved land management. The supply of sediment from tributaries is also believed to have decreased markedly as a result of river engineering and management. However, there is no consensus on the degree of reduction as a proportion of the previous 'natural' or undisturbed load, the time distribution of the reduction or how the trajectory of past and present trends may change in the future.

Cumulative land loss in Louisiana over a 50-yr period represents on the order of 80% of the coastal land loss in the United States. The Louisiana Coastal Area (LCA) was released by the United States Army Corps of Engineers (USACE) in 2004 and included the consideration of approximately twenty-three diversions of water and sediment from the Mississippi River, with a total diversion capacity in the range of 150,000 to 200,000 cfs. This does not include the Third Delta diversion, with a proposed capacity of 120,000 to 240,000 cfs. The proposed LCA diversions pose significant management and engineering challenges and will require detailed modelling to support their design. The availability of reliable data on flows and associated sediment loads to support modelling would seem to be a prerequisite for meeting these challenges successfully.

Research to make available reliable sediment-transport data began by extending the database compiled by Thorne *et al.* (2001). Work focused on measured suspended-sediment loads. Updating the database involved: (i) adding recent measurement collected by the USACE New Orleans and Vicksburg Districts; and (ii) adding available historic measurements extending as far back as the earliest available records from the mid-19th Century. In compiling the database, considerable assistance was provided by the USACE ERDC, USACE Vicksburg District, USACE New Orleans District, USACE Lower Mississippi Valley Division, and the United States Geological Survey (USGS). The database is on the CD-ROM that accompanies this report.

In using the database, it is important to recognize uncertainty in assessing the level of confidence, reliability, and accuracy of analyses based on the sediment records. In this context, the study investigated various approaches to calculating sediment loads from point measurements of suspended-sediment concentration and the associated uncertainties introduced through sampling and calculation. A preliminary quantification of some of the sources of uncertainty was developed and overlapping sediment records from different sources were used to interpret the reliability of the sediment records. Also, the effects of changing sampling technology on uncertainties in the measured sediment loads were considered.

A range of sampling strategies and calculation methodologies has been used for measuring and calculating the load carried by the lower Mississippi River. Several of these sampling strategies introduce uncertainties in excess of 20% in concentration of coarse sediment, though uncertainty in the concentration of fines and the total concentration is much lower. This can be attributed to the greater variability in coarse concentration within the cross-section. Generally, the higher the number of point-concentration measurements in a sampling strategy, the lower variability is in the calculated load.

Uncertainties in calculations of the annual sediment load arise because they are based on records of sediment measurements made on a variable number of sample days and involve assumptions about how sediment load varies between measurements. To investigate the importance of sampling frequency, a synthetic daily record of sediment load was resampled at less frequent sampling intervals. The results suggest that uncertainty introduced by the process of estimating annual load remains relatively low provided measurements are taken at least once a month – a sampling frequency equalled or exceeded by nearly all modern sediment-monitoring programs on the Lower Mississippi River. Of the methods employed to interpolate between sample days, linear interpolation of average concentration was found to be most appropriate for estimating the annual load.

The locations of some hydrometric stations have changed through time. As a result, it is necessary to assess the effects of changing sampling location on estimates of historic changes in sediment loads and concentrations. Uncertainty analysis focused on the Tarbert Landing data record to provide a preliminary indication of this uncertainty.

It was concluded that uncertainty arising from changes in sampler type in the modern era is small compared to historic measurements made prior to the 1930s.

To assess overall uncertainty a sequential approach was adopted. This allowed daily load calculations to be adjusted to account for the uncertainties arising from each source at the appropriate stage of the calculation. For Tarbert Landing, the estimated uncertainty is highly variable, but can be as much as 15% of the calculated daily load. Other stations have greater variability due to less frequent sampling and large data gaps. Levels of uncertainty in post-1960 measurements are believed to be low in comparison to earlier records, although in most cases it was not possible to quantify uncertainty in the historical records.

Preliminary comparison between annual sediment loads estimated from records at different stations indicate that the data-quality issues discussed above should be investigated further. To address this, it is recommended that further investigations be undertaken using the sediment records from Natchez and Arkansas City.

Variability and historical trends in the sediment load are of great importance to plans to redistribute Lower Mississippi River sediments to restore coastal marshes and wetlands in Louisiana. To address these issues, statistical analyses were applied to recent records for Tarbert Landing, with other older stations being used to supply historical data. Tarbert Landing was used because: it is located in the upper delta and, therefore, can be considered to be representative of the load available to the coastal region; and it has the longest record of routine monitoring.

Seasonal analysis shows that in the spring, the median total load is approximately four times the median total load in the fall. Variability in monthly loads for peak-flow months during the spring is also higher than during the other (lower flow) seasons, particularly with respect to coarse load. The median sediment size is overwhelming silt, but it coarsens during the winter and spring, while the D_{90} is typically fine sand.

The average annual load at Tarbert Landing during the period 1963 to 2005 is approximately 150 million tons, varying between a minimum of 70 million tons and a maximum of 230 million tons. The median annual coarse suspended-sediment load over the same period is highly variable, varying from 5 to 80 million tons. Five-year total suspended-sediment loads for the last 40 yrs are less variable, ranging between 580 and 960 million tons, with coarse sediments constituting 40 to 320 million tons and the remainder being fines.

The trend apparent in 19th and late-20th Century average loads suggests that there has indeed been a long-term decline in the average annual load. This simple assessment must, however, be treated with an appropriate degree of caution because: (i) robust statistical treatment of the data is hampered by large gaps in the record; (ii) data are sourced from multiple locations; (iii) there are high but unquantified uncertainties associated with early measurements of sediment load; and (iv) calculated measured loads will underestimate the coarser fractions of suspended load, and do not include sediment moving as bed load at all. Linear regression analyses for data from Tarbert Landing during the period 1959 to 2005 indicate that on-going, declining trends in suspended-sediment concentrations may have been partially offset by an increasing trend in water discharge, resulting in there being no significant trend in the annual sediment load.

This study has compiled a comprehensive database of available measured sediment-load data for the Lower Mississippi and, for the first time, made it easily accessible. Preliminary analyses have been performed to assess the reliability of the data and investigate variability and historical trends in the records.

It is hoped that further analyses will now be performed by researchers with Federal, State, and local agencies as well as those in the academic and private sectors.

Part II of the report presents a preliminary assessment of the implications for sediment diversions, achieved either through reconnection of the river to its deltaic plain or through the use of dredged sediment to create or restore coastal marshes and wetlands.

In considering the implications, the work of Barras *et al.* (2004) is used as the basis to assume a loss rate of 13.5 sq mi/yr [35 km^2/yr], with an error range of ±25%. The error range yields a maximum loss rate of 16.9 sq mi/yr [43.8 km^2/yr], and a minimum loss rate of 10.1 sq mi/yr [28.2 km^2/yr]. Based on available dredging records, the total annual dredging by the New Orleans District appears to be sufficient to satisfy the needs of beneficial use placement; however, several caveats must be carefully considered: (i) first, the sources of dredge material may not coincide with convenient locations for beneficial placement, perhaps placing a burden of high cost on projects; (ii) second, historical dredging records may have quality-control issues beyond the present standard of practice; and (iii) third, the range of acceptable sediment gradations for dredge-material placement is poorly defined, and a portion of the total dredged material may be unsatisfactory for the intended use.

Another example of the available supply of sediment can be drawn from the work of Andrus (2007). Based on his estimate of 8,050 tons of sediment per day, and assuming a depth required of 3 ft and 75% containment of sediment, the West Bay diversion could supply sediment sufficient to satisfy about 29% of the total annual sediment required to create a platform for 13.5 sq mi annually. Based on the error in land loss estimated by Barras *et al.* (2004) of 25%, the capacity of West Bay would need to be multiplied by 2.5 to 4.3 to satisfy the full estimated land-loss amount.

Once the platform of dredge material is constructed, water, nutrients, and sediment will be required to promote and sustain marsh development. Using the McKay *et al.* (2008) model, and assuming that marsh building of 0.5 ft/yr is sufficient, an average discharge of approximately 8,600 cfs of diversion would be required to build and sustain 13.5 sq mi of marsh. With a range of ±25% of the mean flow, the maximum discharge would be 10,700 cfs and the minimum would be 6,414 cfs. By comparison, several existing diversions already exist with discharges in excess of 8,000 cfs.

Designing sediment and water diversions that optimize marsh development and achieve high percentages of sediment retention will be challenging. The scenario presented here is expressed in terms of average discharges and sediment concentrations. In reality the high variability evident in the records means that high- or low-flow periods and major floods must also be accounted for. For example, events such as the flood of 1973 would present the opportunity to divert more resources to marsh creation and these should be seized.

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Part I: Sediment Database and Analysis

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SYMBOLS, UNITS, AND ABBREVIATIONS

Part I: Sediment Database and Analysis

Symbols

D_{50}	median sediment size
D_{90}	90th percentile sediment size
R^2	coefficient of determination
X, Y, and Z	unknown values
X, Y	axes

Units

%	percent
cfs	cubic feet per second
cm	centimeter(s)
cu ft	cubic feet
cu yds	cubic yard(s)
ft	feet
in.	inch(es)
m^3	cubic meter(s)
mm	millimeter(s)
ppm	parts per million
RM	river mile
yr(s)	year(s)

Abbreviations

1D	one dimensional
2D	two dimensional
ADCP	Acoustic Doppler Current Profiler
AK	Alaska
approx.	approximately
AR	Arkansas
.BOK	file extension for data file
E	electronic
ERDC	Engineer Research and Development Center
GCLAS	Graphical Constituent Loading Analysis System
IL	Illinois

KY	Kentucky
LA	Louisiana
LCA	Louisiana Coastal Area
MO	Missouri
MRC	Mississippi River Commission
MR&T	Mississippi River and Tributaries
MS	Mississippi
n/a	not available
No.	Number
P	paper
®	registered
TN	Tennessee
Std Dev	standard deviation
USACE	U.S. Army Corps of Engineers
USGS	United States Geological Survey

Part II: Implications for Sediment Diversions

Symbols

$\%TNP$	percent of nitrogen and phosphorus in plant biomass
B	average water width (ft)
H	average water depth (ft)
P_r	plant productivity rate
TNP	total nitrogen and phosphorus
$TNP_{background}$	background concentration of nitrogen and phosphorus (mg/L)
TNP_{source}	source concentration of nitrogen and phosphorus (mg/L)
$U_{tide,max}$	maximum tidal velocity (ft/s)
z_0	roughness height (m, ft)
ρ_i	upper-horizon (top 50 cm) bulk densities

Units

%	percent
%/yr	percent per year
acres/yr, acre/yr^{-1}	acres per year
cfs	cubic feet per second
cm	centimeter(s)
cm/yr	centimeter(s) per year

cu yds	cubic yards
cu yds/acre	cubic yards per acre
ft	feet
ft/s	feet per second
ft/yr	feet per year
g/cm^3, $g\ cm^{-3}$	gram(s) per cubic centimeter
$g/cm^3/m$	gram(s) per cubic centimeter per meter
$g/m^2/yr$	gram(s) per square meter per year
ha	hectare(s)
km	kilometer(s)
km^2	square kilometer(s)
km^2/yr, km^2/yr^{-1}	square kilometer(s) per year
m	meter(s)
m^3	cubic meter(s)
m^3/s, $m^3\ s^{-1}$	cubic meter(s) per second
mg/L, mg/L^{-1}	milligram(s) per liter
mi	mile(s)
mm	millimeter(s)
mm/yr	millimeter(s) per year
mo	month
ppt	parts per thousand
RM	river mile
sq mi	square mile(s)
sq mi/yr, sq mi/yr^{-1}	square mile(s) per year
T/km^2	ton(s) per square kilometer
tons/day	ton(s) per day
tons/mo	ton(s) per month
yds/acre	yard(s) per acre
yr(s)	year(s)

Abbreviations

CWPPRA	Coastal Wetlands Planning, Protection and Restoration Act
FWOP	future without project
GIWW	Gulf Intracoastal Waterway
IPCC	Intergovernmental Panel on Climate Change
LaCPR	Louisiana Coastal Protection and Restoration
LCA	Louisiana Coastal Area
LDNR	Louisiana Department of Natural Resources

Max	maximum
Min	minimum
MRGO	Mississippi River Gulf Outlet
N	nitrogen
NAS	National Academy of Science
NAVD	North American Vertical Datum
P	phosphorus
RSLR	relative sea-level rise
Std Dev	standard deviation
TSS	suspended sediment
USACE	U.S. Army Corps of Engineers

PART I: SEDIMENT DATABASE AND ANALYSIS

1 Introduction

1.1 Background

Questions concerning past, present, and future temporal trends in the sediment load of the lower Mississippi River are of great importance because the redistribution of available Mississippi River sediment is the centerpiece of the on-going effort to halt loss and restore coastal land loss in Louisiana.

The lower Mississippi River, extending from Cairo, Illinois, to the Gulf of Mexico, currently transports approximately 150 million tons of sediment annually. Historically, the quantity and caliber of sediment derived from catchment erosion have been affected by changes in land-use and river management; increasing in the 19th and early-20th Centuries, before decreasing due to soil conservation and improved land management. The supply of sediment from tributaries is also believed to have decreased markedly as a result of river engineering and management. Specifically, the construction of large dams as part of the Mississippi River and Tributaries (MR&T) Project has trapped sediment that would otherwise have been supplied to the Mississippi, particularly by the Missouri River. Marked changes have also occurred in the extent of eroding banklines along the Mississippi and these must have reduced the input of sediment derived from that source. For example, during the last 3 decades, a sustained construction program of bank revetments and dikes has produced a stable planform alignment.

Given these trends in sediment supply from catchment, tributary, and bank sources, it is not surprising that most studies of sediment movement report a large decrease in measured sediment loads at selected monitoring stations along the Mississippi River over the last 70 to 150 yrs. However, there is no consensus on either the degree of reduction as a proportion of the previous ‘natural’ or undisturbed load, or the time distribution of the reduction and how the trajectory of past and present trends may change in the future. Based on the Tarbert Landing record for example, Keown *et al.* (1981) suggest that the total annual suspended-sediment load declined from 427 million tonnes prior to 1963 to 251 million tonnes by 1981. Robbins (1977) compared measured suspended-sediment records for the periods 1921 to 1931 and 1967 to 1974 and found that total suspended-sediment loads had decreased since 1931 by roughly 40% at both Arkansas City and Vicksburg. Extending the historical analysis further by using data from the Humphreys and Abbot (1861) report, Kesel (1988, 1989) suggested that total suspended-sediment loads on the lower Mississippi River have declined by approximately 80% in the period 1851 to 1982.

Cumulative loss in Louisiana over a 50-yr period represents 80% of the coastal land loss in the entire United States (Dean, 2006). Among the plans that have been considered, the *Louisiana Coastal Area (LCA)* was released by the United States Army Corps of Engineers (USACE, 2004) and included the consideration of approximately twenty-three diversions of water and sediment from the Mississippi River (in the approximate range of 1,000 to 15,000 cubic feet per second (cfs) each). Although the LCA did not provide detailed design capacities for each diversion, available information suggests a cumulative diversion capacity in the range of 150,000 to 200,000 cfs at these twenty-three sites. Not included in the proposed twenty-three sites is the Third Delta diversion with a proposed capacity of 120,000 to 240,000 cfs. Dean (2006) provides an example calculation that suggests an average subsidence of 0.25 cm (0.1 in.) per year would result in an annual deficit volume of 75 million m^3 (2.65 $x10^9$ cu ft).

The scope of the proposed LCA diversions is potentially greater than that of the Atchafalaya River diversion at the Old River, and would occur at many sites, posing significant management challenges. The availability of reliable data on flows and associated sediment loads would seem to be a prerequisite for meeting these challenges successfully.

1.2 Research aims and objectives

The aim of the project was to compile a comprehensive database of measured loads in the Lower Mississippi River and collect information on the behavior of sediment at diversions so that statistical techniques could be used to assess uncertainties in the data and analyze long-, medium-, and short-term changes in the sediment load at selected hydrometric stations. It was intended that the results of this research might inform plans to divert water and sediment out of the river to support coastal wetland enhancement and rehabilitation in the delta.

In pursuing this aim, the objectives of the research were to:

- Extend and update an existing database on measured sediment loads in the lower Mississippi River that was compiled by Thorne *et al.* (2001).

- Use available evidence to identify trends and uncertainties in historic sediment loads to inform the debate on the way that sediment loads supplied to the Mississippi Delta have changed through time.

- Explore the significance of inter-annual variations and seasonal fluctuations in sediment load together with information on sediment behaviour at diversions to inform plans to divert water and sediment out of the river to support coastal restoration, marsh creation, and wetland rehabilitation.

The work was performed through work packages organized into the following four phases, employing a range of methods and techniques appropriate to each task:

Phase I – Data Assembly and Reduction

Phase II – Historical Trend and Uncertainty Analysis

Phase III – Seasonal, Inter-annual, and Longer-term Variability

Phase IV – Implications for Sediment Diversions

1.3 Previous research

To investigate trends in total and bed-material loads in the lower Mississippi River, a predecessor project was performed in 2000 to 2001 to compile a database of available data on measured sediment loads and bed gradations for the lower Mississippi River and perform initial analysis on the data to identify and evaluate trends in space and time (Thorne *et al.*, 2001). The project compiled a database of available measured sediment-transport data for the lower Mississippi River collected since the 1970s.

This research has extended the database compiled by Thorne *et al.* (2001) by updating: (i) recent measurement collected by the USACE New Orleans and Vicksburg Districts; and (ii) available historic measurements extending as far back as the earliest available records.

1.4 Consultation

A detailed understanding of the available data sets of sediment measurements, sampling strategies, and data-processing methodologies was gained through undertaking consultation with key personnel from the USACE Engineer Research and Development Center (ERDC), USACE Vicksburg District, USACE New Orleans District, USACE Lower Mississippi Valley Division, and the United States Geological Survey (USGS). A buy-in consultee workshop was held in October 2007. Minutes from this meeting are contained on the accompanying CD ROM.

2 Sediment-transport Data Assembly

This chapter describes the sources of sediment-measurement data, the variability in the types of data available, and the sampling procedures used to collect the original measurement data.

2.1 Definition of sediment-transport terms

To avoid confusion in the interpretation and analysis of the database, it is necessary to list the definitions of different types of sediment load referred to in this report. The definitions are summarized in Table 2.1.

Table 2.1 Different ways to classify sediment load

Measurement Method	Transport Mechanism	Sediment Source
Measured Load	**Suspended Load**	**Wash Load**
		Bed-material Load
Unmeasured Load	**Bed Load**	

Bed Load
Component of total sediment load made up of particles moving in frequent, successive contact with the bed. Transport occurs at or near the bed, with the submerged weight of particles supported by the bed. Bed load movement takes place by processes of rolling, sliding or saltation.

Suspended Load
Component of the total sediment load made up of sediment particles moving in continuous suspension within the water column. Transport occurs above the bed, with the submerged weight of particles supported by anisotropic turbulence within the body of the flowing water.

Bed-material Load
Portion of the total sediment load composed of grain sizes found in appreciable quantities in the stream bed. The bed-material load is the bed load plus the portion of the suspended load composed of particles of a size that are found in significant quantity in the bed.

Coarse Load
Portion of the total sediment load composed of grains coarser than 0.063 mm. The coarse load of the Mississippi River consists of sand.

Wash Load
Portion of the total sediment load composed of grain sizes finer than those found in appreciable quantities in the stream bed.

Fine Load
Portion of the total sediment load composed of grains finer than 0.063 mm. The fine load of the Mississippi River consists of silt and clay.

Measured Load
Portion of the total sediment load measured by conventional suspended-load samplers. Includes a large proportion of the suspended load but excludes that portion of the suspended load moving very near the bed (that is, below the sample nozzle) and all of the bed load.

Unmeasured Load
That portion of the total sediment load that passes beneath the nozzle of a conventional suspended-load sampler, by near-bed suspension and as bed load.

Total Sediment Load
The total mass of sediment transported by the stream. It can be broken down by source, transport mechanism or measurement status (Table 2.1).

This project focused on measured suspended-sediment loads in the lower Mississippi River. Measured loads generally underestimate the actual suspended-sediment load because sediment-measurement methodologies do not adequately account for the unmeasured load between the deepest point of sampling and the river bed.

2.2 Data sources

This project built upon the existing database of suspended-sediment and bed-material measurements compiled by Thorne *et al.* (2001), which included sediment measurements collected on the lower Mississippi River, Atchafalaya River, Red River, and the Old River since the 1970s.

This project extended the existing database for the lower Mississippi River by compiling all available historic measurements within the USACE Vicksburg District and New Orleans District (*i.e.*, downstream from Arkansas City). Data were compiled from a variety of sources including:

- USACE Vicksburg District
- USACE New Orleans District
- USGS
- Wide range of historical records extending back to the 1850s

Data were obtained in a variety of formats and with differing amounts and types of post-collection processing from the original field measurements. Appendix A provides a summary of post-1930 data sets including the location of sampling, the organization undertaking data collection, the time period covered, and a brief description of information contained within each data set. A summary of pre-1930 data sets is provided in Appendix B. Data refer to measurements of some, or all, of the following variables: suspended-sediment concentration and particle size, discharge, suspended-sediment discharge, and flow velocity. Metadata information describing the types of sampling; sampling strategy, and laboratory procedures are provided in Appendices A and B where they are known.

A summary of the principal sampling stations at which sediment data were collected and included within the database is given in Table 2.2. Given the focus of this project on the USACE Vicksburg District and New Orleans District on the main stem of the lower Mississippi River, sediment data have been updated as part of this study for gauging stations located in the Vicksburg and New Orleans Districts only (*i.e.*, downstream from Arkansas City). However, all data that have been compiled as part of both this study, and the earlier study in 2001, are included on the accompanying CD-ROM.

Table 2.2 Sediment-transport gauging stations included in the study

River	Station Name	River Mile (RM) (above Head of Passes, LA)
Mississippi River	St. Louis, MO	179.8[*]
	Chester, IL	110[*]
	Thebes, IL	43.8[*]
	Memphis, TN	735
	Arkansas City, AK	554
	Lake Providence	487
	Vicksburg, MS	436
	Natchez, MS	363
	Coochie, LA	317
	Tarbert Landing, LA	306
	Red River Landing	302
	St. Francisville, LA	266
	Baton Rouge	228
	Donaldsville	175
	Carollton	103
	Belle Chasse	76
	Venice	11
	South Pass	0
Red River	Alexandria, LA	105[†]
	Madame Lee Revetment, LA	35[†]
Atchafalaya River	Simmesport	6[‡]
	Melville	30[‡]
	Morgan City	115[‡]
Old River	Knox Landing	312
	Low Sill Outflow	314

[*] Above the confluence of the Mississippi and Ohio Rivers
[†] Above the confluence of Red and Atchafalaya Rivers
[‡] Below the confluence of Red and Atchafalaya Rivers

2.3 Post-1930 measurements

2.3.1 USACE New Orleans District

The longest record of routine sediment measurements on the lower Mississippi River has been collected by the USACE New Orleans District where records extend as far back as 1949. Routine sediment measurements were collected at: Baton Rouge from 1949 to 1958; at Red River Landing from 1958 to 1963; and have been collected at Tarbert Landing since 1963 (Keown *et al.*, 1981).

Calculated sediment loads for each survey dating back to 1956 have been found for the gauging stations listed in Table 2.2 and included within the database, as shown in Appendix A. Calculated sediment loads for Tarbert Landing between 1974 and 2005 had already been compiled by the New Orleans District. These records report average coarse, fine, and total suspended concentrations; mean suspended-sediment gradation data; and mean bed-material gradation data. Pre-1974 sediment data were obtained in a mix of hardcopy and electronic formats from the USACE ERDC. These records all contain calculated sediment loads and most contain mean coarse, fine, and total suspended-sediment concentrations and discharge information. For the period 2001 to 2005, records of suspended-sediment concentration measured at each sample point within each cross-section survey were obtained from the New Orleans District.

Although it was not possible to find, and include in the database, sediment loads for survey dates in the period 1949 to 1955, calculated annual sediment loads originating from the Old River Sediment Study (Old River Hydroelectric Partnership, 1999) are included for the period 1949 to 1969. However, the approach used to calculate annual loads is not detailed in the Old River study.

2.3.2 USACE Vicksburg District

Routine suspended-sediment sampling programs have been undertaken by the USACE Vicksburg District at Arkansas City, Vicksburg, and Natchez since 1967, 1968, and 1972, respectively (Keown *et al.*, 1981). Over this period of time, sampling has usually been undertaken at weekly to monthly intervals.

Data for the USACE Vicksburg District have been found and included within our database back to 1979 (Appendix A). These data sets contain the original point measurements of fine and coarse suspended-sediment concentration at each vertical in the sampled cross-section on each survey date. This original measurement information has been used to calculate the sediment load on each survey date as described in Section 2.6.1.

A spreadsheet showing cross-section averaged fine coarse and total suspended-sediment concentration is also included in the sediment database for the period 1969 to 1979. However, these data have two limitations that must be recognized: first, the information is of unknown origin and, therefore, the data collection, analysis, and processing procedures are unknown; second, no survey dates are attached to the coarse and total concentration data and so temporal trends cannot be evaluated.

2.3.3 U.S Geological Survey

Routine sediment measurements were undertaken by the USGS at Vicksburg between 1973 and 1994 and at St. Francisville between 1978 and 1993. These data sets are included in the sediment database alongside other USGS sediment measurements upstream from Arkansas City that were compiled as part of the original database by Thorne *et al.* (2001). USGS water-quality data sets are also included for Belle Chasse (1976 to 2008) and Venice (1973 to 1999). These data sets have been downloaded from the USGS water-quality website (http://nwis.waterdata.usgs.gov; USGS (2008)) and include measurement of discharge, suspended-sediment concentration, and suspended-sediment load.

The Vicksburg and St. Francisville USGS data sets include measurements of average coarse, fine, and total suspended-sediment concentration and load data for each survey date. However, the sampling frequency is considerably less than either the USACE Vicksburg or New Orleans Districts. In this study, USGS records have been used at locations such as at Vicksburg where USGS data are available in conjunction with USACE data. Comparison of the temporal record at these locations provides an indication of data accuracy and introduces the possibility of measurement calibration.

2.3.4 Other post-1930 data sets

Sediment measurements at Vicksburg and Arkansas City reported by Robbins (1977) were compiled by Thorne *et al.* (2001) and are included in the sediment database. Measurements for two sampling periods are reported: 1929 to 1932 and 1967 to 1974.

Suspended-sediment measurements have been undertaken by the New Orleans Water and Sewerage Board at the Carrollton Plant intake since 1932 (Kesel, 1988). However, these measurements are not included in the sediment database because data are not readily available in an electronic format, or in a hardcopy format which can be easily digitized. It should also be noted that this record is based on surface measurements of total suspended solids at an existing intake and, therefore, its reliability as an indicator of temporal changes in sediment loads is questionable (personal communication, USGS).

2.4 Pre-1930 measurements

Historic measurements of suspended-sediment concentration prior to 1930 are described in detail within USACE Paper H (Vogel, 1930). This is summarized in Appendix B. Documented records extend back to the measurements made by Captain Talcott in 1838 in southwest and southeast passes. Although these measurements provide a historical baseline against which recent measurements can be compared, it is important to note that there is little consistency in the location of sampling, sampling strategies and sampling technology, and laboratory procedures used. Furthermore, many of these early measurements of sediment concentration were based on a limited number of samples within a cross-section, so resulting cross-section average concentrations should be interpreted with caution. Historical measurements which include estimates of sediment load, or measurements from which estimates of sediment load can be calculated, are included within the analysis of historical changes in sediment load in Chapter 4.

2.5 Principal data records: sampling strategies and data processing

To allow detailed analysis of changes in sediment load, analysis focused on two principal data records within the USACE Vicksburg and New Orleans Districts: Vicksburg and Tarbert Landing. These are the longest records of routine sediment measurements and nearly all published work investigating historic changes in sediment load refers to these records.

2.5.1 Vicksburg

Sediment measurements between 1979 and 2006 were obtained from the Vicksburg District in a customized text file .BOK format. To import these valuable data into a workable spreadsheet format, a tool was created to extract the data from the BOK data file. Prior to data import, initial screening of the data identified a number of data-quality concerns including random and more systematic data errors. Obvious errors within the BOK files were manually corrected prior to data import. To identify remaining data-quality concerns, a data-quality flagging procedure was developed within the import tool to highlight inconsistencies and categorize data into three quality bands (A, B, and C). Key errors identified include poor formatting, missing data, erroneous individual values, and systematic sampling errors. This data-quality flagging procedure and definition of the three quality bands is described in Appendix C.

For the Vicksburg District, the analysis presented in this report is based on the sediment record at the Vicksburg gauging station. The Vicksburg record was chosen in preference to the Natchez or Arkansas City records because: (i) comparison of data quality between the three gauging stations revealed better data quality (a smaller proportion of measurements within the lowest data-quality band – these were removed prior to analysis); and (ii) a USGS sediment record is also available at Vicksburg for the period 1979 to 1994, allowing direct comparisons with the USACE record.

The Vicksburg District sampling procedure has remained consistent since the earliest data were collected. Suspended-sediment and bed-material samples are taken at the end of each discharge measurement. Four samples are routinely taken at six vertical locations, spaced at approximately equal-width across the river (Figure 2.1).

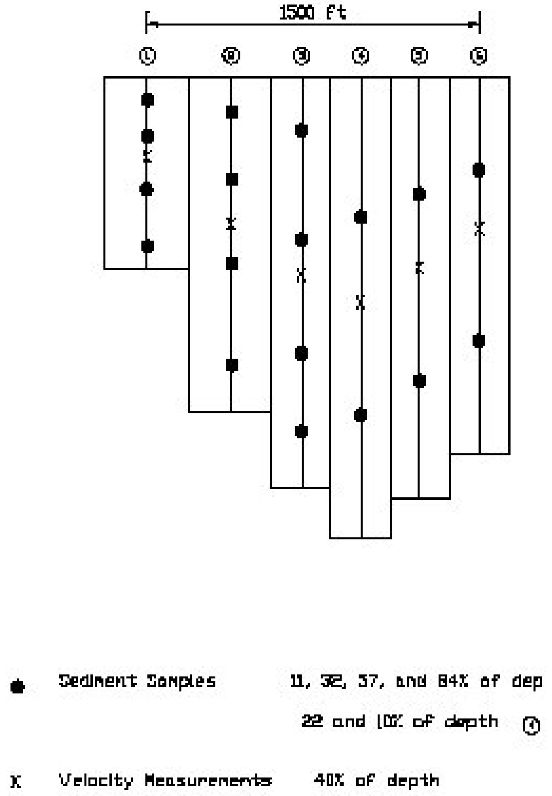

Figure 2.1 The USACE Vicksburg District suspended-sediment sampling routine

These locations correspond to 8, 25, 42, 58, 75, and 92% of the total width. Suspended-sediment samples are taken using US P-61 or US P-63 suspended-sediment samplers.

At Arkansas City and Natchez, a total of twenty-four samples are collected on each survey date. Point samples are taken at each of the six verticals, at 10.7, 32.3, 57.0, and 84.0% depths of each vertical. At Vicksburg however, only eighteen samples are collected on each survey date because the sampled cross-section is located at a bend where the channel next to the right bank consists of a point bar and the channel next to the left descending bank consists of a deep pool. Measurements at Vicksburg are taken at six verticals, with four measurements in the right three verticals and two measurements in the left three verticals at 22 and 70% depths. Cross-section sediment load is calculated by multiplying the average total suspended-sediment concentration in the cross-section (based on measured fine and coarse sediment concentrations at each sample depth in each vertical), with the measured discharge.

Since 1994, Acoustic Doppler Current Profiler (ADCP) technology has been used to measure discharge at all stations in the USACE Vicksburg District, replacing conventional stream gauging techniques.

2.5.2 Tarbert Landing

The sampling strategy adopted by the USACE New Orleans District at Tarbert Landing has undergone several changes since 1983, with respect to the both number of verticals and the number of samples in each vertical. The type of sampler used also varied for a period of time between a P-61 sampler and a P-63 sampler. These changes are documented in Appendix D. The USGS is responsible for all laboratory analysis of the suspended-sediment samples collected by the USACE New Orleans District. Cross-section sediment load is calculated by multiplying the average total suspended-sediment concentration in the cross-section (based on measured fine and coarse sediment concentrations at each sample depth in each vertical), with the measured discharge.

Since the mid-1990s, the New Orleans District has continued to use conventional discharge measurements alongside the introduction of ADCP technology.

3 Calculation of sediment loads and estimating uncertainties

Previous analysis of suspended-sediment load on the Mississippi River has not explicitly considered uncertainty in estimated loads (*e.g.*, Keown *et al.* (1981) and Kesel (1988)). It is important to investigate uncertainty to understand the level of confidence, reliability, and accuracy in statements regarding changes in sediment load.

This chapter investigates various different approaches for calculating sediment loads from point measurements of suspended-sediment concentration and the associated uncertainties introduced through sampling and calculation. This study provides a preliminary quantification of some of the sources of uncertainty and compares overlapping sediment records from different sources to interpret the reliability of the conclusions drawn from the sediment records.

3.1 Sources of uncertainty

The overall uncertainty associated with a particular calculated sediment load is a combination of multiple sources of uncertainty. These include:

- **Sampling procedures** – difference between sampled concentration and actual instantaneous point concentration.

- **Sampling strategy and cross-section concentration calculation** – degree to which the sampling strategy and calculation of cross-section average concentration captures the distribution of sediment within the section.

- **Measurement of discharge** – there are a variety of uncertainties associated with discharge measurement. Sediment load is a function of concentration and discharge.

- **Calculation of annual load** – degree to which calculated annual load (based on measurements spaced throughout the year) adequately replicates the temporal changes in load within each year.

- **Location transfer** – comparability of sediment loads measured at different stations where data from one station are being compared against data from a different station.

This study focused on estimating uncertainty arising from sampling strategy, calculation of annual load, and location transfer.

3.2 Describing uncertainty

Overall uncertainty can be divided into two separate components: *bias* and *variability*. Each source of uncertainty can introduce one or both of the following components of uncertainty:

1. **Bias** – the difference between measured and assumed actual. With respect to sampling strategy, for example, this could be expressed as 'using sampling strategy *X* results in calculated cross-section average concentrations which are, on average, *Y*% less than the assumed actual concentration'. This is equivalent to accuracy in statistical terms.

2. **Variability** – the random unpredictable component of overall uncertainty. Variability can be represented by a probability distribution. This is equivalent to precision in statistical terms.

These components of uncertainty are shown graphically in Figure 3.1. Variability is represented by the probability distribution of the measured values (expressed as calculated value/actual value – which may be more or less than 100%) and the bias is represented by the difference between the actual value and the center of the probability distribution of the measured values. It should be noted that both bias and variability *may* have temporal components which have not been investigated as part of this study.

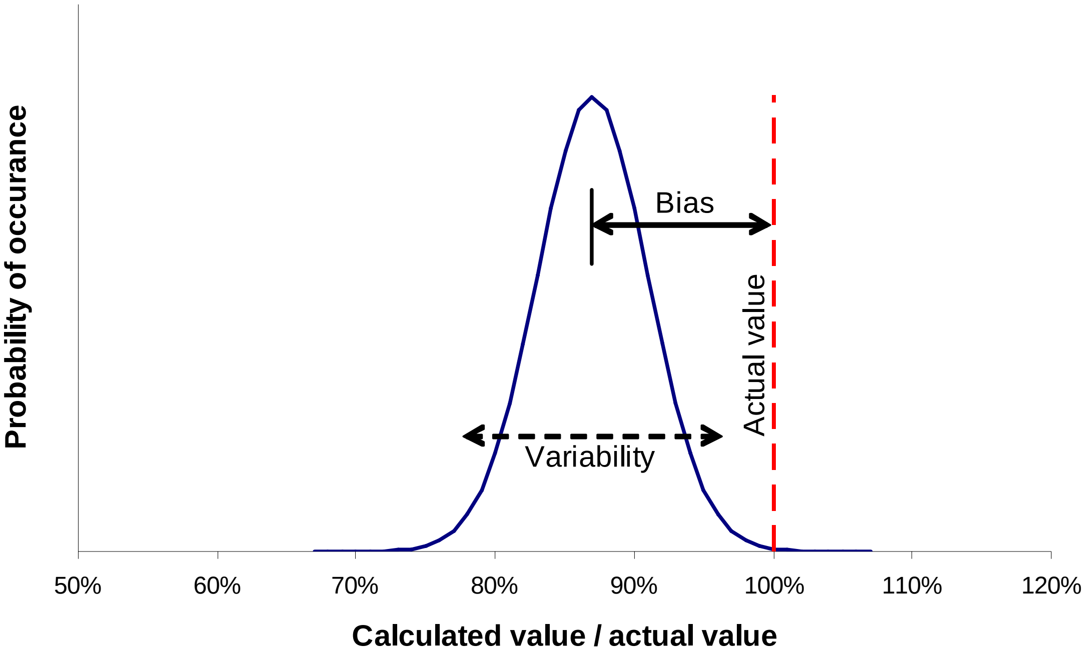

Figure 3.1 Defining uncertainty using bias and variability

By considering uncertainty as being made up of these two elements, uncertainty can be described as follows:

- Bias can be quantified either: as absolute bias where, for example sampling strategy *X* generally overestimates sediment concentration by an average of *Y* parts per million (ppm); or as relative bias where, for example, sampling strategy *X* generally overestimates sediment concentration by an average of *Y*%.

- Variability can be described as one of many probability distributions and provided the distribution is known, the properties of the distribution can be described statistically. To allow a simple statistical description of the variability, variability was assumed to follow a normal distribution in this study. Variability with respect to sampling strategy may, for example, be expressed as follows: using sampling strategy *X* results in calculated cross-section average concentrations which vary with a standard deviation (Std Dev) of Z% from the assumed actual cross-section average concentration.

Both bias and variability can be described as relative or absolute terms. However, because bias and variability are generally higher at high flows, when sediment loads are also higher, relative measures of uncertainty are used throughout this report.

3.3 Sampling procedures

Sampling technology has changed through time and these changes will have impacts upon the overall uncertainty of measured sediment loads.

The type and design of samplers used to measure suspended sediment in the lower Mississippi River are detailed in the Potamology studies that are reported by Dardeau and Causey (1990). At Tarbert Landing, the USACE New Orleans District used a US P-46 sampler from 1949 to 1974, before switching to a US P-61 sampler which is still used predominantly today. The Tarbert Landing data record does, however, show that over the last 20 yrs, the US P-63 sampler has sometimes been used interchangeably with the US P-61 sampler as part of the routine sediment-monitoring program. In the USACE Vicksburg District, data records show that the US P-61 sampler has been used continuously since 1968 to collect suspended-sediment samples. All three of the above samplers are operated from a boat and are suspended by cable, reel, and crane into the water column.

To begin to understand the levels of uncertainty introduced through changes in sediment sampler, Dardeau and Causey (1990) undertook a simple comparison of sediment concentrations obtained by the US P-46 and US P-61 samplers for comparable flows in consecutive years of measurement. This study concluded that the change of samplers at Tarbert Landing had no impact on suspended-sediment loads. Although this should only be interpreted as a preliminary analysis and Dardeau and Causey (1990) do further state that neither the US P-61 nor the US P-63 samplers have been fully evaluated in either the laboratory or the field, it is reasonable to assume that uncertainty arising from sampler type in the modern data is small in comparison to more historic measurements.

Sampler types for sediment measurements undertaken prior to 1930 are generally well documented in USACE Paper H (Vogel, 1930) and are included in Table B.1 in Appendix B. It is clear that the types of sampler used were highly variable and samplers were often only of basic design.

3.4 Sampling strategy and cross-section load calculation

A range of sampling strategies and calculation methodologies has been used for measuring and calculating cross-section load on the lower Mississippi River. Variation through time in sampling strategy for the USACE New Orleans District station at Tarbert Landing, for example, is shown in Appendix D.

3.4.1 Approach

Sampling strategy is the number and spatial arrangement of point measurements in a cross-section. Different sampling strategies can introduce bias and influence variability in the measured concentration in relation to actual concentration (see Section 3.2 for a definition of bias and variability). Specifically:

- A sampling strategy with a greater number of point-concentration measurements generally results in lower *variability* in cross-section load for a given flow. This occurs because uncertainty from individual point measurements is averaged over a greater number of measurements within the cross-section.

- *Bias* may result from sampling strategies where the spatial distribution of the point measurements either under-represents or over-represents the distribution of load within the cross-section. Sampling strategies typically account poorly for sediment transport in the lower profile close to the bed. Hence, the 'measured load' tends to systematically underestimate the actual load because it does not account for the 'unmeasured load'.

The methodology for calculating cross-section average concentration and load from point-concentration measurements is a separate influence on the level of uncertainty arising from sampling strategy. However, the two sources are closely related because: (i) particular calculation methodologies have been used for different sampling strategies; and (ii) the uncertainty introduced by a particular calculation methodology is dependent on the sampling strategy used. Uncertainties introduced by sampling strategy and calculation methodology have, therefore, been investigated together in this study.

The most common calculation methodologies used include:

- **Simple averaging** of all point-concentration measurements within the cross-section to calculate cross-section average concentration.

- **Area weighting** point-concentration measurements so that measurements representing a larger area of the cross-section are given more weight.

- **Discharge weighting** point-concentration measurements so that measurements representing parts of the cross-section with higher velocity and/or area are given more weight because there is greater flow through these parts of the section. Discharge weighting should produce the most accurate estimate of cross-section load. However, discharge weighting is reliant on understanding the velocity distribution. This information is sometimes available (from ADCP measurements) but is rarely linked to concentration measurements and was not available for this study.

  Some sampling strategies use a 'pseudo' discharge weighting, involving weighting according to an assumed discharge profile, or by sampling at intervals of approximately equal discharge across the cross-section.

- **Vertical/horizontal combinations of the above**. For example: averaging point-concentration measurements in a given vertical and then discharge weighting the different verticals; or averaging point data at each depth and then calculating a weighted average of different depths based on a logarithmic velocity profile.

3.4.2 Analysis of 1D concentration distributions

The distribution of suspended sediment within the cross-section at Tarbert Landing was investigated to understand where the majority of the sediment is transported within the cross-section and to estimate the uncertainties introduced by different sampling strategies and calculation methods. The distribution of suspended sediment was investigated by analysing point-concentration measurements from thirty-eight sets of measurements from 2001 to 2005 supplied by the New Orleans District of the USACE. These data sets are from a period when the river was comprehensively sampled at 20 points within the cross-section (four verticals with five samples on each vertical).

Initially, the horizontal and vertical variations in velocity were investigated by comparing concentration at a given point with the average of concentration of all the samples in that particular vertical or horizontal for the particular gauge day. This was carried out with coarse, fine, and total concentrations independently. By doing this for all the point measurements in all thirty-eight data sets, box plots (see Glossary for explanation of box plots) of horizontal and vertical variations in concentration were produced. Figure 3.2 and Figure 3.3 show the average vertical variation in coarse and total concentration within the cross-section. The X-axis shows the relationship between point concentration and mean concentration in a given vertical and the Y-axis shows the sample depth as a proportion of total depth from the surface. The box plots show the spread of values obtained from the 760 point samples investigated.

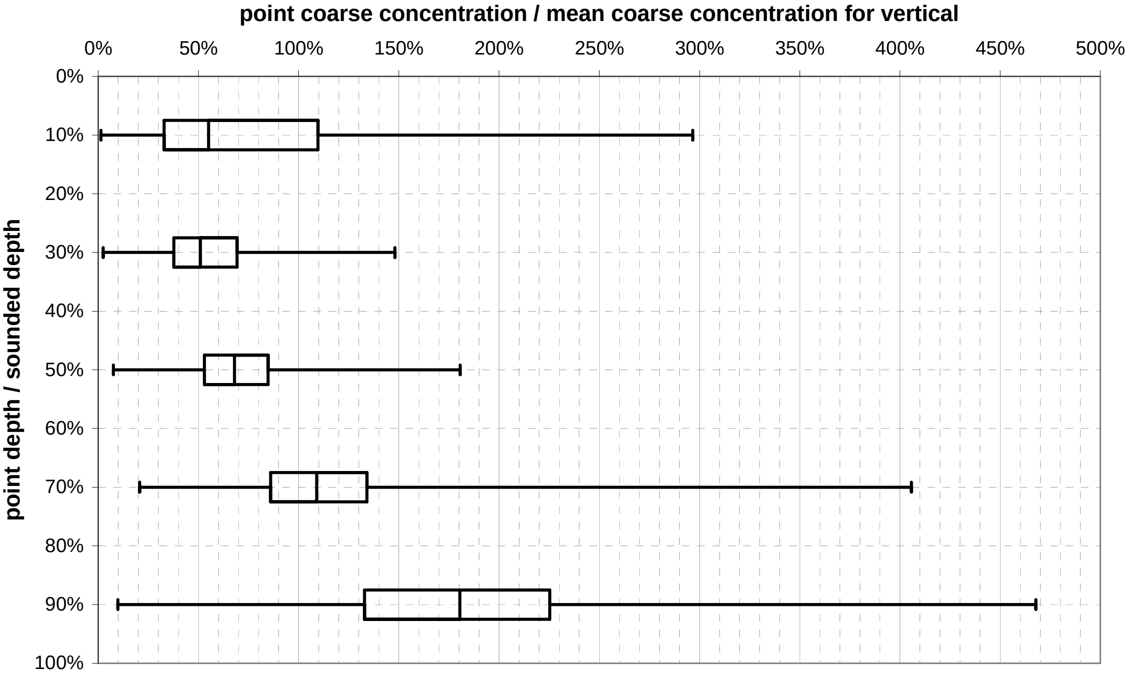

Figure 3.2 Vertical variation in coarse suspended-sediment concentration

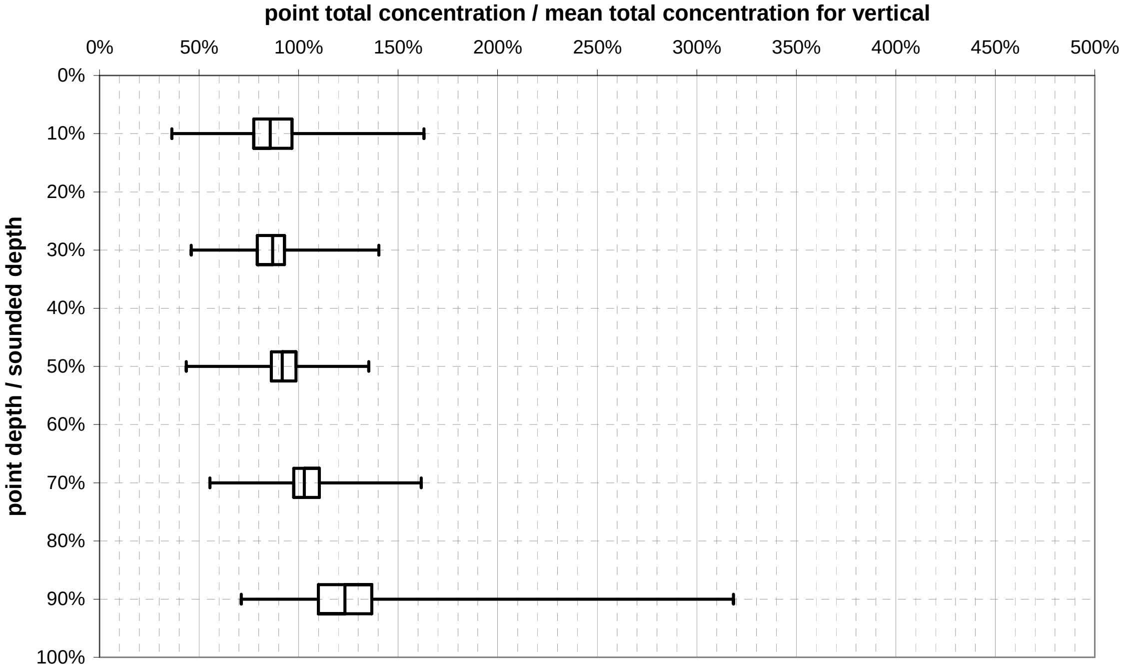

Figure 3.3 Vertical variation in total suspended-sediment concentration

These figures show that coarse concentration has a much greater variation with depth than total concentration. Median coarse concentration at 10% depth is only approximately 30% of median coarse concentration at 90% depth, whereas median total concentration at 10% depth is approximately 70% of median total concentration at 90% depth. Total concentration is strongly influenced by fine concentration because fine concentrations are typically much higher than coarse concentrations. In general, concentration is greater and more variable lower in the cross-section.

3.4.3 Analysis of 2D concentration distributions

The 2D distribution of concentration in the cross-section was further investigated by calculating the relative difference between each point concentration within the cross-section and the average cross-section concentration from that gauge day. These differences between point and cross-section average concentrations have been temporally averaged across the different gauge days. The results of this analysis are shown in Figure 3.4 and Figure 3.5 as contour plots of the cross-section. The colours on each plot represent the temporally averaged difference between the point concentration and the cross-section average concentration (expressed as a percentage of the cross-section average concentration). In Figure 3.4, the average coarse sediment concentration at a point is expressed as a percentage of the cross-section average coarse concentration across all measurement days, and in Figure 3.5, average total sediment concentration at a point is expressed as a percentage of the cross-section average total concentration across all measurement days.

Further, Figure 3.4 and Figure 3.5 show that there is generally greater overall variation in coarse concentration than total concentration and the highest concentrations at Tarbert Landing are found in the center of the channel close to the bed. A simple explanation for this is that coarser sediments can only be entrained and maintained in intermittent suspension in zones of greatest shear in the center of the channel and close to the bed.

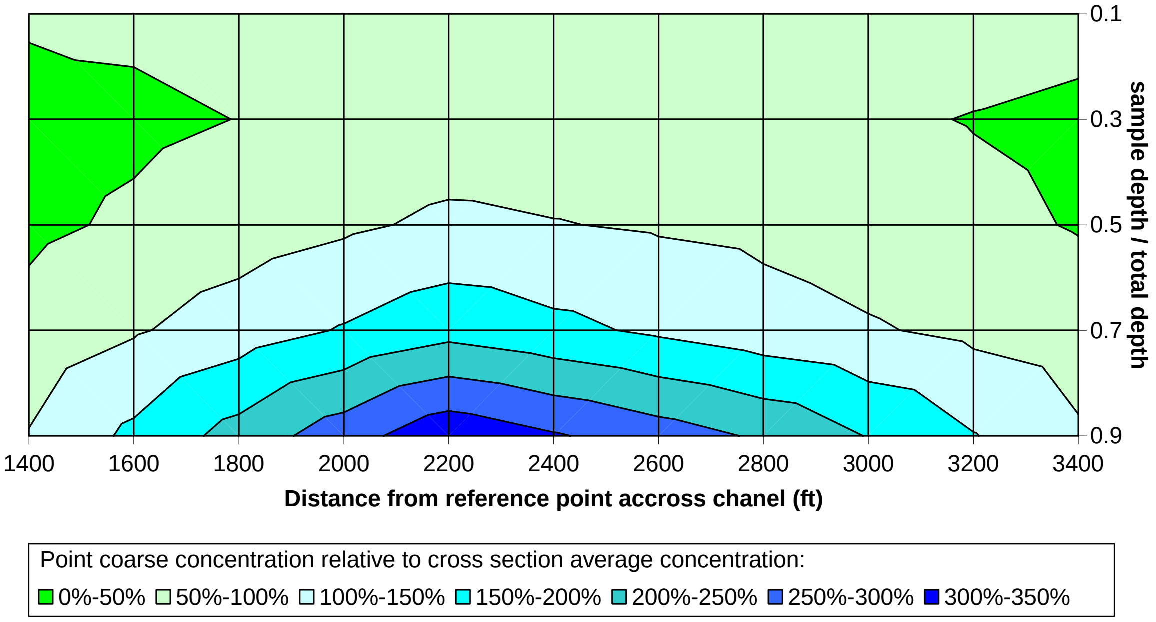

Figure 3.4 Temporally averaged distribution of coarse concentration in the cross-section at Tarbert Landing

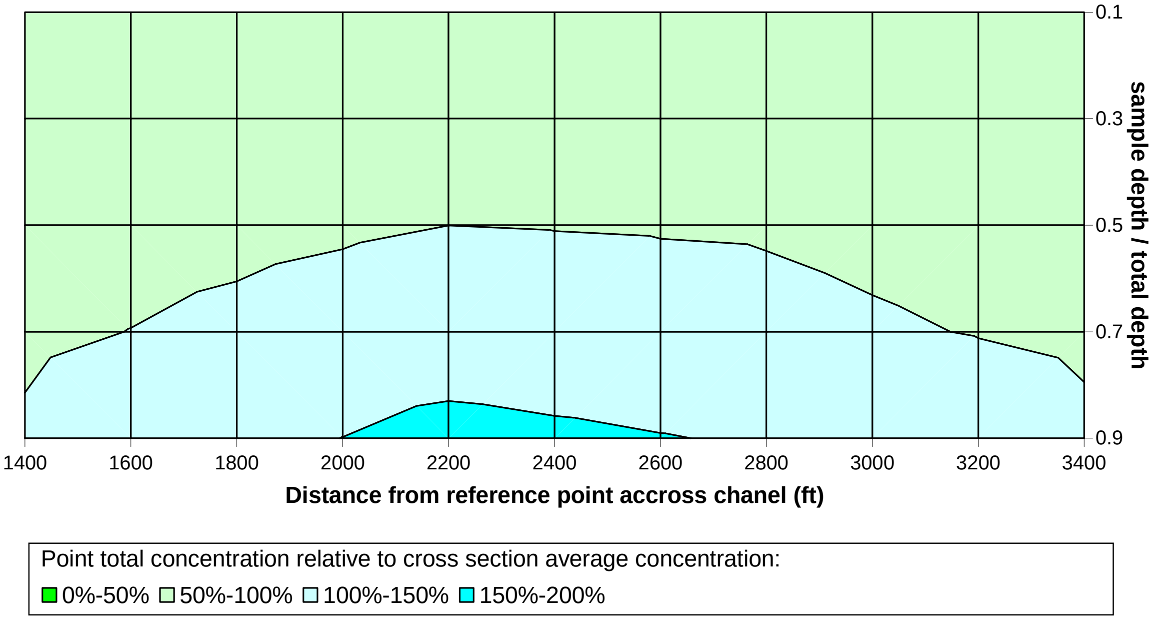

Figure 3.5 Temporally averaged distribution of total concentration in the cross-section at Tarbert Landing

3.4.4 Bias and variability introduced by different sampling strategies

To investigate the bias and variability introduced by different sampling strategies at Tarbert Landing, the highest quality 2001 to 2005 Tarbert Landing data were resampled to replicate sampling strategies with lower spatial resolutions. The following approach was used to estimate bias and variability for each sampling strategy:

1. For each survey date for the 2001 to 2005 survey, create a 2D contour plot for coarse, fine, and total suspended-sediment concentrations from point measurements to provide a 'best-estimate' distribution of sediment concentration throughout the cross-section (Figure 3.4 and Figure 3.5 show the average of all the data sets analysed).

2. Calculate a 'best estimate' of average cross-section coarse, fine, and total concentrations for each gauge day based on the distributions.

3. Resample the 'best-estimate' distributions using the different sampling strategies which have been used historically.

4. Calculate cross-section load from each set of resampled data using a range of different calculation methods.

5. Compare coarse, fine, and total concentrations calculated from resampled data with 'best-estimate' coarse, fine, and total concentrations calculated from the concentration distributions.

6. Calculate bias (average deviation of sampled concentration from best-estimate concentration) and variability (standard deviation of the difference between sampled and best-estimate concentration) that different sampling strategies and load calculation techniques introduce.

Estimates of bias and variability obtained from applying the above approach are shown in Table 3.1. Several sampling strategies introduce in excess of 20% bias in coarse concentration but bias in fine and total concentration is much lower. This can be attributed to the greater variability in coarse concentration within the cross-section.

Table 3.1 Bias and variability associated with different sampling strategies

No. of Verticals	Samples per Vertical	No. of Fine Samples	No. of Coarse Samples	Sample Depths	Calculation Methodology	Coarse Concentration		Fine Concentration		Total Concentration	
						Bias	Varia-bility (Std Dev)	Bias	Varia-bility (Std Dev)	Bias	Varia-bility (Std Dev)
						% of Sample Value		% of Sample Value		% of Sample Value	
8	3	24	24	0, 0.5, "near bottom"	Average	12.08%	9.26%	0.28%	2.22%	3.64%	2.70%
4	5	20	20	0.1, 0.3, 0.5, 0.7, 0.9	Average	-5.60%	1.49%	0.10%	0.24%	-1.21%	0.40%
4	2	8	8	0.5, 0.7	Average	-13.26%	16.32%	-0.07%	3.38%	-3.20%	4.69%
4	3	12	12	0.5, 0.7, 0.95	Average	23.50%	13.26%	2.56%	2.88%	7.25%	4.57%
8	5	40	40	0.15, 0.3, 0.5, 0.7, 0.95	Average	0.54%	5.46%	0.17%	0.82%	-0.31%	1.58%
4	5	20	20	0.15, 0.3, 0.5, 0.7, 0.9	Average	-6.32%	2.51%	0.21%	0.60%	-1.32%	0.76%
8	5	40	40	0.15, 0.3, 0.5, 0.7, 0.9	Average	-1.67%	2.69%	0.25%	0.44%	-0.06%	0.78%
4	3	12	12	0.5, 0.7, 0.9	Average	19.90%	11.51%	2.56%	2.88%	7.60%	4.55%
6	4	24	6	0.11, 0.32, 0.57, 0.84	Vertical, then horizontal averaged	-8.42%	5.45%	-1.31%	3.31%	n/a	n/a
6	4/2	20	6	0.11, 0.32, 0.57, 0.85	Vertical, then horizontal averaged	-15.26%	7.31%	-1.31%	3.31%	n/a	n/a
8	5	40	40	0.15, 0.3, 0.5, 0.7, 0.8	Average	-10.44%	3.68%	-0.35%	0.70%	-2.85%	1.25%
3	2/3	8	8	Surface, 0.5, bottom	Average	20.96%	13.30%	0.52%	2.93%	4.53%	4.13%
3	1	3	3	Surface	Scaled according to previous observations	20.96%	64.78%	0.52%	8.44%	4.53%	13.38%

n/a = not available

One key area of uncertainty which has not been quantified is the effect of the velocity/discharge distribution within the cross-section. As a result, calculation of bias and uncertainty is based on cross-section averaged concentration rather than estimates of total cross-section load. To estimate bias and uncertainty for total cross-section load, information is required regarding the distribution of velocity within the cross-section. For future sediment measurements, this information should be obtained in parallel with sediment monitoring using ADCP technology.

3.5 Calculating annual suspended-sediment load

Calculations to estimate annual sediment load from a record of sediment measurements generally use assumptions about how sediment load varies during periods of time between measurements to estimate a daily sediment load. Daily loads are then summed to give an estimate of annual load. Uncertainties introduced by this process are derived from:

- The method of estimating daily loads from consecutive measurements of sediment concentration/load spaced at irregular intervals throughout a year.

- The degree to which the frequency of sampling captures the temporal variation in sediment load throughout the year.

3.5.1 Methods of estimating daily loads

Different methods can be used to estimate daily sediment loads, each of which has different advantages and disadvantages and is more or less appropriate for different data sets.

Two USGS publications provide guidance on estimating daily loads from irregularly sampled measurements of cross-section average suspended-sediment concentration:

1. "Techniques of Water-Resources Investigations of the United States Geological Survey" (Porterfield, 1972).

2. "Users manual for the Graphical Constituent Loading Analysis System (GCLAS)" (Koltun *et al.*, 2006) (GCLAS is USGS software which can be used for the temporal analysis of concentration measurements).

These two publications recommend sediment concentrations are plotted against time and discharge, and then estimated daily concentrations are inserted into the time series to fill intervals between consecutive measurements. There are several different methods by which the intervening concentrations can be estimated including: manually positioning, interpolating, and using the observed relationship between concentration and discharge to estimate concentration based on observed discharge (extrapolation). The choice of method depends on the frequency of concentration measurements available, the reliability of the relationship between concentration and discharge, and the rate of change of concentration and load in the river.

With these considerations in mind, three methods for calculating annual sediment load from a series of cross-section load estimates were investigated:

1. **Linear interpolation of load** – Sediment loads for non-gauged days are estimated based on simple linear interpolation. Annual sediment load is then calculated by summing daily loads.

2. **Linear interpolation of concentration** – Sediment concentrations for non-gauged days are estimated using simple linear interpolation. Daily sediment loads are calculated by multiplying estimated daily sediment concentration with daily gauged discharge. Annual sediment load is then calculated by summing daily loads. This method differs to the 'linear interpolation of load' method

because daily sediment load is obtained using a linearly interpolated estimate of concentration multiplied by daily measured discharge, rather than a simple linear interpolation of load.

3. **Rating-curve approaches** – A best-fit trend line or 'rating curve' is fitted to a plot of measured sediment concentration against discharge. The rating curve is then used to estimate sediment concentration for each day of the year using gauged daily discharge. Daily sediment loads are calculated by multiplying estimated daily sediment concentration with daily gauged discharge. Annual sediment load is then calculated by summing daily loads.

The above three methods were all trialled using the USACE Tarbert Landing data for the period 1963 to 2004. Daily sediment loads calculated using each method are shown in Figure 3.6 for the water year 1999. Discharge is also shown for reference.

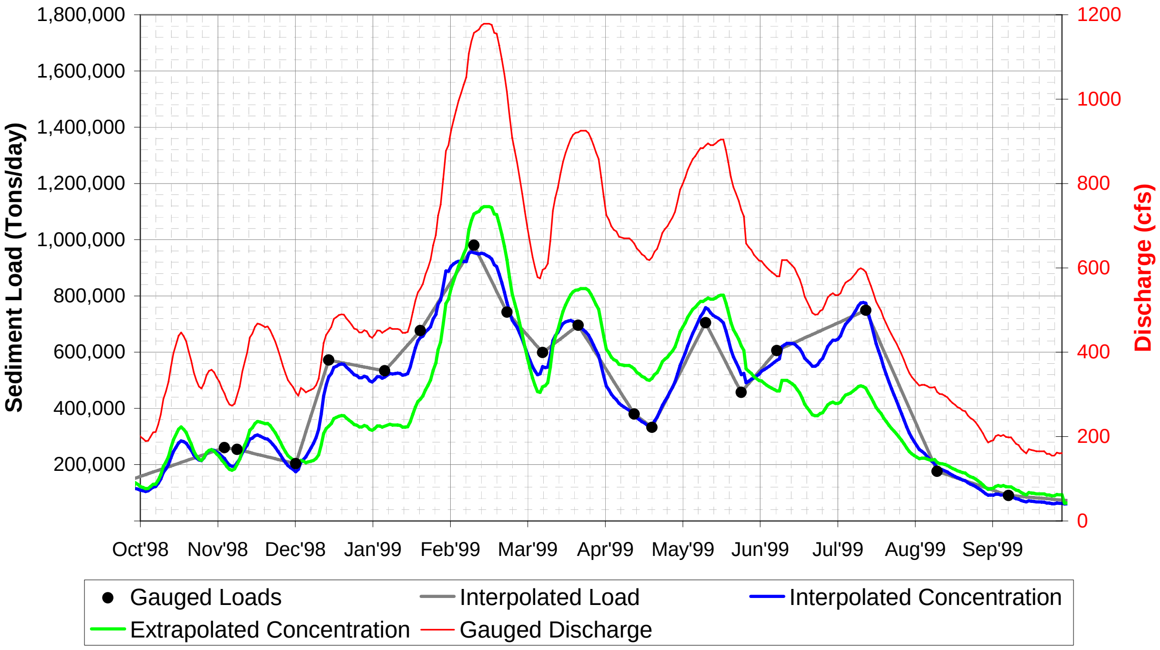

Figure 3.6 Sediment load in water year 1999 calculated using different techniques to estimate daily load

The linear interpolation of concentration method was considered most appropriate for using the measured sediment records to estimate daily loads for the following reasons:

- the Mississippi River does not have a stable sediment rating relationship between flow and discharge (required for extrapolation). This is shown in Figure 3.7.

- Interpolation of concentration introduces fewer assumptions and uncertainties than interpolation of load (discussed further later in this section).

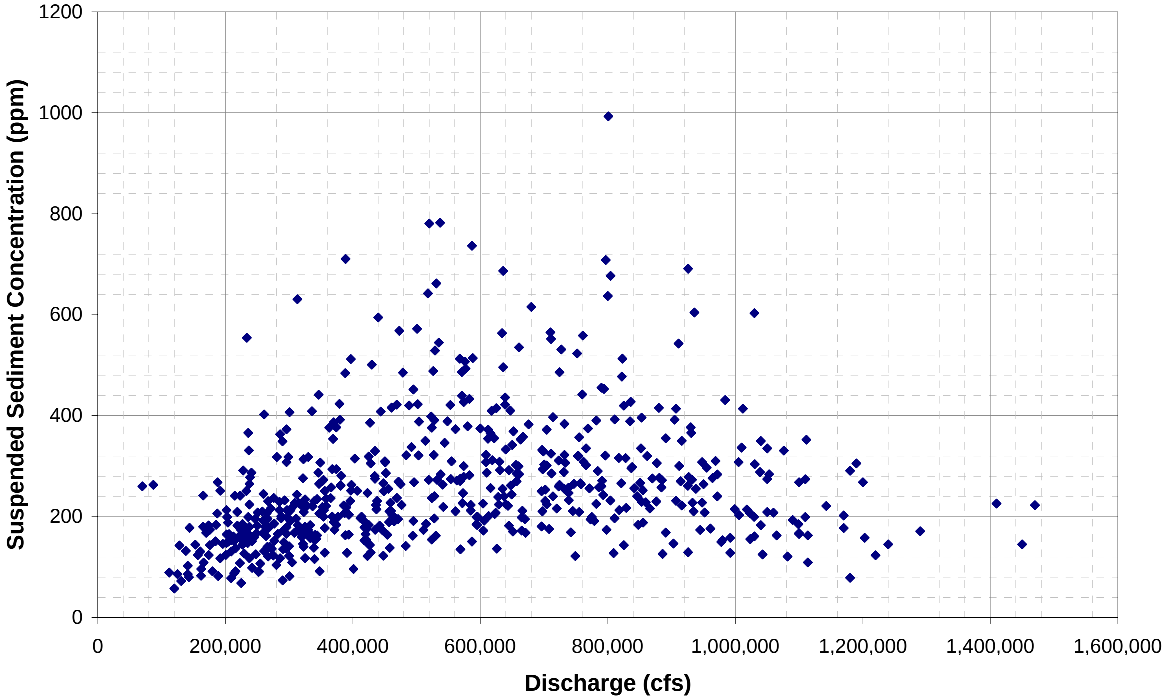

Figure 3.7 Suspended-sediment concentration against discharge at Tarbert Landing, 1980 to present

3.5.2 Number of sampling days

To investigate the importance of sampling frequency in the estimation of an annual sediment load, a synthetic daily record of sediment load was resampled at less frequent sampling intervals (*i.e.*, degraded). The synthetic data set was generated by fitting a cubic spline function to the measured Tarbert Landing total sediment-concentration data record for the period 1964 to 2004. A cubic spline was selected because it is capable of broadly replicating the frequencies of oscillations in the data series and, therefore, provides a suitable proxy indicator of the bias and variability introduced by reducing sampling frequency.

The following approach was used:

1. Resample the synthetic data series at intervals ranging from 7 days to 365 days. This covers the range of sample frequencies used in the routine sediment-measurement programs.

2. Calculate annual load for each year from resampled data using interpolation of concentration method to calculate daily loads. Compare to 'best-estimate' annual loads calculated from a complete year of synthetic data.

3. Record the difference between sediment load calculated from the full set of synthetic data and from the resampled data for each year along with the number of sediment gauge days in the year.

4. Calculate the bias and variability associated with particular methods to estimate daily load and sampling frequency from the above results. Bias is defined as the mean difference between resampled and 'best-estimate' loads (expressed as a percentage of best-estimate load). Variability is calculated as the standard deviation of the difference between resampled and 'best-estimate' loads. See Section 3.2 for explanation of bias and variability.

The above analysis shows that bias introduced by reducing the sampling interval is generally small until sampling becomes less frequent than approximately ten sets of measurements each year, when calculated load tends to be an underestimate actual annual load. This is because major fluctuations in discharge are generally seasonal events rather than individual events due to the size of the contributing catchment, and hence amalgamate many, irregular events.

Variation in coarse, fine, and total loads (described by standard deviation as a percentage of best-estimate annual load) are plotted against sampling frequency in Figure 3.8. Variation in annual load begins to increase where the sampling frequency falls below approximately fifteen sets of sediment measurements each year. This plot also shows that variation in calculations of coarse annual load is greater than fine annual load because coarse load changes more markedly with variations in discharge (Section 4.2).

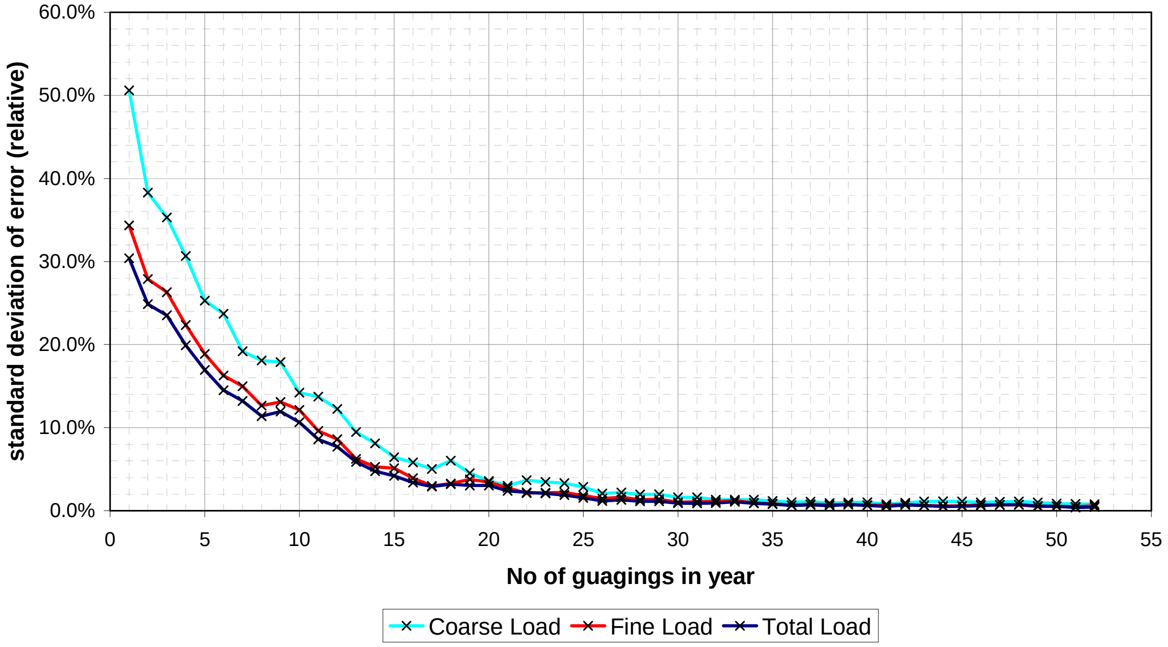

Figure 3.8 Variability of annual load against sampling intervals

These results suggest that the level of uncertainty introduced by the process of estimating annual load is likely to remain relatively low as long as sediment measurements are undertaken at least once a month (equivalent to twelve times a year). Appendix A shows that nearly all modern sediment-monitoring programs on the Lower Mississippi River have maintained at least this frequency of measurement and hence should not dramatically underestimate or overestimate annual suspended-sediment load.

An additional source of uncertainty that was investigated was the effect of data gaps. These are defined as periods of time in an otherwise regular gauging regime in which no measurements were undertaken. It was considered important to investigate these data gaps because they are present in much of the older and some of the more modern data. The effect of data gaps was investigated using the same approach of resampling the synthetic data. The results of this analysis are shown in Figure 3.9.

Data gaps have little effect on variability where variability is already high due to an infrequent gauging regime. They do have a significant effect on uncertainty during years where there are frequent gauging measurements except for the data gap. The data gap has the effect of setting a minimum level of variability no matter how many other measurements are collected that year.

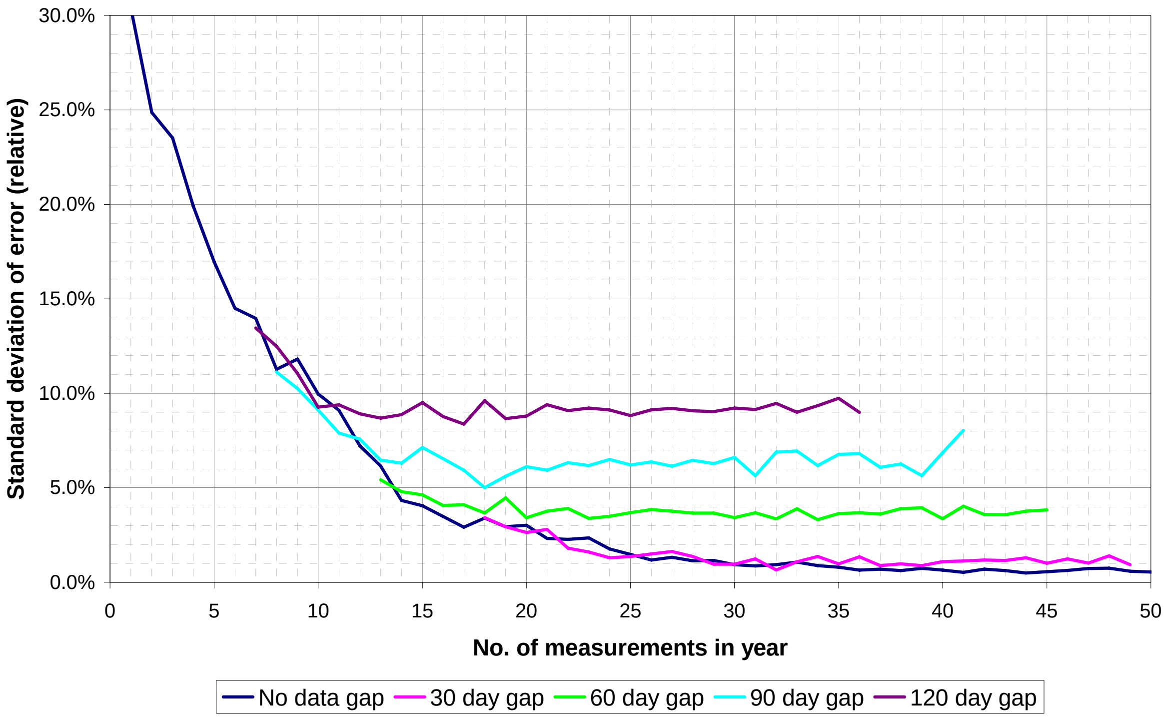

Figure 3.9 Effect of data gaps on variability of calculated total load

3.6 Location transfer

In addition to records of sediment monitoring along the lower Mississippi River being fragmentary (especially pre-1950s), the locations of routine monitoring have changed through time. As a result, it is necessary to assess the effects of changing sampling location on estimates of historic changes in sediment loads and concentrations. For example, within the New Orleans District, the station used for routine sediment sampling changed from Baton Rouge (1949 to 1958) to Red River Landing (1958 to 1963) to Tarbert Landing (1963 to present).

Differences between measured sediment loads for different stations depend on spatial separation and, with this, changes in morphology, discharge, bedload transport and bedform regime, and washload inputs.

Uncertainty analysis presented in this study has focused on consideration of the Tarbert Landing data record. Although it is beyond the scope of this study to investigate downstream differences in sediment load along the river, differences between sediment load at the different gauging stations do provide a preliminary indication of this uncertainty.

3.7 Combining multiple sources of uncertainty

To estimate overall uncertainty in annual load, the bias and variability were considered separately.

To assess overall uncertainty arising from bias, a sequential approach was adopted. This ensured that load calculations were adjusted to 'correct' for the estimated bias arising from each source at the appropriate stage of the calculation. Specifically:

1. The bias arising from the calculation of cross-section average concentration was estimated after cross-section average concentration was calculated from point measurements. A correction was then applied to account for the bias.

2. The corrected cross-section average concentrations were then used in the annual load calculations, after which annual load was corrected for bias introduced during the process of calculating annual load.

It is important to note that multiple sources of bias may cancel each other out (if there is some negative and some positive bias) or they may combine to increase the overall difference between load calculated with and without consideration of bias.

Figure 3.10 shows the gauged daily load record for 1994 at Tarbert Landing before and after adjusting for overall estimated bias. During this water year, there were significant changes in sampling strategy (and corresponding changes in bias).

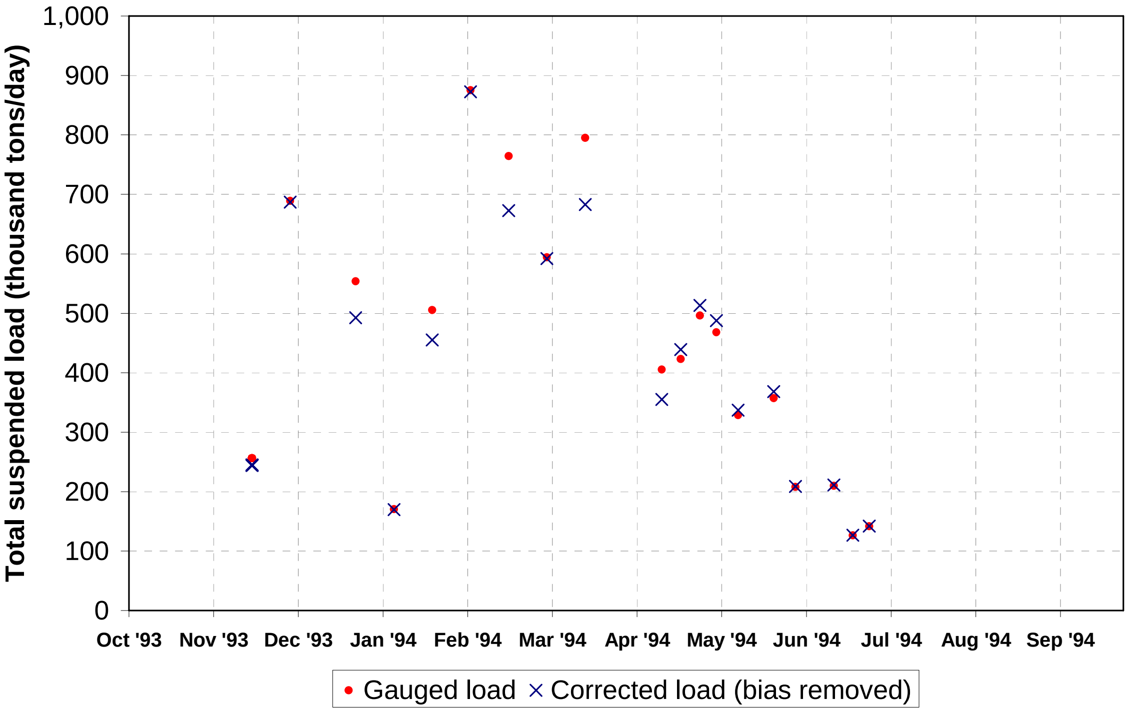

Figure 3.10 Differences between 'raw' sediment load and load estimated following the removal of bias for water year 1994 at Tarbert Landing

Figure 3.10 shows that overall estimated bias is highly variable but can account for up to a 15% difference in load calculations. The reason for variation in bias is that prior to mid-May 1994, the sampling strategy alternated between a comprehensive strategy with eight verticals and five sample depths in each vertical, and a strategy with four verticals and three sample depths in each vertical (all in the lower half of the section), which may have overestimated the actual load. After mid-May a strategy of four verticals with five samples in each vertical was used, with much lower levels of associated bias.

Because each source of variability was estimated assuming a normal distribution, overall uncertainty from multiple sources of variability was estimated by using standard calculations to combine different normal distributions. Figure 3.11 shows the same Tarbert Landing load calculations as in Figure 3.10, but with additional error bars attached to the bias-removed (*i.e.*, corrected) estimates of load, to show uncertainty arising from overall variability.

Uncertainty in estimated loads arising from variability can also be plotted as a box plot showing the estimated 5th percentile, lower quartile, median, upper quartile, and 95th percentiles of the variability distribution. An example of this is shown in Figure 3.12, in which variability distributions for estimated annual load are shown for the 1979 to 1997 period of record at the St. Francisville USGS gauging station.

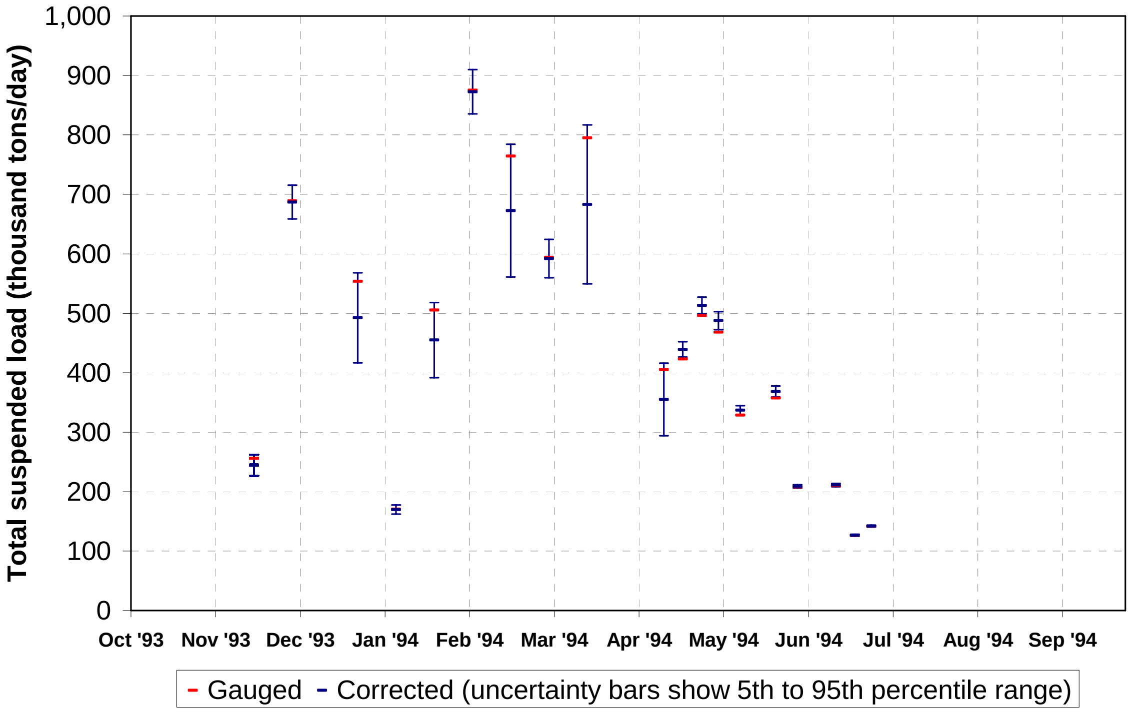

Figure 3.11 Gauged load showing uncertainty as error bar for water year 1994 at Tarbert Landing

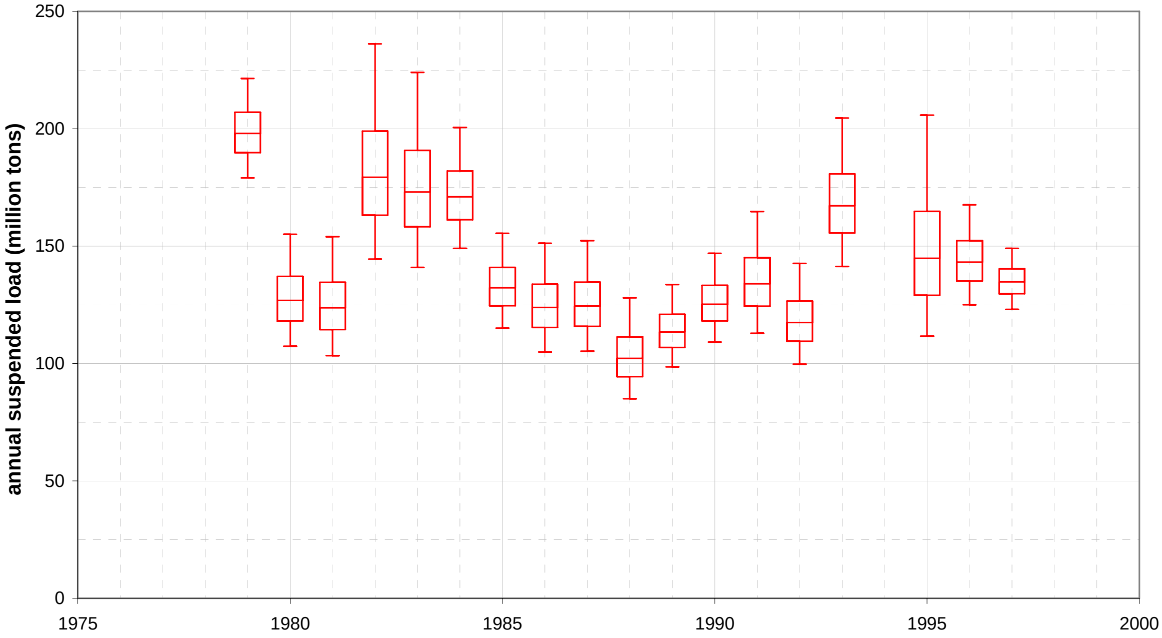

Figure 3.12 Annual sediment load at St. Francisville (USGS gauging station) showing the variability distribution as box plots (1979 to 1997)

Table 3.2 shows the average of annual load bias and variability from 1985 to present at some of the modern gauging stations on the lower Mississippi. For some periods of record there is no metadata accompanying the measured concentration data to describe the sampling strategy. In these cases, assumptions have been made regarding the sampling strategy based on known sampling strategies used by the relevant sampling organization elsewhere.

Table 3.2 Annual load bias and variability at key gauging stations, temporally averaged from 1985 to present day

Station	Average Annual Load Bias			Average Annual Load Variability (Std Dev)		
	Coarse	Fine	Total	Coarse	Fine	Total
Vicksburg USACE*	-11.5%	-2.1%	-7.8%	16.0%	11.0%	14.7%
Tarbert Landing USACE	-4.0%	-0.1%	-0.3%	3.8%	2.6%	2.8%
Vicksburg USGS	-8.3%	-3.2%	-4.4%	40.2%	26.9%	29.2%
St. Francisville USGS	-4.0%	-0.3%	-1.2%	13.3%	9.8%	10.6%

*See additional comments in Section 3.8 regarding reliability of Vicksburg USACE data. Also note variability is strongly influenced by data gaps introduced by previous data-quality assurance checks (see Appendix C).

Table 3.2 shows that the impact of bias is generally low. Variability, however, varies significantly between gauging stations. The USACE gauge at Tarbert Landing has low uncertainty due to its frequent gauging regime with few data gaps and a reasonably reliable sampling strategy. Other gauges have greater variability due to their less frequent sampling strategy and large data gaps. Poor gauging regimes do not generally result in large annual variability due to averaging over the number of individual gauge days in each year.

3.8 Comparison of simultaneous records to assess confidence

To further assess confidence in calculated annual loads, overlapping records collected by different organizations were compared for the same (or geographically very close) gauging stations.

A comparison of annual loads for the 1979 to 1997 period that overlaps between the Tarbert Landing USACE and the St. Francisville USGS records is shown in Figure 3.13. These gauging stations are both located downstream of the Old River Control Structure and are only separated by a distance of approximately 40 river miles.

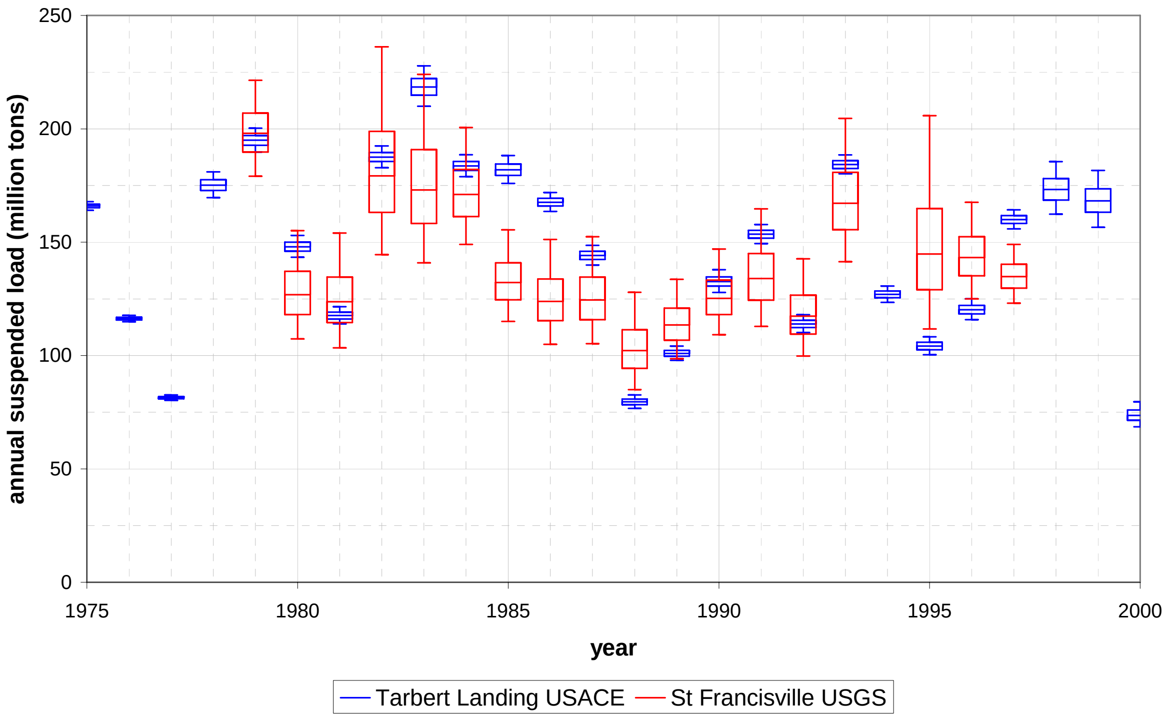

Figure 3.13 Comparison of annual suspended load at Tarbert Landing and St. Francisville gauging stations

Figure 3.13 shows that annual suspended loads calculated from both records are reasonably consistent, with a similar magnitude of total load and degree of inter-annual variation. This provides confidence in the quality of data at these stations. In approximately one third of the cases, however, the uncertainty bars do not overlap, indicating that the uncertainty bars may slightly underestimate the variability within any single year. This may reflect the fact that all sources of uncertainty are not being considered, or alternatively it may reflect actual differences in load between the two stations.

A further comparison is available at Vicksburg where the USGS sediment-measurement program between 1979 and 1993, was undertaken in parallel with the ongoing USACE record. A comparison of these is provided in Figure 3.14 for the period 1985 to 1994. Again, the two records show a similar temporal pattern in annual suspended-sediment load, although it is important to note that the USACE record estimates a lower annual load than the USGS record in 2 out of the 8 yrs that are compared. Furthermore, although the 'best-estimate' sediment load is close in some years such as 1986, the 'best-estimate' annual load estimated from the two measurement programs differs by almost 150 million tons in 1990.

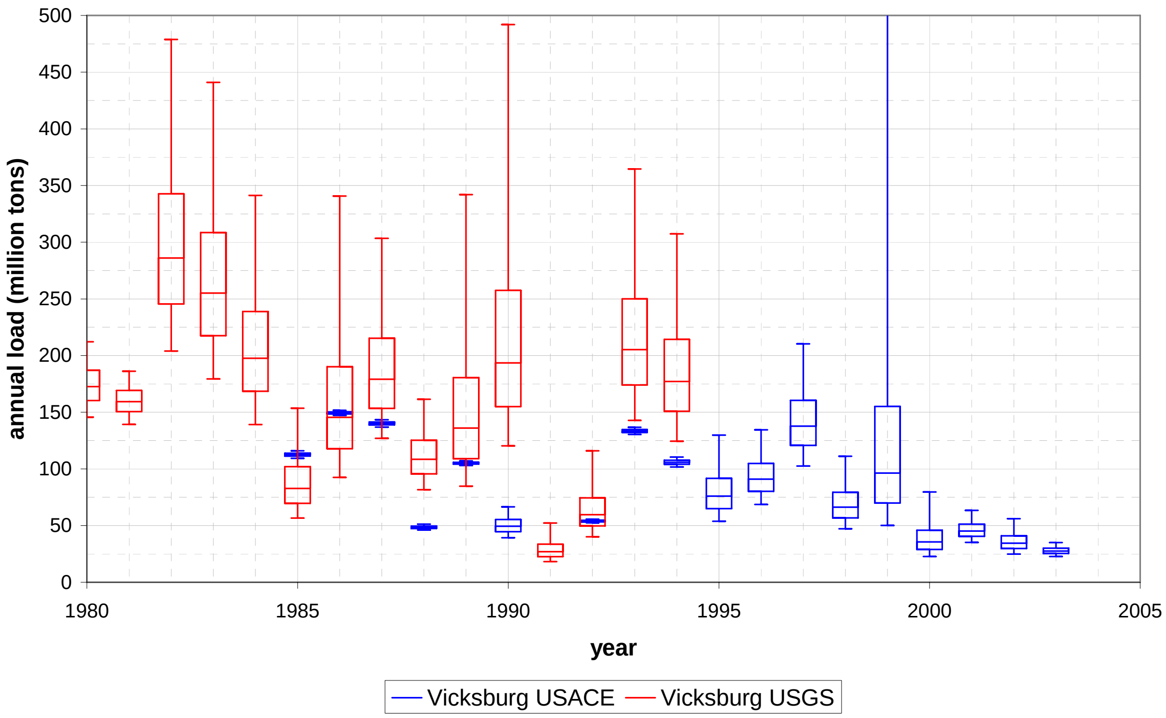

Figure 3.14 Comparison of annual suspended load measured by USACE and USGS at the Vicksburg gauging station

In Figure 3.15, annual loads estimated from the USACE record at Vicksburg are compared to those at Tarbert Landing, approximately 130 river miles further downstream. In the majority of years compared, there are marked differences between annual loads estimated at the two gauging stations. Estimated annual loads are consistently lower at Vicksburg than at Tarbert Landing, and the degree of difference has generally increased since 1997.

Cross-comparison with annual loads estimated from the USGS Vicksburg record in Figure 3.14 suggests that the USGS Vicksburg record provides better comparability with the USACE Tarbert Landing record than the USACE Vicksburg record. These comparisons tend, therefore, to indicate that the data-quality issues discussed in Appendix C should be the subject of further investigation. More generally, it is apparent from these preliminary comparisons that annual sediment loads estimated from records at different gauging stations can vary considerably. To explore this further, it is recommended that further investigations are undertaken using the sediment-measurement records that have been collected at other gauging stations such as Natchez and Arkansas City.

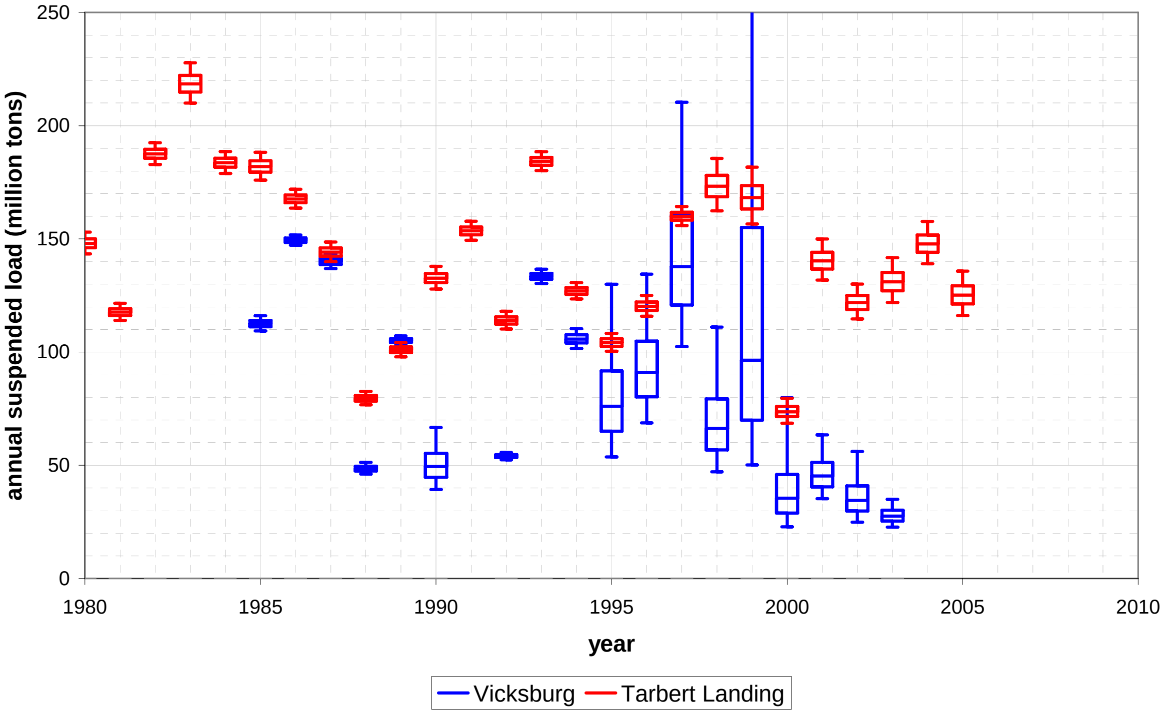

Figure 3.15 Comparison of annual load measured at Vicksburg and Tarbert Landing USACE gauging stations

4 Historical trends, seasonal variations, and current sediment loads

Questions concerning the past, present, and future temporal trends in sediment load are now of great importance because the redistribution of available Mississippi River sediment is critical to on-going efforts to reduce land loss in coastal Louisiana (see Chapter 1 Introduction). This chapter explores the seasonal, inter-annual, and longer-term historical trends in suspended-sediment records.

4.1 Seasonal variation

Seasonal variation in suspended-sediment measurements was undertaken by investigating how concentration and load vary each season and each month. The Tarbert Landing record was used for this analysis (1963 to present) because: (i) it is located in the upper delta region and, therefore, can be considered representative of the load through the coastal wetland region; and (ii) it is the longest record of routine monitoring on the lower river.

When analysing variations in sediment concentration and load, it is important to consider variations in discharge. Seasonal flow exceedance curves at Tarbert Landing (1963 to 2005) are shown in Figure 4.1. As a very general rule, discharge is approximately twice as high during periods of peak flow during the spring than low flow which typically occurs in the fall. Discharge is, however, highly variable in any season with 5% exceedance flows being typically three times as high as 95% exceedance flows.

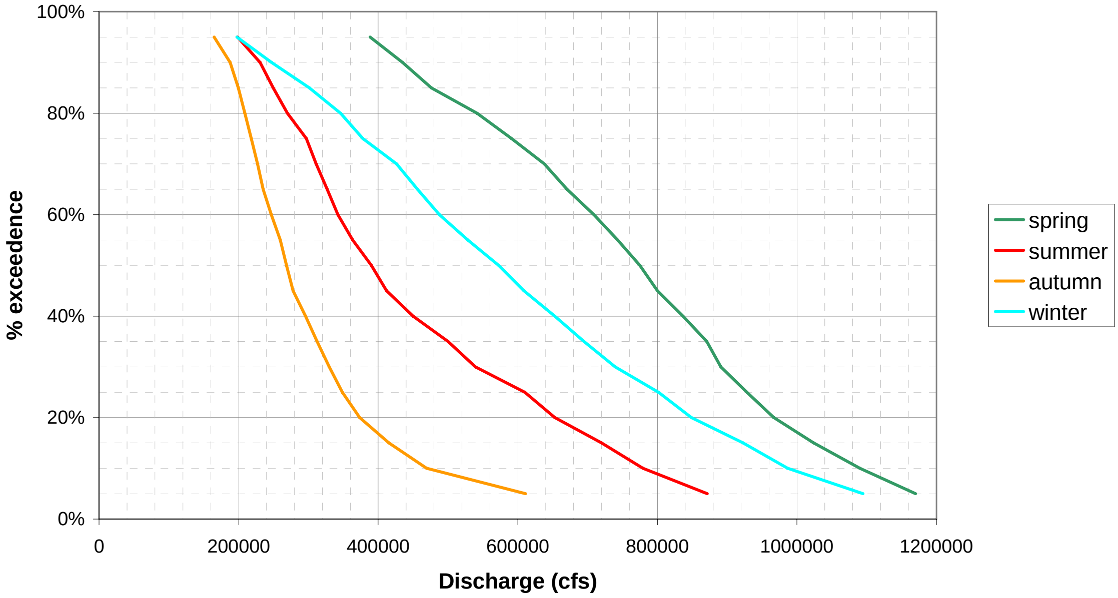

Figure 4.1 Seasonal flow-duration curves at Tarbert Landing (1963 to 2005)

Over the same period of record, box plots showing the variation in coarse and fine concentrations within each month are shown in Figure 4.2 and Figure 4.3, respectively.

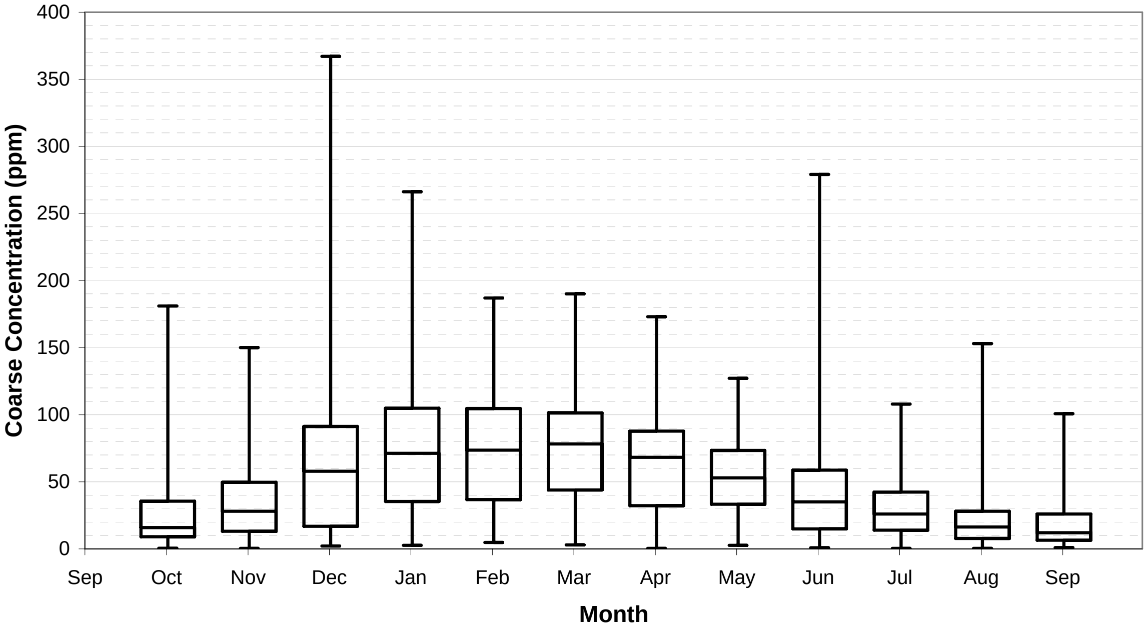

Figure 4.2 Monthly variation in coarse concentration at Tarbert Landing

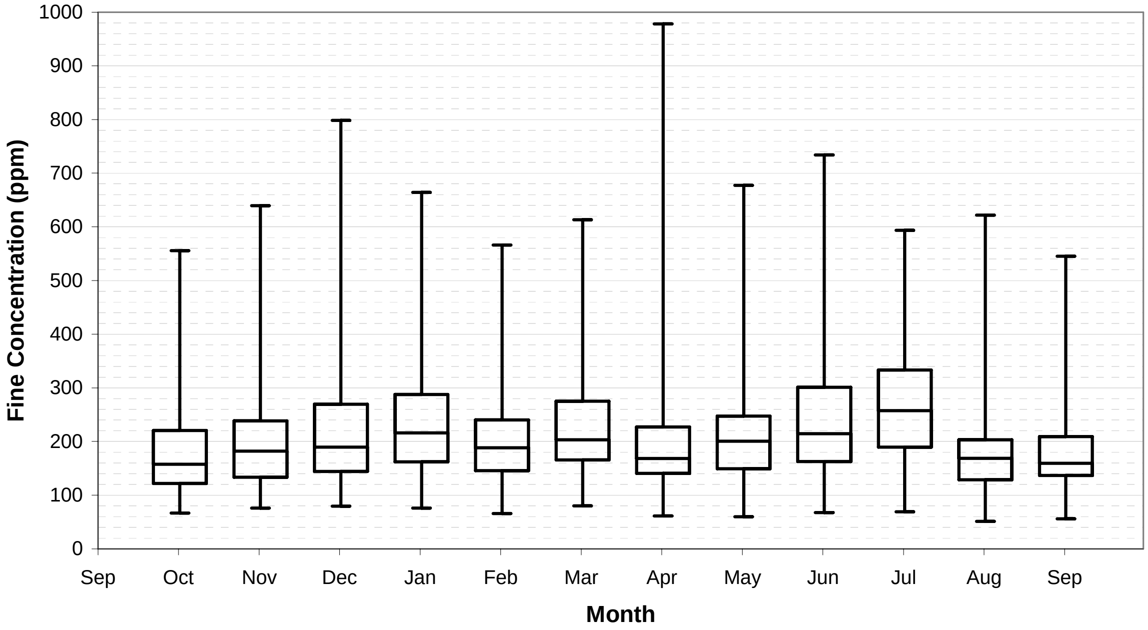

Figure 4.3 Monthly variation in fine concentration at Tarbert Landing

Figure 4.2 clearly shows that the concentration of coarse suspended sediment is much greater and more variable during the months of winter and spring than at other times of the year, when maximum coarse concentrations can reach in excess of 350 ppm. During periods of low and intermediate flows however, coarse concentrations are usually less than 50 ppm. Figure 4.3 shows considerably lower inter-month variation in fine load with median values being consistently in the 150- to 250-ppm range. However, inter-month variations can be high, with the maximum concentration recorded close to 1,000 ppm.

In Figure 4.4 and Figure 4.5, box plots showing the variation in measured load transported each month are presented for the record at Tarbert Landing. Loads for each month for the period of record have been calculated by estimating loads for each day of the year using the interpolation of concentration method (as described in Section 3.5) and summing daily loads within each month. The minimum, 25th percentile, median, 75th percentile, and maximum values from each monthly distribution have then been used to generate each box plot.

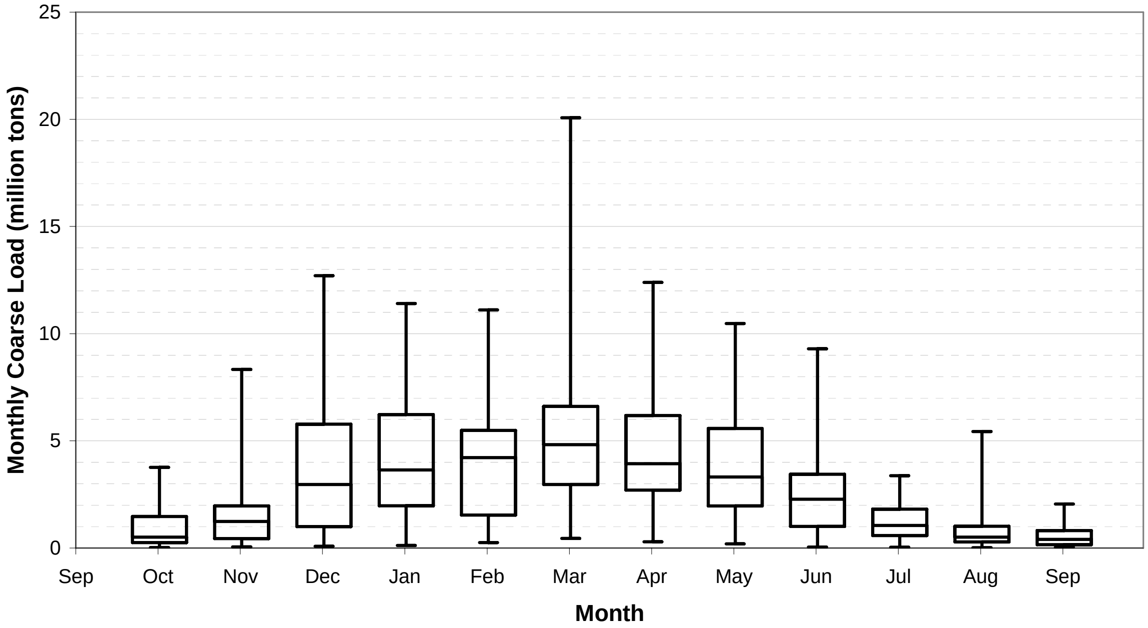

Figure 4.4 Variation in coarse monthly load at Tarbert Landing

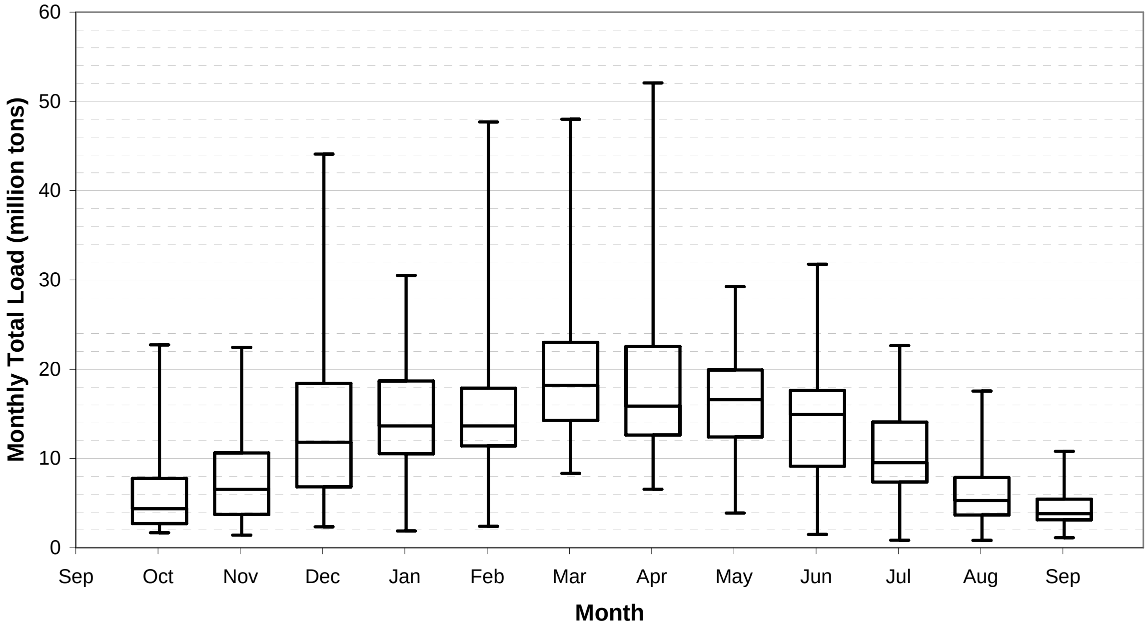

Figure 4.5 Variation in total monthly load at Tarbert Landing

The large variation in monthly coarse load is clearly evident from Figure 4.4. The median spring coarse load is approximately fifteen times the median fall load. The same seasonal pattern is evident for monthly total loads in Figure 4.5, although the magnitude of variation is considerably lower. It is also evident that the variability in monthly load for peak-flow months during the spring is higher than during lower-flow seasons, particularly with respect to coarse load.

To further investigate the seasonal variations in the *size* of sediment in transport, the cross-section average D_{50} (median) and D_{90} (90th percentile) sediment sizes were calculated from the Tarbert Landing suspended-sediment gradation records. Box plots showing the variation of these sediment sizes during each month are presented in Figure 4.6 and Figure 4.7. It should be noted that no sediment-size gradation information is available for sediment finer than 0.0039 mm (clay)

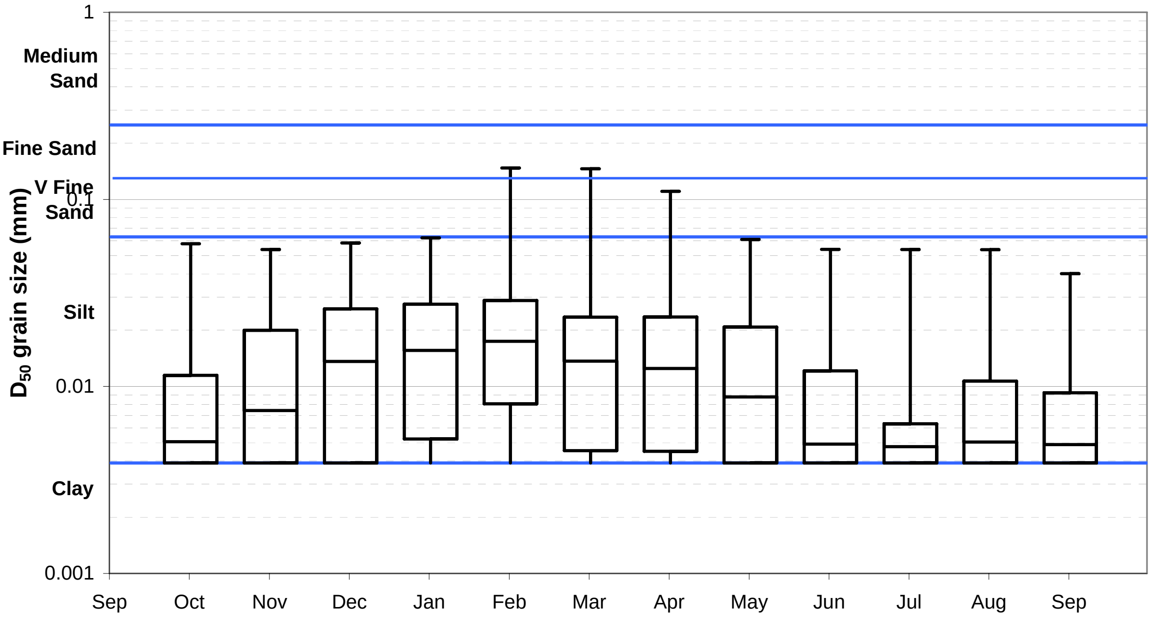

Figure 4.6 Monthly variation in D_{50} at Tarbert Landing

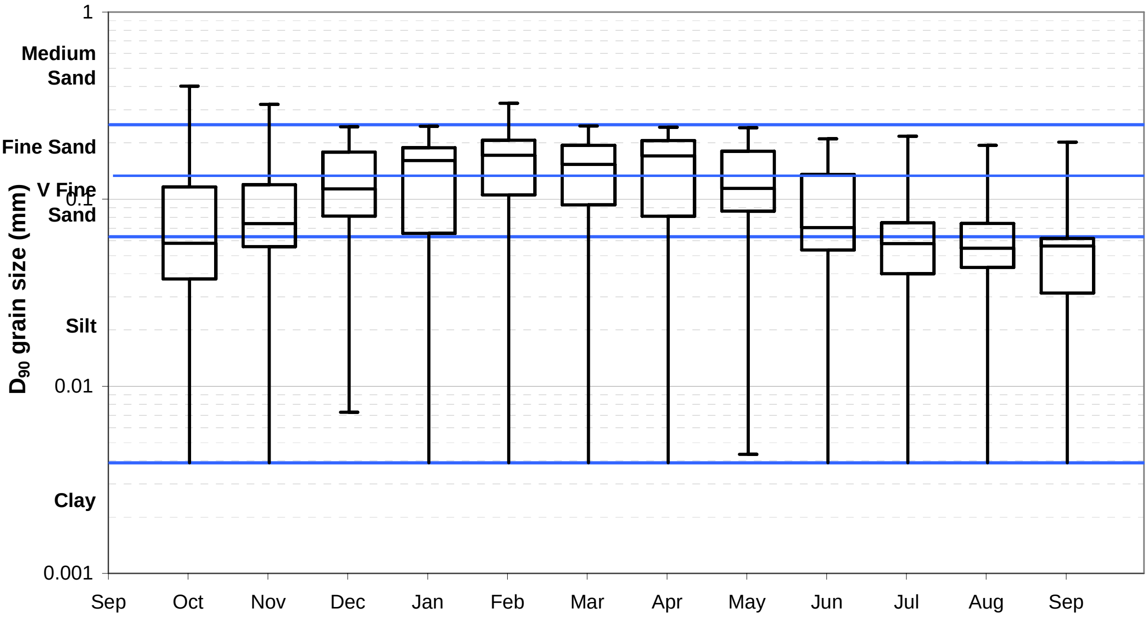

Figure 4.7 Monthly variation in D_{90} at Tarbert Landing

Figure 4.6 shows that the median sediment size is overwhelmingly silt-sized and becomes slightly more coarse during the winter and spring. The D_{90} is generally coarse silt during typically low-flow months, and very fine sand during months with typically intermediate and high flows. This is an important point because it illustrates that the measured suspended-sediment data are composed predominately of the fine load in the river. The coarser fraction (greater than fine sands) which typically compose the channel bed, are not found in appreciable quantities in the measured suspended-sediment data.

4.2 Current annual loads and inter-annual variation

Variation in annual loads was investigated using calculated annual coarse, fine, and total loads for Tarbert Landing between 1965 and 2005.

Figure 4.8 shows changes in coarse, fine, and total annual loads for the period of record. The box plots represent estimated uncertainty attributable to sampling strategy and calculation of annual load from records of routine measurements (see Chapter 3 for uncertainty calculations). The inter-annual variation in sediment loads is shown by percentage exceedance curves in Figures 4.9. Consecutive annual loads were also summed using a moving 5-yr window to investigate the variation in the total sediment load delivered in any 5-yr period. The 5-yr load exceedance curves are shown in Figure 4.10.

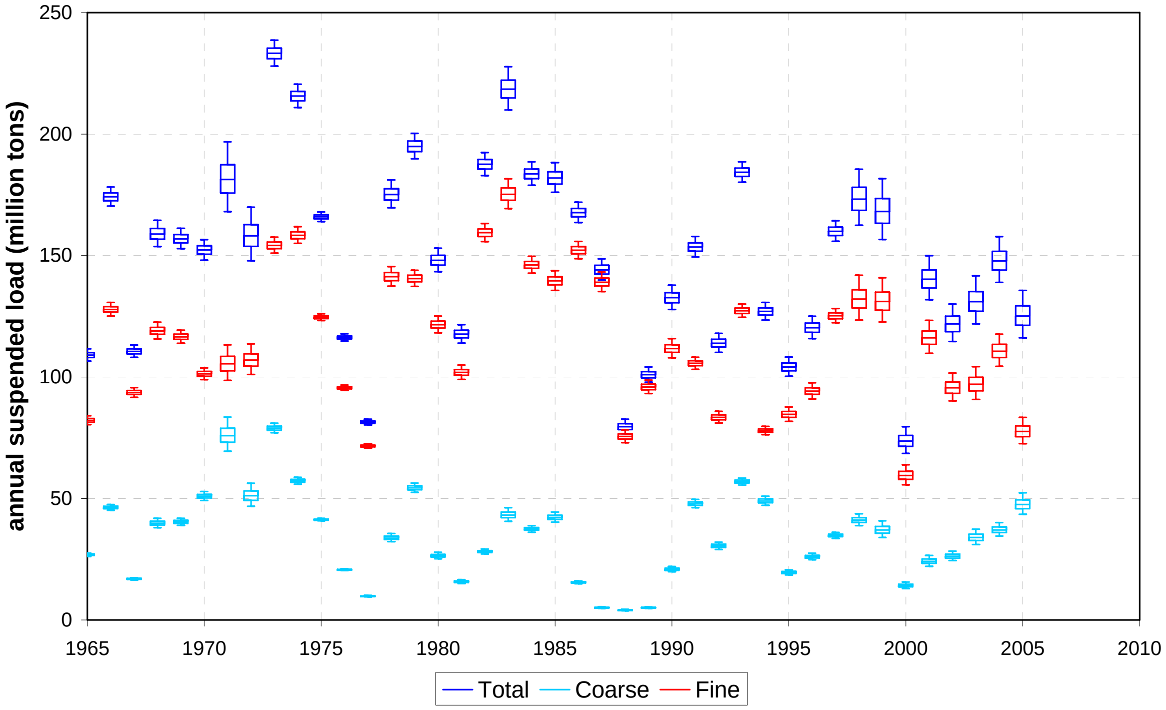

Figure 4.8 Annual suspended-sediment load at Tarbert Landing 1965 to 2005

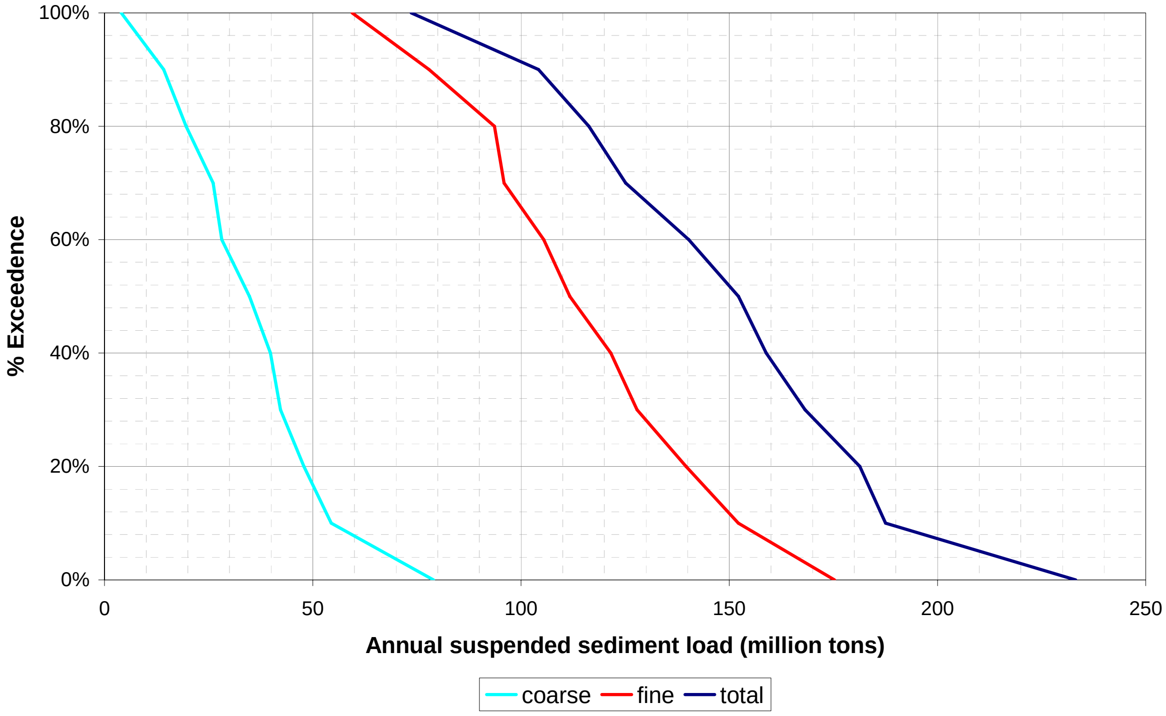

Figure 4.9 Annual load percentage exceedance curves, 1965 to 2005 at Tarbert Landing

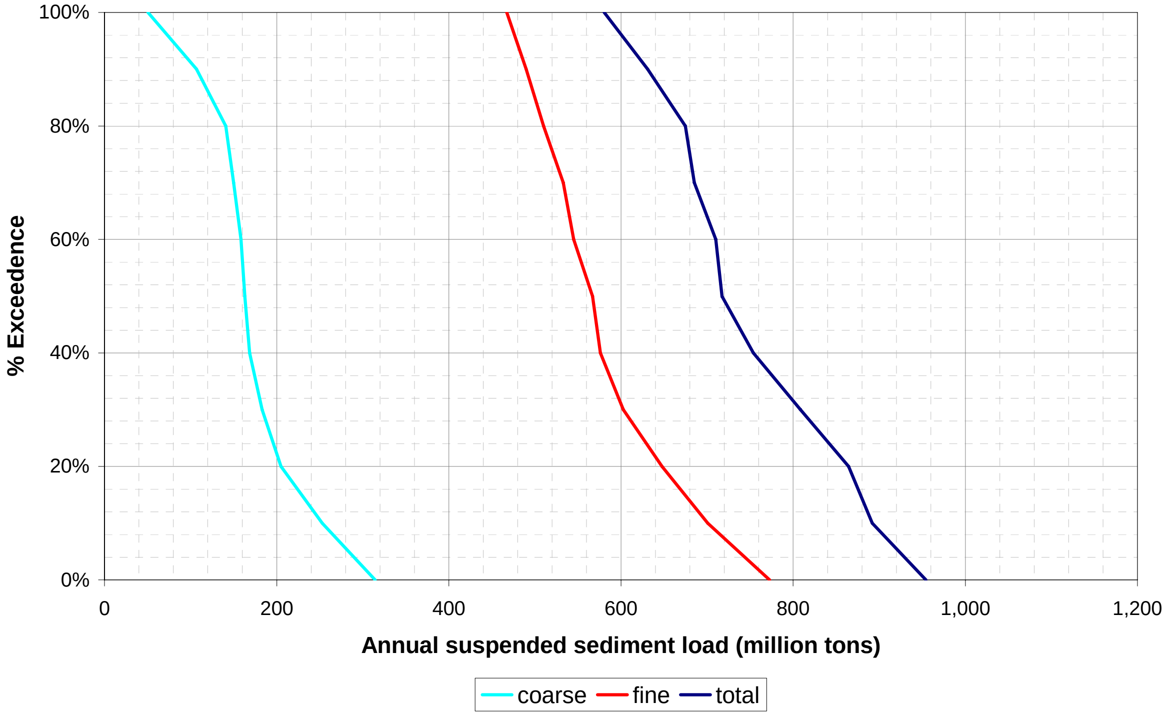

Figure 4.10 Five-year load percentage exceedance curves, 1965 to 2005 at Tarbert Landing

Figure 4.8 shows the degree of inter-annual variation in coarse, fine, and total loads, and is perhaps suggestive of a downward trend in loads at Tarbert Landing over the period 1965 to 2005. According to Figure 4.9, the median annual suspended load at Tarbert Landing is approximately 150 million tons, having varied between a minimum of 70 million tons and a maximum of 230 million tons in years over the period of record. This variation is approximately ±50% of median annual total load. Median annual coarse suspended-sediment load is approximately 40 million tons. This constitutes 27% of the median total suspended load. However, annual coarse suspended load is highly variable in comparison to annual total load, varying from 5 to 80 million tons (approximately ±90% of median).

Total variation in load over a 5-yr period is lower than inter-annual variation because the importance of individual high- or low-flow years is diluted. From Figure 4.10, it is evident that 5-yr total suspended-sediment loads over the last 40 yrs varied between 580 and 960 million tons, with coarse sediments constituting 40 to 320 million tons and the remainder being fine load.

4.3 Historical changes in load

Historical changes in sediment load were investigated using calculated annual loads for Tarbert Landing alongside older available records that either contained annual loads, or contained sets of sediment measurements from which annual loads could be calculated. These historical records are described in Table 4.1. Annual loads were estimated only where regular sediment measurements have been undertaken, usually over a complete calendar year. Where possible, the uncertainty associated with each annual load calculation was estimated using the approach described in Chapter 3 with uncertainty presented as a box plot. Where there was insufficient information to use this approach (*e.g.*, annual loads for 1949 to 1969), or major additional sources of uncertainty (*e.g.*, sampling at different station), directional arrows are used to showcase estimated potential uncertainties in annual loads.

Historical changes in suspended-sediment load and concentration using these combined records are shown in Figure 4.11 and Figure 4.12, respectively. Estimated annual loads are shown using available records from 1851 to 2005. Variations in total annual discharge are also presented over the period of record.

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Table 4.1 Sediment records used in historical changes in load analysis

Dates	Sampling Station	Source Organization	Available Data Types	Key Uncertainties
1964-2005	Tarbert Landing, RM 306	USACE New Orleans District	Coarse, fine, and total suspended-sediment concentrations at 2- to 4-week intervals	Frequent changes in sampling strategy, especially in period 1990 to 1994 (see Appendix D).
1959-1963	Red River Landing, RM 302	USACE New Orleans District, obtained from Old River Hydroelectric Study archives	Coarse, fine, and total suspended-sediment concentrations at 2- to 4-week intervals	This record is labelled as Tarbert Landing although measurements in the period 1959 to 1963 were taken 4 mi downstream at Red River Landing. Discharge measurements from the Tarbert Landing record have been used in sediment-load calculations.
1956-1958	Baton Rouge, RM 230	USACE New Orleans District, obtained from Old River Hydroelectric Study archives	Daily records for coarse, fine, and total concentrations	Unknown how daily record has been calculated. Discharge from Tarbert Landing record has been used in sediment-load calculations.
1949-1969	Baton Rouge, Red River Landing, and Tarbert Landing	USACE New Orleans District, reported in Old River Hydroelectric Study	Annual loads	Only available as calculated annual loads. Therefore, was not possible to estimate uncertainty from sampling strategy and annual load calculation.
1931	Red River Landing, RM 302	USACE, obtained from Paper U (1931)	Discharge and average concentration for surface, mid and near bottom samples, taken every 2 to 7 days over a 6-mo period	Annual load calculated by using a rating-curve approach to extend the 6 mo of data. Indicative error bars have been used in Figures 4.11 and 4.12 to show the high uncertainties associated with this approach.
1879-1893	South Pass, below Head of Passes	Quinn Survey, reported by Kesel (1995)	Annual loads	Large indicative error arrows have been used in Figures 4.11 and 4.12 to indicate high uncertainty in using this data to represent sediment loads in the main Lower Mississippi River.
1851-1853	Carollton, RM 103	Forshey – obtained from USACE Paper H (Vogel, 1930)	Approximately weekly measurements of discharge and average total concentration over a 2-yr period	In Figures 4.11 and 4.12, arrows have been used to indicate possible additional uncertainty due to location transfer.

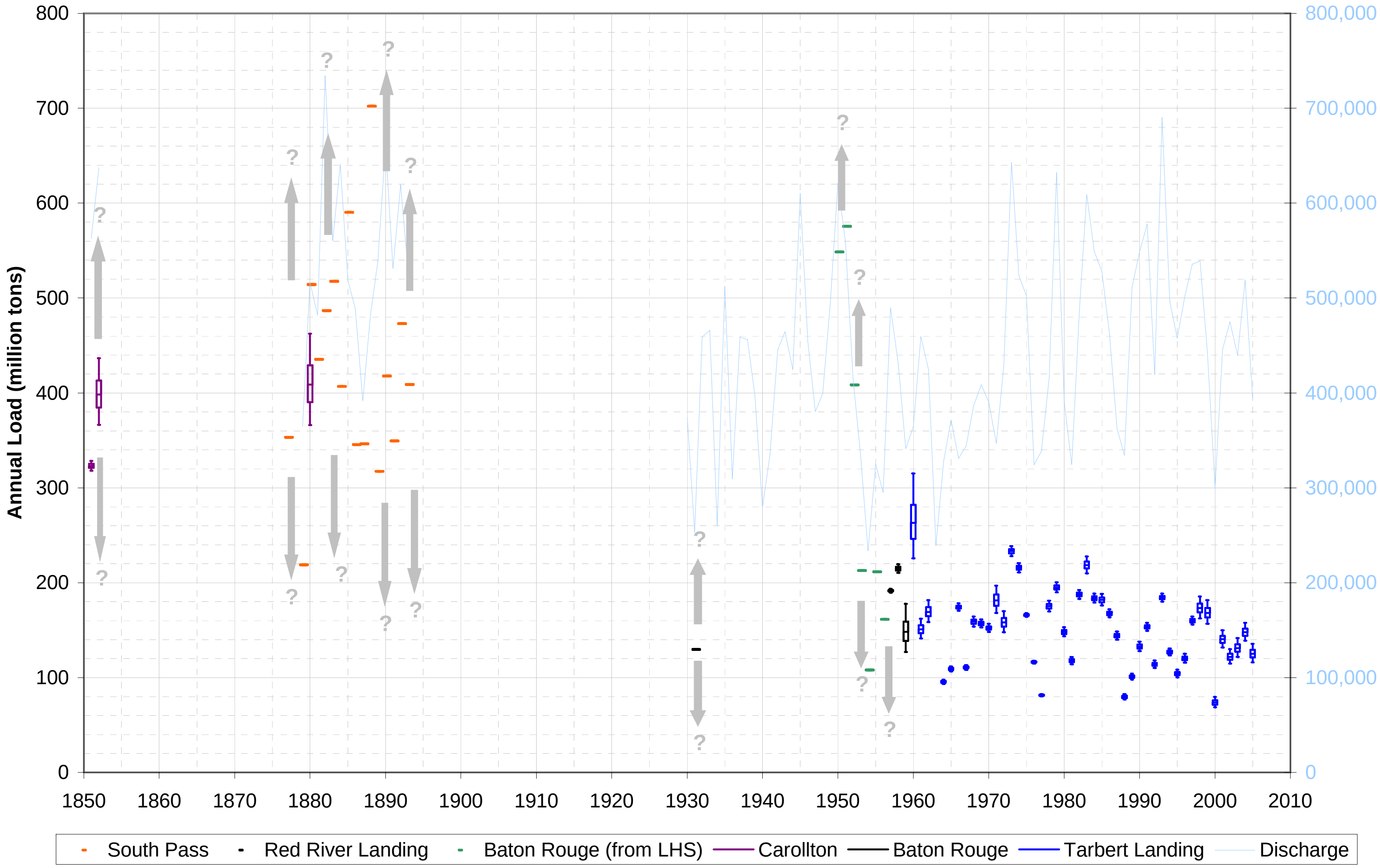


Figure 4.11 Long-term changes in annual load on the Mississippi River from multiple stations

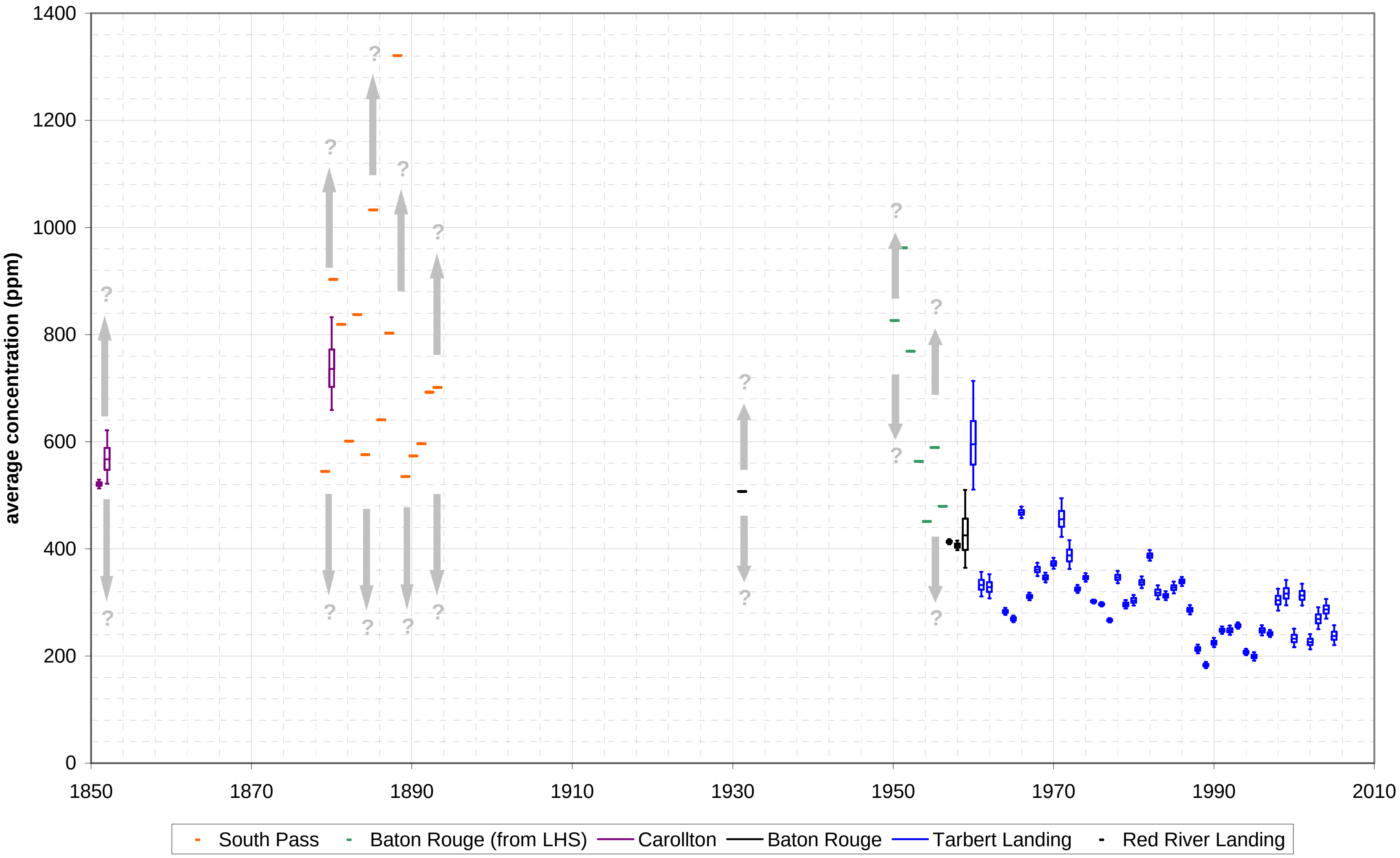


Figure 4.12 Long-term changes in annual average suspended-sediment concentration on the Mississippi River from multiple stations

The Mississippi River Basin has been subjected to numerous alterations in the past century that have impacted sediment loads in the river. The primary features that have contributed to a reduction in supply of sediment to the Lower Mississippi River include: (i) construction of the dams in the upper basin; (ii) the comprehensive bank-revetment program; and (iii) soil-conservation programs initiated throughout the watershed by several Federal and State agencies. The cumulative impact of these programs, which were initiated in the mid-1900s has been a reduction in the supply of sediment (particularly fine sediments) to the Lower Mississippi River. The resulting decline in sediment loads in the lower river has been documented by several investigators. Based on comparison of average annual loads for the period 1949 to 1963 with average annual loads post-1963, Keown *et al.* (1981) reported that the annual load at Tarbert Landing had decreased by just over 40%. Kesel (1988, 1989) reported an 80% decline in annual sediment loads between 1851 and 1982. These are large reductions, but may not be unreasonable given the magnitude of the dams, revetments, and conservation programs in the basin. In fact, cursory examination of the data in Figures 4.11 and 4.12 seems to support the existence of a marked decline in sediment loads. Such a cursory examination must be treated with appropriate caution, however, for four reasons. First, data for the period prior to 1963, were obtained from four different locations (Carollton, Baton Rouge, Red River Landing, and South Pass). Annual sediment loads estimated from records at different gauging stations can vary considerably. Second, there are significant gaps in the data record during the first half of the 20th Century. Third, comparisons of loads between the 19th and late-20th Centuries are limited by the high uncertainties associated with the early estimates of annual load. Consequently, while the pre-1950s data are intriguing and do provide gross insights into the historical sediment loads, they are not sufficient for statistically valid comparisons to the post-1950s data. Fourth, it is important to remember that our calculated loads are based on measured suspended-sediment loads. These almost certainly under represent the coarser fraction of the suspended-sediment load, and do not account for bed load at all.

As previously discussed, there have been basin changes since the mid-1900s that have reduced the supply of sediment to the river system. In order to assess how these initiatives may have impacted sediment loads in the Lower Mississippi River, a preliminary analysis of the Tarbert Landing data was conducted. Figures 4.13, 4.14, and 4.15 show annual sediment concentrations, sediment loads, and water discharges, respectively, at Tarbert Landing for the period 1959 to 2005. There is considerable variability in these data, and as indicated by the low coefficient of determination (R^2), only a small percentage of the variability is explained by the trend line. There may also be cyclical trends in the data during this period. Consequently, there are several ways to interpret the trends. A rigorous analysis of these data to explore these various interpretations was not attempted in the preliminary analysis conducted here. Instead, a simple linear regression of the data was applied to: (i) assess the general temporal trends, and (ii) illustrate the utility of the database for analysis and interpretation of the data. Students t-tests were performed to determine whether the slope in the regression equation was significantly different from zero. The following P-value criteria were used to accept or reject whether the regression slope was significantly different from zero. If the P-value is less than about 0.01, the slope is taken to be significantly different from zero – that is, a significant trend does exist. If the P-value is greater than about 0.10, the slope is not significantly different from zero – that is, there is no significant trend. If the P-value falls with the approximate range of 0.01 to 0.10, the results are inconclusive.

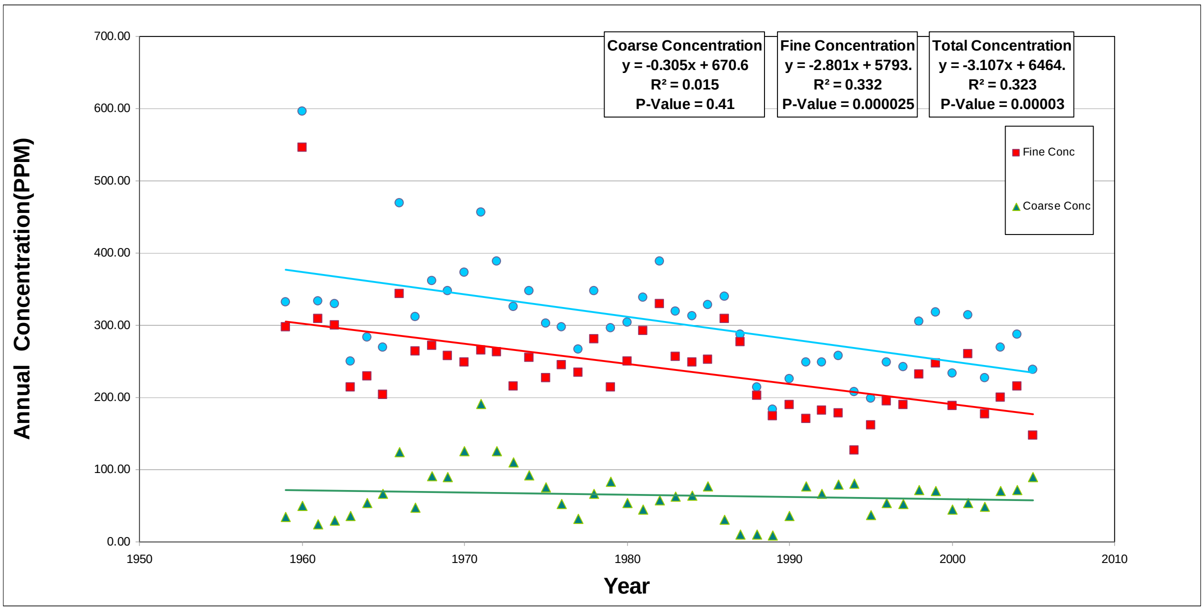


Figure 4.13 Tarbert Landing sediment concentrations, 1959 to 2005

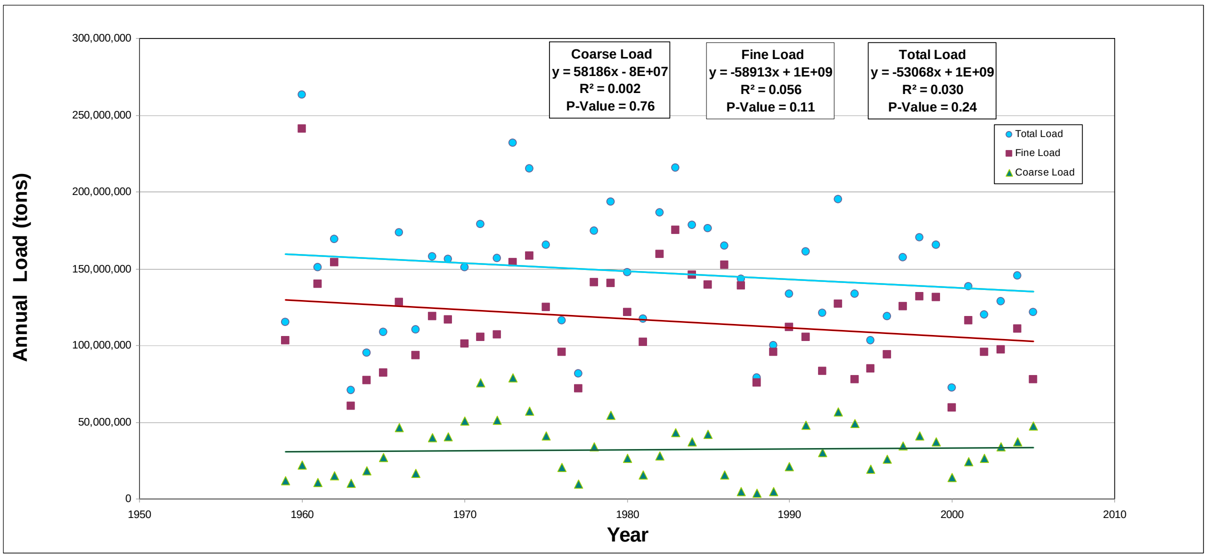


Figure 4.14 Tarbert Landing sediment loads, 1959 to 2005

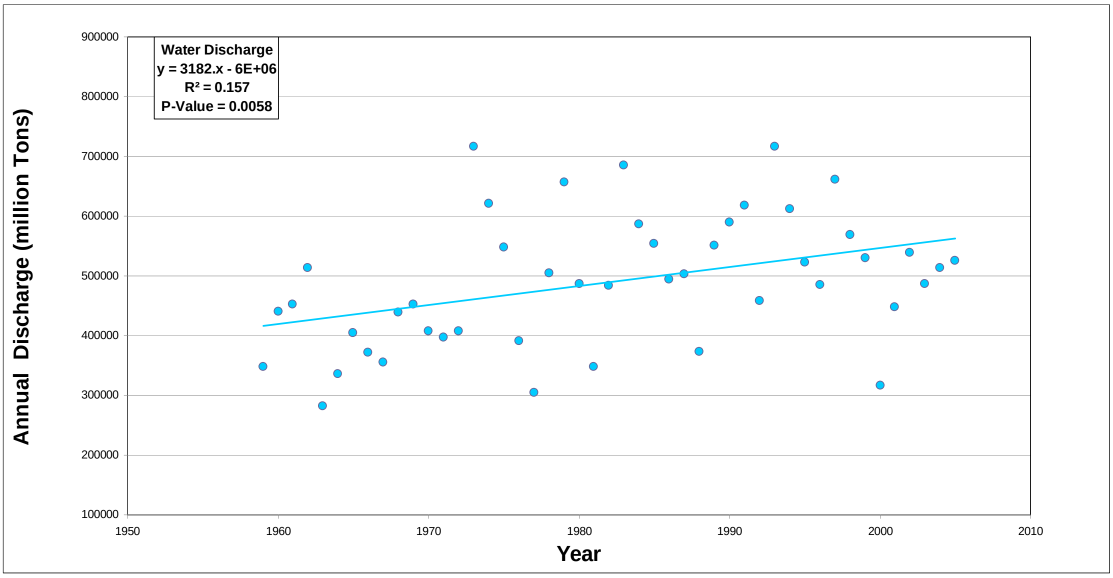


Figure 4.15 Annual water discharges at Tarbert Landing, 1959 to 2005

As indicated in Figure 4.13, there is no significant trend in the coarse concentrations during the period 1959 to 2005. However, while there are considerable fluctuations in the fine and total concentrations, there is an apparent downward trend in the data between 1959 and 2005, and the P-values for the regression curves indicate that these downward trends are statistically significant.

A similar analysis was conducted for the annual sediment loads at Tarbert Landing (Figure 4.14). A slight increasing trend is apparent in the coarse sediment loads during the period 1959 to 2005. However, according to the P-values for the regression curve, this is not statistically significant. The fine and total loads appear to have downward trends, but these are also not statistically significant.

Thus, while there may have been a slight decline in fine and total sediment concentrations between 1959 and 2005, the change in annual load is statistically insignificant. The lack of any trends in the sediment-load data, given the decreasing trends in the fine and total sediment concentrations, may be partially explained by the trend in annual water discharge between 1959 and 2005 (Figure 4.15). This shows a slight increasing trend, which the P-value confirms to be statistically significant. Apparently, the decline in sediment concentrations may have been partially offset by increasing water discharges, resulting in there being no significant change in the annual sediment loads.

It is important to note that this analysis is no more than a preliminary assessment of historical trends within the data. It is recommended that a more rigorous assessment be undertaken to investigate the complex behaviour represented in the historical record (*e.g.*, temporal periodicity, periods of no change, periods of slow change, periods of short-term, rapid change) employing the appropriate statistical techniques in time-series and trend analyses.

5 Conclusions and Recommendations

5.1 Conclusions

5.1.1 Database compilation

This project has extended the earlier database compiled by Thorne *et al.* (2001) for the lower Mississippi River by collating all available historic measurements within the USACE Vicksburg District and New Orleans District (*i.e.*, downstream from Arkansas City). Data were compiled from a variety of sources including the USACE Vicksburg District; the USACE New Orleans District; the USGS; and range of historical sources extending back to the 1850s. Data from each hydrometric station refer to measurements of some, or all, of the following variables: suspended-sediment concentration and particle size; discharge; suspended-sediment load; and flow velocity.

All original and final data sets (*i.e.*, post processing) are included on the accompanying CD-ROM, together with a collection of selective references, and electronic copies of meeting minutes and final workshop presentations. Metadata information describing the types of sampling, sampling strategy, and laboratory procedures are provided in Appendices A and B where they are known.

5.1.2 *Calculation of sediment load and estimating uncertainties*

- Uncertainty has been represented in terms of both bias (accuracy) and variability (precision). Bias and variability introduced via sampling strategy are dependent on the arrangement and number of point measurements within the cross-section. Bias in measurements of coarse concentration in the cross-section is typically much higher than bias in measurements of fine concentration, because coarse concentration is more variable in the cross-section and is dependent on measurements within the lower profile. In general, a sampling strategy with a greater number of point-concentration measurements results in lower *variability* in cross-section load for a given flow.

- Uncertainty introduced by the process of estimating annual load is relatively low as long as sediment measurements are undertaken at least once a month (equivalent to twelve times a year). Nearly all modern sediment-monitoring programs on the Lower Mississippi River have maintained at least this frequency of measurement and hence should not dramatically underestimate or overestimate annual suspended-sediment load.

- Annual sediment loads estimated from records at different gauging stations can vary considerably and should be the subject of further investigation.

- Overall uncertainty at the USACE gauge at Tarbert Landing is low due to its frequent gauging regime with few data gaps, and a frequent and generally high-resolution sampling strategy. Other gauging stations such as the USACE Vicksburg station have greater variability due to their less frequent sampling strategy and large data gaps.

- Levels of uncertainty in post-1960 suspended-sediment measurements should generally be considered low in comparison to earlier records when levels of uncertainty were probably much higher, although in most cases this is not possible to quantify.

5.1.3 Historical trends, seasonal variations, and current loads

- The median spring total load is approximately four times the median fall total load. Variability in monthly load for peak-flow months during the spring is higher than during lower-flow seasons, particularly with respect to coarse load. Median sediment size is overwhelmingly silt-sized and becomes slightly more coarse during the winter and spring when the D_{90} is typically fine sand.

- At Tarbert Landing, average annual load over the period 1963 to 2005 is approximately 150 million tons, varying between a minimum of 70 million tons and a maximum of 230 million tons in the period. Median annual coarse suspended-sediment load over the same period is highly variable, varying from 5 to 80 million tons. Over longer periods, the importance of individual high- or low-flow years is diluted. For example, the 5-yr total suspended-sediment loads over the last 40 yrs varied between 580 and 960 million tons, with coarse sediments constituting 40 to 320 million tons and the remainder being fine load.

- Comparison of 19th and late-20th Century average loads *suggests* that there has been a long-term decline in average annual load. This simple assessment, however, must be treated with a appropriate caution, however, because: (i) a robust assessment is limited by gaps in the data record and data from multiple locations; (ii) there are high uncertainties associated with early estimates of sediment load; and (iii) calculated measured loads will underestimate the coarser fractions of suspended load, and do not include bed load. Simple regression analysis for the Tarbert Landing data in the period 1959 to 2005 indicated that declining sediment concentrations may be partially offset by the increasing water discharges, resulting in no trends in sediment loads.

5.2 Recommendations

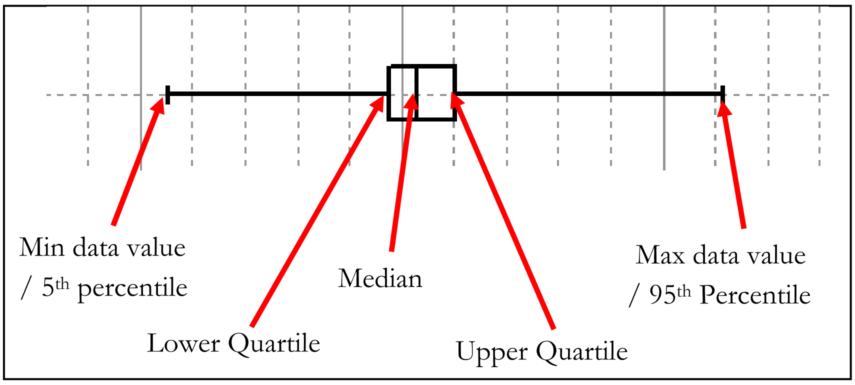
- Undertake further analysis of data from stations along the Lower Mississippi River to examine downstream variation in measured sediment loads and perform analysis of data records for hydrometric stations at Old River and stations in the lower reaches of the Red River and Atchafalaya River to establish spatial distributions in the river network.

- In parallel with conventional monitoring, trial the potential for ADCP backscatter technology to investigate cross-sectional variability in suspended-sediment concentrations.

- Review the Vicksburg District sediment data-management program, and further investigate differences between USACE and USGS Vicksburg data.

- Undertake a more rigorous assessment to investigate the complex behavior represented in the historical record (*e.g.*, temporal periodicity, periods of no change, periods of slow change, periods of short-term, rapid change) employing the appropriate statistical techniques in time-series and trend analysis.

6 Glossary

Bias	The average difference between measured and actual data (see Section 3.2).
Box plot	Graph showing: 
Coarse concentration	Concentration of suspended sediment 0.063 mm or greater in diameter (fine sand or coarser). Usually expressed in parts per million.
D_i	Diameter of i^{th} percentile size fraction of a sediment mixture. For example, D_{50} represents the median (50th percentile) grain size and D_{90} represents the 90th percentile grain size. D_{90} is larger (coarser) than D_{50}.
Extrapolation	Method of calculating the annual sediment load based on use of a sediment-rating curve between measured concentrations and discharges. This method was found unsuitable for the Lower Mississippi River as the sediment-rating relationship required for extrapolation was not sufficiently stable.
Fine concentration	Concentration of suspended sediment finer than 0.063 mm in diameter (clays and silts). Usually expressed in parts per million.

Grain-size classification

The following table gives the part of the standard Wentworth grain-size scale used for classifying sediment size:

Size Fraction	Diameter (mm)
Coarse Sand	0.5 - 1
Medium Sand	0.25 - 0.5
Fine Sand	0.125 - 0.25
Very Fine Sand	0.0625 - 0.125
Coarse Silt	0.0312 - 0.0625
Medium Silt	0.0156 - 0.0312
Fine Sift	0.0078 - 0.0156
Very Fine Silt	0.0039 - 0.0078
Clay	< 0.0039

Interpolation of concentration

Using linear interpolation to estimate concentrations (and hence loads) for non-gauged days in order to annualize sediment data (see Section 3.5).

Interpolation of load

Sediment loads for non-gauged days are estimated based on linear interpolation between days with sediment measurements. The annual sediment load is then calculated by summing the daily loads.

Variability

The random unpredictable part of the uncertainty. Variability can be represented by a probability distribution (see Section 3.2).

7 References

Dardeau, E. A. and Causey, E. M. (1990). Downward trend in Mississippi River suspended-sediment loads. *U.S. Army Corps of Engineers Potamology Program (P-1), Report 5*, Waterways Experiment Station, Vicksburg, MS, 67 pp.

Dean, R. G. (2006). New Orleans and the wetlands of southern Louisiana, National Academy of Engineering Website. http://www.nae.edu/NAE/bridgecom.nsf/weblinks/MKEZ-6MYST9?OpenDocument.

Humphreys, A. A. and Abbot, H. L. (1861). Report upon the physics and hydraulics of the Mississippi River. United States Army Corps of Topographic Engineers.

Humphreys, A. A. and Abbot, H. L. (1876). Report on the physics and hydraulics of the Mississippi River. *Professional Paper*, Government Printing Office, Washington, DC.

Keown, M. P., Dardeau, E. A., and Causey, E. M. (1981). Characterisation of the suspended-sediment regime and bed-material gradation of the Mississippi River Basin. *United States Army Corps of Engineers Potamology Program (P-1) Report*, Vicksburg, MS, 44 pp.

Kesel, R. H. (1988). The decline in the suspended load of the Lower Mississippi River and its influence on adjacent wetlands. *Environmental Geology and Water Sciences*, 11 (3), 271-281.

Kesel, R. H. (1989). The role of the Mississippi River in wetland loss in southeastern Louisiana, USA. *Environmental Geology and Water Sciences*, 13 (3), 183-193.

Kesel, R. H. (1995). Historical sediment discharge trends for the lower Mississippi River.

Koltun, G. F., Eberle, M. Gray, J. R., and Glysson, G. D. (2006). Users manual for the Graphical Constituent Loading Analysis System (GCLAS).

Old River Hydroelectric Partnership. (1999). Old River Hydroelectric Study.

Porterfield, G. (1972). Techniques of water-resources investigations of the United States Geological Survey. In: Computation of Fluvial-Sediment Discharge.

Robbins, L. G. (1977). Suspended sediment and bed material studies on the Lower Mississippi River. *Potamology Investigations*, *Report 300-1*, United States Army Corps of Engineers, Vicksburg District, Vicksburg, MS.

Thorne, C. R., Harmar, O. P., and Wallerstein, N. (2001). Morphodynamics of the Lower Mississippi River. United States Army Research, Development and Standardisation Group-U.K., London.

USACE. (1931). Sediment investigations on the lower Mississippi River and its tributaries 1930-31. *Paper U* of the United States Army Engineer Waterways Experiment Station.

USACE. (2004). Louisiana Coastal Area (LCA), Louisiana – Ecosystem Restoration Study. *Volume 1: LCA Study – Main Report*, United States Army Corps of Engineers, New Orleans District, November, 34 pp.

USGS. (2008). USGS water-quality website. http://nwis.waterdata.usgs.gov, United States Geological Survey, Accessed: July 2008.

Vogel, H.D. (1930). Sediment investigations on the Lower Mississippi River and its tributaries prior to 1930. *Paper H* of the United States Army Engineer Waterways Experiment Station.

Appendix A Post-1930 Data Inventory

Table A.1 Post-1930 data inventory

Name of Gauging Station	Organization	Paper/ Electronic	Dates	Interval	Data Reported
LOWER MISSISSIPPI RIVER					
Chester	USGS	E	1980-1994	daily	Coarse, fine, and total concentrations and loads, temperature October 82 - April 91, Bed data September 80 - August 89, no point measurements.
Memphis	USGS	E	1973-1994	4 weeks	Coarse, fine, and total concentrations and loads, no temperature or bed data. Coarse and fine data to 1980 only, no point measurements.
Arkansas City	USACE Vicksburg District	E	1979-2006	weekly to monthly	Coarse and fine load and concentrations, most with bed-material gradation, summary, and point-measurement data.
	Robbins (1977)	E	1929-1931, 1967-1974	3 days to monthly	1929-1931: total concentrations and loads only (some gaps). 1967-1974: fine and coarse loads and concentrations. No point measurements.
	Other	E	1969-1979	approx. 2 weeks	Lumped data, no dates given, coarse, fine, and total concentrations and loads. Some gaps, no point measurements.
Vicksburg	USACE Vicksburg District	E	1979-2006	weekly to monthly	Coarse and fine load and concentrations, most with bed-material gradation, summary and point-measurement data.
	USGS	E	1973-1994	irregular	Coarse, fine, and total concentrations and loads only, some gaps, no raw data.
	Robbins (1977)	E	1929-1931, 1967-1974	3 days to monthly	1929-1931: total concentrations and loads only (some gaps). 1967-1974: fine and coarse loads and concentrations. No point measurements.
	Other	E	1969-1979	approx. 2 weeks	Lumped data, no dates given, coarse, fine, and total concentrations and loads. Some gaps, no point measurements.
Natchez	USACE Vicksburg District	E	1979-2006	weekly to monthly	Coarse and fine loads and concentrations, most with bed-material gradation, summary and point-measurement data.
	Other	E	1969-1979	approx. 2 weeks	Lumped data, no dates given, coarse, fine, and total concentrations and loads. Some gaps, no point measurements.
Coochie	USACE New Orleans District	E	1967-1997	2 weeks	Suspended and bed-material gradation, computed loads only.
Tarbert Landing	USACE New Orleans District	E	1974-2005	2 weeks	Suspended and bed-material gradation, computed loads only.

Name of Gauging Station	Organization	Paper/ Electronic	Dates	Interval	Data Reported
	USACE New Orleans District paper summaries	E	1963-1973	2-4 weeks (estimate)	Suspended loads only, no gradation, computed loads only (digitized July 2007).
	USACE New Orleans District paper originals	P	1967-1970 and 1974	2-4 weeks (estimate)	Coarse and fine suspended loads with bed-material gradation, original data sheets.
Red River Landing	USACE New Orleans District	E	1973-1997	2 weeks	Suspended and bed-material gradation.
	USACE New Orleans District paper originals	P	1959-1963	2-4 weeks (estimate)	Coarse and fine suspended loads with bed-material gradation, original data sheets.
	USACE New Orleans District digital data	E	1959-1962	approx. 1 week	Labeled as Tarbert Landing. Coarse, fine, and total suspended-sediment concentrations, no discharge.
St. Francisville	USGS	E	1978-1993	2-4 weeks	Coarse and fine loads and concentrations, no bed-material information, no point-measurement information.
Baton Rouge	USACE New Orleans District digital data	E	1956-1959	daily	Daily records for coarse, fine, and total concentration. No discharge data. Unknown how daily record has been calculated.
	USACE New Orleans District digital data	E	1954	approx. 2 weeks	Original raw data, no discharge information.
Donaldsville	USACE New Orleans District paper originals	P	1949-1951	2-4 weeks (estimate)	Coarse and fine suspended loads with bed-material gradation, original data sheets.
Belle Chasse	USGS Water-quality data	E	1976-2008	1-4 weeks (estimate)	Total suspended-sediment concentrations and loads.
Venice	USGS Water-quality data	E	1973-1999	1-4 weeks (estimate)	Total suspended-sediment concentrations and loads.
Other	Old River Study (USACE)	E	1949-1969	annual load	Coarse, fine, and total annual sediment load record. From Baton Rouge (1949-1958).
					Red River Landing (1959-1962) and Tarbert Landing (1963-1969). No original data (digitized July 2007).
RED RIVER					
Alexandria	USACE New Orleans District	E	1971-1979	approx. 2 weeks	
	USGS	E	1973-1995	irregular	Several gaps in record.
Madam Lee Revetment	USACE New Orleans District	E	1992-1996	2 weeks	

Name of Gauging Station	Organization	Paper/ Electronic	Dates	Interval	Data Reported
OLD RIVER CONTROL					
Low Sill Outflow	USACE New Orleans District	E	1989-1991	2 weeks	Suspended gradation very patchy.
Knox Landing (C-89)	USACE New Orleans District	E	1974-1997	2 weeks	
ATCHAFALAYA					
Melville	USGS	E	1978-1995	daily	
Simmesport	USACE New Orleans District	E	1950-1997	2 weeks	Some data gaps.
	USGS	E	1972-1989	daily	

Appendix B Pre-1930 Data Inventory

Table B.1 Pre-1930 data inventory

Collector	Period	Location	Sampling Frequency and Strategy	Laboratory Analysis	Results
Captain Talcott	1838	Southeast and Southwest Passes	Not known.	Not known.	Reported ratio of sediment to water (concentration ratio) as 1:1724 for southeast pass. Reported surface and below surface ratios for southeast pass as 1:1580 and 1:1043, respectively, and adopted a combined ratio for Southwest Pass of 1:1256.
Riddell	1843	Randolph, TN (Mile 183); Carthage Landing, MS (Mile 709); and New Orleans, LA (Mile 969)	Not known.	Sediment was allowed near 10 days for natural subsidence; it was then collected, allowed to dry and carefully weighed (Humphreys and Abbot, 1876).	Average concentration ratio of suspended sediment to Mississippi river water was 1:1245 based on the analysis results of lower Mississippi river sediment samples.
Riddell	21 May and 13 August 1846	New Orleans	Eighteen surface observations at 3-day intervals.	Collected two 1-pint samples, allowed the samples to settle for 2 days, decanted approximately two-thirds of the clear water and poured the remaining water containing sediment through double filters. Weighed the contents when dry.	Computed an average concentration ratio of 1:1158.

Collector	Period	Location	Sampling Frequency and Strategy	Laboratory Analysis	Results
Brown	1 July 1846 and 30 July 1848	Natchez	484 surface samples of know volume, representing 'the different conditions and stages for the river's height and velocity'.	Each sample poured into a 48-in. long cylindrical tin vessel. Water in the tin column dripped slowly through a small brass cock into a glass vessel while the sediment settled in the column.	Brown reported that he had collected a total of 46.5 in. of sediment out of a total water column height of 22,232 in. represented by the 484 samples. Based on the assumed final settlement of 44 in., he concluded that the mean proportional volume of sediment to water was 1:528.
Marr	April - July 1849	Memphis	Daily surface observations.	Placed a known quantity of river water in a box, removed the water as it became clear, and weighed the dry sediment.	The average concentration ratio was 1:596.
Marr	1 March 1850 and 1 March 1851	Memphis	Not known.	Obtained quantity of water from the middle of the surface of the river and placed in a barrel. Obtained and measured the proportion of sediment to water.	Ratio of water to sediment found to be 1:2950. Not possible to determine if the reported changes in concentrations between 1849 and 1851 could have been attributable to changes in the river itself, or to differences in the methods used.

<table>
<tr><th>Collector</th><th>Period</th><th>Location</th><th>Sampling Frequency and Strategy</th><th>Laboratory Analysis</th><th>Results</th></tr>
<tr><td>Forshey</td><td>1851-1853</td><td>Carrollton, LA</td><td>Collected samples 6 days each week (except Sundays) from three verticals in a cross-section. Verticals were positioned: about 300 ft from the left (east) bank; in the middle of the river; and about 400 ft from the right (west) bank. Three samples were taken from the left bank and center verticals, while only surface and near-bottom samples were collected from the right bank vertical.</td><td>Sampling device was a small weighted keg with a large valve attached to the end. Valves permitted free passage of the water through the body of the sampler during descent, but closed when the sampler was being pulled back to the surface.

Laboratory procedure detailed in Dardeau and Causey (1990).</td><td><table>
<tr><td>Period</td><td>Maximum</td><td>Mean</td><td>Minimum</td></tr>
<tr><td>1851-1852</td><td>1:681</td><td>1:1808</td><td>1:6383</td></tr>
<tr><td>1852-1853</td><td>1:572</td><td>1:1499</td><td>1:8584</td></tr>
</table>
The estimated annual suspended-sediment load at Carrollton for 1851-1852 was 379 million tons computed by using concentration and discharge data.</td></tr>
<tr><td>Fillebrown, Webster, and Jones</td><td>1858</td><td>Columbus, KY, 21 mi downstream from Ohio</td><td>Taken at points midway between the banks, surface water only.</td><td>Weight of sediment contained in water determined. Mean concentration for river calculated by multiplying the numerical mean of the results of the observations by 1.2, the ratio between the surface and the 'true mean' at all depths, derived from the Carrollton observations.</td><td>Results highly variable.
<table>
<tr><td>April 10th 1858</td><td>1 to 1681</td></tr>
<tr><td>October 19th 1858</td><td>1 to 17449</td></tr>
<tr><td>November 1st 1858</td><td>1 to 5073</td></tr>
</table></td></tr>
</table>

Collector	Period	Location	Sampling Frequency and Strategy	Laboratory Analysis	Results
Humphreys and Abbot	Measurements 1850s – early 1870s. Reported 1876.	Multiple	Field personnel measured flow velocities at various depths and made observations of water-surface slope and sediment movement in various reaches of the lower Mississippi river.	Not applicable.	Concluded that if the mean annual discharge of the Mississippi is 19,500,000,000,000 cu ft (618,000 cfs), it follows that 406.2 million tons of sediment are yearly transported in a state of suspension to the Gulf.
Corps of Engineers	26 March 1877 for 1 yr.	South Pass	Measurements using a trap bucket.	Not known.	• Computed the total suspended-sediment load through South Pass upstream from Grand Bayou during this initial observation as 23.4 million cu yds. • Estimated the South Pass carried 10% of suspended-sediment load of the Mississippi (based on the proportion of the total Mississippi River discharge carried by South Pass, making the 1877-1878 annual estimate for all passes approximately 234 million cu yds (373 million tons).
Corps of Engineers	1879-1898	South Pass near Port Eads	One-quart samples collected twice each week.	Not known.	Concentration ratios ranged for 1878-1898 ranged from 1:2191 to 1:910, with the mean being 1:1453. Annual suspended-sediment loads for this period ranged from 18.5 to 53.2 million tons. The discharge and suspended-sediment load through South Pass was reported as 10% of the river's total for 1877-1881 but only 8% for 1894. If a constant decrease in the percentage of discharge carried by South Pass during 1881-1884, the estimated mean annual sediment load through all passes for the period 1879-1893 would have been 314.5 million tons.

Collector	Period	Location	Sampling Frequency and Strategy	Laboratory Analysis	Results
Mississippi River Commission (MRC)	November 1879 and November 1880	Fulton, TN (Mile 175); Lake Providence, LA (Mile 542); and Carrollton, LA (Mile 960)	Surface, mid-depth, and near-bottom samples in eight verticals evenly spaced across sections of the Lower Mississippi River.	Surface samples were collected with a pail, mid-depth, and near-bottom samples were obtained with a slip bottle, a hollow iron cylinder that moved on a vertical axis. At an appropriate depth, an observer in a boat released a string-activated catch to fill the slip bottle.	Detailed in Vogel (1930) – Paper H.
Low Water Board	1878-1879	Columbus (Mile 21); Hampton Landing, AR (Mile 242); Helena, AR (Mile 306); and Kings Point, MS (Mile 595)	Suspended-sediment observations.	Little detailed documentation remains on the kinds of sampling equipment or the methods of analysis used by the Low Water Board.	Detailed in Vogel (1930) – Paper H.

Appendix C Vicksburg District Data-quality Assessment

Project	Current and Historical Sediment Loads on the Lower Mississippi River	**Date**	15 January 2008
Note	Vicksburg District Data-quality assessment	**Ref**	WBLMIS
Author	Oliver Harmar and Richard Measures		

Summary

As part of the Study into Current and Historical Sediment Loads on the Lower Mississippi River the USACE Vicksburg District sediment data records have been analysed. The sediment data are stored in data files known as BOK files. In order to analyse the data, a tool has been created to extract the data from the BOK data files and place them into a spreadsheet. Obvious errors within the BOK files have also been manually corrected and a data-quality flagging tool has been created in order to flag potential sources of error within the data. Key errors identified include: poor formatting, missing data, erroneous individual values, and systematic sampling errors.

Introduction

Sediment data measured by the USACE Vicksburg District are stored in text files with a standard format known as "BOK" files. These files contain information about suspended-sediment concentration and bed-material composition measurements.

Several problems have been found when trying to extract the sediment data from the BOK files into a standard spreadsheet format. The nature of these problems is discussed within the technical note "Data Quality Issues" 16th August 2007. This technical note describes the methodology which has been applied to repair and quality flag the data. It also gives a detailed description of each of the data-quality warnings which can be returned.

This note is intended for reference use.

BOK file formatting

Correct formatting

No specification for BOK file layout, content, and formatting has been found. Visual inspection reveals that they contain the following:

- Each set of gauged measurements forms a data block. Data blocks are separated by a line of 80 dashes.

```
--------------------------------------------------------------------------------
```

- The first part of the data block contains summary data. Spaces are used to organize the headings, units, and data into columns.

```
RANGE   DATE MEAN GAGE      MEAN   MAXIMUN     TOTAL    TOTAL    TOTAL    WATER
               READING  VELOCITY  VELOCITY DISCHARGE     AREA    WIDTH     TEMP
                  FEET       FPS       FPS       CFS  SQ FEET     FEET      DEG
56590 12 785     10.64      3.19      4.10   392000.     123.     300.       0.
```

- The next part of the data block contains summary information about the suspended-sediment measurements.

```
RANGE    DATE     AIR   WATER  NOZZLE    TYPE
          DMY    TEMP    TEMP    SIZE SAMPLER

56590  12 785      81      80             P61
```

- The third part of the data block contains the suspended-sediment concentration measurements at each vertical station across the river section, followed by the calculated average concentration and load. Spaces are used to organize the data into columns in a consistent format.

```
STATION SOUNDED  SAMPLE   OBSERVED   PPM   PPM   SAMPLE   OBSERVED   PPM   PPM
          DEPTH   DEPTH   VELOCITY  SAND  -230    DEPTH   VELOCITY  SAND  -230
           FEET    FEET        FPS                 FEET        FPS

   4600    35.0
                    3.7       3.00     3    61     11.3              3
                   19.9                3           29.4              2

   4200    44.0
                    4.7       3.65     3           14.2              5    66
                   25.0                2           37.0              2

   3800    54.0
                    5.8       3.79     4           17.4              3
                   30.8                5    52     45.4              2

   3400    53.0
                    5.7        .86     6           17.1             11
                   30.2                6           44.5              6    59

   3000    45.0
                    4.8       4.08     4    23     14.5              3
                   25.6                3           37.8              2

   2600    42.0
                    4.5       3.79     2           13.6              1    48
                   23.9                1           35.3              2
Blank or 0 ppm-230 indicates that no measurement was made.
If observed velocities are identically equal thru the vertical then the
   velocity measurement was made at the 0.4 depth.
AVERAGE CONCENTRATION FOR SECTION=     59. PPM        TONS/DAY=   62181.
```

- The fourth part of the data block contains summary data about the bed-material size measurements.

```
RANGE    DATE     AIR   WATER    TYPE
          DMY    TEMP    TEMP SAMPLER

56590  12 785     81      80    BM54
```

- The final part of the data block contains bed-material composition data.

```
                     BED MATERIAL SIEVE ANALYSIS
STATION    SIEVE  PERCENT    SIEVE  PERCENT    SIEVE  PERCENT
        DIAMETER  PASSING DIAMETER  PASSING DIAMETER  PASSING
            (MM)              (MM)               (MM)

   4600
           19.05    100.0    9.525    100.0     4.76     99.9
            2.38     99.9     1.19     99.9    0.841     99.9
           0.595     99.8    0.420     99.1    0.297     96.3
           0.210     57.4    0.149      6.8    0.105      0.9
           0.074      0.2
   4200
           19.05    100.0    9.525    100.0     4.76    100.0
            2.38    100.0     1.19     99.9    0.841     99.8
           0.595     99.1    0.420     97.5    0.297     72.0
           0.210     13.5    0.149      1.6    0.105      0.2
           0.074      0.0
   3800
           19.05    100.0    9.525    100.0     4.76    100.0
            2.38     99.7     1.19     99.6    0.841     99.6
           0.595     99.4    0.420     98.7    0.297     78.4
           0.210     20.0    0.149      3.1    0.105      0.3
           0.074      0.1
   3400
           19.05    100.0    9.525    100.0     4.76    100.0
            2.38    100.0     1.19    100.0    0.841     78.8
           0.595     35.4    0.420     21.7    0.297      5.3
           0.210      1.0    0.149      0.5    0.105      0.1
           0.074      0.0
   3000
           19.05    100.0    9.525    100.0     4.76    100.0
            2.38     99.6     1.19     99.4    0.841     99.3
           0.595     99.2    0.420     98.7    0.297     85.9
           0.210      7.6    0.149      0.6    0.105      0.2
           0.074      0.1
   2600
           19.05    100.0    9.525    100.0     4.76     99.4
            2.38     98.9     1.19     98.9    0.841     98.8
           0.595     98.4    0.420     72.2    0.297      1.4
           0.210      0.8    0.149      0.3    0.105      0.1
           0.074      0.0
```

Problems and corrections

While importing data from the BOK file, the following two basic formatting issues were noted:

1. the format of the files is not always consistent between different measurement dates; and

2. errors exist where decimal points are missing or data are incorrectly aligned into columns.

To correct basic formatting errors, a manual check of the BOK file was carried out and corrections made where it was clearly evident what the correct formatting should be. Manual corrections included:

- replacing tabs with spaces
- correcting column alignment using spaces
- inserting decimal places where they were missing

Manually corrected BOK files are available for future use.

To detect remaining errors present in the data files following manual correction, an automated data-quality flagging procedure has been built into the macro developed to import BOK information into standard Microsoft® Office Excel format. This process is described below.

Data-quality flagging

Principles/methodology

BOK files were imported into Microsoft Microsoft® Office Excel using a macro which scans through the text of the BOK file and extracts the data into the spreadsheet. Several quality-checking procedures were incorporated into the macro to try and identify potential errors in the data which could not be identified through manual correction. These errors may be as a result of random or systematic errors within the data of the BOK file or as a result of incorrect formatting preventing the macro from importing the data correctly.

The macros only investigate the sensibility of the raw data values. Note that this is a highly subjective procedure. A data-quality warning does not necessarily mean the data are erroneous, but rather they are a significant departure from expected data values. The data-quality flagging procedure has only been applied to check raw data – *i.e.*, it has not been applied to check calculated sediment loads.

Where potential sources of error are identified, data-quality warnings are given as a text string in the last column of the imported data table. Multiple errors are separated by commas.

Quality warnings

The quality-flagging procedure may return one or more of the following warnings for each gauge day (each data block). In addition to returning data-quality warnings, data quality is flagged as A, B, or C: A means there are no quality warnings for that gauge date; B means there are minor quality warnings but the suspended-sediment data can still be used but may require minor interpolation to fill in data gaps; and C means the data are suspect and will be disregarded in this study.

“more than one velocity measurement per vertical” (A)

Velocity measurements are generally taken once within each vertical. If there is more than one different velocity measurement for a given vertical then this error is returned. Note that sometimes this error is caused by incorrect formatting aligning columns incorrectly. This error does not impact the calculation of load but suggests there may be inconsistencies in the data, so are flagged “B”.

“date mismatch error” (C)

The gauge date is repeated at the start of the 1st and 3rd parts of the data block. If the dates are not consistent then this error message is returned. This error makes it uncertain which date the data were collected on and generally means the block of data within the BOK file have significant inconsistencies, so are flagged “C”.

“no bed material data” (A)

The macro finds no bed-material data following the initial data block of the BOK file. This may be because it is not there or because it is incorrectly formatted – in the corrected BOK files most formatting errors have been corrected. This error does not impact the suspended-sediment data, so are flagged “A”.

“1 vertical missing 1 or more suspended sediment or velocity measurement” (B)

One vertical from the suspended-sediment measurements is missing 1 or more of velocity measurement, fine concentration measurement or 1 or more coarse concentration measurement. This error impacts the calculation of load but because most of the data are still present, it is possible to interpolate to fill in missing data. These errors are flagged “B”.

“more than 1 vertical with missing suspended sediment or velocity data” (C)

More than one vertical is missing either velocity, coarse-concentration, or fine-concentration data. These errors significantly affects calculation of load, so are flagged “C”.

“missing suspended sediment or velocity data in all verticals” (C)

All verticals are missing items of data – usually this error occurs because the suspended-sediment data block is missing. It is impossible to calculate load for these data, so are flagged “C”.

“1 suspended sediment value excessively large” (B)

There is one suspended-sediment values in excess of 1,000 parts per million. Only one value is erroneous so this value is ignored and the data are flagged “B”.

“Several suspended sediment values excessively large” (C)

There is more than one suspended-sediment value in excess of 1,000 parts per million. Several values are erroneous so the data are considered very unreliable and are flagged “C”.

“1 suspended sediment value is negative” (B)

There is one suspended-sediment values which is negative. Only 1 value is erroneous so this value is ignored and the data are flagged “B”.

“several suspended sediment values negative” (C)
There is more than one suspended-sediment values which is negative. Several values are erroneous so the data are considered very unreliable and are flagged “C”.

“possible systematic error in coarse suspended sediment values” (B)
At three or more of the six verticals the maximum coarse suspended-sediment measurement occurs at the same depth as the fine suspended-sediment measurement. This issue is discussed in more detail in the technical note “Data Quality Issues”. This error may occur purely coincidentally but may indicate that the data are suspect. They are flagged “B”.

“likely systematic error in coarse suspended sediment values” (C)
At five or more of the six verticals the maximum coarse suspended-sediment measurement occurs at the same depth as the fine suspended-sediment measurement. This issue is discussed in more detail in the technical note “Data Quality Issues”. It is very likely that there is a systematic error in these data and are flagged as “C”.

“other error” (C)
This error message is returned when the macro encounters a problem. This is generally due to poor formatting of the BOK file resulting in the macro returning text when it is looking for a number. This error message does not occur when extracting data from the corrected BOK files (see Section 2.2). This error message returns a “C” data flag.

Results

The BOK files supplied for Vicksburg, Natchez, and Arkansas City contain data from 1984 to 2004. They have been imported for analysis using the data-quality flagging spreadsheet. A summary of the data-quality flagging results is tabulated below:

Quality Flag	No. of Gauge Days		
	Vicksburg	Natchez	Arkansas City
A	278	230	158
B	108	85	117
C	48	121	145
Total	434	436	420

Recommendations

It is recommended that a review of the quality control of the collection of sediment data and storage in BOK files is carried out to improve the quality of future sediment data. The current records of sediment data are very valuable but the errors and inconsistencies make it very difficult to use the data and reduce confidence in their application.

Appendix D Sampling Strategy at Tarbert Landing

Table D.1 Sampling strategy at Tarbert Landing

Date	Verticals	Samples per Vertical	Sample Depths	Samples
1974	8	5	0.15, 0.3, 0.5, 0.7, and 0.9	40
1975	8	5	0.15, 0.3, 0.5, 0.7, and 0.9	40
1976	8	5	0.15, 0.3, 0.5, 0.7, and 0.9	40
1977	8	5	0.15, 0.3, 0.5, 0.7, and 0.9	40
1978	8	5	0.15, 0.3, 0.5, 0.7, and 0.9	40
1979	8	5	0.15, 0.3, 0.5, 0.7, and 0.9	40
1980	8	5	0.15, 0.3, 0.5, 0.7, and 0.9	40
1981	8	5	0.15, 0.3, 0.5, 0.7, and 0.9	40
1982	8	5	0.15, 0.3, 0.5, 0.7, and 0.9	40
1/13/83	8	5	0.15, 0.3, 0.5, 0.7, and 0.9	40
1/27/83	8	5	0.15, 0.3, 0.5, 0.7, and 0.9	40
02/10/83	8	5	0.15, 0.3, 0.5, 0.7, and 0.9	40
2/23/83	8	5	0.15, 0.3, 0.5, 0.7, and 0.9	40
03/10/83	8	5	0.15, 0.3, 0.5, 0.7, and 0.9	40
3/24/83	8	5	0.15, 0.3, 0.5, 0.7, and 0.9	40
04/07/83	8	5	0.15, 0.3, 0.5, 0.7, and 0.9	40
05/06/83	8	5	0.15, 0.3, 0.5, 0.7, and 0.9	40
5/30/83	4	2	0.5 and 0.7	8
6/15/83	4	2	0.5 and 0.7	8
6/29/83	4	2	0.5 and 0.7	8
7/13/73	4	2	0.5 and 0.7	8
7/27/83	4	2	0.5 and 0.7	8
08/10/83	4	2	0.5 and 0.7	8
8/24/83	4	2	0.5 and 0.7	8
09/08/83	4	2	0.5 and 0.7	8
9/22/83	4	2	0.5 and 0.7	8
10/04/83	4	2	0.5 and 0.7	8
10/18/83	4	2	0.5 and 0.7	8
11/04/83	4	2	0.5 and 0.7	8
11/15/83	4	2	0.5 and 0.7	8
11/29/83	4	2	0.5 and 0.7	8
12/16/83	4	2	0.5 and 0.7	8
12/30/83	4	2	0.5 and 0.7	8
1984	4	2	0.5 and 0.7	8

Date	Verticals	Samples per Vertical	Sample Depths	Samples
1985	4	2	0.5 and 0.7	8
1986	4	2	0.5 and 0.7	8
1987	4	2	0.5 and 0.7	8
1988	4	2	0.5 and 0.7	8
1989	4	2	0.5 and 0.7	8
01/09/90	4	2	0.5 and 0.7	8
1/22/90	4	2	0.5 and 0.7	8
02/08/90	4	2	0.5 and 0.7	8
2/22/90	4	2	0.5 and 0.7	8
03/05/90	4	2	0.5 and 0.7	8
3/19/90	4	2	0.5 and 0.7	8
04/02/90	4	2	0.5 and 0.7	8
4/16/90	4	2	0.5 and 0.7	8
4/30/90	4	3	0.5, 0.7, and 0.95	12
5/14/90	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
5/29/90	4	3	0.5, 0.7, and 0.95	12
06/11/90	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
6/25/90	4	3	0.5, 0.7, and 0.95	12
07/09/90	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
7/23/90	4	3	0.5, 0.7, and 0.95	12
08/06/90	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
8/22/90	4	3	0.5, 0.7, and 0.95	12
09/04/90	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
9/17/90	4	3	0.5, 0.7, and 0.95	12
10/03/90	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
10/15/90	4	3	0.5, 0.7, and 0.95	12
10/29/90	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
11/13/90	4	3	0.5, 0.7, and 0.95	12
11/26/90	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
12/10/90	4	3	0.5, 0.7, and 0.95	12
12/27/90	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
1/16/91	4	3	0.5, 0.7, and 0.95	12
1/28/91	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
02/11/91	4	3	0.5, 0.7, and 0.95	12
2/27/91	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
03/11/91	4	3	0.5, 0.7, and 0.95	12

Date	Verticals	Samples per Vertical	Sample Depths	Samples
3/25/91	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
04/08/91	4	3	0.5, 0.7, and 0.95	12
4/22/91	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
05/08/91	4	3	0.5, 0.7, and 0.95	12
5/20/91	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
06/03/91	4	3	0.5, 0.7, and 0.95	12
6/17/91	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
07/01/91	4	3	0.5, 0.7, and 0.95	12
7/17/91	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
7/29/91	4	3	0.5, 0.7, and 0.95	12
08/12/91	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
8/26/91	4	3	0.5, 0.7, and 0.95	12
09/11/91	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
9/24/91	4	3	0.5, 0.7, and 0.95	12
10/07/91	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
10/23/91	4	3	0.5, 0.7, and 0.95	12
11/04/91	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
11/18/91	4	3	0.5, 0.7, and 0.95	12
12/02/91	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
12/16/91	4	3	0.5, 0.7, and 0.95	12
1/13/92	4	3	0.5, 0.7, and 0.95	12
1/29/92	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
02/10/92	4	3	0.5, 0.7, and 0.95	12
2/20/92	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
03/11/92	4	3	0.5, 0.7, and 0.95	12
3/23/92	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
04/06/92	4	3	0.5, 0.7, and 0.95	12
4/20/92	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
05/04/92	4	3	0.5, 0.7, and 0.95	12
5/19/92	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
06/01/92	4	3	0.5, 0.7, and 0.95	12
6/15/92	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
6/29/92	4	3	0.5, 0.7, and 0.95	12
7/13/92	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
7/27/92	4	3	0.5, 0.7, and 0.95	12
08/12/92	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40

Date	Verticals	Samples per Vertical	Sample Depths	Samples
8/24/92	4	3	0.5, 0.7, and 0.95	12
09/10/92	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
9/23/92	4	3	0.5, 0.7, and 0.95	12
10/13/92	4	3	0.5, 0.7, and 0.95	12
10/19/92	4	3	0.5, 0.7, and 0.95	12
11/02/92	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
11/16/92	4	3	0.5, 0.7, and 0.95	12
11/30/92	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
12/14/92	4	3	0.5, 0.7, and 0.95	12
12/30/92	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
01/11/93	4	3	0.5, 0.7, and 0.95	12
1/25/93	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
02/08/93	4	3	0.5, 0.7, and 0.95	12
2/22/93	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
03/08/93	4	3	0.5, 0.7, and 0.95	12
3/22/93	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
04/05/93	4	3	0.5, 0.7, and 0.95	12
4/19/93	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
05/03/93	4	3	0.5, 0.7, and 0.95	12
5/17/93	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
06/01/93	4	3	0.5, 0.7, and 0.95	12
6/28/93	4	3	0.5, 0.7, and 0.95	12
07/12/93	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
7/21/93	4	3	0.5, 0.7, and 0.95	12
7/26/93	4	3	0.5, 0.7, and 0.95	12
7/28/93	4	3	0.5, 0.7, and 0.95	12
08/02/93	4	3	0.5, 0.7, and 0.95	12
08/04/93	4	3	0.5, 0.7, and 0.95	12
08/09/93	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
08/12/93	4	3	0.5, 0.7, and 0.95	12
8/16/93	4	3	0.5, 0.7, and 0.95	12
8/18/93	4	3	0.5, 0.7, and 0.95	12
8/23/93	4	3	0.5, 0.7, and 0.95	12
09/07/93	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
9/20/93	4	3	0.5, 0.7, and 0.95	12
10/04/93	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40

Date	Verticals	Samples per Vertical	Sample Depths	Samples
10/18/93	4	3	0.5, 0.7, and 0.95	12
11/01/93	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
11/15/93	4	3	0.5, 0.7, and 0.95	12
11/29/93	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
12/23/93	4	3	0.5, 0.7, and 0.95	12
01/06/94	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
1/20/94	4	3	0.5, 0.7, and 0.95	12
02/03/94	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
2/17/94	4	3	0.5, 0.7, and 0.95	12
03/03/94	8	5	0.15, 0.3, 0.5, 0.7, and 0.95	40
4/14/94	4	3	0.5, 0.7, and 0.95	12
4/21/94	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
4/28/94	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
05/04/94	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
05/12/94	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
5/25/94	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
06/02/94	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
6/16/94	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
6/23/94	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
6/29/94	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
7/14/94	4	3	0.5, 0.7, and 0.9	12
7/27/94	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
08/10/94	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
10/06/94	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
11/10/94	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
12/22/94	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
12/29/94	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
01/11/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
1/26/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
02/09/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
2/23/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
03/09/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
3/22/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
04/06/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
05/04/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
5/17/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20

Date	Verticals	Samples per Vertical	Sample Depths	Samples
06/01/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
6/15/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
6/29/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
07/12/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
08/03/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
8/31/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
9/14/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
9/26/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
10/26/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
11/09/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
11/22/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
12/06/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
12/14/95	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
02/01/96	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
2/15/96	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
3/14/96	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
3/28/96	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
04/11/96	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
4/25/96	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
5/22/96	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
06/06/96	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
6/19/96	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
7/18/96	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20
08/01/96	4	5	0.15, 0.3, 0.5, 0.7, and 0.9	20

Appendix E Sediment Database CD-ROM

The enclosed CD-ROM includes the original and processed sediment data files, final project report files, meeting minutes and presentations, and selected references.

Files can be easily accessed using the hyperlinks contained within the '*Mississippi_Sediment_Data_CD.xls.'*

Alternatively, all files can be manually accessed by browsing the directory structure. Data are stored in the following first tier directory structure:

Directory	Contents
Sediment Data	Original and processed sediment data sets. Scanned pdf files are included where digital data files are not available. Includes data sets for the lower Mississippi River, Red River, Old River, and the Atchafalaya River.
Discharge Data	Historic discharge records for Vicksburg and Tarbert Landing.
Report	Electronic copy of the final project report and appendices.
References	Selected references in pdf format.
Meeting and presentations	Minutes of meetings held during the project and pdf presentations from the final workshop.

PART II: IMPLICATIONS FOR SEDIMENT DIVERSIONS

Acknowledgement

The invaluable contributions of J. Craig Fischenich to the preparation of this part of the report are gratefully acknowledged.

1 Introduction

In this part of the report, we address four primary tasks: (i) quantify sediment discharges from the Mississippi River at existing diversions; (ii) assemble estimates of sediment quantities and sediment sizes available for diversions planned to promote coastal marsh restoration; (iii) develop estimates of sediment loads required for restorations and estimates of uncertainty; and (iv) identify seasonal timing for diverting sediment from the river for marsh and wetland restoration. In addition, we develop estimates of the quantity of sediment and river water discharge required for a conservative program of marsh reconstruction.

2 Background

The quantity of technical literature pertaining to the problem of coastal Louisiana land loss is voluminous, and encompasses a wide variety of topics. A few of these topics will be covered to promote understanding of the complexity of the problem of the loss of Louisiana coastal lands.

Like most things in Louisiana, the coast was formed on the give-and-take of natural processes: sediment from the various courses of the Mississippi being deposited to build the marshes and natural subsidence allowing the new land to sink below global sea-level rise. When the building of land was balanced by the subsidence and sea-level rise, the net land area was reasonably constant. However, in the last 200 to 300 yrs, human intervention has altered the long-term trend of the natural process, which has caused widespread land loss along the Louisiana coastline (National Academy of Science (NAS), 2006).

Numerous factors have contributed to the accelerated loss of coastal land. The following causes are frequently associated with the land-loss problem:

- Mining of natural resources has resulted in canals that have disrupted natural flow patterns in the marsh, altering the natural distribution of fresh and saline water.

- Flood-control levees have restricted the movement of the Mississippi River that, over time, had formed a series of alternating lobes to feed water and sediment to the marsh; and, in protecting citizens and infrastructure, have confined the river flow to deliver the sediment to the Gulf of Mexico and not directly to the marsh.

- The relative sea-level rise (RSLR), defined as subsidence plus global sea-level rise, appears to be accelerating as a result of climate change, and is estimated to be in the range of 1.0 to 1.2 cm/yr for coastal Louisiana (Penland and Ramsey, 1990).

- Earlier chapters (in Part I) of this report suggest another potential cause: erosion control projects throughout the Mississippi River Basin have reduced the available sediment supply.

2.1 Land loss

An important component in developing an estimate of sediment loads required for restoration of coastal Louisiana land is to establish the present and future rates of loss. Barras (2006) provides a recent study of land-area change in coastal Louisiana. His investigation focused on the effects of Hurricanes Katrina and Rita that occurred in 2005, and that study provides quantification of transitory land loss; however, estimation of permanent losses require several more years of data. The study (Barras, 2006) also provided a map of the land loss for the 48-yr period of 1956 to 2004, which included the effects of several hurricanes that are not specifically identified. The total land loss for the period was 1,149 sq mi [2,975 km^2], averaging 23.9 sq mi/yr [61.9 km^2/yr]. Barras *et al.* (2004) provide a thorough review of historical rates (1978 to present) and provide a projected rate of loss for the period to 2050. Figure 2.1 is a map of the Louisiana Coastal Area (LCA) boundaries that were used by Barras *et al.* (2004) to sub-divide the study area. Table 2.1 provides a summary table of land-loss rates by subprovince for the period 1978 to 2000.

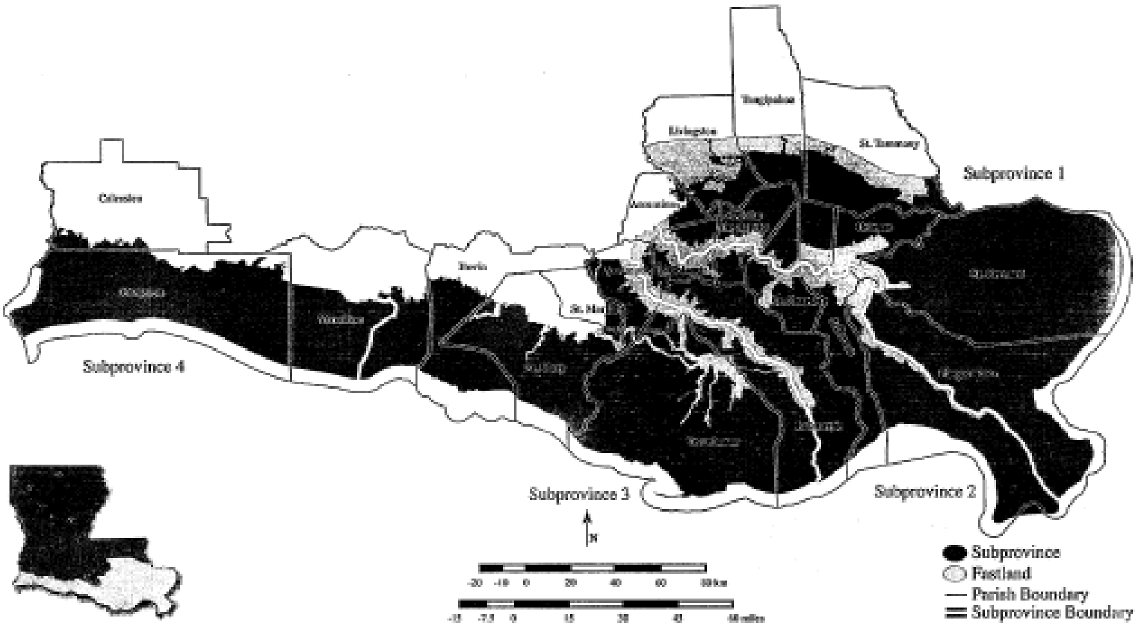


Figure 2.1 LCA subprovince boundaries are shown (after Barras *et al.* (2004))

Table 2.1 The data for net land-loss trends by subprovince for the period 1978 to 2000 are shown (after Barras *et al.* (2004))

	1978 - 1990 Net Loss (sq mi)*	1990 - 2000 Net Loss (sq mi)	1978 - 2000 Cumulative Loss (sq mi)	Annual Loss (sq mi/yr)	% Total Loss by Area
Subprovince 1	52	48	100	4.5	15.2%
Subprovince 2	148	65	213	9.7	32.4%
Subprovince 3	134	72	206	9.4	31.3%
Subprovince 4	85	54	139	6.3	21.1%
Total sq mi [km^2]	419 [1,085]	239 [619]	658 [1,704]	29.9 [77.4]	100%

*1978 to 1990 net loss figures were based on Barras *et al.* (1994). The 1978 to 1990 basin-level and coast-wide trends used in this study were aggregated to reflect LCA subprovinces for comparison with the 1990 to 2000 data. The basin boundaries used in Barras *et al.* (1994) were based on older CWPPRA planning boundaries and are not directly comparable to the LCA boundary used to summarize the 1990 to 2000 trend data. The 1990 to 2000 net loss figures include actively managed lands for comparison purposes with the 1978 to 1990 data.

In Table 2.2, Barras *et al.* (2004) explain that the projected change from 2000 to 2050 is a result of an estimated 674 sq mi of land loss and a gain of 161 sq mi [417 km^2] related to existing restoring projects (Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA) projects, Caernarvon, Davis Pond, and delta building at the mouth of the Mississippi and Atchafalaya Rivers). For the purposes of estimating the annual sediment required to stop coastal land loss, the total land loss of 674 sq mi [1,746 km^2] is appropriate. This represents an annual loss rate of 13.5 sq mi/yr [35 km^2/yr]. Barras *et al.* (2004) estimate the trend error range at ±25%.

Table 2.2 The projected net land-loss trends by subprovince are shown for the period 2000 to 2050 (after Barras *et al.* (2004))

	Land in 2000 (sq mi)	Land in 2050 (sq mi)	Net Land Loss (sq mi)	% Land Loss between 2050 and 2000	Land Loss (sq mi/yr)	% Total Loss by Area
Subprovince 1	1,331	1,270	61	4.61%	1.23	12%
Subprovince 2	1,114	928	186	16.68%	3.71	36%
Subprovince 3	1,975	1,746	229	11.59%	4.58	45%
Subprovince 4	1,431	1,394	37	2.59%	0.74	7%
Total sq mi [km^2]	5,851 [15,154]	5,338 [13,825]	513 [1,329]	8.77%	10.26 [26.57]	100%

Note that total percentage of land loss is the percentage of total net land loss (513 sq mi) in 2050 to the existing land (5,851 sq mi) in 2000.

The method used by Barras *et al.* (2004), as they point out, can only be used for projection of future trends based on events that have occurred in the past. For example, factors such as past sea-level rise are assumed to continue at the same rate in the future; however, Barras *et al.* (2004) point out that over the last 2 decades, Louisiana marshes have adjusted to high rates of RSLR by as much as 1 cm/yr, which may be a sufficient rate to include in the projection given the challenge of estimating the future rate.

In addition to the uncertainty of sea-level rise, other factors introduce uncertainty. For example, much of the sediment that is supplied by the Atchafalaya River is from either the Mississippi River through the Old River Control Structure or from the Red River. Operation of the Old River Control Structure is now mandated to distribute 70% of the flow to the Lower Mississippi River and 30% to the Atchafalaya River. This distribution could be changed. The Red River Waterway was authorized in 1968 and following completion of the five major navigation locks, the sediment delivery from the upper Red River basin to the Atchafalaya River dramatically changed. Since that time, the amount of erosion downstream of L.C. Boggs Lock & Dam 1 has increased and this erosion is supplying sediment to the Atchafalaya River. The effect of a decision to change the distribution of flow at Old River Control or a decision to reduce the erosion on the Red River could affect sediment supplied by the Atchafalaya River.

On a broad watershed scale, the effect of climate change on sediment delivery is challenging. Less river discharge may reduce sediment delivery, but a change to high-intensity rainfall and more flash flooding in the basin could make more sediment available for transport.

2.2 New coastal land

DeLaune *et al.* (2003) report that Louisiana coastal marshes represent a thin veneer of primary organic soil material, which supports vegetative growth, and is overlying a mineral sediment layer deposited earlier by the present Mississippi River and previous distributaries. For locations in coastal Louisiana at which the vertical rate of accretion is less than the rate of RSLR, marsh deterioration can occur due to salt-water intrusion and other factors. Penland and Ramsey (1990) document submergence rates in the Mississippi River deltaic plain in excess of 1.0 cm/yr.

In many cases in Louisiana coastal marshes, organic-matter accumulation defines vertical accretion rather than mineral-matter accumulation (Hatton *et al.*, 1983; Nyman *et al.*, 1990). DeLaune *et al.* (2003) explain that even though marsh soil accretion is primarily through organic accumulation, small quantities of organic matter are required for plant growth, to provide nutrients, and to supply iron that neutralizes sulfides that can be toxic to marsh vegetation. Nyman *et al.* (1990) reported that salt marsh requires a greater quantity of sediment in the soil profile to support plant growth than in freshwater marsh. Figure 2.2, developed using data estimated by Nyman *et al.* (1990) and proposed by DeLaune *et al.* (2003) illustrates that decreasing salinity, for example by freshwater diversion, reduces the quantity of sediment required for successful coastal marsh rehabilitation.

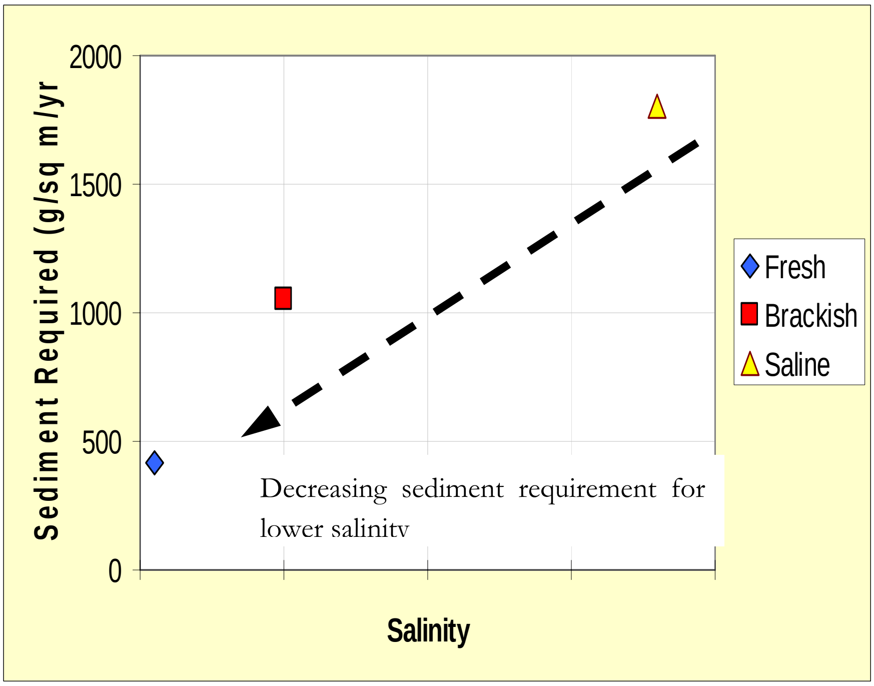


Figure 2.2 The amount of sediment required to meet marsh-restoration goals is a moving target, and by reducing salinity (more freshwater) the amount of sediment required is decreased (after DeLaune *et al.* (2003)) – data estimated by Nyman *et al.* (1990)

Quoting DeLaune *et al.* (2003): *To maximize marsh creation at Mississippi River freshwater diversions sites, the critical nutrient, salinity and mineral sediment required for acceleration of plant biomass production (the source of peat or organic soil formation) should be provided. If the specific nutrient, salinity level and mineral sediment requirements for marsh maintenance are known for a certain marsh area in the region, diverted water could be more effectively directed or distributed, maximizing marsh creation over a larger area.*

McKay *et al.* (2008) emphasize that the character of the discharge body may influence the relative importance of organic or inorganic inputs (Boustany, 2007). They suggest that if a region is initially unvegetated, sediment inputs will be necessary to establish a soil platform for dense vegetative growth. With the establishment of dense vegetative growth, organic inputs may dominate, and the dense vegetation will encourage retention of a high percentage of suspended sediment. This positive feedback system necessitates inclusion of both sediment and vegetative inputs in planning the required vertical accretion for long-term stability (personal communication, Fischenich (2008)).

2.3 Diversions

The New Orleans District furnished a listing of fifteen Mississippi River diversions recognized in their HEC-6T model. This list is presented as Table 2.3. Several existing diversions were investigated to provide information for the primary tasks, including the controlled diversions at Old River, Caernarvon, and Davis Pond, the uncontrolled diversion at West Bay, and several direct dredge-disposal sites. These sites include a broad range of discharge capacity, complexity, and detail of available data.

Table 2.3 Mississippi HEC-6T diversions

Diversion	Mile
Burrwood Bayou	-14.4
Outlets 11.8W W-1 W-2	-10.7
Joseph Bayou and Overbank Flows	-4.5
Southwest Pass @ Mile 3.0 West	-3.05
South Pass and Pass-a-Loutre	0
Cubits Gap and Overbank Flows	3.15
West Bay Diversion Canal	3.83
The Jump	10.5
Baptiste Collette	11.5
Bohemia Spillway	45
Caernarvon	81
Davis Pond	108.1
Bonnet Carre Spillway	125
Bonnet Carre Diversion Structure	128
Old River Outflow Channel	310.6

Three existing projects were chosen for further discussion based on available data and are representative of three types of diversion: (i) West Bay Sediment Diversion, (ii) Caernarvon Freshwater Diversion, and (iii) Bayou LaBranche Wetland Creation. Each project utilizes different techniques to create wetlands, and each of these three projects has rigorous documentation of project aspects.

2.3.1 West Bay Sediment Diversion

The West Bay Sediment Diversion project, located at River Mile (RM) 4.7 above Head of Passes on the right descending bank, is an example of an artificial crevasse. The project area, shown in Figure 2.3, is composed of 12% freshwater marsh and tidal flats and 88% open water, for a total of 12,294 acres (4,975 ha) (Carter, 2003).

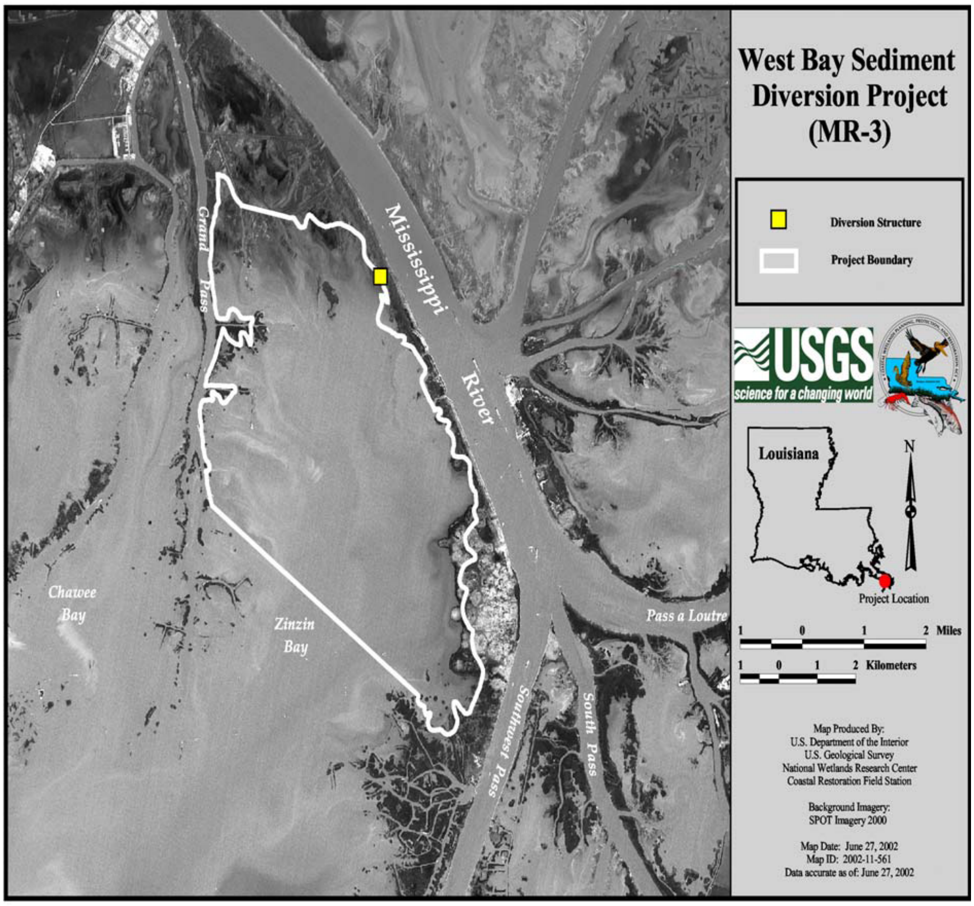


Figure 2.3 Vicinity map of the West Bay Sediment Diversion project is shown

Processes that form land in the lower Mississippi River Delta are important to recognize and to gain some understanding of the spatial and temporal scales of the formation of sub-deltas and crevasse splays. The following explanation is taken from the Louisiana Department of Natural Resources (LDNR) (Carter, 2003) and Andrus (2007). Sub-deltas are smaller versions of the deltaic cycle, reduced both in size and time of formation. Coleman and Gagliano (1964) document that sub-deltas consist of relatively large receiving bays (300 to 400 km^2) with depths of 10 to 15 m. Boyer (1996) suggests that crevasse splays are approximately 0.6 km^2 in extent. In nature, crevasse splays are developed as the natural levee of a major channel is eroded and deliver sediment-rich river flow to adjacent bays. Changing energy to deliver available sediments tends to distribute materials by size; with clays and organic material along the forward periphery of active deposition, followed by silts and colloidal clays that may be colonized by marsh vegetation, and finally by sands that are deposited closest to the crevasse origination (Coleman and Gagliano, 1964; Andrus, 2007). As flow from the crevasse diminishes, the sub-delta ceases to grow and begins to subside. The life cycle of a sub-delta may be tens of years to hundreds of years, depending on the size of the depositional extent. The spatial and temporal scales that are manifest with artificial sub-delta and crevasse-splay development require consideration of time periods beyond accepted engineering perspectives.

Creating artificial crevasses has been documented (LDNR; Carter, 2003) to be successful in creating new wetlands: three crevasses in 1986 (Pass-a-Loutre, South Pass, and Loomis Pass) produced over 266 ha of emergent marsh in 6 yrs; and four crevasses in 1990 (South Pass and Pass-a-Loutre) produced 162 ha of emergent marsh in 3 yrs (LDNR; Carter, 2003; Trepagnier, 1994). Kelley (1996) also documented that the LDNR Small Sediment Diversions project cumulatively produced 127 ha of emergent marsh during the 1986 to 1993 period.

The purpose of the West Bay Sediment Diversion project is to promote the formation of emergent marsh by construction of an artificial crevasse (Carter, 2003). To achieve the initial design discharge, a cut through the levee was dredged that was approximately 25-ft deep and a level section 95-ft wide. Andrus (2007) states that a low weir to enhance deposition, was not constructed and could be added later as the 20,000 cubic feet per second (cfs) discharge of Phase 1 was increased to 50,000 cfs in a later phase. He also alludes to studies by Roberts (1997) concerning wind-driven wave currents that detrimentally affect the deposition efficiency. On the Wax Lake outlet, wind-driven re-suspension of sediment coincides with periods of peak sediment delivery during February through March (Roberts, 1997; Allison *et al.*, 2000; Bentley, 2003).

Andrus (2007) compiled data pertaining to the grain size, volume of depositions, Mississippi River sediment load, and other information. The average median bed-material samples collected were: 0.0088 mm in spring 2004, 0.0096 mm in fall 2004, 0.023 mm in fall 2005 following Hurricane Katrina, and 0.015 mm in spring 2006. All samples were predominantly in the silt range; however, a few sand samples were collected.

Andrus (2007) also compiled discharge and sediment-concentration data for two gauging sites on the Mississippi River, at Tarbert Landing (RM 306.3) and at Belle Chase (RM 76.0). The average annual Mississippi River discharge at Tarbert Landing is shown as Figure 2.4 and sediment concentration for the same period and location is shown in Figure 2.5.

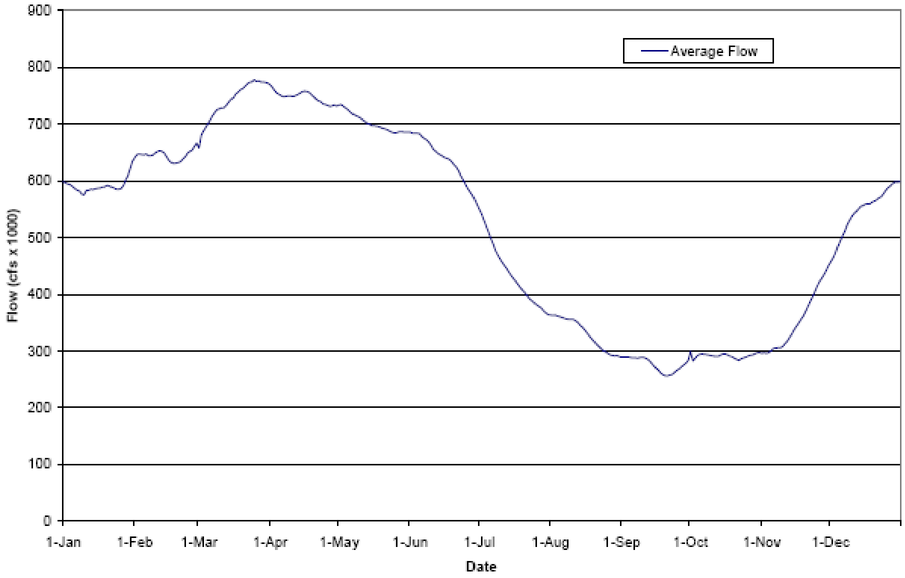


Figure 2.4 The average (1978 to 2006) annual Mississippi River discharge hydrograph at Tarbert Landing is shown (from Andrus (2007))

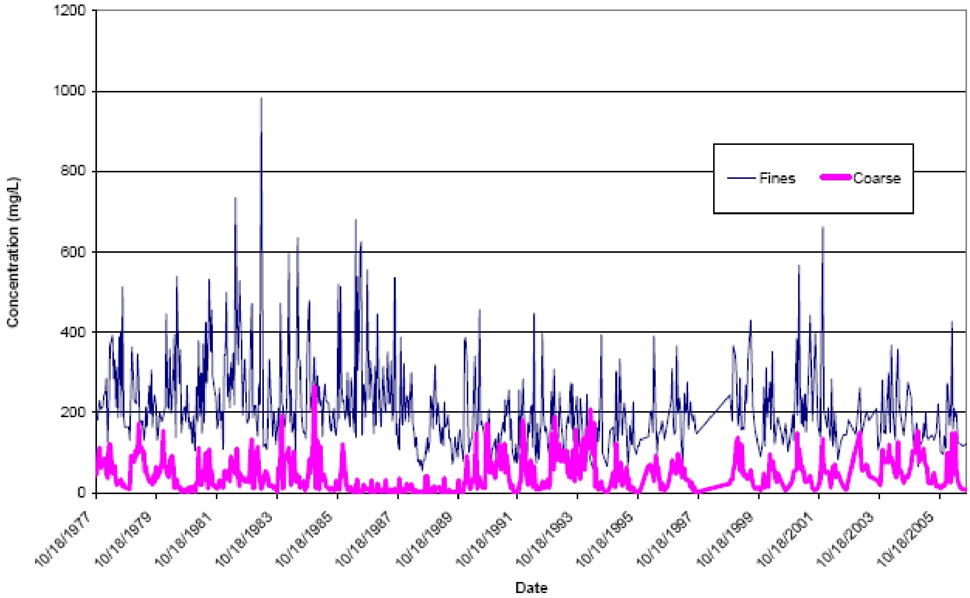


Figure 2.5 The average (1978 to 2006) annual Mississippi River sediment concentration hydrograph is shown for Tarbert Landing – fine particles are smaller than 0.0625 mm

Data from Figures 2.4 and 2.5 were combined by Andrus (2007) into composite annual hydrographs for sediment and discharge, which are shown in Figure 2.6.

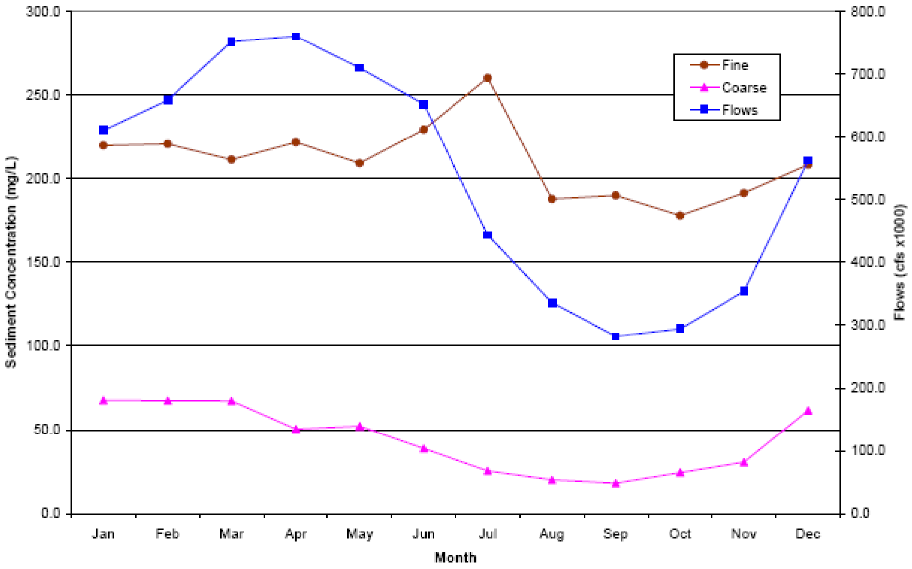


Figure 2.6 Composite annual hydrographs for sediment and discharge at Tarbert Landing are shown

Figures 2.7 and 2.8 are Mississippi River discharge and sediment concentrations, respectively, for the Belle Chase gauge.

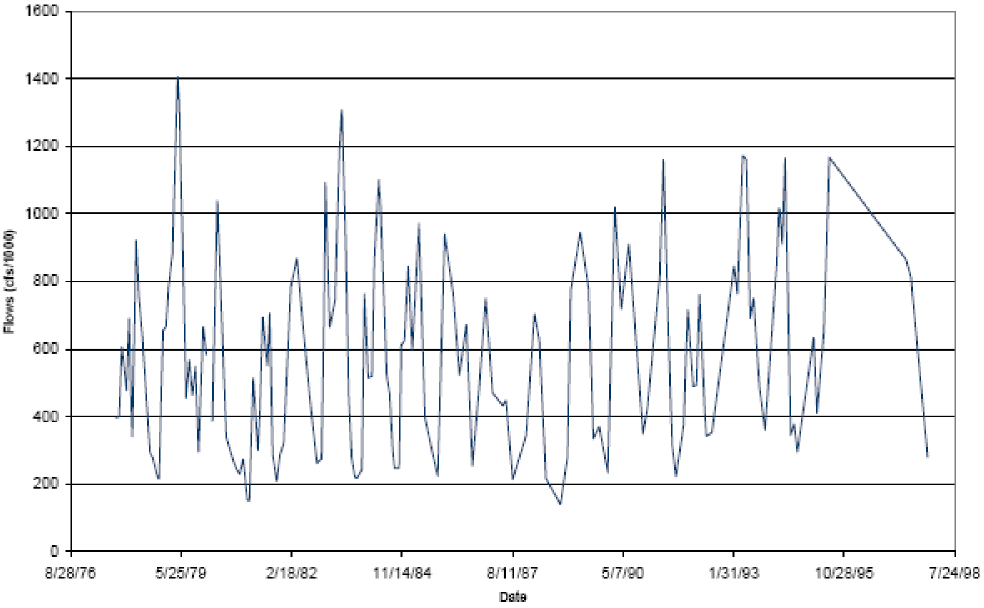


Figure 2.7 The discharge hydrograph for the Belle Chase gauge for the period 1978 to 1998 is shown

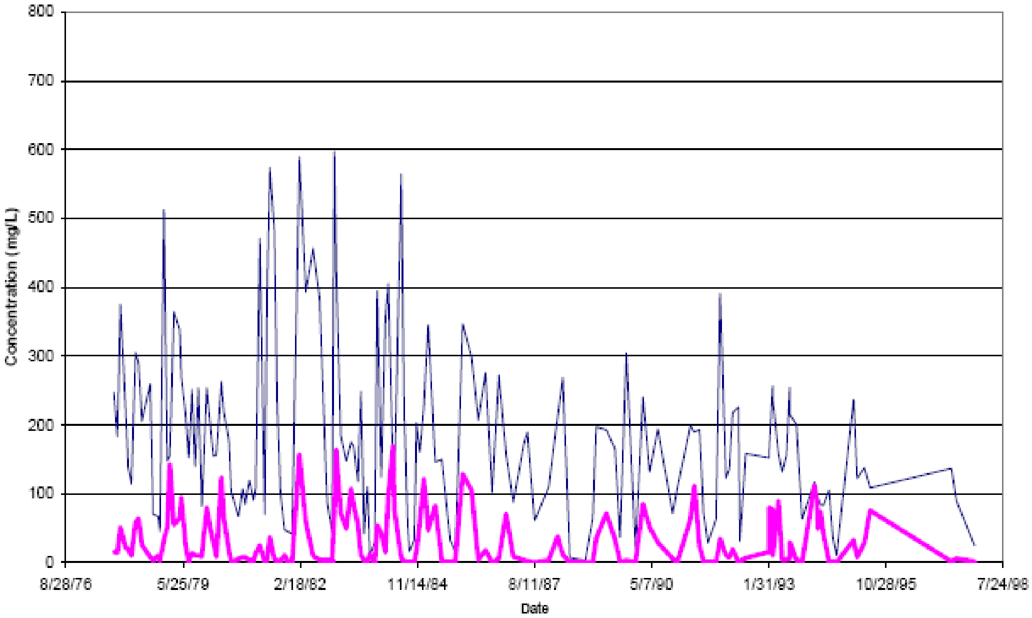


Figure 2.8 Sediment concentration for the Belle Chase gauge is shown – the pink line represents coarse sediments (>0.0625 mm) and the blue line represents fine sediments (<0.0625 mm)

At Tarbert Landing, concentrations of fine sediment average approximately 225 mg/L from January to June, and peak in July slightly in excess of 250 mg/L. From August through November the concentration is less than 200 mg/L. Coarser sediment averages approximately 70 mg/L during peak flows and drop to approximately 35 mg/L for the lower discharges. The sediment concentration of fine material at Belle Chase averages approximately 180 mg/L and ranges from 5 to 600 mg/L, and coarse-material concentration averages 30 mg/L and ranges from 0 to 170 mg/L. Comparison of the Tarbert Landing and Belle Chase data suggests that the fine concentrations are about the same, while the coarse-sediment concentrations are less at Belle Chase.

Figure 2.9 (Andrus, 2007) portrays the relationship between measured Mississippi River discharge measurements and West Bay diversion discharge measurements. Andrus suggests that the points above the line are related to increased conveyance as the diversion becomes more efficient. The point of negative flow (from the West Bay into the river) occurred near a minimum discharge of 100,000 cfs on the Mississippi River. Andrus (2007) reported that the channel formed by the diversion into the bay was deepening, based on repeat surveys.

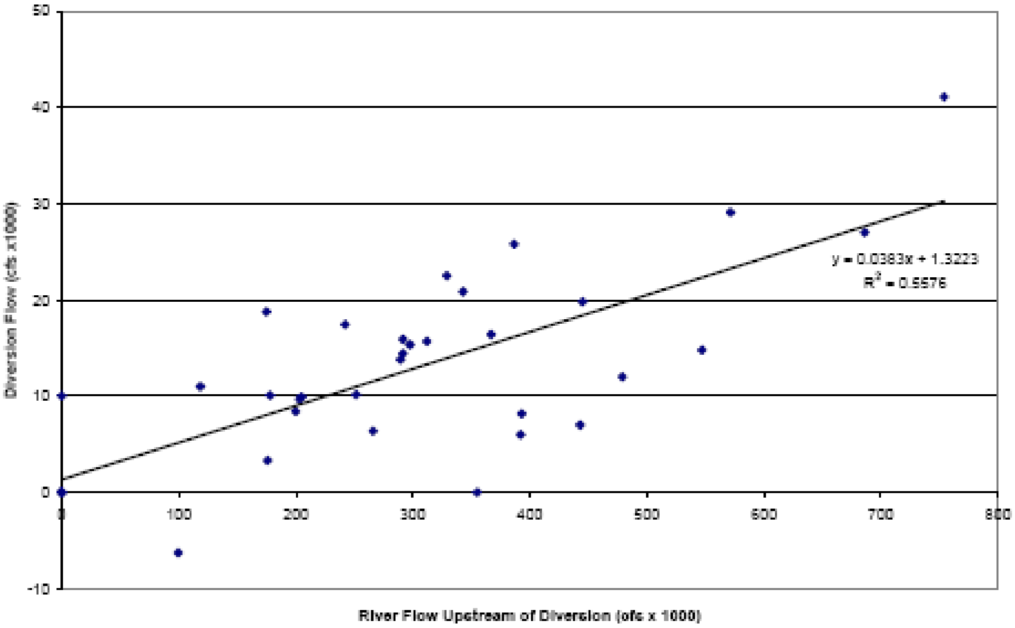


Figure 2.9 Measured Mississippi River and West Bay diversion discharges

Average salinity for the West Bay Diversion was 0.45 parts per thousand (ppt). The estimated monthly sediment discharge into the Diversion is shown in Figure 2.10 (Andrus, 2007). During the period of repeat surveys, Hurricane Katrina occurred and probably caused significant re-suspension of deposited sediment within the Bay; therefore, the net deposition for the period was negative. Andrus (2007) estimated the potential sediment rates (Table 2.4) based on the sediment concentration, the diverted discharge into the Diversion, and on a range of percentage retention. The percentage retention is based on the portion of the sediment supplied that is retained within the constructed site, not on the extent of barriers around the site. For example, only 50% retention of sediment may occur with a complete barrier (100%) around the site because of current and wave action.

The period of maximum sediment diversion can be estimated to be from January through May; however, as shown in Figure 2.10, sediment concentrations may begin to increase in November. Andrus (2007) concludes that engineering strategies should place as much focus on receiving area configuration and trapping efficiency as sediment delivery to maximize sediment retention.

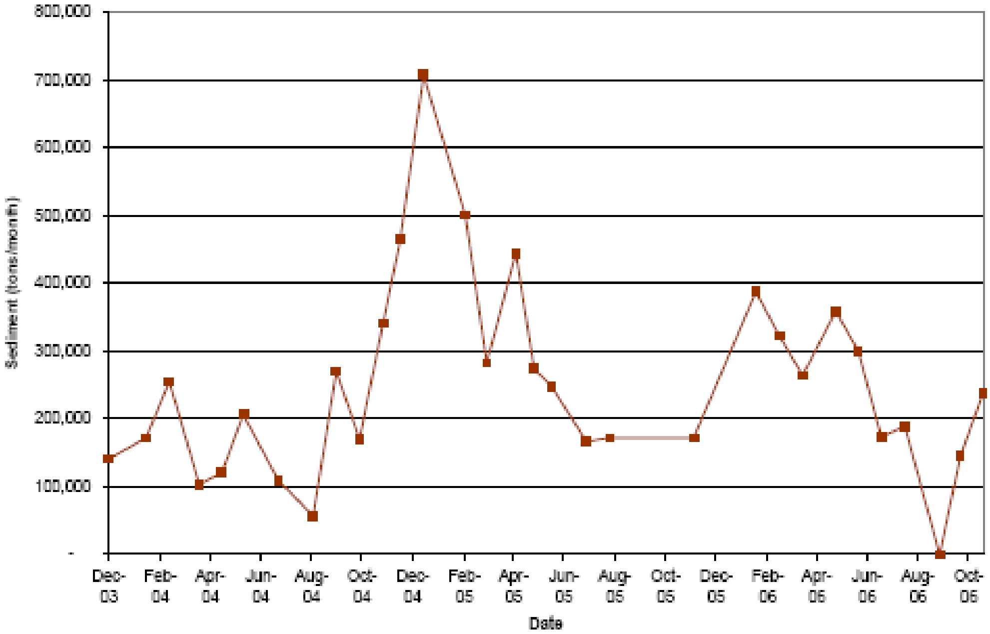


Figure 2.10 Estimated sediment discharge passing through the Diversion (Andrus, 2007)

Table 2.4 Estimated (a) sedimentation concentrations, (b) sediment flux, and (c) rates of sediment deposition (after Andrus (2007))

(a) Sediment concentrations (mg/L)

Location	Maximum	Minimum	Average
Tarbert Landing	992	57	259
Bell Chase	746	3	213
West Bay*	155	53	82

*Values estimated from calibrated turbidity data.

(b) Sediment flux

Range	Date of Occurrence	Diversion Flow (cfs)	Diversion Flow (m^3/s)	Monthly Sediment Flux (tons/mo)	Daily Sediment Flux (tons/day)
Maximum	February 2005	41,100	1,160	1.33×10^0	44,300
Average	January 2004 - November 2006	13,800	390	0.24×10^0	8,050
Minimum	September 2004*	3,310	94	0.04×10^0	1,250

*Date of lowest observed positive flow (river to bay). A negative flow (bay to river) was observed in September 2006.

(c) Rates of sediment deposition

% Retention	Inches per Year		Centimeters per Year		Centimeters per Month if Deposited over 6 Months	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
25%	0.5	1.0	1.3	2.4	0.22	0.40
50%	1.1	1.9	2.7	4.8	0.45	0.81
75%	1.6	2.9	4.0	7	0.67	1.21
100%	2.1	3.8	5.4	10	0.90	1.61

2.3.2 Caernarvon Freshwater Diversion

Upstream from the West Bay Sediment Diversion is the Caernarvon Freshwater Diversion (left bank, RM 81.0). Mississippi River water is diverted into the Breton Sound estuary through gated, box culverts, and as opposed to the free discharge at West Bay, the Caernarvon Freshwater Diversion is a controlled outlet. Snedden (2007) states that flow through the open gates can occur as the stage at Carrollton exceeds about 1.2 m North American Vertical Datum (NAVD) 88, and is designed to discharge up to 225 $m^3 s^{-1}$ of Mississippi River water. He reports (Figure 2.11) that the average monthly suspended-sediment (TSS) concentration of the surface river water varies from 15 mg/L in September to 130 mg/L in February. The sediment-rating curve is shown in Figure 2.12. Grain-size data collected by Snedden (2007) in 2003 showed a particle size distribution of 63% silt, 36% clay, and 1% sand.

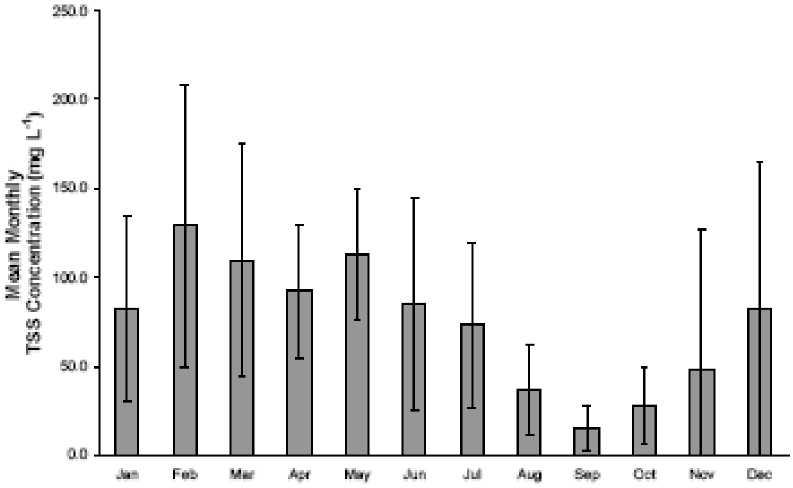


Figure 2.11 Mean monthly TSS concentrations of Mississippi River surface water at Belle Chase, from 1991 to 2004 – error bars extend a standard deviation (Std Dev) of the monthly mean value (Snedden, 2007)

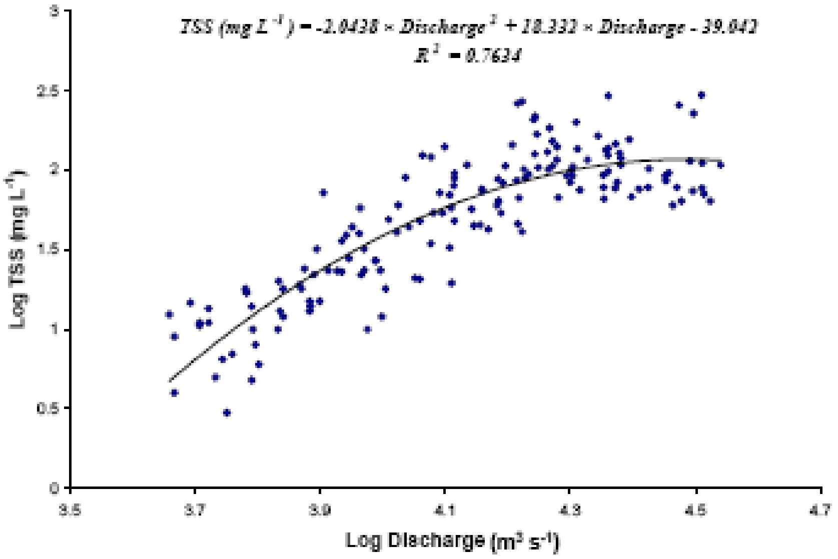


Figure 2.12 The relationship between TSS at Belle Chase and discharge for 158 measurements is shown (Snedden, 2007)

During 2002 and 2003, Caernarvon was operated in a series of four pulses to determine the response of the estuary to large discharges of Mississippi River water. Table 2.5 provides summary data for the four pulsed diversion events. Snedden (2007) provided the data.

Table 2.5 Summary data for four pulsed Caernarvon Freshwater Diversion events

Event	Date	Average Diversion Discharge (m^3/s^{-1})	Duration (day)	Average River Discharge (m^3/s^{-1})	Average TSS (mg/L^{-1})	Total Sediment Delivery (metric tons)	Metric tons day^{-1}
Pulse 1	28 Jan – 11 Feb 2002	180	14	2.04×10^4	143	3.02×10^4	2.16×10^3
Pulse 2	04 Mar – 17 Mar 2002	166	14	1.22×10^4	57	1.13×10^4	0.81×10^3
Pulse 3	18 Feb – 03 Mar 2003	195	13	1.97×10^4	197	4.38×10^4	3.29×10^3
Pulse 4	17 Mar – 31 Mar 2003	193	15	2.01×10^4	101	2.46×10^4	1.64×10^3
Mean		184	14	1.81×10^4	125	2.75×10^4	1.98×10^3

In Table 2.6, Snedden (2007) compares the sediment deposition measured as a result of the 1927 Caernarvon Crevasse, the observed deposition following the four pulses, and the maximum deposition if the Caernarvon diversion were operated to maximize sediment. He states that even if all the sediment from the four pulses were confined to the upper estuary, the loading rates would be insufficient to offset RSLR, estimated to be 2.8 to 3.8 mm/yr (sea-level rise of 1 to 2 mm/yr (Intergovernmental Panel on Climate Change (IPCC), 2001); subsidence of 1.8 mm/yr (CWPPRA, 2002)). Operating the diversion structure to maximize sediment diversion would exceed RSLR.

Table 2.6 Sediment delivery and deposition for Caernarvon (Snedden, 2007)

Event	Date	Area (km^2)	Sediment Yield ($\times 10^6$ m^3)	Deposition (mm)
Caernarvon Crevasse	1927	226	20	89
Caernarvon Observed	2002-2003	57	0.07	1.3
Caernarvon Maximum		57	0.32	5.6

DeLaune *et al.* (2003) reported that Louisiana coastal marshes represent a thin veneer of primarily organic soil material supporting vegetative growth overlying previously deposited mineral sediment.

Figure 2.13 is taken from DeLaune *et al.* (2003), and shows the location of twenty marsh sites downstream of the Caernarvon Freshwater Diversion.

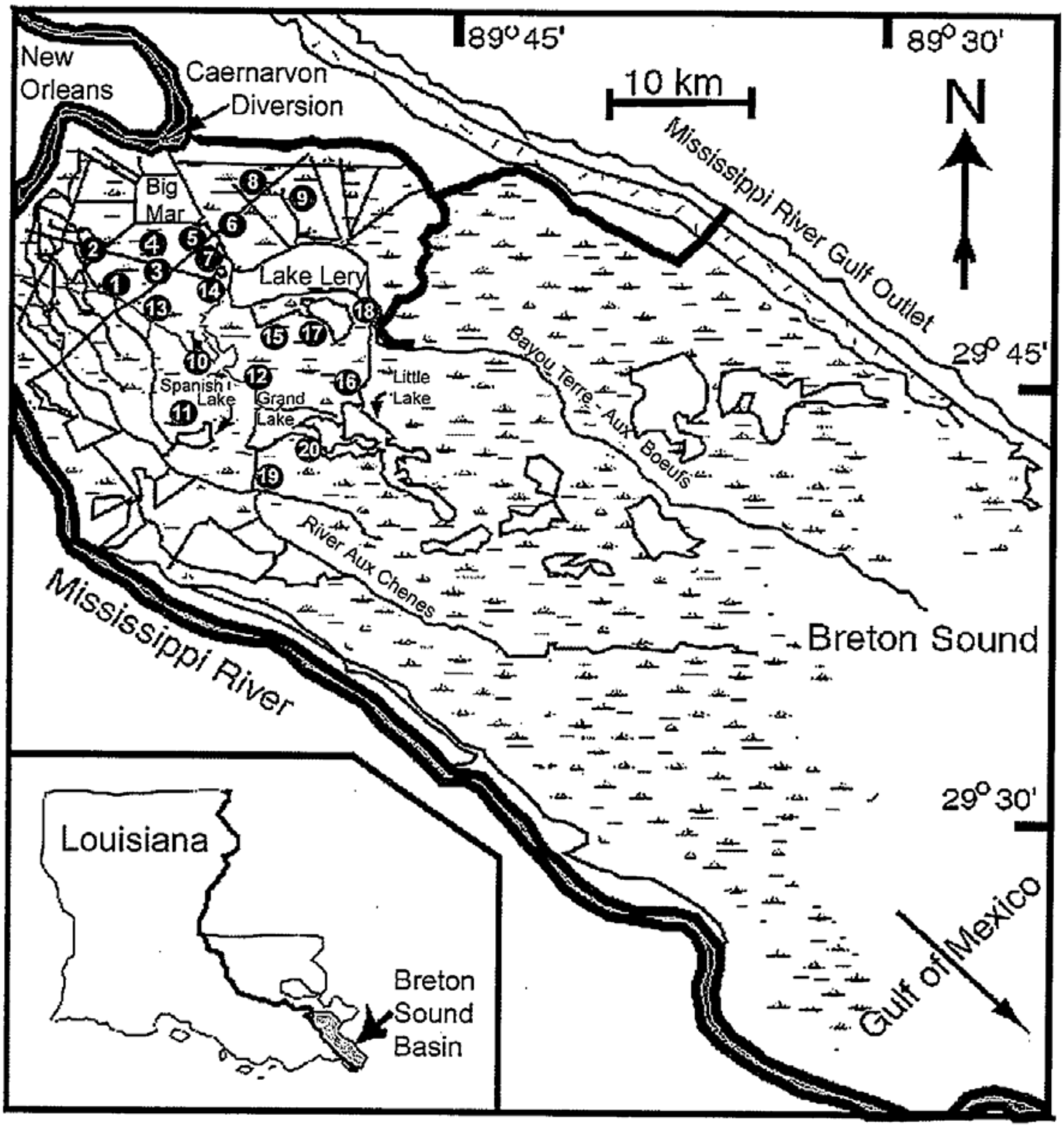


Figure 2.13 The Caernarvon Diversion and Breton Sound estuary are shown, along with twenty sample sites utilized by DeLaune *et al.* (2003) – notice the first ten sites are nearer the point of freshwater diversion

Their results show that vertical accretion rates average 1.72 cm/yr for the nearer sites (Sites 1 to 10) compared with 1.34 cm/yr for Sites 11 to 20. Bulk density is greater for the nearer sites, with greater mineral and organic content in Sites 1 to 10. The paper provides significant quantitative data to document the results.

2.3.3 Bayou LaBranche Wetland Creation

The Bayou LaBranche project is on Lake Pontchartrain, located approximately 3 mi north of Norco, Louisiana (St. Charles Parish), and is bounded on the south by U.S. Interstate 10 and on the north by Lake Pontchartrain. Figure 2.14 is based on an aerial photograph and shows the project area.

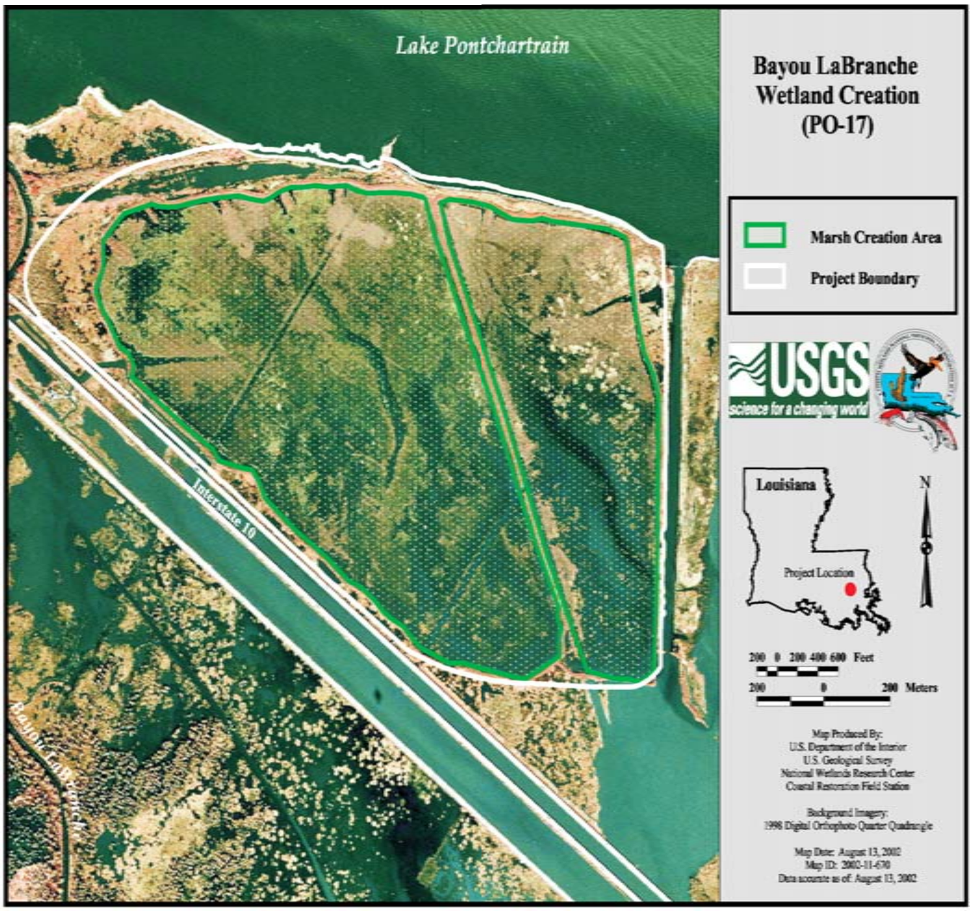


Figure 2.14 The Bayou LaBranche project is shown in the aerial photograph (from Louisiana Coastal Wetlands Conservation and Restoration Task Force (2002))

The primary cause of wetland loss in the area was the failure of agricultural impoundments and subsequent intrusion of salt water into the area. The general restoration strategy was to create an area of 70% land and 30% water within a period of 5 yrs following construction. A new emergent marsh was created in a 435-acre (174-ha) location that previously was open water by depositing 2.7 million cu yds of dredged sediment from Lake Pontchartrain. An earthen containment berm was constructed to protect the emergent marsh and to contain the deposited material. The construction was completed in 1994 (*Bayou LaBranche Fact Sheet*; Louisiana Coastal Wetlands Conservation and Restoration Task Force (2002); www.LaCoast.gov).

Boshart (2003) documented the evolution of the deposited material for the period 1994 to 2002. Results at the constructed site were compared with an adjacent wetland, as shown in Figure 2.15.

Figure 2.15 The proposed construction is shown on the left and the existing wetland (reference area) is shown on the right in this figure

The following figures provide information pertaining to the change in sediment elevation, percentage organic matter, bulk density, and percentage of moisture. The average salinity for the project area (5.3 ppt) was greater than the reference-area salinity (4.6 ppt). Boshart (2003) attributed the difference in salinity to the impoundment of the project area that caused less flushing and increased concentration of salt due to evaporation. Sediment elevation decreased (Figure 2.16) as organic matter increased (Figure 2.17), and as bulk density decreased (Figure 2.18).

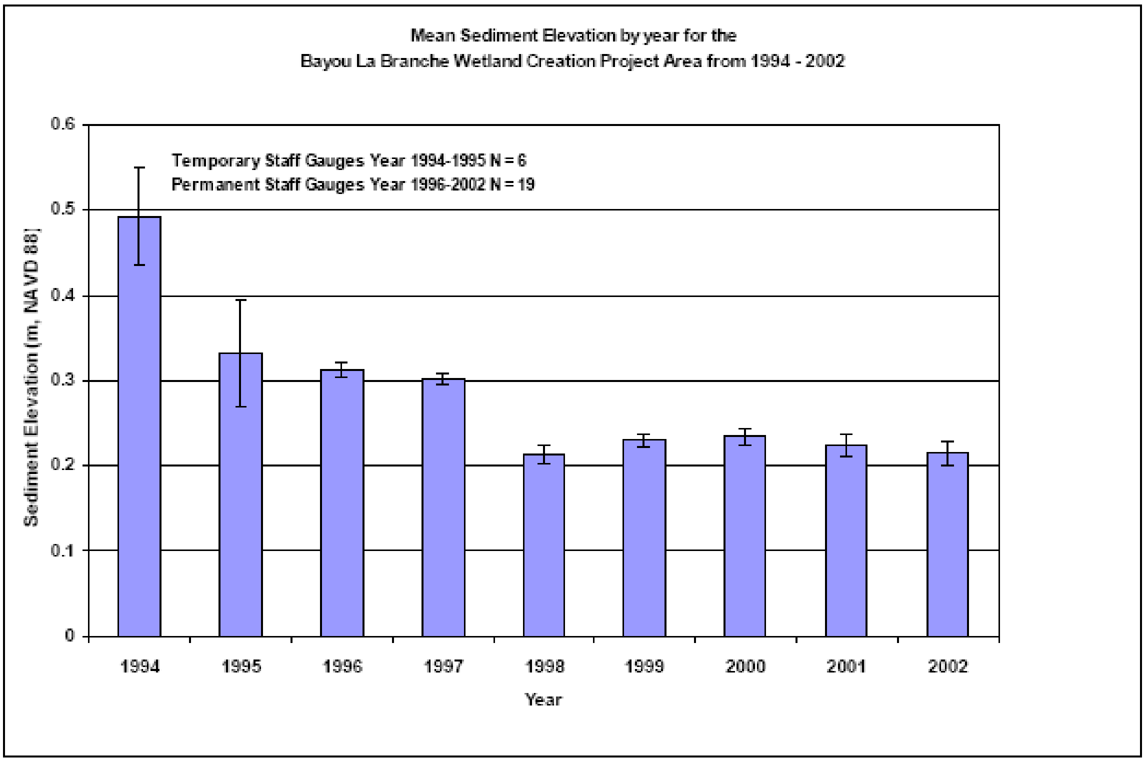


Figure 2.16 The mean sediment elevation in the project area exhibits a decreasing trend during the period of measurement

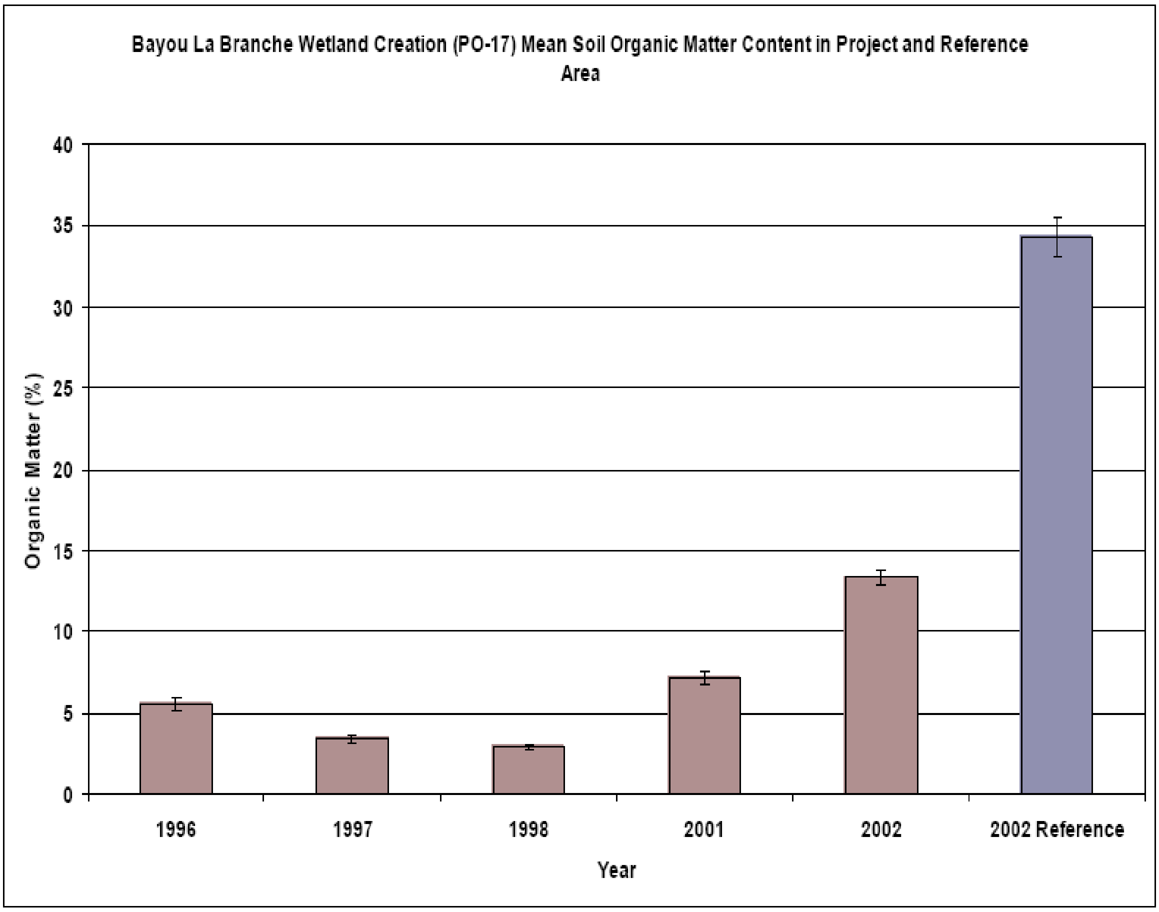


Figure 2.17 The percentage of organic matter increased through time and was significantly less than the percentage organic matter in the reference area

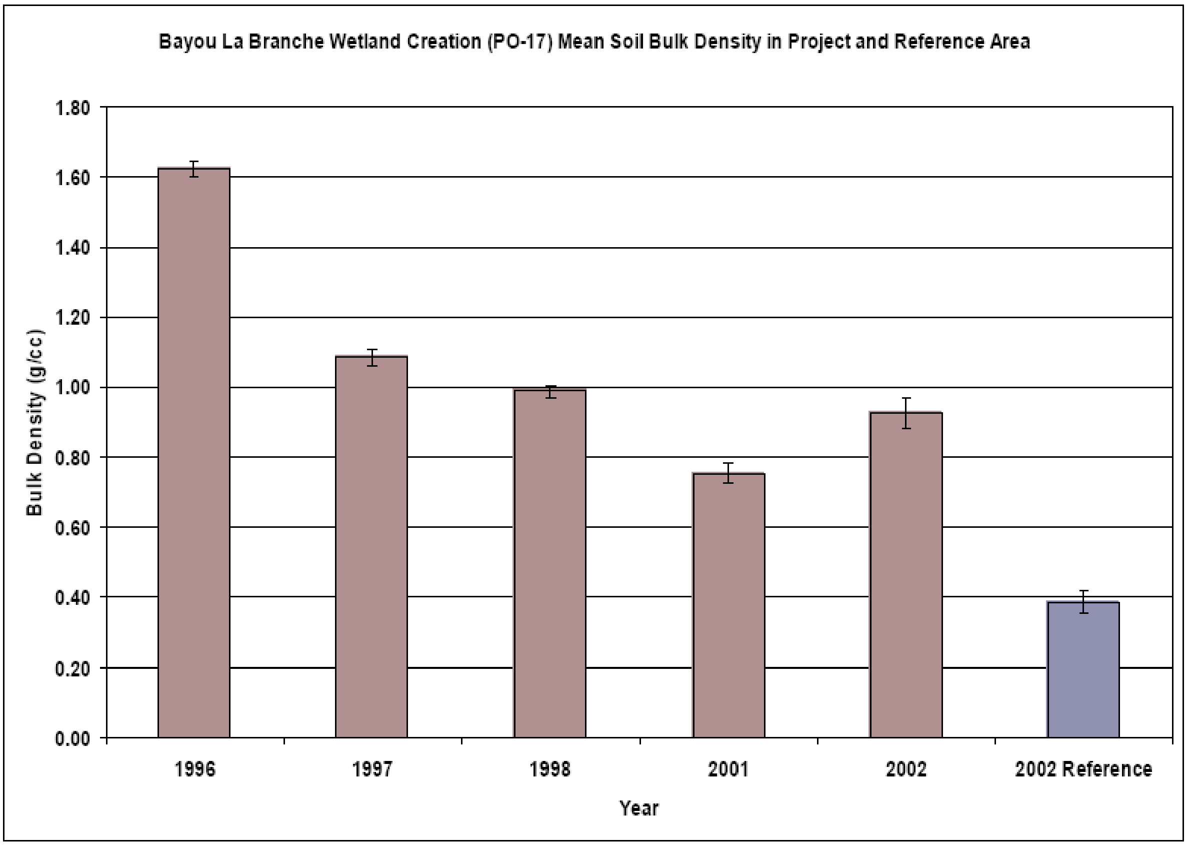


Figure 2.18 The trend in the project area is to decrease bulk density, and move toward the reference-area condition

3 Estimates of Sediment Resources Required for Marsh Restoration in Coastal Louisiana

The purpose of this effort is to present a reasonable likely range of sediment quantities required for marsh creation in coastal Louisiana using either: (i) mechanical placement of dredged material, or (ii) freshwater diversions. In the latter case, benefits from nutrients are included in the assessment.

3.1 Mechanical placement of dredged material

The amount of sediment contained within a 1-km^2 marsh is a function of the marsh height and the sediment bulk density. Marsh height varies directly with depth, of course, but the top elevation of marshes also varies. For the computations herein, it is assumed that the marsh elevation is 1 ft above mean sea level.

Bulk density is also highly variable, but is known to be a function of depth and salinity. Data summarized by Boustany (2007) suggest that estimates for upper-horizon (top 50 cm) bulk densities (ρ_i) for fresh/intermediate marshes are about 0.1 g/cm^3, and about 0.2 g/cm^3 for brackish/saline marshes. Below this horizon, a linear increase in bulk density at a rate of 0.6 g/cm^3/m was assumed; yielding the following depth-averaged bulk densities (a fresh or intermediate marsh was assumed). Representative values of bulk density for fresh and brackish marshes are shown in Table 3.1 (personal communication, Fischenich (2008)).

Table 3.1 Representative values of bulk density, weight, and volume for fresh and brackish mature marsh are shown

Depth (ft)	Bulk density (g/cm^3)		Weight (T/km^2)		Volume (cu yds/acre)
	Fresh/ Intermediate	Brackish/ Saline	Fresh/ Intermediate	Brackish/ Saline	
0.5	0.1	0.2	50,400	100,800	1,415
3	0.16	0.26	215,000	349,400	3,772
6	0.39	0.49	917,300	1,152,500	6,602

For the indicated depths, allowing for 1 ft above mean sea level as a finish grade, and using the indicated bulk densities, the quantities of sediment found within a 1.0-km^2 marsh are shown in Table 3.1. The limited available data on sediment bulk densities suggest that this factor can vary by 25%, which provides some notion of the uncertainty to be attributed to the values in Table 3.1.

The right column in Table 3.1 shows the volume of sediment required, and for typical depths the volume ranges from 1,415 cu yds/acre to 6,602 yds/acre. Previous experience by the U.S. Army Corps of Engineers (USACE), New Orleans District, indicates that approximately 4,000 cu yds of dredge material per acre of newly created wetland is required (Barras *et al.*, 2004). Using the data in Table 3.1, the District average agrees with placement in approximately 3 ft of depth. In comparison, the Bayou LaBranche site required 4,345 cu yds of dredge material to create emergent marsh.

The quantities in Table 3.1 reflect the quantity of sediment within a mature marsh. The actual amount of material required to construct the marsh may be considerably greater than this value. Additional material may be needed to account for poor retention during placement and for vertical marsh adjustment. Retention of sediments for open-water placement is generally quite poor; on the order of 40 to 50% for placement in 3 ft of water. For this reason, marsh is typically constructed within a contained dike system. The marsh is initially constructed at the construction grade, which is higher than the design grade to allow for initial consolidation and dewatering of the hydraulic fill. Constructed marshes are subject to three modes of vertical adjustment:

1. consolidation, as the hydraulic fill placed in the marsh dewaters (1 to 12 mo);

2. subgrade compression and settlement due to the overburden of placed material (estimated at 15% of consolidated overburden thickness; 1 to 5 yrs); and

3. RSLR, which consists of eustatic sea-level rise and regional land subsidence rates.

Factors 1. and 2. are accounted for with the bulk-density estimates. RSLR is not accounted for, however, and the effective life of constructed marshes can be quite low (10 to 20 yrs) where RSLR is high, suggesting the need for a continuing river water supply to flow through these sites to enhance organic accumulation (personal communication, Fischenich (2008)).

Figures 2.16, 2.17, and 2.18 presented data from the Bayou LaBranche dredge deposition project. Through time (1994 to 2004), sediment elevation decreased, percentage organic material increased, and bulk density decreased. Deposition of the Bayou LaBranche material was made within a confining dike. Analysis of the fill material (*e.g.*, settling column tests) can refine estimate consolidation during planning and design.

The New Orleans District, USACE, operation and maintenance dredging program dredges an annual average of 70 million cu yds (53.6 million m^3). During 2004, approximately 14.5 million cu yds (11.1 million m^3) was being utilized beneficially for the surrounding environment. At that time, the District proposed to use 30 million cu yds (23 million m^3) of an average annual 70 million cu yds for beneficial use. Therefore, a total of 44.5 million cu yds (14.5 million cu yds existing plus the additional 30 million cu yds) was reasonably available for beneficial use, which is 64% of the annual average dredge volume. The District qualified this proposal by stating that a portion of the total volume was unavailable for beneficial use because some of the material is re-suspended from upstream maintenance (Barras *et al.*, 2004).

It is important to review the dredging records to investigate any trends in the total dredging volume available and to get some idea of the location of the sediment stream. Figure 3.1 illustrates the variability of the total dredge volume of the New Orleans District. Dredging records were furnished by the New Orleans District Operations Section, and each year the volume shown is the total of several sources, including the Mississippi River, Atchafalaya River, Calcasieu River, Mississippi River Gulf Outlet (MRGO), Gulf Intracoastal Waterway (GIWW), Old River Control, and numerous other projects. The average annual dredging for the period 1970 through 2006 is 79.3 million cu yds (61 million m^3), which compares closely with the 70 million cu yds previously attributed to the New Orleans District in the LCA (Barras *et al.*, 2004). Variation in dredging quantities from year-to-year is dependent on the annual volume of river discharge, the shape of the hydrograph, project goals for the year, and other factors.

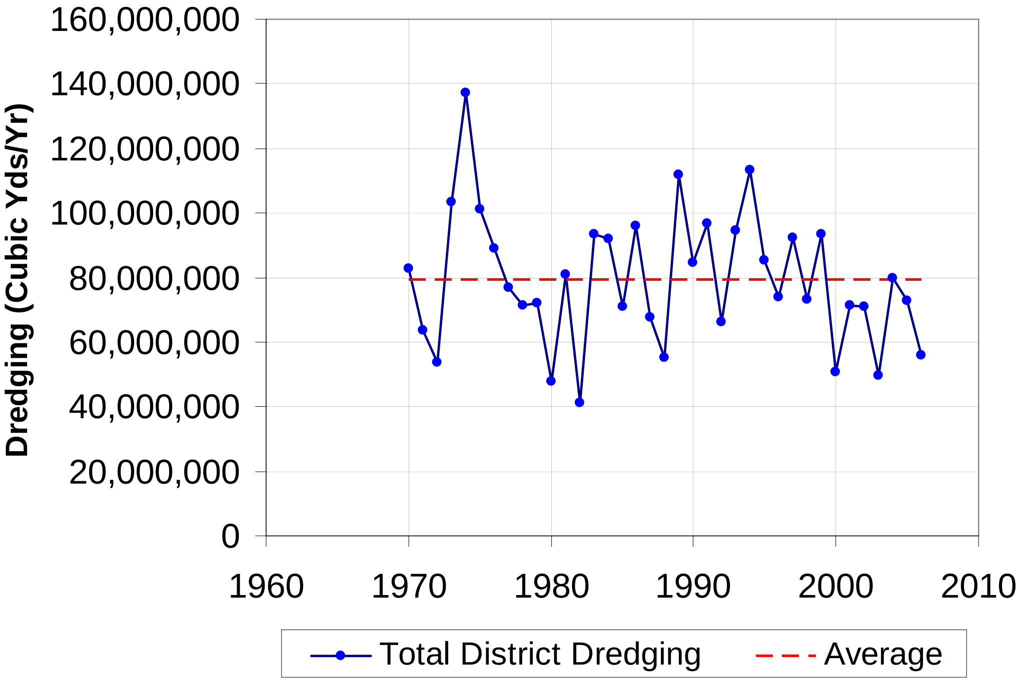


Figure 3.1 The total volume of dredging occurring in each year for the New Orleans District is shown

Figure 3.2 shows primary sources of dredge material from the Mississippi River, the data having been extracted from the same source as Figure 3.1. The total average annual dredge volume from the sources shown in the legend of Figure 3.2 is 36.6 million cu yds (28.2 million m^3). Comparison of the data in Figures 3.1 and 3.2 suggests that efficient use of the dredge-material resource would be affected by project availability to the dredge site.

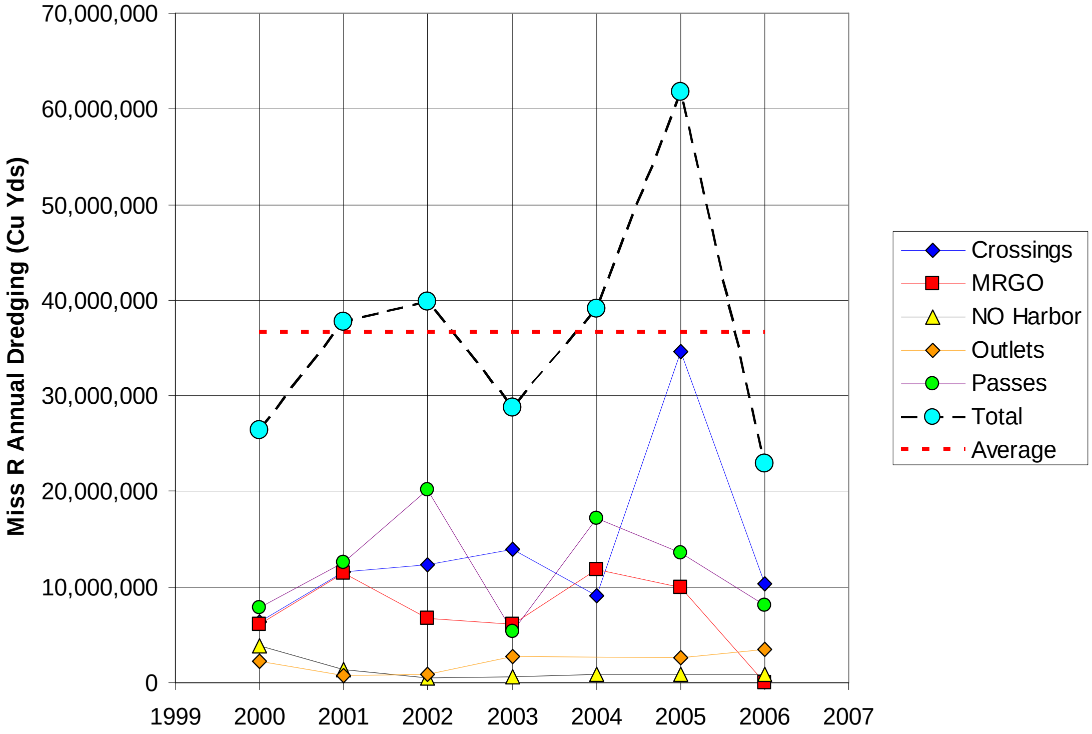


Figure 3.2 Annual average dredge volumes from several sources along the Mississippi River are shown

Using the percentage of annual average dredging reported by the District (64%) and the annual average from Figure 3.2 (79.3 million cu yds [61 million m^3]), 50.7 million cu yds could be available for beneficial use. The District experience (Barras *et al.*, 2004) suggests that on average, an acre of coastal land created requires 4,000 cu yds, which yields 12,667 acres (19.8 sq mi [51.3 km^2]), assuming no loss of sediment in placement. Using the data in Table 3.1, at a depth of 0.5 ft the area created could be 35,830 acres, at a depth of 3 ft the area could be 13,341 acres, and at a depth of 6 ft the area could be 7,679 acres. As previously stated, the long-term sustainability of dredge-material placement is dependent on continued river water and sediment flow into the marsh for organic material accumulation to offset RSLR. The logistics and administrative challenges to arrange placement of the dredge-material resource at the disposal site would be significant. When new land is created with dredged materials, an additional 10% of material is needed to account for losses when placement is within a confined area.

The amount of sediment needed to create marsh is a function principally of: (i) the marsh depth/height, (ii) the bulk density of the sediments, and (iii) the efficiency of the methods used to create the marsh. The amount of material in a marsh is a function of only the first two factors, depth and bulk density. The amount of material needed is roughly double if an open-water placement strategy is used, depending upon the water depth and tidal velocity.

Marshes created with dredged material alone may succumb to RSLR in a short period (decades). In contrast, the continued supply of sediments and nutrients from diversions may sustain the marsh if flow volumes are sufficient.

3.2 Freshwater diversions

Marsh can be created using freshwater diversions, wherein the sediments and nutrients of the diverted water contribute to both marsh creation and sustainability. To assess the potential for marsh creation using freshwater diversions, a desktop model developed for the Louisiana Coastal Protection and Restoration (LaCPR) Program (McKay *et al.*, 2008) was used to simulate marsh creation at the Caernarvon Diversion. Their program was based on the Boustany (2007) composite nutrient and sediment model and to demonstrate the utility of their program, a simulation was made using the diversion and river hydrographs (Figure 3.3) of 1994, which was chosen as an approximate average year.

Figure 3.4 was taken from McKay *et al.* (2008) and shows observed values of marsh area, and estimates of marsh area using the Boustany (2007) model and the McKay *et al.* (2008) model. The estimated future without project (FWOP) is shown as the solid red line. Comparison of the Boustany (2007) model and the McKay *et al.* (2008) model indicated the value of the Caernarvon Diversion in reducing the rate of land loss. However, with all three trend lines sloping downward, it is clear that changes to the 1994 operation strategies are necessary to produce an increasing land area or a flat trend of no loss.

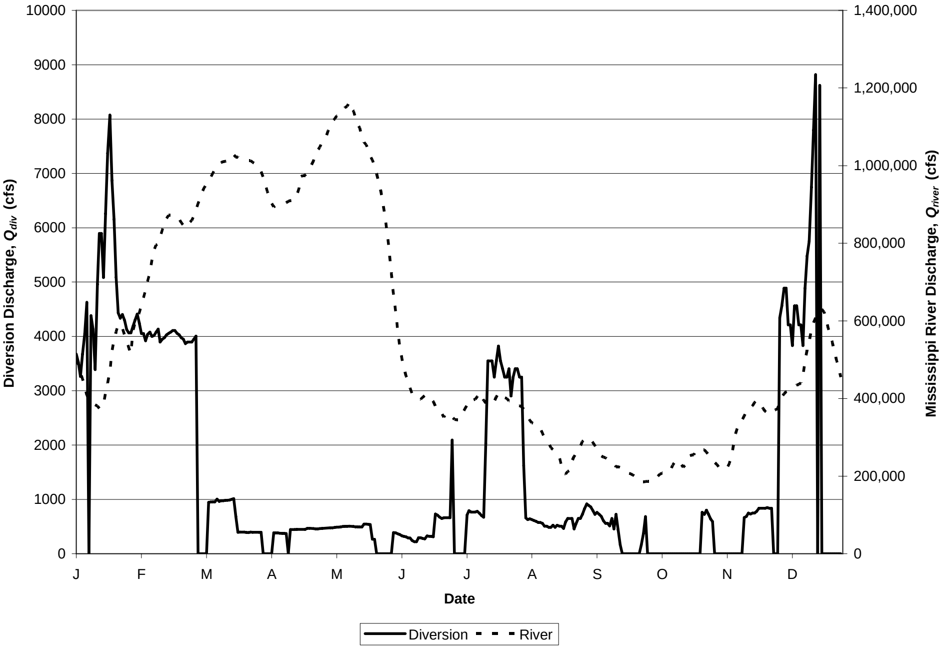


Figure 3.3 The diversion and Mississippi River hydrographs for 1994 are shown (from McKay *et al.* (2008))

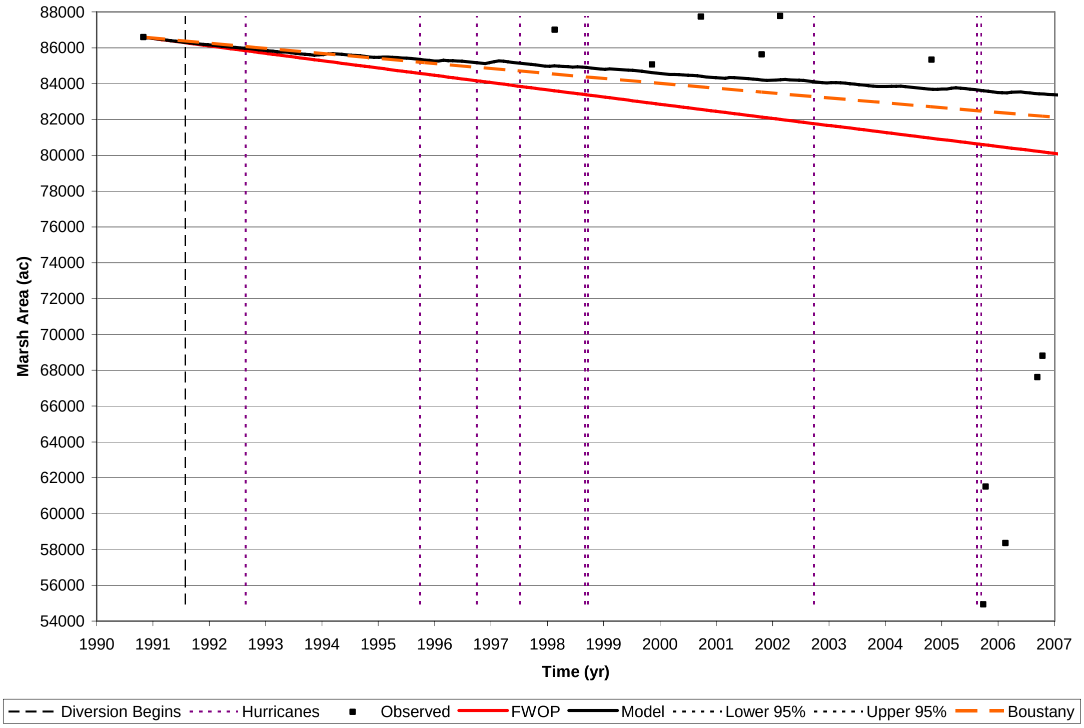


Figure 3.4 Trend lines of the FWOP, Boustany (2007) model and McKay *et al.* (2008) model; and observed data and hurricane occurrences (from McKay *et al.* (2008)) – the upper and lower 95% trends are not shown

Previous studies have shown that the operations of Caernarvon, while typical, are also highly inefficient in terms of marsh creation (Snedden, 2007; McKay *et al.*, 2008). Snedden (2007) showed that most of the flow of water and sediment from the river circumvents the marsh and flows down the marsh through two major routes at flows less than 3,500 cfs, and only when flows exceed 3,500 cfs do nutrients and sediment flow in sheet flow to the active marsh. Large pulses, as suggested by Day *et al.* (1995), not only provide discharges above the threshold, but also carry greater concentrations of sediment. McKay *et al.* (2008) have demonstrated that the same volume of water withdrawn at different times (to coincide with high river discharges) or from lower in the water column (with siphons, for example), would yield much higher sediment acreages in a given year. A Monte Carlo analysis of parametric uncertainty (Table 3.2) for marsh creation using freshwater diversions, while maintaining a constant depth indicated that uncertainty grows over time as shown in Figure 3.5 (McKay *et al.*, 2008).

Table 3.2 The range of model variables used in the Monte Carlo simulation is shown (after McKay *et al.* (2008))

Values Implemented	Max	Min	Mean	Std Dev		Best Guess	Range
Plant Productivity Rate, P_r (g/m^2y^1)	4500	1500	3000	500		3000	±50%
% Retention	0.75	0.25	0.5	0.083333		0.5	±50%
Percent of N and P in Plant Biomass, $\%_{TNP}$	0.0102	0.0034	0.0068	0.001133		0.0068	±50%
Background Conc. of N and P, $TNP_{background}$ (mg/L)			0.35	0.08		0.35	±0.08, data
Source Conc. of N and P, TNP_{source} (mg/L)			2	0.22		2	±0.22, data
Land Loss Rate	-0.0066	-0.0022	-0.0044	-0.00073		-0.0044	±50%
Average Water Depth, H (ft)	3.3	2.7	3	0.1		3	±10%
Average Water Width, B (ft)	69521	49521	59521	3333.333		59521	±10,000 ft
Roughness Height, z_0 (m)	0.0015	0.0005	0.001	0.000167		0.001	±50%
Maximum Tidal Velocity, $U_{tide,max}$ (ft/s)	0.9	0.3	0.6	0.1		0.6	±50%
Coefficient	0.01635	0.00545	0.0109	0.001817		0.0109	±50%, sediment data
Exponent	do not vary					1.2297	do not vary
Upper Horizon Bulk Density (g cm^{-3})			0.1	0.044			data
Slope	0.8	0.4	0.6	0.066667			±0.2
f fine sand	0.015	0.005	0.01	0.001667		0.01	±50%
f silt	0.945	0.315	0.63	0.105		0.63	±50%
f clay	1-fsand-fsilt						
f flocs	0.7	0.3	0.5	0.066667		0.5	±0.2
Ws fine sand	0.0125	0.0075	0.01	0.000833		0.01	±25%
Ws silt	0.000375	0.000225	0.0003	0.000025		0.0003	±25%
Ws clay	8.75E-06	5.25E-06	0.000007	5.83E-07		0.000007	±25%
Ws flocs	0.00025	0.00015	0.0002	1.67E-05		0.0002	±25%
Assumed (Max - Mean)/3 = Std Dev							

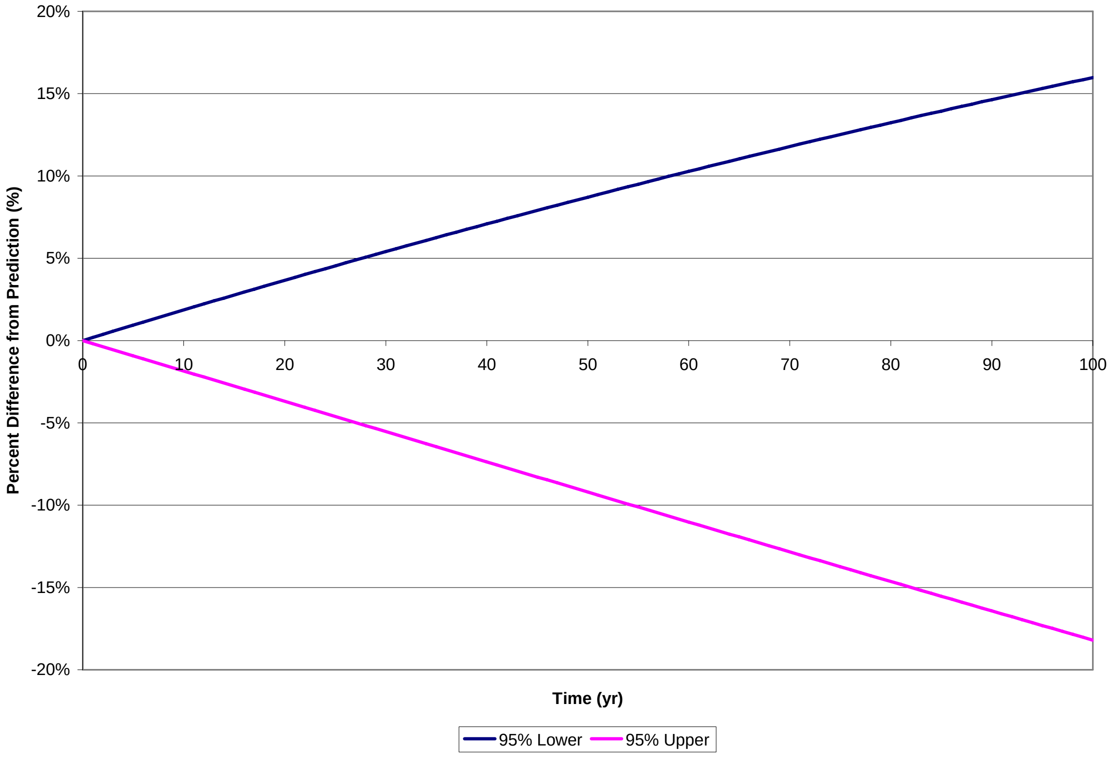


Figure 3.5 Results of the Monte Carlo simulation by McKay *et al.* (2008) indicate the extreme variation possible over extended time periods

A desktop model assessment of the Caernarvon Diversion was undertaken to assess the variability in marsh formation as a function of depth and tidal velocity, and to establish estimates of freshwater diversion quantities for marsh restoration. The model analysis (Table 3.3) showed depth to be the more significant factor. Using the 1994 operational hydrograph for Caernarvon and the river discharge hydrograph for that same year, roughly twice the time is needed to create 247.1 acres [1 km^2] of wetland in 3 ft of water than is needed for this same acreage in 0.5 ft of water. The time to create this acreage of wetland in 6 ft of water relative to 0.5 ft of water is a factor of three to four (personal communication, Fischenich (2008)).

Table 3.3 The results from modeling of the Caernarvon Diversion using 1994 operational hydrograph are shown

Run No.	Variables		Annual Output			No. Days for 247.1 Acres
	Depth (ft)	Tidal Velocity (ft/s)	Nutrient (acres)	Sediment (acres)	Total (acres)	
1	0.5	0.1	24.7	135	159.7	565
2	0.5	0.6	24.7	134.8	159.5	565
3	3	0.1	24.7	65.8	90.5	997
4	3	0.6	24.7	48	72.7	1241
5	6	0.1	24.7	16.9	41.6	2168
6	6	0.6	24.7	12.1	36.9	2444

For the model simulations, 1994 diversion and river hydrographs were used as this year was very near average in terms of annual discharge volumes, and the peak magnitudes were well represented. Other model parameters are summarized in Table 3.4.

Table 3.4 Model parameters employed for freshwater diversion simulations

Parameter	Best Estimate
Initial Land Area (acre)	0
Project Area (acre)	247.1 acre [1 km^2]
Average Water Depth, H (ft)	0.5, 3, 6 ft
Average Water Width, B (ft)	3,280 ft [1 km]
Maximum Tidal Velocity, $U_{tide\ max}$ (ft/s)	0.1, 0.6
Roughness Height, z_0 (ft)	0.005
Land-loss Rate (%/yr)	0.48
Bulk Density (g/cm^3)	0.1 (upper 50 cm)
Plant Productivity Rate (g/m^2/yr)	7,300
TNP Background (mg/L)	0.35
TNP Source (mg/L)	2.0
Nutrient Retention (%)	50
Percent of N and P in Plant Biomass (%TNP)	72

Model results show that for the designated area and hydrographs, 24.7 acres of wetland are created annually solely from the nutrients in the diverted water. The remainder, which varies from 12 to 135 acres/yr, is due to the sediments. The sediment-rating curve for Belle Chase was used to assess sediment delivery as a function of river discharge. Grain-size distribution was 36% clay, 63% silt, and 1% fine sand. It was further assumed that half of the clay fraction consisted of flocs. Sediment retention varied from 29 to 63% (personal communication, Fischenich (2008)).

4 Conclusions

Day *et al.* (2007) point out four general approaches to Louisiana coastal land restoration:

1. use dredged sediments to create and restore wetlands;
2. reconnect the river to the deltaic plain by river diversions;
3. restore barrier islands; and
4. restore hydrological processes that have been interrupted by spoil banks and canals.

This part of the report presents a preliminary assessment using approaches 1. and 2. using freshwater and sediment resources from dredging and riverine sources. Obviously, the array of possible scenarios for halting the rate of land loss for coastal Louisiana is varied; however, a single general approach has been selected and quantified.

The approach is to utilize dredged material to build a platform on which the vegetated marsh will be nourished by freshwater, sediment, and nutrients from a riverine source. Based on the work of Barras *et al.* (2004), a loss rate of 13.5 sq mi/yr [35 km^2/yr] is used, along with an error range of ±25%. The error range yields a maximum loss rate of 16.9 sq mi/yr [43.8 km^2/yr], and a minimum loss rate of 10.1 sq mi/yr [28.2 km^2/yr].

Table 4.1 lists the mean, maximum, and minimum land-loss rates in three different units, and includes the amount of dredge material required to compensate for each conditions. The dredge-material volumes are based on 4,000 cu yds/acre. These values would, of course, change depending on the depth of water at the site.

Table 4.1 Land-loss rates and dredge-material quantities required to begin restoration are shown

	Land-loss Rate			Dredge Material (million cu yds)
	(sq mi/yr^{-1})	(km^2/yr^{-1})	(acre/yr^{-1})	
Maximum	16.9	43.8	10,816	43.3
Mean	13.5	35	8,640	34.6
Minimum	10.1	28.2	6,464	25.9

As shown in Figure 4.1, the portion of the total annual dredging by the New Orleans District appears to be sufficient to satisfy the needs of beneficial use placement; however, several caveats must be carefully considered:

- The sources of dredge material may not coincide with convenient locations for beneficial placement, perhaps placing a burden of high cost on projects.
- Dredging records may be fraught with quality-control issues beyond the present standard of practice, for example the difficulty of obtaining an accurate hydrographic survey in the vicinity of hyper-concentrations of fine suspended material.
- The range of acceptable sediment gradations for dredge-material placement is poorly defined, and a portion of the total dredged material may be unsatisfactory for the intended use.

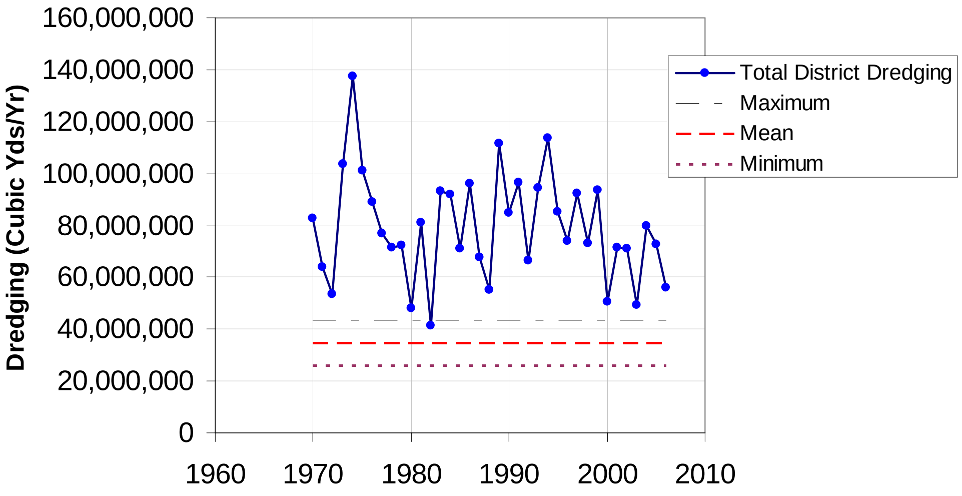


Figure 4.1 The total New Orleans District dredging is shown along with three levels of dredge material for beneficial use

Another example of the available supply of sediment can be drawn from the work of Andrus (2007). Based on his estimate of 8,050 tons/day of sediment, and assuming a depth required of 3 ft and 75% containment of sediment, the West Bay diversion could supply sediment sufficient to satisfy about 29% of the total annual sediment required to create a platform for 13.5 sq mi annually. Based on the error in land loss estimated by Barras *et al.* (2004) of 25%, the capacity of West Bay would need to be multiplied by 2.5 to 4.3 to satisfy the full estimated land-loss amount.

Once the platform of dredge material is constructed; freshwater, nutrients, and sediment will be required to promote and sustain marsh development. Using the McKay *et al.* (2008) model, and assuming that marsh building of 0.5 ft/yr is sufficient, an average discharge of approximately 8,600 cfs of diversion would be required to build and sustain 13.5 sq mi of marsh. With a range of ±25% of the mean flow, the maximum discharge would be 10,700 cfs and the minimum would be 6,414 cfs. By comparison, several existing diversions are listed in Table 4.2, with discharges of 8,000 to 600,000 cfs.

Table 4.2 Listing of existing Mississippi River diversions below Natchez (from Andrus (2007))

	Diversion	River Mile (above head of passes)	Description of Control Structure	Purpose	Maximum Design Discharge (cfs)	Date Completed
1.	Old River Control Complex					
	Low-sill	314.5	Controlled Spillway	Maintain Distribution of Flow and Sediment	500,000	1962
	Overbank	314.5	Controlled Spillway	Flood Control	150,000	1962
	Auxiliary	312	Controlled Spillway	Maintain Distribution of Flow and Sediment	350,000	1986
	Hydropower	316.5	Controlled Spillway	Power Generation	170,000	1990
2.	Morganza	285	Controlled Spillway	Flood Control	600,000	1963
3.	Bonnet Carre	133	Controlled Spillway	Flood Control	250,000	1932
4.	Caernarvon	85	Box Culverts	Freshwater Diversion	8,000	1991
5.	Davis Pond	122	Box Culverts	Freshwater Diversion	10,050	2003
6.	West Bay	4.5	Uncontrolled Channel	Sediment Diversion	20,000*	2003

*Design discharge at 50% river stage. Initial discharge is planned to be increased to 50,000 cfs (from CH2M Hill *et al.* (2004)).

While making provisions for the sediment and river diversion quantities, planning the site to optimize marsh development with high percentages of sediment retention will be challenging. In addition, the scenario presented is in terms of average discharges and sediment concentrations; however, with large Mississippi River and Atchafalaya River discharges, such as occurred in 1973, the opportunity to divert more resources to marsh formation should be seized.

5 References

Allison, M. A., Kineke, G. C., Gordon, E. S., and Goni, M. A. (2000). Development and reworking of a seasonal flood deposit on the inner continental shelf off the Atchafalaya River. *Continental Shelf Research*, 20, 2267-2294.

Andrus, T. M. (2007). Sediment flux and fate in the Mississippi River diversion at West Bay: Observation study. M.S. Thesis, Louisiana State University and Agricultural and Mechanical College, Department of Oceanography and Coastal Sciences, Baton Rouge, LA, December.

Barras, J. A. (2006). Land area change in coastal Louisiana after the 2005 hurricanes: A series of three maps. *U.S. Geological Survey Open-File Report 06-1274.*

Barras, J. A., Bourgeois, P. E., and Handley, L. R. (1994). Land loss in coastal Louisiana 1956-1990. *Open File Report OFR 94-01*, National Biological Survey, National Wetlands Research Center, Lafayette, LA.

Barras, J., Beville, S., Britsch, D., Hartley, S., Hawes, S., Johnston, J., Kemp, P., Kinler, Q., Martucci, A., Porthouse, J., Reed, D., Roy, K., Sapkota, S., and Suhayda, J. (2004). Historical and projected coastal Louisiana land changes: 1978-2050. *U. S. Geological Survey Open File Report OFR 03-334*, U.S. Department of the Interior (revised January 2004).

Bentley, S. J. (2003). Wave-current dispersal of fine-grained fluvial sediments across continental shelves: The significance of hyperpycnal plumes. In: E. D. Scott, A. H. Bouma, and W. R. Bryant (Eds.), Siltstones, Mudstones and Shales: Depositional Processes and Characteristics, Society for Sedimentary Geology/Gulf Coast Association of Geological Societies Joint Publication, pp. 35-48.

Boshart, W. (2003). Bayou La Branche wetland creation summary data and graphics. PO-17, Louisiana Department of Natural Resources, Coastal Restoration Division, Baton Rouge, LA, May, 36 pp.

Boustany, R. G. (2007). A method of estimating the benefit of freshwater introduction into coastal wetland ecosystems: Nutrient and sediment analysis. April 2007 Draft Report, U. S. Department of Agriculture, Natural Resources Conservation Service, Lafayette, LA.

Boyer, M. E. (1996). Constructed crevasses as a technique for land gain in the Mississippi River Delta. M.S. Thesis, Louisiana State University, Baton Rouge, LA, 110 pp.

Carter, B. (2003). Monitoring plan for West Bay Sediment Diversion. *State Project Number MR-03*, Priority Project List 1, Monitoring Section, Coastal Restoration Division, Louisiana Department of Natural Resources, LDNR/Coastal Restoration and Management, August, 11 pp.

CH2M Hill, Mussetter Engineering, Inc., Mobile Boundary Hydraulics, PPLC, and Eustis Engineering Company, Inc. (2004). Phase 1 reconnaissance-level evaluation of the third Delta Conveyance Channel Project. Final Report Prepared for the Louisiana Department of Natural Resources.

CWPPRA. (2002). Geology of the Breton Sound Basin. www.lacoast.gov/geography/bs/index.asp, Coastal Wetlands Planning, Protection and Restoration Act.

Coleman, J. M. and Gagliano, S. M. (1964). Cyclic sedimentation in the Mississippi River deltaic plain. *Gulf Coast Association of Geological Societies Transactions*, 14, 67-80.

Day, Jr., J. W., Boesch, D. F., Clairain, E. J., Kemp, G. P., Laska, S. B., Mitsch, W. J., Orth, K., Mashriqui, H., Reed, D. R., Shabman, L., Simenstad, C. A., Streever, B. J., Twilley, R. R., Watson, C. C., Wells, J. T., and Whigham, D. F. (2007). Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita. *Science*, 315(5819):1679-1684, DOI: 10.1126/science.1137030.

Day, Jr., J. W., Pont, D., Hensel, P. F., and Ibanez, C. (1995). Impacts of sea-level rise on deltas in the Gulf of Mexico and the Mediterranean: The importance of pulsing events to sustainability. *Estuaries*, 18, 636-647.

DeLaune, R. D., Jugsujinda, A., Peterson, G. W., and Patrick, Jr., W. H. (2003). Impact of Mississippi River freshwater reintroduction on enhancing marsh accretionary processes in a Louisiana estuary. *Elsevier, Estuarine, Coastal, and Shelf Science*, 58, 653-662.

Hatton, R. S., DeLaune, R. D., and Patrick, Jr., W. H. (1983). Sedimentation, accretion, and subsidence in marshes of Barataria Basin, Louisiana. *Limnology and Oceangraphy*, 8 (3), 494-502.

IPCC. (2001). Climate change 2001: The scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, P. J., X. Dai, K. Maskell, and C. A. Johnson, Eds.), Cambridge University Press, Cambridge, UK, and New York, NY, 881 pp.

Kelley, S. (1996). Small sediment diversions (MR-01). *Progress Report No. 2*, Louisiana Department of Natural Resources, Baton Rouge, LA, 12 pp.

Louisiana Coastal Wetlands Conservation and Restoration Task Force. (2002). Bayou LaBranche Wetland Creation (PO-17). *Fact Sheet*, Louisiana Department of Natural Resources, Baton Rouge, LA (www.LaCoast.gov), in conjunction with the U.S. Army Corps of Engineers, New Orleans, LA, October.

Louisiana Coastal Wetlands Conservation and Restoration Task Force. (2003). The 2003 evaluation report to the U.S. Congress on the effectiveness of Coastal Wetland Planning, Protection and Restoration Act Projects. Louisiana Department of Natural Resources, Baton Rouge, LA.

McKay, S. K., Fischenich, J. C., and Smith, J. (2008). Quantifying benefits of flow diversion to coastal marshes, I: Theory. U.S. Army Corps of Engineers, Engineer Research and Development Center, Environmental Laboratory, Coastal and Hydraulics Laboratory.

NAS (2006). Drawing Louisiana's new map. National Academy of Science, The National Academies Press, Washington, DC.

Nyman, J. A., DeLaune, R. D., and Patrick, Jr., W. H. (1990). Wetland soil formation in the rapidly subsiding Mississippi River deltaic plain: Mineral and organic matter relationships. *Estuarine, Coastal and Shelf Science*, 31, 37-52.

Penland, S. and Ramsey, L. E. (1990). Relative sea level rise in Louisiana and the Gulf of Mexico: 1908-1988. *Journal of Coastal Research*, 6 (2), 323-342.

Snedden, G. (2007). River, tidal, and wind interactions in a deltaic estuarine system. Ph.D. Dissertation, Louisiana State University and Agricultural and Mechanical College, Department of Oceanography and Coastal Sciences, Baton Rouge, LA, May.

Roberts, H. H. (1997). Dynamic changes of the Holocene Mississippi River Delta plain: The delta cycle. *Journal of Coastal Research*, 13, 605-627.

Trepagnier, C. M. (1994). Near coastal waters pilot project: Crevasse splay portion. *Final Report to U.S. Environmental Protection Agency Region VI*, *Grant No. X-006518-01-2*, Louisiana Department of Natural Resources, Coastal Restoration Division, Baton Rouge, LA, 37 pp. (plus appendices).