RECENT AND HISTORICAL SEDIMENT LOADS IN THE LOWER MISSISSIPPI RIVER

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Abstract: This paper reports the results of a study initiated by the USACE Engineer Research and Development Center (ERDC) and funded by the USACE New Orleans District that assembled available data on sediment loads in the Lower Mississippi River (LMR) and assessed its reliability and temporal variability. The database that resulted includes modern data collected by USACE New Orleans and Vicksburg Districts and historical measurements extending as far back as the mid-19th Century. In using the database, it is important to recognize variability and uncertainty in the records and a preliminary assessment was performed using the record for Tarbert Landing. The average annual measured load at Tarbert Landing between 1963 and 2005 was ~150 million tons, varying between 70 and 230 million tons. The median annual coarse suspended-sediment load over the same period was highly variable, varying from 5 to 80 million tons. The trend apparent in 19th and late-20th Century average loads suggests that, as widely perceived, there has been a long-term decline in the average annual suspended sediment load. This simple statement must, however, be treated with an appropriate degree of caution because: (i) robust statistical treatment of the data is hampered by gaps in the available records; (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 underestimate the coarser fractions of the suspended load, and do not include sediment transported as bed load at all. 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. The database is available free and may be obtained on request from any of the authors, making the data easily accessible both in the USA and globally.

OVERVIEW

This paper reports the results of a project performed by Nottingham University, Halcrow (now part of CH2MHill) and the Biedenharn Group, in collaboration with the Army Corps of Engineers' Engineer Research and Development Center (ERDC), Vicksburg, Mississippi. The project assembled available data on sediment loads in the Lower Mississippi River, assessed its reliability, demonstrated its variability and performed a preliminary examination of historical trends.

The Lower Mississippi River extends from Cairo, Illinois to the Gulf of Mexico and 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 that has almost eliminated the input of sediment due to bank erosion. Finally, extensive dike fields installed in the Lower Mississippi River for navigation have trapped substantial quantities of sediment that might otherwise have been transferred downstream.

The Mississippi River Basin has been subjected to numerous alterations in the past century that have affected sediment loads in the river. The resulting decline in sediment loads in the lower river has been documented by several investigators. However, there is no consensus on the degree of reduction as a proportion of the previous 'natural' or undisturbed load, the time profile of that reduction or how current trends may change in the future. For example, based on the record for Tarbert Landing, Keown *et al.* (1981) suggest that the total annual suspended-

sediment load declined from 427 million tons prior to 1963 to 251 million tons 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 by roughly 40% since 1931 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 in the Lower Mississippi River declined by approximately 80% in the period 1851 to 1982. These large reductions may not be unreasonable given the magnitude of the dams, length of revetments, and effectiveness of soil conservation programs in the basin.

Questions concerning past, present, and future temporal trends in the sediment load of the Lower Mississippi River are pertinent because the redistribution of available Lower Mississippi River sediment is vital to on-going efforts to reduce land loss and restore coastal marshes and wetlands in the Mississippi Delta. 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 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 modeling to support their design. The availability of reliable data on flows and associated sediment loads to support modeling would seem to be a prerequisite for meeting these challenges successfully.

Research to make available reliable sediment-transport data focused on compiling a database of measured suspended-sediment loads. Building this involved: (i) accessing recent measurements collected by the USACE New Orleans and Vicksburg Districts; and (ii) assembling available historical measurements extending as far back as the earliest available records, from the mid-19th Century.

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. Preliminary analysis focused on sediment load measurements at Tarbert Landing, which was selected because it is located in the upper part of the Mississippi Delta and, therefore, can be considered to be representative of the load available to the coastal region; and because it has the longest record of routine monitoring.

The average annual load at Tarbert Landing between 1963 and 2005 was approximately 150 million tons, varying between a minimum of 70 million tons and a maximum of 230 million tons. The median annual coarse load over the same period is highly variable, varying from 5 to 80 million tons.

Examination of historical measurements from the 19th and 20th Centuries suggests that there has been a long-term decline in the average annual load. This simple conclusion must, however, be treated with 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.

The analyses reported below are preliminary. It is proposed that further analyses be performed by researchers with Federal, state, and local agencies, as well as interested parties in the academic and private sectors. This study has facilitated further analyses by compiling a comprehensive database of available measured sediment-load data for the Lower Mississippi River and making it freely available and easily accessible. Copies of the database may be obtained from any of the authors of this paper.

Definition of sediment-transport terms: To avoid confusion in the interpretation and analysis of the database, the definitions of different types of sediment load referred to in this report are defined below.

Total Sediment Load: total mass of granular sediment transported by the river. This can be broken down by source, transport mechanism or measurement status.

Measured Load: portion of the total load measured by conventional suspended-load samplers. It 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 the entire bed load.

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

Bed Load: component of total 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 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 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 (often taken to be coarser than D_{10} of the bed material).

Wash Load: portion of the total load composed of grain sizes finer than those found in appreciable quantities in the stream bed (often taken to be finer than D_{10} of the bed material).

Coarse Load: portion of the total load composed of grains coarser than 0.063 mm. The coarse load of the Mississippi River consists almost entirely of sand finer than 2 mm.

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

DATA ANALYSIS

Data sources: The project built on a previous database of suspended-sediment and bed-material measurements compiled by Thorne *et al*. (2001), which assembled sediment measurements made in the Lower Mississippi, Atchafalaya, Red, and Old Rivers since the 1970s. This project extended the existing database by compiling all available historic measurements made 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, US Geological Survey and a wide range of historical records by multiple organizations, extending back to the 1850s.

Data were obtained in a variety of formats and with differing amounts and types of post-collection processing of the original field measurements. The project report (which is available from the US Army Engineer Research and Development Center or the authors) 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. Data include measurements of some, or all, of the following variables: suspended-sediment concentration and particle size, discharge, suspended-sediment discharge, and flow velocity. Available metadata information describing the types of sampling, sampling strategy, and laboratory procedures are provided in the project report. The sediment sampling stations from which sediment data were collected and included within the database are listed in Table 1.

Seasonal variability: Seasonal variability in measured sediment concentrations and loads was investigated using the record for Tarbert Landing between 1963 and 2005. When analyzing variations in sediment concentration and

load, it is important to consider variations in discharge; seasonal flow exceedance curves for Tarbert Landing are shown in Figure 1. As a very general rule, during periods of peak flow in the spring, discharge is approximately double that during periods of peak flow in the fall. Discharge is, however, highly variable in any season, with 5% exceedance flows being typically three times higher than 95% exceedance flows.

Table 1 Sediment gauging stations included in the database.

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

Variations in coarse and fine sediment concentrations between 1963 and 2005 are shown using box and whisker plots in 2(a) and 2(b), respectively. In these plots, the 25th and 75th percentiles define the box, the minimum and maximum values define the whiskers, and the monthly median is indicated by the central bar. Concentrations of coarse suspended-sediment vary from 350 to less than 50 ppm, being both higher and more highly variable during winter and spring (Figure 2(a)).

Fine suspended-sediment concentrations range between 150 and 250 ppm and though they are less variable seasonally, intra-month variability can be extreme: for example concentrations measured in April varied from around 60 to close to 1,000 ppm. 3(a) and 3(b) illustrate variation in measured coarse and fine suspended-sediment loads at Tarbert Landing, respectively. Monthly loads have been calculated by summing daily loads estimated using the concentration interpolation method.

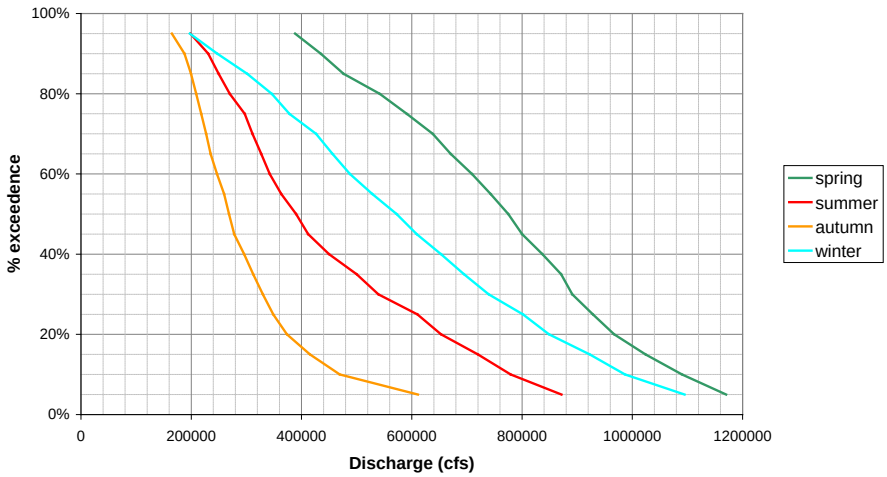

Figure 1 Seasonal flow-duration curves at Tarbert Landing (1963 to 2005).

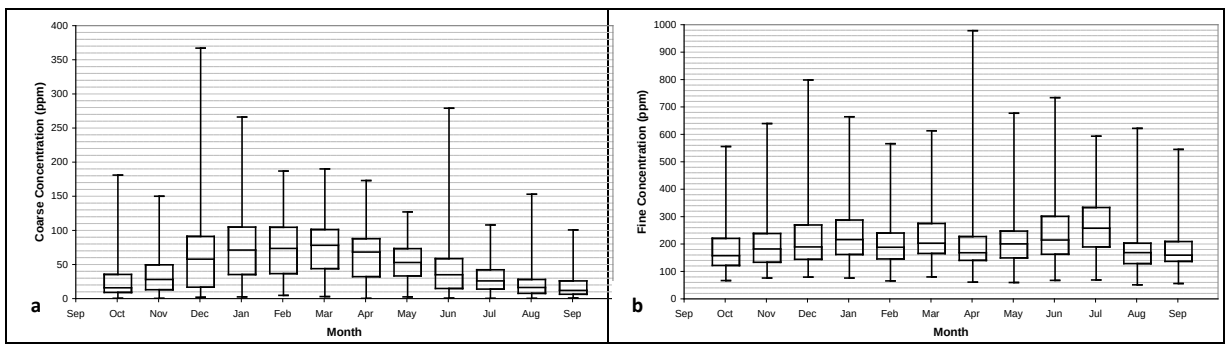

Figure 2 (a) Coarse suspended-sediment concentrations at Tarbert Landing (1963 to 2005).
(b) Fine suspended-sediment concentrations at Tarbert Landing (1963 to 2005).

High seasonal variability in monthly coarse suspended-sediment loads is evident in 3(a). For example, the median coarse load during Spring is approximately fifteen times that in the Fall. The same pattern is present for monthly total loads (Figure 3(b)), although the range of variation is smaller. Intra-month variability is also greater during the spring, particularly for the coarse load.

To further investigate the seasonal variations in the grade of sediment in transport, the cross-section-averaged D_{50} (median) and D_{90} (90th percentile) grain sizes were calculated and these are plotted in
Figure and 4(b). It should be noted that size gradations are not available for the clay fraction (sediment finer than 0.0039 mm).

The median (D_{50}) grain size at Tarbert Landing is overwhelmingly silt-sized though it does coarsen slightly during the winter and spring. The D_{90} is generally coarse silt during summer and fall, but coarsens to very fine sand during winter and spring, when discharges are higher. This indicates that suspended-sediment in the Lower Mississippi River is composed predominately of sediment smaller than fine sand, which differentiates it from the bed material, which is typically coarser than fine sand. As the bulk of the measured suspended load comprises sediment that is finer than that found in appreciable quantities in the bed, the load of the river can be said to be dominated by wash load.

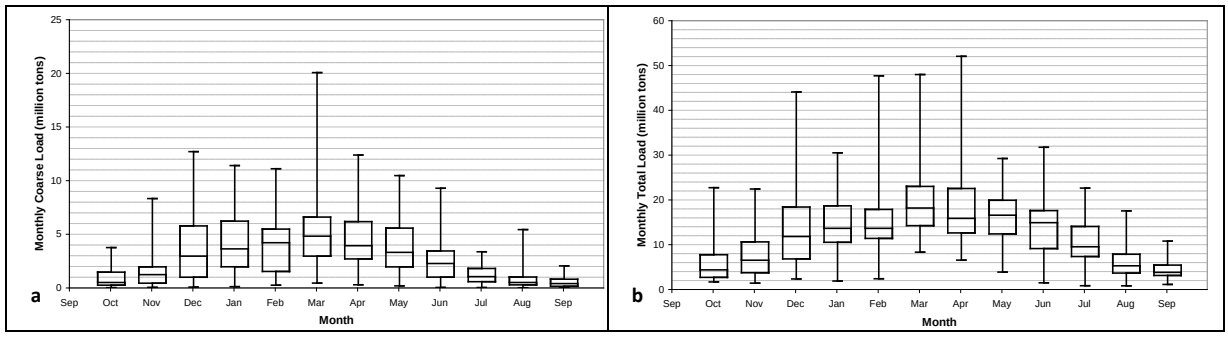

Figure 3 (a) Variation in monthly coarse suspended-sediment loads at Tarbert Landing (1963 to 2005). (b) Variation in monthly total suspended-sediment loads at Tarbert Landing (1963 to 2005).

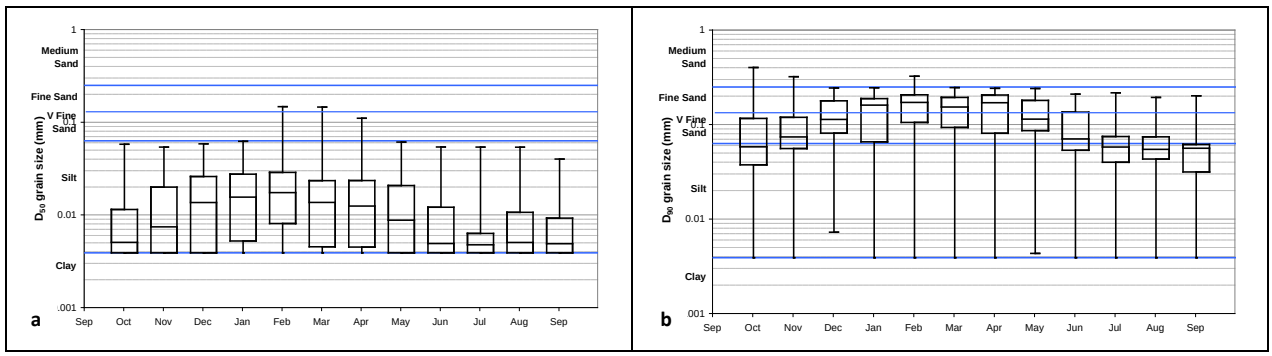

Figure 4 (a) Monthly variation in D_{50} at Tarbert Landing (1963 to 2005). (b) Monthly variation in D_{90} at Tarbert Landing (1963 to 2005).

Trend Analysis:

Historical trends: Historical trends in sediment load were investigated by plotting calculated annual loads for Tarbert Landing alongside historical loads based on older records that either reported annual loads, or included measurements from which annual loads could be calculated (Table 2). The results are plotted in Figures 5 and 6, which support the existence of a marked decline in sediment loads. However, in estimating how much loads and concentrations have decreased, caution must be exercised for four reasons. First, pre-1963 data were obtained from four different locations (Carollton, Baton Rouge, Red River Landing, and South Pass) and loads estimated from records at different gauging stations can vary considerably. Second, there are large gaps in the data during the first half of the 20th Century. Third, comparisons of loads between the 19th and late-20th centuries are limited by the high uncertainty concerning the early estimates of annual load. While the early data provide valuable insights, they are not sufficient to support statistical comparison to later data. Fourth, annual loads are based on measured suspended-sediment loads that almost certainly under-represent the coarser fraction of the suspended-sediment load, and do not account for bed load at all.

Recent trends: To assess whether loads in the Lower Mississippi River are continuing to decrease, a preliminary analysis of the Tarbert Landing data was conducted and Figures 7, 8 and 9 illustrate recent trends in annual sediment concentrations, suspended loads, and water discharges between 1959 and 2005. While scatter is present in data representing fine and total concentrations in Figure 7, P-values for the regression lines fitted to these data indicate downward trends that are statistically significant. Conversely, there is no significant trend in concentrations of coarse sediment. With respect to the annual sediment loads plotted in Figure 8, a slight, but statistically insignificant increasing trend is apparent in the coarse sediment loads. Fine and total loads appear to have slight 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. Lack of significant trends in sediment loads is unexpected given the decreasing trends identified in fine and total sediment concentrations. This apparent paradox may be explained at least in part by a slight, though statistically insignificant,

increasing trend in annual water discharges in Figure 9. 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 preliminary and it is recommended that full assessment be undertaken to investigate the complex behavior represented in the historical and recent records (*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.

Table 2 Sediment records used in assessing historical trends.

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.
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 labeled 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 8 and 9 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 8 and 9 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 8 and 9, arrows have been used to indicate possible additional uncertainty due to location transfer.

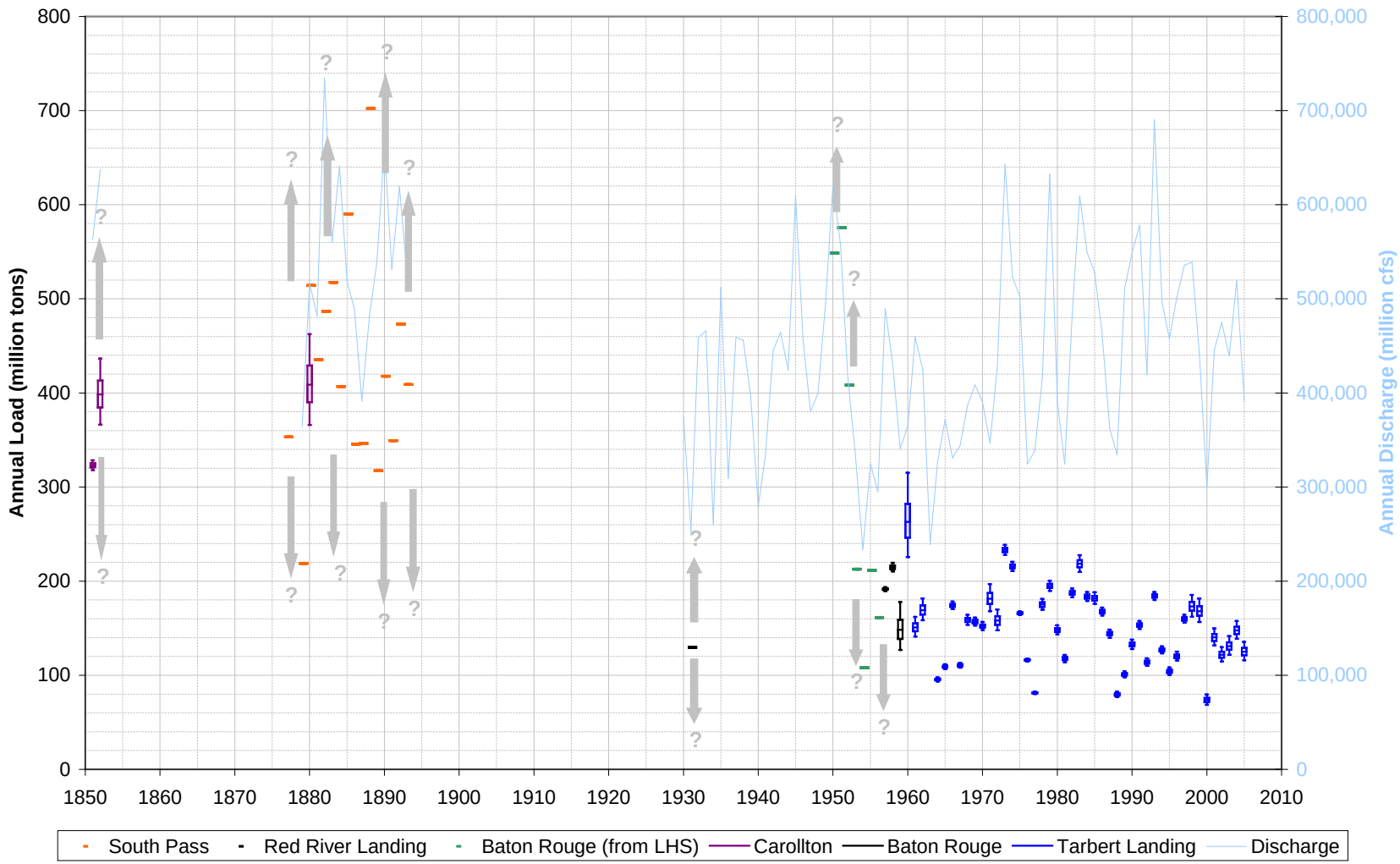

Figure 5 Long-term changes in the annual sediment load on the Mississippi River from multiple stations.

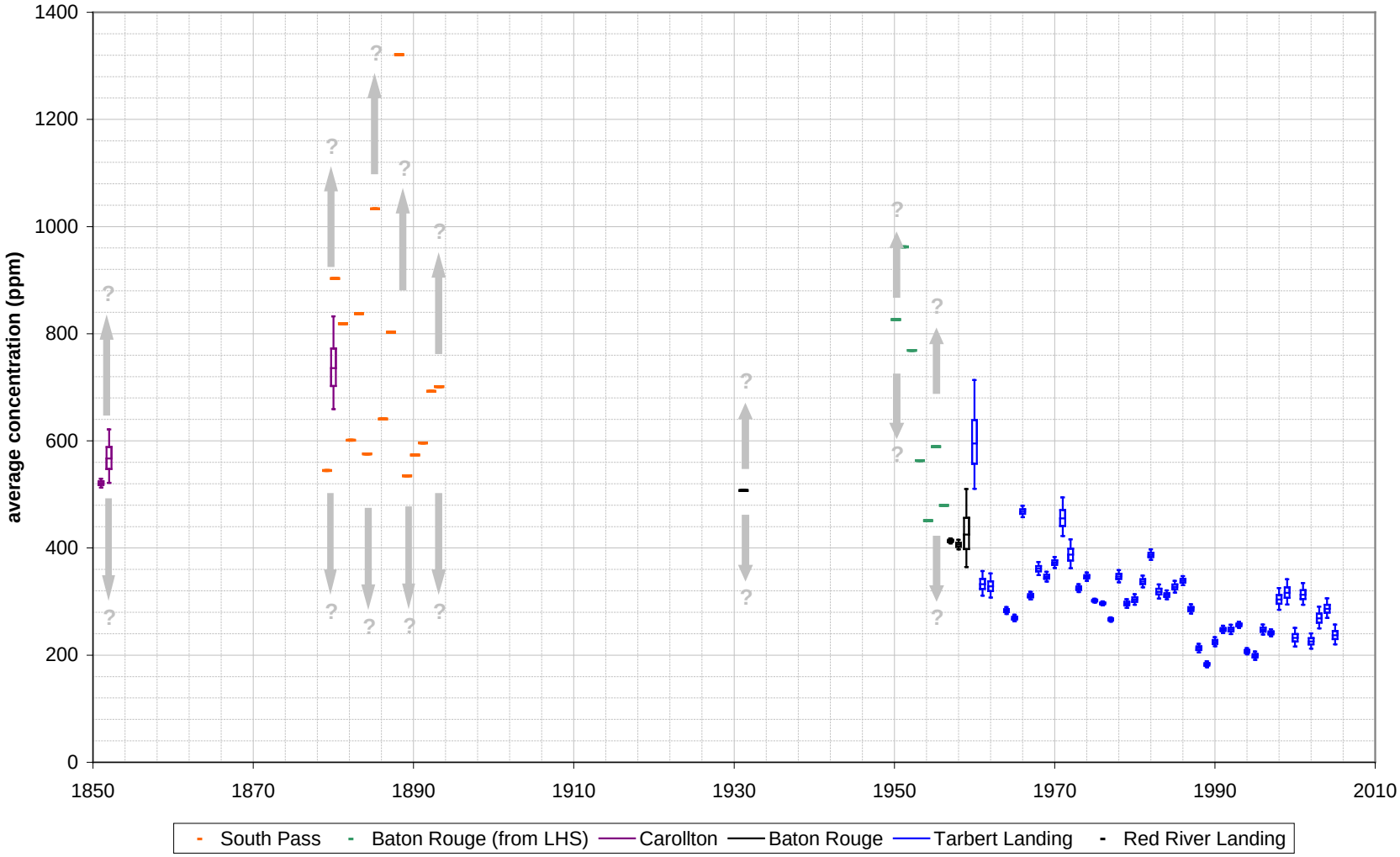

Figure 6 Long-term changes in annual average suspended-sediment concentration in the Mississippi River from multiple stations.

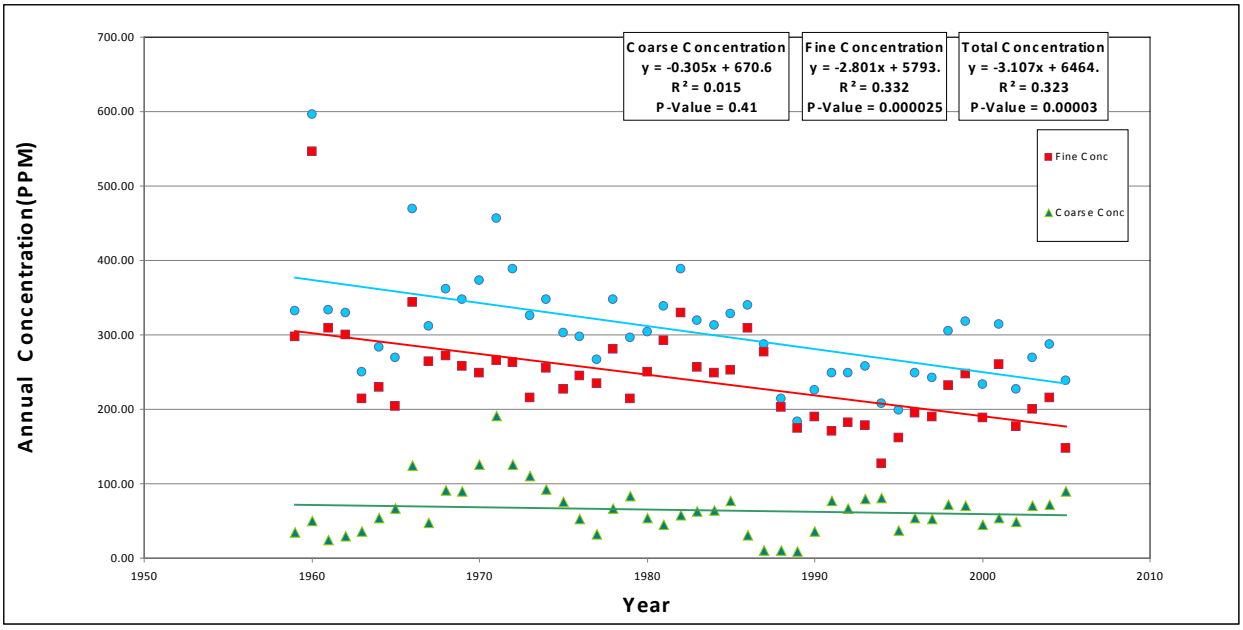

Figure 7 Tarbert Landing sediment concentrations, 1959 to 2005.

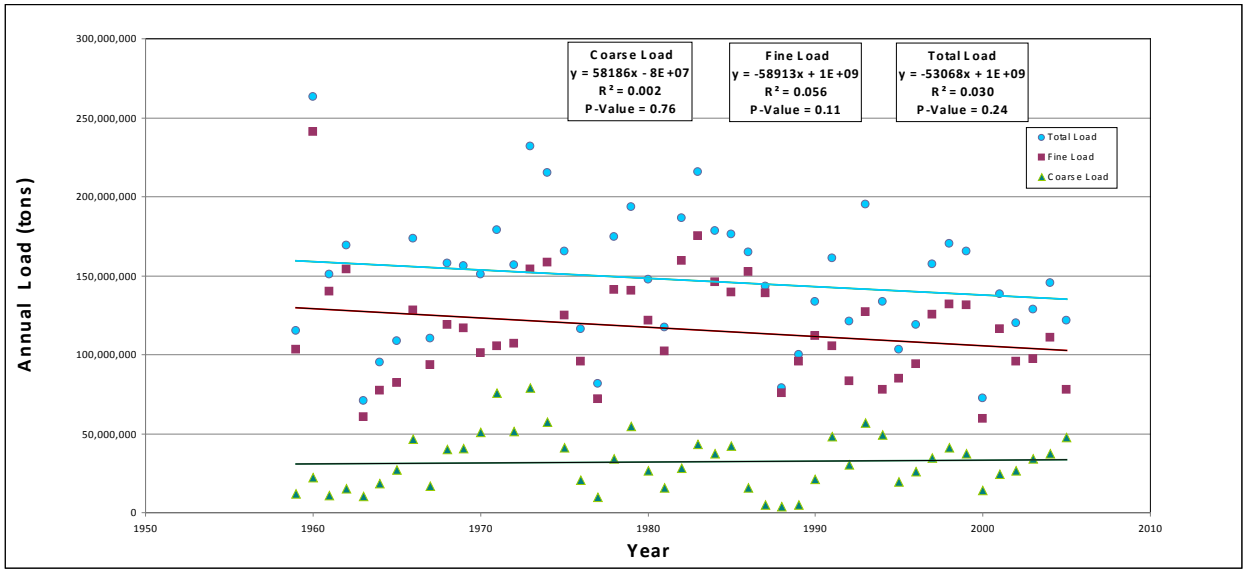

Figure 8 Tarbert Landing sediment loads, 1959 to 2005.

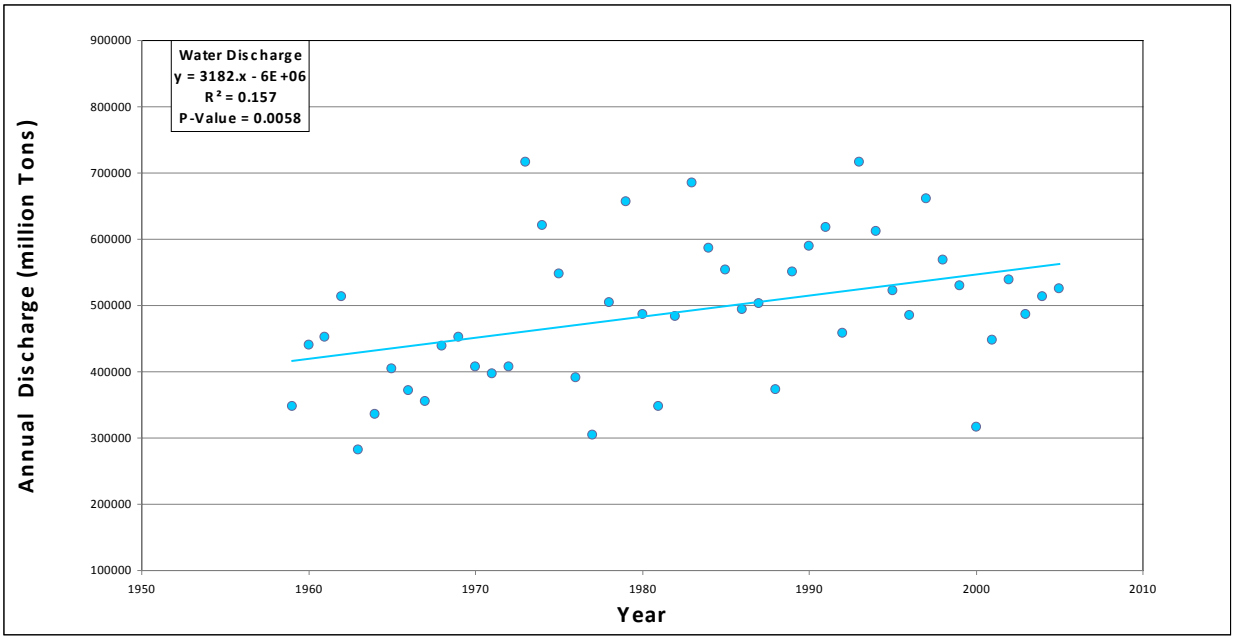

Figure 9 Annual water discharges at Tarbert Landing, 1959 to 2005.

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