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Human modifications to the sediment regime of the Lower Mississippi River flood plain

R.H. Kesel*

Department of Geography and Anthropology, Louisiana State University, 227 Howe-Russell Geoscience Complex, Baton Rouge, LA 70803, USA

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Abstract

The Mississippi River is one of the most regulated rivers in the world. Human modifications constructed mainly after 1920 include dams and reservoirs, artificial levees, dikes, concrete revetments and a series of channel cutoffs. This paper examines some of the effects of these modifications on the channel and sediment budget of the river. In particular, the changes to the thalweg profile and the size of channel bars are examined in detail. It is concluded, that prior to the 1930s, when major modifications were introduced, the Lower Mississippi River was an aggrading meandering river. The role of the flood plain has also changed. Prior to modifications, the flood plain was the major sediment source as the result of bank caving. Today the flood plain provides only a minor amount of sediment. It can be shown that major degradation to the channel including the growth of channel bars has occurred as a result of these engineered modifications. The data also indicates that the different geomorphic regions respond to modifications in different ways.

Keywords: Flood plain; Mississippi River; Thalweg; Channel bars; Human modification

1. Introduction

The Lower Mississippi River is an exceedingly complex fluvial system. In order to understand spatial and temporal changes to any part of the system, it is necessary to examine them in the context of the entire system. The rates of channel migration and bank caving, for example, can vary as the river shifts its position in space and time and the channel encounters different bed and bank materials. Any analysis of change is further complicated because the river has undergone many human modifications. Some modifications to maintain flood control and navigation on the river were introduced as early as the 18th century, although most of the major ones were constructed after about 1920 (Kesel, 1988). Some modifications have disrupted or eliminated sediment and water pathways into adjacent flood plains and wetlands and modified the amount and character of the sediment carried by the river. The purpose of this paper is to examine the effects of these modifications on the Lower Mississippi River, particularly on the sediment regime as reflected by temporal and spatial changes to the thalweg profile, channel bar volume and the role of the flood plain as

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* Fax: +1-225-478-4420.

E-mail address: gakesel@lsu.edu (R.H. Kesel).

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a sediment source. Changes to the sediment regime as well as the placement of artificial levees are of particular importance to the Louisiana Gulf coast wetlands where the river has played a major role in creating and maintaining the wetlands and delta. Artificial levees prohibit sediment from entering the wetlands and it is estimated that they are being lost at rates as high as 100 km^2/year (Gagliano et al., 1981). Day et al. (2000) argue that major input of river sediments into these areas is the major means of combating this loss. Thus it is important to understand how much the sediment regime of the river has been altered and what impact it would have if redirected into the wetlands.

2. Background

2.1. Physical description

The Mississippi River drains approximately 3.2 × 10^6 km^2 and follows a 3700 km course from its

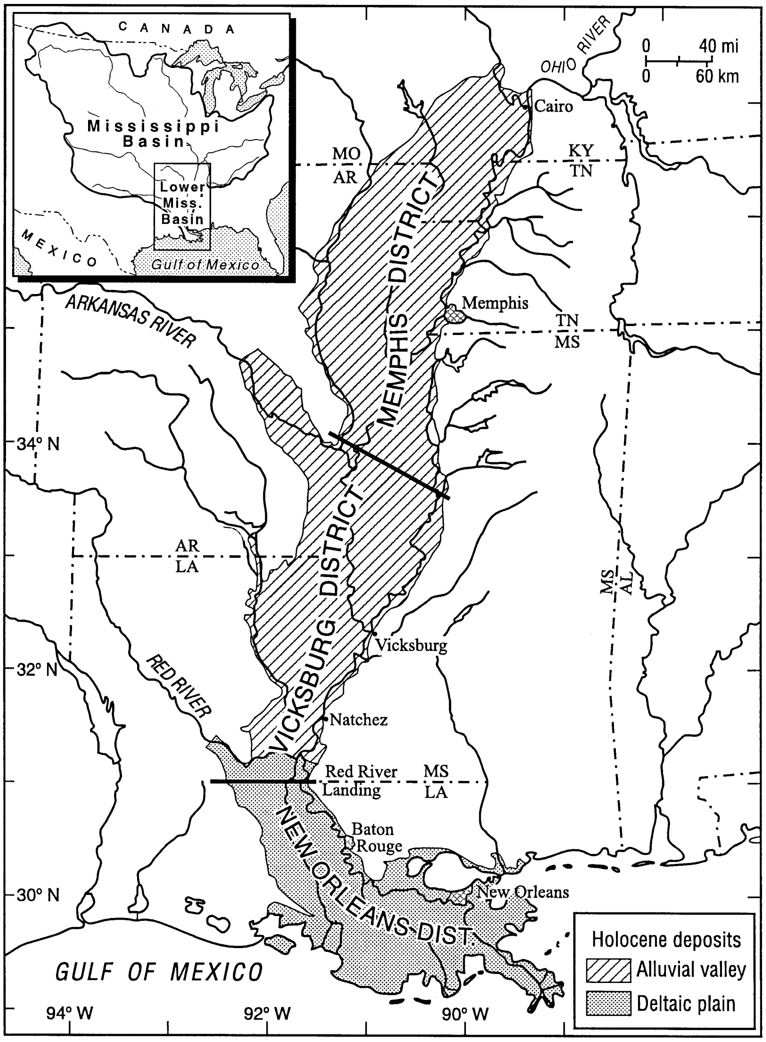

Fig. 1. Geomorphic divisions of the Lower Mississippi River flood plain. U.S. Army Corps of Engineer divisions noted elsewhere in text are shown.

source to the Gulf of Mexico. The 1600 km portion from the mouth of the Ohio River at Cairo, IL to the Gulf is among the worlds most intensely regulated rivers and is the focus of this paper. This lower portion of the river can be subdivided into different geomorphological sections. The upper two-thirds of the lower river, from Cairo to the Red River Landing (including the Old River diversion) (Fig. 1) flows through a flood plain which ranges from 40 to 200 km wide and is composed of alluvial sands, silts and clays. The river in this upper portion prior to modification meandered freely, for the most part, with an average annual lateral migration of 25 m/year (Kesel et al., 1992; Hudson and Kesel, 2000). The lower third of the river extends from Red River Landing to the Gulf and flows through a deltaic plain with banks composed largely of clay sediment which has limited lateral migration of the river to an annual rate of 3 m/year (Kesel et al., 1992). Since 1963, approximately 30% of the annual sediment and water discharge flowing to this segment has been diverted through the Old River diversion structure into the Atchafalaya Basin (Fig. 1).

2.2. Modifications

Human modifications to the river were introduced largely after 1920. Between 1929 and 1942, the river was channelized and shortened 245 km to improve and maintain navigation. As the result of shortening, 15 meander bends were cut-off and isolated from the main-stem channel. The river was shortened an additional 88 km between 1939 and 1955 by chute cutoffs. After their formation, cutoffs acted as sediment storage locations, essentially removing channel and point bar sediments from the active sediment budget of the main-stem channel.

Although artificial levees were constructed along the river since the 1700s, they were not effective in controlling overbank flooding until built to federal standards. Following the 1927 flood, 3000 km of artificial levees were either raised or constructed, reducing overbank inundation on the flood plain by 90% as well as eliminating crevasse splays. The channel has been stabilized by the construction of 1400 km of concrete revetments which have greatly reduced bank caving and all but eliminated lateral migration of the channel. Most revetment construction occurred after 1940 (Fig. 2A). Dikes have been constructed, largely since 1955 (Fig. 3), to trap bed sediments in order to constrict channel width, thereby increasing flow velocities in order to encourage bed scour at low discharge stages. Dam and reservoir construction during the 1950s and 1960s on such major tributaries as the Missouri and Arkansas rivers has reduced the suspended sediment load reaching the Gulf by estimates ranging from 50% (Keown et al., 1986; Meade and Parker, 1985) to over 70% (Kesel, 1988, 1989).

3. Data and methods

This study relies on historical documents published by the Mississippi River Commission (MRC) and the U.S. Army Corps of Engineers (USACE). Hydrographic surveys published by the MRC for the periods 1880, 1915, 1935, 1948, 1962, 1974 and 1988 were used to measure and analyze channel characteristics over time. These surveys vary in the length of time used to conduct each survey and in the topographic detail necessary to allow quantitative measurements of all channel and channel bar characteristics (Table 1). Prior to the 1962 survey, sufficient contour information is available on the surveys to analyze changes to channel dimensions, thalweg elevation and profile and channel bar size and volume. Subsequent to that time, contour information outside the low water channel was no longer available, although some estimate of point bar change from 1962 to 1974 was determined using USGS topographic quadrangles available for that period. Elevations on the 1880 and 1915 surveys must also be corrected because their relation to mean Gulf level (NGVD) was incorrect (Elliott, 1932, p. 147).

Map data generated from these surveys included channel bar volumes and thalweg elevations and profiles. The net change in channel bar volume and thalweg profile elevations was determined by comparing the values from two successive surveys. Because the length of the main-stem channel and the length of time between successive map periods varied, it was necessary to convert total amounts to a unit value. This was done by dividing the total amounts by the length of main-stem channel involved and the number of years between map periods. The first two surveys

Table 1
Mississippi River Commission hydrographic surveys (scale = 1:20,000)

River location	Dates of survey	Number of maps in series	Contour lines
1880			
Cairo, IL–HOP[a]	1877–1894	84	yes
1915			
Cairo, IL–RR, LA[b]	1911–1914		yes
RR, LA–HOP	1921–1924	84	yes
1935			
Cairo, IL–Rosedale, MS	1937	103	yes
Rosedale, MS–Vicksburg, MS	1937	78	yes
Vicksburg, MS–Angola, LA	1937–1938	50	yes
Angola, LA–HOP	1935–1938	65	yes
1948			
Cairo, IL–Arkansas River	1948–1949	31	yes
Arkansas River–Vicksburg, MS	1948–1949	77	yes
Vicksburg, MS–Angola, LA	1948–1951	50	yes
Angola, LA–HOP	1949–1952	80	yes
1962			
Cairo, IL–White River	1961–1963	98	no
White River–Black Hawk, LA	1962–1963	108	no
Black Hawk, LA–HOP	1961–1963	84	no
1974			
Cairo, IL–White River	1973–1975	98	no
White River–Black Hawk, LA	1975	110	no
Black Hawk, LA–HOP	1973–1975	84	no
1988			
Cairo, IL–White River	1987–1989	98	no
White River–Black Hawk, LA	1988–1989	110	no
Black Hawk, LA–HOP	1983–1985	84	no

[a] HOP = Head of Passes, LA.
[b] RR = Red River Landing, LA.

(1880 and 1915) were also used to construct an estimate of the sediment budget for the river prior to the introduction of most human modifications. A detailed account of the budget and the methods and procedures used to construct it are described by Kesel et al. (1992).

4. Sediment regime prior to modifications

Prior to major modifications in the 1930s, the Lower Mississippi River was a classic meandering river that was aggrading its channel throughout much of its length (Fig. 5). This aggradation is reflected in the growth of channel bars and the increase in thalweg elevation prior to 1935 (Fig. 5). An estimate of the average annual sediment load reaching the Gulf of Mexico at that time included a suspended load of 270×10^6 m^3/year and a bed load that may have been as much as 130×10^6 m^3/year (Kesel et al., 1992). The components of the Lower Mississippi River sediment regime include both sediment input sources and short- and long-term storage locations within the fluvial system. These data indicate that the river had two distinct sediment regimes which reflected the geomorphological subdivisions noted previously. As much as two-thirds of the sediment load transported by the river from Cairo to Red River Landing was generated by bank caving as the river meandered on the flood plain. Within this segment, approximately twice as much sediment was stored as short-term storage within the channel, mostly in river bars, as was stored as longer term overbank storage on the flood plain (Kesel et al., 1992). The growth of channel bars during the period was largely a function of bank caving. The close relationship between channel bar growth and bank caving can be seen in Fig. 6.

Below Red River, the river acted as a conduit for transporting sediment from the upper segment to the Gulf. Little new sediment was added in this segment either by tributaries or bank caving. Two-thirds of sediments stored in this lower segment was as longer term overbank deposits on the flood plain. Kesel et al. (1992) argue that as much as one-third of the sediment reaching the Gulf was carried as bed load. A relatively high proportion of bed load might be expected in a river with large amounts of bank caving and aggrading river bars.

5. Effects of modifications

The overall influence of modifications on the sediment regime include a major decrease in sediment input both from major tributaries and channel and flood plain sources. The most significant change has been a greater than 90% reduction in bank caving sediments as the result of revetment construction (Fig. 2B). Based on bank caving data from Smith (1963), most of this decrease occurred after 1941. A sizeable reduction in sediment input from the Missouri and Arkansas rivers occurred after 1950 as the result of dam and reservoir construction (Keown et al., 1986; Kesel, 1988, 1989). Further reductions in the amount of sediment reaching the mouth of the river results from increased storage capacity. The construction of dike fields starting in 1955 (Fig. 3) promoted the accretion of bed load sediments, largely sand, creating or enlarging channels bars. By the mid-1970s, the amount of sediment, largely bed load, trapped in these dike fields (Mississippi River Commission (MRC), 1987) exceeded the volume of sediment stored on unregulated active bar locations. Channel segments isolated during the cutoff program in the 1930s and 1940s removed point bar and channel sediments from the sediment budget. As a result of these modifications, it may be expected that a negative balance would be produced in the sediment budget and the amount of sediment reaching the Gulf of Mexico would be greatly reduced, particularly the bed load portion.

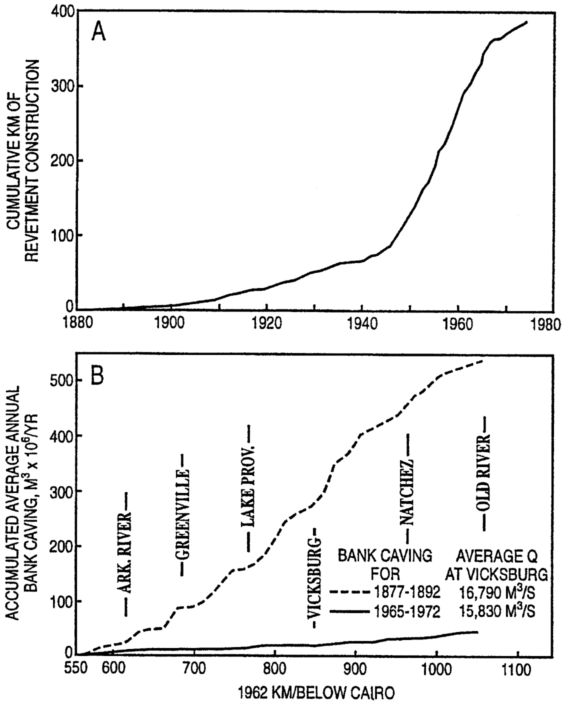

Fig. 2. (A) History of revetment construction Vicksburg District (USACE), (B) bank-caving history for Vicksburg District, before and after revetment construction (modified from Winkley, 1977).

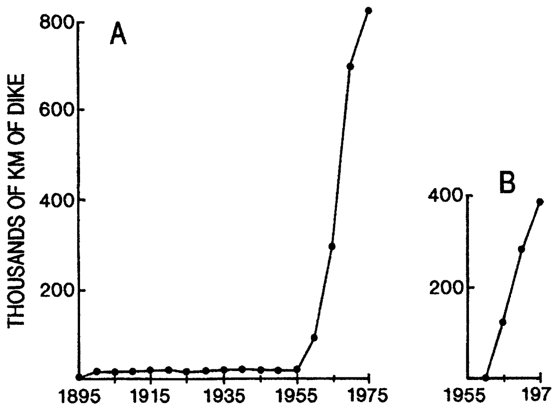

Fig. 3. History of dike construction (A) Memphis District and (B) Vicksburg District (modified from Westphal et al., 1976).

These losses in the available sediment supply have been partially balanced by other changes. Levee construction has reduced the available overbank storage capacity on the flood plain from 89,600 km^2 in 1882 (Elliott, 1932, p. 97) to slightly more than 7000 km^2, a reduction of over 90%. Artificial levees have also markedly altered the sediment dispersal pathways into adjacent flood plain basins. This reduction in pathways is very evident in the Louisiana Gulf coast wetlands, where prior to levees, sediment could enter the wetlands through unconfined overbank flood flow, channel distributaries and numerous crevasse splays (Fig. 4). Sediment accumulation prior to 1900 during overbank flooding below Baton Rouge was estimated to be 1.2 mm/year (Kesel, 1989). From 1849 to 1927, the Mississippi River below Baton Rouge experienced 23 flood years which produced crevasse splays. The number of crevasses per flood year was generally less than 4, but as many as 20 were recorded in 1892 (Vogel, 1930). During the same period, Gunter (1950) estimated that a crevasse occurred once every 2 years in the vicinity of New Orleans. The average area covered by a crevasse splay was about 1500 km^2, with the largest covering 5600 km^2 (Vogel, 1930). Currently, artificial levees prevent the transfer of sediment by these methods in the adjacent wetlands (Fig. 4).

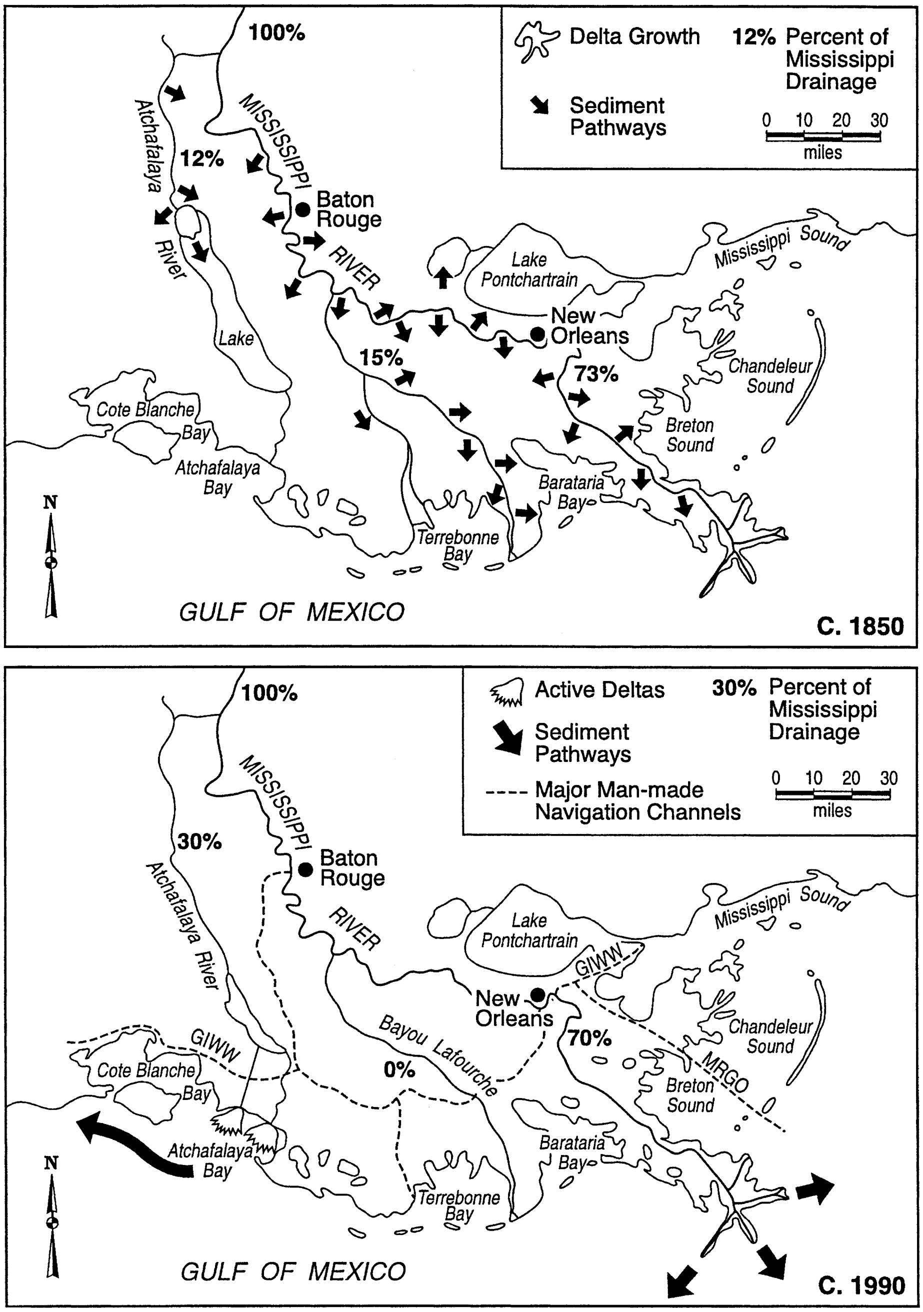

Fig. 4. Comparison of the percentage of Mississippi River discharge flowing into the adjacent wetlands and distributary channels on the Louisiana Deltaic plain for the periods 1850 and 1990.

During cutoff construction and for the 10 years following, alignment dredging added almost 1200×10^6 m^3 of extra sediment to the channel (Winkley, 1977, p. 24). The construction of chute cutoffs introduced an additional 380×10^6 m^3 of dredged sediment to the channel (Winkley, 1977, p. 30).

These modifications either singularly or in combination have brought about changes to a number of channel features. Among the most significant changes are to the channel bars, which include point bars, side and mid-channel bars and the thalweg profile. The analysis of channel bars for different periods based on the MRC hydrographic surveys is shown in Fig. 5. These data represent the net volume change of channel bars measured above the low water plane. The elevation of the 1960 low water plan was used throughout to insure uniformity between each period. Most of the change in the size of channel bars occurs in the river from Cairo to Red River Landing. The river below Red River Landing has only a small number of channel bars and these exhibit relatively little change between map periods (Fig. 5a).

During the 1880–1911 period, channel bars were aggrading throughout the entire upper segment of the river (Fig. 5a). There is little doubt that bank caving was a major source of sediment for channel bars. The variation in the amount of growth in the bars during the period mirrors the distribution of sediment produced by bank caving, particularly, in the 800–1200 km reach of the river (Fig. 6). The lower segment of the river below Red River Landing had only a minor portion of channel bars and thus saw little of the growth.

Channel bar aggradation continued into the 1911–1935 period, with a growth rate almost 50% greater than the previous period (Fig. 5a). However, this volume only represents deposition in the active channel. An additional 25% of channel bar growth occurred in those channel segments removed from the active channel as a result of the channel cutoff program. This increase in bed load may reflect a period when the rate of bank caving was well above normal due to above average discharge flows. During the period from 1907 to 1935, 10 floods with above bankfull discharge occurred with five in the top 10 largest events including the top flood of 1927 (Winkley, 1977, Fig. 10).

The period from 1935 to 1948 saw the amount of sediment being deposited on channel bars reduced by almost 80% from the previous period (Fig. 5a). A portion of this loss is the result of sediment depos-

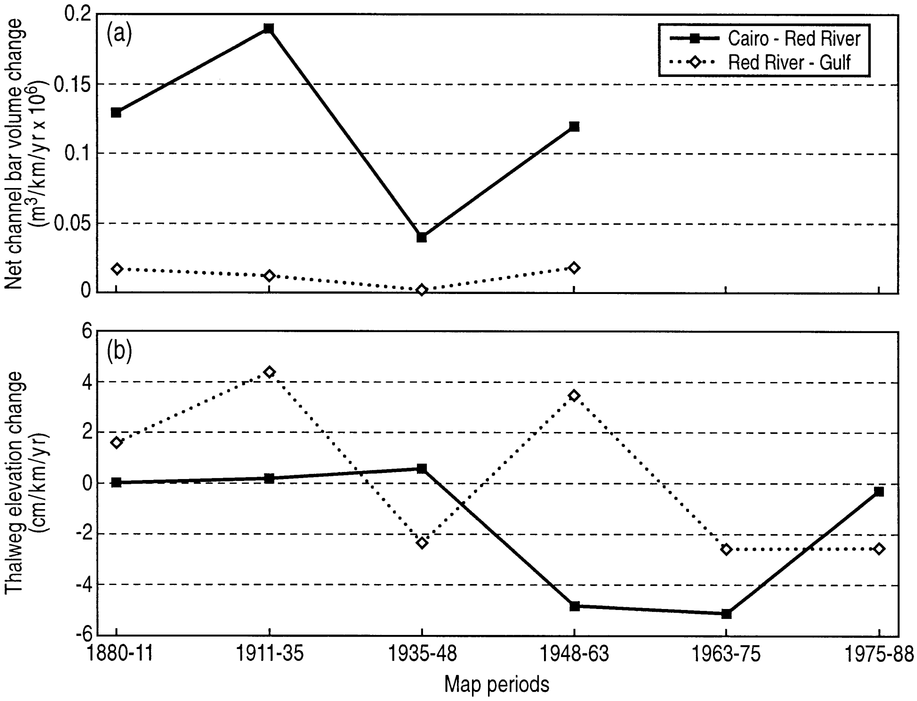

Fig. 5. Lower Mississippi River channel bar and thalweg changes by map period: (a) net change in channel bar volume and (b) change in thalweg elevation.

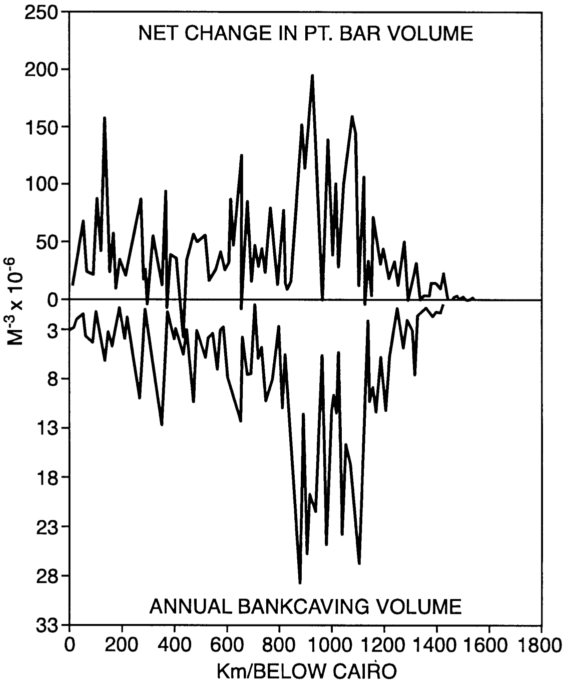

Fig. 6. Comparison of variation in net change of channel bar volume during map period 1880–1911 and average annual bank caving volume prior to 1900 for the Lower Mississippi River (former from Kesel et al., 1992 and latter from Ockerson, 1892).

ited in the active channel but removed when the channel segment was isolated because of the cutoff program.

During the period from 1948 to 1963 the rate of aggradation on channel bars increased significantly. This increase is probably in large part due to the large quantity of dredging undertaken to construct the channel cutoffs. Although quantitative data is scarce for more recent periods, some point bar degradation was evident in the lower portion of the river during the 1970s and 1980s (Fig. 7). By the 1970s, more than 60% of channel bars were associated with dike fields (MRC, 1987).

A comparison of thalweg elevation change for different map periods is shown on Fig. 5b. The data indicate that from 1880 to 1935 the river was aggrading particularly in the segment below Red River Landing. This aggradation may reflect the high proportion of bed load estimated in the earlier sediment budget for the Mississippi River (Kesel et al., 1992). The most dramatic impact on the channel has been the cutoff construction program. The initial degradation resulting from the program began in the early 1930s (Winkley, 1977), but the major degradation occurred during the 1935–1948 period as the cumulative effect was transmitted upriver. The effect of the cutoffs was

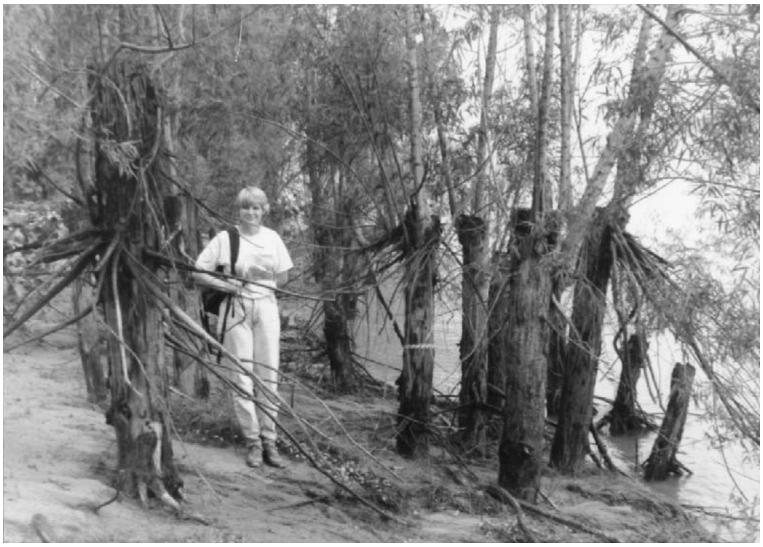

Fig. 7. Photo taken in 1989. Sandbar willows (*Salixexique nutt*) were originally cut-off at ground level during pipeline construction. The cut surface on the trees is 1.2 m above the bar surface. Degradation occurred over a 10-year period.

still evident through the 1963–1975 period (Fig. 5b). The thalweg data from the 1975–1988 period suggests that the river has made a considerable recovery and may be approaching some form of equilibrium.

Fig. 5 also suggests some interesting differences between the two geomorphic divisions and their ability to respond and adjust to change. The river from Cairo to Red River Landing (Fig. 1), which is the meandering portion of the river, tends to exhibit greater flexibility to change the amount and size of channel bars (Fig. 5a). Whereas, the portion below Red River Landing, because the channel is confined and does not migrate, has fewer channel bars that show little variation in size. The change in thalweg elevation exhibits the opposite trend (Fig. 5b). Except for the major adjustment during and immediately after the cutoff program, changes to the thalweg elevation in the upper river remained small or close to unchanged. The upper river in the 1975–1988 period, in fact, appears to be approaching the no change line suggesting the river is adjusting to the effects of the cutoffs. The river below Red River Landing exhibits a much greater variability in thalweg elevation. It is suggested here that changes to the thalweg is how this portion of the river adjusts to change especially from upriver. Thus, the lower river segment, for example, adjusts to changes in the volume of sediment arriving from the upper river by aggradation or degradation of the channel bed and not by changes in the number or size of channel bars. It is also interesting to note that prior to the placement, some modifications, the lines representing the channel bar change in the upper river and the thalweg change in the lower river, have the same trend. It is unclear how valid this comparison is, but these data suggest further investigation is warranted.

6. Conclusions

Previous investigations into the sediment regime of the Lower Mississippi River prior to the introduction of human modifications indicate that the river between Cairo and Red River Landing was basically an aggrading meandering channel. The river between Red River Landing to the Gulf of Mexico acted as a conduit for sediment to reach the coast. This lower reach of the river had little sediment storage capacity nor was any new sediment produced. However, thalweg data in this paper indicates that this lower reach was undergoing considerable aggradation which may have been the result of a high proportion of bed load. The data also suggests that this segment of the river responds to external or internal change by modifying the elevation of the thalweg through aggradation or degradation.

The construction of dams on major tributaries and revetments on the main-stem channel have greatly reduced the sediment input to the river. Because the river is no longer allowed to meander, the sediment storage capacity of the channel has been greatly altered. There is little channel storage although the amount stored in channel bars may equal or exceed that of the pre-modification period as the result of dike construction. The growth rate of channel bars decreased into the 1950s, but has shown a reversal of this trend since dike construction began at that time. Locally, some bars may still be experiencing degradation. Prior to engineering modifications, the river from Cairo to Red River Landing may, in fact, have varied channel bars size as a way of adjusting to changing hydraulic conditions.

The construction of artificial levees has reduced water and sediment storage on the flood plain by over 90%. Artificial levees have also greatly reduced the number of sediment pathways into adjacent flood plain basins. This is strikingly true along the Louisiana coast where sediment is no longer able to enter adjacent wetlands but is funneled out to the continental shelf where it is lost to deeper water.

Thalweg profile data shows the dramatic impact of the cutoff program on the channel bed. Degradation in the vicinity of cutoffs had been transmitted upstream throughout the river within the next 20 years. These data also suggest that by the mid-1970s, the degradation was much reduced and that some type of equilibrium may be taking place.

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