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# Hysteresis and nonlinearity of discharge-sediment relationships in the Atchafalaya and lower Mississippi rivers

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**ABSTRACT** The Atchafalaya and lower Mississippi rivers in south Louisiana show the following characteristics: 1) Hysteresis effects are pronounced, especially during high discharge years where the sediment concentration and load maxima precede discharge maxima by several months and show decreased sediment concentrations by the time discharge peaks; 2) The silt-clay and sand components of the suspended sediment operate distinctively; 3) The total suspended-sediment concentration and the suspended silt-clay concentration follow quadratic power relationships; 4) Downstream differences in discharge-sediment relationships are apparent.

## INTRODUCTION

The Atchafalaya and lower Mississippi rivers in south-central and southeastern Louisiana are two of the largest rivers in the United States and are an important source of fresh water and sediment for the Louisiana coastal zone. The drainage area of the Atchafalaya River at Simmesport, just downstream of the head and confluence of the Red River and Old River, is approximately 228,410 km$^2$, not including the Mississippi River area. The Mississippi River is the largest river on the North American continent, draining approximately 3,224,000 km$^2$.

The Atchafalaya's flow consists of that from the Red River and controlled diversion at all stages from the Mississippi through the Old River Outflow Channel. Use of the Old River Control Structure, completed in 1963, and the Auxiliary Structure, completed in 1987, has increased flow in the Atchafalaya and decreased flow in the Mississippi. Flow is also diverted from the Mississippi to the Atchafalaya basin through the Morganza Floodway and to the Pontchartrain basin through the Bonnet Carre Spillway during floods.

The Atchafalaya is approximately one-third the length and one-half the width of the Mississippi. In both rivers, bed material size decreases downstream; in the lower Mississippi it decreases from about 99% fine and medium sand near Old River to about 20% fine sand and 80% silt and clay at the Head of Passes (Keown, 1981; 1986). Suspended sediment in the lower Mississippi River also varies with depth; higher concentrations occur near the river bottom, primarily because of variations in sand concentration (Fisk, 1952; Wells, 1980).

Other studies suggest that the suspended-sediment concentration and load in the lower Mississippi River are both discharge-dependent (Jordan, 1965; Robbins, 1977; Sedimentation Seminar, 1977) and location-dependent (Everett, 1971; Wells, 1980; Meade, 1985). Studies of discharge-dependent behavior generally show linearity, because concentration being statistically independent from discharge, was not examined in detail as was load, a dependent variable. Robbins (1977), in contrast, found that a linear power function did not represent the relationship between concentration and discharge for the 1973 water year. However, he did not attempt to apply a nonlinear relationship. Studies of location-dependent behavior are based on short-term data sets, and may be inadequate to characterize river behavior. The timing of sediment transport, statistical relationships in the Atchafalaya, and the differences in behavior between the two rivers have not been examined in detail previously.

This investigation examines some of the physical relationships between discharge and sediment in the Atchafalaya and lower Mississippi rivers. The objectives are: 1) examining temporal variations in sediment transport to identify the physical factors that contribute to these variations between both rivers and downstream along these rivers; and 2) assessing the statistical relationships between discharge, sediment concentration and its components, and sediment load so that these interactions can be better understood.

## DATA BASE AND APPROACH

The data base consisted of several instantaneous measurements of discharge, suspended sediment concentration, suspended sediment load, and percentage sand in the suspended load; they were collected periodically between 1972 and 1986 on the Atchafalaya River at Simmesport (n = 438), the Lower Atchafalaya River at Morgan City (n = 174), and on the lower Mississippi River at Tarbert Landing (n = 460) and at Belle Chasse (n = 93) by the U.S. Geological Survey and the U.S. Army Corps of Engineers. The composite suspended sediment samples consist of 15 and 40 point-integrated samples (Federal Inter-Agency Sedimentation Project, 1963; Guy and Norman, 1970) on the Atchafalaya and lower Mississippi, respectively (Keown et al., 1977).

Time series were plotted for each water year. Statistical relationships between discharge and sediment characteristics in the Atchafalaya and lower Mississippi River were examined using a linear least-squares regression, or power relationship, with discharge ($\log_{10}$) as the independent variable, and concentration ($\log_{10}$), sand concentration ($\log_{10}$), silt-clay concentration ($\log_{10}$), suspended sediment load ($\log_{10}$), and the percentage sand as dependent variables. It was determined that a quadratic power function should also be applied once the suspended sediment data were plotted.

The quadratic and linear statistical models were compared by means of a test of the full and reduced regression (Neter et al., 1983). This test was attempted to determine whether the additional parameters in the quadratic model substantially reduce the variance of the observations around the fitted regression line. The test statistic, F*, is a function of the error sum of squares of the reduced model SSE(R), and the error sum of squares of the full model SSE(F), namely:

$$F^* = \frac{SSE(R) - SSE(F)}{df_R - df_F} - \frac{SSE(F)}{df_F}$$

where $df_R$ and $df_F$ are the degrees of freedom for the reduced and full models.

## TEMPORAL VARIATIONS AND HYSTERESIS

During high discharge years, the sediment concentration and load maxima may precede discharge maxima by several months, showing a deficit in sediment supply by the time discharge peaks (Fig. 1). The hydrographs in both rivers show similar patterns, but in some years the sediment time series are very different. In high-discharge years, the highest suspended-sediment loads generally occur in the winter and early spring.

During low discharge years, sediment maxima occur only shortly before or coincide with discharge maxima (Fig. 2). Most of the maxima are associated with pronounced increases in discharge. In low- and average-discharge years, the sediment load shows stronger seasonal relationships, and the highest loads occur during the spring and early summer.

Extreme short-term variations in sediment concentration and load during both falling and rising stages are common. These variations occur in both rivers but are more frequent in the Atchafalaya. Some possible causes of these variations are bank failures, turbulent fluctuations of stream velocity, local dredging, and measurement and other errors.

## STATISTICAL RELATIONSHIPS AND NONLINEARITY

Upstream, at Simmesport and Tarbert Landing, the relationship between discharge and silt-clay concentration in both rivers is nonlinear (Fig. 3; Table 1). The silt-clay component of the suspended load increases at first, then levels, and may then decrease as discharge increases. Downstream, at Morgan City and Belle Chasse, the quadratic pattern is less well-defined but nonetheless evident. Correlation coefficients for the linear least-squares relationship between the silt-clay component and discharge range from $r = 0.30$ to $0.54$ for the Atchafalaya and $r = 0.12$ to $0.68$ for the Mississippi, increasing downstream; quadratic correlation coeffients range from $r = 0.60$ to $0.65$ and $r = 0.58$ to $0.72$. The sand concentration is more nearly linear, with correlation coefficients of $r = 0.72$ to $0.88$ and $r = 0.73$ to $0.83$, also increasing downstream.

The relationship between total suspended concentration and discharge also showed nonlinearity, because the silt-clay component is the larger proportion of the total concentration. The discharges with highest sediment concentrations range from 5,000 to 15,000 $m^3 s^{-1}$ in the Atchafalaya and 10,000 to 30,000 $m^3 s^{-1}$ in the lower Mississippi rivers. The discharges below and above these ranges show lower concentrations. Linear correlation coefficients of $r = 0.48$ to $0.62$ and $r = 0.39$ to $0.77$, and quadratic correlation coefficients of $r = 0.66$ to $0.72$ and $r = 0.65$ to $0.78$ were computed.

Quadratic power functions produced better correlations than linear power functions in all cases. The comparative test of the models using the F* statistic shows that, overall, the quadratic power model produces a better fit. The hypothesis is highly significant for most parameters, particularly for the silt-clay and

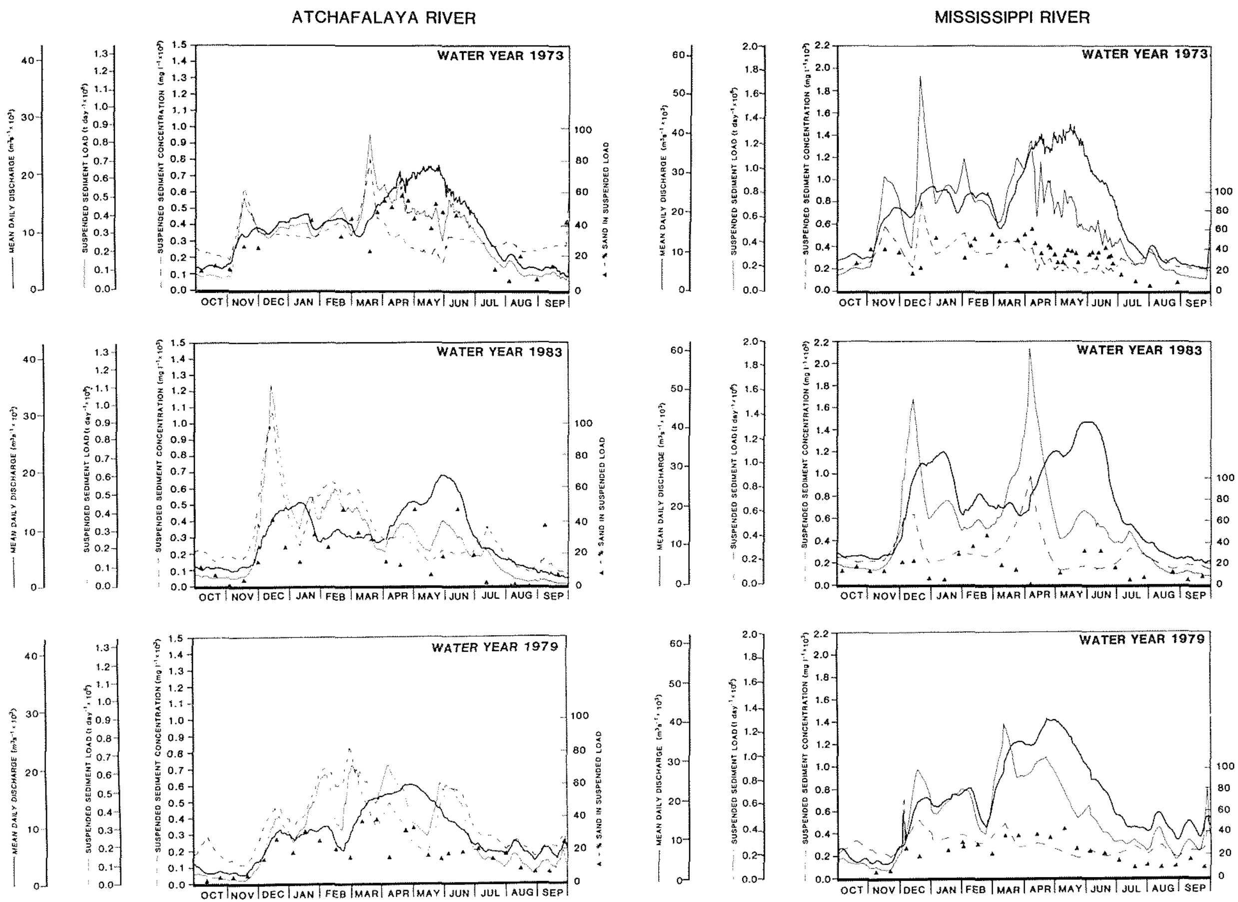


Fig. 1 Time series of discharge and sediment conditions for three high discharge years on the Atchafalaya River at Simmesport and on the lower Mississippi River at Tarbert Landing.

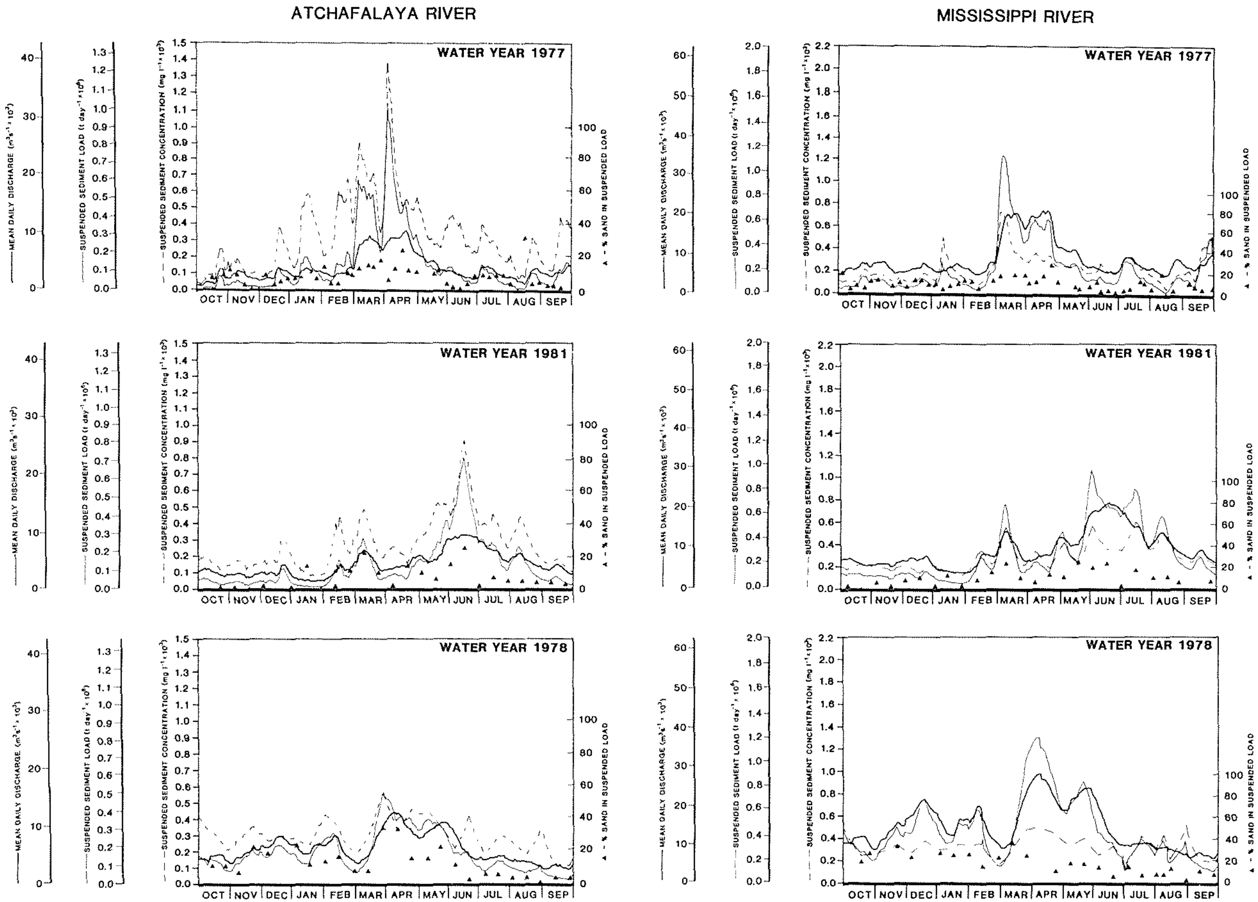


Fig. 2 Time series of discharge and sediment conditions for three low discharge years on the Atchafalaya River at Simmesport and the lower Mississippi River at Tarbert Landing.

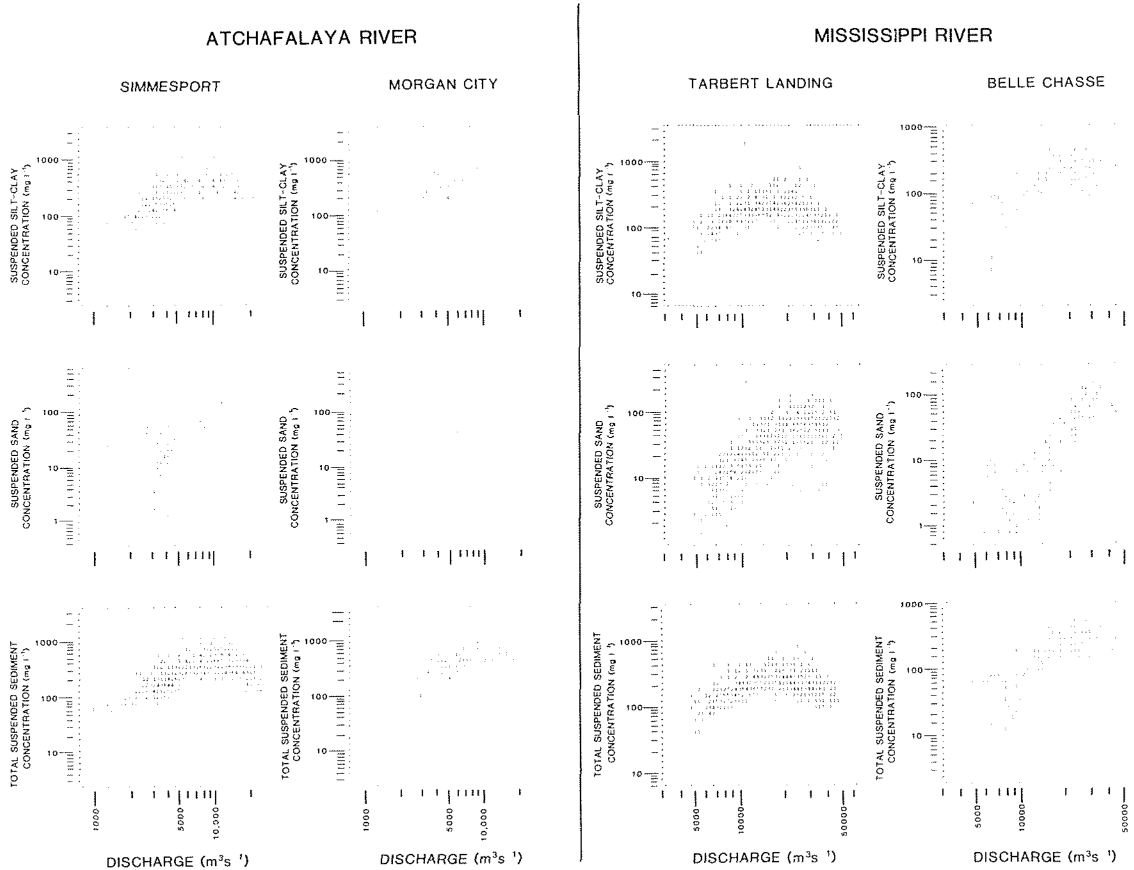


Fig. 3 Relationships between discharge and the silt-clay, sand, and total suspended-sediment concentration on the Atchafalaya River ar Simmesport and Morgan City and the lower Mississippi River at Tarbert Landing and Belle Chasse. The number on the plot represents the number of measurements located at the same graphic position.

Table 1. Coefficients of linear and quadratic regression relationships between discharge and sediment on the Atchafalaya River at Simmesport and Morgan City and the lower Mississippi River at Tarbert Landing and Belle Chasse and the test and significance level of the model comparison.

| VARIABLES | N | LINEAR EQUATION CORRELATION COEFFICIENT (r) | LINEAR EQUATION COEFFICIENT OF DETERMINATION ($r^2$) | QUADRATIC EQUATION CORRELATION COEFFICIENT (r) | QUADRATIC EQUATION COEFFICIENT OF DETERMINATION ($r^2$) | MODEL STATISTIC ($F^*$) | SIGNIFICANCE LEVEL |
|---|---|---|---|---|---|---|---|
| SIMMESPORT | | | | | | | |
| STCL vs. Q | 438 | 0.30 | 0.09 | 0.60 | 0.36 | 182.40 | .001 |
| SAND vs. Q | 428 | 0.72 | 0.52 | 0.74 | 0.55 | 23.45 | .001 |
| TSSC vs. Q | 438 | 0.48 | 0.23 | 0.66 | 0.43 | 159.06 | .001 |
| %SAND vs. Q | 438 | 0.67 | 0.44 | 0.69 | 0.48 | 29.57 | .001 |
| LOAD vs. Q | 438 | 0.87 | 0.62 | 0.91 | 0.82 | 155.25 | .001 |
| MORGAN CITY | | | | | | | |
| STCL vs. Q | 139 | 0.54 | 0.29 | 0.65 | 0.42 | 34.93 | .001 |
| SAND vs. Q | 120 | 0.88 | 0.77 | 0.89 | 0.79 | 11.76 | .001 |
| TSSC vs. Q | 170 | 0.62 | 0.39 | 0.72 | 0.52 | 47.40 | .001 |
| %SAND vs. Q | 139 | 0.81 | 0.65 | 0.91 | 0.82 | 174.76 | .001 |
| LOAD vs. Q | 170 | 0.91 | 0.83 | 0.93 | 0.87 | 47.42 | .001 |
| TARBERT LANDING | | | | | | | |
| STCL vs. Q | 460 | 0.12 | 0.02 | 0.58 | 0.33 | 218.77 | .001 |
| SAND vs. Q | 457 | 0.73 | 0.53 | 0.77 | 0.59 | 62.39 | .001 |
| TSSC vs. Q | 460 | 0.39 | 0.15 | 0.65 | 0.42 | 214.42 | .001 |
| %SAND vs. Q | 460 | 0.72 | 0.51 | 0.73 | 0.53 | 10.93 | .001 |
| LOAD vs. Q | 460 | 0.88 | 0.77 | 0.92 | 0.84 | 214.42 | .001 |
| BELLE CHASSE | | | | | | | |
| STCL vs. Q | 93 | 0.68 | 0.47 | 0.72 | 0.52 | 10.43 | .005 |
| SAND vs. Q | 89 | 0.82 | 0.68 | 0.85 | 0.72 | 14.50 | .001 |
| TSSC vs. Q | 93 | 0.77 | 0.59 | 0.78 | 0.61 | 5.57 | .025 |
| %SAND vs. Q | 93 | 0.54 | 0.29 | 0.68 | 0.46 | 28.96 | .001 |
| LOAD vs. Q | 93 | 0.91 | 0.82 | 0.91 | 0.83 | 5.57 | .025 |

LEGEND
Q = Discharge ($m^3 s^{-1}$)
STCL = Suspended silt-clay concentration (mg $l^{-1}$)
SAND = Suspended-sand concentration (mg $l^{-1}$)
TSSC = Total suspended-sediment concentration (mg $l^{-1}$)
%SAND = Percentage sand in the suspended load

total suspended-sediment concentrations. Although applications of quadratic power functions to sediment data are limited, they have produced better correlations with other types of hydraulic and geomorphic data, including changes of roughness and channel geometry with discharge, that do not fit simple linear power functions (Church, 1967; Richards, 1973). The physical explanation for the nonlinearity of these relationships could be hysteresis effects and discontinuities of hydraulic, geomorphic, and sedimentologic factors, or combinations of these conditions. Hydraulic discontinuities may be a result of the change from lower to upper regimes of flow, which produces attendant changes in sediment transport, bedforms, and roughness. Geomorphic discontinuities include the change from below- to above-bankfull flow. Sedimentologic discontinuities include the exhaustion of specific sizes of material available for transport, as at the upstream stations with small amounts of silt and clay in the bed material available for resuspension.

## CONCLUSIONS

There are several distinctive relationships between discharge and sediment in the Atchafalaya and lower Mississippi rivers. These relationships, which are important both theoretically and practically, are: 1) The hysteresis effect, which is most pronounced during high discharge years; 2) differences in response between the silt-clay and sand components of the suspended load; 3) quadratic statistical relationships between sediment concentration and discharge unlike the linearity found in other studies; and 4) downstream variations in discharge-sediment relationships.

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