CHANNEL STABILITY OF SELECTED STREAMS IN NORTHERN MISSISSIPPI

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INTRODUCTION

Background

Many of the alluvial streams in Mississippi have been modified by such engineering practices as straightening, dredging, clearing, snagging, and dam construction to help alleviate flooding problems. Channel adjustments resulting from these types of modifications have been shown to result in channel and bank instability and, in some cases, to contribute to bridge failure. In Mississippi channels, widening in excess of 2 to 3 times the premodified width and degradation of as much as 19 feet have been documented by Wilson (1979).

Alluvial channels are dynamic and adjust naturally to altered conditions, such as changes in base level or climate. The rate at which these channels adjust is related to the magnitude of the discharge and the channel gradient. The capacity of a stream to transport the sediment resulting from channel adjustment processes was termed "stream power" by Lane (1955) who proposed the following stream-power equation:

$$QS \qquad Q_s d_{50}, \qquad (1)$$

where

Q = discharge,
S = channel gradient,
Q_s = bed-load discharge, and
d_{50} = median grain size of bed load.

Under natural conditions, channel adjustments usually occur slowly. However, when stream conditions are altered by channelization (channel shortening and deepening), both channel discharge (Q) and channel gradient (S) can be dramatically increased. This results in increases in bed-load discharge (Q_s) and the size of transported bed-material (d_{50}), which, in turn, can cause rapid and significant morphologic change both upstream and downstream from the area of disturbance. In time, the channel adjustments may progress until the energy gradient of the stream approaches that of its unaltered state.

Channel-bed degradation heightens and steepens the stream banks and causes channel widening by mass wasting processes. With time, channel-bed aggradation reduces bank heights and continued mass failures reduce bank angles, allowing bank surfaces to stabilize and become revegetated.

Channel degradation and widening proceed upstream along unmodified reaches and tributaries as a result of downstream modifications. In the case of dam construction, these processes usually migrate downstream from the dam (Williams and Wolman, 1984). Increases in erosion rates upstream lead to substantial aggradation downstream and loss of channel capacity.

Assessment and prediction of channel morphology are needed to adequately protect existing bridges and culverts and to aid in the design of proposed structures. The U.S. Geological Survey, in cooperation with the Mississippi State Highway Department, began a quantitative study using documented techniques to estimate near-future channel-adjustment processes such as channel-bed degradation or aggradation, channel-bank widening, and channel-bank stability. The techniques used in this study have been shown to be applicable to alluvial channels in similar geologic settings, where there is no bedrock control of base level (Wilson, 1979, Simon and Hupp, 1986a, 1986b, 1987).

Purpose and Scope

The purpose of this paper is to present the results of a study of channel stability at selected sites on alluvial streams in northern Mississippi. The major objectives of the study were to:

- Identify channel instability;
- Estimate the amounts of near-future channel-bed degradation or aggradation and channel-bank widening or accretion; and
- Describe the expected stable channel geometry at sites undergoing channel adjustment.

General Description of Study Sites

Ten sites on streams in northern Mississippi were studied (fig. 1). Drainage areas of the sites ranged from 0.26 to 428 mi^2 (square miles). All of the sites studied are in channel reaches that had been modified or affected by downstream channel modifications. The sites are located in four physiographic districts (Black Belt, Pontotoc Ridge, Fall Line Hills, and North Central Plateau) of the East Gulf Coastal Plain (Thornbury, 1965). The composition of the channel beds and banks at the sites consisted of clay, fine sand and (or) dense chalky-sand, clay or silt (Selma Chalk).

The sites as numbered on figure 1 are: (1) Standing Pine Creek and (2) its tributary at State Highway 488, (3) Big Black River Canal at the mouth of Big Black River Canal tributary and (4) the tributary at U.S. Highway 82, (5) Sand Branch and (6) its tributary at State Highway 342, (7) Twentymile Creek at State Highway 370, and (8) Twentymile, (9) Wolf, and (10) Osborne Creeks at U.S. Highway 45. Sand Branch and its tributary, and Twentymile, Wolf, and Osborne Creeks are in the Tombigbee River basin. Big Black River Canal and its tributary are in the Big Black River basin, and Standing Pine Creek and its tributary are in the Pearl River basin.

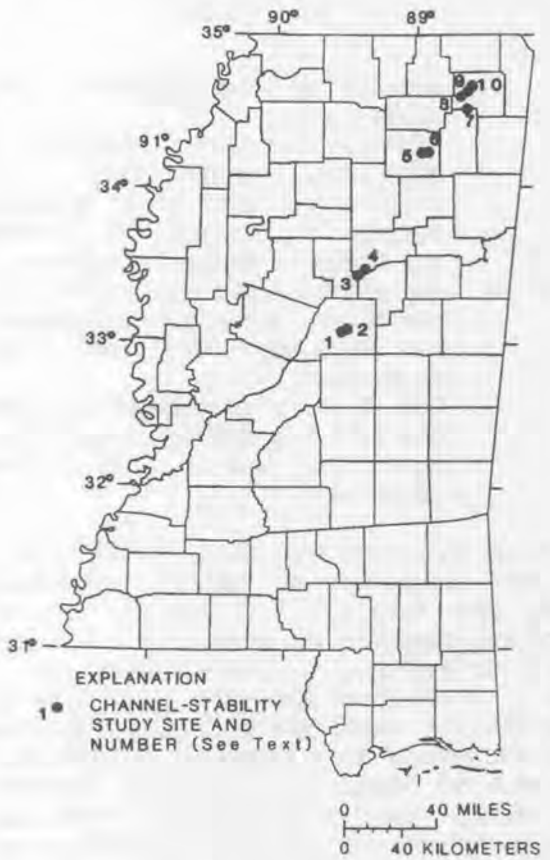

Figure 1. Location of channel-stability study sites in Mississippi.

METHODS

In this investigation, the stability of channel beds and banks was assessed by determining the ages, types, and growth patterns of trees on channel banks, obtaining bulk unit weights and shear-strength properties of bank materials, and surveying channel cross sections and profiles. The potential for near-future degradation was estimated by log-linear regression of channel-bed elevations over time since the channel was modified. The potential for channel-bank failure and near-future widening was estimated using existing channel geometry, shear-strength properties and bulk unit weights of the bank material, and log-linear regression of channel-bank widths over time since channel modification.

Data Collection

Botanical evidence present in trees and other woody perennials growing on unstable bank surfaces was collected at each site. Bank failures along unstable channel reaches may kill, tilt, or scar existing woody plants, and create fresh surfaces upon which plants may become established. Scars and sprouts from tilted parental stems yield accurate (within 1 year, often to the season) dates of bank failure (Sigafoos, 1964, Hupp, 1987, 1988). Increment borings and sapling and tilt sprout cross sections were obtained at selected locations along the channel reach to date bank failures and floods.

Eccentric growth, resulting in anomalous tree-ring series, occurs when the stem is inclined. This type of growth easily can be determined by examination of tree cross sections where concentric ring formation abruptly shifts to the eccentric because ring width is greater in the upslope direction. Trees growing below top of banks can indicate rates of aggradation or degradation through measurement of the thickness of sediment burial, or exhumation, from the root collar, which is established at the ground surface during germination. In this investigation, botanical evidence was collected and examined, using methods described by Simon and Hupp (1987), to estimate past channel-widening rates, bank accretion rates, and the location and timing of bank failures.

Bank stability is a function of shear strength and other forces within the soil matrix that tend to resist failure and those forces, such as gravity, that tend to drive the bank toward failure. For each individual soil strata composing the channel banks, dry bulk unit weights were determined from in-situ density samples and shear strength properties were obtained from field tests run with the Iowa Borehole Shear Tester (BST) (Handy and Fox, 1967). (The use of trade or product names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.)

The BST consists of three major parts: the expandable shear head, a pulling device, and a console controlling the carbon dioxide gas pressure used to expand and contract the shear head. After the borehole has been dug, the shear head attached to a steel pull rod is lowered to the soil stratum to be tested. A normal pressure from the console is then applied to expand the shear plates normal to the walls of the borehole. After time for consolidation, the expanded shear head is pulled axially in the hole, and the pulling force is monitored. The maximum pulling force divided by the two contact plate areas gives the shearing strength, and the expansion force divided by one plate area gives the normal stress. This test sequence is repeated at successively higher normal stresses without removal of the apparatus from the hole. Shearing strength is then plotted with normal stress to give a Mohr-Coulomb type failure envelope (Das, 1984). The slope of the line best fitting the points is the angle of internal friction, and the intercept at zero normal stress is the cohesion. Data obtained using the BST correlate well with standard laboratory unconfined shear-strength tests (Thorne and others, 1981). The instrument allows for repeated in-situ testing at various normal pressures with a considerable monetary savings relative to laboratory testing.

Channel cross sections and stream profiles were surveyed in the vicinity of each site. Top-bank widths, bank heights, and bank angles were obtained. These data, representing existing channel-bed conditions, were then used as a basis for bank-stability analyses and estimates of near-future channel-bank widening.

Quantitative descriptions of changes in channel geometry at a given location were obtained from various sources including the following:

- Existing channel surveys;
- Bridge plans and maintenance reports;
- Modification proposals and design plans;
- Pre-modification data;
- Gaging station records;
- Previous studies; and
- Local drainage district records.

The channel-bed elevations and channel-bank widths were obtained from channel surveys, inspection reports and channel modification plans obtained from the Mississippi Department of Archives and History, the Mississippi State Highway Department, the U.S. Army Corps of Engineers, the U.S. Soil Conservation Service, and the U.S. Geological Survey.

Data Analysis

Channel-bed elevations and channel-bank widths used in this investigation were assumed to be representative of the stream reach at the time of the measurement. However, the majority of channel-bed elevations and channel-bank widths used to analyze degradation or aggradation and channel-bank widening were obtained near bridges, where there was a possibility of localized scour associated with constricted bridge openings. At those sites where localized scour was substantial, the cross sections may not have been representative of the reach and some error may have been introduced into estimates of rates of channel adjustment.

Rates of channel-adjustment in this investigation were based on historical rates and do not take into account additional channel modifications or unusually large destructive flooding that could alter the channel-adjustment processes.

Channel-Bed Gradation Processes

Channel-bed gradation processes for the study streams were estimated based on the assumption that change in channel-bed elevation can be expressed as a power function with time, as developed from studies on alluvial streams in west Tennessee by Simon and Hupp (1986b), in the general form:

$$E = a \cdot t^{\mathbf{b}}, \qquad (2)$$

where

- E = elevation of the channel bed, in feet above sea level;
- a = regression constant, indicative of channel-bed elevation prior to the onset of the channel-bed gradation process in response to channel modification, in feet above sea level;
- b = regression coefficient, indicative of the rate of the gradation process (negative for degradation and positive for aggradation);
- t = time, in years, since beginning of the channel-bed gradation process, ($t = 1$ during the first year of channel adjustment).

In this report, sea level datum was used at all sites for comparison of gradation processes. Datums other than sea level may be used for channel-bed elevations (E) in equation 2 if there is no tie to sea level datum, but this will affect values of **a** and **b**. If elevations above the datum used are greater than they would be if referenced to sea level datum, the value of **a** will increase, but the absolute value of **b** will decrease. If elevations above the datum used are less than they would be if referenced to sea level datum, the value of **a** will decrease, but the absolute value of **b** will increase. Also, by varying the datum, an imposed logarithmic offset for the log-linear relation will change; thus, in some cases, improving or worsening the log-linear statistical fit of the data points. In the Tennessee studies, channel-bed elevations were analyzed by varying the datum and no significant effects on the gradation trends were detected (Andrew Simon, U.S. Geological Survey, oral commun., 1988).

Channel-Bank Stability

Channel-bank stability analysis was used to determine a factor of safety for potential bank failures. The factor of safety is defined as the ratio of the resisting force (shear-strength of the bank material) to the driving force (weight of the bank material), both applied along the failure surface. When the driving force is equal to the resisting force, the factor of safety is equal to 1 and failure is imminent (Huang, 1983). This is based on the assumption that all of the forces are known. A factor of safety of at least 1.5 is usually used in design.

Shear-strength properties and dry bulk unit weights for individual soil strata composing the channel banks were used with channel cross sections to develop minimum factors of safety for various degrees of bank saturation. Using computer software developed by Huang (1983) and Wright (1986), factors of safety for various geometrical bank failures were computed.

Channel-Bank Widening

Estimates of near-future (10 to 20 years) bank widening were obtained by projecting the streambank slough-line on a plotted cross section (Simon and Hupp, 1986a) or extending temporary angles of stability. Temporary angles of stability were estimated for each bank in channel cross sections by averaging the existing bank angle and the angle of internal friction of the bank material, a technique developed by Spangler and Handy (1973). These projections were used in conjunction with bank widening rates obtained from botanical evidence of bank failures. Where enough channel-width information was available, a power function of bank width with time was developed in the form:

$$W = c.t^{d}, \tag{3}$$

where W = channel top-bank width, in feet;

c = regression constant, indicative of top-bank width prior to the onset of widening processes in response to channel modification, in feet;

d = regression coefficient, indicative of the rate of bank widening; and

t = time, in years, since beginning of the bank widening process, ($t = 1$ during the first year of channel adjustment).

This equation may be unsuitable in estimating widening where trees growing below top of bank reinforce and increase the stability of the bank.

DISCUSSION

Channel-adjustment processes for the study streams appear to have progressed in the upstream direction because of modifications to the stream itself and (or) the stream into which it flows, and for some streams, adjustment processes appeared to have been initiated or affected by extreme floods. Channel-bed degradation in these streams increased bank heights and angles and caused channel-bank widening by mass wasting.

Channel-beds

Profiles

For Big Black River Canal tributary, about 10 and 8 feet of degradation were estimated using botanical evidence (observing amounts of exhumation from the root collar for trees growing below top of banks) at the mouth and 3,600 feet upstream of the mouth (near U.S. Highway 82), respectively (fig. 2). A 2-1/2 foot knickpoint incised into a hard clay strata at about 3,600 feet upstream from the mouth is evidence of headward progressing degradation. On Sand Branch tributary, about 5 to 6 feet of degradation at the mouth and 3 to 4 feet of degradation at a point about 780 feet upstream of the mouth (near State Highway 342) were estimated using root-collar botanical evidence (fig. 2). Change in slope of the existing channel bed (composed of clay) between 250 and 500 feet upstream of the mouth of Sand Branch tributary represents an accumulation of failed bank material (consisting mostly of low-erodible clay). Vegetation indicates that the failed material has stabilized. Also, the channel-bed profile just downstream and upstream from of the failed material nearly parallels the estimated channel-bed profile prior to degradation (fig. 2).

Three profiles for Standing Pine Creek and Standing Pine Creek tributary are also presented in figure 2. These profiles were obtained from the U.S. Soil Conservation Service (SCS), except for portions of the 1987-88 profile that were surveyed by the U.S. Geological Survey. The channel bed of Standing Pine Creek and its tributary is composed of fine sand. From 1973 (year of completed channelization) to 1988, Standing Pine Creek aggraded in the reach extending from the mouth to about 10,000 feet upstream and degraded further upstream (fig. 2). The reach of channel from the mouth to about 11,000 to 13,000 feet upstream of the mouth filled and was dredged twice during the period 1973 to 1978 (U.S. Soil Conservation Service, 1987). The channel-bed profile for Standing Pine Creek tributary indicates a scour hole about 5,900 feet upstream of the mouth (fig. 2). When the tributary was channelized in 1973, SCS installed riprap along the channel in the vicinity of the State Highway 488 bridge. Degradation has since progressed upstream causing the riprap on the banks to fall into the channel bed, and this has formed a grade control that has prevented some degradation from moving further upstream. The increased channel-bed slope through the area has resulted in increased flow velocities and local scour just downstream of the riprap.

The channel-bed profiles for all four streams shown in figure 2 are examples of channel-bed degradation decreasing channel gradients with time in order decrease the stream power (equation 1). For each stream, it is evident that the degradation process has progressed in the upstream direction.

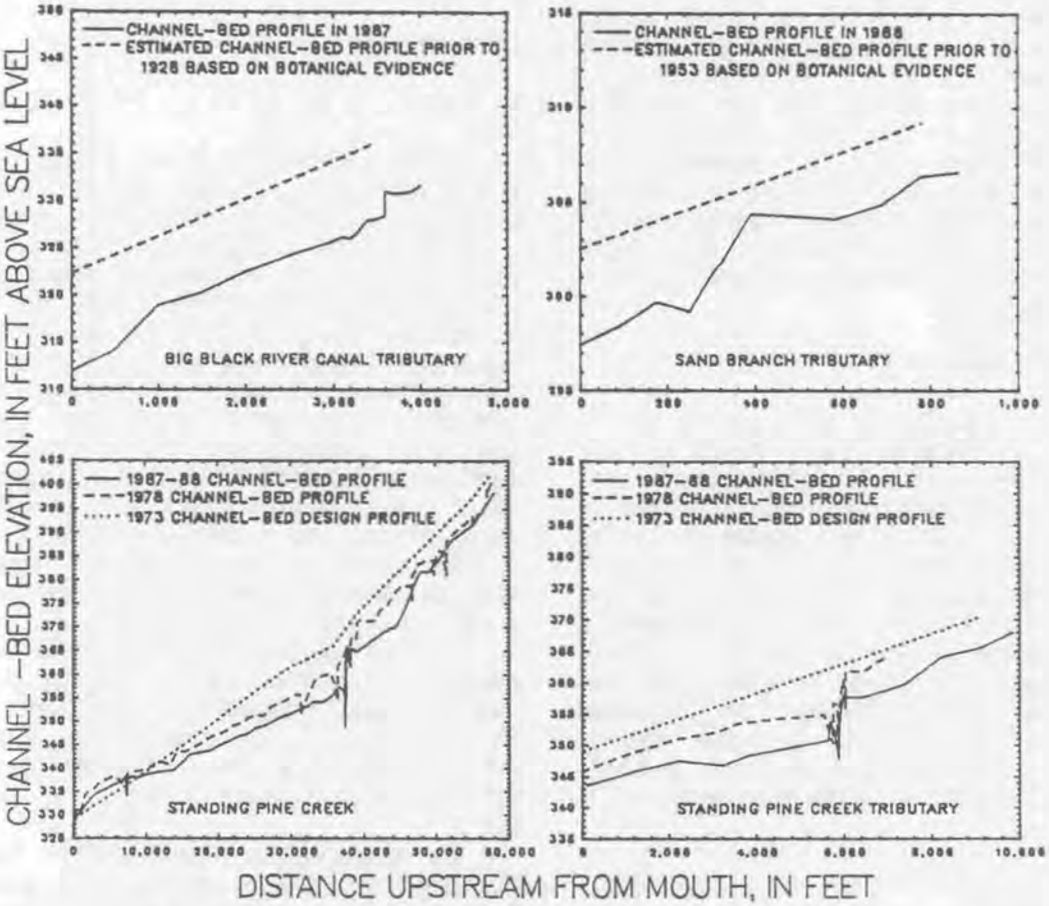

Figure 2. Examples of past and present channel-bed profiles.

Gradation Processes

In the study reaches, the cumulative gradation process was channel-bed degradation which ranged from about 3 to 14 feet. Projected near-future (about 20 years) channel-bed degradation ranged from about 0 to 3 feet; however, additional channel modifications or unusually large destructive flooding could begin other channel adjustment processes. Assuming stream power is proportional to channel-bed composition and bed-load discharge (equation 1), bed composition will subsequently affect the rate of the channel-bed gradation process (b) in equation 2. Values of b, where more than two data points were available, ranged from -0.00928 to -0.00252 for degradation and 0.00159 to 0.00399 for aggradation. The coefficient of determination (R^2) for the gradation processes using equation 2 with more than two data points ranged from 0.86 (four data points) to 1.00 (three data points) (fig. 3). In using equation 2, extreme flood events were assumed in some cases to have initiated channel-bed adjustment processes and were used to select t in equation 2.

Channel-bed degradation on Twentymile Creek at State Highway 370 has totaled about 14 feet since 1910. Two log-linear regressions were performed. One used all of the data points (except for the highest 1915 elevation and the 1975 elevation), and the other was based on the assumption that the March 1955 flood (known to have been an extreme flood in the vicinity) initiated another process (fig. 3). The highest 1915 elevation of about 315 feet was not used in the regression because it represented failed bank material that had fallen into the channel bed and had not yet been removed by streamflows (Ramser, 1930). The 1975 elevation was not used because of the extreme variation from the three data points shown after 1975. Twentymile Creek from the mouth to about 17 miles downstream of State Highway 370 was channelized again in 1966, and an extreme flood occurred in May 1983. However, the available channel-bed elevations do not indicate any other processes being initiated. A grade-control structure was installed by the U.S. Army Corps of Engineers in 1983 just downstream of State Highway 370, and thus, affects the 1988 channel-bed elevation. The projected channel-bed elevation by the year 2010, ignoring and not ignoring the March 1955 flood, is 0.7 feet higher and 0.6 feet lower, respectively, than the 1988 elevation.

Channel-bed elevations on Standing Pine Creek in 1973 (when channelized) and 1978 indicate an aggradation process, but the crossing is located in a reach that was dredged twice between 1973 and 1978 (fig. 3). The stream did aggrade from 1973 to 1978, but to a much greater extent than the available elevations indicate. Also, the elevations for 1978, 1987, and 1988 indicate a possible degradation pattern from 1978 to 1988; however, an extreme flood occurred in April 1979 on Standing Pine Creek. It is likely that the 1979 flood scoured the sand channel bed, but the extent of the scour is unknown. Because the channel-bed of this stream consists mostly of fine-grained sand, channel-bed shifts are likely even during moderate flows. Because of these factors, no estimates of the future channel-bed gradation or aggradation were made.

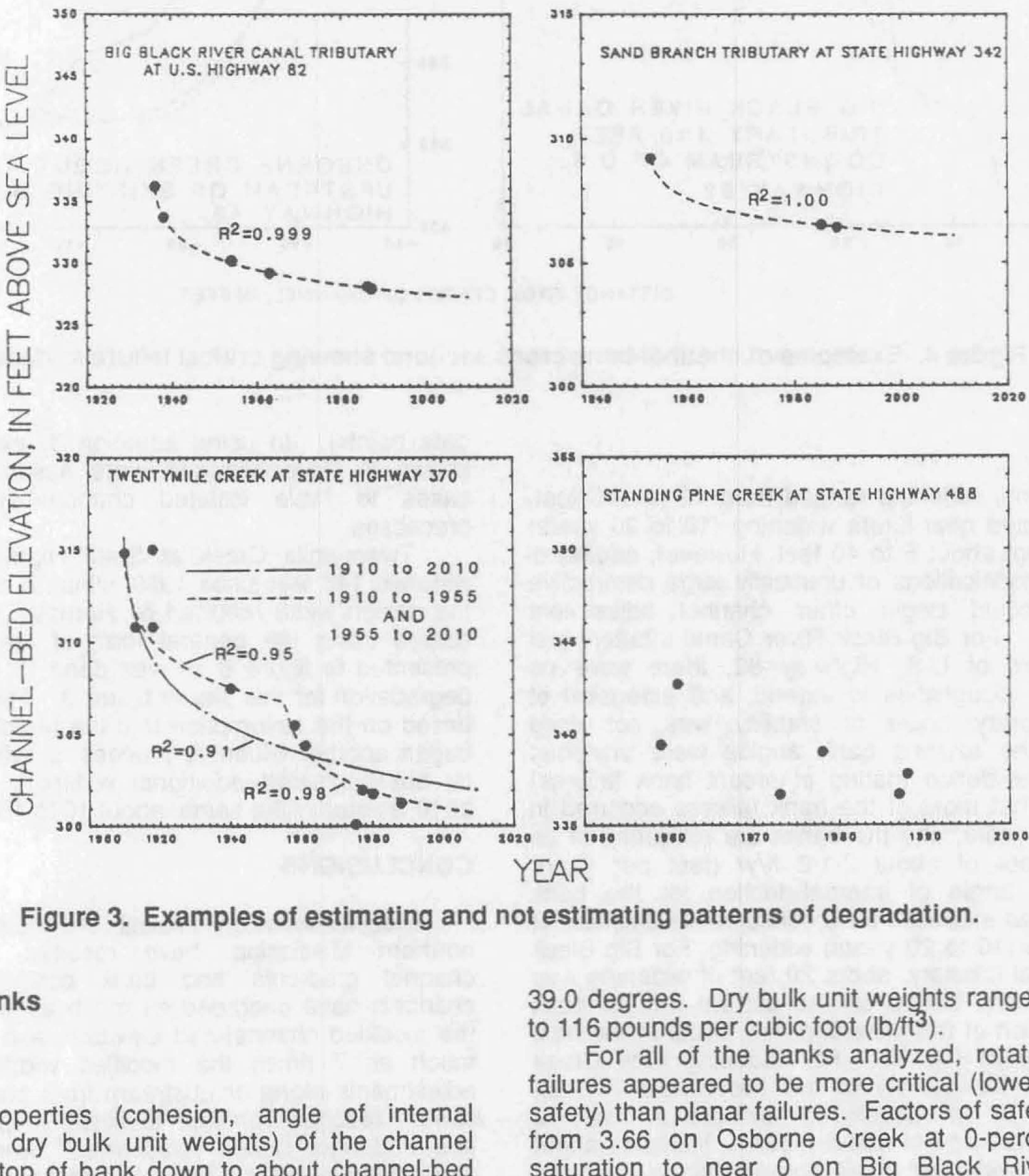

Figure 3. Examples of estimating and not estimating patterns of degradation.

Channel Banks

Stability

Soil properties (cohesion, angle of internal friction, and dry bulk unit weights) of the channel banks from top of bank down to about channel-bed level were determined at seven sites. Values of cohesion ranged from 0 to 640 pounds per square foot (lb/ft^2) and angle of internal friction from 16.2 to 39.0 degrees. Dry bulk unit weights ranged from 89 to 116 pounds per cubic foot (lb/ft^3).

For all of the banks analyzed, rotational-bank failures appeared to be more critical (lower factor of safety) than planar failures. Factors of safety ranged from 3.66 on Osborne Creek at 0-percent bank saturation to near 0 on Big Black River Canal tributary at 100-percent bank saturation, and the potential bank-failure widths ranged from 13 to 1 foot, respectively (fig. 4).

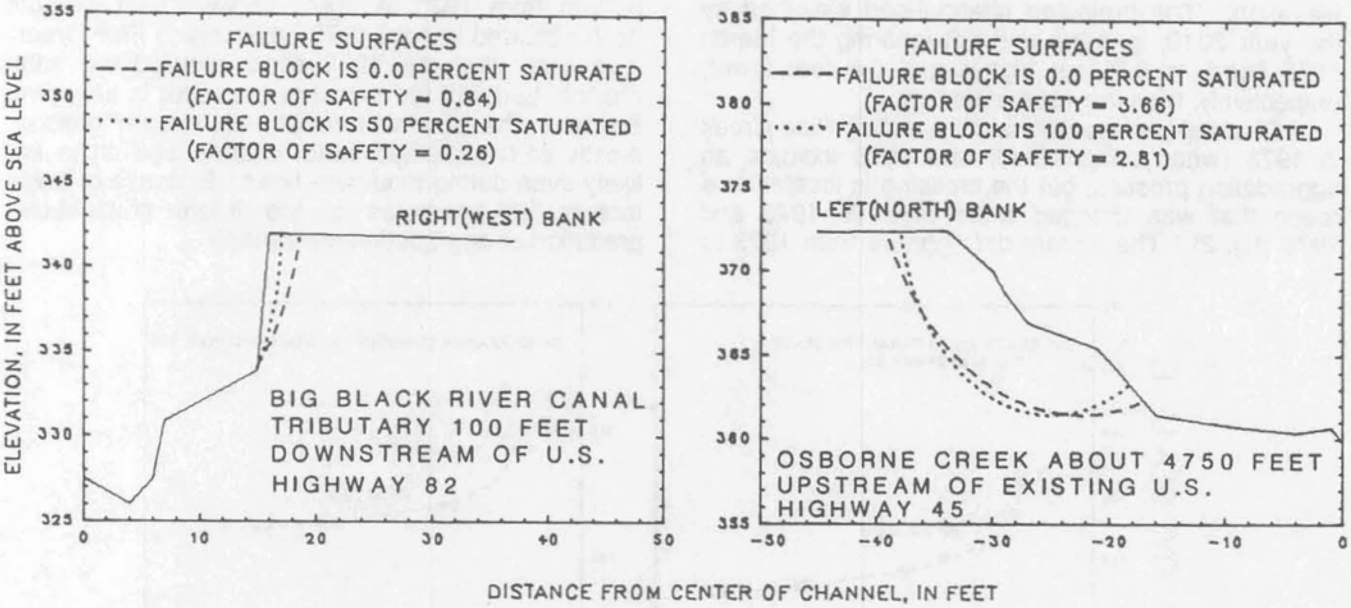

Figure 4. Examples of channel-bank cross sections showing critical failure surfaces.

Widening

Channel widening ranged from 12 to 145 feet, and projected near-future widening (10 to 20 years) ranged from about 5 to 40 feet. However, additional channel modifications or unusually large destructive flooding could begin other channel adjustment processes. For Big Black River Canal tributary just downstream of U.S. Highway 82, there were no developed sloughlines to extend, and extension of the temporary angle of stability was not used because the existing bank angles were unstable. Botanical evidence (dating of recent bank failures) indicated that most of the bank failures occurred in the last 5 years, and the banks are retreating at an average rate of about 2-1/2 ft/yr (feet per year). Therefore, angle of internal friction for the bank material was extended for a conservative estimate of near-future (10 to 20 years) widening. For Big Black River Canal tributary, about 20 feet of widening was estimated, and based on the current rate of bank retreat, much of this widening may occur in the next 5 to 10 years (fig. 5). For Standing Pine Creek tributary in the vicinity of the scour hole (fig. 2), projection of a developed sloughline, with a maximum tree age of about 7 years, indicates about 40 feet of widening could possibly occur over the next 10 to 20 years (fig. 5). Equation 3 was used where enough typical channel widths were available over a period of time. Values of **d** in equation 3 using more than two data points ranged from 0.114 to 0.396, and the coefficient of determination (R^2) ranged from 0.83 (five data points) to 0.997 (four data points). In using equation 3, extreme floods known to have occurred were assumed in some cases to have initiated channel-bank widening processes.

Twentymile Creek at State Highway 370 has widened 145 feet since 1910, which is about 7 times the design width reported by Ramser (1930). Three curves using the general form of equation 3 are presented in figure 6 as was done for channel-bed degradation for this site in figure 3. The two curves based on the assumption that the March 1955 flood began another widening process, provides a tighter fit; but estimated additional widening to the year 2010 is virtually the same, about 10 to 15 feet.

CONCLUSIONS

Modifications on alluvial channels studied in northern Mississippi have resulted in unstable channel gradients and bank conditions. The channels have degraded as much as 14 feet below the modified channel-bed elevation and widened as much as 7 times the modified width. Channel adjustments along or upstream from some modified stream reaches continue to result in property loss and endanger bridge structures. Some channels could degrade up to 3 feet and widen up to 40 feet in the near future.

Channel-bed and channel-bank adjustment processes in the past are assumed to be representative of probable processes in the near future; however, additional channel modifications or unusually large, destructive flooding could begin other channel adjustment processes. In these analyses, botanical evidence of bank failure and degradation were used in conjunction with available channel-bed elevations, channel-bank widths, and knowledge of significant floods in the basin to assess channel instabilities.

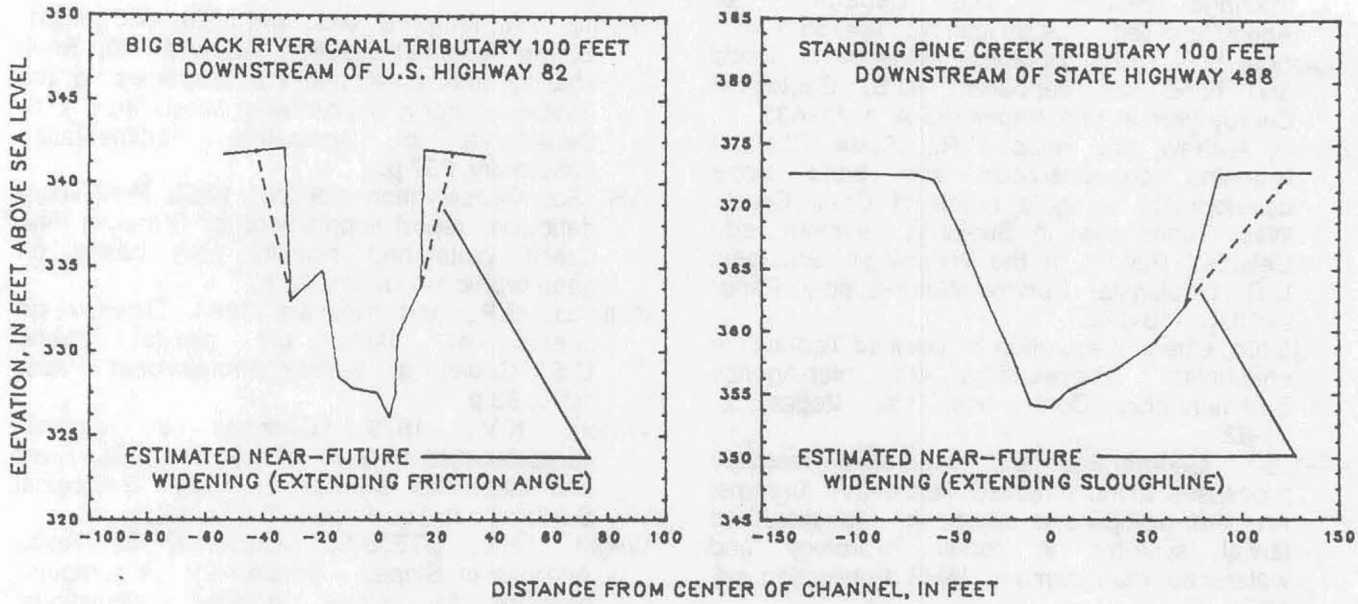

Figure 5. Examples of estimating near-future widening by using bank material properties and existing channel geometry.

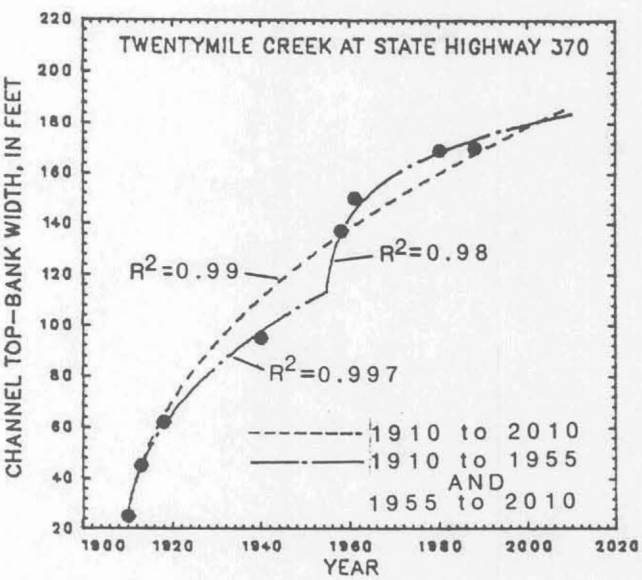

Figure 6. Example of estimated patterns of channel-bank widening.

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