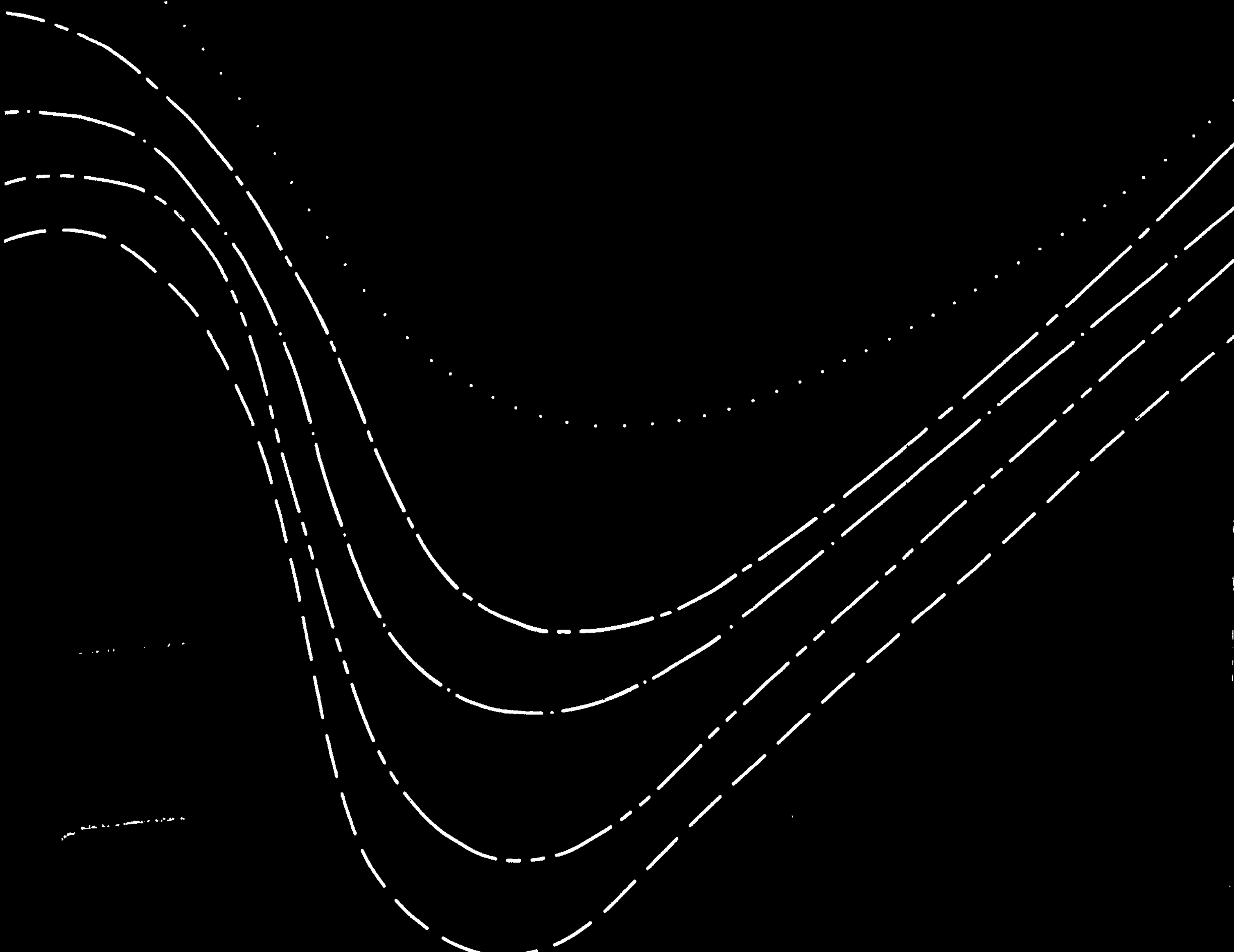
Open-File Report 91-502

# GEOMORPHIC AND VEGETATIVE RECOVERY PROCESSES ALONG MODIFIED STREAM CHANNELS OF WEST TENNESSEE



Prepared by the
U.S. GEOLOGICAL SURVEY

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Cover: Modified profiles of projected channel bed-level lowering over time for North Fork of the Forked Deer River. (See page 52 for detailed illustration.)

# GEOMORPHIC AND VEGETATIVE RECOVERY PROCESSES ALONG MODIFIED STREAM CHANNELS OF WEST TENNESSEE

By Andrew Simon and Cliff R. Hupp

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Nashville, Tennessee
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| Multiply | By | To obtain |
|---|---|---|
| inch (in.) | 25.4 | millimeter |
| foot (ft) | 0.3048 | meter |
| foot per year (ft/yr) | 0.3048 | meter per year |
| square foot ($ft^2$) | 0.0929 | square meter |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second |
| mile (mi) | 1.609 | kilometer |
| square mile ($mi^2$) | 2.590 | square kilometer |
| pound (lb) | 0.454 | kilogram |
| pound per square inch ($lb/in^2$) | 6.89 | kilopascal |

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# GEOMORPHIC AND VEGETATIVE RECOVERY PROCESSES ALONG MODIFIED STREAM CHANNELS OF WEST TENNESSEE

**By Andrew Simon and Cliff R. Hupp**

## ABSTRACT

*Hundreds of miles of streams in West Tennessee have been channelized or otherwise modified since the turn of century. After all or parts of a stream are straightened, dredged, or cleared, systematic hydrologic, geomorphic, and ecologic processes collectively begin to reduce energy conditions towards the premodified state. One hundred and five sites along 15 streams were studied in the Obion, Forked Deer, Hatchie, and Wolf River basins. All studied streams, except the Hatchie River, have had major channel modification along all or parts of their courses.*

*Bank material shear-strength properties were determined through drained borehole-shear testing (168 tests) and used to interpret present critical bank conditions and factors of safety, and to estimate future channel-bank stability. Mean values of cohesive strength and angle of internal friction were 1.26 pounds per square inch and 30.1 degrees, respectively. Dendrogeomorphic analyses were made using botanical evidence of channel-bank failures to determine rates of channel widening; buried riparian stems were analyzed to determine rates of bank accretion. Channel bed-level changes through time and space were represented by a power equation. Plant ecological analyses were made to infer relative bank stability, to identify indicator species of the stage of bank recovery, and to determine patterns of vegetation development through the course of channel evolution. Quantitative data on morphologic changes were used with previously developed six-stage models of channel evolution and bank-slope development to estimate trends of geomorphic and ecologic processes and forms through time.*

*Immediately after channel modifications, a 10- to 15-year period of channel-bed degradation ensues at and upstream from the most recent modifications (area of maximum disturbance). Channel-bed lowering by degradation was as much as 20 feet along some stream reaches. Downstream from the area of maximum disturbance, the bed was aggraded by the deposition of sediment supplied by knickpoint migration upstream; aggradation also occurred in initially degraded sites with time. Additionally, if degradation caused an increase in bank height beyond the critical limits of the bank material, a period of channel widening by mass wasting followed. Degradation knickpoints migrated upstream at rates greater than 1 mile per year; the rates attenuated with distance above the area of maximum disturbance. Channel widening rates of up to 16 feet per year were documented along some severely degraded*

*reaches. Planar failures were generally more frequent but rotational failures dominated the most rapidly widening reaches. Total volumes of bank erosion may represent 75 percent or more of the total material eroded from the channel, but this material generally exits the drainage basin. Mean factors of safety vary with the stage of channel evolution with the lowest values for planar and rotational failures occurring during the threshold stage (stage IV) 1.00 and 1.15, respectively. As channel gradients decrease, degradation ceases and then a period of "secondary aggradation" (at lesser rates than degradation) and bank accretion begins that may fill the channel to near flood-plain level. This shift in process represents an oscillation in channel bed-level adjustment. Streams in basins underlain by loess may require an order of magnitude more time than sand-bed streams to stabilize due to a lack of coarse-grained material (sand) for aggradation.*

*A systematic progression of riparian species that reflects the six-stage model of channel evolution has been identified. This progression can be used to infer ambient channel stability and hydrogeomorphic conditions. Woody vegetation establishes on low- and mid-bank surfaces (the slough line, initially) at about the same time that bank accretion begins. This slough line forms at a mean temporary stability angle of 24 degrees and expands upslope with time by the accretion of sediments. Species involved in this initial revegetation are hardy, fast growing, and can tolerate moderate amounts of slope instability and sedimentation; these species include river birch, black willow, boxelder, and silver maple. Vegetation appears to enhance bank stability, and with increasing stability, species such as bald cypress, tupelo gum, and various hydric oaks, which are more characteristic of stable, premodified riparian settings, begin to establish. Detrended-correspondence analysis indicated species assemblages associated with the six stages of channel evolution and bank-slope development. Ordination of site variables based on species data such as channel widening, bank accretion, and woody vegetative cover also reflects the temporal changes identified by the models.*

*Long-term channel geometry was estimated from a quantitative model of bed-level change, and from documented trends in channel widening. An idealized stable channel of a major sand-bed stream may have a width/depth ratio near 10 and bank slopes of about 24 degrees. This stable channel will ultimately undergo the development of point-bars and incipient meanders, characteristic of unmodified streams.*

## INTRODUCTION

Alluvial channels are dynamic geomorphic features that naturally adjust to altered environmental conditions. This ability to adjust indicates that a natural or man-induced change imposed on a fluvial system will cause channel adjustments that offset the change for some distance upstream and downstream.

Lane (1955) describes this general balance in terms of the stream power proportionality:

$$QS \propto Q_S d_{50}, \quad (1)$$

where Q = water discharge,
S = channel gradient,
$Q_S$ = bed-material discharge, and
$d_{50}$ = median particle size of channel-bed material.

Natural channel adjustments can be exceedingly slow and progressive, practically imperceptible by human standards. When natural stream channels are altered by dredging or straightening (shortening), both bankfull discharge (Q) and channel gradient (S) can be increased. Equation 1 indicates that such channel modifications will result in an increase in bed-material discharge ($Q_S$) and (or) median grain size of the channel-bed material ($d_{50}$), such that rapid and observable morphologic changes occur.

Man-induced changes often involve shortened timeframes relative to naturally induced adjustments. This temporal difference presents an opportunity to examine successive process-response mechanisms through the course of fluvial adjustment over a short period of time. Channelization is a common and controversial engineering practice aimed at controlling flooding or draining wetlands. Channel modifications from 1959 to 1978 throughout most of West Tennessee have created a natural laboratory for the study of channel adjustments and evolution in modified fluvial networks. Quantification of channel responses can be of substantial value in efforts to mitigate the effects of channelization on river-crossing structures and on lands adjacent to, and upstream and downstream from affected channels.

This study was undertaken by the U.S. Geological Survey in cooperation with the Tennessee Department of Transportation to obtain a more complete understanding of the potential effects of alluvial channel changes on West Tennessee bridges and highways. The report is a comprehensive summary of four previous studies of modified streams in West Tennessee and builds on this earlier work.

### *Historical Background*

Prior to major deforestation in the West Tennessee region after the Civil War, rivers "flowed with good depths year round" (Ashley, 1910). Clearing of large tracts of land led to intense erosion of the uplands and to gullying in fields. The eroded material was deposited on the flood plains (Maddox, 1915) and in the stream channels; this resulted in a general loss of channel capacity (Ashley, 1910). Channels became extremely sinuous, choked with sediment and debris, and were subject to frequent and prolonged flooding (Morgan and McCrory, 1910). Early (circa 1910) surveys of the Obion and South

Fork Forked Deer Rivers indicated mild channel gradients of approximately 0.000114 foot per foot (ft/ft) and broad flood plains 1 to 3 miles wide (U.S. Army Corps of Engineers, 1907; Hidinger and Morgan, 1912). Hidinger and Morgan (1912) advocated enlargement of West Tennessee channels and the construction of levees to convey and contain flood waters. Conservation measures were proposed to protect and reclaim the gullied landscape (Maddox, 1915).

Most stream channels in West Tennessee, with the exception of Hatchie River main stem, had been dredged and straightened by 1926 in an effort to decrease the magnitude and frequency of out-of-bank flows (Speer and others, 1965). Further enlargement of the channels occurred in response to the modifications (Ramser, 1930). Subsequent accumulation of debris (trees and stumps) from failed banks caused backwater and sedimentation at the downstream ends of the forks of the Obion and Forked Deer Rivers (Speer and others, 1965). Continued aggradation and debris accumulation through the 1930's necessitated bank clearing and channel snagging (removal of trees and stumps) of about 170 miles of main stem, forks, and tributaries of the Obion River system in the late 1930's and 1940's. After this work was completed, the cycle began again and channel filling occurred through the 1940's and 1950's (Robbins and Simon, 1983). This resulted in the formulation of a regional program to further channelize or rechannelize many of the drainage systems in West Tennessee. Channel work on the Hatchie River during the period 1938-52 was limited to channel snagging, which preserved its meandering course.

From the late 1950's through the 1970's, various types of channelization projects were undertaken in West Tennessee in basins ranging in size from 10.7 to 2,440 $mi^2$; these projects resulted in the adjustment of entire fluvial networks (fig. 1). A short reach of the lower Obion River was modified in 1984 but was not included in this study. The West Tennessee Tributaries Project, which provided for the enlargement and straightening of 118 miles in the Obion River system and 105 miles in the Forked Deer River system, was temporarily halted by court order in 1970 when it was about one-third complete (Robbins and Simon, 1983). At that time, channelization in the Obion River system had extended into the lower reaches of its three forks (fig. 1).

Most downstream reaches of the constructed channels typically began to fill with accumulated sediment and debris emanating from eroding reaches farther upstream (Robbins and Simon, 1983). The entire length of the Obion River main stem has become a depository for material eroded from the North, South and Rutherford Forks. Rates of aggradation along this river range from 0.1 foot per year (ft/yr) at the confluence of the forks, to 0.4 ft/yr, 8.5 miles downstream. At the most downstream study site on the South Fork Forked Deer River, 7.2 feet of infilling took place over a 12-year period after channelization.

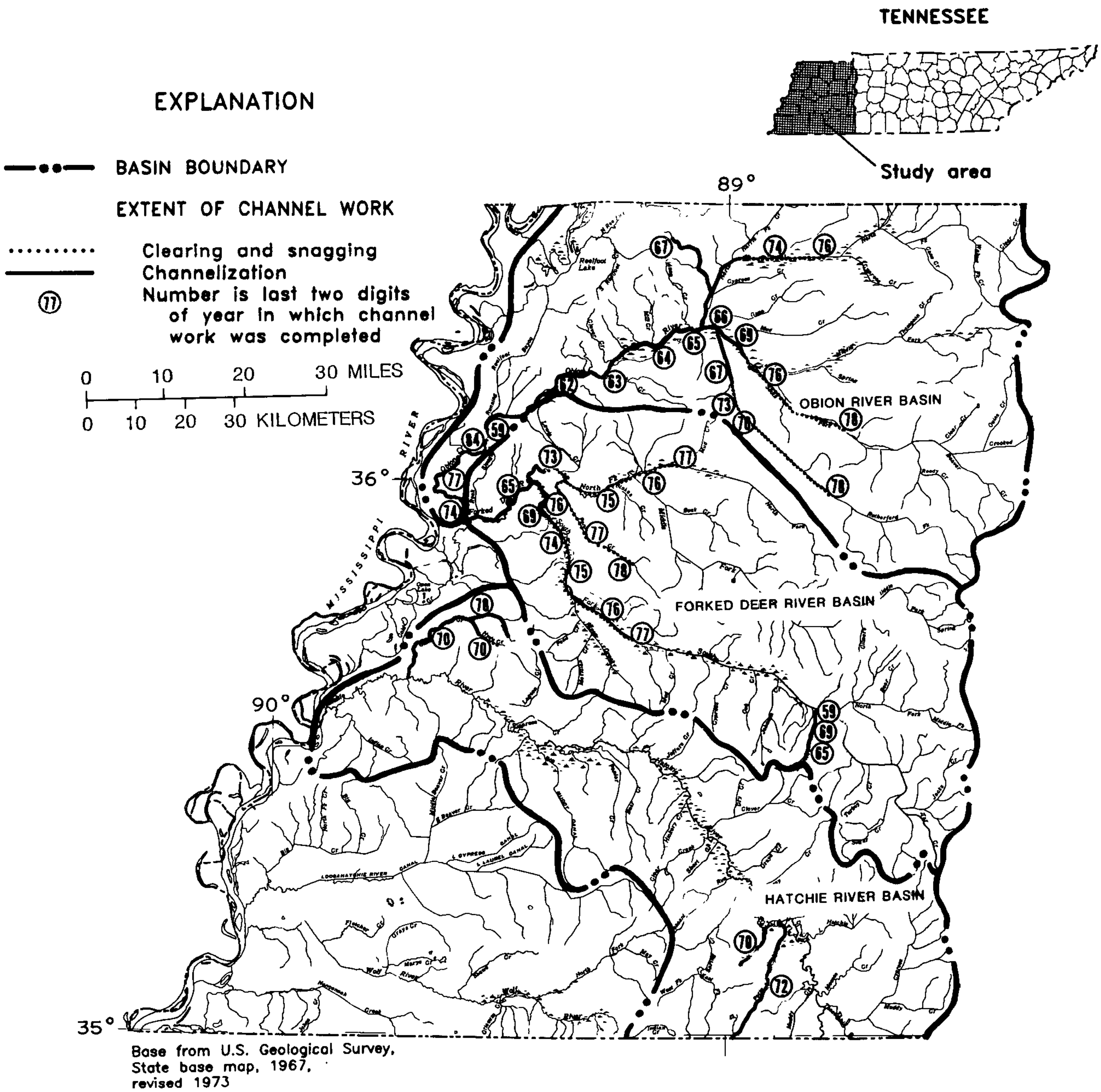


Figure 1.--Extent of recent channel work in West Tennessee.

About 51 miles of channels in the Forked Deer River system and 67 miles of channels in the Obion River system were cleared from 1973 to 1978. Additional dredging and straightening activities on the lower Obion main stem were done in the late 1970's and early 1980's.

Channelization projects of lesser geographic extent than the West Tennessee Tributaries Project also were included in this study (fig. 1). The affected streams were shortened as much as 44 percent, steepened as much as 600 percent, and lowered by as much as 170 percent (Simon, in press). The Hatchie River reflects largely "natural" fluvial development, because the only direct alterations involved snagging and clearing between 1938 and 1952 with no alteration to pattern or profile. It is one of the few sinuous channels remaining in West Tennessee and has shown relative stability in profile (Robbins and Simon, 1983). Therefore, it was excluded from the quantitative analysis of adjustment trends. The Hatchie River, however, cannot be interpreted as representing presettlement conditions because of post-Civil War deforestation, and because its tributary basins are intensely farmed and channelized.

### *Purpose and Scope*

The overall objective of this study was to quantify changes in alluvial-channel morphology after channel modifications, and to provide information regarding expected future changes as a result of those modifications. The purpose of this report is to present the results of a 3-year study, which builds on four previous studies of channelized streams in West Tennessee (Robbins and Simon, 1983; Simon and Hupp, 1986a; Simon and Hupp, 1986b; Simon and Robbins, 1987; Simon and Hupp, 1987; Simon, 1989). These previous studies are discussed in greater detail later in this report. The work described in this report emphasizes interdisciplinary approaches to analysis of fluvial adjustment. Specific objectives of this report are:

1. Quantification of channel-bed and bank adjustments caused by channelization over time and space;

2. Estimation of the amounts of channel-bed degradation, aggradation, channel widening, and bank accretion in order to attain a stable channel cross section;

3. Determination of the relative role of shear-strength and mass-wasting processes in affecting channel morphology over the course of fluvial adjustment;

4. Determination of the reliability of riparian (streambank) vegetation as a major diagnostic criterion for denoting channel processes;

5. Estimating the time required to attain a stable-channel geometry by "natural" adjustment processes;

6. Testing of previously developed six-stage conceptual models of bank-slope development and channel evolution with quantitative data;

7. Incorporation of a previously developed quantitative model of bed adjustment, with quantitative data on channel-width adjustment, into an empirical model of channel evolution;

8. Determination of the ecological response of woody riparian species and their relation to the six-stage models of bank-slope development and channel evolution; and

9. Description of the interdisciplinary methods needed to estimate potential morphologic changes and long-term channel geometry in other unstable alluvial-stream systems.

Analysis of the adjustment of West Tennessee alluvial channels in this report is limited to consideration of the effects of channelization work that was done from the late 1950's through the 1970's (tables 1 and 2). This includes documentation of the trends of geomorphic and vegetative response and the estimation of future, stable-channel geometries over the course of channel evolution. The timeframe involved for these adjustments are in the order of 50 to 100 years (Simon, in press).

### *Study Area*

The study area includes approximately 10,600 $mi^2$ in West Tennessee bounded by the Mississippi River on the west and the Tennessee River divide on the east (fig. 1). This area is entirely within the Mississippi embayment and is part of the Gulf Coastal Plain province (Fenneman, 1938). All stream systems studied drain to the Mississippi River and are in the Obion, Forked Deer, Wolf, and Hatchie River basins (fig. 1, table 1). These rivers flow through unconsolidated and highly erosive sediments (U.S. Department of Agriculture, 1980), predominantly of Quaternary age. The Obion and Forked Deer Rivers flow through Mississippi River alluvial deposits in their most downstream reaches, and loess-derived alluvium farther upstream, and in their forks (fig. 2). Most tributary streams flow across deposits of loess that thin eastward from 100 feet along the bluffs of the Mississippi River, to less than 5 feet near the outcrop of the Claiborne and Wilcox Groups of Tertiary age (Miller and others, 1966; fig. 2). These groups, composed predominantly of sand, are the source of sand for the major drainages of the region, as well as for the eastern tributaries (fig. 2). There is a complete lack of bedrock control of local base level, assuring unrestricted channel adjustment. During the course of this study, none of the studied reaches in the Obion-Forked Deer or Wolf River basins were affected by grade-control structures. Grade-control structures on Cane Creek (upstream of the study sites) and on Cub and Porters Creeks did not influence data analysis.

Table 1.--*Drainage basins, drainage areas, and dominant surficial geology of the study area*

| Basin | Drainage area (square miles) | Dominant surficial geologic units |
|---|---|---|
| Obion River[1,2] | 2,445 | Loess |
| North Fork Obion River | 578 | Loess |
| Hoosier Creek | 34.3 | Loess |
| South Fork Obion River | 426 | Loess |
| Rutherford Fork Obion River. | 277 | Loess |
| Forked Deer River[1] | 2,080 | Holocene alluvium |
| North Fork Forked[1] Deer River. | 952 | Loess |
| Pond Creek | 69.6 | Loess |
| South Fork Forked[1] Deer River | 1,061 | Loess, Claiborne and Wilcox Groups. |
| Wolf River[1] | 816 | Loess, Claiborne and Wilcox Groups. |
| Hatchie River[1] | 2,609 | Loess, Claiborne, and Wilcox Groups. |
| Cane Creek | 86.6 | Loess |
| Hyde Creek | 10.7 | Loess |
| Cub Creek | 16.7 | Midway Group |
| Porters Creek | 63.7 | Midway Group |

[1]Larger streams also flow through substantial alluvial deposits of Holocene age.
[2]Upstream from mouth of Forked Deer River.

The native vegetation growing along channelized streams in many West Tennessee bottomlands has been affected either directly or indirectly by channel modifications (Miller, 1985; Hupp and Simon, 1986). However, a few large tracts of bottomland forest along the Hatchie River main stem remain relatively unaffected by channel work; these tracts function as control areas for this study. The bottomlands are characterized by low gradient, meandering streams with scattered stands of bald cypress (*Taxodium distichum*) and water tupelo (*Nyssa aquatica*). Southern bottomland forests, are on slightly higher elevations, and are composed of green ash (*Fraxinus pennsylvanica*), soft maples (*Acer rubrum*, *A. saccarhinum*), and various hydric oaks (*Quercus*). Cottonwood (*Populus deltoides*), sycamore (*Platanus occidentalis*), black willow (*Salix nigra*), and river birch (*Betula nigra*) also grow in disturbed areas of the bottomland, particularly along the channels.

Table 2.--*Periods and extents of recent channel modifications on studied streams (1959-78)*

[Data from Corps of Engineers, Soil Conservation Service, and Obion-Forked Deer Basin Authority construction plans]

| Stream | Modification type | Distance (miles) | Dates |
|---|---|---|---|
| Obion | Enlarging and straightening | 46.6 | 1959-66 |
| | Clearing and snagging | 4.2 | 1976 |
| | Enlarging and straightening | -- | 1974-77 |
| North Fork Obion River. | Enlarging and straightening | 10.9 | 1967 |
| | Clearing and snagging | 10.8 | 1974-76 |
| Hoosier Creek | Enlarging and straightening | 7.4 | 1967 |
| Rutherford Fork Obion River. | Enlarging | 7.4 | 1967 |
| | Clearing and snagging | 17.9 | 1973-78 |
| South Fork Obion River. | Enlarging | 6.0 | 1967,69 |
| | Clearing and snagging | 17.1 | 1976-78 |
| North Fork Forked Deer River. | Enlarging and straightening | 4.3 | 1973 |
| | Clearing and snagging | 19.6 | 1974-77 |
| Pond Creek | Clearing and snagging | 13.1 | 1976-78 |
| South Fork Forked Deer River. | Enlarging and straightening | 4.4 | 1969 |
| Meridian Creek | Enlarging and straightening | 1.6 | 1959? |
| | Enlarging and straightening | 5.2 | 1969 |
| | Enlarging | 1.6 | 1969 |
| Cane Creek | Enlarging and straightening | 32.3 | 1970 |
| | Enlarging and straightening | 13.0 | 1978 |
| Hyde Creek | Enlarging and straightening | 0.8 | 1970 |
| Cub Creek | Enlarging and straightening | 9.7 | 1970 |
| Porters Creek | Enlarging and straightening | 21.4 | 1972 |
| Wolf River | Enlarging and straightening | 21.8 | 1964 |

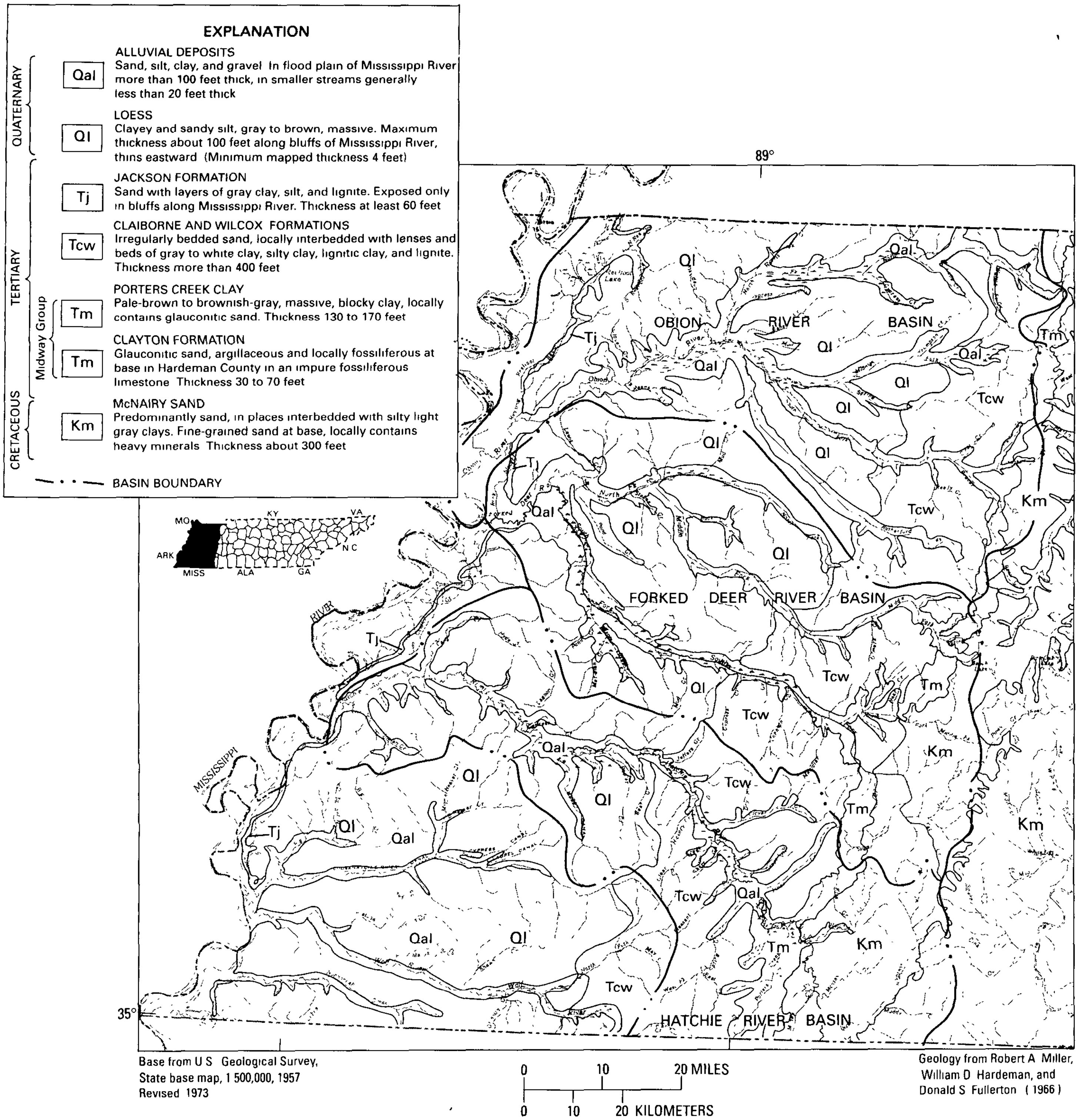


Figure 2.--Surficial geology of West Tennessee.

### *Acknowledgments*

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## CONSEQUENCES OF CHANNEL MODIFICATIONS

Upstream-progressing degradation and downstream aggradation are common attributes of channelized streams, and are caused by increases in channel gradient and capacity. Additional consequences of degradation are bank failures (from overheightening and oversteepening) and undermining of hydraulic structures, such as bridges.

Daniels (1960) reports that straightening of the Willow River in southwestern Iowa, led to approximately 30 feet of degradation in some reaches. Canyon-type gullies formed and extended into the surrounding countryside, damaging agricultural land and forcing the repair and reconstruction of roads and bridges (Ruhe, 1970). Channelization projects between 1938 and 1940 on the lower reaches of the Homochitto River in southwestern Mississippi caused up to 19 feet of degradation, accelerated bank caving, and led to the collapse of several bridges (Wilson, 1979). After channelization of the Blackwater River in Missouri, degradation and channel widening increased channel cross-sectional area by as much as 1,000 percent, which also caused several bridge failures (Emerson, 1971). The channel-bed elevation was lowered about 17 feet in 10 years along some reaches of Cane Creek, West Tennessee, in response to channelization activities (Simon and Hupp, 1986b).

Sediment that eroded from upstream degrading reaches and tributary streams generally is deposited along the low gradient downstream reaches. Such aggradation leads to a loss of channel capacity, increased frequency of flooding, and increased magnitudes of peak flows; this counters the purpose of the channelization (Parker and Andres, 1976). The downstream reaches of Cub and Porters Creeks, Hardeman County, Tenn., became filled with sediments within 2 years after these streams were channelized.

The lowering of channel-bed levels can create an unstable, overheightened and oversteepened bank profile. Continual basal erosion undercuts and removes support for the top part of the bank which ultimately results in "slab failure" (Thorne and others, 1981). High, low-angle slopes may fail along a circular arc as "deep-seated rotational slides" as a result of prolonged wetting and (or) incision (Bradford and Piest, 1980). Fluvial erosion of bank material does not contribute substantially to bank retreat in the loess-derived materials that characterize streams of the West Tennessee study area (Simon, 1989). Channel widening in these materials takes place primarily by mass-wasting processes that occurs when critical conditions (bank height and angle) are exceeded (Lohnes and Handy, 1968). The critical bank height ($H_c$) is a function of the amount of material at the slope base, the slope angle, and moisture and soil conditions. A complete discussion of bank-stability analyses is given in Lohnes and Handy (1968) and Thorne and others (1981).

Bank-stability analyses have been used to assess bank stability in typical loess and loess-derived materials of Iowa and West Tennessee (Lohnes and Handy, 1968; Bradford and Piest, 1980; and Simon and Hupp, 1986b) and northern Mississippi (Thorne and others, 1981; and Little and others, 1982).

Tension cracking and piping are common in loess soils. Tension cracking which develops at the ground surface and proceeds downward (Thorne and others, 1981) serves to destabilize the bank internally. Piping, an erosion process started by the percolation of water through a soil mass, further weakens banks composed of loess-derived alluvium (Simon and Hupp, 1986b).

Channel widening after degradation also is well documented in the literature. Increases in channel width (between tops of banks) and channel capacity as a result of channelization are reported by Hidinger and Morgan (1912), Ramser (1930), Daniels (1960), Parker and Andres (1976), Wilson (1979), Thorne and others (1981), Harvey and others (1983), and Robbins and Simon (1983). Simon and Hupp (1986b) report 150 feet of widening by rotational failures between 1970 and 1980 along some parts of Cane Creek, West Tennessee, after channelization.

### *Channel Adjustment--General*

Channel-bed adjustments through time are best described by nonlinear functions which approach a condition of apparent or quasi-equilibrium. The description of channel adjustment and evolution by nonlinear decay functions is well documented (Schumm and Lichty, 1965; Graf, 1977; Bull, 1979, Hey, 1979, Robbins and Simon, 1983). There seems to be considerable disagreement however as to the mathematical form of the function. Graf (1977) used exponential functions to describe the "relaxation time" necessary to achieve equilibrium after a disturbance. Simon and Robbins (1987) used similar equations to model gradient adjustment through time. Williams and Wolman (1984) found that hyperbolic functions were appropriate for describing channel-bed degradation downstream from dams.

Detailed analytical studies of channel response to channelization are not common in the literature. Most studies of channel response are relatively descriptive; Others deal with network rejuvenation derived from experimental-flume studies (Schumm and Parker, 1973; Begin and others, 1981), and with theoretical models (Schumm, 1973; Graf, 1977; Bull, 1979; and Hey, 1979). Notable exceptions are studies done in northern Mississippi (Schumm and others, 1984), and in West Tennessee. The Tennessee studies are based on field data and attempt to quantify adjustment trends after channelization.

Five studies (including this one) were conducted on the unstable stream channels of West Tennessee between the mid-1970's and the mid-1980's. The first study was designed to investigate channel stability problems near bridges that were initially attributed to localized bridge scour. It was during the course of this investigation that it was realized that scour was of secondary importance, and that entire fluvial net-works were adjusting to man-induced disturbances (Robbins and Simon, 1983; Simon and Robbins, 1987).

The second study was designed specifically to address the problem of channel bed-level changes through time and to associate these changes with the magnitude and extent of the imposed disturbances (dredging and channelization). As a result of this study, a bed-level model was developed (Simon and Hupp, 1986a); comparison of observed and predicted values were provided (Simon, in press); and the conceptual models of bank-slope development and channel evolution were advanced (Simon, 1989; Simon, in press). It was also during this study that the importance of channel widening by mass-wasting processes was first realized.

A third study concentrated on channel adjustments after channelization along a reach of Cane Creek, Lauderdale County, and resulted in the development of a method to estimate future channel widening (Simon and Hupp, 1986b). A fourth study was conducted in cooperation with the Soil Conservation Service along the length of Cane Creek. This work was comprehensive in scope and investigated channel adjustments along a disturbed channel that had no appreciable sand load for downstream aggradation.

Results of the fifth West Tennessee study are given in this report and provide a comprehensive summary of previous work. This report couples detailed analyses of channel-bank processes and forms, and plant ecology, with previously documented models of bank-slope development and channel evolution. Preliminary results of this study were reported in Simon and Hupp (1987).

The northern Mississippi studies concentrate on developing quantitative relations that can be used to recognize channels that would be the most receptive to mitigation measures. An area-gradient index and space-for-time substitutions were used to predict changes in channel morphology (Schumm and others, 1984). The West Tennessee studies have resulted in a quantitative model of bed-level adjustment, and in conceptual models of bank-slope development and channel evolution (Simon and

Hupp, 1986a; Simon, 1989). Because the approach of this study was dictated to some extent by the results of previous work in West Tennessee, a fairly detailed review of those studies will follow in a later section.

### *Vegetation Response*

Vegetation analyses (dendrochronological and plant ecological) are an integral part of the present study. The use of vegetation analyses in the interpretation of geomorphic disturbances, is a relatively recent activity (Graf, 1977; White, 1979: Cairns, 1980; Hupp, 1988). Only a few analyses of riparian vegetation along channelized streams have been conducted (McCall and Knox, 1978; Shields and Nunnally, 1985; Simon and Hupp, 1986a; 1986b; Hupp, 1987).

All of the above-mentioned studies of vegetative response rely on certain basic dendrochronologic concepts that are based on the annual-growth increment of woody plants--the tree ring. Hydrogeomorphic events such as floods and bank failures usually affect the growth rate of woody plants such that datable anomalies can be detected in wood tissue. These anomalies include corrasion scars, tilt sprouts, eccentric growth rings, and suppression or release sequences. Thus, by coring or taking cross-sections of affected stems and counting the number of growth rings since the plant was affected, the number of years since the event occurred can be determined. These techniques have been used in West Tennessee to obtain rates of channel widening and bank accretion (Hupp and Simon, 1986; Hupp, 1987) and to determine the date of initial bank stability.

The magnitude and timing of geomorphic processes are reflected in the presence and character of riparian plants along modified channels or along channels upstream from modifications. Vegetation can be virtually absent along unstable reaches, whereas dense thickets of black willow, river birch, or silver maple can dominate in stable reaches (Hupp and Simon, 1986). The degree of revegetation on the channels banks has been used as an indicator of the general stage of bank-slope development (Simon and Hupp, 1986a, and Simon, 1989).

### *Examples From West Tennessee Studies*

System-wide channel adjustments along streams in West Tennessee have been studied since 1983 by the U.S. Geological Survey. These adjustments involve drastic changes to both the channel bed and banks.

## Channel Bed-Level Adjustments

The general form given by Simon and Hupp (1986a) and used to describe bed-level adjustments through time is:

$$E = a(t)^b \tag{2}$$

where E = elevation of the channel bed for a given year, in feet above sea level;
a = coefficient determined by regression, representing the premodified elevation of the channel bed, in feet above sea level;
t = time since beginning of adjustment process, in years, where $t_0$ = 1.0 (year prior to onset of adjustment process); and
b = dimensionless exponent, determined by regression and indicative of the nonlinear rate of change on the channel bed.

The power function was used because it consistently provided better fits to the measured data than an exponential function. The exponential function, although having a greater physical basis, did not mirror the measured data well when "t" was small. Discussions regarding observed and predicted values using the power function are given in Simon (in press).

Trends of channel bed-level change through time at stream gaging stations (where bed elevation is measured every 4 to 6 weeks) having periods of record of up to 20 years were analyzed by regression of equation 2 and by using a mean channel-bed elevation for each year. Derived trends supported the concept of nonlinear bed-level adjustment (fig. 3). Once it was established that power functions provided the best fit to this gaged data, data from periodically surveyed sites were similarly fitted. Sites with just two recorded channel-bed elevations were included because of confidence in the general trend of adjustment at a site, and to increase areal coverage of the data network.

In situations where disturbed reaches undergo an initial phase of general degradation (-b), followed by a period of general aggradation (+b), the data set was divided into separate degradation and aggradation periods. The separate data sets were then analyzed by regression using equation 2. The curve of the relation described by equation 2 shows that the rate of channel bed-level adjustment at a site is initially rapid and then diminishes with time as the slope of the curve becomes very flat. Values of b calculated in this and previous studies are listed by stream in table 3.

A bed-level model developed by (Simon, 1989) is summarized using the Obion River system as an example (fig. 4). Maximum rates of degradation (largest negative b-values) occur along the stream reach just upstream from the area of maximum channel disturbance (AMD; near river mile 68), which is labeled A in figure 4, as a response to the significant increase in stream power imposed by the

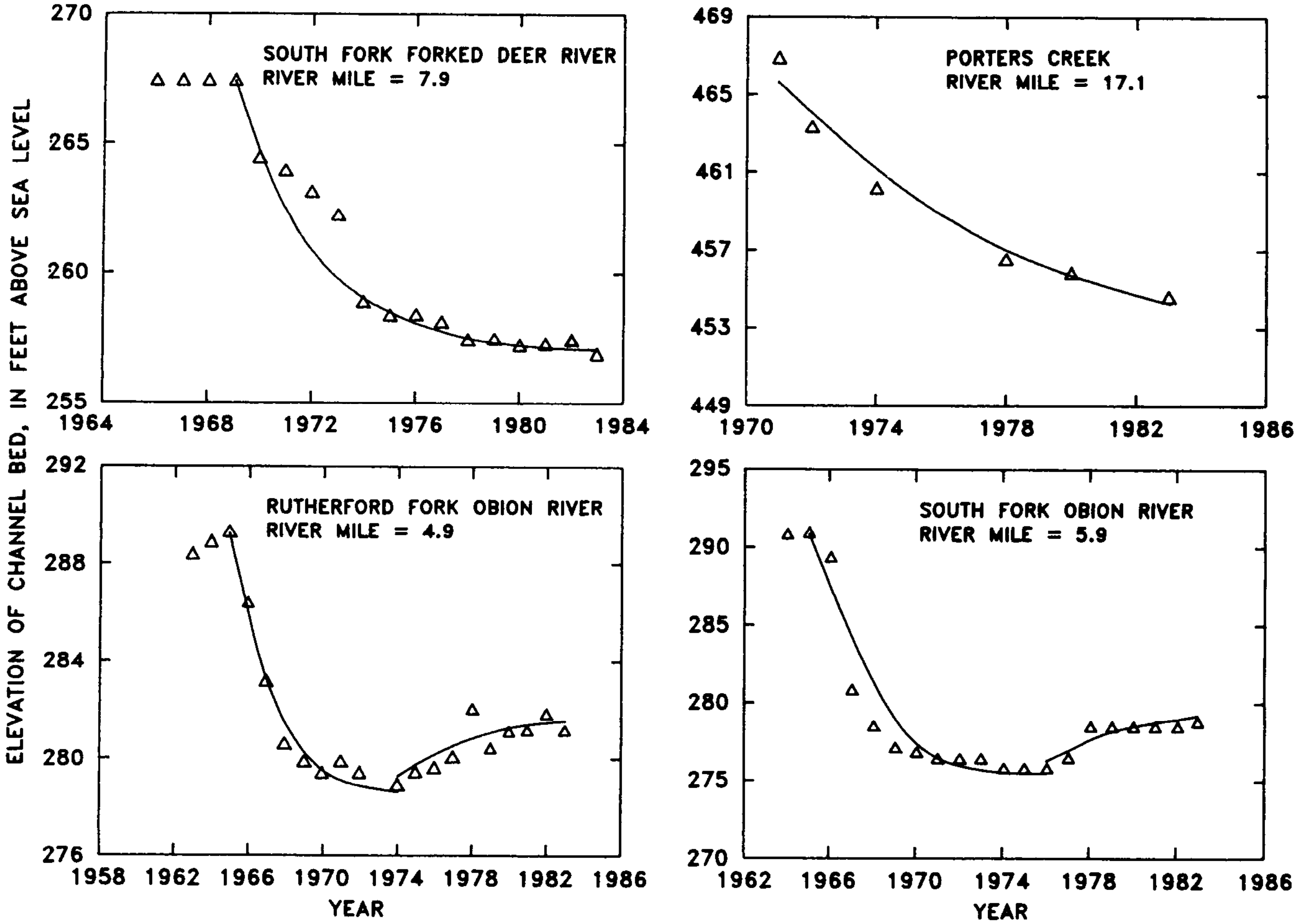



Figure 3.--Relation of channel-bed elevation and time since channel modification for selected stream sites in West Tennessee (curves are visually fitted). (Modified from Simon, 1989.)

channel work here in 1967. The effect of this degradation is to reduce channel gradient (Simon and Robbins, 1987). Degradation rates decrease nonlinearly with distance upstream (curve C in fig. 4). Curve C also represents the headward migration of the degradation process and therefore has a temporal ($t_0$ in table 3), as well as spatial component. Channel-bed degradation continues for 10 to 15 years at sites just upstream from the AMD. The effect of the channel modifications on upstream channel beds decreases with distance, resulting in minimal degradation rates at about river mile 94 (b = 0.0) This is analogous to Bull's (1979) threshold of critical stream power. Further upstream (E in fig. 4), the channel beds of the Obion River system (including upstream reaches of the North, South, and Rutherford Forks) are unaffected by the downstream channel modifications; reaches aggrade at "background" rates (b= 0.003 to 0.006).

Table 3.--*Indicator of nonlinear rates of aggradation and degradation (b values)*

[b=indicator of nonlinear gradation rate; n=number of observations; $r^2$=coefficient of determination, and are provided for gaged stations only to provide a measure of data scatter; RM=river mile, add 62.4 miles to value for sites on Hoosier Creek and the Obion River forks to match with figure 4; $t_0$=year prior to beginning of gradation process; *=specific gage data used; --=not applicable; b values column=calculated from equation 2 ($E = a(t)^b$), page 15]

| Stream | Station number | b | n | $r^2$ | RM | $t_0$ |
|---|---|---|---|---|---|---|
| Cane Creek | 07300025 | -0.00989 | 6 | -- | 16.53 | 1969 |
| | 07300022 | -0.00930 | 6 | -- | 15.95 | 1969 |
| | 07300020 | -0.00560 | 6 | -- | 15.36 | 1969 |
| | 07300019 | -0.01060 | 6 | -- | 14.83 | 1969 |
| | 07300018 | -0.01430 | 6 | -- | 14.05 | 1969 |
| | 07300017 | -0.01660 | 6 | -- | 13.39 | 1969 |
| | 07300016 | -0.01540 | 6 | -- | 12.59 | 1969 |
| | 07300015 | -0.01620 | 6 | -- | 11.84 | 1969 |
| | 07300014 | -0.02020 | 6 | -- | 11.31 | 1969 |
| | 07300013 | -0.02330 | 6 | -- | 11.05 | 1969 |
| | 07300012 | -0.02300 | 6 | -- | 10.26 | 1969 |
| | 07300011 | -0.02470 | 6 | -- | 9.92 | 1969 |
| | 07300010 | -0.02210 | 6 | -- | 8.98 | 1969 |
| | 07300009 | -0.03140 | 6 | -- | 7.99 | 1969 |
| | 07300008 | -0.03090 | 6 | -- | 7.06 | 1969 |
| | 07300007 | -0.02960 | 6 | -- | 6.19 | 1969 |
| | 07300006 | -0.02860 | 6 | -- | 5.71 | 1969 |
| | 07030005 | -0.02780 | 6 | -- | 4.06 | 1969 |
| | 07300004 | -0.02730 | 6 | -- | 3.6 | 1969 |
| | 07300003 | -0.01660 | 6 | -- | 2.52 | 1969 |
| | 07300002 | -0.01480 | 6 | -- | 1.95 | 1969 |
| | 07300001 | -0.01480 | 6 | -- | 0.61 | 1969 |
| Cub Creek | 07029447 | -0.00243 | 3 | -- | 6.92 | 1969 |
| | 07029448 | -0.00342 | 3 | -- | 5.73 | 1969 |
| | 07029449 | -0.00565 | 4 | -- | 2.16 | 1969 |
| | 07029450 | -0.00905 | 5 | -- | 1.54 | 1969 |
| | 07029450 | 0.00272 | 2 | -- | 1.54 | 1976 |
| Hoosier Creek | 07025660 | -0.00843 | 3 | -- | 5.15 | 1967 |
| | 07025666 | -0.01130 | 4 | -- | 2.99 | 1966 |
| | 07025690 | -0.02081 | 3 | -- | 0.55 | 1965 |

Table 3.--*Indicator of nonlinear rates of aggradation and degradation (b values)*--Continued

| Stream | Station number | b | n | $r^2$ | RM | $t_o$ |
|---|---|---|---|---|---|---|
| Hoosier Creek | 07025690 | 0.00274 | 2 | -- | 0.55 | 1968 |
| | 07025691 | -0.02630 | 3 | -- | 0.01 | 1965 |
| Hyde Creek | 07030007 | -0.00737 | 2 | -- | 2.37 | 1969 |
| | 07030004 | -0.01070 | 4 | -- | 1.38 | 1969 |
| | 07030002 | -0.01380 | 3 | -- | 0.74 | 1969 |
| | 07030001 | -0.02050 | 4 | -- | 0.01 | 1969 |
| North Fork Forked Deer River. | 07028500 | 0.02370 | 16 | 0.92 | 34.60 | 1954* |
| | 07028820 | -0.00740 | 4 | -- | 23.90 | 1977 |
| | 07028835 | -0.01076 | 5 | -- | 20.18 | 1974 |
| | 07028840 | -0.00839 | 4 | -- | 18.82 | 1978 |
| | 07029100 | -0.01720 | 10 | 0.95 | 5.30 | 1973* |
| | 07029105 | -0.02297 | 3 | -- | 3.83 | 1972 |
| | 07029105 | 0.01024 | 6 | -- | 3.83 | 1979 |
| North Fork Obion River. | 07025320 | 0.0011 | 15 | 0.69 | 36.90 | 1969* |
| | 07025340 | -0.00206 | 2 | -- | 26.40 | 1979 |
| | 07025375 | -0.00490 | 2 | -- | 21.10 | 1975 |
| | 07025400 | -0.00372 | 13 | 0.80 | 18.00 | 1972* |
| | 07025500 | -0.01240 | 6 | 0.93 | 9.84 | 1965* |
| | 07025600 | -0.02470 | 4 | 0.85 | 5.90 | 1965* |
| | 07025600 | 0.00303 | 5 | 0.89 | 5.90 | 1967* |
| Obion River | 07024800 | -0.02220 | 10 | 0.95 | 68.50 | 1965* |
| | 07024800 | 0.00463 | 10 | 0.74 | 68.50 | 1974* |
| | 07025900 | -0.04030 | 4 | 0.81 | 62.20 | 1965* |
| | 07025900 | 0.00235 | 16 | 0.76 | 62.20 | 1968* |
| | 07026000 | 0.00908 | 19 | 0.93 | 53.70 | 1965* |
| | 07026300 | 0.00518 | 15 | 0.84 | 34.20 | 1963* |
| | 07027200 | 0.00585 | 16 | 0.74 | 20.80 | 1960* |
| Pond Creek | 07029060 | -0.00828 | 5 | -- | 11.37 | 1977 |
| | 07029065 | -0.00799 | 4 | -- | 9.82 | 1977 |
| | 07029070 | -0.01233 | 4 | -- | 7.32 | 1977 |
| | 07027080 | -0.00900 | 5 | -- | 1.06 | 1977 |
| Porters Creek | 07029437 | -0.01069 | 7 | -- | 17.10 | 1971 |
| | 07029439 | -0.01320 | 7 | -- | 11.20 | 1971 |
| | 07029440 | -0.00578 | 6 | -- | 8.89 | 1971 |
| Rutherford Fork Obion River. | 07024900 | 0.00149 | 19 | 0.60 | 29.90 | 1969* |

Table 3.--*Indicator of nonlinear rates of aggradation and degradation (b values)*--Continued

| Stream | Station number | b | n | $r^2$ | RM | $t_o$ |
|---|---|---|---|---|---|---|
| Rutherford Fork | 07025000 | -0.00317 | 4 | -- | 17.90 | 1977 |
| Obion River. | 07025025 | -0.00493 | 3 | -- | 15.20 | 1977 |
| | 07025050 | -0.00991 | 4 | -- | 10.40 | 1972 |
| | 07025050 | 0.00356 | 4 | -- | 10.40 | 1977 |
| | 07025100 | -0.01728 | 9 | 0.93 | 4.90 | 1965* |
| | 07025100 | 0.00433 | 9 | 0.88 | 4.90 | 1974* |
| South Fork Forked | 07027720 | -0.00895 | 6 | -- | 27.60 | 1976 |
| Deer River. | 07027800 | -0.00950 | 10 | 0.92 | 16.30 | 1974* |
| | 07028000 | -0.00978 | 5 | -- | 13.30 | 1969 |
| | 07028050 | -0.01264 | 5 | -- | 11.90 | 1969 |
| | 07028100 | -0.01630 | 15 | 0.94 | 7.90 | 1969* |
| | 07028200 | 0.01180 | 13 | 0.92 | 3.30 | 1969* |
| South Fork Obion | 07024800 | -0.02430 | 11 | 0.87 | 5.80 | 1965* |
| River. | 07024800 | 0.00544 | 9 | 0.88 | 5.80 | 1975* |
| | 07024300 | 0.00030 | 25 | 0.07 | 38.50 | 1963* |
| | 07024350 | 0.00133 | 13 | 0.90 | 34.40 | 1969* |
| | 07024430 | -0.00054 | 4 | -- | 28.40 | 1972 |
| | 07024460 | -0.00238 | 6 | -- | 23.20 | 1972 |
| | 07024500 | -0.00661 | 7 | 0.90 | 19.20 | 1977* |
| | 07024525 | -0.00573 | 5 | -- | 16.80 | 1972 |
| | 07024550 | -0.00932 | 4 | -- | 11.40 | 1972 |
| Hatchie River | 07030050 | 0.00310 | 18 | 0.85 | 33.30 | 1964* |
| | 07029500 | 0.00100 | 19 | 0.52 | 135.1 | 1964* |
| Wolf River | 07031650 | -0.00560 | 5 | -- | 18.90 | 1969 |
| | 07030500 | 0.00060 | 13 | 0.50 | 44.40 | 1972* |

Sites downstream from the AMD (line B in fig. 4) aggrade immediately after channel modification with material delivered from eroding reaches upstream. Aggradation (near 'D', but upstream of the AMD, in fig. 4) occurs at previously degraded sites where gradient has been significantly reduced by incision and knickpoint migration. Flows become incapable of transporting the greater bed-material loads being generated from upstream channel beds. The channel therefore aggrades (according to eq. 1) and increases gradient and transporting capacity. This "secondary aggradation" migrates headward with time and is apparently a response to excessive lowering (overadjustment) by the degradation phase (Simon, in press). This represents the first of a possible series of channel-bed degradation and aggradation oscillations (Simon, in press). Hey (1979) and Alexander (1981) similarly argue for alternating phases of degradation and aggradation following rejuvenation of an alluvial channel. Thus,

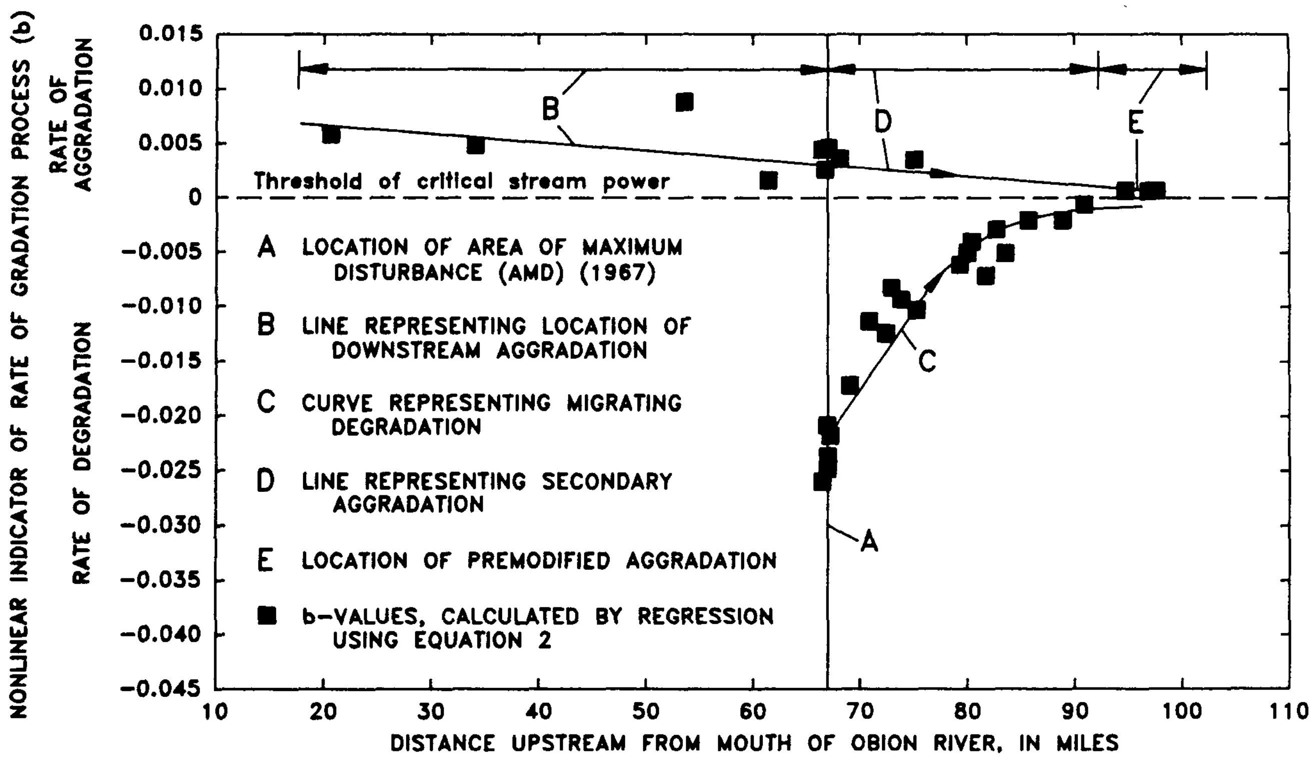



Figure 4.--Model of channel bed-level response to channel disturbance in the Obion River system.

channel bed-level adjustment does follow nonlinear trends, both over time at a site (fig. 3), and over time with distance upstream (fig. 4).

## Lateral Adjustments

Previous studies in West Tennessee concentrated on the role of channel degradation in instigating bank instabilities and channel widening. Simon (in press) found a direct relation between the amount of channel bed-level lowering and subsequent widening. By combining the bed-adjustment model with observed morphologic changes on the channel banks, and by substituting observed morphologic changes that were occurring over space as changes over time, conceptual models of bank-slope development and channel evolution were developed (tables 4 and 5). Dominant channel processes were used to differentiate the six-stages in these models.

Three dynamic surfaces were identified on the channel banks and are outlined in table 4: vertical face, upper bank, and slough line (Simon and Hupp, 1986a, b; fig. 5). The vertical face and upper bank are located on the upper two-thirds of the bank and represent the location of the failure plane and the failed material. The slough line, representing the location of initial bank stability, forms during the

Table 4.--*Stages of bank-slope development*

[-- = not applicable; AMD = area of maximum disturbance]

| Stage No. | Stage Name | Bed-level adjustment type | Location in network | Process on channel bed | Active widening | Failure types | Bank surfaces present | Approximate bank angle, in degrees |
|---|---|---|---|---|---|---|---|---|
| I | Premodified | Premodified | Upstream-most reaches. | Transport of sediment or mild aggradation. | No | -- | -- | 20-30 |
| II | Constructed | -- | Where applicable. | Dredging | By man | -- | -- | 18-34 |
| III | Degradation | Migrating degradation. | Upstream from the AMD. | Degradation | No | -- | -- | 20-30 |
| IV | Threshold | Migrating degradation. | Close to the AMD. | Degradation | Yes | Rotational, slab, pop-out. | Vertical face<br>upper bank. | 70-90<br>25-50 |
| V | Aggradation | Secondary aggradation. | Upstream of the AMD. | Aggradation | Yes | Rotational, slab, pop-out, low-angle slides. | Vertical face<br>upper bank<br>slough line. | 70-90<br>25-40<br>20-25 |
| VI | Restabilization | Downstream-imposed aggradation. | Downstream of the AMD. | Aggradation | No | Low-angle slides, pop-out. | Vertical face<br>upper bank<br>slough line. | 70-90<br>25-35<br>15-20 |

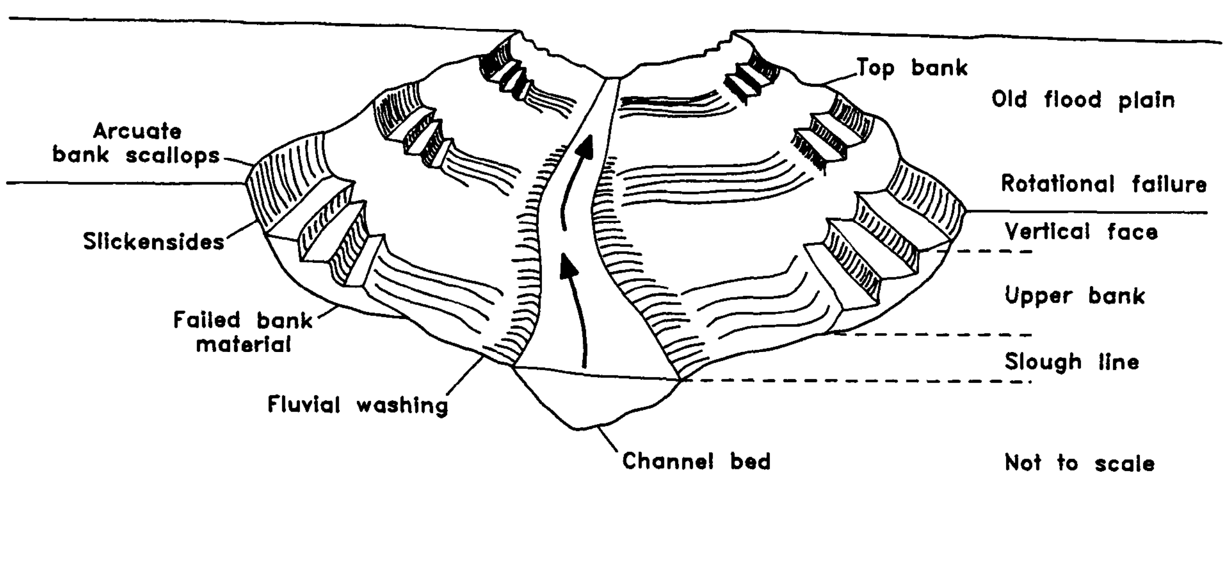



Figure 5.--Generalized streambank section showing typical geomorphic surfaces.

Table 5.--*Stages of channel evolution*

[-- = not applicable]

| Stage No. | Stage Name | Dominant processes: Fluvial | Dominant processes: Bankslope | Characteristic forms | Geobotanical evidence |
|---|---|---|---|---|---|
| I | Premodified | Sediment transport, mild-aggradation; basal erosion on outside bends; deposition on inside bends. | -- | Stable, alternate bars, convex, top-bank shape; flow-line high relative to top bank; channel straight or meandering. | Vegetated banks to flow-line. |
| II | Constructed | -- | -- | Trapezoidal cross section linear bank surfaces; flow-line lower relative to top bank. | Removal of vegetation (?). |
| III | Degradation | Degradation; basal erosion on banks. | Pop-out failures | Heightened and steepended stream banks; alternate bars eroded; flow-line lower relative to top bank. | Riparian vegetation high relative to flow-line and may lean to channel. |
| IV | Threshold | Degradation; basal erosion on banks. | Slab, rotational and pop-out failures. | Large scallops and bank retreat; vertical-face and upper-bank surfaces; failure block on upper bank; some reduction in bank angles; flow-line very low relative to top bank. | Tilted and fallen riparian vegetation. |
| V | Aggradation | Aggradation; development of meandering thalweg; initial deposition of alternate bars; reworking of failed material on lower banks. | Slab, rotational and pop-out failures; low-angle slides of previously failed material. | Large scallops and bank retreat; vertical face upper bank, and slough line; flattened bank angles; flow line low relative to top bank; development of new flood plain (?). | Tilted and fallen vegetation; re-establishing vegetation on bank; deposition of material on root collars of slough-line vegetation. |
| VI | Restabilization | Aggradation; further development of meandering thalweg, further deposition of alternate bars; re-working of failed material; some basal erosion of outside bends. | Low-angle slides; some pop-out failures near flow line. | Stable, alternate channel bars; Convex-short vertical face at top bank; flattened bank angles, development of new flood plain (?); flow-line high relative to top bank. flow-line high relative to top bank. | Re-establishing vegetation extends up slough-line and upper-bank; deposition of material above root collars slough-line and upper-bank vegetation; vegetation establishing on bars. |

aggradation stage (stage V) from colluvium moving further down slope under saturated conditions, and by the deposition of fluvial sediments. Woody vegetation becomes established on the slough line and can be dated by dendrochronologic techniques to establish the timing of lower bank stability (Hupp, 1987). A simplified summary of the types of geobotanical evidence used to aid in differentiating among stages of channel evolution is given in table 5 (Simon, 1989).

Certain species are useful as surrogate indicators of the physical conditions associated with a particular site. The presence of any established woody plants on "affected" banks suggests some bank stability. After initial stabilization pioneer vegetation becomes established and increasingly more complex vegetation assemblages grow on these previously disturbed banks. Thus, progressive suites of vegetation are indicators of increasingly stable bank conditions (Hupp, 1987).

## METHODS OF INVESTIGATION

The methods used in this study are interdisciplinary. They include the fields of geomorphology, soil mechanics and geotechnical engineering, hydrology, dendrochronology, and ecology. A total of 105 sites were used.

### *Site Selection*

The streams studied reflect varying magnitudes and types of channel modifications from 1959 through the 1970's (table 2). A sufficient number of sites was selected along each stream system to assess adjustment trends and processes and to develop quantitative relations with distance upstream (fig. 6 and table 6). At least two previous channel cross sections (a premodified cross section and the constructed cross section) were used to analyze adjustment trends. An attempt was also made to include channels representative of the various geologic formations that crop out in the region (table 1). Because all of the study sites are near bridges, particular caution was used to avoid channel sections that reflected a strong hydraulic influence by the bridge. In most cases, cross sections were surveyed away from the hydraulic influence of the bridge structure and fill materials.

### *Data Collection, Compilation, and Analysis*

Channel-geometry measurements were made from 1983 through 1987 at the sites indicated in table 6 as part of this and previous studies. These data were combined with previously assembled data sets (Simon, in press).

### Channel Morphology

Channel-geometry data were used to determine amounts of morphologic change and to trace channel evolution over time and space. Data included channel-bed (thalweg) elevation, channel width, bank angles, bank height, and classification of various geomorphic surfaces.

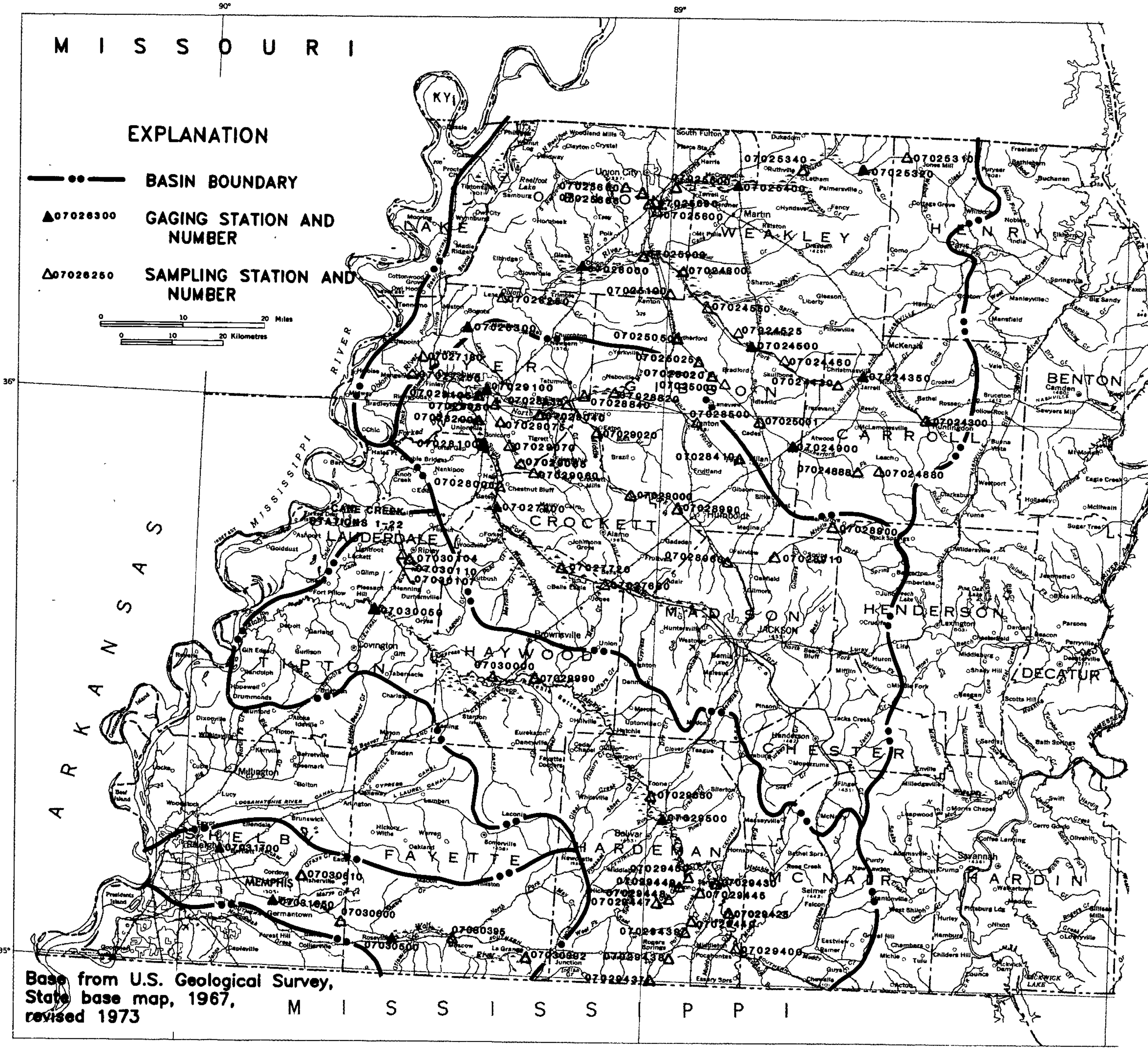



**Figure 6.—Location of sites in study area.**

Table 6.--*Summary of data collected at study sites*

[b=indicator of nonlinear gradation rate; BST=shear strength testing]

| Stream | Station number | River mile | b | Cross section | BST | Dendro-geomor-phology | Modified channel? |
|---|---|---|---|---|---|---|---|
| | | | ***Obion River Basin*** | | | | |
| Obion River | 07027200 | 20.8 | X | X | X | X | Yes |
| | 07027180 | 25.6 | | X | X | X | Yes |
| | 07026300 | 34.2 | X | X | X | X | Yes |
| | 07026250 | 42.4 | | X | X | X | Yes |
| | 07026000 | 53.7 | X | X | X | X | Yes |
| | 07025900 | 62.2 | X | X | X | X | Yes |
| | 07024800 | 68.5 | X | X | X | X | Yes |
| South Fork Obion River. | 07024800 | 5.8 | X | X | X | X | Yes |
| | 07024550 | 11.4 | X | X | X | X | No |
| | 07024525 | 16.8 | X | X | X | X | No |
| | 07024500 | 19.2 | X | X | X | X | No |
| | 07024460 | 23.2 | X | X | X | X | No |
| | 07024430 | 28.5 | X | X | X | X | No |
| | 07024350 | 33.8 | X | X | | X | No |
| Rutherford Fork Obion River. | 07025100 | 4.9 | X | X | X | X | Yes |
| | 07025050 | 10.4 | X | X | X | X | No |
| | 07025025 | 15.2 | X | X | X | X | No |
| | 07025020 | 17.1 | | X | X | X | No |
| | 07025001 | 24.5 | | | | X | No |
| | 07025000 | 17.9 | X | X | X | X | No |
| | 07024900 | 29.9 | X | X | X | X | No |
| | 07024888 | 39.4 | | | X | X | No |
| North Fork Obion River. | 07025600 | 5.9 | X | X | X | X | Yes |
| | 07025500 | 10.0 | X | X | X | X | Yes |
| | 07025400 | 18.0 | X | X | X | X | No |
| | 07025375 | 21.1 | X | X | X | X | No |
| | 07025340 | 26.4 | X | X | X | X | No |
| | 07025320 | 34.9 | X | X | X | X | No |
| Hoosier Creek | 07025690 | 0.55 | X | X | X | | Yes |
| | 07025666 | 2.99 | X | X | X | | Yes |
| | 07025660 | 5.15 | X | X | X | | Yes |
| | | | ***Forked Deer River Basin*** | | | | |
| North Fork Forked Deer River. | 07029105 | 3.83 | X | X | X | X | Yes |
| | 07029100 | 5.30 | X | X | X | X | Yes |
| | 07029040 | 13.55 | | X | X | X | No |
| | 07028840 | 18.82 | X | X | X | X | No |
| | 07028835 | 20.18 | X | X | X | X | No |
| | 07028820 | 23.9 | X | X | X | X | No |
| | 07028500 | 34.6 | X | X | X | X | No |
| | 07028410 | 39.6 | | X | | X | No |

Table 6.--*Summary of data collected at study sites*--Continued

| Stream | Station number | River mile | b | Cross section | BST | Dendro-geomor-phology | Modified channel? |
|---|---|---|---|---|---|---|---|
| | | | ***Forked Deer River Basin***--Continued | | | | |
| South Fork Forked Deer River. | 07028200 | 3.3 | X | X | X | X | Yes |
| | 07028100 | 7.9 | X | X | X | X | No |
| | 07028050 | 11.9 | X | X | X | X | No |
| | 07028000 | 13.3 | X | X | X | X | No |
| | 07027800 | 16.3 | X | X | X | X | No |
| | 07027720 | 27.6 | X | X | X | X | No |
| | 07027680 | 33.7 | | X | X | X | No |
| Middle Fork Forked Deer River. | 07029020 | 5.2 | | X | | X | No |
| | 07029000 | 14.6 | | X | | X | No |
| | 07028990 | 21.5 | | X | | X | No |
| | 07028900 | 44.9 | | X | | X | No |
| | 07028960 | 30.5 | | X | | X | No |
| | 07028910 | 37.0 | | X | | X | No |
| Pond Creek | 07029080 | 1.1 | X | X | X | X | No |
| | 07029075 | 3.1 | | X | X | X | No |
| | 07029070 | 7.3 | X | X | X | X | No |
| | 07029065 | 9.8 | X | X | X | X | No |
| | 07029060 | 11.4 | X | X | X | X | No |
| | | | ***Hatchie River Basin*** | | | | |
| Hatchie River | 07030050 | 33.3 | X | | | X | No |
| | 07030000 | 68.4 | | | | X | No |
| | 07029650 | 121.1 | | | | X | No |
| | 07029500 | 135.1 | X | | | X | No |
| | 07029430 | 162.3 | | | | X | No |
| | 00029400 | 181.8 | | | | X | No |
| | 07029270 | 200.1 | | | | | No |
| Cane Creek | 1 | .61 | X | X | X | X | Yes |
| | 2 | 1.95 | X | X | X | X | Yes |
| | 3 | 2.52 | X | X | X | X | Yes |
| | 4 | 3.64 | X | X | X | X | Yes |
| | 5 | 4.02 | X | X | X | X | Yes |
| | 6 | 5.72 | X | X | X | X | Yes |
| | 7 | 6.27 | X | X | X | X | Yes |
| | 8 | 7.06 | X | X | X | X | Yes |
| | 9 | 7.99 | X | X | X | X | Yes |
| | 10 | 8.99 | X | X | X | X | Yes |

Table 6.--*Summary of data collected at study sites*--Continued

| Stream | Station number | River mile | b | Cross section | BST | Dendro-geomor-phology | Modified channel? |
|---|---|---|---|---|---|---|---|
| | | | ***Hatchie River Basin*--Continued** | | | | |
| Cane Creek | 11 | 9.92 | X | X | | X | Yes |
| | 12 | 10.25 | X | X | X | X | Yes |
| | 13 | 11.05 | X | X | | X | Yes |
| | 14 | 11.36 | X | X | X | X | Yes |
| | 15 | 11.84 | X | X | | X | Yes |
| | 16 | 12.58 | X | X | X | X | Yes |
| | 17 | 13.39 | X | X | | X | Yes |
| | 18 | 13.98 | X | X | X | X | Yes |
| | 19 | 14.85 | X | X | X | X | Yes |
| | 20 | 15.34 | X | X | X | X | Yes |
| | 22 | 15.95 | X | X | | X | Yes |
| Hyde Creek | 1 | 0.15 | X | X | X | X | Yes |
| | 2 | 1.21 | X | X | X | X | Yes |
| | 4 | 1.9 | X | X | X | X | Yes |
| Porters Creek | 07029445 | 4.5 | | X | X | X | Yes |
| | 07029440 | 8.9 | X | X | X | X | Yes |
| | 07029439 | 11.2 | X | X | X | X | Yes |
| | 07029438 | 13.9 | | X | | X | Yes |
| | 07029437 | 17.1 | X | X | X | X | Yes |
| Cub Creek | 07029450 | 1.5 | X | X | X | X | Yes |
| | 07029449 | 2.2 | X | X | | X | Yes |
| | 07029448 | 5.7 | X | X | X | X | Yes |
| | 07029447 | 6.9 | X | X | X | X | No |
| | | | ***Wolf River Basin*** | | | | |
| Wolf River | 07031700 | 9.1 | | | X | X | Yes |
| | 07031660 | 15.4 | | X | | X | Yes |
| | 07031650 | 18.9 | X | X | X | X | Yes |
| | 07030610 | 23.6 | | X | X | X | No |
| | 07030600 | 31.2 | | X | X | X | No |
| | 07030500 | 44.4 | X | X | X | X | No |
| | 07030395 | 57.5 | | X | X | X | No |
| | 07030392 | 69.9 | | | | X | No |

### *Channel-Bed Elevations*

The average annual water-surface elevation at a given low-flow discharge can be used to infer an average annual channel-bed level by assuming that changes in water-surface elevation at that discharge are caused by bed-level changes (Blench, 1973). This technique was used at gaged sites to determine average annual changes in channel-bed level because historic bed-elevation data were not available. A low-flow discharge was used to minimize the effect of variations in channel width on flow depth. At all ungaged sites, channel-bed elevation was obtained from surveyed cross sections of the channel (rounded to tenths of feet). Data for premodified and constructed cross sections also were obtained from the U.S. Geological Survey, Corps of Engineers (COE), TDOT, Soil Conservation Service (SCS), and Obion-Forked Deer Basin Authority (OFBA). All ungaged sites were surveyed annually from 1983 to 1987 during low-flow conditions. Channel-bed elevation, if measured in the vicinity of a bridge, is defined for this study as the mean of the minimum nonscoured channel elevations at the upstream and downstream sides of the bridge. The differences between elevations on the upstream and downstream sides generally were insignificant and were used as a reference for assessing the potential hydraulic influence of the bridge.

Changes in bed elevation over time are represented by the parameter "b" (from eq. 2), through a method developed by Simon (1989), and discussed earlier (table 3). Equations derived from the relations such as those shown in figures 4 and 7 are used to estimate changes in bed elevation with time during fluvial adjustment; these rates decrease with distance upstream. Projected amounts of aggradation and degradation are calculated by solving equation 2 for the desired time period using the premodified elevation of the channel bed. Channel-bed elevations for studied streams are calculated at 5-year intervals from 1970 to 2000. If the timing of the start of the adjustment process is unknown, a series of curves can be generated using different starting times (B.A. Bryan, U.S. Geological Survey, written commun., 1987; fig. 8). For example, in figure 8 the differences in the estimated curves are a function of the different starting dates; 1975 and 1981.

Degradation migrates upstream and usually continues for 10 to 15 years at a site in response to channel modifications (Simon and Hupp, 1986a). After 10 to 15 years of degradation at a site, a period of aggradation follows, which also progresses upstream with time. On the basis of analysis of 14 sites in West Tennessee, Simon and Hupp (1986a) report that the aggradation exponent (+b) can be approximated as 0.22 times the degradation exponent (-b) with a standard error ($S_e$) of 5.8. Data for this analysis are reported in Simon (in press). Therefore, channel-bed elevations over the long term can be estimated. When combined with projected changes in channel width and known flood-plain elevations, channel-bed elevations can be used to estimate future channel geometry. Projections of future channel geometry are provided at the request of TDOT and are intended to be used as general guides.

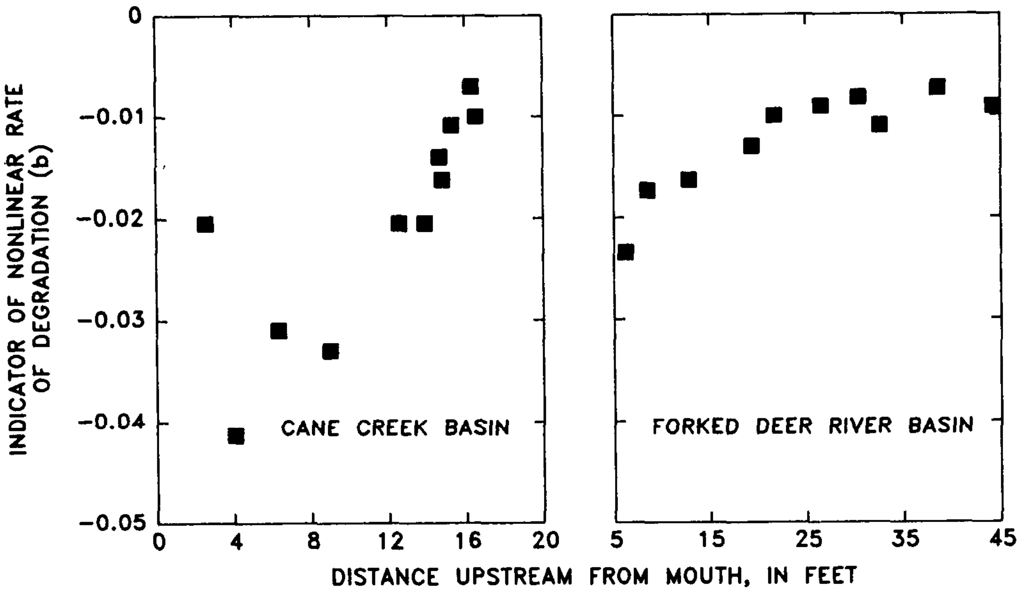



Figure 7.--Bed degradation trends in the Cane Creek and Forked Deer River basins, West Tennessee.

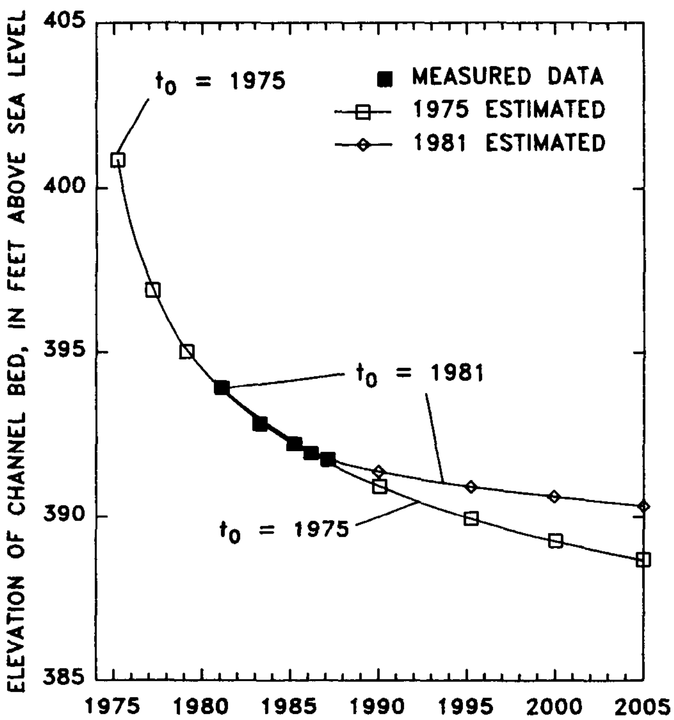



Figure 8.--Example of estimated trends of degradation when time of initial adjustment ($t_0$) is unknown, Lick Creek, Crockett Co., Tenn. (From B.A. Bryan, U.S. Geological Survey, written commun., 1987.)

### *Channel Width, Bank Height, and Bank Angles*

Unless otherwise noted, channel widths represent top-bank widths as measured from the flood-plain surface. Premodified and constructed were obtained from dredging plans (OFBA, SCS, and COE); subsequent width data were acquired from cross sections measured by the U.S. Geological Survey and, in some cases, from Corps of Engineers and U.S. Geological Survey gaging station records.

Bank height was defined as the difference between the elevation of the flood plain and the elevation of the channel bed. In cases where a man-made levee is an integral part of the bank, bank height is calculated from the top of the levee and represents a maximum height. Bank angles were obtained in one of two ways: they were (1) calculated from available cross-sectional data, or (2) measured during this study. Angles were obtained for the vertical face, upper bank, slough line, and depositional surfaces (fig. 5).

### *Volumetric Changes in Channel Size*

Variation in channel-forming processes during fluvial adjustment causes changes in channel area and morphology through the removal or deposition of materials. By comparing cross sections over the length of a given stream for different time periods, estimates of the volume of material eroded or deposited can be made.

Measured cross sections provided by the COE, OFBA, and SCS were used as the primary data base for documenting changes in channel areas and volumes (table 7). The cross sections cover the period from the mid-1960's through the mid-1980's.

For each cross section (assuming bankfull dimensions) channel area, mean depth, and width were digitized, calculated, and plotted by river mile for each time period. Because cross-sectional data were obtained from a variety of sources, direct section-to-section comparisons were not always possible. Instead a trend line was visually fitted through the data and was used to represent values of a given parameter over the length of the stream, and for the specified period. By overlaying the plots for the specific feature and by digitizing the area between the trend lines, estimates could be made of changes in that feature due to adjustment processes acting between the date of construction (or initial adjustment) and the present date.

The integration of depth changes at a site over the stream length studied provides information regarding the amount of vertical change in square feet. By then multiplying by the bottom width, the volume of material eroded or deposited from the channel bed by fluvial processes can be determined. Because changes in channel width generally occur after significant incision, a constant bottom width was

Table 7.--*Dates of cross-section measurements and data sources used to compute volumes of channel materials eroded or deposited during fluvial adjustment*

| Stream | Year | Data source |
|---|---|---|
| Obion River mainstem | 1963 | U.S. Corps of Engineers |
| | 1975 | U.S. Corps of Engineers |
| | 1982 | U.S. Corps of Engineers |
| | 1983 | U.S. Geological Survey |
| | 1987 | U.S. Geological Survey |
| North Fork Obion River | 1965 | U.S. Corps of Engineers |
| | 1975 | Continental Engineering |
| | 1983 | U.S. Geological Survey |
| | 1987 | U.S. Geological Survey |
| South Fork Obion River | 1965 | U.S. Corps of Engineers |
| | 1978 | U.S. Corps of Engineers |
| | 1983 | U.S. Geological Survey |
| | 1987 | U.S. Geological Survey |
| Rutherford Fork Obion River | 1964 | U.S. Corps of Engineers |
| | 1978 | Continental Engineering |
| | 1979 | Continental Engineering |
| | 1983 | U.S. Geological Survey |
| | 1987 | U.S. Geological Survey |
| North Fork Forked Deer River | 1974 | Continental Engineering |
| | 1983 | U.S. Geological Survey |
| | 1987 | U.S. Geological Survey |
| South Fork Forked Deer River | 1966 | U.S. Corps of Engineers |
| | 1975 | Continental Engineering |
| | 1979 | Continental Engineering |
| | 1985 | U.S. Corps of Engineers |
| | 1987 | U.S. Geological Survey |
| Cane Creek | 1968 | Soil Conservation Service |
| | 1970 | Soil Conservation Service |
| | 1985 | Soil Conservation Service |
| | 1987 | U.S. Geological Survey |

used to estimate the volume of material eroded by degradation. Similarly, plots of width changes provide data (in square feet) that is multiplied by bank height to calculate volumes eroded from the channel banks by mass-wasting processes. Plots of changes in total channel area represent total volumes of sediment eroded or deposited in the channel (fig. 9).

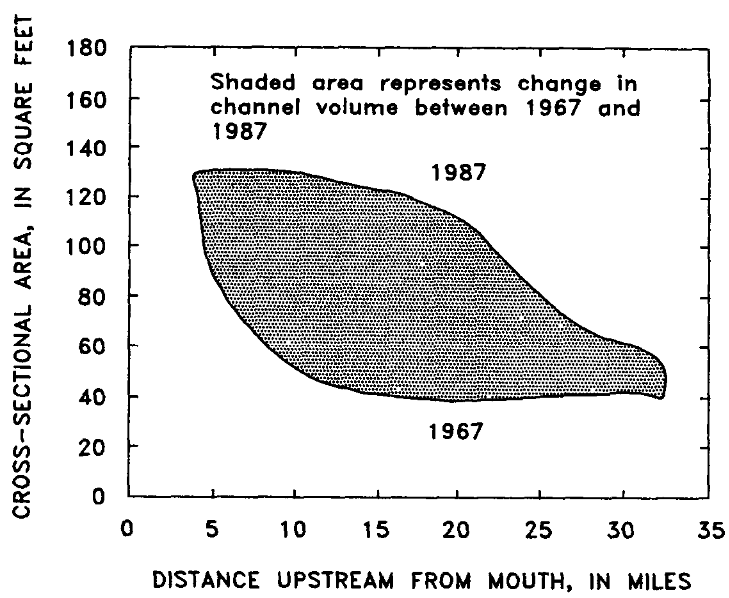



Figure 9.--Idealized example showing determination of change in channel volume using cross-sectional area data.

### *Geomorphic Surfaces and Stage Identification*

The variation in adjustment processes over the course of fluvial recovery from a channel modification results in the formation of specific geomorphic surfaces below the flood-plain level (Simon and Hupp, 1986b; Simon, 1989; and fig. 5). Characteristics of these surfaces such as angles, vegetation, and the presence or absence of bank failures are diagnostic in determining the relative stability of a reach and its stage of channel evolution. The specific geomorphic and botanical attributes of reaches in each of the six stages are summarized in tables 4 and 5. The identification of stage is important in assessing past, present, and future adjustment processes at a site. Field reconnaissance was carried out from 1985 to early 1987 for all sites included in the study (table 6). Data collection involved: (1) locating and dating riparian vegetation on newly stabilized surfaces to determine the timing of initial stability for that surface, and on unstable bank surfaces to estimate rates of bank retreat, (2) noting fluvial undercutting or deposition (bank accretion), (3) noting failure types, block widths and angles, and (4) measuring the height of the banks.

Independent hydrologic characteristics such as flow duration were calculated from mean-daily discharges for gaging stations within the area of study (table 8). The purpose of this was to ascertain (1) the flow durations corresponding to given geomorphic surfaces, and (2) the extent to which the form and development of those surfaces can be related to flow duration.

Elevations (relative to sea level) of the different geomorphic surfaces (vertical face, upper bank, slough line, shelf and bar) were determined from measured cross sections. These elevations were assigned gage-height elevations according to standard gage datums reported by the U.S. Geological Survey and the Corps of Engineers. The water discharge corresponding to that gage height was then

Table 8.--*Streamflow stations and period of record used in flow-duration analysis*

| Station name | Station number | Period of record |
|---|---|---|
| North Fork Obion River near Martin, Tenn. | 07025400 | 1941-81 |
| North Fork Obion River near Union City, Tenn. | 07025500 | 1931-70 |
| South Fork Obion River near Greenfield, Tenn. | 07024500 | 1931-86 |
| Rutherford Fork Obion River near Milan, Tenn. | 07024900 | 1970-79 |
| Rutherford Fork Obion River near Bradford, Tenn. | 07025000 | 1930-57 |
| Obion River at Obion, Tenn. | 07026000 | 1930-58<br>1967-86 |
| Obion River near Bogota, Tenn. | 07026300 | 1956-84 |
| North Fork Forked Deer River at Trenton, Tenn. | 07028500 | 1952-71 |
| North Fork Forked Deer River at Dyersburg, Tenn. | 07029100 | 1948-85 |
| South Fork Forked Deer River at Jackson, Tenn. | 07027500 | 1930-73 |
| South Fork Forked Deer River near Gates, Tenn. | 07027800 | 1969-81 |
| South Fork Forked Deer River at Chestnut Bluff, Tenn. | 07028000 | 1930-57 |
| South Fork Forked Deer River near Halls, Tenn. | 07028100 | 1955-83 |
| Beaver Creek at Huntingdon, Tenn. | 07024300 | 1963-86 |
| Hatchie River at Pocahontas, Tenn. | 07029400 | 1942-69 |
| Hatchie River at Bolivar, Tenn. | 07029500 | 1931-86 |
| Hatchie River near Stanton, Tenn. | 07030000 | 1930-58 |
| Hatchie River at Rialto, Tenn. | 07030050 | 1956-79 |
| Wolf River at Rossville, Tenn. | 07030500 | 1931-71 |
| Wolf River at Germantown, Tenn. | 07031650 | 1981-85 |
| Wolf River at Raleigh, Tenn. | 07031700 | 1938-69 |

obtained from updated rating curves (relation between gage height and discharge) provided by those agencies. By interpolating between points on the flow-duration curve, a flow duration corresponding to the elevation of a given geomorphic surface was obtained.

Differentiation between stages I and VI is based on whether or not a reach has ever been channelized. Stage I reaches generally are sinuous and have not been modified, being represented in this study by the Hatchie River, upstream reaches of the Wolf River and some downstream reaches of the Obion and Forked Deer River forks for the periods prior to any channel work. As in the case of the non-channelized Hatchie River, stage I may encompass long periods of time before abruptly becoming a stage II channel upon construction (such as Cane Creek).

Stage II (constructed) is theoretically an instantaneous condition, followed immediately by either degradation (stage III) or aggradation (stage V), depending on the whether the reach is located upstream or downstream of the AMD, respectively (Simon, 1989). Degradation spans stages III and IV, lasts for 10 to 15 years, and is represented by reaches upstream of the AMD. Maximum rates of degradation occur during stage III. Stage IV is characterized by the onset of bank failures by mass-wasting processes (table 4).

Stages are V and VI are of long duration and are characterized by aggradation, incipient meandering, and bank failures that bring the channel to a stable configuration. Field evidence indicates that the period required for restabilization may be 50 to 100 years from the onset of aggradation during stage V. Small modification lengths and magnitudes may require less time for restabilization.

## Shear Strength and Bank Stability

The relative stability of a channel bank is measured by the factor of safety (FS) which is the ratio of the forces that tend to resist mass movement and the gravitational forces that tend to drive that bank towards failure. To assess the roles of these forces in determining bank stability, shear-strength determinations of the bank material are required. Shear strength can be calculated using the Coulomb equation. For a failure plane of unit width and length, and if there is zero pore-water pressure,

$$s = c + \sigma \tan \phi \tag{3}$$

where

$s$ = shear strength, in pounds per square foot;
$c$ = cohesion, in pounds per square foot;
$\sigma$ = normal stress, in pounds per square foot; and
$\phi$ = angle of internal friction, in degrees.

Also, $$\sigma = W (\cos\theta) \quad (4)$$

where W = weight of the failure block, in pounds per square foot, and
$\theta$ = angle of the failure plane, in degrees.

Other required variables for calculating the normal stress, such as bank heights and angles, are determined from field surveys. Soil density is an integral component in the calculation of the weight of the failure block and therefore, slope stability (Grissinger, 1982). Soil density samples were obtained at each shear-test location and depth. From these samples, ambient moisture content was calculated assuming a specific gravity of soil solids of 0.096 lbs/in$^3$.

Soil-mechanics properties, cohesion, and friction angle were determined from field tests using the Iowa Borehole Shear Test Device (BST). This instrument is used to conduct rapid, in situ, direct-shear tests on the walls of a 3-inch diameter borehole (fig. 10). The BST has a number of analytical features different from conventional, laboratory-conducted triaxial-shear tests:

1. Cohesion and friction angle are evaluated separately;
2. A number of separate trials (5 to 12) on the same sample are run for each test, to produce a single c and $\phi$ value;
3. Data obtained from the instrument are plotted on site, allowing for repetition if the results are unreasonable; and
4. Tests can be carried out at various depths in the bank to locate weak areas (Thorne and others, 1981).

The BST was introduced by Handy and Fox (1967) as an instrument used to make direct-shear tests on the periphery of a borehole. The BST has seen increasing use following a study by Lohnes and Handy (1968) concerning slope stability in loess

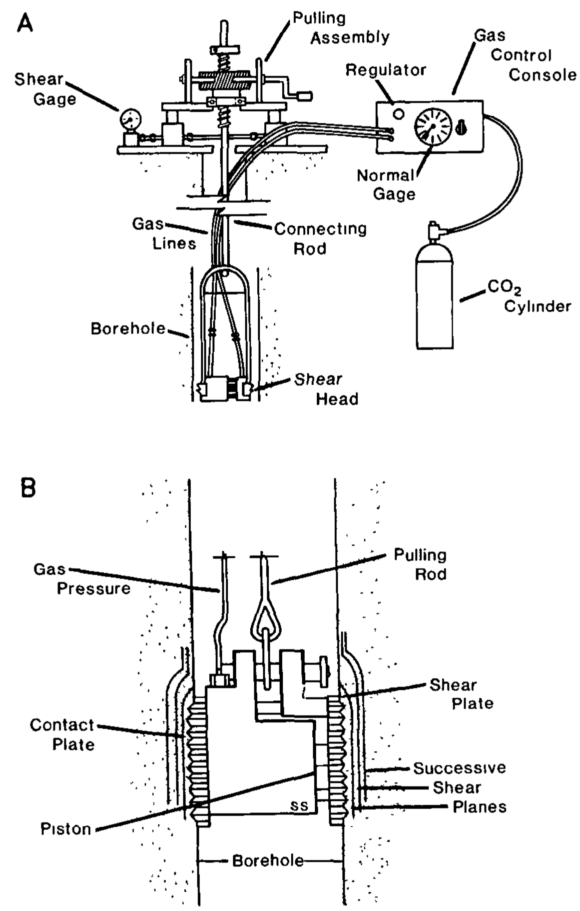



Figure 10.--Schematic drawings of (A) borehole shear-test assembly and (B) detail of shear head in borehole. (Modified from Thorne and others, 1981.)

deposits of Iowa and West Tennessee. The instrument has been subsequently used to study a variety of geomorphic processes. Luttenegger and Hallberg (1981) and Thorne and others (1981) provide a review of BST techniques and applications.

The BST was used in the current study because of the project's scope (105 sites) and because it provided the only practical means of acquiring large amounts of shear strength data (168 tests) within the time and budgetary limits of the project. Direct comparison of BST results with more conventional methods such as triaxial shear were well beyond the financial means of the project. Moreover, Lambrechts and Rixner (1981) and Lutenegger (1987) report that the shear-strength determinations made with the BST have the same inherent variability as triaxial shear tests. A good indication of the accuracy of the BST when compared with triaxial data is that the BST achieves $\phi$ values of +/- 3 degrees and c values of +/- 0.7 pounds per square inch (Wineland, 1975; R. Jacobson, written commun., 1991).

A brief summary of BST operating procedures is given below. The shear head of the BST is lowered into the borehole to the desired depth and expanded under gas pressure to provide the normal force (fig. 10). The soil in contact with the shear head is then allowed to consolidate for at least 10 minutes under the applied normal force. BST tests conducted during this study were considered as drained tests; sufficient consolidation times were used in conjunction with a pore-pressure sensor (mounted on the shear head) to assure that all positive pore pressures were dissipated. Because most soils tested were silts of low plasticity (Simon, in press), and testing was conducted during the summer months, in very few cases were positive pore pressures observed.

The shear head is pulled vertically by means of a pulling assembly located at the surface. The vertical force provides the shearing force on the walls of the borehole and is increased until failure of the soil occurs. Failure is identified by either a decrease in the shearing-force gage or by a constant gage reading over 40 to 50 turns of the pulling assembly (fig. 10). The maximum shearing force, divided by the area of the shear plates represents the shear stress at failure, and when plotted with the corresponding normal stress, produces a point on the Mohr-Coulomb line (fig. 11). Additional trials at increasingly higher normal forces produce a series of points, which by regression, define cohesion (y-intercept) and the angle of internal friction (slope of the line) (fig. 11).

It was found that too short consolidation times resulted in an increased scatter of points, a nonlinear relation between the normal and shear forces, or a flat Mohr-Coulomb failure envelope. In these few cases, the tests were redone with longer consolidation times for each increment of applied normal force.

Drained shear-strength tests were carried out in various materials encountered in the boreholes. Preliminary analysis of COE boring logs indicated relatively homogeneous silt bank materials along all

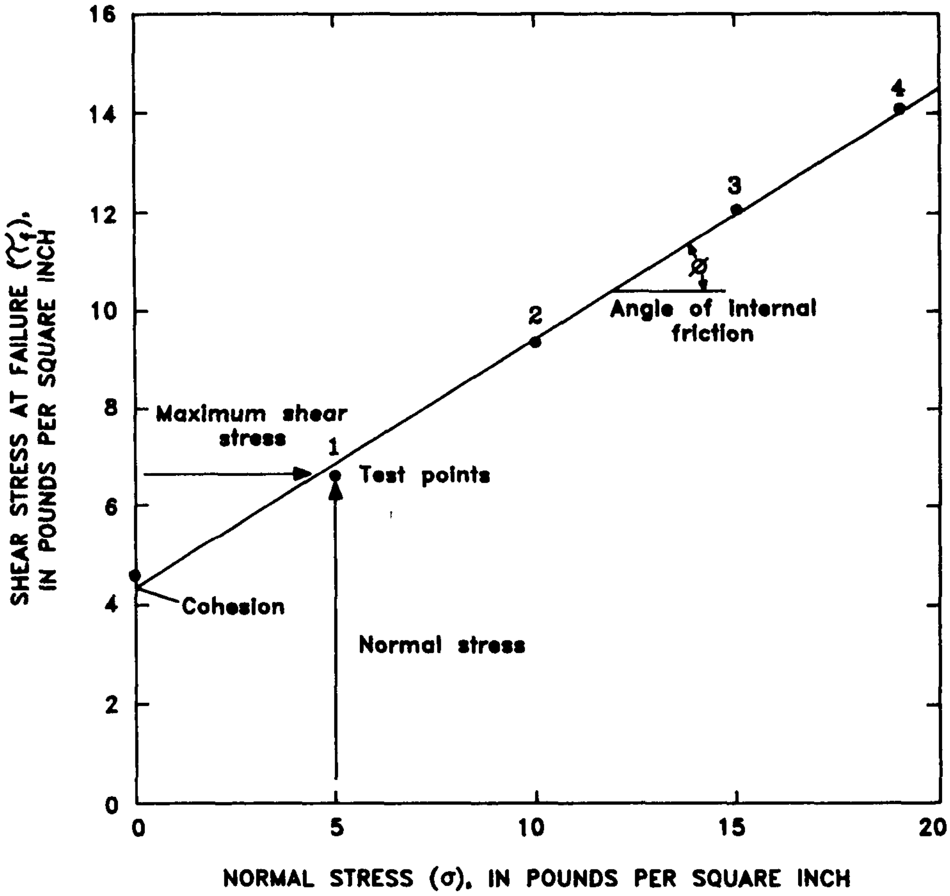



Figure 11.--Idealized relation between normal stress and shear stress (Mohr-Coulomb failure envelope) as derived from borehole shear-test data.

the studied streams. Hand augers were used for holes up to 10-feet deep; mobile drill rigs (supplied by TDOT) were used for tests at greater depths.

At least two tests were performed in fine-grained material (silt-clay) at each site (table 6). Sand-sized materials generally were not tested with the BST because of the absence of cohesion. Angle of internal friction values for these type soils were obtained from the U.S. Bureau of Reclamation (1973). These strata were logged, however, for subsequent use in slope-stability analyses.

### *Analysis of Bank Stability*

The analysis of bank stability may be carried out in a number of ways depending on the assumed shape of the failure surface (planar or curved) and the form of the desired solution (critical conditions or factor of safety).

***Factors of safety.***--Total-stress analytic solutions for both planar and rotational failures were developed (because of a lack of data on pore pressure) in terms of factors of safety (ratio between the resisting and driving forces). For a planar failure of unit length and width, the factor of safety is:

$$FS = \frac{c + W \cos\theta \tan\phi}{W \sin\theta} \quad (5)$$

and is shown in figure 12. For heterogeneous banks, mean values of c, $\phi$, and saturated density ($\gamma_{sat}$) were used. The angle of the failure plane was calculated from (Lohnes and Handy, 1968):

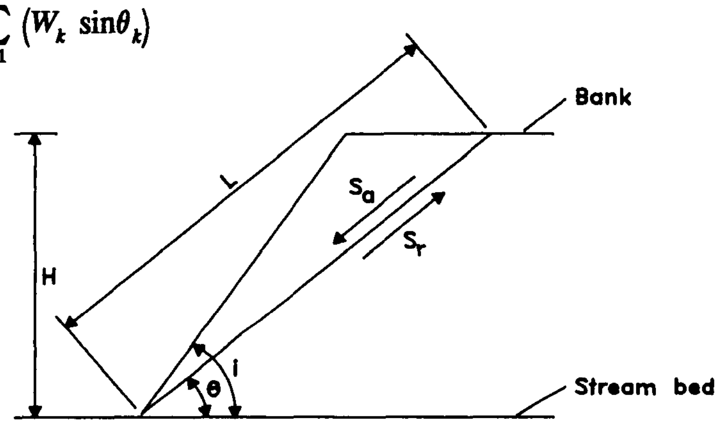
$$\tan\theta = \tan\left[\frac{1}{2}i + \frac{1}{2}\phi\right] \quad (6)$$

where i = bank angle, in degrees.

For rotational failures the minimum FS must be determined from a large number of potential-failure "circles". If the circles and failing mass are divided into "k" slices (fig. 13), the factor of safety can be determined by:

$$FS = \frac{\sum_{k=1}^{k=n} c_k + \tan\phi_k}{\sum_{k=1}^{k=n} (W_k \sin\theta_k)} \quad (7)$$

This is a laborious technique, particularly when further complicated by a heterogeneous bank. For these reasons, computer software developed by Huang (1983) was used for the analysis of rotational failures. The program selects the least stable failure surface and is constrained by the elevation of the channel bed (failures are not permitted below this elevation). Required input data include shear-strength properties c, $\phi$ and $\gamma_{sat}$ for each soil unit, the configuration of the bank, and the pore-water pressure. Owing to a lack of information on phreatic surfaces and in order to include the effect of pore pressure on calculations of shear strength and factors of safety, a pore-pressure ratio ($r_u$) is used (Huang, 1983):




EXPLANATION

H = BANK HEIGHT
L = FAILURE PLANE LENGTH
c = COHESION
$\phi$ = FRICTION ANGLE
Y = BULK UNIT WEIGHT
i = BANK ANGLE
$S_a$ = Wsinθ (Driving force)
$S_r$ = cL + Ntan$\phi$ (Resisting force)
N = Wcosθ
θ = (0.5i + 0.5$\phi$) (Failure plane angle)

For the critical case $S_a = S_r$ and :

$$H = \frac{4c \sin i \cos\phi}{Y(1 - \cos[i - \phi])}$$

Figure 12.--Shear failure along a planar slip-surface through the toe. (Modified from Thorne and others, 1981.)

$$r_u = \frac{\textit{volume of failing mass under water x unit weight of water}}{\textit{volume of failing mass in air x unit weight of soil}} \tag{8}$$

Pore-pressure ratios of 0.0 (dry) 0.125, 0.25, 0.375, and 0.50 (saturated) were used to represent the complete range of moisture conditions in this study. The effect of increasing values of $r_u$ is a general decrease in the factor of safety through reduction in the normal-force component by:

$$1 - r_u, \text{ to} \tag{9}$$

$$\sigma = (1-r_u)\, W \cos\theta \tag{9a}$$

Previous investigations in West Tennessee have shown that mass-bank failures generally occur during or after the recessional limb of storm hydrographs when the bank is still saturated and the support of the flowing water has been removed (Simon, 1989). Bank stability was therefore modeled assuming low-flow elevations in the channel.

***Critical-bank conditions***.--Critical-bank conditions are defined as the bank angle and height above which failure is expected to occur. This type of analytic solution is desirable for predicting stable-bank configurations on presently unstable banks. Carson and Kirby (1972), defined a dimensionless stability equation of the general form:

$$\frac{\gamma H}{c} = N_s = function(\phi,\ i) \tag{10}$$

where $N_S$ = dimensionless stability number,
H = bank height, and
$\gamma$, c, $\phi$, i = are as previously defined.

This relation provides information regarding the maximum stable slope in terms of the stability number $N_S$ and i. This analysis was found useful in describing mass-bank failures along degraded streams of northern Mississippi Thorne and others (1981).

Stability charts developed by Chen (1975) were used to calculate critical-bank heights ($H_c$) by solving equation 10 for a range of bank angles (40 to 90 degrees), and by using ambient, site-specific values of c, $\phi$ at $\gamma_{sat}$ (fig. 14). Critical heights for worst-case (saturated) conditions were obtained assuming that $\phi$ and the frictional component of shear strength goes to 0.0 (Lutton, 1974). Results of solutions of equation 10 for both ambient and worst-case conditions were then plotted on semi-logarithmic paper to produce bank-stability charts like those of Thorne and others (1981) and

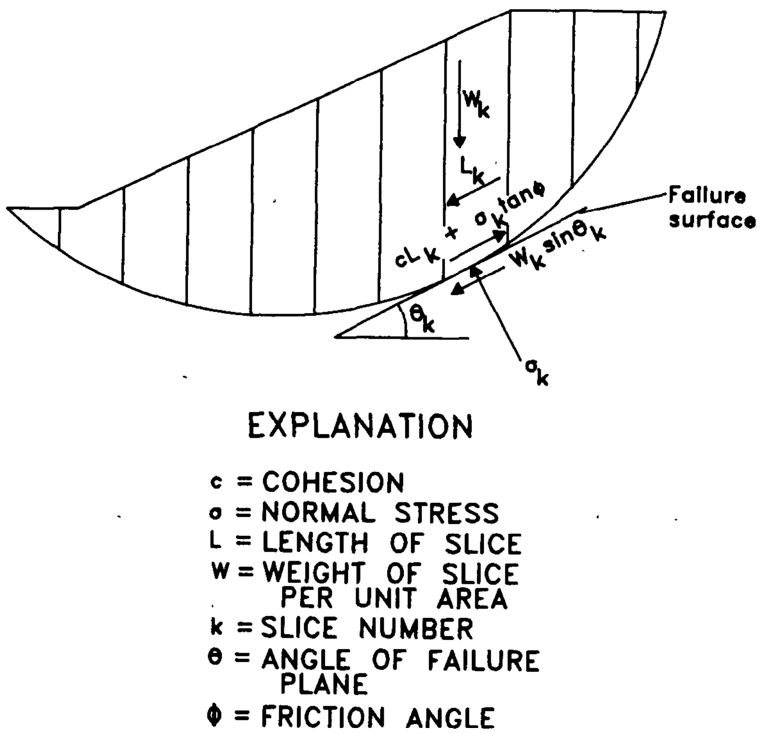



Figure 13.—Rotational failure surface. (Modified from Huang, 1983.)

shown in figure 15. These graphs can be used to estimate relative bank stability and stable-bank geometries for a given reach.

Only the solutions for FS of rotational failures treat characteristics of individual soil units uniquely. All other analytic solutions use mean values of c, $\phi$, and $\gamma_{sat}$ for a given site to calculate FS and, (or) critical-bank conditions.

### Dendrogeomorphic Analyses

Dendrogeomorphology is defined as the study of geomorphic processes (types and rates) determined and interpreted through tree-ring analyses of trees (and shrubs) affected by geomorphic processes. Dendrogeomorphic analysis of alluvial channels requires careful geomorphic documentation of bank form, bank heights, bank-slope angles, and hydrologic conditions. Field procedure at each site included the traversing of bank slopes and noting the general condition of the bank (stable or unstable), presence of bank failures and affected woody plants, presence of establishing woody species, and determination of bank-widening rates and bank-accretion rates. Bank conditions along straight reaches are generally the same on both the left and right banks. However, along bends and where incipient meanders are forming, there are distinct inside- and outside-bend differences. Where obvious differences existed between left and right banks, both banks were studied.

#### *Channel widening*

Channel widening refers to the increasing distance between left and right top banks. In the study area channel widening occurs largely through mass-wasting processes, usually following recession of flood stages. Rotational, slab, and pop-out failures carry trees and shrubs down the bank, usually accumulating on a stepped, concave upward upper bank (fig. 16). Woody vegetation affected by bank failure was analyzed using standard dendrogeomorphic techniques (Shroder, 1978; Hupp, 1983, 1984;

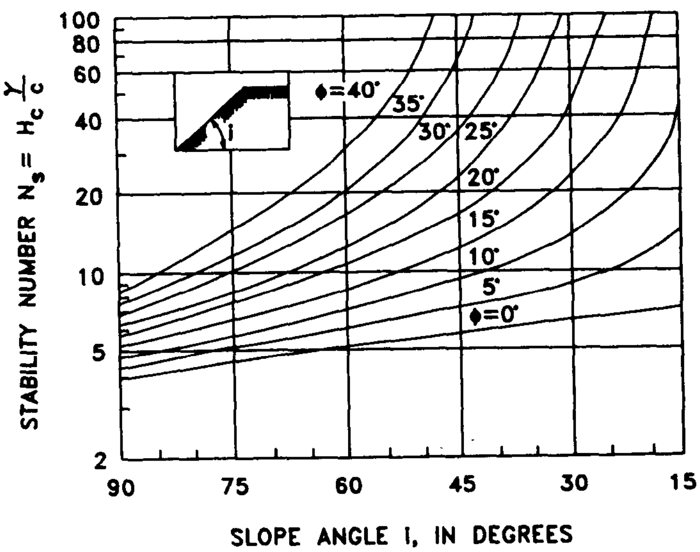



Figure 14.--Stability number ($N_s$) as a function of bank angle (i) for a failure surface passing through the toe. ($\gamma$=bulk unit weight; c=cohesion; $\phi$=friction angle.) (Modified from Thorne and and others, 1981.)

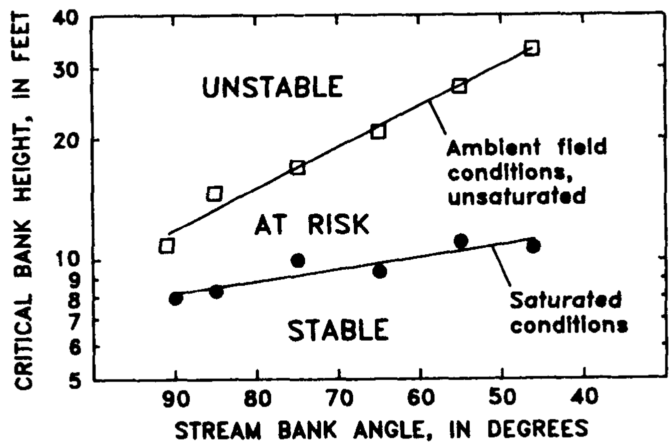



Figure 15.--Example of slope-stability chart giving critical-bank heights for various bank angles.

Phipps, 1985) for dates of bank-failure episodes. The effect of bank failures on woody plants is illustrated in figure 16.

Three basic types of botanical evidence of mass wasting were used in this study (fig. 17): (1) corrasion of stems by other trees and debris during bank failure, (2) adventitious sprouting along the parent trunk (tilt sprouts), and (3) eccentric annual growth. All of these types of botanical evidence can be used to indicate the timing of bank failure; all yield the exact year of failure, while scars and eccentric growth may yield the season of occurrence. Cross sections and increment cores were taken from affected tree and shrubs using handsaws and increment borers. Ring counts were made either in the field or from specimens taken to the laboratory for microscopic analysis. Standard dendrochronologic techniques of cross dating (Cleaveland, 1980; Phipps, 1985) were used when it was felt that multiple or missing rings would affect ring counts.

Dates of bank failure were combined with measurements of failure-block width or the horizontal distance between affected specimen and the present edge of top bank (fig. 16). Average width of failure (horizontal distance into bank), was divided by the time since failure (years) to obtain the amount and rate of channel widening by site.

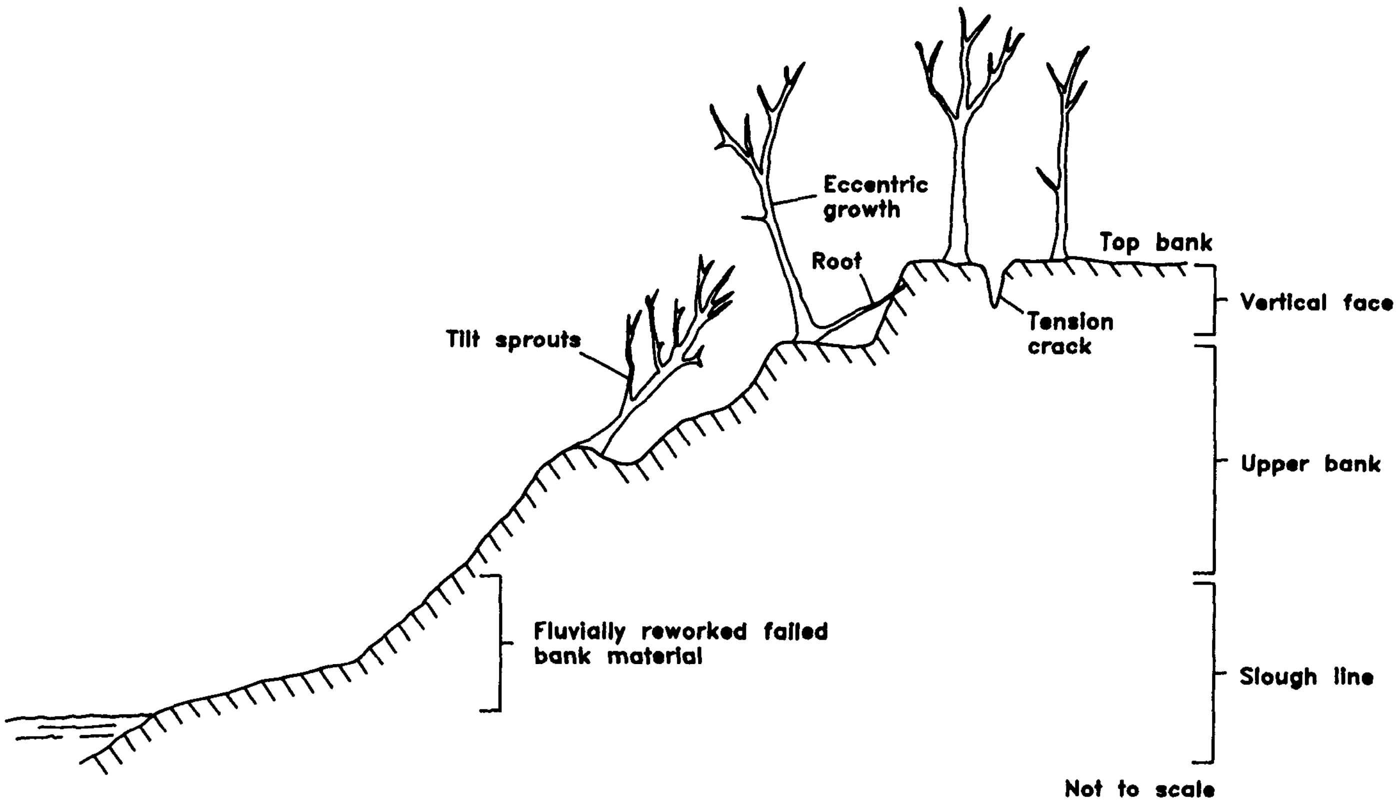



Figure 16.--Generalized bank cross section of modified channel after extensive channel-bed degradation and channel widening. Failure blocks and botanical evidence are shown. Note location of typical streambank forms, indicated on right.

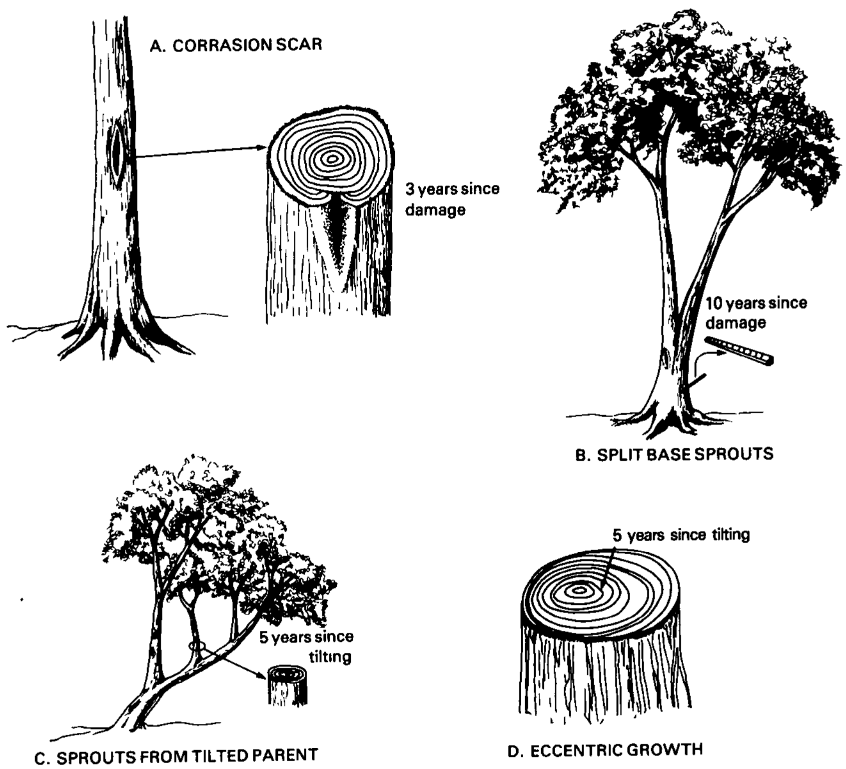



Figure 17.--Types of botanical evidence associated with typical geomorphic disturbances. (Modified from Hupp, 1988.)

### *Bank Accretion*

Woody plants, upon germination, form root tissue at and immediately below the ground surface. The initial rootlets, with time, form major root trunks that radiate out and down from the initial germination point. Above this initial germination point, the plant forms stem wood and the photosynthetic part of the plant. The flare of roots (root collar) just below the ground surface is a distinctive part of the morphology of woody plants. Thus, accretion above this root collar can usually be recognized and measured (fig. 18). Congested root zones along buried stems indicate a hiatus in accretion and can be used to infer episodic burial events and differing annual rates of accretion (fig. 18). Successive burial and adventitious root-production episodes is termed layering, a common feature of some riparian species.

Dendrogeomorphic analysis of layered woody specimens was conducted at sites where bank accretion was noted. This consisted of measuring the depth of burial above the major root flare of a specimen and cross sectioning or coring the plant to determine its age (as described in the previous

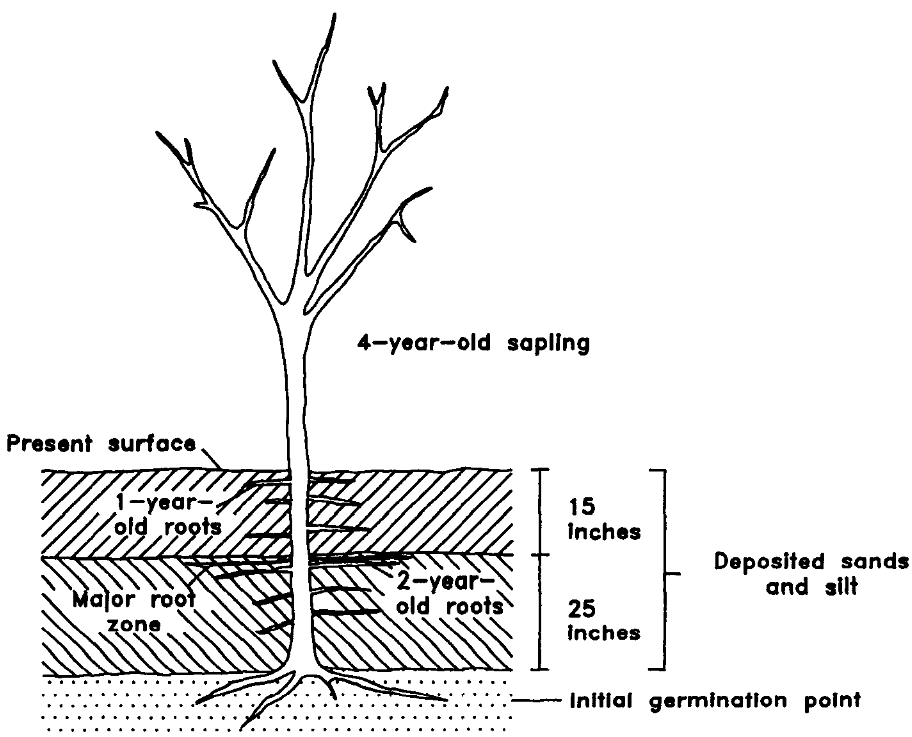



Figure 18.--Generalized buried sapling showing timing and depths of sediment deposition.

section). The measured burial depth was then divided by the age of the plant to determine the rate of bank accretion. Ten to 20 plants were analyzed at aggrading sites to determine average accretion through the site.

### *Woody Vegetative Cover*

Among the most significant indicators of bank stability is the amount of woody species cover. Woody cover, as a percentage of ground covered or shaded by the woody species canopy was estimated for each site from oblique visual observation from the top of the opposite bank. One cover value was estimated for a 100 yard reach at each site and includes the area from the top bank to the low-water edge. All cover values were estimated during the growing season.

### *Timing of restabilizing bank conditions*

High rates of bank widening preclude the successful establishment of any woody plant. However, as bank widening slows, "pioneer" species may begin to grow on low-bank surfaces. The ages of these initial plants indicate the time necessary for stable-bank conditions to occur after channel modification. Ages of trees that germinated on affected bank slopes were determined by coring or cross-sectioning their stems near the base. Date of channel work was subtracted from germination dates to determine the time necessary for quasi-stable-bank conditions to occur.

## Plant Ecology Analyses

One primary type of ecological analysis was used in the study: simple presence-absence (binary) data for all species occurring at a site. Presence-absence data were collected for all woody species identified on streambanks in the vicinity of the site. Lists of species present were compiled by site. Botanical nomenclature follows Radford and others (1968). Bank species from the top bank to the low-water surface were noted for $^1/_4$ to $^1/_2$ mile above and below the bridge crossing. These data were collected at the same sites at which dendrogeomorphic analyses were conducted (table 6). Binary data are rapidly obtained, are based on site-specific vegetation patterns, and avoid possible complications that species interactions impose on abundance data (Hurleburt, 1969; Zimmermann and Thom, 1982). Binary-vegetation data have been used with considerable success in defining vegetation and geomorphic relations (Strahler, 1978; Hupp and Osterkamp, 1985).

Two types of statistical treatments were conducted on the binary vegetation data. Binary Discriminant Analysis (BDA) was performed on the species presence-absence data by site variables (bank-widening rate, bank-accretion rate, percent-vegetative cover). Stahler (1978) provides a detailed description of the BDA procedure which includes contingency analyses. Contingency tables were constructed for each species with the above variables. Frequency data (number of occurrences versus number of possible occurrences) from the contingency tables were converted to standardized residuals using the equation given in Haberman (1973), This procedure places common and rare species on equal grounds. Standardized residuals are useful in identifying trends in species "preference" and "avoidance" for particular site conditions. These standardized residual values are then placed in a matrix with species as rows and site variables as columns. This matrix becomes input for Detrended Correspondence Analysis (DCA) and the development of a graphic (orthogonal) representation of the species - site-variables relation or pattern (Hill and Gauch, 1980). DCA is a standard (multivariate) plant ecological ordination technique that plots similar species or site variables near each other on two dimensional axes. The DCA was conducted using the DECORANA program (Hill, 1979).

### Detailed Accretion Analyses

Stands of establishing vegetation occur along many reaches where some bank stability has been attained (Hupp and Simon, 1986). Selected reachesof this nature were analyzed in detail for accretion amounts, accretion rates, and angles of depositional surfaces. Tree ages were determined for specimens growing in the accreted deposits to infer the timing of initial-bank accretion after the period of active bank widening. Field procedure consisted of coring stem bases to determine their age, excavating buried stems to their original root collar to determine the amount (depth) of deposition and then dividing by the age of the specimen to determine accretion rate. These data are combined with data obtained from analyses described earlier including depth of sedimentation, bank angles, and location on the bank, to characterize depositional areas.

## GEOMORPHIC AND VEGETATIVE RECOVERY PROCESSES

Channel recovery involves geomorphic, hydraulic, geotechnic, and biologic processes that need to be considered in concert to understand this fluvial system. Changes in one aspect of a fluvial system (for example, bed degradation) can affect other aspects of the system (such as bank stability and riparian-species distributions). Generally, changes in channel gradient or stream energy (caused by channel modifications) cause a shift to non-equlibrium conditions and the initiation of adjustment processes such as degradation and aggradation.

## *Channel Bed-Level Changes*

Some of the most rapid and dramatic adjustments that take place along an alluvial channel occur on the channel bed. Channel-bed degradation and aggradation are important recovery processes by which a channel adjusts towards its premodified energy level.

### Theoretical Considerations

Channel modifications (straightening, dredging, or clearing), are intended to drain water from the landscape through the channel, and generally at greater than "normal" velocities. Straightening and dredging increase channel gradient, and capacity while channel clearing reduces channel roughness (Manning's "n"). The net result of any of these modifications is a general increase in stream power at high discharges and, by equation 1, a corresponding increase in the stream's capacity to erode greater volumes and greater sizes of sediment from the channel bed (stages III and IV, table 5). Studies by Yang (1976) indicate that a stream will minimize its stream power (discharge-gradient product) and its expenditure of energy. Assuming that precipitation-runoff relations are consistent from year to year, sudden increases in stream power resulting from man's activities will be initially compensated for by channel processes that result in a general decrease in channel gradient (Simon and Robbins, 1987).

Previous studies in West Tennessee have shown that in sand-bed streams, gradient reduction occurs by upstream degradation and downstream aggradation (Simon and Hupp, 1986a; Simon, 1989). These vertical processes apparently are an efficient means of stream-power reduction. With sediment transport taking up a small percentage of a stream's total energy (Rubey, 1933), the remainder being expended through frictional losses along its perimeter, gradient reduction by channel lengthening (meander extension and migration) probably represents an inefficient means of initial adjustment. Early researchers similarly noted that a stream's initial adjustment to a channel disturbance (uplift) was downcutting (Gilbert, 1880; Davis, 1905). Both channelization and uplift can be considered analogous because both involve an increase in total stream energy.

Channel bed-level changes dominate the initial phase of channel adjustment in these streams and serve to decrease channel gradient--rapidly at first, and diminishing thereafter to some minimum value (Schumm and Lichty, 1965; Simon and Robbins, 1987). Streams cannot however degrade below their local base level, such as the channel bed of the trunk stream. If the stream's power is still excessive at this time, gradient reduction then takes the form of channel lengthening. This is apparently the case along Cane Creek, where up to 30 feet of channel-bed degradation occurred between 1970 and 1985. Because of the lack of sand-sized particles however, aggradation, even at the confluence with the non-channelized Hatchie River, has been negligible. The channel therefore remains in its degraded state. As such, it allows backwater from the Hatchie River to extend upstream. Degradation in the lower reaches is therefore abated, and further gradient reduction occurs by incipient meandering.

Gradient reduction in a sand-bed stream by downstream aggradation and upstream degradation can decrease gradients to an order of magnitude less than even the predisturbed values (Simon and Robbins, 1987). This is because a straightened channel generally maintains greater energy than a sinuous one due to reduced frictional losses along its perimeter. Therefore, because of its straight alignment, vertical channel-bed processes initially dominate. When degradation at a site has reduced gradients to the point at which stream power is no longer capable of transporting the increased loads coming from upstream, "secondary aggradation" takes place and with it, the beginning of largely lateral processes, a meandering low-flow thalweg, and point-bar formation (stage V, table 5; Simon, 1989).

As general aggradation migrates upstream, channel gradients are increased. However, meandering of the low-flow thalweg serves to lengthen the stream's low-flow path, and to reduce low-flow channel gradient and stream power. It seems reasonable to speculate that during this phase of adjustment, moderate and high flows moving through a straight alignment serve to deliver sediment to the reach, causing aggradation. The low flows moving through a sinuous alignment then redistribute the bed sediment, forming point bars and incipient meanders by cutting laterally into the channel banks.

The processes described above (stage V) have been observed along the downstream reaches of all the forks of the Obion and Forked Deer Rivers where secondary aggradation is prevalent. Point-bar deposition and incipient meandering represent a shift from vertical-bed processes to processes which operate laterally (stages V and VI; table 5). Incipient meanders with wavelengths of approximately 200 feet have been measured in the field and verified by recent (1987) aerial photography.

The changes that occur on the bed of an alluvial channel after channel modification may be analogous to those changes that occur in "natural" settings over long periods of time (Gilbert, 1880; Mackin, 1948; Hack, 1960). Assuming no bedrock control of base level and uninterrupted adjustment, the exceptional difference with man-induced channel adjustments is one of temporal and spatial scales. The shortened time under which channel adjustments occur makes accurate documentation possible. It further allows for quantification of the processes that control channel adjustment and evolution. Extrapolation of relations over time to fit into the context of "natural" channel development needs to be tested.

## Empirical Data by River Mile

Channel bed-level adjustments are described over time, at a site, by the parameter "b" (in equation 2; $E=at^b$), which represents the nonlinear rate of change on the bed (Simon and Hupp, 1986a, Simon, 1989). A list of calculated b-values for studied sites is given in table 3. In using b-values to calculate channel bed-level changes, one must keep in mind that "$t_o = 1$" represents the year before the particular channel-bed process became active at the site, and not necessarily the time at which channel construction was completed. When plotted by river mile, b-values consistently show the attenuation of the degradation process with increasing distance upstream (fig. 19).

A key point in the extrapolation of channel bed-level changes through time is the nature of the parameter "b". Because "b" represents a nonlinear rate of change which decreases with time (fig. 3), the assumption is that rates of aggradation and degradation are in fact time based. Extrapolation into the future is of course uncertain, however, the nonlinear attenuation of the degradation process with distance above the AMD (fig. 4), and at a site through time, accounts for much of the inherent variability through time.

### *Degradation*

Projected amounts of channel bed-level lowering by degradation were calculated by solving equation 2 at 5-year increments from 1970 to 2000 (figs. 20-22). These projections (table 9) should be regarded as maxima, in that some estimates represent degradation for more than 15 years, the upper end of the range specified by Simon (1989) for sand-bed streams in West Tennessee. Recent surveys of Cane Creek by the U.S. Geological Survey and the Soil Conservation Service indicate that although degradation has slowed considerably since 1970, it is still occurring. The 10 to 15 year time period previously reported may need to be extended for streams without an appreciable sand load. However, for the purposes of this study, estimates of long-term-channel geometry are based initially on a 15-year degradation period according to calculated b-values (table 3).

The presentation of data derived from b-values in this fashion displays the time-based reduction in degradation (distance between successive curves in figures 20-22; and the asymptotic nature of curves in fig. 3). The plot of North Fork Obion River data (fig. 20) shows the headward migration of degradation over time (curves 1970, 1975, 1980).

Because of the relatively homogeneous channel-bed sediments along a given stream in West Tennessee (Simon, in press), significant variations from the generally smooth asymptotic shape of the curves (figs. 20-22) can be attributed to the delivery of large amounts of bed material from sand-bearing tributary streams. The most pronounced variations are projected on the North Fork Forked Deer River between river miles 15 and 24 (fig. 21). The entrance of the larger Middle Fork Forked Deer River, at river mile 15.6, supplies the North Fork with large amounts of channel-bed sediment that otherwise would have been eroded in these reaches from the channel bed of the North Fork. This effectively

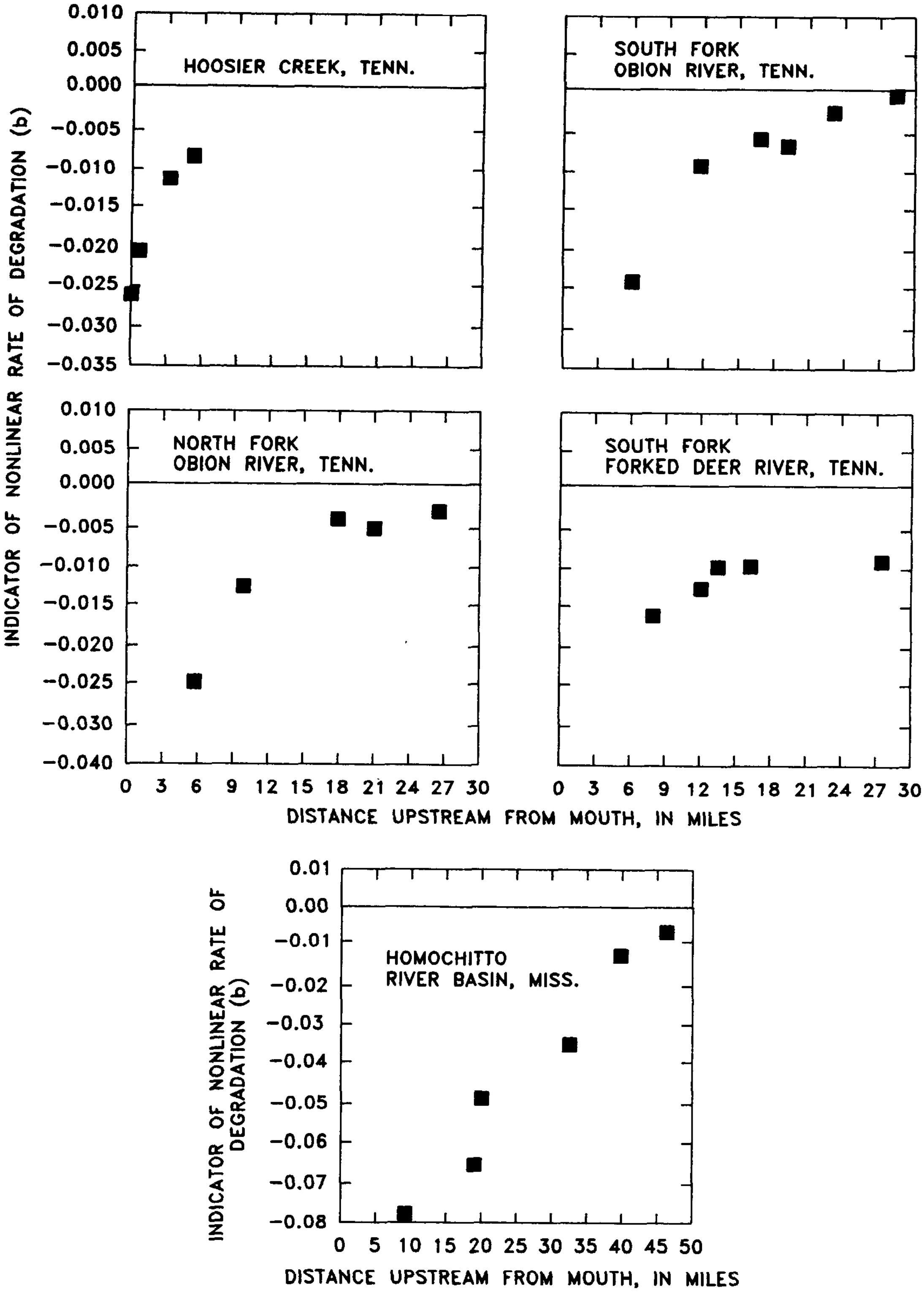



Figure 19.--Relation between indicator of nonlinear rate of degradation (b) and river mile for selected streams in Mississippi and Tennessee. (Data for Homochitto River from Wilson, 1979.)

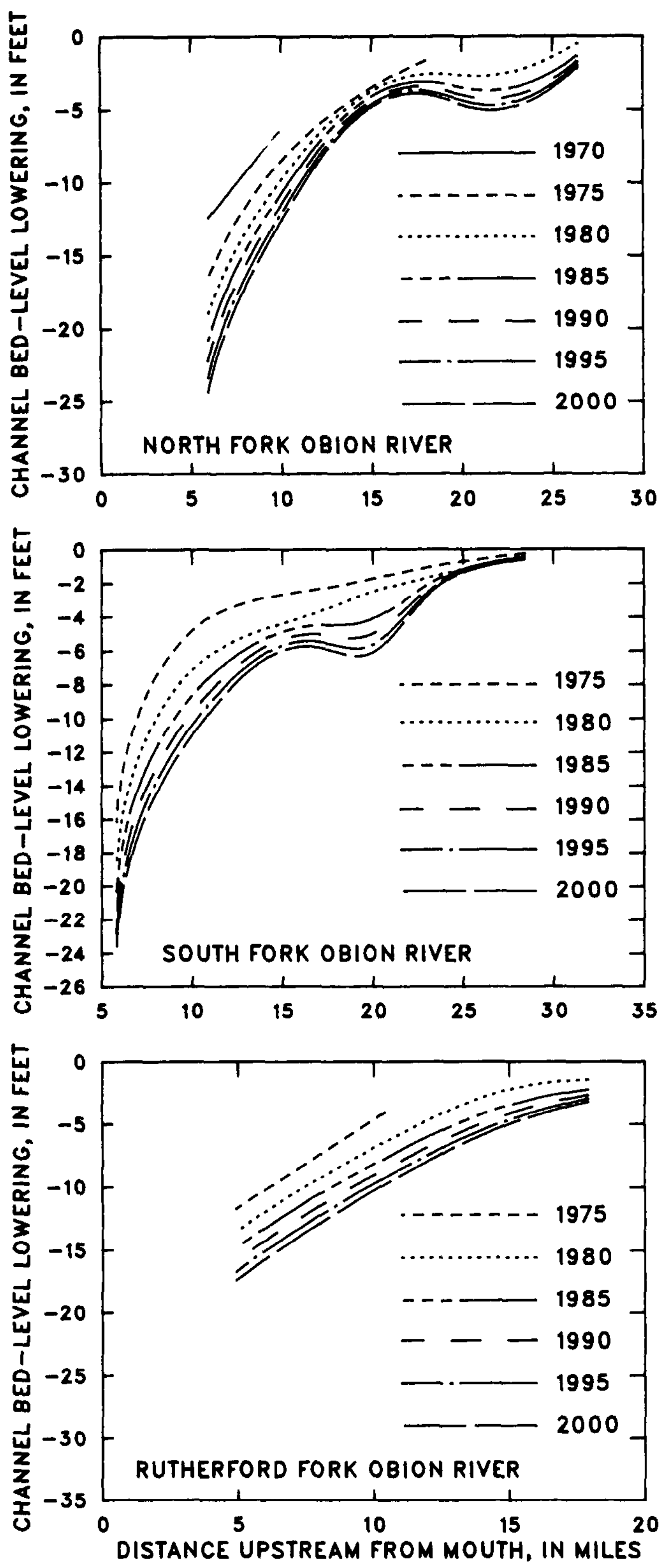



Figure 20.--Projected channel bed-level lowering for North Fork, South Fork, and Rutherford Fork of the Obion River.

dampens the degradation response of the North Fork Forked Deer River in the vicinity of river mile 15 and causes the wave-like shape of the curve in figure 21.

Plots of channel profiles for various time periods that were overlain on each other were used to calculate the volumes of material eroded from the channel bed (using a constant bottom width) after channel modification, and to delineate the upstream advance of degradation (figs. 23-25). Values ranged from 5.5 $Mft^3$ (million cubic feet) over 20 years along the sand bed of the Rutherford Fork Obion River, to 32.2 $Mft^3$ over 15 years along the silt bed of Cane Creek. With the exception of Cane Creek, no other studied stream has eroded more than 14.0 $Mft^3$ from its bed since modification (table 10). The dramatic response of Cane Creek is even more pronounced when viewed in terms of the volume eroded per square mile of drainage area; approximately 400,000 $ft^3/mi^2$. The next greatest values were an order of magnitude less and occur on the Obion River forks where roughly 20,000 $ft^3/mi^2$ of channel-bed material have been eroded (table 10). The large difference in channel-bed degradation between Cane Creek and the other streams of the region is a function of three variables that control the response of alluvial streams:

1. the magnitude of the imposed disturbances;
2. the erodibility of the channel bed; and
3. the presence/absence of coarse particle sizes (sand) for aggradation.

Cane Creek was channelized throughout its length and shortened by approximately

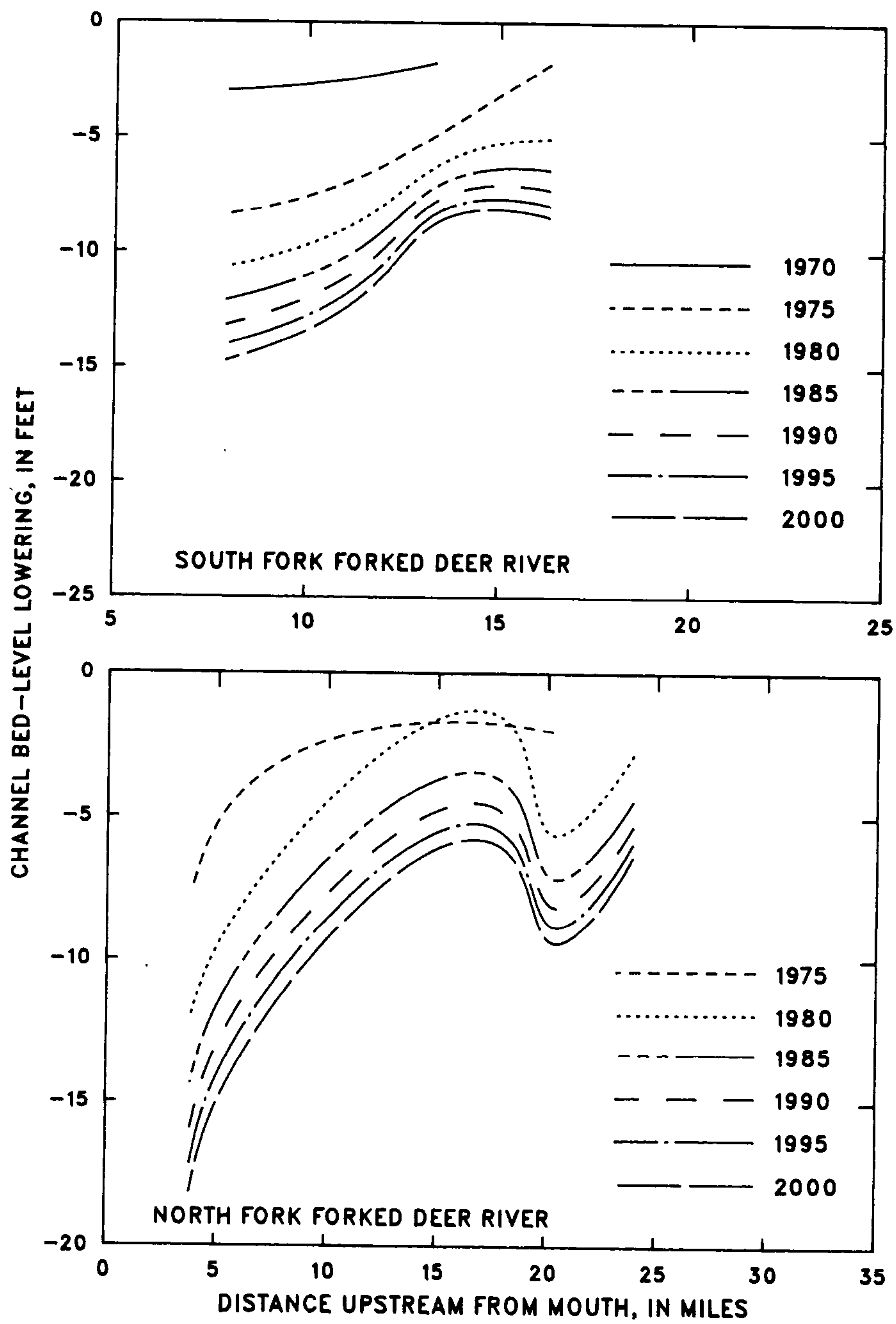



Figure 21.--Projected channed bed-level lowering for South Fork and North Fork of the Forked Deer River.

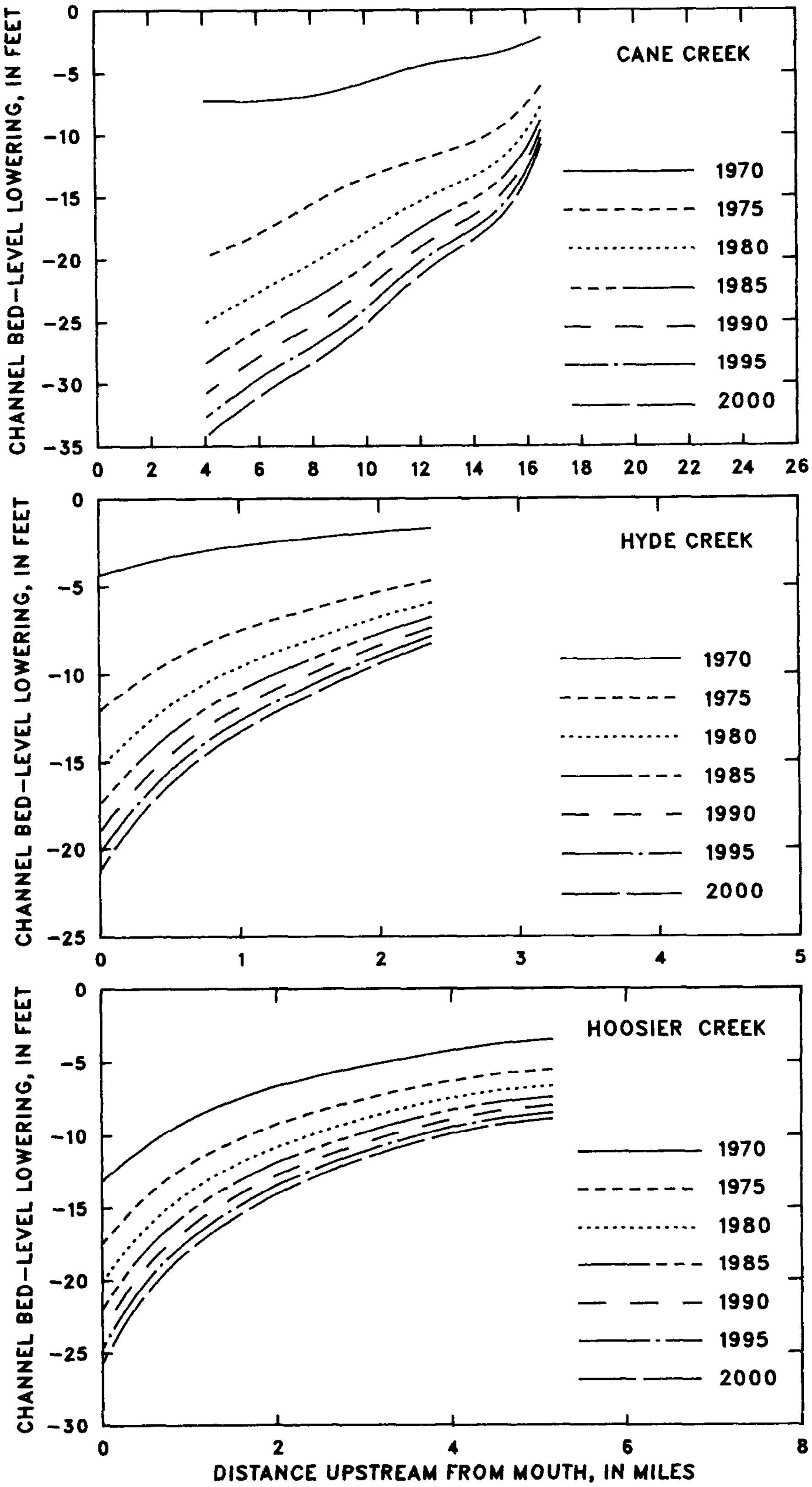



Figure 22.--Projected channel bed-level lowering for Cane Creek, Hyde Creek, and Hoosier Creek.

Table 9.--*Calculated amounts of channel-bed degradation at 5-year intervals to the year 2000*

[. = no data]

| Station number | River mile | Year 1970 | 1975 | 1980 | 1985 | 1990 | 1995 | 2000 |
|---|---|---|---|---|---|---|---|---|
| | | | | **Cane Creek** | | | | |
| 07000001 | 0.61 | . | - 3.05 | - 4.07 | - 4.70 | - 5.15 | - 5.51 | - 5.80 |
| 07000002 | 1.95 | . | - 6.35 | - 8.46 | - 9.75 | -10.69 | -11.42 | -12.02 |
| 07000003 | 2.52 | . | - 7.16 | - 9.53 | -10.99 | -12.04 | -12.86 | -13.53 |
| 07000004 | 3.64 | . | -11.94 | -15.85 | -18.24 | -19.96 | -21.29 | -22.39 |
| 07000005 | 4.06 | . | -12.26 | -16.28 | -18.72 | -20.48 | -21.86 | -22.98 |
| 07000006 | 5.71 | . | -13.03 | -17.29 | -19.89 | -21.76 | -23.21 | -24.41 |
| 07000007 | 6.19 | . | -13.60 | -18.03 | -20.73 | -22.68 | -24.20 | -25.44 |
| 07000008 | 7.06 | . | -14.48 | -19.20 | -22.07 | -24.14 | -25.74 | -27.06 |
| 07000009 | 7.99 | . | -14.90 | -19.75 | -22.70 | -24.83 | -26.48 | -27.83 |
| 07000010 | 8.98 | . | -10.76 | -14.31 | -16.48 | -18.04 | -19.26 | -20.26 |
| 07000011 | 9.92 | . | -12.24 | -16.26 | -18.72 | -20.49 | -21.87 | -23.00 |
| 07000012 | 10.26 | . | -11.43 | -15.91 | -17.49 | -19.15 | -20.44 | -21.50 |
| 07000013 | 11.05 | . | -11.47 | -15.25 | -17.55 | -19.22 | -20.51 | -21.58 |
| 07000014 | 11.31 | . | -10.33 | -13.74 | -15.82 | -17.33 | -18.50 | -19.47 |
| 07000015 | 11.84 | . | - 8.37 | -11.14 | -12.84 | -14.07 | -15.03 | -15.82 |
| 07000016 | 12.59 | . | - 8.06 | -10.74 | -12.38 | -13.58 | -14.50 | -15.26 |
| 07000017 | 13.39 | . | - 8.85 | -11.79 | -13.59 | -14.89 | -15.91 | -16.74 |
| 07000018 | 14.05 | . | - 7.76 | -10.34 | -11.93 | -13.07 | -13.97 | -14.70 |
| 07000019 | 14.83 | . | - 5.80 | - 7.74 | - 8.93 | - 9.79 | -10.47 | -11.02 |
| 07000020 | 15.36 | . | - 3.14 | - 4.19 | - 4.84 | - 5.31 | - 5.68 | - 5.98 |
| 07000022 | 15.95 | . | - 5.24 | - 7.00 | - 8.08 | - 8.86 | - 9.47 | - 9.97 |
| | | | | **Cub Creek** | | | | |
| 07029447 | 6.92 | 0.73 | - 2.05 | - 2.61 | - 2.98 | - 3.25 | - 3.46 | - 3.64 |
| 07029448 | 5.73 | 0.96 | - 2.69 | - 3.44 | - 3.91 | - 4.27 | - 4.55 | - 4.78 |
| 07029449 | 2.16 | 1.43 | - 4.00 | - 5.10 | - 5.81 | - 6.34 | - 6.75 | - 7.10 |
| 07029450 | 1.54 | 2.25 | - 6.27 | - 7.99 | - 9.10 | - 9.92 | -10.56 | -11.10 |
| 07029450 | 1.54 | . | . | . | . | . | . | . |
| | | | | **Hoosier Creek** | | | | |
| 07025660 | 5.15 | - 3.52 | - 5.57 | - 6.67 | - 7.44 | - 8.02 | - 8.49 | - 8.88 |
| 07025666 | 2.99 | - 5.31 | - 7.57 | - 8.88 | - 7.81 | -10.53 | -11.11 | -11.61 |
| 07025690 | 0.55 | . | . | . | . | . | . | . |
| 07025690 | 0.55 | -10.48 | -13.93 | -16.05 | -17.57 | -18.76 | -19.74 | -20.57 |
| 07025691 | 0.01 | -13.11 | -17.40 | -20.02 | -21.91 | -23.38 | -24.59 | -25.61 |
| | | | | **Hyde Creek** | | | | |
| 07030002 | 0.74 | - 2.99 | - 8.32 | -10.58 | -12.04 | -13.11 | -13.96 | -14.66 |
| 07030004 | 1.38 | - 2.37 | - 6.61 | - 8.42 | - 9.58 | -10.43 | -11.11 | -11.68 |
| 07030104 | 2.37 | - 1.67 | - 4.67 | - 5.95 | - 6.77 | - 7.38 | - 7.87 | - 8.27 |
| 07030111 | 0.01 | - 4.34 | -12.03 | -15.28 | -17.36 | -18.89 | -20.10 | -21.10 |

Table 9.--*Calculated amounts of channel-bed degradation at 5-year intervals to the year 2000*--Continued

| Station number | River mile | Year 1970 | 1975 | 1980 | 1985 | 1990 | 1995 | 2000 |
|---|---|---|---|---|---|---|---|---|
| | | **North Fork Forked Deer River** | | | | | | |
| 07028820 | 23.90 | . | . | - 2.80 | - 4.43 | - 5.31 | - 5.92 | - 6.38 |
| 07028835 | 20.18 | . | - 2.00 | - 5.59 | - 7.11 | - 8.10 | - 8.82 | - 9.39 |
| 07028840 | 18.82 | . | . | - 2.46 | - 4.63 | - 5.70 | - 6.41 | - 6.95 |
| 07029100 | 5.30 | . | - 4.86 | - 9.12 | -11.20 | -12.59 | -13.62 | -14.46 |
| 07029105 | 3.83 | . | - 7.64 | -12.00 | -14.34 | -15.94 | -17.16 | -18.15 |
| 07029105 | 3.83 | . | . | . | . | . | . | . |
| | | **North Fork Obion River** | | | | | | |
| 07025320 | 34.90 | . | . | . | . | . | . | . |
| 07025340 | 26.40 | . | . | - 0.47 | - 1.33 | - 1.70 | - 1.93 | - 2.11 |
| 07025375 | 21.10 | . | . | - 2.78 | - 3.72 | - 4.29 | - 4.71 | - 5.04 |
| 07025400 | 18.00 | . | - 1.60 | - 2.53 | - 3.03 | - 3.38 | - 3.65 | - 3.86 |
| 07025500 | 9.84 | - 6.45 | - 8.59 | - 9.91 | -10.87 | -11.61 | -12.23 | -12.75 |
| 07025600 | 5.90 | -12.21 | -16.22 | -18.67 | -20.44 | -21.81 | -22.94 | -23.90 |
| 07025600 | 5.90 | . | . | . | . | . | . | . |
| | | **Obion River** | | | | | | |
| 07024800 | 68.50 | -11.11 | -14.78 | -17.01 | -18.63 | -19.89 | -20.92 | -21.80 |
| 07024800 | 68.50 | . | . | . | . | . | . | . |
| 07025900 | 62.20 | . | . | . | . | . | . | . |
| 07025900 | 62.20 | . | . | . | . | . | . | . |
| 07026000 | 53.70 | . | . | . | . | . | . | . |
| 07026000 | 53.70 | . | . | . | . | . | . | . |
| 07026300 | 34.20 | . | . | . | . | . | . | . |
| 07026300 | 34.20 | . | . | . | . | . | . | . |
| 07027200 | 20.80 | . | . | . | . | . | . | . |
| | | **Pond Creek** | | | | | | |
| 07029060 | 11.37 | . | . | - 3.18 | - 5.02 | - 6.02 | - 6.71 | - 7.24 |
| 07029065 | 9.82 | . | . | - 3.01 | - 4.75 | - 5.69 | - 6.34 | - 6.84 |
| 07029070 | 7.32 | . | . | - 4.60 | - 7.25 | - 8.68 | - 9.67 | -10.42 |
| 07029080 | 1.06 | . | . | - 3.22 | - 5.08 | - 6.10 | - 6.79 | - 7.32 |
| | | **Porters Creek** | | | | | | |
| 07029437 | 17.10 | . | - 7.97 | -11.36 | -13.33 | -14.72 | -15.80 | -16.68 |
| 07029439 | 11.20 | . | - 8.67 | -12.35 | -14.48 | -15.99 | -17.16 | -18.11 |
| 07029440 | 8.89 | . | - 3.63 | - 5.18 | - 6.09 | - 6.73 | - 7.23 | - 7.63 |
| | | **Rutherford Fork Obion River** | | | | | | |
| 07024900 | 29.90 | . | . | . | . | . | . | . |
| 07025000 | 17.90 | . | . | - 1.41 | - 2.23 | - 2.68 | - 2.98 | - 3.22 |
| 07025025 | 15.20 | . | . | - 2.13 | - 3.37 | - 4.04 | - 4.51 | - 4.86 |
| 07025050 | 10.40 | . | - 4.07 | - 6.43 | - 7.71 | - 8.59 | - 9.26 | - 9.80 |
| 07025050 | 10.40 | . | . | . | . | . | . | . |
| 07025100 | 4.90 | - 8.81 | -11.73 | -13.52 | -14.81 | -15.82 | -16.65 | -17.35 |
| 07025100 | 4.90 | . | . | . | . | . | . | . |

Table 9.--*Calculated amounts of channel-bed degradation at 5-year intervals to the year 2000*--Continued

| Station number | River mile | Year 1970 | 1975 | 1980 | 1985 | 1990 | 1995 | 2000 |
|---|---|---|---|---|---|---|---|---|
| | | **South Fork Forked Deer River** | | | | | | |
| 07027720 | 27.60 | . | . | - 4.06 | - 5.80 | - 6.80 | - 7.52 | - 8.07 |
| 07027800 | 16.30 | . | - 1.76 | - 4.91 | - 6.25 | - 7.11 | - 7.75 | - 8.26 |
| 07028000 | 13.30 | - 1.77 | - 4.95 | - 6.31 | - 7.18 | - 7.82 | - 8.33 | - 8.75 |
| 07028050 | 11.90 | - 2.27 | - 6.32 | - 8.05 | - 9.15 | - 9.97 | -10.62 | -11.15 |
| 07028100 | 7.90 | - 2.87 | - 7.97 | -10.14 | -11.53 | -12.55 | -13.36 | -14.03 |
| 07028200 | 3.30 | . | . | . | . | . | . | . |
| | | **South Fork Obion River** | | | | | | |
| 07024300 | 35.80 | . | . | . | . | . | . | . |
| 07024350 | 34.40 | . | . | . | . | . | . | . |
| 07024430 | 28.40 | . | - 0.24 | - 0.39 | - 0.46 | - 0.52 | - 0.56 | - 0.59 |
| 07024460 | 23.20 | . | - 1.04 | - 1.64 | - 1.97 | - 2.20 | - 2.37 | - 2.51 |
| 07024500 | 19.20 | . | . | - 2.78 | - 4.40 | - 5.27 | - 5.88 | - 6.34 |
| 07024525 | 16.80 | . | - 2.38 | - 3.76 | - 4.51 | - 5.03 | - 5.43 | - 5.75 |
| 07024550 | 11.40 | . | - 3.76 | - 5.94 | - 7.11 | - 7.93 | - 8.55 | - 9.05 |
| 07024800 | 5.80 | -12.14 | -16.13 | -18.57 | -20.32 | -21.69 | -22.82 | -23.77 |
| 07024800 | 5.80 | . | . | . | . | . | . | . |

40 percent. Gradients were constructed at approximately 9.6 X $10^{-4}$ ft/ft, representing an increase of over 500 percent from premodified-gradient values. Imposed gradient increases on the forks of Obion and Forked Deer Rivers (relative to their mouths) were generally in the 5 to 30 percent range (Simon, in press). In addition, the channel bed of Cane Creek is composed of low plasticity silt that requires little stream energy to transport. The sand-bed channels of the larger streams offer greater hydraulic resistance and therefore require more energy for erosion. Furthermore, without an appreciable sand load, gradient reduction by downstream aggradation does not occur on Cane Creek. By Lane's (1955) stream-power equation (eq. 1) the channel bed must continue to degrade to reduce gradient and stream power.

It is streams such as Cane, Hoosier, Hyde, and Pond Creeks that are the most susceptible to large amounts of degradation due to the fine-grained nature of their sediment loads. These types of streams are extremely "sensitive" to changes in controlling variables such as gradient or velocity. Adjustments on Pond Creek, although mild in comparison (table 9), are apparently due to increases in flow velocities due to a reduction in Manning's "n" from clearing operations.

The volume of channel-bed material eroded per square mile of drainage area from the forks of the Obion River is nearly constant (table 10). This is consistent with previous discussions regarding the

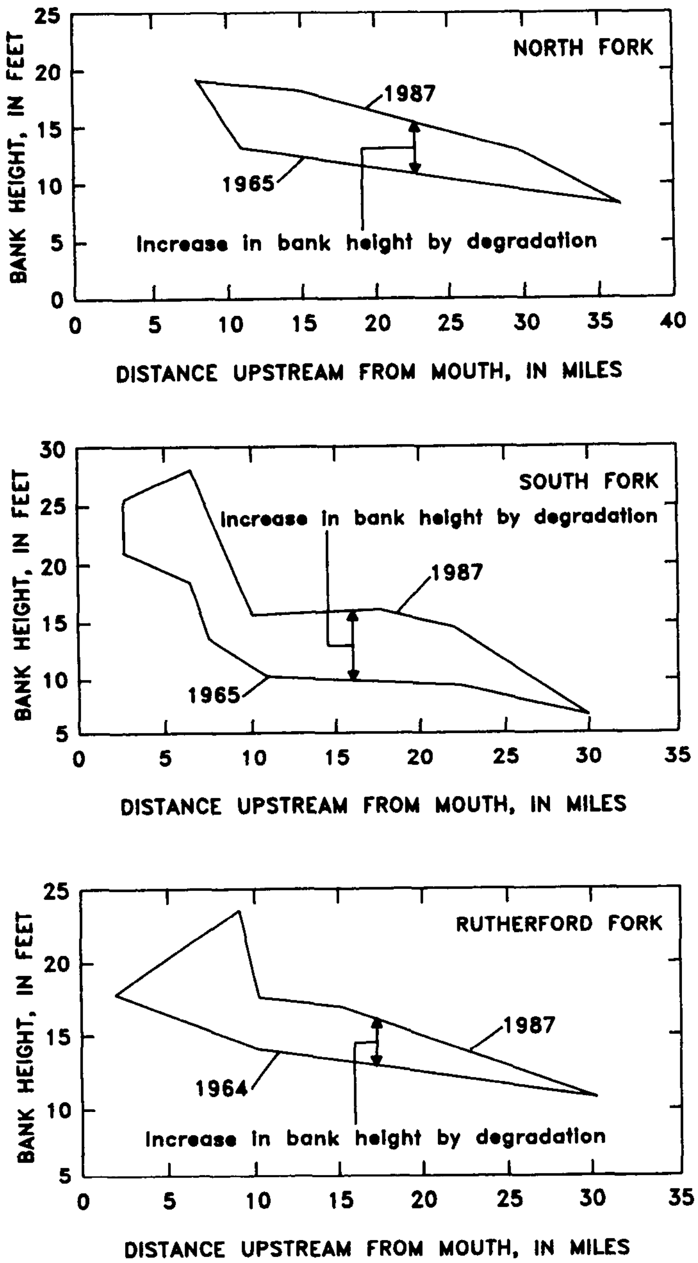



Figure 23.--Changes in bank heights by degradation along the North Fork, South Fork, and Rutherford Fork Obion River, 1964, 1965, and 1987.

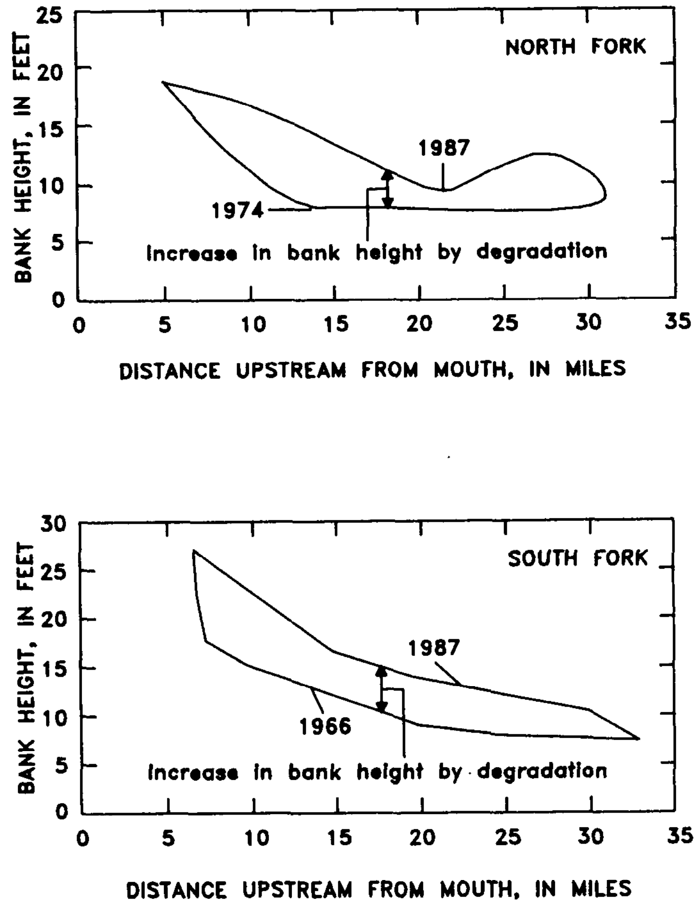



Figure 24.--Changes in bank heights by degradation along the North Fork and South Fork Forked Deer River, 1966, 1974, and 1987.

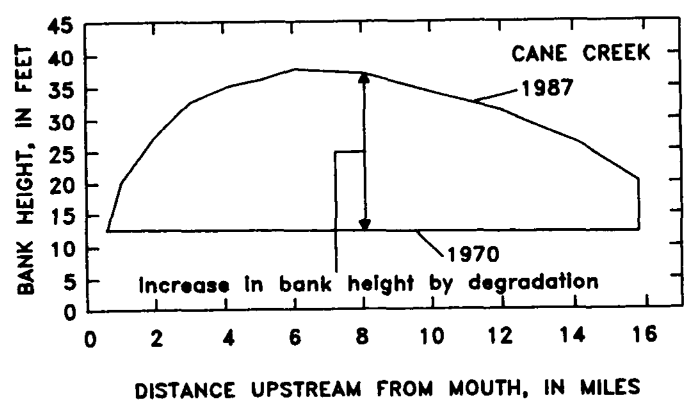



Figure 25.--Changes in bank heights by degradation along Cane Creek, 1970 and 1987.

Table 10.--*Volumes of channel-bed material eroded by degradation*

[-- = Not applicable]

| Stream | Volume (millions of cubic feet) | |
|---|---|---|
| | Total | Per square mile of drainage area |
| North Fork Forked Deer | 8.71 | 0.26 |
| South Fork Forked Deer | 14.0 | .41 |
| Middle Fork Forked Deer[1] | 10.0 | -- |
| ***Total for Forked Deer River system*** | 32.7 | |
| North Fork Obion River | 11.4 | .31 |
| South Fork Obion River | 9.54 | .32 |
| Rutherford Fork Obion River | 5.50 | .18 |
| Middle Fork Obion River | 8.81 | -- |
| ***Total for Obion River system*** | 35.2 | |
| ***Total for Cane Creek*** | 32.2 | .37 |

[1]Estimated data.

disturbance magnitude and sediment character on bed-level adjustments. All forks of the Obion River are responding to the same disturbance; the dredging and straightening of the Obion River main stem. These streams also have very similar channel-bed-material particle sizes (mean $d_{50}$ = 0.42 mm, standard deviation = 0.047 mm; Simon, in press). The result is that similar volumes of material (unitized by drainage area) have been eroded from the channel beds of the Obion River forks by upstream degradation (table 10).

Upstream limits of present (1987) degradation can be obtained by noting the river mile at which the predisturbed trend lines meet the 1987 trend lines (figs. 23-25). The channel lengths affected by degradation were obtained by subtracting the river-mile location of the AMD from this upstream limit; channel lengths range from 23.1 to 30.6 miles for the Obion and Forked Deer River forks (table 11). Dividing by the number of years since the channel was modified gives an average rate of upstream migration of the degradation process. Values obtained range from 1 to 2 miles per year along the sand-bed streams of West Tennessee. These values (table 11) can be used to estimate the location of knickpoints and expected degradation in years to come, assuming the degradation process continues to migrate at the same rate, and there is no further disruption of the channel.

### *Aggradation*

Channel-bed aggradation and bank accretion are important attributes of adjusting fluvial systems. Aggradation reduces bank heights and thereby aids in bank restabilization. It also reduces channel

Table 11.--*Upstream limit of channel-bed degradation and rate of headward migration of knickpoints, 1987*

[AMD=Area of maximum disturbance]

| Stream | Location of AMD (river mile) | Year channel work was completed | Upstream limit of degradation (river mile) | Rate of headward migration (miles per year) |
|---|---|---|---|---|
| North Fork Forked Deer | 4.3 | 1973 | 33.0 | 2.02 |
| South Fork Forked Deer | 4.4 | 1969 | 35.0 | 1.70 |
| North Fork Obion River | 10.9 | 1967 | 36.5 | 1.28 |
| South Fork Obion River | 6.0 | 1969 | 30.0 | 1.33 |
| Rutherford Fork Obion River | 7.4 | 1967 | 30.5 | 1.16 |

capacity and consequently, stream power, by causing successively lower discharge flows to spread over the flood plain and dissipate stream energy. In general, aggradation occurs at a site downstream from the AMD immediately after the completion of channel work, and just upstream from the AMD after 10 to 15 years of degradation (Simon, 1989). Recorded rates of this secondary aggradation (+b) are generally 78 percent less than the corresponding rate of initial degradation (-b; Simon, in press), and represent the onset of stage V conditions (table 5). Aggradation also occurs at low rates along reaches well upstream of the migrating degradation process because of "natural" fluvial processes and land-use practices commonly associated with the Gulf Coastal Plain.

Projected amounts of aggradation calculated from empirical data are available for 17 sites and range from 0.3 to 9.7 feet to the year 2000 (table 12). Maximum values occur along the most downstream reaches of the North and South Forks Forked Deer River and along the Obion River main stem. These sites represent stage V or stage IV conditions, and are recovering by adjustment processes. The lowest values of projected aggradation occur along the unaffected reaches of the Obion River forks (fig. 4 and table 12); 0.3 - 1.9 feet to the year 2000. It is assumed that similar rates are presently (1987) operative upstream from river mile 28 in the Forked Deer River system (fig. 7).

Future rates and amounts of aggradation are estimated from -b for those sites that are presently (1987) degrading. Empirical data regarding secondary aggradation are somewhat limited because most sites encountered upstream of the AMD are still degrading. Figure 3c and 3d from Simon (1989) graphically demonstrate the concept of secondary aggradation. The decrease in +b with distance upstream (fig. 4) is a function of the magnitude of the former degradation, which also approaches 0.0 upstream (figs. 4, 19). Like the degradation process that migrates upstream to reduce channel gradients, aggradation also migrates upstream, but in this case, to cause a subsequent increase in channel gradients. This type of oscillatory response is reported by Schumm (1973) and Alexander (1981), and is discussed in detail by Simon (in press). Gradient reduction at a site, after 10 to 15 years of downcutting, decreases stream power to such an extent that the available stream power is insufficient

Table 12.--*Calculated amounts of channel-bed aggradation at 5-year intervals to the year 2000 for sites with existing degradation data*

[Estimates start at different times due to timing of adjustment process at a site; -- =Not applicable]

| Stream | Station number | River mile | Year 1970 | 1975 | 1980 | 1985 | 1990 | 1995 | 2000 |
|---|---|---|---|---|---|---|---|---|---|
| Cub Creek | 07029450 | 1.54 | -- | -- | 1.54 | 2.21 | 2.60 | 2.88 | 3.10 |
| Hoosier Creek | 07025690 | .55 | 0.83 | 1.57 | 1.94 | 2.19 | 2.38 | 2.53 | 2.65 |
| North Fork Forked Deer River | 07029105 | 3.83 | -- | -- | 1.66 | 4.70 | 6.01 | 6.87 | 7.50 |
| North Fork Obion River | 07025320 | 34.90 | .28 | .78 | 1.00 | 1.14 | 1.25 | 1.33 | 1.40 |
| | 07025600 | 5.90 | 1.16 | 1.84 | 2.21 | 2.47 | 2.67 | 2.83 | 2.96 |
| Obion River | 07024800 | 68.50 | -- | .89 | 2.51 | 3.21 | 3.66 | 3.99 | 4.26 |
| | 07025900 | 62.20 | .67 | 3.17 | 3.58 | 3.89 | 4.13 | 4.34 | 4.51 |
| | 07026000 | 53.70 | 4.13 | 3.79 | 4.17 | 4.46 | 4.71 | 4.91 | 5.10 |
| | 07026300 | 34.20 | 2.57 | 3.17 | 3.58 | 3.89 | 4.13 | 4.34 | 4.51 |
| | 07027200 | 20.80 | 3.28 | 3.79 | 4.17 | 4.46 | 4.71 | 4.91 | 5.10 |
| Rutherford Fork Obion River | 07024900 | 29.90 | .96 | 1.29 | 1.49 | 1.64 | 1.75 | 1.85 | 1.93 |
| | 07025050 | 10.40 | -- | -- | 1.46 | 2.31 | 2.78 | 3.10 | 3.35 |
| | 07025100 | 4.90 | -- | .84 | 2.36 | 3.01 | 3.44 | 3.76 | 4.01 |
| South Fork Forked Deer River | 07028200 | 3.30 | 1.91 | 5.42 | 6.94 | 7.93 | 8.66 | 9.25 | 9.73 |
| South Fork Obion River | 07024300 | 35.80 | .16 | .22 | .25 | .27 | .29 | .31 | .33 |
| | 07024350 | 34.40 | .32 | .89 | 1.13 | 1.29 | 1.41 | 2.50 | 1.58 |
| | 07024800 | 5.80 | -- | -- | 2.65 | 3.55 | 4.11 | 4.51 | 4.83 |

to transport increased sediment loads emanating from newly eroding upstream reaches (Simon, 1989). The result is a trend of general aggradation that migrates headward from the AMD. This mildly increases gradient and thereby increases the capability of the stream to transport its bed load.

Estimates of the location and timing of the onset of secondary aggradation (to the year 2000) along the Obion and Forked Deer systems are presented in table 13. By assuming a degradation period (stages III and IV) of 15 years, the location of the aggradation wave can be estimated. Using the North Fork Obion River as an example (table 13), degradation reaches river mile 14.7 in 1970 and lasts until 1985; 15 years. Accordingly, secondary aggradation would then begin at this site. In this way the location of the aggradation wave can be estimated for the time period desired.

The volumes of sediment (generally fine and medium sand) deposited by channel-bed aggradation and bank accretion along stage V and VI reaches are calculated from plots showing changes of channel cross-sectional area over the stream lengths studied (fig. 9). With the exception of the Obion River main stem, volumes of deposition in the Obion-Forked Deer River system range from 8.3 to 13.9 $Mft^3$ on the Rutherford Fork Obion and the South Fork Forked Deer Rivers, respectively (table 14). The Obion River main stem, being completely downstream of the AMD and receiving tractive sediment from all of its forks, has accumulated 373 $Mft^3$ of sediment in the 20 years since modification. This value, averaged over 62.3 river miles and using an average bottom width of 150 feet represents approximately 7.5 feet of channel bed-level recovery throughout the Obion River from 1967 to 1987.

Table 13.--*Projected location and timing of degradation knickpoint (D) and secondary aggradation wave (A)*

[-- = Not applicable]

| Stream | | Year 1970 | 1975 | 1980 | 1985 | 1990 | 1995 | 2000 |
|---|---|---|---|---|---|---|---|---|
| | | (miles upstream from mouth) | | | | | | |
| North Fork Forked Deer | (D) | -- | 8.7 | 18.8 | 28.9 | 39.0 | 49.1 | 59.2 |
| | (A) | -- | -- | -- | -- | 8.7 | 18.8 | 28.9 |
| South Fork Forked Deer | (D) | 6.1 | 14.6 | 23.1 | 31.6 | 40.1 | 48.6 | 57.1 |
| | (A) | -- | -- | -- | 6.1 | 14.6 | 23.1 | 31.6 |
| North Fork Obion | (D) | 14.7 | 21.1 | 27.5 | 33.9 | 40.3 | 46.7 | 53.1 |
| | (A) | -- | -- | -- | 14.7 | 21.1 | 27.5 | 33.9 |
| South Fork Obion | (D) | 7.3 | 14.0 | 20.6 | 27.3 | 33.9 | 40.6 | 47.2 |
| | (A) | -- | -- | -- | 7.3 | 14.0 | 20.6 | 27.3 |
| Rutherford Fork Obion | (D) | 10.9 | 16.7 | 22.5 | 28.3 | 34.1 | 39.9 | 45.7 |
| | (A) | -- | -- | -- | 10.9 | 16.7 | 22.5 | 28.3 |

Table 14.--*Volumes of sediment deposited by aggradation and accretion, from modification to 1987*

[-- = Not applicable]

| Stream | Volume deposited (millions of cubic feet) | Percent of total eroded | Starting date |
|---|---|---|---|
| North Fork Forked Deer | 11.7 | 24.2 | 1973 |
| South Fork Forked Deer | 13.9 | 20.8 | 1969 |
| North Fork Obion | 10.2 | 21.5 | 1967 |
| South Fork Obion | 10.5 | 15.4 | 1967 |
| Rutherford Fork Obion | 8.32 | 16.7 | 1967 |
| Obion | 373 | -- | 1959 |
| Cub | .47 | -- | 1970 |
| Porters | 2.99 | -- | 1972 |

Aggradation in the loess tributaries (Cane, Hyde, Pond, and Hoosier Creeks) is extremely limited, even in backwater areas, due to the lack of an appreciable sand load. If these channels undergo significant and widespread degradation (Cane and Hyde Creeks) a long period of instability can be expected. Tributary streams with tractive sediments such as Cub and Porters Creek recover through aggradation and bank accretion. The most downstream reaches of both Cub and Porters Creeks filled with sand just two years after their construction and were re-dredged. Volumes of material deposited (calculated from dredging plans and resurveys) were 0.47 $Mft^3$ for Cub Creek and 2.99 $Mft^3$ for Porters Creek.

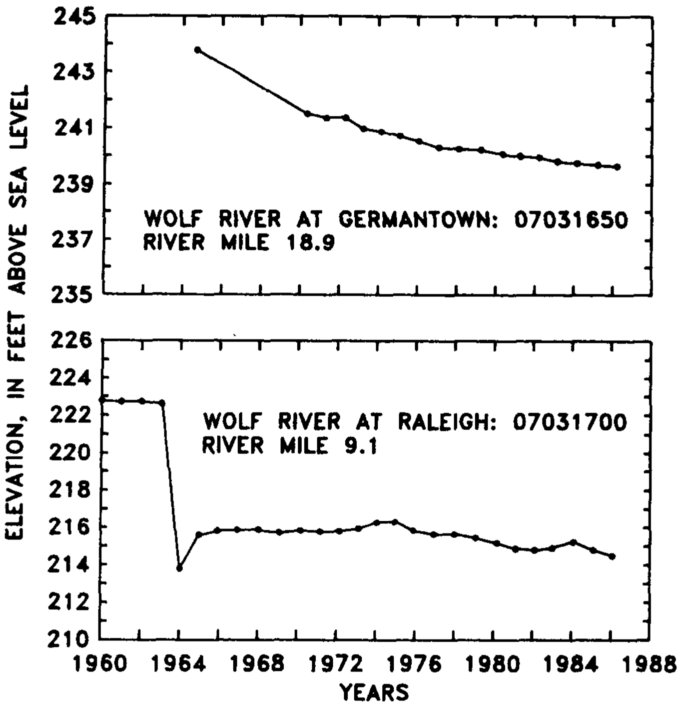



Figure 26.--Trends of channel-bed elevation with time for two sites on the lower Wolf River.

Trends of aggradation along the lower Wolf River are not distinct and do not comply with documented aggradation trends on other rivers. Reaches downstream from the AMD that would be expected to maintain aggrading, stage V conditions, probably do not because of repeated localized re-dredging of the most downstream reaches. Trends of aggradation are, therefore obscured by the direct removal of deposited sand. As a result, reaches of the Wolf River downstream from the AMD tend to maintain their depths or to mildly degrade (fig. 26).

Along some reaches of the Obion River main stem, aggradation has occurred for nearly 25 years (Robbins and Simon, 1983). This trend may be interrupted because of dredging and the construction of a number of cut-offs near river mile 25 in 1984.

### *Bank Processes and Evolution*

Most streambanks in West Tennessee located upstream from areas of maximum disturbance (AMD) can be considered unstable, or at risk of failing. Exceptions include those located far upstream, beyond the effects of the downstream channel work. The primary cause of bank instability is prolonged and significant channel-bed degradation due to channel modifications. This is the period (stage III) when the rate of stream-channel incision upstream from the AMD is at its maximum. The effect of degradation is most pronounced in areas where moderate flows impinge on low-bank surfaces such as outside bends. The resulting basal scour steepens banks and, where cohesionless units make up the bank toe, may lead to complete loss of support for the upper part of the bank and subsequent slab failure (Thorne and others, 1981; Grissinger, 1982).

Bank failures occur by a variety of mechanisms along West Tennessee streams including:

1. slab, by fluvial undercutting and the loss of support for the upper part of the bank;

2. rotational, considered most critical due to a smaller surface area per unit mass (Huang, 1983) in low-angle slopes of homogeneous materials;

3. planar, considered most critical in steep slopes of very low cohesion with failure depths much smaller than failure lengths (Huang, 1983);

4. pop-out, due to excessive pore-water pressure, and unloading (These failures are generally smaller than those mentioned previously.); and

5. secondary, shallow slides that generally occur in previously failed materials and accreted bank sediments, as a result of the reduction in shear strength (Carson and Kirkby, 1972).

### Bank-Material Properties

Bank material of West Tennessee streams is loess-derived alluvium that can be classified generally as highly erodible silt of low cohesion (U.S. Department of Agriculture, 1980). Mean values of cohesion (c) and angle of internal friction ($\phi$) as determined by the BST are 1.26 lbs/in$^2$ ($S_e$ = 0.1) and 30.1 degrees ($S_e$ = 0.6), respectively (168 tests). Frequency histograms of these shear-strength variables, and field density for all sites are shown in figure 27. Total shear strength along failure planes of unit length is commonly less than 13.9 lbs/in$^2$. Additional bank-properties data are provided in Simon (in press). Although loess often stands in vertical cliffs when dry, high degrees of saturation (mean of 86 percent) leave the channel banks vulnerable to complete saturation by moderate rises in river stage or a substantial local rainstorm. Upon saturation, the angle of internal friction, and

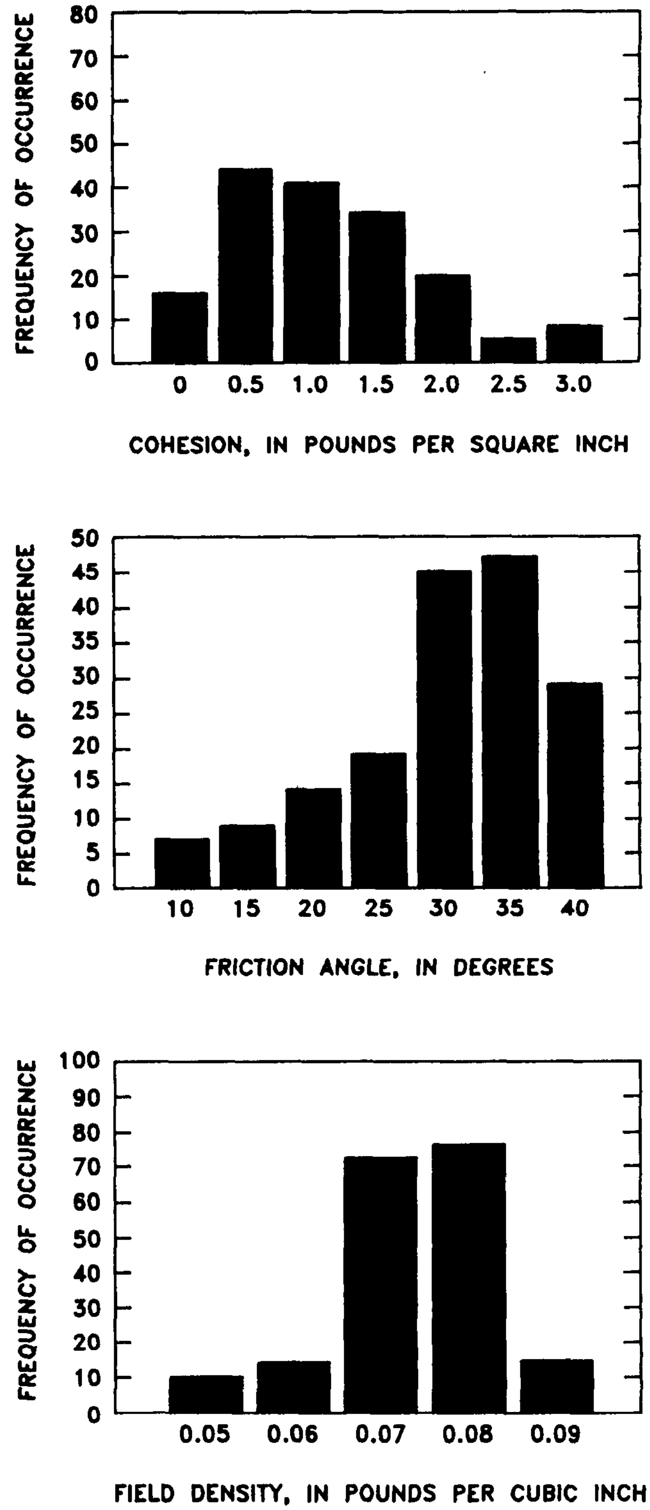



Figure 27.—Frequency histograms of soil-mechanics data.

therefore the frictional component of resistance becomes 0.0 (fig. 28; Lutton, 1974), leaving only the cohesion component to resist mass failure. Because the cohesion component on the average makes up only 10 percent of the strength of the channel banks, failure usually follows saturation. Along degraded reaches failure occurs during or after recession of river stage (a rapid drawdown condition) as the bank loses the support afforded by the water. Mean soil-mechanics data obtained with the BST for studied streams are summarized in table 15. These results are in general agreement with triaxial-test data given for the Obion-Forked Deer system (U.S. Army Corps of Engineers, written commun., 1965), within the range of other BST data for areas around the Cane Creek basin (Lohnes and Handy, 1968), and with values reported in textbooks for similar materials (low plasticity silt).

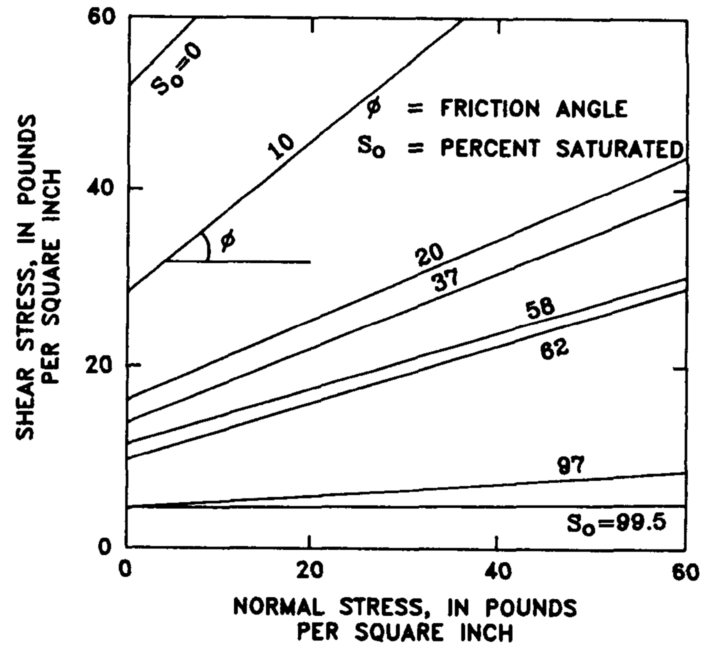



Figure 28.--Relation between normal stress and shear stress for loess at various degrees of soil saturation. (Modified from Lutton, 1974.) $S_o$ values are in percent.

Table 15.--*Mean values for soil-mechanics data for studied streams*

[n=number of samples; ( )=standard deviation]

| Stream | Cohesion (pounds per square inch) | Friction angle (degrees) | Degree of saturation (percent) | Saturated density (pounds per cubic inch) | n |
|---|---|---|---|---|---|
| Cane Creek | 0.89 (0.58) | 29.5 ( 7.1) | 89 (32) | 0.071 (0.003) | 34 |
| Cub Creek | 1.15 ( .44) | 31.0 (12.8) | 99 (46) | .072 ( .005) | 4 |
| Hoosier Creek | 0.78 ( .53) | 35.7 ( 6.9) | 93 ( 8) | .071 ( .002) | 6 |
| Hyde Creek | 1.07 ( .63) | 37.8 ( 5.4) | 75 ( 6) | .067 ( .002) | 5 |
| North Fork Forked Deer River | 1.51 (1.11) | 29.8 ( 8.7) | 89 (14) | .070 ( .003) | 17 |
| North Fork Obion River | 1.47 ( .44) | 27.9 ( 6.7) | 86 (17) | .070 ( .002) | 14 |
| Obion River | 2.09 (2.36) | 30.5 ( 7.9) | 88 (21) | .072 ( .003) | 18 |
| Pond Creek | 1.51 ( .85) | 30.3 ( 5.2) | 91 ( 7) | .068 ( .003) | 8 |
| Porters Creek | 0.93 ( .72) | 28.6 (10.1) | 88 (41) | .069 ( .006) | 9 |
| Rutherford Fork Obion River | 0.95 ( .66) | 26.1 ( 9.6) | 99 (34) | .073 ( .003) | 12 |
| South Fork Forked Deer River | 1.65 (1.26) | 31.8 ( 7.4) | 68 (20) | .070 ( .004) | 16 |
| South Fork Obion River | 1.10 ( .93) | 27.6 (10.4) | 99 (24) | .073 ( .003) | 12 |
| Wolf River | 0.81 ( .51) | 32.3 ( 4.6) | 65 (34) | .065 ( .006) | 13 |
| All sites | 1.26 (1.12) | 30.1 ( 8.0) | 86 (29) | .071 ( .007) | 168 |

### Bank Evolution--General

Reaches that have degraded beyond the critical conditions of the bank material, and are failing, often represent stage IV conditions (Simon and Hupp, 1986a; Simon, 1989). Channel widening by slab, rotational, and planar failures are common during this stage. Only the relatively small pop-out failures that occur at the base of the bank take place during the previous stage (stage III; degradation). This is attributable to an increase in shear stress with depth, with no corresponding increase in shear strength due to unloading of the bank (degradation). Although Bishop and Bjerrum (1960) associate this process with excavation in unconsolidated materials, unloading due to degradation is a natural analogy. Secondary failures generally occur along stage V reaches on low- and mid-bank surfaces in previously failed materials that maintain only residual strengths. These failures are shallow relative to their downslope length and are aided by the additional weight of saturated accreted sediments. Secondary failures are common along the Obion River main stem where bank accretion has occurred for at least 25 years.

Mass wasting of the channel banks is the dominant channel-shaping process during stage IV. Therefore, this stage is the most appropriate to interpret bank-failure variability. However, to more completely understand changes in bank stability over time and space it is necessary to take other channel processes into account. The following discussions of bank-failure mechanisms that contribute to top-bank widening (planar and deep-seated rotational failures) are arranged according to the stage of bank-slope development. Quantitative information on shear strength and factors of safety are generalized and assimilated into the conceptual framework of the models of channel evolution and bank-slope development, from stage I to stage VI (fig. 29). Stages are considered time-independent in this analysis and represent the assimilation of data bases from (1959-1987). Factors of safety are based on calculated values at saturation. Factors of safety were computed from equation 5 for planar failures and equation 7 for rotational failures at all

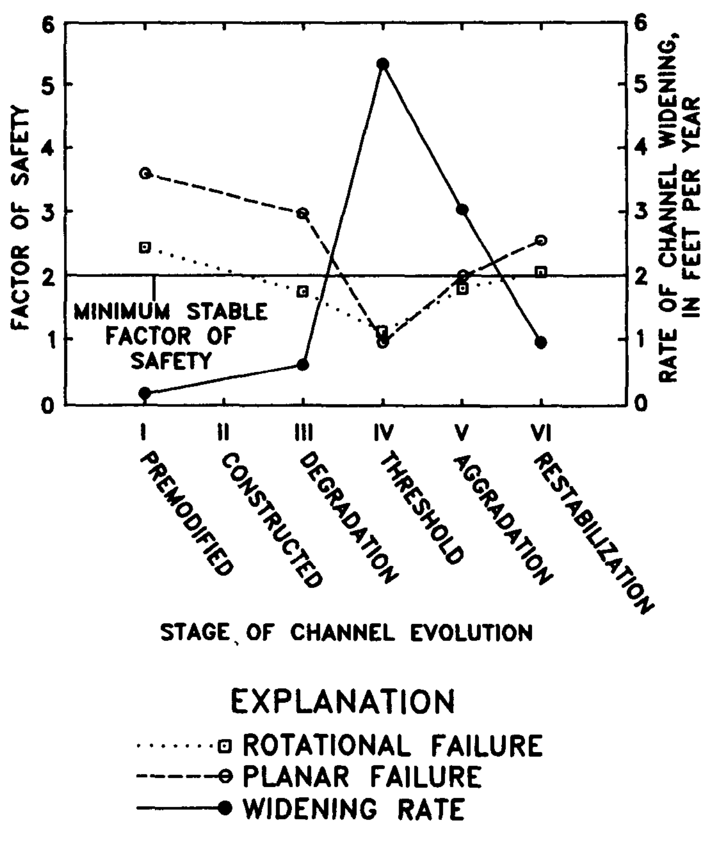



Figure 29.--Factors of safety for mass-bank failures and rate of channel widening by stage of channel evolution.

sites where shear-strength data and bank-geometry data were available (table 6). These data were then grouped according to stage of channel evolution and the average for each stage was computed. Mean values of factors of safety (FS) data for both planar and rotational failures are compared with mean rates of channel-widening (from dendrogeomorphic analyses) for each stage and show bank-stability trends over the course of fluvial adjustment (fig. 29). As would be expected there is an inverse relation between widening rates and factors of safety.

Assuming that large-scale bank failures do not occur during stages I, III, and VI, figure 29 can be separated into two sections with a horizontal line can be drawn at approximately FS=2.0. The upper section represents generally unstable, failing banks, and the lower section represents generally stable banks. Using stages I, III, and VI to represent generally stable bank conditions, and stages IV and V as generally unstable bank conditions, the line at FS=2.0 can represent a minimum, stable factor of safety. These results suggest that for streambanks of loess-derived alluvium the use of factors of safety of 1.5 to designate stable banks may be tenuous. Discussion of the role of various mass-wasting processes during the six stages of bank development (Simon and Hupp, 1986a; Simon, 1989) follows:

## Stage I - Premodified

Stage I reaches are stable and bank failures by mass wasting generally do not occur. Banks are densely vegetated, often down to the low-flow channel, and are the product of "natural" fluvial processes (fig. 30). Minor amounts of fluvial erosion (less than 0.2 ft/yr) on outside bends of meanders take place in conjunction with sediment accretion and point-bar extension on inside bends. Mean FS for both planar and rotational failure are well above critical values at 3.61 and 2.44, respectively (fig. 29). Reaches representative of stage I conditions are common on the Hatchie River and upstream reaches of the Wolf River. These banks remain stable even though shear-strength values may be relative low. For example, cohesion and shear-strength values for stage I sites on the Wolf River are very low--less than 1.0 $lb/in^2$ and 6.9 pounds per square foot ($lbs/ft^2$), respectively. Yet because the channel bed has not degraded, bank heights above the low-flow water surface remain less than 7 feet and the banks are stable. Mean FS for the three most upstream sites are 4.07 for planar failures and 2.48 for rotational failures (fig. 31).

## Stage II - Constructed

Factors of safety decrease for rotational and planar failures during stages II and III (construction and degradation) due to an increase in bank heights. Because not all the studied reaches have been recently modified by man, some banks (those upstream from the limit of channel modifications) pass directly from stage I to stage III as degradation migrates upstream from the AMD. In contrast,

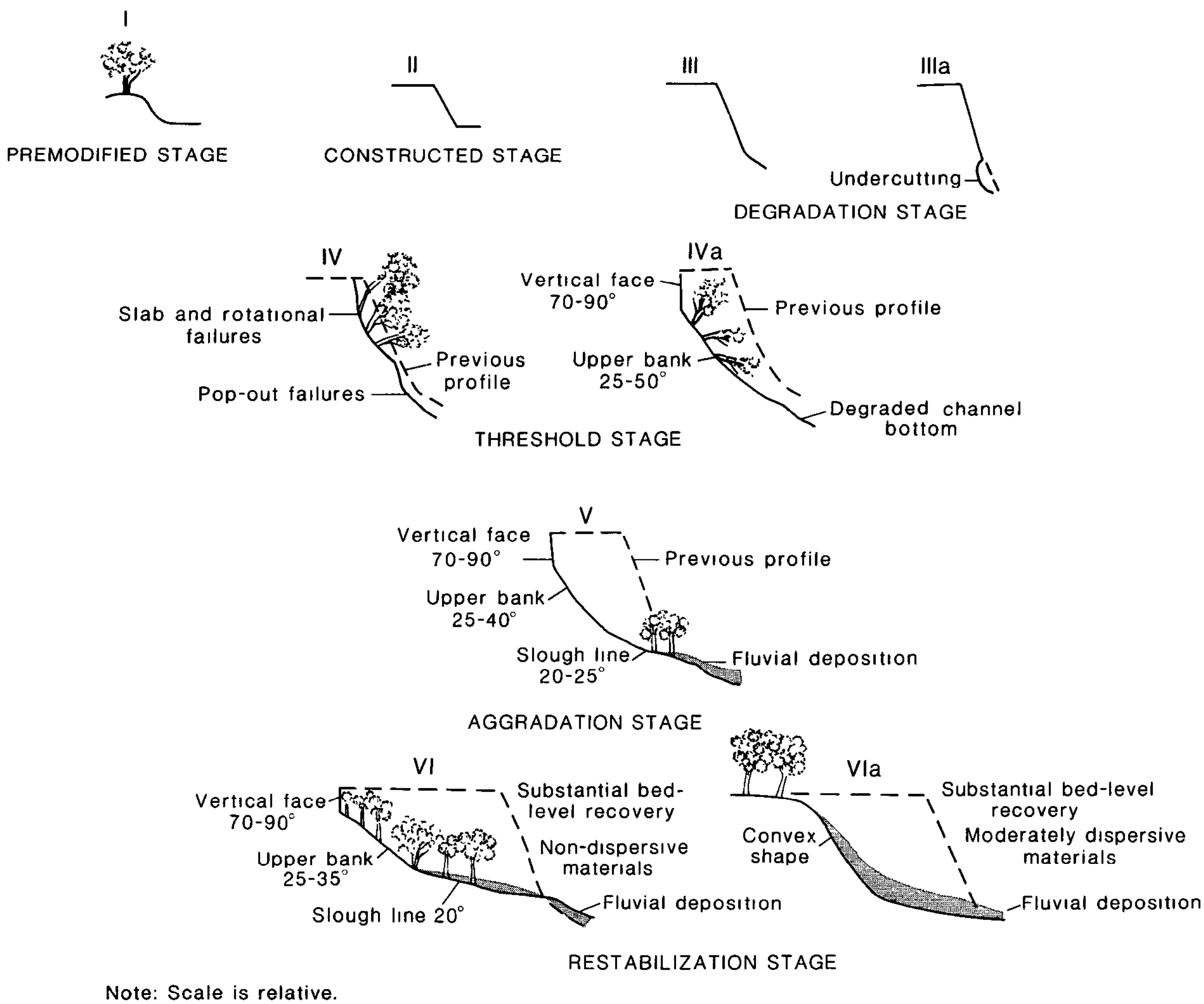



Figure 30.--Six-stage model of bank-slope development in disturbed channels. (From Simon, 1989.)

channelized (stage II) reaches are generally trapezoidal in shape and were constructed with factors of safety, for planar failures, of 1.5 (U.S. Army Corps of Engineers, written commun., 1963 through 1978). Stability analyses conducted in this study give similar results (mean factor of safety = 1.66) for rotational failures and were conducted using as-built construction plans furnished by the COE and the SCS.

The only stage II reaches observed during field surveys (1985-87) are the most downstream two sites on the Obion River main stem. These reaches were recently channelized, maintain FS > 2.0, and are not experiencing top-bank widening by mass wasting (fig. 32). By definition, stage II reaches are located downstream of the AMD. Those reaches that are constructed with stable banks are likely to remain stable because subsequent aggradation further reduces bank heights. The combination of generally stable banks and aggrading conditions on the channel bed indicates passage from stage II directly to stage V (aggradation), or stage VI (restabilization).

## Stage III - Degradation

Degradation, due to downstream increases in channel gradient and stream power causes increases in bank heights and steepening of bank slopes by fluvial undercutting and pop-out failures at the bank toe (fig. 30). Mean FS for all stage III sites decrease accordingly from their stage I values (3.61 and 2.44) to 3.00 and 1.79 for planar and rotational failures, respectively (fig. 29). Values of this magnitude indicate a continuation of generally stable-bank conditions and limited channel widening. For reaches located upstream from the AMD, factors of safety decrease with the progression of downcutting at a site over time. Similarly, deteriorating FS should migrate upstream with the degradation process.

## Stage IV - Threshold

Mean factors of safety sharply drop to near 1.0 and mark the onset of full-scale channel widening during stage IV (fig. 29). Though channel-bed degradation occurs at lesser rates than during stage III, continued downcutting creates bank heights and angles in excess of the critical conditions of the material. Rates of channel widening range from 3 to 13 feet per year along highly unstable reaches (Hupp and Simon, 1986).

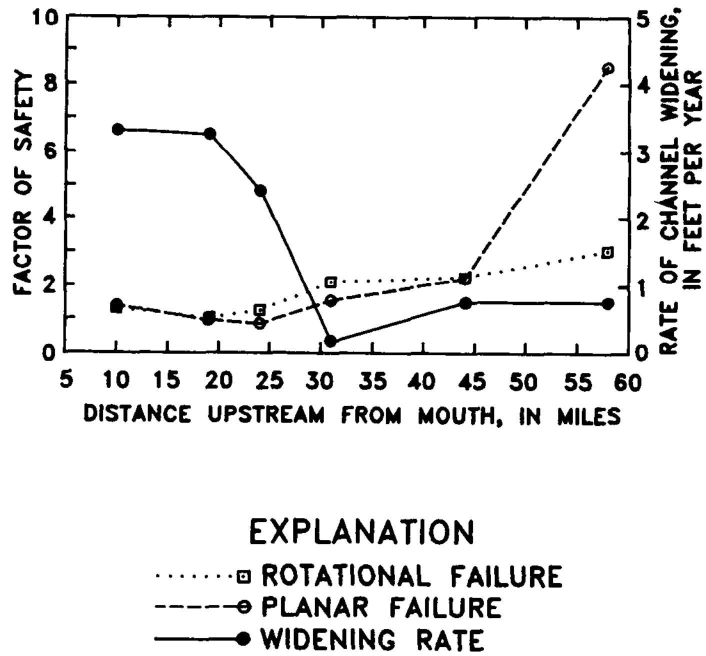



Figure 31.--Factors of safety and recent widening rates along the Wolf River.

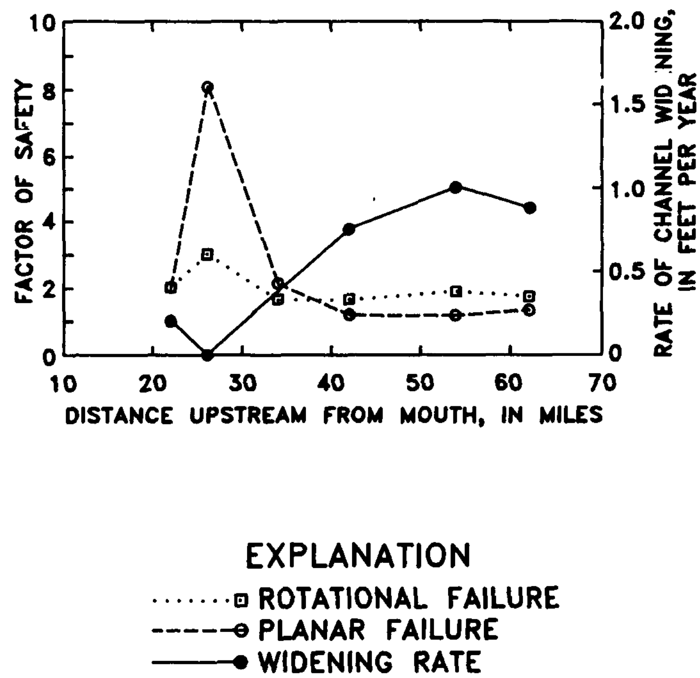



Figure 32.--Factors of safety and recent widening rates along the Obion River main stem.

Channel widening by mass wasting is the dominant channel-shaping process during stage IV. Banks subject to rotational failures take on a scalloped appearance in plan view. Bank scallops up to 200 feet long and 40 feet wide that represent a single-failure event have been observed along reaches of Cane Creek (Simon and Hupp, 1986b).

### *Rotational Compared Against Planar Failures*

Planar failures generally are more critical than rotational failures along the majority of the streams studied (table 16). However, the most rapidly widening reaches are dominated by rotational failures. Field observations and theoretical considerations suggest that deep-seated rotational failures can be the dominant failure mechanism under certain conditions. In cohesive materials, shear stress increases more rapidly with depth than does the strength of the bank, and at greater depths may be larger than the shear strength, leading to rotational failure (Carson and Kirkby, 1972). Nonvertical and compound-slope banks are also subject to rotational failures due to the variable nature of the direction of the major principal plane.

Table 16.--*Mean values for factors of safety for planar and rotational failures during threshold stage (stage IV) dominated by channel widening by mass-wasting processes*

[n= number of observations; -- = no data]

| Stream/Basin | Planar failures | | | Rotational failures | | |
|---|---|---|---|---|---|---|
| | Mean value for factor of safety | Standard deviation | n | Mean value for factor of safety | Standard deviation | n |
| North Fork Obion River | 0.98 | 0.18 | 6 | 1.35 | 0.27 | 4 |
| South Fork Obion River | 0.90 | .18 | 5 | 1.09 | .31 | 6 |
| Rutherford Fork Obion River | 0.82 | .27 | 6 | 1.26 | .71 | 5 |
| **Obion River Basin** | 0.91 | .21 | 17 | 1.22 | .45 | 15 |
| North Fork Forked Deer River | 1.15 | .06 | 3 | 1.25 | .42 | 3 |
| South Fork Forked Deer River | 1.19 | .34 | 5 | 1.27 | .08 | 5 |
| **Forked Deer Basin** | 1.17 | .26 | 8 | 1.26 | .23 | 8 |
| Wolf River | .98 | .30 | 3 | 1.14 | .13 | 3 |
| Cane Creek | 1.03 | .40 | 12 | .84 | .22 | 5 |
| Hoosier Creek | 1.11 | .30 | 2 | 1.18 | .38 | 3 |
| Hyde Creek | .92 | .07 | 3 | -- | -- | -- |
| Pond Creek | 1.19 | .19 | 2 | 1.46 | .37 | 2 |
| **Loess Tributaries** | 1.08 | .38 | 19 | 1.07 | .37 | 10 |
| Cub Creek | 1.10 | .31 | 2 | .94 | .11 | 2 |
| Porters Creek | .74 | .12 | 2 | .92 | .13 | 2 |
| **Tributaries in Tertiary rocks.** | 1.01 | .27 | 4 | .93 | .10 | 4 |
| **All Sites** | 1.00 | .29 | 51 | 1.15 | .36 | 40 |

Field evidence from West Tennessee supports Skempton's (1953) observation that shallow, planar failures become critical earlier in the downcutting phase. A corollary to this observation is that only those reaches that experience the greatest amount of bed-level lowering will produce deep-seated rotational failures and rapidly widening banks. Most reaches of Cane Creek illustrate this point. Increases in bank heights from 6 to 10 feet in 1970 to 35 to 50 feet in 1985 caused 100 to 150 feet of widening over the same time period. Cane Creek banks are the highest and most homogenous (c=0.89 psi; standard deviation=0.10) encountered in the study. More significantly, however, are the calculated FS values for stage IV reaches along this creek; 0.84 for rotational failures, and 1.03 for planar failures (table 16).

The reduction in bank angles by deep-seated rotational failures may be the only geomorphic mechanism to ameliorate mass-bank instability in streams with little or no sand load for aggradation and bank-height reduction. Large rotational failures flatten bank slopes and increase FS for a given bank height and materials strength. These failures also result in a reduction in stream energy for a given high-flow discharge by creating a wider, shallower flow area. The presence of rotational failures along a reach are indicative of the most unstable, rapidly widening sections, which have probably gone through a milder widening phase by planar failures. These reaches are usually identified easily on field inspection by the presence of slickensides on failure surfaces and vegetation tilted towards the top-bank edge (fig. 33). Rotational failures dominate streambanks of the severely degraded loess tributaries and have been observed on at least some reaches of all streams except the Obion River main stem.

Figure 33.--Slickensides along vertical face after differential movement and failure, Cane Creek.

Planar failures are more critical overall (table 16) during stage IV, but generally do not reduce bank-slope angles (Carson and Kirkby, 1972; Simon, in press). Steep bank angles are maintained in part, because material from planar failures are generally not deposited on the bank slope, but are delivered directly to the stream. In contrast, material from rotational failures is often stored on bank slopes until reworked by fluvial action. This difference is probably associated with the greater horizontal distance between the low-water channel and the failing top-bank edge along reaches dominated by rotational failures. Banks dominated by planar failures generally do not have a scalloped appearance but can often be identified by sharp breaks in slope between the vertical face and the upper bank (figs. 30 and 34). These failures are the most frequent types of failures on most reaches of the studied streams except for the loess tributaries. This distinction is not clear in all cases and rotational failures share dominance with planar failures in the most degraded reaches just upstream from the AMD.

Figure 34.--Typical planar failure, South Fork Obion River (station number 07024550, river mile 11.4, 1984).

## Stage V - Aggradation

During stage V, aggradation on the channel bed and reworking of previously failed material tends to ameliorate bank instabilities by reducing bank heights and angles, respectively. Mean factors of safety increase to 2.03 for planar failures, and 1.87 for rotational failures (fig. 29). As expected, there is a commensurate decrease in widening rates during stage V (fig. 29). This is in accordance with the model of bank-slope development (Simon and Hupp, 1986a), which stipulates that top-bank widening continues at lower rates as low-bank surfaces begin to stabilize and revegetate.

Stage V conditions are found (1) downstream of the AMD along channelized reaches and (2) upstream of the AMD after 10 to 15 years of channel-bed degradation. Stage V conditions migrate upstream of the AMD with time. This migration can be traced through dendrogeomorphic analyses of accreted bank sediments around establishing woody plants.

Trends toward increased stability during stage V are minimal along the loess tributaries due to limited bed-level recovery and bank accretion. Mean FS for stage V reaches remain relatively low for deep-seated rotational failures along these streams (mean FS=1.20, table 17), lending further support to the hypothesis that the deep-seated rotational failures play an important role in the ultimate restabilization of grossly unstable banks.

Table 17.--*Mean values for factors of safety for planar and rotational failures during aggradation stage (stage V) dominated by widening and aggradation on the channel bed*

| Basin | Planar failures: Mean values for factor of safety | Planar failures: Standard deviation | Rotational failures: Mean values for factor of safety | Rotational failures: Standard deviation |
|---|---|---|---|---|
| Obion River | 2.34 | 2.60 | 1.89 | 0.57 |
| Forked Deer River | 1.51 | .48 | 2.65 | 1.16 |
| Loess tributaries | 1.82 | .84 | 1.20 | .03 |
| Tributaries in Tertiary rocks | 1.57 | .81 | 1.33 | .11 |
| All sites | 2.03 | 1.73 | 1.87 | .78 |

Where accreted sediments overlie previously failed materials, shallow failures, generally less than 3-feet deep are common (possibly after each major flow event) on mid-bank surfaces. The additional load of the saturated sediment, above material at residual strength, results in shallow rotational failures that further reduce bank angles (fig. 30; Skempton, 1953, Carson and Kirkby, 1972; Simon, 1989). Stability analyses of these failures for sites on the Obion main stem were excluded from the calculation of mean FS because they do not contribute to top-bank widening and because their critical nature (FS near 1.0) would bias the interpretation.

Planar failures that occur during stage V on sand-bed streams are apparently not as dominant, or as critical as the rotational failures (table 17).

Possible explanations include:

1. bank heights are still very high owing to the slow rate of aggradation relative to previous degradation,

2. bank angles are constantly being reduced by rotational failures, causing the orientation of the principal plane to be variable and the failure plane curved, and

3. there are fewer steep segments on stage V banks making conditions less favorable for planar failures.

### Stage VI - Restabilization

Factors of safety continue to increase during stage VI due to decreasing bank heights and angles. Mass wasting usually does not occur and vegetation extends upslope towards the flood plain (fig. 30). Mean-widening rates decrease dramatically (fig. 29). Field evidence indicates that failures that do occur are localized in areas where the thalweg cuts into the bank toe.

The six-stage conceptual model of bank-slope development (Simon and Hupp, 1986a; Simon, 1989) is supported by FS data derived from the BST and from standard slope-stability analyses (fig. 29). Stage IV reaches are clearly the most unstable (mean FS near 1.0), and banks widen rapidly. Most widening is done by deep-seated rotational failures. Where these failures dominate, such as along Cane Creek, mean widening rates may reach 8 feet per year as compared to 3.6 feet per year for the remaining stage IV reaches.

### Critical Bank Conditions

Critical bank conditions, defined as the bank height and angle above which failure is likely to occur, are controlled by the amount of channel-bed degradation, shear strength and degree of saturation of the bank materials, and the presence or absence of fluvial undercutting. Stability charts are produced for sites using a dimensionless stability equation (Carson and Kirkby, 1972; eq. 10) and values of the stability number ($N_s$) reported by Chen (1975).

Representative stability charts are shown in figure 35 and illustrate the three classes of bank stability: unstable, at risk, and stable (Thorne and others, 1981). Ambient-moisture conditions are used to differentiate between unstable and at-risk conditions. This is in contrast to the "mean" conditions used by Thorne and others (1981). The approach used here is justified on the basis that moisture contents remain high in banks of degraded streams even during low-flow periods, as the ground-water table slowly adjusts downward. Seepage lines along the bank are apparent at many sites where degradation has been severe. Saturated conditions are used to differentiate between at-risk and stable conditions, because if shear strength is greater than the corresponding shear stress even at saturation, the bank will remain stable.

For a given river, variations in the location of the lines that differentiate between the stability classes occur as a function of the strength of the bank materials. A shifting of the lines upward means greater bank-material strengths which is generally a function of soil cohesion. Such variability exists longitudinally along a channelized stream because of the different valley-fill units that were truncated at the time of channel construction. Deposits of cohesive clay tend to be localized in areas of past slack, or standing water such as in channel fills (meander cutoffs), on top of channel bars, in flood basins (lowest part of flood plain), and on flood plains (Reineck and Singh, 1975). If a channel is cut through these types of clay deposits, greater cohesive strengths can be expected, and the threshold lines should shift upward. In contrast, silt banks, without appreciable amounts of cohesive clay, or sand for frictional strength, are extremely weak when saturated and cause a shifting of the threshold lines downward.

The frequency of bank failure for the three stability classes is subjective and is based primarily on empirical field data. An unstable-channel bank can be expected to fail at least annually, and possibly after each major flow event (assuming there is at least one in a given year). At-risk conditions translate to a bank failure every 2 to 5 years, again assuming that there is a major flow event to saturate the banks. Stable banks by definition do not fail by mass-wasting processes. However, channel banks on outside meander bends may widen from particle-by-particle erosion and, if this erosion is concentrated at the bank toe, may lead eventually (5 to 10 years) to bank caving. For the purposes of this discussion, stable-bank conditions refer to the absence of mass wasting.

Typical unstable, at-risk, and stable sites are depicted in figure 35a, b, and c, respectively by locating the region of the plots in which the existing bank height and bank angle fall. With the understanding that the lines defining the regions of the plot are relatively static (for a given site), stable-bank configurations can be estimated by decreasing the bank height and (or) angle until the data point falls into the stable region of the plot. For example, a reduction in bank angle from 54 to 45 degrees at Cane Creek

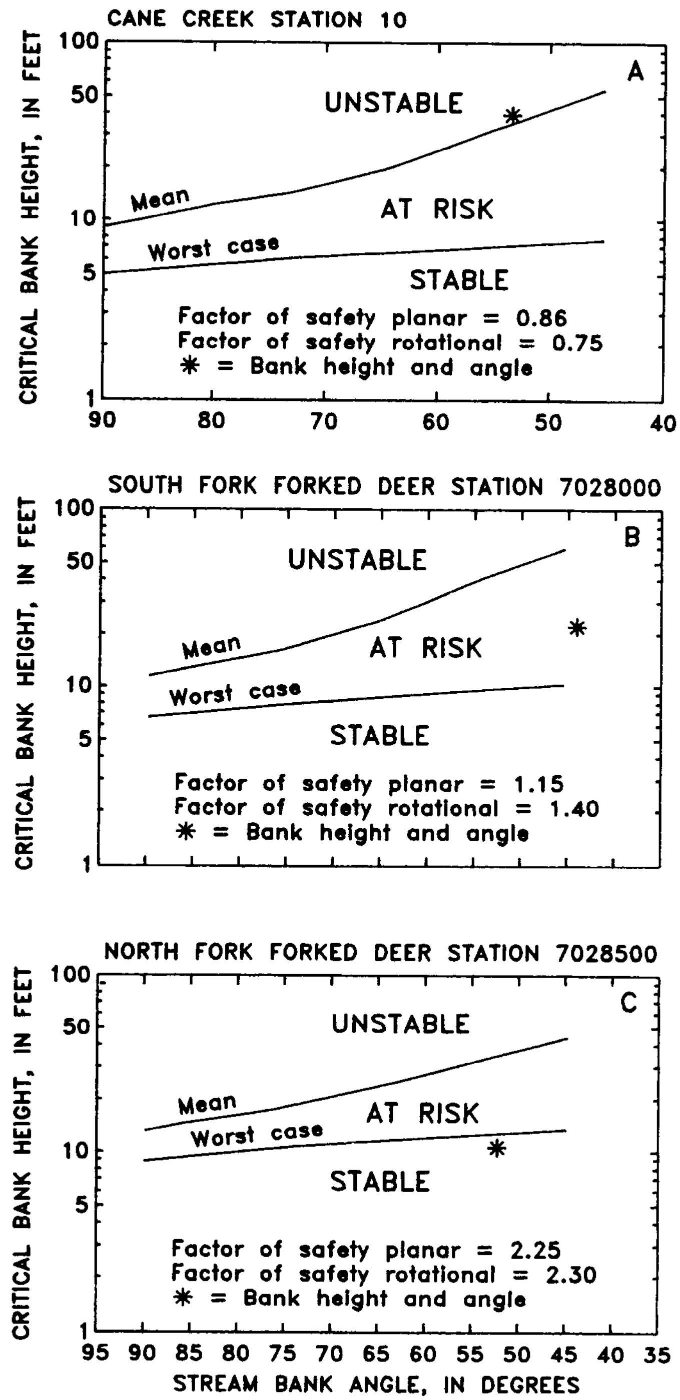



Figure 35.—Slope-stability charts for (A) unstable, (B) at risk, and (C) stable bank-slope configurations.

station 10 (fig. 35a) indicates that stability would be improved. A reduction in bank height to approximately 6 feet at South Fork Forked Deer River station 07028000 (fig. 35b) should result in a stable configuration.

The stabilization of channel banks by reductions in bank height and (or) angle can occur by "natural" adjustment processes, or constructed by man. Bed aggradation will decrease bank heights, and bank accretion and rotational failures will flatten slopes. The magnitude of these adjustment processes at a given site, which aid in bank stabilization, are a function of:

1. presence of a coarse sediment load,

2. location of the site relative to the area of maximum disturbance,

3. location of the site in the drainage network, and

4. time since channel response began.

The Tennessee Department of Transportation has recently used constructed-bank angles from 18.4 degrees (3:1) to 21.8 degrees (2 1/2:1) along degraded West Tennessee streams, in an effort to attain stable bank sections near bridges.

Comparison of critical-bank heights at 90 degrees on the bank-stability charts for Cub Creek stations 07029450 and 07029448 suggests that saturated critical heights for these two stations are 7 and 3.1 feet, respectively. The difference is attributable to different cohesive strengths--1.52 lbs/in$^2$ at station 07029450 and 0.68 lb/in$^2$ at station 07029448. Bank-stability charts for South Fork Forked Deer River stations 07028050 and 07028100 are also quite different, and reflect varying cohesive strengths; 2.78 lbs/in$^2$ for the former station, and 1.24 lbs/in$^2$ for the latter. These variations are common in relocated channels and demonstrate the need for detailed testing at each site. A "mean" bank-stability chart for a given river would an oversimplification of material strengths with the potential for order-of-magnitude errors in estimating critical-bank conditions.

Generalizations about critical-bank heights and angles can be made with knowledge of the variability in cohesive strengths. Sites are broken into five categories based on mean cohesive strengths of the channel banks (in pounds per square inch): 0.00 to 0.50, 0.51 to 1.00, 1.01 to 2.00, and greater than 2.01. Critical-bank heights above the mean low-water level, and saturated conditions are used for figure 36 because failures typically occur during or after the recession of peak flows. The result is a nomograph giving critical-bank heights for a range of bank angles and cohesive strengths (fig. 36). The potential value of this nomograph is its use in determining stable-bank configurations for worst-case conditions (saturation during rapid drawdown) at a given cohesive strength. For example, a vertical-saturated bank with a cohesion of 1.75 lbs/in$^2$ could support a bank height of no more than 7.6 feet (fig. 36). Similarly, bank instability may be estimated for a site from figure 36 if increases in bank height by bed degradation can be anticipated. Banks at 90-degrees have been undercut fluvially and have been subjected to toe removal.

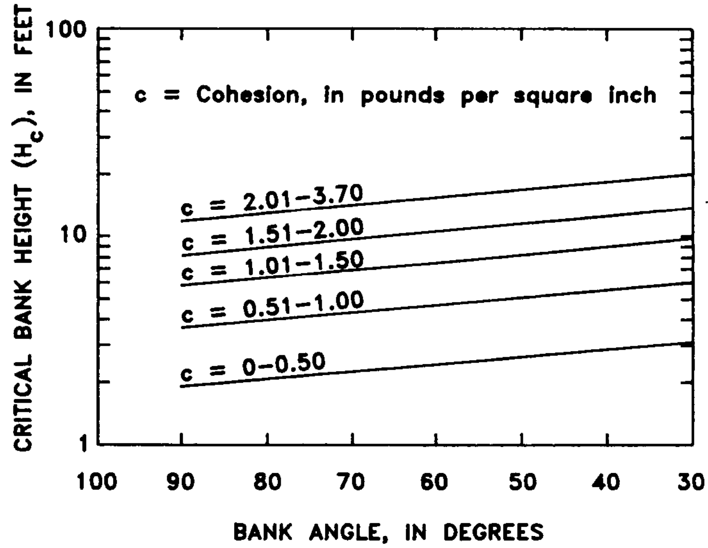



Figure 36.--Critical bank-slope configurations for various ranges of cohesive strengths under saturated conditions.

### *Channel Widening*

According to models of bank-slope development and channel evolution (Simon and Hupp, 1986a; Simon, 1989), bank instabilities and channel widening occur during stage IV after significant degradation (stage III), and continue through the aggradation stage (stage V; table 4). These stages are not static over time or space. Channel widening, like channel-bed degradation, migrates upstream from the AMD, yet lags behind degradation because a sufficient increase in bank height is required to instigate bank failures. Trends of channel widening can be related to the magnitude of bed degradation and distance upstream from the AMD (Simon, in press), but will also be a function of; (1) variable shear strength of the bank materials, and (2) the presence-absence of fluvial undercutting.

The adjustment of channel width can be characterized by three separate analyses representing recent, total, and future channel widening:

1. Recent rates of channel widening, determined from dendrogeomorphic techniques;

2. Total amounts of channel widening from the premodified-constructed state to present; determined by comparing digitized channel cross sections; and

3. Projected amounts of future channel widening, determined by mean friction angles and temporary angles of stability.

## Recent Widening

Recent widening rates along modified channels ranged from zero in upstream reaches, in some reaches downstream from the AMD, and along some natural streams, to nearly 8 feet per year along some of the most degraded reaches (table 18). Widening rates determined through tree-ring analyses reflect only the most recent (past 2-3 years) period of widening. It should not be assumed that these rates have been in effect for long periods, or that they will continue for long periods. In general, rates of widening at a given site are initially low (stage I and III), reach a maximum during stage IV, diminish through stage V, and again become minimal during stage VI (fig. 29).

Overlain plots of bank widening, bank accretion, percent vegetative cover, and number of riparian species versus river mile, are used to identify trends of channel-bank response (fig. 37). This organization facilitated the systematic interpretation of recent widening rates by river or basin, and the interpretation of channel widening in relation to the stage of bank-slope development. The relation between channel widening, bank accretion, vegetative cover, and river mile is shown in figure 37. Together, the three dendrogeomorphic variables describe the bank-site conditions used to characterize the stages of bank-slope development.

Channel widening is perhaps the single most important process limiting the establishment and growth of woody riparian vegetation during early periods of channel recovery. Vegetation presence, once established tends to stabilize bank features and enhance bank accretion. Along the forks of the Obion and Forked Deer Rivers, peak rates of channel widening coincide with minima of vegetative cover and species numbers (fig. 37a-c and e-f). In the Obion River system, this presently (1987) occurs at about 10 to 20 miles up the North, South, and Rutherford Forks (fig. 37). Upstream limits of these areas are approximately 11 to 18 miles upstream from the imposed AMD (along the Obion River main stem) and represent stage V conditions. Riparian trees, 6 to 8 years old, are now common along the Obion River main stem and reflect the stabilizing low-bank conditions characteristic of stage V. Reaches of the Obion River forks upstream from river mile 30 coincide with sites located near "E" in fig. 4 and represent the most upstream reaches (stage VI) that remain unaffected by downstream-channel adjustments (fig. 37a-c).

Similar spatial relations between widening, accretion, species presence, and river mile occur along reaches of the Forked Deer River system as well (fig. 37e and f). High rates of widening preclude high numbers of species. Species presence increases in reaches above river miles 24 to 28 along the North Fork and South Fork Forked Deer Rivers respectively. Degradation and widening have been negligible in these upstream reaches since the last period of channel modifications.

Channel widening has migrated upstream at rates approximating 0.6 mile per year in the forks of the Obion and Forked Deer Rivers. Bed degradation migrates more rapidly--1.6 miles per year (mi/yr)

## Table 18.--*Rates of recent channel widening as determined from dendrogeomorphic evidence*

| Stream | Station number | Widening rate (feet per year) |
|---|---|---|
| South Fork Obion River | 7024350 | 0.00 |
| | 7024430 | 0.00 |
| | 7024460 | 4.92 |
| | 7024525 | 4.92 |
| | 7024550 | 4.92 |
| Obion River | 7024800 | 0.98 |
| Rutherford Fork Obion River | 7024880 | 0.32 |
| | 7024888 | 0.33 |
| | 7024900 | 0.98 |
| | 7025000 | 3.94 |
| | 7025001 | 0.66 |
| | 7025020 | 2.95 |
| | 7025025 | 2.62 |
| | 7025050 | 2.95 |
| | 7025100 | 1.64 |
| North Fork Obion River | 7025320 | 1.31 |
| | 7025340 | 0.82 |
| | 7025375 | 3.93 |
| | 7025400 | 3.60 |
| | 7025500 | 4.26 |
| | 7025600 | 4.92 |
| Middle Fork Forked Deer River | 7028900 | 0.33 |
| | 7028910 | 1.64 |
| | 7028960 | 0.32 |
| | 7028990 | 0.66 |
| | 7029000 | 4.92 |
| | 7029020 | 0.98 |
| Pond Creek | 7029060 | 3.61 |
| | 7029065 | 1.31 |
| | 7029070 | 3.28 |
| | 7029075 | 3.28 |
| | 7029080 | 2.95 |
| | 7029100 | 3.69 |
| Hatchie River | 7029400 | 0.16 |
| | 7029430 | 0.07 |
| Porters Creek | 7029437 | 3.90 |
| | 7029438 | 0.98 |
| | 7029439 | 2.13 |
| | 7029440 | 0.49 |
| | 7029445 | 1.64 |
| Cub Creek | 7029447 | 2.95 |
| | 7029449 | 1.15 |
| | 7029448 | 6.56 |
| | 7029449 | 1.15 |
| | 7029450 | 2.29 |
| Obion River | 7025900 | 0.98 |
| | 7026000 | 4.82 |
| | 7026250 | 0.66 |
| | 7026300 | 3.28 |
| | 7027180 | 0.00 |
| | 7027200 | 0.16 |
| South Fork Forked Deer River | 7027680 | 0.16 |
| | 7027720 | 5.41 |
| | 7027800 | 3.03 |
| | 7028000 | 5.08 |
| | 7028050 | 4.26 |
| | 7028100 | 4.92 |
| | 7028150 | 7.54 |
| | 7028200 | 2.84 |
| North Fork Forked Deer River | 7028410 | 0.00 |
| | 7028500 | 0.33 |
| | 7028820 | 5.90 |
| | 7028835 | 6.56 |
| | 7028840 | 1.96 |
| | 7029040 | 5.74 |
| | 7029105 | 0.00 |
| Hatchie River | 7029500 | 0.16 |
| | 7029630 | 0.16 |
| | 7029900 | 0.16 |
| | 7030000 | 0.16 |
| Wolf River | 7030025 | 0.49 |
| | 7030392 | 0.98 |
| | 7030395 | 1.80 |
| | 7030500 | 0.96 |
| | 7030600 | 0.16 |
| | 7030610 | 2.28 |
| | 7031650 | 3.28 |
| | 7031700 | 6.28 |
| Cane Creek | 1 | 0.10 |
| | 2 | 2.00 |
| | 3 | 0.80 |
| | 4 | 6.60 |
| | 5 | 2.40 |
| | 6 | 7.00 |
| | 7 | 4.50 |
| | 8 | 6.00 |
| | 9 | 6.40 |
| | 10 | 7.40 |
| | 11 | 0.50 |
| | 12 | 8.20 |
| | 13 | 5.00 |
| | 14 | 9.80 |
| | 15 | 10.00 |
| | 16 | 14.70 |
| | 17 | 10.00 |
| | 18 | 25.60 |
| | 19 | 7.00 |
| | 20 | 10.20 |
| | 22 | 7.80 |

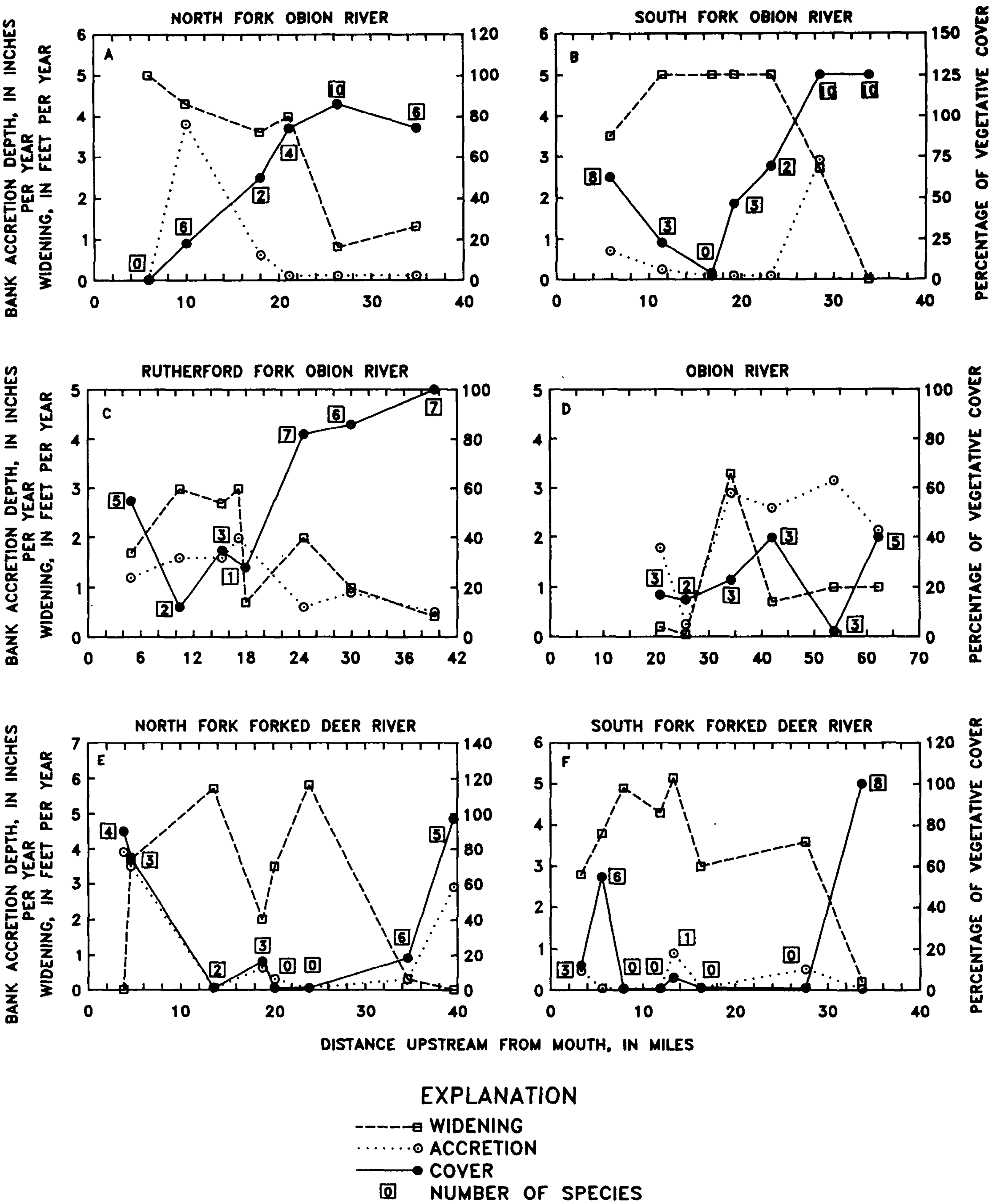



Figure 37.--Channel widening, bank accretion depth, and percentage of vegetative cover at selected locations in the (A to D) Obion River system and (E to F) the Forked Deer River system.

on the South Fork Forked Deer (Simon and Robbins, 1987), and 1.0 mi/yr on the Obion River forks. These data support the aforementioned time lag between bed degradation and channel widening.

Rates of channel widening along Cane Creek represent some of the largest values recorded in the region (up to 16 ft/yr). This worst-case scenario is due to the low cohesive strengths of bank materials, above average degrees of saturation, and large amounts of channel-bed degradation, which are the three major controlling variables to widening. The association between channel-bed degradation and subsequent channel widening is supported by a linear correlation between the absolute value of the degradation exponent (|-b|) and recent widening rates (fig. 38; $r^2$ = 0.84). Widening rates decrease in the lowermost reaches due to the extension of Hatchie River backwater, and far upstream because a large concrete box culvert has restricted migration of bed degradation (fig. 38).

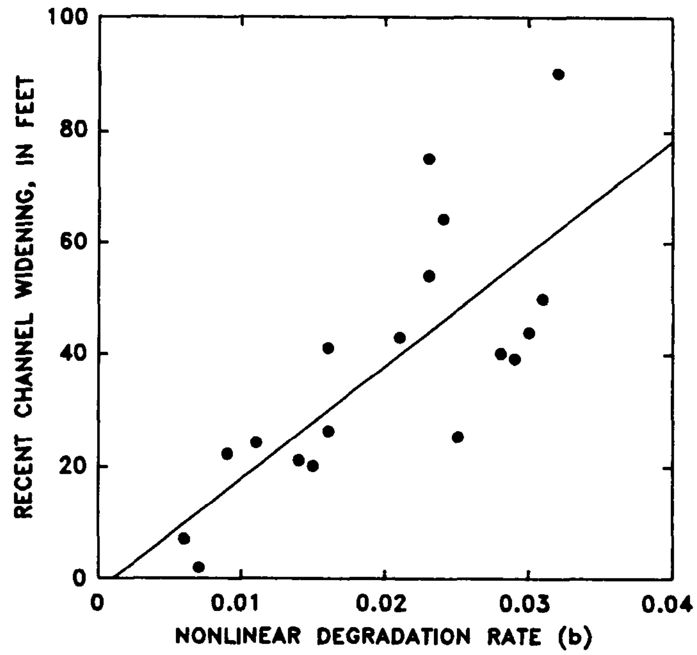



Figure 38.—Relation between bed degradation (b) and recent channel widening, Cane Creek.

The major dredging of the Wolf River occurred in 1964 from its mouth to a point 0.5 mile downstream from site 07030610 (river mile (RM)=23.6; fig. 6). Above this reach, the river is a meandering, relatively "natural" stream (stage I) except for local channel deepening along a 1-mile reach near site 07030395 (RM 57.5). Widening rates below RM 23.6 range from about 2.5 to 3.3 ft/yr, while widening rates from RM 30 to the Mississippi State line are one foot or less per year (figs. 6 and 39). Channel-bed degradation, which is ultimately responsible for increased rates of channel widening, has not proceeded upstream from RM 30, (fig. 39). This is most likely because of the input of large amounts of coarse sediment (gravel) from modified tributary channels along these reaches.

The Wolf River is unique among the study streams in that it has not been straightened throughout most of its course by earlier channel work. Thus, the upstream three-fourths of the river largely functions as a "natural" stream. Repeated downstream dredging has maintained high widening rates (2.5 - 3.3 ft/yr) at the three most downstream sites and has delayed the development of stabilizing, stage V conditions (fig. 39). The most downstream site (07031700) is in stage V of bank-slope development, having relatively stable, vegetated banks on inside bends. Upstream from this site, but below station 07030600 (RM 31.2), the channel is in stage IV. Reaches upstream of the most upstream site head in a large bottomland marsh and swamp as do many of the other studied streams.

The Hatchie River is the study-control stream and has been designated a State scenic river. Bank-widening rates do not exceed 0.6 ft/y, and any widening is due largely to "natural" bank caving through fluvial action on outside bends. The entire length of the Hatchie River is in stage I of the bank-slope development model. Bank heights rarely exceed 4 to 5 feet; cut banks are usually near vertical in cross section while inside point bars have low angles and are highly depositional. Bank accretion is uniform throughout its length, reaching a maximum of 0.5 in/y (fig. 40).

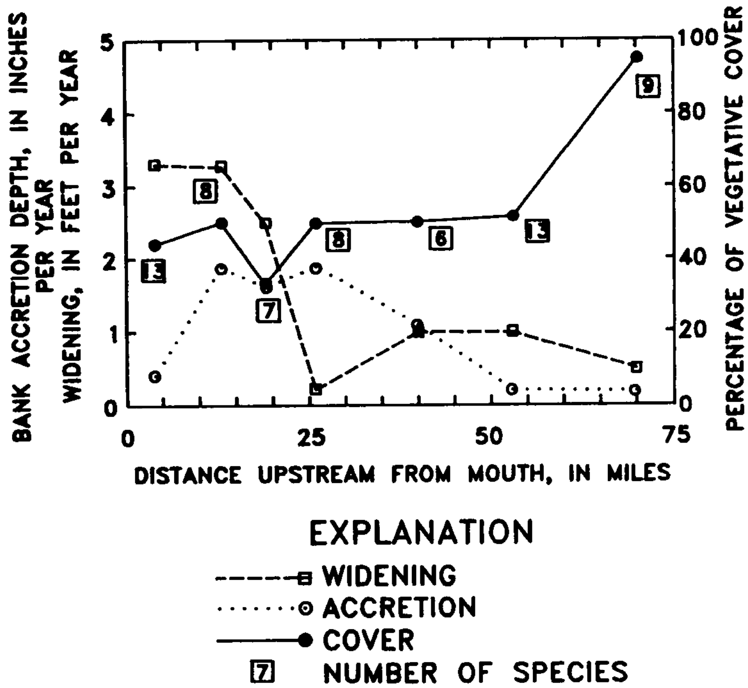



Figure 39.—Channel widening, bank accretion depth, and percentage of vegetative cover at selected locations along the Wolf River.

Perhaps the most distinctive characteristic of Hatchie River reaches is the nearly complete cover of mature riparian vegetation. The low banks support a diverse multistoried canopy of woody species down and into the low-water channel, particularly along inside bends. The highest number of woody riparian species at a site (16) occurs along the Hatchie River at river mile 81 (fig. 40). High species diversity (species richness) is strongly related to low widening rates and general bank stability. This association is obvious along the banks of the Hatchie River. However, widening rates on both the Wolf and Hatchie Rivers may be somewhat exaggerated, in that where bank retreat is indicated (figs. 39 and 40), there is typically concomitant narrowing on the opposite bank through point-bar extension.

## Total Widening

Except for the Obion River main stem and the most downstream reaches of the South and North Forks Forked Deer River that serve as depositories for bed sediment eroded upstream, remaining reaches have experienced degradation and at least some kind of bank failure. Total widening and top-width data are available for sites in the Obion and Forked Deer River basins (fig. 41a-e). A detailed set of data was also acquired for Cane Creek as part of another study (fig. 41f). Cane Creek has undergone the most widening of the studied streams. Along Cane Creek, increases in top width of

100 feet at a site are common. Banks have remained high (40 to 50 feet) due to a lack of sand-sized material in the basin for aggradation. This, in conjunction with low cohesive strengths (mean c=0.89 lb/in$^2$), causes some of the largest and most dramatic rotational failures in the region. Maximum amounts of widening along the forks of the Obion and Forked Deer Rivers are between 50 and 60 feet in areas just upstream of the AMD. Total amounts of widening approach 0, approximately 26 to 33 miles up the forks of the Obion River and Forked Deer Rivers, respectively (fig. 41). Top-bank widths in these locations range from 60 to 80 feet. Assuming that the Middle Forks of both the Obion and Forked Deer Rivers have experienced similar adjustments in channel width over about 30 river miles, mass wasting of channel banks is occurring along 100 miles of the Obion River system, and 90 miles of the Forked Deer River system (fig. 41).

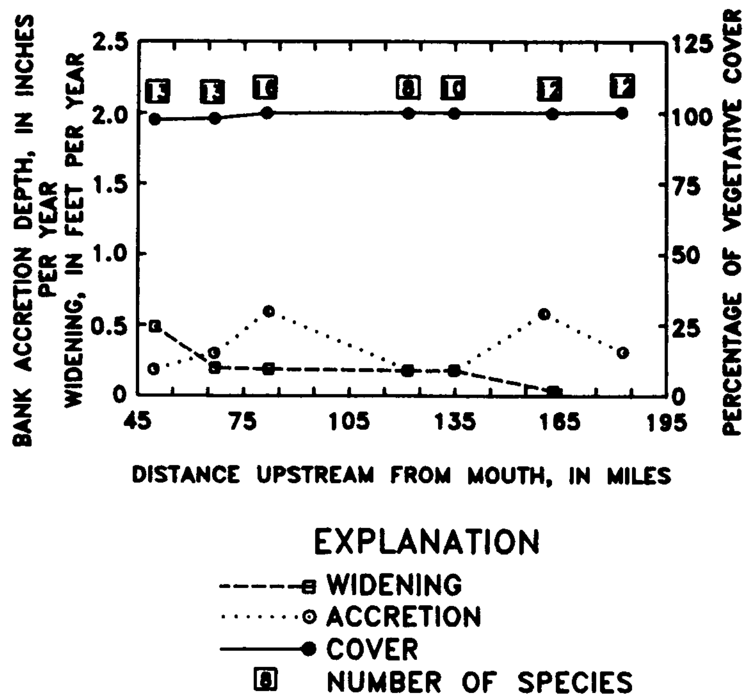



Figure 40.—Channel widening, bank accretion depth, and percentage of vegetative cover at selected locations along the Hatchie River.

## Volumes of Bank Erosion

Total volumes of loess-derived alluvium that have been eroded by mass wasting on the channel banks is integrated over the affected lengths of the rivers. In the Obion-Forked Deer system values range from 36.1 Mft$^3$ on the North Fork Obion River, to 53.3 Mft$^3$ on the South Fork Obion River (fig. 41 and table 19). By taking mean values for the forks of each basin and applying those values to the respective Middle Forks, total volumes eroded from the banks of the major forks in each basin can be estimated. They are about: 178 Mft$^3$ over 22 years for the Obion River forks and about 140 Mft$^3$ over 17 years for the Forked Deer Forks, or on the average, about 8 Mft$^3$ per year for both basins.

The total eroded volumes are divided by the affected lengths to further illustrate the relative constancy of eroded volumes (table 19). The resulting mean unit volume eroded is about 1.5 Mft$^3$/mi (standard error=0.036 Mft$^3$/mi). Only very small percentages of silt and clay are found on the channel beds or accreted on the channel banks (Simon, in press) indicating that over 300 Mft$^3$ of Obion Forked

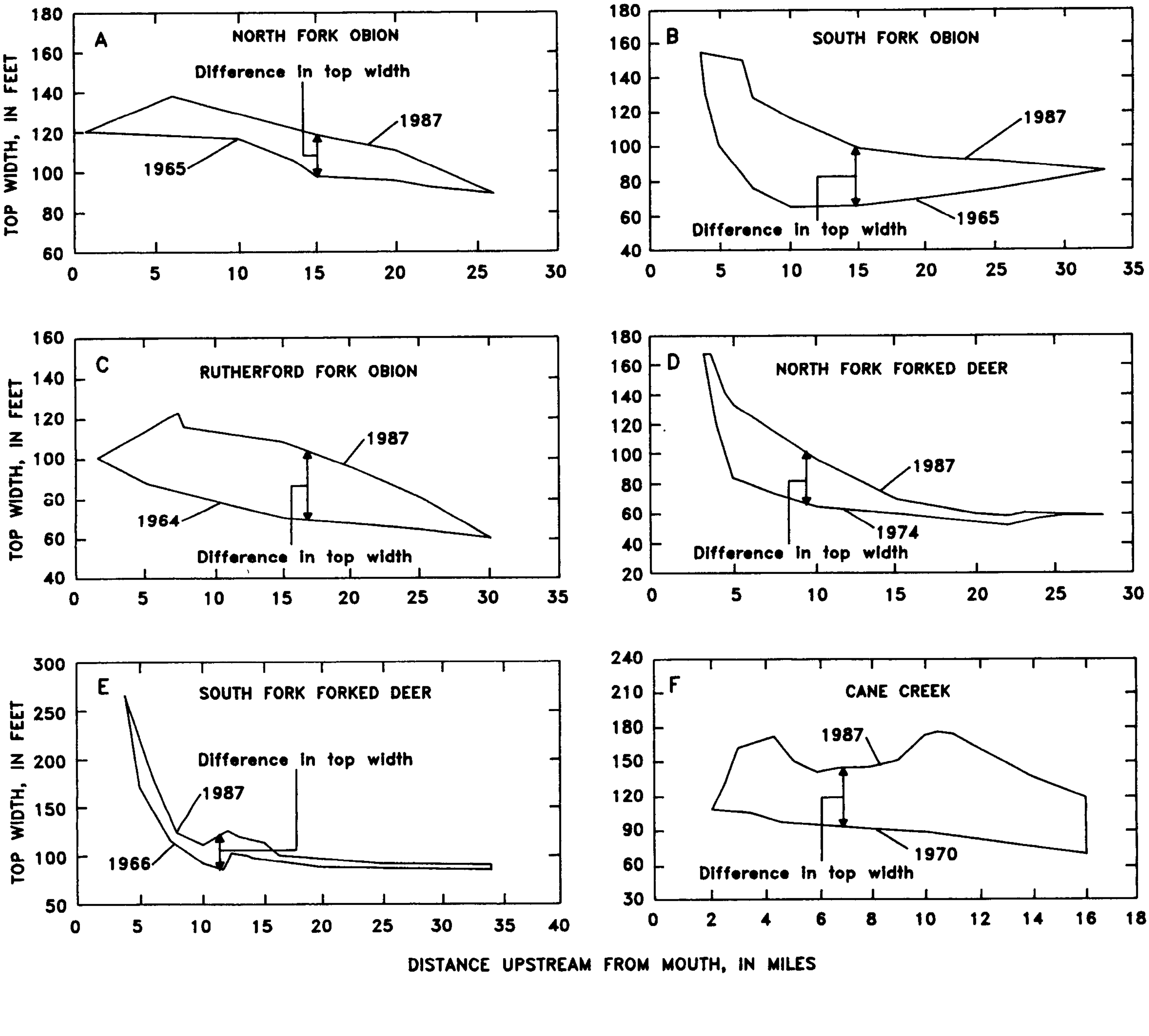



Figure 41.--Changes in channel top width along the (A) North Fork Obion, (B) South Fork Obion, (C) Rutherford Fork Obion, (D) North Fork Forked Deer, (E) South Fork Forked Deer Rivers, and (F) Cane Creek.

Table 19.--*Volumes of bank material eroded by mass-wasting processes*

[-- = No data]

| Stream/Basin | Drainage area (square miles) | Miles affected | Volume Eroded: Total (millions of cubic feet) | Volume Eroded: Unit (millions of cubic feet per mile) |
|---|---|---|---|---|
| North Fork Obion River | 578 | 26.0 | 36.1 | 1.39 |
| South Fork Obion River | 426 | 33.0 | 53.3 | 1.61 |
| Rutherford Fork Obion River | 277 | 30.0 | 44.5 | 1.48 |
| Middle Fork Obion River[1] | 310 | -- | 44.6 | |
| ***Total for Obion River Basin*** | | 178.5 | | |
| North Fork Forked Deer River | 952 | 27.0 | 39.7 | 1.47 |
| South Fork Forked Deer River | 1,061 | 34.0 | 52.8 | 1.55 |
| Middle Fork Forked Deer River[1] | 485 | -- | 46.5 | |
| ***Total for Forked Deer River Basin*** | | 139.0 | | |
| Total for Cane Creek | 87 | 16.0 | 96.5 | 6.03 |

[1]Estimated data.

Deer system flood plains have been eroded and transported to the Mississippi River from 1965 to 1987. Sufficient historical data were not available for the other streams (except Cane Creek) to allow such a detailed analysis of total widening. However, the discussion that follows will address recent and projected widening for the other streams.

Previous sections on widening emphasize width adjustment of the recent past and present due to the time-dependent nature of the data. Rates and amounts of widening however, cannot be extrapolated over time and space because of attenuation of the widening process over those dimensions. Therefore, to estimate future and long-term widening other techniques are required.

## Projected Widening

The concept of projected widening is based on the understanding that the ultimate restabilization of a bank will take place once bank heights and angles attain noncritical values. The following analysis used mean $\phi$ data for each site and measured bank angles. As bank angles recede, a threshold will be reached where, at a given bank height, a low-angle surface will become stable enough to support pioneer woody plants (Hupp and Simon, 1986; Simon and Hupp, 1986a, b). The angle attained by this surface may be represented by the same equation used to calculate the failure-plane angle (eq. 6). Carson and Kirkby (1972) suggest that:

$$\tan i = 1/2 \tan \phi \qquad (11)$$

where $\phi$ and i are as previously defined, can be used to estimate a temporary angle of stability during slope development. Friction angles for the studied streams range from 26 to 38 degrees. By equation 11, resulting angles of stability would range from 14 to 21 degrees for the streams studied.

Simon and Hupp (1986b) projected future channel widening along a reach of Cane Creek, Lauderdale County using equation 11. They identified a stable low-bank surface termed the slough line. This surface is composed of failed material, topped with fluvially deposited sediments that are reworked by 10- to 50-percent duration flows or less. The angle of this surface was projected to the flood-plain elevation. The horizontal distance between the intersection of the projected angle with the flood plain and the present top bank is the projected widening for one side of the channel.

Calculated temporary stability angles from 14 to 21 degrees are low compared to observations of initially stable surfaces made along stage V reaches in West Tennessee (20 to 30 degrees) and reported in Simon and Hupp (1986b). A possible explanation of this disparity is that once the stable surface has established with vegetation, and aggradation decreases bank heights, steeper stable angles can be maintained. Using equation 6, bank height is considered through "tan i", and the properties of the material, are considered through "tan $\phi$". Values obtained from equation 6 seem more reasonable and conceptually appropriate for estimating channel widening over the long term. Projected widening values assume minimal future changes in bed elevation. Where further degradation is expected, projected widening values should be considered as minima.

Amounts of projected widening over the long term are a function of (1) the depth of downcutting during stages III and IV, and (2) the amount of bed-level recovery and the angles of stability established during stages V and VI. Projected future widening as estimated by equation 6 is 0.0 along (1) stable reaches of the Obion River main stem, (2) nondegraded upstream reaches and (3) reaches with high cohesive strengths; up to 62 feet of widening is projected along severely degraded reaches of low cohesive strengths (table 20). Results suggest that middle reaches of the Obion River forks, Cane Creek, and sections of South Fork Forked Deer River and Porters Creek will widen an additional 40 to 60 feet before the banks will become stable (table 20).

### *Obion-Forked Deer River Forks*

Minimum projected changes in channel width occur in the most downstream reaches, all below the AMD, and all, stage V and VI. In these reaches, a combination of bed aggradation, bank accretion and woody-plant establishment appear to have restabilized bank surfaces. Sites on the Obion River forks between river mile 5 and 18 are expected to widen appreciably (37 to 62 feet; fig. 42a). These sites have undergone at least 10 years of active downcutting (up to 17 feet) and have low cohesive strengths. Similarly, projected widening along the forks of the Forked Deer River reaches a maximum between river mile 6 and 14 (fig. 42b) but is of lesser magnitude than along the Obion River forks.

Table 20.--*Projected amounts of channel widening as determined by soil mechanics data and temporary stability angles*

| Stream | Station number | River mile | Friction angle (degrees) | Temporary stability angle (degrees) | Projected widening (feet) |
|---|---|---|---|---|---|
| Cane Creek | 1 | 0.61 | 33.3 | 26.3 | 3 |
| | 2 | 1.95 | 33.5 | 26.4 | 3 |
| | 3 | 2.52 | 26.8 | 20.8 | 6 |
| | 4 | 3.64 | 23.6 | 18.1 | 16 |
| | 5 | 4.02 | 31.2 | 24.6 | 11 |
| | 6 | 5.72 | 32.9 | 25.9 | 10 |
| | 7 | 6.27 | 26.0 | 20.2 | 44 |
| | 8 | 7.06 | 26.6 | 20.6 | 45 |
| | 10 | 8.99 | 30.7 | 24.1 | 38 |
| | 12 | 10.25 | 31.1 | 24.4 | 45 |
| | 16 | 12.58 | 21.7 | 21.7 | 3 |
| | 18 | 13.98 | 24.2 | 24.2 | 9 |
| | 19 | 14.85 | 27.2 | 27.2 | 10 |
| | 20 | 15.34 | 35.0 | 27.7 | 0 |
| Cub Creek | 07029447 | 6.90 | 38.0 | 30.4 | 5 |
| | 07029448 | 5.70 | 38.7 | 31.0 | 7 |
| | 07029450 | 1.50 | 23.6 | 18.5 | 10 |
| Hoosier Creek | 07025660 | 5.15 | 41.3 | 33.4 | 0 |
| | 07025666 | 2.99 | 30.1 | 23.7 | 0 |
| | 07025690 | .55 | 35.6 | 28.3 | 0 |
| Hyde Creek | 07030001 | .15 | 39.7 | 31.9 | 22 |
| | 07030002 | 1.20 | 39.6 | 31.9 | 11 |
| | 07030004 | 1.90 | 35.0 | 27.8 | 0 |
| North Fork Forked Deer River | 07028500 | 34.60 | 29.0 | 15.8 | 31 |
| | 07028820 | 23.97 | 27.5 | 21.5 | 10 |
| | 07028835 | 20.33 | 33.8 | 26.7 | 8 |
| | 07028840 | 18.82 | 30.0 | 23.6 | 8 |
| | 07029040 | 13.69 | 35.3 | 28.0 | 14 |
| | 07029100 | 5.71 | 27.9 | 22.1 | 23 |
| | 07029105 | 4.04 | 31.6 | 24.8 | 0 |
| North Fork Obion River | 07025320 | 34.90 | 29.5 | 23.0 | 28 |
| | 07025340 | 26.40 | 21.9 | 16.8 | 51 |
| | 07025375 | 21.10 | 29.8 | 23.3 | 11 |
| | 07025400 | 18.00 | 23.8 | 18.4 | 23 |
| | 07025500 | 10.00 | 34.9 | 27.7 | 20 |
| | 07025600 | 5.90 | 31.5 | 24.7 | 19 |
| Obion River | 07024800 | 68.50 | 37.1 | 29.7 | 2 |
| | 07025900 | 62.20 | 26.4 | 20.5 | 0 |
| | 07026000 | 53.70 | 31.2 | 24.4 | 10 |
| | 07026250 | 42.40 | 34.7 | 27.4 | 0 |
| | 07026300 | 34.20 | 31.8 | 25.0 | 0 |
| | 07027180 | 25.60 | 22.3 | 17.5 | 4 |
| | 07027200 | 20.80 | 30.1 | 23.6 | 0 |
| Pond Creek | 07029060 | 11.40 | 34.1 | 27.0 | 6 |
| | 07029065 | 9.80 | 29.7 | 23.2 | 6 |
| | 07029070 | 7.30 | 24.4 | 18.8 | 20 |
| | 07029075 | 3.10 | 28.6 | 22.2 | 5 |
| | 07029080 | 1.10 | 37.2 | 29.6 | 4 |
| Porters Creek | 07029437 | 17.10 | 24.6 | 19.3 | 42 |
| | 07029439 | 11.20 | 27.6 | 21.7 | 25 |
| | 07029440 | 8.90 | 33.0 | 26.0 | 11 |
| | 07029445 | 4.50 | 32.6 | 25.7 | 5 |

Table 20.--*Projected amounts of channel widening as determined by soil mechanics data and temporary stability angles*--Continued

| Stream | Station number | River mile | Friction angle (degrees) | Temporary stability angle (degrees) | Projected widening (feet) |
|---|---|---|---|---|---|
| Rutherford Fork Obion River | 07024900 | 29.90 | 37.8 | 30.2 | 5 |
| | 07025000 | 17.90 | 34.6 | 27.4 | 0 |
| | 07025020 | 17.10 | 31.4 | 24.7 | 13 |
| | 07025025 | 15.20 | 18.6 | 14.2 | 36 |
| | 07025050 | 10.40 | 13.7 | 10.4 | 61 |
| | 07025100 | 4.90 | 29.5 | 23.2 | 16 |
| South Fork Forked Deer River | 07027680 | 33.70 | 34.2 | 27.1 | 0 |
| | 07027720 | 27.60 | 33.9 | 26.7 | 13 |
| | 07027800 | 16.30 | 30.5 | 24.2 | 14 |
| | 07028000 | 13.30 | 29.6 | 23.2 | 19 |
| | 07028050 | 11.90 | 21.6 | 16.7 | 44 |
| | 07028100 | 7.90 | 33.3 | 26.2 | 0 |
| | 07028200 | 3.30 | 38.0 | 30.4 | 0 |
| South Fork Obion River | 07024430 | 28.50 | 27.6 | 20.2 | 22 |
| | 07024460 | 23.20 | 31.7 | 24.9 | 8 |
| | 07024500 | 19.20 | 34.6 | 27.4 | 16 |
| | 07024525 | 16.80 | 16.7 | 12.7 | 61 |
| | 07024550 | 11.40 | 19.8 | 15.3 | 62 |
| | 07024800 | 5.80 | 37.1 | 29.7 | 2 |
| Wolf River | 07030395 | 57.50 | 35.6 | 28.3 | 0 |
| | 07030500 | 44.40 | 31.4 | 24.8 | 2 |
| | 07030600 | 31.20 | 35.1 | 20.7 | 7 |
| | 07030610 | 23.60 | 26.7 | 20.7 | 21 |
| | 07031650 | 18.90 | 32.9 | 25.9 | 8 |

Amounts of downcutting and widening on the North Fork Forked Deer River have been moderated somewhat by the input of bed load from the larger Middle Fork, at river mile 15.6. Partial burial of the Middle Fork channel in its low reaches attests to this condition. The Middle Fork delivers large quantities of sand to the North Fork, thereby reducing significant bed degradation on the North Fork. Lower bank heights promote restabilization. The issue of the Middle Fork Forked Deer River has been discussed more fully in the preceding section on channel-bed changes and projected degradation. The major controlling factor of projected widening up to this point has been the relative amount of bed-level lowering, which is a function of the imposed change in channel gradient.

Maximum cohesive-strength values coincide with drops in projected widening between river miles 80 and 83 on all Obion River forks (table 21). Reaches adjacent to these sites have degraded from 2 to 5 feet. Although these reaches have widened recently and will probably continue to do so (fig. 42a), they show some signs of recovery (establishing woody plants; a trait of stage V). These are cases where greater shear strengths, even at saturation, cause stage IV reaches to exhibit signs of stability.

Future channel widening would be expected to continue to decrease with increasing distance upstream as a result of diminishing degradation. The plotted data suggest however that this is not necessarily true (fig 42a; river miles 26 to 35). A plausible explanation of this variation and the relatively high values for projected widening just upstream from river mile 24 is the recent (1985 to

1987) onset of degradation due to re-dredging. Steep bank angles due to associated undercutting and the presence of minor slab and pop-out failures suggest that mass bank failures are likely to occur in the near future.

### *Obion River Main Stem*

A good example of the restabilization of banks through channel-adjustment processes is the Obion River main stem. Projections of future channel widening along the stage V reaches range from 0 to 10 feet. Continued bed aggradation, bank accretion, and shallow low-angle slides for up to 25 years have reduced bank angles and bank heights to produce relatively stable-bank configurations. Channel banks of the Obion River are, on the average, more cohesive than those of other West Tennessee streams, having a mean cohesive strength of greater than 2 lbs/in$^2$. Still, reaches of this river required approximately 25 years to pass from stage V to stage VI (restabilization). This timeframe suggests that streams of the region, with banks of lower cohesion or with little sand-sized sediment for deposition, may require a substantially longer period of time to attain stable-bank conditions.

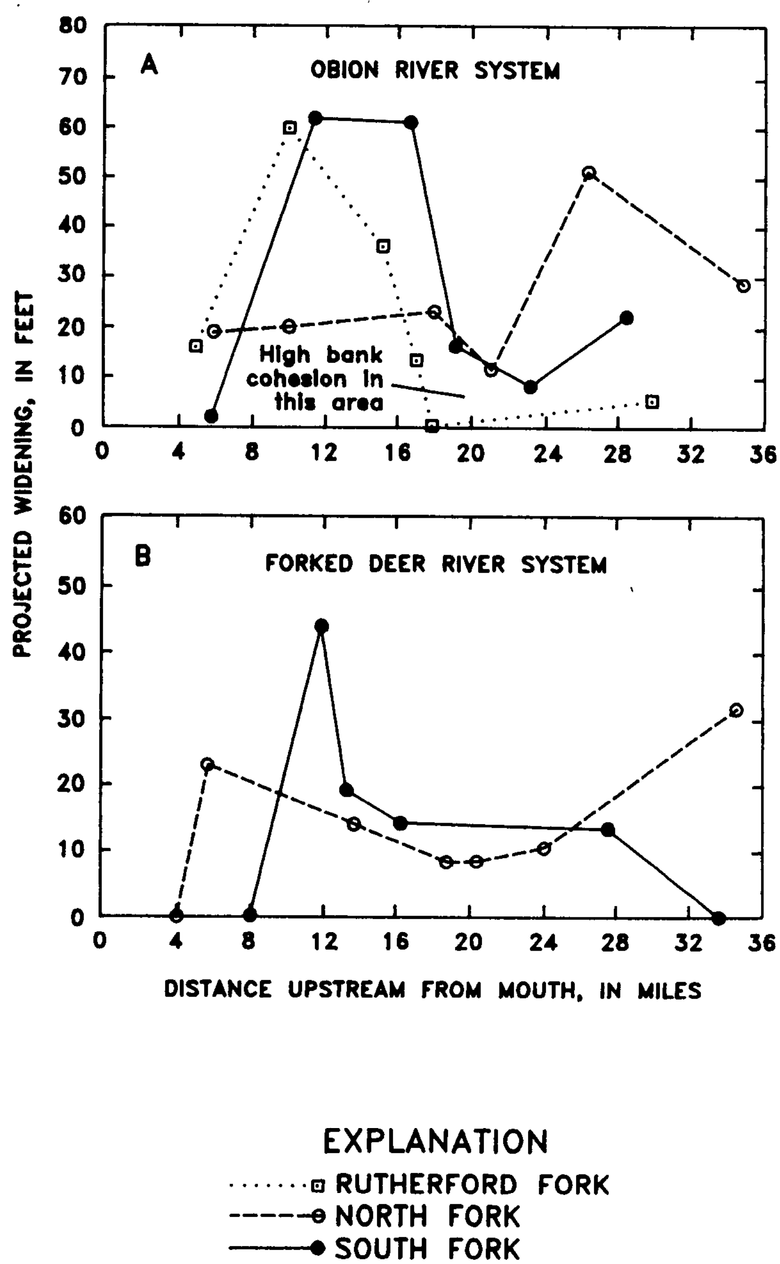



Figure 42.--Projected widening along the (A) Obion River and (B) Forked Deer River systems.

### *Cane Creek*

Cane Creek represents a worst-case scenario in terms of channel widening. Amounts of projected widening along Cane Creek suggest a strong response to modification. Some of the largest deep-seated

Table 21.--*Maximum values of cohesion at a site on the Obion River forks*

[n=number of samples; $S_e$=standard error]

| Stream | Maximum cohesion at a site (pounds per square inch) | Obion system river mile | Mean cohesion, all sites, (pounds per square inch) | $S_e$ | n |
|---|---|---|---|---|---|
| North Fork Obion River | 2.18 | 83.5 | 1.51 | 0.12 | 14 |
| South Fork Obion River | 3.19 | 81.6 | 1.01 | .27 | 12 |
| Rutherford Fork Obion River | 2.57 | 82.6 | .95 | .19 | 12 |

rotational failures and total amounts of degradation anywhere in West Tennessee occurs along the middle reaches of Cane Creek. Thus, the calculated values of projected widening along the middle reaches (table 20) are high (fig. 43a). The extreme downstream and upstream reaches have lesser amounts of projected widening (fig. 43a). Downstream reaches have maintained relative bank stability due to limited initial degradation checked through backwater encroachment from the Hatchie River. The upstream reaches may be protected somewhat by grade control structures upstream of the study sites. These structures limit degradation.

Woody vegetation has begun to proliferate (1) in some reaches where the slough line is broad and well developed, (2) in areas protected by backwater effects, and (3) along inside bends. However, moderate flows can still top the slough line, undercut the vertical face and cause mass failure, even on inside bends. The result is a stream channel that can carry flows in excess of the 150-year event (C.R. Gamble, U.S. Geological Survey, written commun., 1988).

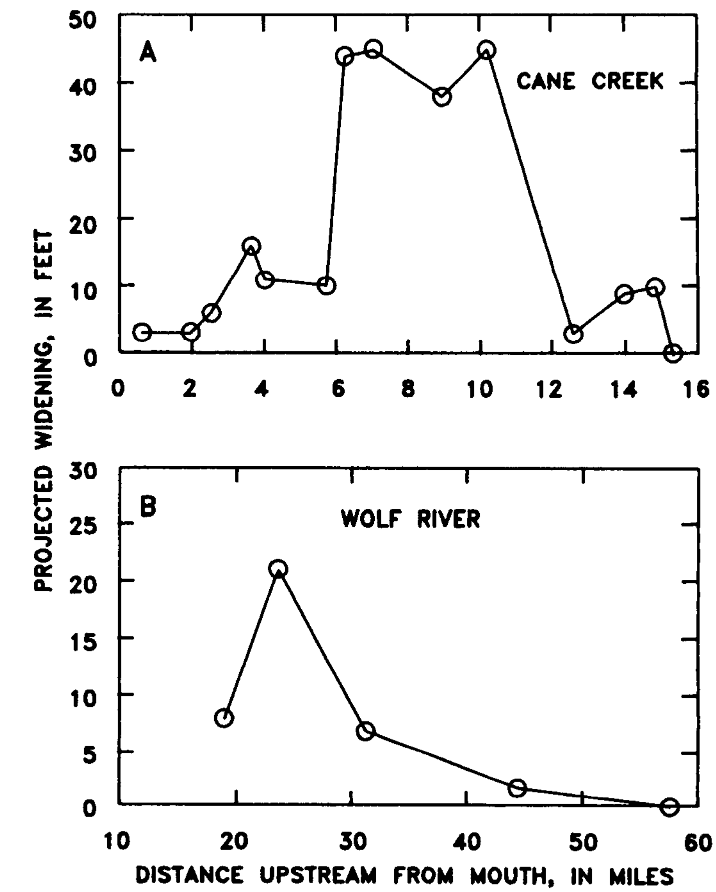



Figure 43.--Projected widening along (A) Cane Creek and (B) Wolf River.

### *Wolf River*

Projected widening along the Wolf River is moderate in comparison to Cane Creek, although mean cohesion is the lowest encountered in the study (mean c =0.81 lb/in$^2$). Figure 43b represents calculations of projected widening along a largely sinuous channel. Bank retreat on an outside bend is often associated with sediment accretion and channel narrowing on the corresponding inside bend, resulting in meander migration. The data indicate that reaches from river mile 10 to 24 will remain unstable and may widen an additional 20 feet. Reaches above river mile 30 have not degraded and are stable stage I reaches with little to no projected widening (fig. 43b).

### *Cub and Porters Creeks*

Future projected widening on Cub and Porters Creeks ranges from 5 to 42 feet depending on the relative amount of bed-level lowering (fig. 44). Due to the placement of grade-control structures at various times, longitudinal relations with widening are not longitudinally consistent (Simon, in press). These channels have adjusted between the structures at magnitudes commensurate with the changes in gradient that were imposed between the structures (Simon, in press). Like noncontrolled streams, degradation migrates upstream, beginning at the upstream side of each structure. Therefore, downcutting and widening along creeks such as Cub and Porters will be high just downstream of the structure, relatively low just upstream of the structure, and increase with distance upstream of the structure. The site on Porters Creek near RM 12 is a severely degraded reach near the downstream side of a structure. The most downstream reaches are in stage V and would certainly be closer to complete restabilization (stage VI) if not for re-dredging of the lower 1.2 miles of Cub Creek and 3.6 miles of Porters Creek after filling just 2 years after the original channel work.

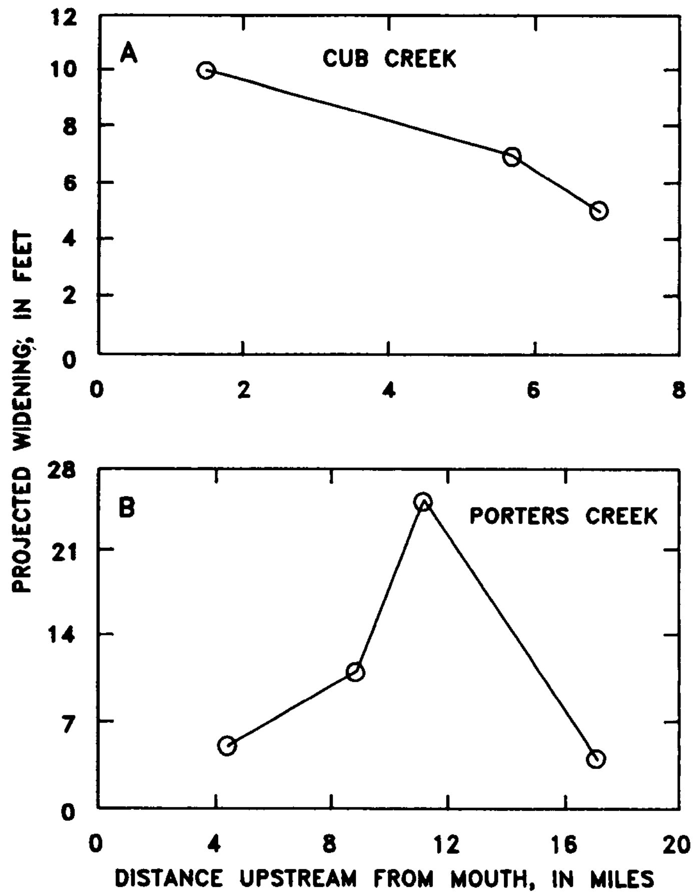



Figure 44.--Projected widening along (A) Cub and (B) Porters Creeks.

## *Hoosier and Pond Creeks*

These loess-bed creeks have strikingly similar material properties (Simon, in press) and show different projected widening trends because of dissimilar modifications. Whereas Hoosier Creek was channelized from its confluence with the North Fork Obion River, Pond Creek (tributary to the North Fork Forked Deer River) was locally dredged by landowners and cleared throughout its length. Like Cane Creek, the banks of Hoosier Creek have been dominated by deep-seated rotational failures since construction of the channel in the mid-1960's. The most downstream reaches of this creek are protected by backwater and, in places where bank angles have been reduced considerably, slough-line surfaces have developed above an inner channel. Top-bank widening has for the most part ceased, after roughly 20 years of widening (fig. 45a).

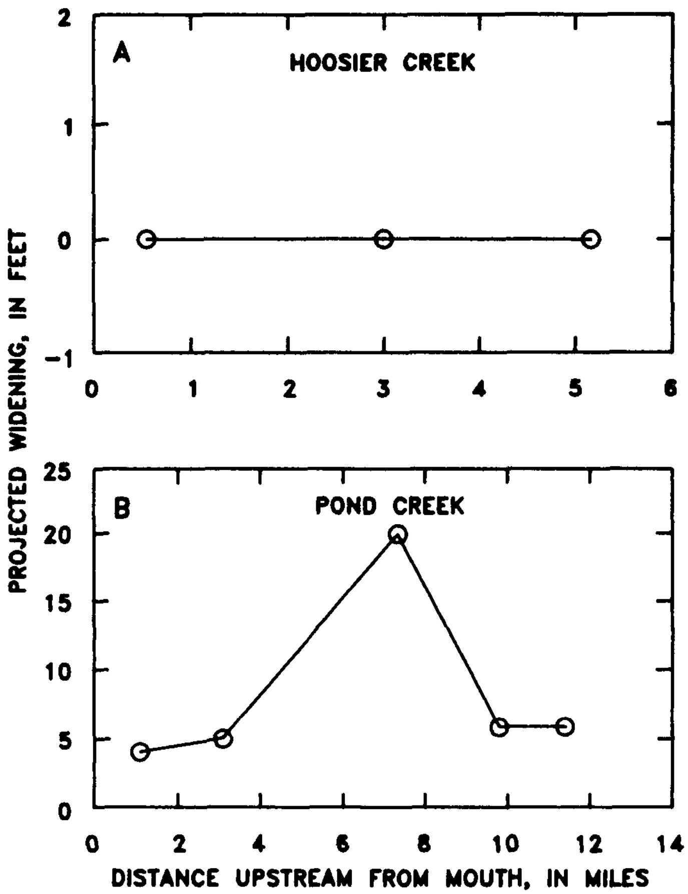



Figure 45.--Projected widening along (A) Hoosier and (B) Pond Creeks.

Pond Creek, also affected by backwater (from the North Fork Forked Deer River) has degraded upstream of some localized disturbances, creating moderately unstable banks. Planar failures appear to be more common than rotational failures. Projected widening ranges from 5 to 20 feet (fig. 45b).

## *System-Wide Channel Recovery--From Dendrogeomorphic and Plant Ecological Evidence*

Systematic trends of channel adjustment begin immediately after modifications to reduce channel gradient and stream power (Simon and Robbins, 1987). Channel bed, bank, and vegetative processes vary through the course of fluvial adjustment and are diagnostic in determining the stage of channel evolution (table 5). The relative roles of channel-bed degradation, channel widening, and shear strength on morphologic changes have been addressed in previous sections. These processes and variables have been shown to vary according to the stage of adjustment, and to yield quantitative information regarding present and future channel changes. Dendrogeomorphic and plant ecological variables such as tree age and species numbers (richness), percent vegetative cover, and rates of sediment accretion can be similarly used to discern present-bank processes at a site. These data can be further used to determine the timing of initial stability and therefore, the number of years required for the channel banks to adjust to a stable configuration. Restabilization of the banks is closely tied to the amount of channel-bed degradation (over 10 to 15 years) and the presence-absence of aggradation.

Plant ecological variables such as vegetative cover, species richness, and species presence vary systematically with stage along all study streams. These variations are distinct and may be used to characterize each stage botanically. Areas characterized by high widening rates (stage IV) typically lack substantial vegetative cover. Only species with broad ecological amplitudes (adapted to a wide range of environmental conditions) like black willow, river birch, and silver maple may germinate. Areas having stable banks (stage I) typically support a relatively wide array of species in a dense riparian zone. Stages V and VI are intermediate between I and IV in terms of bank stability and reflect the onset of aggradation and a trend towards increasing bank stability. Species particularly tolerant of high accretion rates achieve their greatest dominance during these stages. From stage IV through VI, the vegetation reflects a trend of riparian-zone recovery after channel modification. Stage I reaches represent natural-bank conditions unaffected by channel modification. Stage III reaches are a specific variation of stage I reaches, where bed levels have been lowered, but active mass wasting has yet to begin and the old riparian stand is still largely intact.

Plots of dendrogeomorphic and plant ecological data (fig. 46) sorted by stage represent an integration of all streams studied, irrespective of the size of the drainage basin and the dominant geologic formations (table 1). As expected, vegetative cover, species age and numbers, and rate of sediment accretion are inversely related to channel-widening rates (fig. 46). More specifically, these variables display a logical quantitative variation by stage. Minimas of mean vegetative cover (21 percent), age (2 years), and numbers (2), occur during stage IV, when widening rates are greatest (fig. 46a and b). Woody vegetation is most limited during stage IV and increases in vegetative cover and richness from stage V through stage VI, reflecting channel recovery and decreased widening rates (fig. 46a and b).

The greatest values of mean vegetative cover (90 to 100 percent) and species numbers (5 to 8) are attained on banks during stages I, III, and VI, when widening rates are minimal (fig. 46a). These stages reflect the longest periods of time since the last episode of channel modification and therefore have vegetative characteristics corresponding to either natural banks or banks that have been allowed to recover. Banks of stage I and III reaches consequently support the oldest trees (median age 33 and 41 years, respectively). The absolute tree ages for stages I and III are more reflective of past land use [logging and (or) clearing] than they are of recovery time. The oldest riparian trees range in age from 25 to 65 years. Tree ages along stage VI reaches are low (14 years) relative to stages I and III and

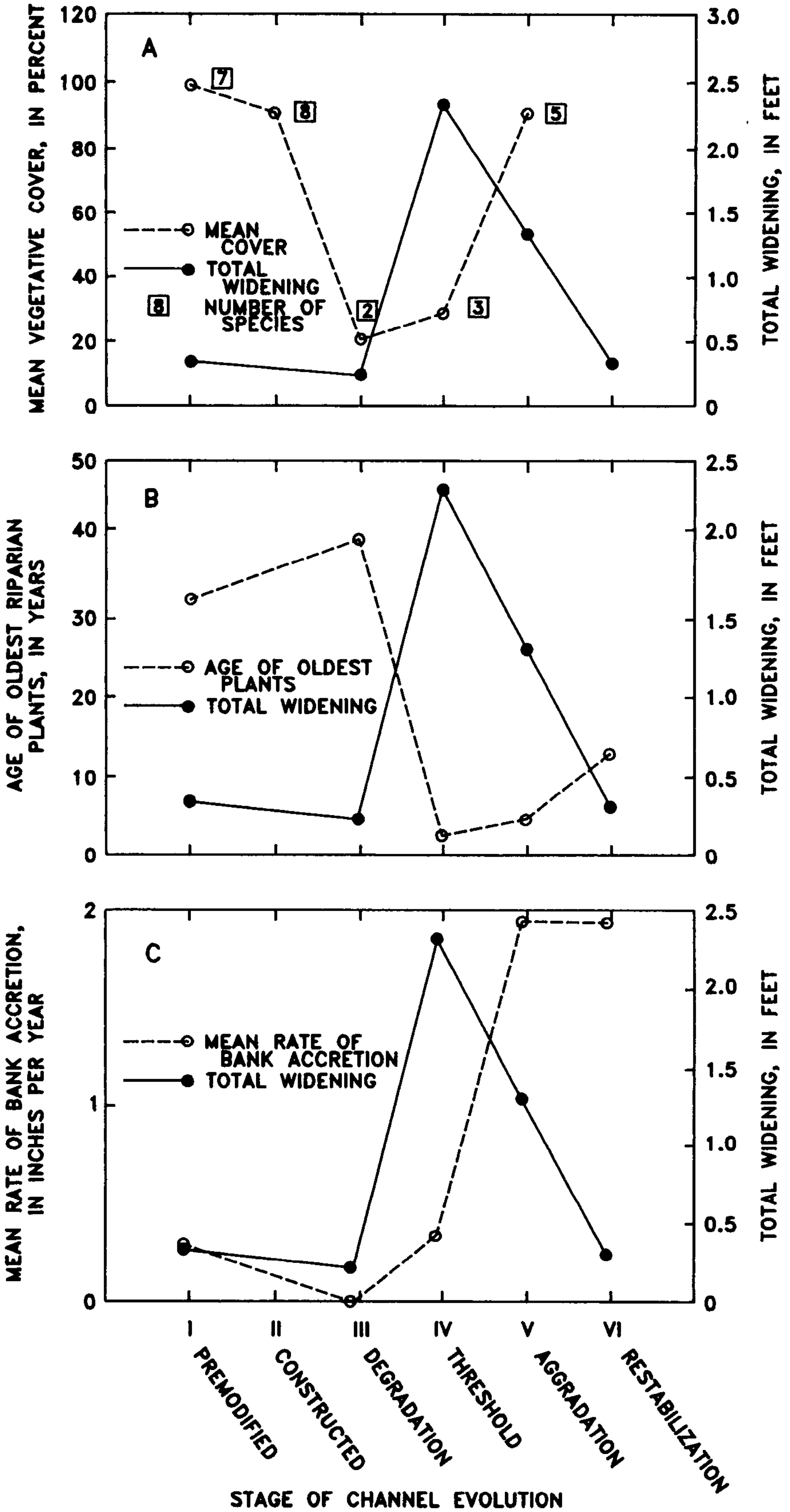



*Figure 46.*--Trends of dendrogeomorphic variables with stage of channel evolution reflecting the effect of bank instabilities on (A) vegetative cover, (B) maximum tree age, and (C) bank-accretion rate.

denote a trend towards restabilization of the channel banks (fig. 46a). The absolute mean age of trees along stage VI reaches is a function of the recovery period as well as the timing of sampling relative to past channel work (for instance, the 1940's).

Due to active mass wasting, banks of stage IV reaches support trees whose mean age is only 2 years and only then, in protected areas. Successful establishment and initial bank recovery does not occur until stage V, during which time channel-bed aggradation, bank accretion, and bank-angle reduction occur (table 4). The shift from degradational processes to aggradational processes is shown by the sharp increase in mean accretion rates during stage V to 1.9 inches per year (fig. 46c).

The ages of trees along stage V reaches reflect the period of time that geomorphic recovery processes (bed aggradation and bank accretion) have operated at a site (since the cessation of stage IV). Maximum pioneer-tree ages along stage V reaches are 14 years on the forks of the Obion River, 11 years on the South Fork Forked Deer and Wolf Rivers, and 7 years on the North Fork Forked Deer River (table 22). These time periods for the sand-bed streams do not represent complete restabilization of the channel banks, but only the period to low- and mid-bank stability. Because top-bank widening may still be prevalent during stage V, the 7- to 14-year range for recovery is conservative. This is particularly true considering that the low value for the North Fork Forked Deer River is attributable to the input of large quantities of bed sediment from the Middle Fork Forked Deer River. As previously discussed, this resulted in a suppressed tendency for channel deepening, widening, and therefore, the time period required to achieve low-bank stability. Conversely, backwater encroachment up the most downstream (stage V) reaches of Cane Creek resulted in an initial-recovery periods of 17 years.

Excluding the North Fork Forked Deer River, sand-bed channels may require approximately 10 to 15 years of stage V recovery processes to achieve low- and mid-bank stability. Degraded loess-bed streams may take considerably longer time. The range of timeframes specified for the sand-bed channels to begin to recover is supported by the mean age of stage VI riparian trees (14 years), and represent reaches that have only recently regained bank stability.

The Obion River main stem receives large volumes of both suspended and tractive sediments from its forks. Since 1967, almost 215 $Mft^3$ of channel materials have been delivered to the main stem (tables 10 and 19), causing high rates of bank accretion and channel-bed aggradation, and necessitating repeated dredging. Rates of bank accretion are among the highest along the banks of the Obion River (table 22), but tree ages are low considering that aggradation has occurred for more than 20 years. A few plant species can tolerate high-accretion rates (black willow, cottonwood, and boxelder). However, even these species become severely limited along many reaches of the Obion River main stem. It may be that the accretion rate is so rapid that even these species cannot elongate their stems and produce new roots fast enough to avoid burial or suffocation. Thus, the main stem Obion River generally lacks the vegetative cover values and tree ages normally associated with stage V reaches.

## Table 22.--*Dendrogeomorphic data for all sites*

[--, no data available]

| Stream | Station number | River mile | Percent vegetative cover | Mean number of species | Maximum tree age (years) | Mean rate of accretion (inches per year) |
|---|---|---|---|---|---|---|
| Cane Creek | 1 | 0.61 | 20 | 4.0 | 13 | 2.48 |
| | 2 | 1.95 | 63 | 6.0 | 0 | 1.97 |
| | 3 | 2.52 | 88 | 4.0 | 7 | 1.97 |
| | 4 | 3.64 | 70 | 3.0 | 7 | .00 |
| | 5 | 4.06 | 75 | 5.0 | 5 | 2.36 |
| | 6 | 5.71 | 63 | 2.0 | 5 | .00 |
| | 7 | 6.19 | 50 | 3.0 | 6 | .00 |
| | 8 | 7.06 | 50 | 6.0 | 5 | 5.90 |
| | 9 | 7.99 | 40 | 2.0 | 7 | .00 |
| | 10 | 8.98 | 35 | 3.0 | 4 | 3.15 |
| | 11 | 9.92 | 35 | 3.0 | 5 | 1.97 |
| | 12 | 10.26 | 15 | 2.0 | 4 | .79 |
| | 13 | 11.05 | 25 | 4.0 | 3 | 1.46 |
| | 14 | 11.31 | 25 | 2.0 | 3 | 1.97 |
| | 15 | 11.84 | 20 | 3.0 | 4 | .00 |
| | 16 | 12.59 | 15 | 2.0 | 2 | 1.38 |
| | 17 | 13.39 | 10 | 1.0 | 3 | .00 |
| | 18 | 14.05 | 15 | 1.0 | 3 | .79 |
| | 19 | 14.83 | 10 | 5.0 | 7 | .00 |
| | 20 | 15.36 | 5 | 1.0 | 0 | .00 |
| | 22 | 15.95 | 10 | 6.0 | 4 | .00 |
| Cub Creek | 07029447 | 6.9 | 25 | 4.5 | 7 | .29 |
| | 07029448 | 5.7 | 12 | 5.0 | 12 | .59 |
| | 07029449 | 2.2 | 36 | 3.5 | 11 | 2.75 |
| | 07029450 | 1.5 | 74 | 11.0 | 8 | 3.97 |
| Hatchie River | 07029400 | 182.0 | 100 | 5.0 | 22 | .29 |
| | 07029430 | 162.0 | 100 | 12.0 | 50 | .59 |
| | 07029500 | 135.0 | 100 | 10.0 | 40 | .19 |
| | 07029650 | 121.0 | 100 | 7.0 | 50 | .19 |
| | 07029900 | 80.8 | 100 | 16.0 | 50 | .59 |
| | 07030000 | 68.4 | 97 | 10.0 | 29 | .29 |
| | 07030025 | 49.5 | 97 | 10.0 | 30 | .19 |
| Middle Fork Forked Deer River | 07028900 | 44.9 | 95 | 11.0 | 50 | .39 |
| | 07028910 | 37.0 | 85 | 12.0 | 26 | .00 |
| | 07028960 | 30.5 | 95 | 9.0 | 46 | .78 |
| | 07028990 | 21.5 | 95 | 3.0 | 21 | .39 |
| | 07029000 | 14.6 | 0 | 0.0 | 0 | .00 |
| | 07029020 | 5.2 | 12 | 1.0 | 6 | .00 |
| North Fork Forked Deer River | 07028410 | 41.6 | 97 | 5.0 | 25 | 2.95 |
| | 07028500 | 34.6 | 18 | 5.0 | 19 | .29 |
| | 07028820 | 23.9 | 0 | 0.0 | 0 | .00 |
| | 07028835 | 20.2 | 0 | 0.0 | 0 | .39 |
| | 07028840 | 18.8 | 17 | 3.0 | 3 | .59 |
| | 07029040 | 13.6 | 1 | 2.0 | 1 | .00 |
| | 07029100 | 5.1 | 75 | 3.0 | 4 | 3.42 |
| | 07029105 | 3.8 | 90 | 4.0 | 6 | 3.94 |
| North Fork Obion River | 07025320 | 34.9 | 75 | 6.0 | 45 | .00 |
| | 07025340 | 26.4 | 87 | 10.0 | 40 | .00 |
| | 07025375 | 21.1 | 75 | 2.0 | 4 | .00 |
| | 07025400 | 18.0 | 50 | 6.0 | 5 | .59 |
| | 07025500 | 10.0 | 19 | 0.0 | 0 | 3.94 |
| | 07025600 | 5.6 | 0 | 0.0 | 0 | .00 |

Table 22.--*Dendrogeomorphic data for all sites*--Continued

| Stream | Station number | River mile | Percent vegetative cover | Mean number of species | Maximum tree age (years) | Mean rate of accretion (inches per year) |
|---|---|---|---|---|---|---|
| Obion River | 07024800 | 68.5 | 49 | 6.0 | 4 | 0.68 |
| | 07025900 | 62.2 | 41 | 4.3 | 5 | 2.16 |
| | 07026000 | 53.7 | 1 | 1.5 | 1 | 3.15 |
| | 07026250 | 42.4 | 40 | 2.0 | 4 | 2.56 |
| | 07026300 | 34.2 | 22 | 1.0 | 4 | 2.95 |
| | 07027180 | 25.6 | 15 | 2.0 | 2 | .19 |
| | 07027200 | 20.8 | 18 | 2.5 | 2 | 1.77 |
| Pond Creek | 07029060 | 11.4 | 20 | 0.5 | 1 | 2.95 |
| | 07029065 | 9.8 | 81 | 2.0 | 5 | 3.74 |
| | 07029070 | 7.3 | 20 | 0.5 | 2 | 2.56 |
| | 07029075 | 3.1 | 1 | 1.0 | 2 | .39 |
| | 07029080 | 1.1 | 75 | 2.0 | 5 | .39 |
| Porters Creek | 07029437 | 17.1 | 75 | 6.0 | 11 | 1.49 |
| | 07029438 | 13.9 | 95 | 6.0 | 12 | .98 |
| | 07029439 | 11.2 | 47 | 4.5 | 6 | .98 |
| | 07029440 | 8.9 | 67 | 6.0 | 9 | 2.10 |
| | 07029445 | 4.5 | 35 | 9.0 | 5 | 4.72 |
| Rutherford Fork Obion River | 07024880 | 43.3 | 75 | 7.0 | 20 | .47 |
| | 07024888 | 39.4 | 100 | 5.0 | 40 | 0.31 |
| | 07024900 | 29.9 | 87 | 4.0 | 30 | .78 |
| | 07025000 | 17.9 | 28 | 5.0 | 3 | 2.08 |
| | 07025001 | 24.5 | 81 | 3.0 | 41 | .59 |
| | 07025020 | 17.1 | 5 | 1.0 | 5 | -- |
| | 07025025 | 15.2 | 35 | 3.0 | 6 | 1.57 |
| | 07025050 | 10.4 | 11 | 2.0 | 3 | 1.57 |
| | 07025100 | 4.9 | 55 | 5.0 | 5 | 1.18 |
| South Fork Forked Deer River | 07027680 | 33.7 | 100 | 8.0 | 65 | .00 |
| | 07027720 | 27.6 | 0 | .0 | 0 | .49 |
| | 07027800 | 16.3 | 0 | .0 | 0 | .00 |
| | 07028000 | 13.3 | 6 | .5 | 1 | .98 |
| | 07028050 | 11.9 | 0 | .0 | 0 | .00 |
| | 07028100 | 7.9 | 0 | .0 | 0 | .00 |
| | 07028150 | 5.6 | 55 | 6.0 | 7 | .00 |
| | 07028200 | 3.3 | 2 | 1.0 | 3 | .47 |
| South Fork Obion River | 07024350 | 33.8 | 100 | 2.5 | -- | -- |
| | 07024430 | 28.5 | 80 | 10.0 | 15 | 2.95 |
| | 07024460 | 23.2 | 55 | 2.0 | 2 | .00 |
| | 07024500 | 19.2 | 37 | 3.0 | 2 | .00 |
| | 07024525 | 16.8 | 1 | .0 | 2 | .00 |
| | 07024550 | 11.4 | 19 | 3.0 | 2 | .39 |
| | 07024800 | 5.8 | 49 | 6.0 | 4 | .68 |
| Wolf River | 07030392 | 69.9 | 95 | 7.0 | 35 | .19 |
| | 07030395 | 57.5 | 52 | 9.5 | 40 | .19 |
| | 07030500 | 44.4 | 50 | 6.0 | 16 | 1.18 |
| | 07030600 | 31.2 | 50 | 6.5 | 16 | 1.97 |
| | 07030610 | 23.6 | 32 | 3.5 | 5 | 1.57 |
| | 07031650 | 18.9 | 50 | 8.0 | 11 | 3.94 |
| | 07031700 | 9.1 | 47 | 6.5 | 7 | .39 |

Dendrogeomorphic and plant ecological variables such as percent vegetative cover, number of species, tree ages, widening rates, and bank-accretion rates reflect varying channel conditions, processes, and the stage of channel evolution (fig. 46). Values of these characteristics, associated with a given stage of bank-slope development or channel evolution, can be diagnostic in determining the stability of a particular channel reach. Relatively stable reaches will generally support high vegetative cover values, species numbers, tree ages, and accretion rates. Conversely, unstable sites have very low values of these variables because young riparian plants cannot survive active mass wasting of the banks.

## Bank-Stability Index

Bank-widening rates (table 18), vegetative cover of woody riparian species, and rates of bank accretion are important indicators of bank stability. These three site variables were used to develop a simple bank-stability index ($I_s$). This index permits rapid interpretation of relative bank stability and comparison among sites using dendrogeomorphic data (table 22). The three site variables are categorized for use here, and in the following section on plant ecology; details on the categorization are given in the subsequent section. Site variable categories and $I_s$ weights are provided in table 23.

The computation of $I_s$ is performed by the addition of numerical weights given to the various variable categories:

$$I_s = W_w + W_c + W_a \qquad (13)$$

where $W_w$ = weighted total-widening rate, in feet per year;
$W_c$ = weighted mean vegetative cover, in percent; and
$W_a$ = weighted mean accretion rate, in inches per year.

The most stable conditions, such as very low widening, medium accretion, and very high vegetative cover are given the lowest weights (table 23). Conversely, the most unstable conditions are given the highest weights. Weights range from one to five (one value for each of the variable categories) for total-widening rate and vegetative cover. The lowest weight for accretion is two because high accretion frequently leads to secondary-bank failures, although moderate rates of accretion are commonly associated with stable, aggrading-channel conditions. Thus, a given site could have an $I_s$ value from 4 (most stable) to 15 (least stable). $I_s$ values and weights for individual categories are listed for 98 sites in table 24.

$I_s$ values below 7 suggest stable conditions with little mass wasting, high vegetative cover, and moderate accretion rates. $I_s$ values above 10 are distinctly unstable and suggest high widening rates, low vegetative cover, and low to no accretion. Thus, there are three $I_s$ ranges; (1) stable ($I_s$ = 4 to 7);

Table 23.--*Site-variable categories, abbreviations, and bank-stability index ($I_S$) weights*

[n, number of sites; ft/yr, foot per year; in/yr, inches per year; %, percent cover; >, greater than]

| Abbreviation | Site-variable category | Range | n | $I_S$ weights |
|---|---|---|---|---|
| | | ***Channel-bank widening*** | | |
| VW | Very low widening | 0.00-0.49 ft/yr | 16 | 1 |
| LW | Low widening | 0.50-0.99 ft/yr | 14 | 2 |
| MW | Medium widening | 1.00-2.99 ft/yr | 17 | 3 |
| HW | High widening | 3.00-3.99 ft/yr | 13 | 4 |
| XW | Very high widening | >4.00 ft/yr | 18 | 5 |
| | | ***Channel-bank accretion*** | | |
| OA | Zero accretion | 0 in/yr | 17 | 5 |
| VA | Very low accretion | 0.01-0.49 in/yr | 21 | 4 |
| LA | Low accretion | 0.60-0.99 in/yr | 12 | 3 |
| MA | Medium accretion | 1.00-2.49 in/yr | 11 | 2 |
| HA | High accretion | >2.50 in/yr | 15 | 2 |
| | | ***Vegetative cover*** | | |
| VC | Very low cover | 0-9 % | 15 | 5 |
| LC | Low cover | 10-24 % | 14 | 4 |
| MC | Medium cover | 25-49 % | 16 | 3 |
| HC | High cover | 50-74 % | 11 | 2 |
| XC | Very high cover | 75-100 % | 22 | 1 |

(2) at risk ($I_S$ = 8 to 10); and (3) unstable ($I_S$ = 11 to 15). This breakdown of relative bank stability is analogous to those described in the critical-bank conditions section. Relative to critical-bank conditions (fig. 35), it can be inferred that on the average; at stable sites no significant mass wasting occurs, at sites at risk any point along a bank fails once every 2 to 5 years, and at unstable sites, any point along a bank can fail annually.

When grouped by stage of bank-slope development, the study sites reveal expected low (stable) mean $I_S$ values at stages I and VI, with relatively high (unstable) mean $I_S$ values at stages IV and V (fig. 47). The trend displayed in figure 47 represents the integration of the individual dendrogeomorphic variables plotted in figure 46.

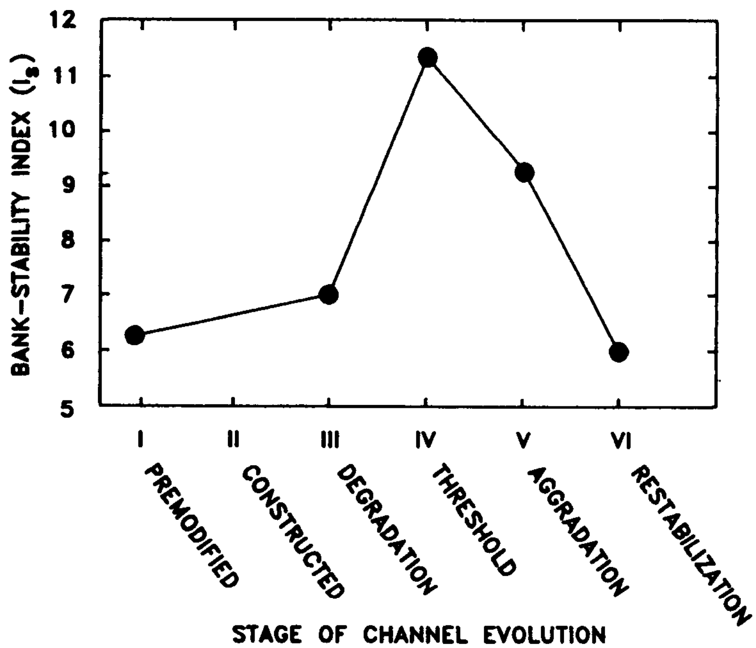



Figure 47.--Mean bank-stability index ($I_S$) reflecting variation in relative stability over the course of channel evolution.

Table 24.--*Bank-stability index for all sites based on classes of dendrogeomorphic data*

[$W_w$=weighted widening; $W_a$= weighted accretion; $W_c$= weighted vegetative cover; $I_s$=stability index; stage I=premodified; stage II=constructed; stage III=degradation; stage IV=threshold; stage V=aggradation; stage VI=restabilization; --=no data]

| Stream | Station number | River mile | $W_w$ | $W_a$ | $W_c$ | $I_s$ | Stage |
|---|---|---|---|---|---|---|---|
| Obion River | 07027200 | 20.8 | 1 | 2 | 4 | 7 | V |
| | 07027180 | 25.6 | 1 | 4 | 4 | 9 | II |
| | 07026300 | 34.2 | 4 | 2 | 4 | 10 | V |
| | 07026250 | 42.4 | 2 | 2 | 3 | 7 | V |
| | 07026000 | 53.7 | 5 | 2 | 5 | 12 | V |
| | 07025900 | 62.2 | 2 | 2 | 3 | 7 | V |
| | 07024800 | 68.5 | 4 | 3 | 3 | 10 | V |
| North Fork Obion River | 07025600 | 5.6 | 5 | 5 | 5 | 15 | IV |
| | 07025500 | 10.0 | 5 | 2 | 4 | 11 | V |
| | 07025400 | 18.0 | 4 | 3 | 2 | 9 | IV |
| | 07025375 | 21.1 | 4 | 5 | 1 | 10 | IV |
| | 07025340 | 26.4 | 2 | 5 | 1 | 8 | III |
| | 07025320 | 34.9 | 3 | 5 | 1 | 9 | I |
| Rutherford Fork Obion River | 07025100 | 4.9 | 3 | 2 | 2 | 7 | V |
| | 07025050 | 10.4 | 3 | 2 | 4 | 9 | V |
| | 07025025 | 15.2 | 3 | 2 | 3 | 8 | IV |
| | 07025001 | 24.5 | 2 | 3 | 1 | 6 | III |
| | 07025000 | 17.9 | 4 | 2 | 3 | 9 | IV |
| | 07024900 | 29.9 | 2 | 3 | 1 | 6 | VI |
| | 07024888 | 39.4 | 1 | 4 | 1 | 6 | VI |
| | 07024880 | 43.3 | 2 | 4 | 1 | 7 | VI |
| South Fork Obion River | 07024800 | 5.8 | 4 | 3 | 3 | 10 | V |
| | 07024550 | 11.4 | 5 | 4 | 4 | 13 | V |
| | 07024525 | 16.8 | 5 | 5 | 5 | 15 | IV |
| | 07024500 | 19.2 | 5 | 5 | 3 | 13 | IV |
| | 07024460 | 23.2 | 5 | 5 | 2 | 12 | IV |
| | 07024430 | 28.5 | 1 | 2 | 1 | 4 | VI |
| Middle Fork Forked Deer River | 07029020 | 5.2 | 2 | 5 | 4 | 11 | VI |
| | 07029000 | 14.6 | 5 | 5 | 5 | 15 | -- |
| | 07028990 | 21.5 | 2 | 4 | 1 | 7 | -- |
| | 07028960 | 30.5 | 1 | 3 | 1 | 5 | -- |
| | 07028910 | 37.0 | 3 | 5 | 1 | 9 | -- |
| | 07028900 | 44.9 | 1 | 4 | 1 | 6 | -- |
| North Fork Forked Deer River | 07029105 | 3.8 | 1 | 2 | 1 | 4 | VI |
| | 07029100 | 5.1 | 4 | 2 | 1 | 7 | V |
| | 07029040 | 13.6 | 5 | 5 | 5 | 15 | IV |
| | 07028840 | 18.8 | 3 | 3 | 4 | 10 | V |
| | 07028835 | 20.2 | 5 | 4 | 5 | 14 | IV |
| | 07028820 | 23.9 | 5 | 5 | 5 | 15 | IV |
| | 07028500 | 34.6 | 1 | 4 | 4 | 9 | I |
| | 07028410 | 41.6 | 1 | 2 | 1 | 4 | I |
| South Fork Forked Deer River | 07028200 | 3.3 | 3 | 4 | 4 | 11 | V |
| | 07028150 | 5.6 | 5 | 5 | 2 | 12 | V |
| | 07028100 | 7.9 | 5 | 5 | 5 | 15 | V |
| | 07028050 | 11.9 | 5 | 5 | 5 | 15 | V |
| | 07028000 | 13.3 | 5 | 3 | 5 | 13 | IV |
| | 07027800 | 16.3 | 4 | 5 | 5 | 14 | IV |
| | 07027720 | 27.6 | 5 | 4 | 5 | 14 | IV |
| | 07027780 | 33.7 | 1 | 5 | 1 | 7 | III |
| Hatchie River | 07030025 | 49.5 | 1 | 4 | 1 | 6 | I |
| | 07030000 | 68.4 | 1 | 4 | 1 | 6 | I |
| | 07029900 | 80.8 | 1 | 3 | 1 | 5 | I |
| | 07029650 | 121.0 | 1 | 4 | 1 | 6 | I |
| | 07029500 | 135.0 | 1 | 4 | 1 | 6 | I |
| | 07029430 | 162.0 | 1 | 3 | 1 | 5 | I |
| | 07029400 | 182.0 | 1 | 4 | 1 | 6 | I |

Table 24.--*Bank-stability index for all sites based on classes of dendrogeomorphic data--Continued*

| Stream | Station number | River mile | $W_w$ | $W_a$ | $W_c$ | $I_s$ | Stage |
|---|---|---|---|---|---|---|---|
| Wolf River | 07031700 | 9.1 | 4 | 4 | 3 | 11 | IV |
| | 07031650 | 18.9 | 4 | 2 | 2 | 8 | IV |
| | 07030610 | 23.6 | 3 | 2 | 3 | 8 | IV |
| | 07030600 | 31.2 | 1 | 2 | 2 | 5 | I |
| | 07030500 | 44.4 | 2 | 2 | 2 | 6 | I |
| | 07030395 | 57.5 | 3 | 4 | 2 | 9 | I |
| | 07030392 | 69.9 | 2 | 4 | 1 | 7 | I |
| Pond Creek | 07029080 | 1.1 | 3 | 4 | 1 | 8 | IV |
| | 07029075 | 3.1 | 4 | 4 | 5 | 13 | IV |
| | 07029070 | 7.3 | 4 | 2 | 4 | 10 | IV |
| | 07029065 | 9.8 | 3 | 2 | 1 | 6 | IV |
| | 07029060 | 11.4 | 4 | 2 | 4 | 10 | IV |
| Porters Creek | 07029445 | 4.5 | 3 | 2 | 3 | 8 | V |
| | 07029440 | 8.9 | 1 | 2 | 2 | 5 | V |
| | 07029439 | 11.2 | 3 | 3 | 3 | 9 | IV |
| | 07029438 | 13.9 | 2 | 3 | 1 | 6 | VI |
| | 07029437 | 17.1 | 5 | 2 | 1 | 8 | IV |
| Cub Creek | 07029450 | 1.5 | 3 | 2 | 2 | 7 | VI |
| | 07029449 | 2.2 | 3 | 2 | 3 | 8 | VI |
| | 07029448 | 5.7 | 5 | 3 | 4 | 12 | V |
| | 07029447 | 6.9 | 3 | 4 | 3 | 10 | IV |
| Cane Creek | 1 | .61 | 1 | 2 | 4 | 7 | IV |
| | 2 | 1.95 | 3 | 2 | 1 | 6 | IV |
| | 3 | 2.52 | 2 | 2 | 1 | 5 | IV |
| | 4 | 3.64 | 1 | 5 | 2 | 8 | IV |
| | 5 | 4.06 | 3 | 2 | 1 | 6 | IV |
| | 6 | 5.71 | 1 | 5 | 2 | 8 | IV |
| | 7 | 6.19 | 1 | 5 | 2 | 8 | IV |
| | 8 | 7.06 | 5 | 2 | 2 | 9 | IV |
| | 9 | 7.99 | 1 | 5 | 3 | 9 | IV |
| | 10 | 8.98 | 4 | 2 | 3 | 9 | IV |
| | 11 | 9.92 | 3 | 2 | 3 | 8 | IV |
| | 12 | 10.26 | 2 | 3 | 4 | 9 | IV |
| | 13 | 11.05 | 3 | 2 | 3 | 8 | IV |
| | 14 | 11.31 | 3 | 3 | 4 | 9 | IV |
| | 15 | 11.84 | 1 | 2 | 3 | 8 | IV |
| | 16 | 12.59 | 3 | 2 | 3 | 8 | IV |
| | 17 | 13.39 | 1 | 5 | 4 | 10 | IV |
| | 18 | 14.05 | 2 | 3 | 4 | 9 | IV |
| | 19 | 14.83 | 1 | 5 | 4 | 10 | IV |
| | 20 | 15.36 | 1 | 5 | 5 | 11 | IV |
| | 22 | 15.95 | 1 | 5 | 4 | 10 | IV |

$I_S$ values generally tend to decrease upstream or with distance from the most recent channel work, indicating greater bank stability. $I_S$ values by river mile for the Obion River basin, the Forked Deer River basin, Cane Creek, Wolf River, and Hatchie River (table 24) are illustrated in figure 48. Exceptions to this relation of decreasing $I_S$ with distance upstream are the Obion River main stem, Cane Creek, and one seemingly anomalous site on the Wolf River. The Wolf River site (07030395, table 6) has been affected by local channel modifications unrelated to downstream modifications; this localized work has mildly affected the site just upstream and has a relatively high $I_S$ value (fig. 48d). Most of the Obion River main stem maintains low vegetative cover values due to rapid accretion. Continued dredging and the subsequent maintenance of bank heights, largely beyond the critical limit, serve to keep $I_S$ values high (fig. 48a).

Cane Creek was channelized from its mouth to near its upstream limit during two operations in 1970 and 1978. Sites downstream from river mile 6 (fig. 48c) are relatively stable owing to backwater control provided by the Hatchie River. Stability generally decreases upstream of river mile 10 (fig. 48c) due to severe degradation. Overall, the $I_S$ values are lower (more stable) than would be expected. This is due largely to the considerable amount of bank-surface area relative to any of the other studied streams. Large bank-surface areas are created by rotational failures. This large amount of area allows vegetation to establish on low-bank locations away from the actively failing vertical faces and above erosive streamflow. Thus, the widening weight ($W_w$) is offset by the vegetative-cover weight ($W_c$) in the calculation of $I_S$ values. In this case, the slope-stability calculations (fig. 35) provide a more accurate estimate of bank stability.

The forks of the Obion River show clear stability differences among the streams at all sites except a site on the South Fork (07024430), which is a bottomland marsh. In order of increasing stability the streams rank: South Fork, North Fork, and Rutherford Fork Obion River (fig. 48a). The Forked Deer River forks clearly show a tendency for resumption of stability downstream, with their middle reaches being quite unstable, and their upstream reaches showing the typical trend towards stability (fig. 48b). The only anomalous site (fig. 48b) is a relatively stable site on the North Fork (07028840), which is influenced by the confluence with the Middle Fork as explained elsewhere.

The Hatchie River is uniformly stable (fig. 48d) with no $I_S$ value above 6, and serves as a comparison for the other studied streams. The mean $I_S$ value for the Hatchie River is 5.71 (n=7, standard deviation=0.49) and is shown as a dashed line in figure 48 (a through c) for comparative purposes. Mean $I_S$ values of other study streams are indicated on figure 48.

## Accretion and Channel Pattern

Detailed accretion analyses were conducted along reaches from late stage IV through stage VI. Variations in bank form, sediment accretion, and therefore the character of the vegetation that may proliferate along a reach during a given stage occur largely because of bends in the channel or thalweg. The bends may represent incipient meanders characteristic of late stage V, as in the lower reaches of the Obion River forks, or true meanders (stage I), as along the Hatchie River and upper reaches of the

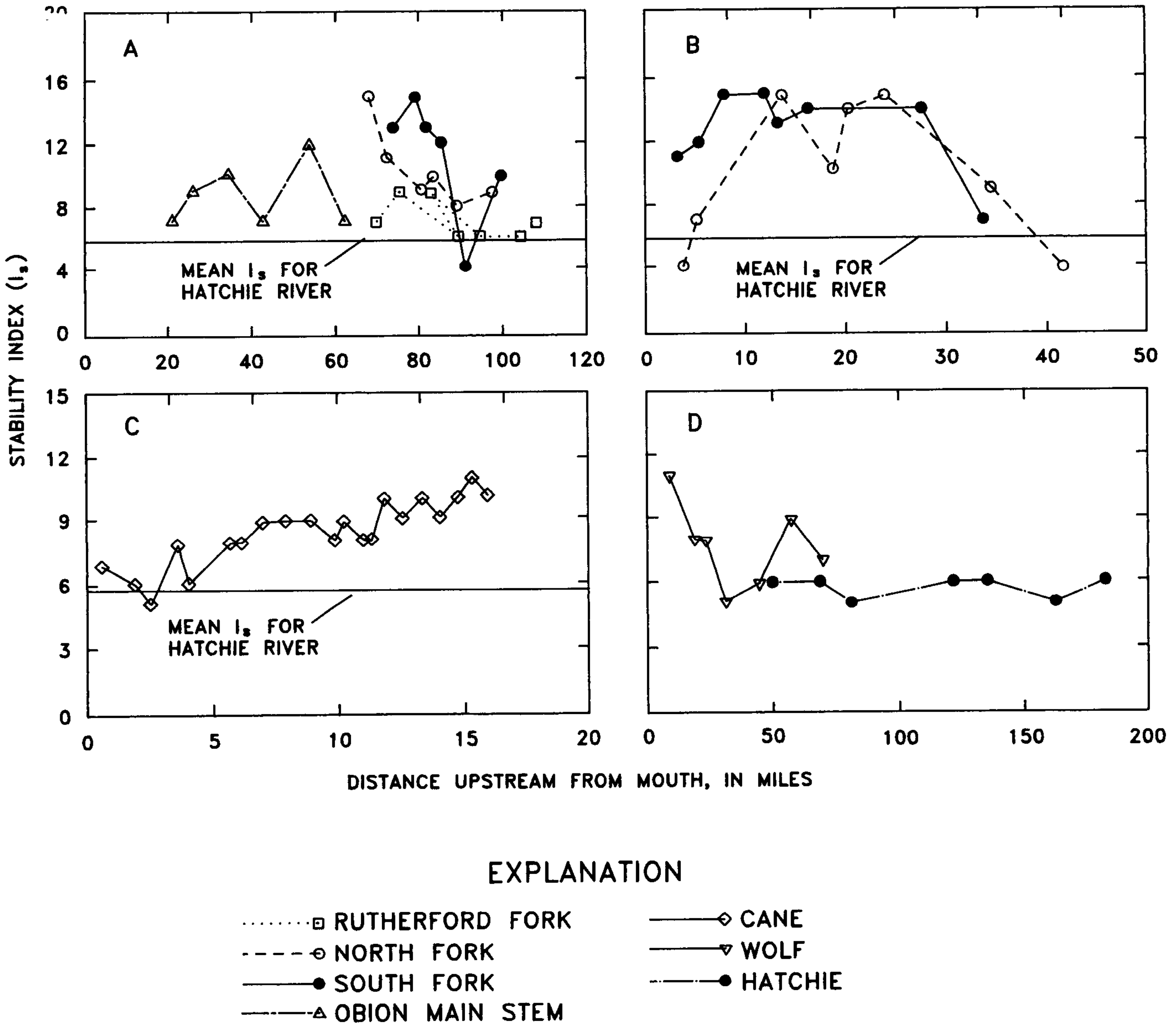



Figure 48.--Bank-stability index ($I_s$) along adjusting stream channels in the (A) Obion River system, (B) Forked Deer River system, (C) Cane Creek, and (D) Hatchie River and Wolf River. (Hatchie River mean $I_s$ is included for contrast with a natural channel.)

Wolf River. For example, a stage V reach with a bend or incipient meander in the channel may have heightened accretion rates, substantial vegetation establishment, and point-bar development along the inside bank. In contrast, the opposite, outside bank with an impinging thalweg and pronounced toe cutting will have generally steep banks, little or no net accretion, poor vegetation establishment, and accelerated lateral erosion. Differences between inside and outside banks are most pronounced in late stage IV and stage V when the establishment of the slough line may be compromised by an outside bend. Although these differences have been generalized in the overall discussion of channel recovery by stage, the topic warrants special treatment, because of the sometimes striking variation in bank forms along a reach.

Examples of differences between inside- and outside-bend configurations are provided in figure 49. Outside bends (fig. 49a) tend to maintain a concave profile in cross section due to mass wasting from the vertical face and upper bank, and removal of failed material by fluvial action. Failed material may remain on the upper bank (fig. 49a) in over-widened and protected areas, but it is still subject to secondary failures that help maintain the concave shape of the outside bank. Lower parts of the upper bank and the slough line may have some localized accretion. However, outside bends tend to be erosional surfaces due to heightened shear velocities that extend meander loops and retard vegetation establishment.

Inside bends (fig. 49b) have substantial accretion that transforms the slough line into a pronounced depositional surface during stage V. Exceptions occur in the loess tributaries such as Cane, Hoosier, and Pond Creeks where little accretion takes place due to a lack of coarse (sand) materials. In these cases, the slough line consists almost entirely of previously failed colluvium.

The depositional surface is a composite of all preceding depositional episodes that expands vertically and laterally with time. This surface takes a convex profile; and over time, it may extend up to, and attach to the flood plain (fig. 49b) depending on bank heights and flow-duration characteristics. These surfaces are generally stable. However, shallow secondary failures of saturated, previously failed materials and accreted sediments may occur low on the depositional surface. Stabilizing depositional processes expand upslope as mass wasting diminishes and channel-bed elevations rise. Characteristic flow durations for the depositional surface (slough line) range from 10 to 50 percent.

Channel shelves (or benches; fig. 49b) commonly occur below the depositional surfaces. Shelf areas are usually depositional, occur at much flatter angles, and appear to be related to point-bar development. Shelves may have a steep profile at the low-water surface where they are truncated by flows, or they may grade into channel bars that extend well into the active channel.

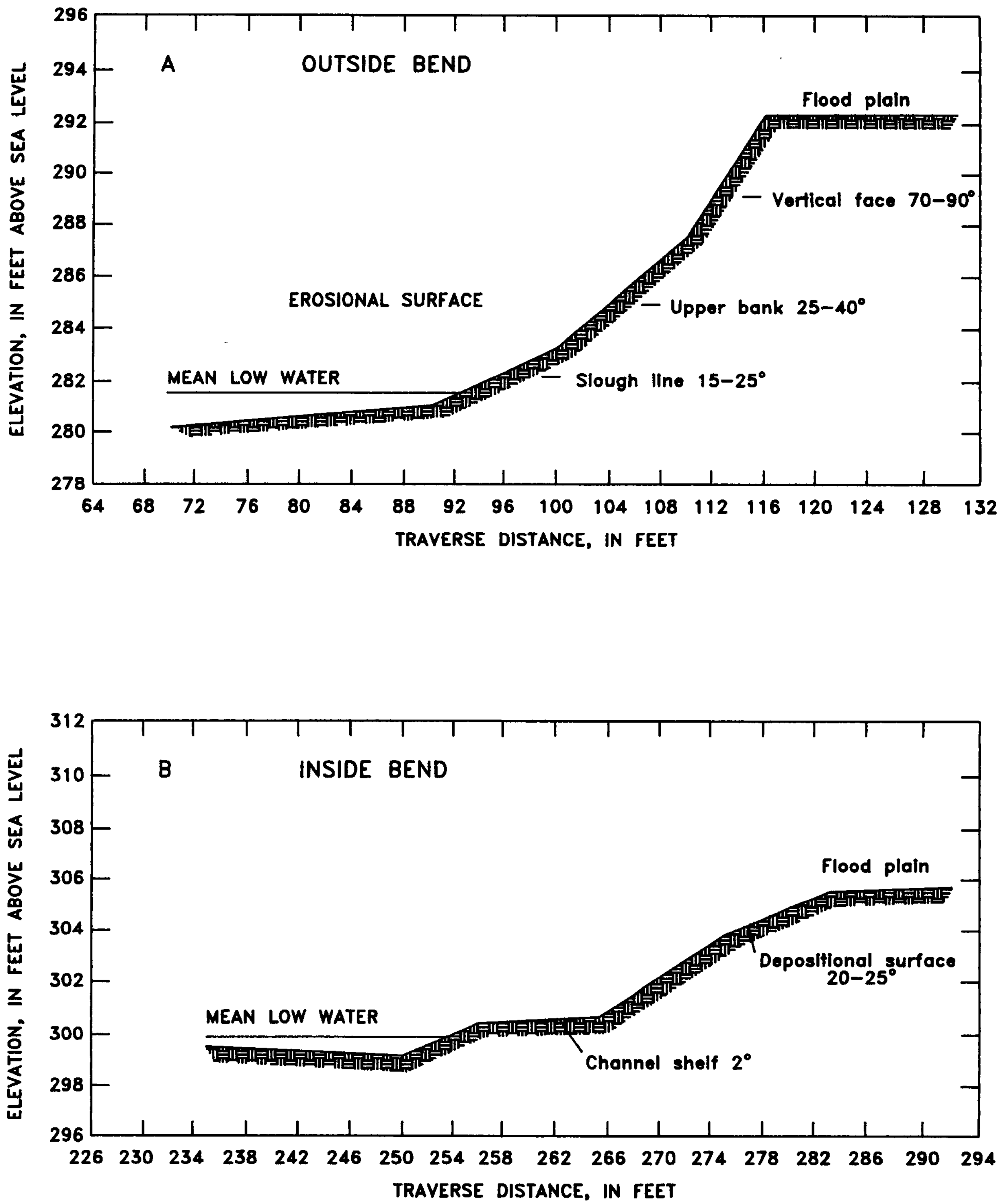



Figure 49.--Typical (A) bank on outside bend in channel and (B) bank on inside bend in channel for aggradation stage reaches (stage V).

Alternating outside- and inside-bend conditions may exist along predominantly straight reaches and are related to a meandering low-flow thalweg that further reduces channel gradients during late stage V (fig. 50). Straight, stage V reaches with no meandering thalweg typically have depositional surfaces, upper banks, and vertical faces on both banks, although bank features are not as pronounced as they are on inside or outside bends (fig. 49).

Figure 50.--Point-bar development along a reach during late aggradation stage (stage V), Porters Creek at Hebron, Tenn. (station number 07029445).

As described above, inside- and outside-bend sections show large relative differences in widening, accretion, and vegetative-cover values, while straight reaches maintain intermediate values. A summary of inside-outside differences for stages IV and V reaches is given in table 25. Accretion along straight reaches during late stage IV is much less than along stage IV inside bends, attesting to the lower shear stresses that exist in areas away from the thalweg. During stage V however, the shift to a generally depositional environment increases accretion rates for both straight reaches and inside bends (tables 4 and 25).

Table 25.--Variation in dendrogeomorphic variables as a function of reach type

[n=number of sites]

| Reach type | Widening (feet per year) | Accretion (inches per year) | Vegetative cover (percent) | n |
|---|---|---|---|---|
| | | Stage IV--Threshold | | |
| Inside | 0.41 | 2.44 | 38.5 | 8 |
| Outside | 3.05 | 0 | 1.3 | 8 |
| Straight | 2.31 | .65 | 12.9 | 22 |
| | | Stage V--Aggradation | | |
| Inside | 0 | 2.32 | 51.2 | 8 |
| Outside | 1.68 | .92 | 9.4 | 8 |
| Straight | 1.60 | 1.98 | 24.3 | 18 |

These data, and the descriptions provided previously, indicate that lateral migration of the thalweg plays an important role in the development of bank features from late stage IV through stage V. These results also suggest a general shift from channel processes dominated by degradation and mass wasting, during stages III and IV, to channel processes dominated by aggradation and fluvial action during stage V and beyond. The greater accretion and vegetation establishment on inside bends provides a natural, physical explanation for increased flow deflection towards the opposite bank. This in turn leads to further point-bar growth on the inside bend, accelerated bank retreat on the outside bend, and consequently, an increase in channel sinuosity as meanders develop.

Woody-riparian vegetation readily establishes and grows on most inside bends during stage V from the shelf to the top of the bank. Initial establishment occurs on the slough line (Simon and Hupp, 1986b). This band of vegetation then spreads somewhat downslope, and to a greater degree, upslope through vegetative runners or "recruitment". Riparian vegetation increases channel roughness, which dissipates flow energy, promotes sediment accretion and aids in bank stability through root-mass development.

Detailed bank-accretion analyses done on vegetated and highly depositional banks, supply information about the increasing influence exerted by role of fluvial processes in determining bank form during stage V. The depositional surface typically occurs between 32 and 79 percent of the total bank elevation (0 percent being the elevation of the channel bed, and 100 percent being the elevation of the flood plain; fig. 51). The typical median location of the depositional surface is about 56 percent. Depth of accretion tends to decrease downslope in depositional areas from a mean of 14.5 inches, through 12.8 inches in middle depositional surfaces, to 9.0 inches on low depositional surfaces.

Typical angles for depositional surfaces are rather constant on middle and upper areas--about 23 degrees, steepening slightly on low depositional surfaces to about 28 degrees (fig. 52). The former value holds important implications towards interpretations of dominant bank-forming processes and long-term changes in channel width. With the depositional surface being an accreted and fluvially reworked slough line, and representing a newly stabilized condition, it is reasonable to assume that the angle of this surface should approximate the angle of the original slough line (as determined by the temporary angle of stability; eq. 11). The fluvial processes that place further sediments on the slough line (described herein as accretion) are the same processes that rework the colluvial material that formed the original slough line. The mean,

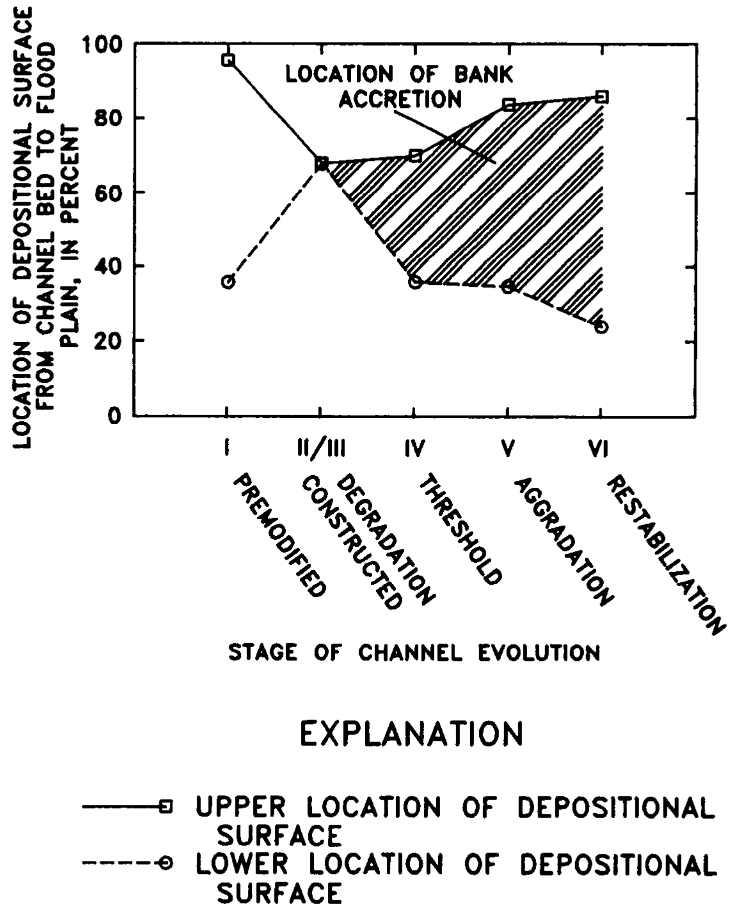



Figure 51.--Variation in location of depositional surface by stage of channel evolution.

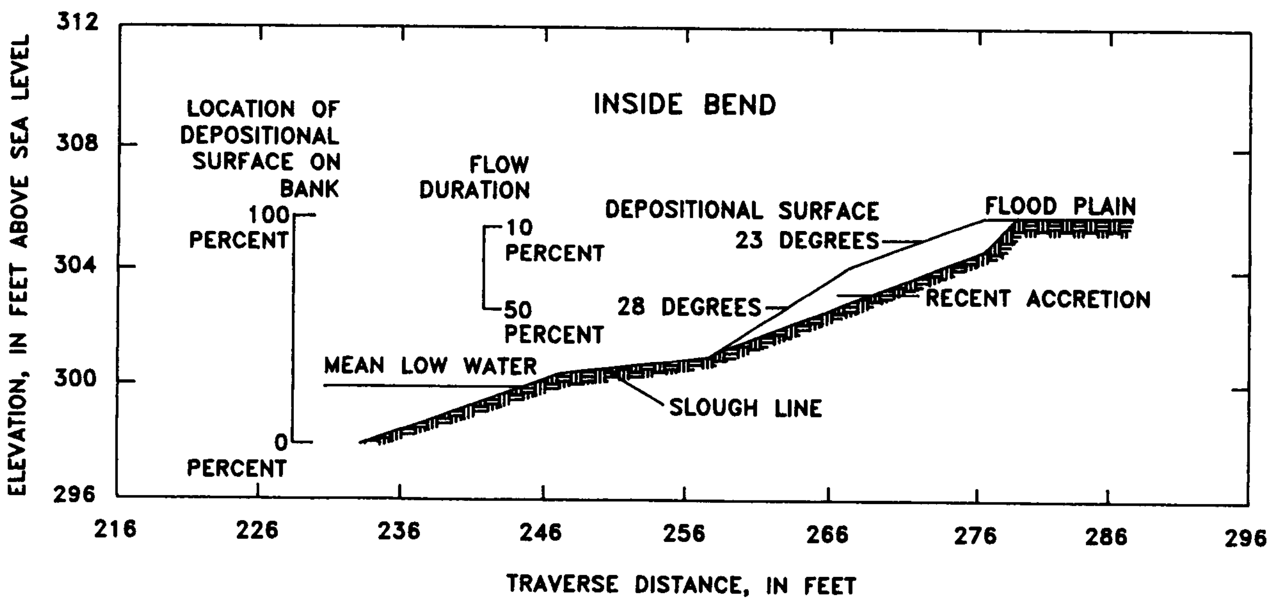



Figure 52.--Channel-bank accretion characteristics for site 07026000 along the Obion River main stem.

temporary angle of stability for 76 sites (table 20) is 24 degrees (standard deviation=4.7) and supports this argument, by being independently substantiated through the dendrogeomorphic analyses. Angles of depositional surfaces are derived from dendrogeomorphic data, whereas temporary angles of stability are based on shear-strength data and Mohr-Coloumb failure envelopes. The angle of the slough line influences the subsequent angle of the depositional surface, which is partly a function of contrasting grain sizes and permeabilities of the sediments comprising these features. Accreted sediments are sand sized (Simon, in press) and allow water to drain down into the silty, colluvial material of the buried slough line. Shallow secondary failures can then occur in the saturated silt. The accreted sand remains on the surface and can reflect the angle determined by the subsurface movement.

The greater mean angle of the low depositional surface (28 degrees) is explained by lateral truncation through stream action. The resulting convex bank shape is therefore a function of previous mass-wasting processes and subsequent lateral-fluvial processes. This sequence is applicable to straight and inside, stage V reaches. Outside bends may show some accretion during stage V (table 25), but their shapes are still determined by fluvial undercutting and mass-wasting processes.

The quantitative characteristics of the depositional surface are shown graphically in figure 52--a generalization based on the cross section of site 07026000 on the Obion River. Note the flow durations for parts of the depositional surface.

The depositional surface (fig. 52) typically ranges from the flood-plain surface (100 percent bank location) down to about the 35-percent bank location along 'natural' West Tennessee streams. During channel construction (stage II), which can be considered an instantaneous condition, the depositional surface is absent. The same is true during stage III (degradation), as high stream power keeps sediment in transport.

Initial development of the depositional surface occurs during late stage IV relatively low on the bank, and corresponds to the position of the slough line (fig. 51). As previously noted, the slough line is the first part of the bank to become stable after a period of active mass wasting. During stage V, the depositional surface expands upslope from 70 to 80 percent of the total bank height (fig. 51). Thus initial accretion occurs low on the bank slope with later expansion upslope. This coincides with trends of spreading vegetation that initially began growing on the slough line. By stage VI, the lower boundary of the depositional surface extends downslope to nearly the 20-percent location, which is substantially lower than the lower boundary for "natural" streams (fig. 51). Continued expansion of the upper depositional boundary during stage VI is also observed and is related to continued aggradation of the streambed. Initial low-bank stability determined in this study supports Thorne and Osman's (1988) suggestion that bank stability is largely controlled at the base of the bank ("basal endpoint control") and provides a link between bed processes and bank processes.

Assuming that channel incision during stages III and IV was not so severe as to render the flood plain a terrace (Simon, in press), it is expected that the upper depositional boundary will attach to the flood plain with time. The pattern of depositional-surface locations through stages of bank-slope development are most pronounced along inside bends. However, straight reaches also follow this same general pattern, albeit at a slower pace. The vertical growth of this surface and its attachment to the flood plain represents flood-plain growth. Patterns of pioneer-vegetation establishment by stage typically coincide with those of depositional-surface location.

Depositional bank angles rapidly flatten to about 23 degrees once accretion begins in late stage IV. Stages V and VI indicate increasing amounts of accreted material and mean depositional surface angles around 23 degrees (fig. 53). Accretion depths were determined through the excavation of buried trees and shrubs. The amount of accretion is related to the age of the plants, and accretion prior to vegetation establishment is not included in accretion estimates. Thus, the accretion estimates include only relatively recent deposition and recent rates of accretion. This limitation is not problematic along modified channels or reaches that have been affected by channel modification, because rates of accretion in depositional reaches of disturbed streams are greatly accelerated. However, along natural streams (stage I), accretion as a natural-channel process has occurred at slow rates for millennia.

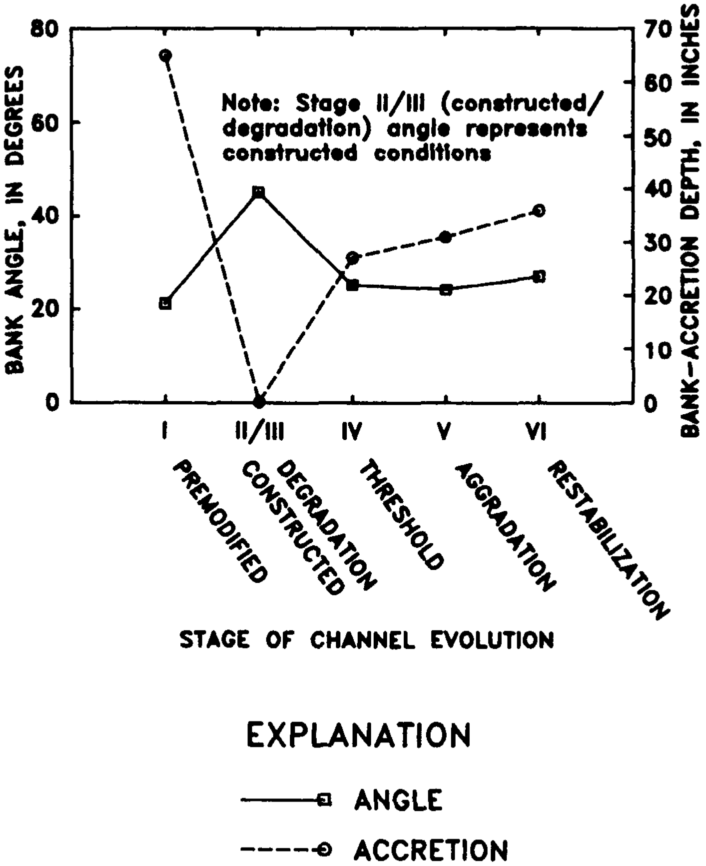



Figure 53.--Variation in bank angles and depths of bank accretion on the depositional surface through stages of channel evolution.

## *Development of Long-Term Channel Geometry*

Previous sections of this report describe adjustment processes and trends throughout a number of fluvial systems in West Tennessee. A bed-level model has been used to estimate future degradation and aggradation along modified channels. Shear-strength determinations and slope-stability analyses have been used to describe thresholds of mass wasting on the channel banks and for differentiating between stable and unstable banks. Factors of safety and probabilities of failure have been found to vary according to the stage of adjustment as described in conceptual models of bank-slope development and channel evolution (Simon, 1989; and tables 4 and 5). Furthermore, accurate rates of channel widening by mass-wasting processes have been obtained through dendrogeomorphic techniques. This section uses these previous analyses for the purpose of estimating long-term (25 to 100 years) channel geometry throughout the studied stream systems.

Changes in the elevation of the channel bed at a site have been described by equation 2 and used to estimate future degradation and aggradation at 5-year intervals to the year 2000 (figs. 20-22, tables 9 and 12). With channel-bed degradation lasting for 10 to 15 years at a site and followed by secondary aggradation, long-term channel depths can be estimated. Projection of future channel depths in this manner is based on the concepts of complex response (Schumm, 1973) and oscillatory channel response (Alexander, 1981; Simon, 1989). The fundamental component of these concepts is that within a trend of bed-level response such as downcutting, there can be alternating periods of deposition and erosion of the channel bed with each episode being of lesser magnitude. This has been shown in the experimental work of Schumm and Parker (1973) and from the empirical data of Simon (in press). In the latter case, only two such episodes were observed and monitored: an initial downcutting phase followed by a phase of secondary aggradation at rates approximately 78-percent less than the initial rate of incision (Simon and Hupp, 1986a). This percentage was derived from comparing rates of degradation and aggradation at 14 sites in West Tennessee (Simon, in press). An idealized representation of this phenomenon, showing a 78-percent reduction in the rate of bed-level change for each episode is shown in figure 54b and 54c.

The difference between complex response and oscillatory-(episodic) channel response seems one of scale. Alternating phases of aggradation and degradation within a larger trend of gradient reduction represent episodic responses as local thresholds are exceeded. These phases may last for a number of years. Conversely, secondary aggradation, which follows the 10 to 15 year period of degradation represents the complex response of the drainage network, and may last 25 to 40 years (based on channel-bed elevation and tree-ring data), or up to about 100 years (based on post-settlement adjustments). Thus, episodic phases of aggradation within the larger trend of channel-bed lowering (episodic response) should not be confused with the subsequent, larger aggradation trend characteristic of stages V and VI of the channel-evolution model (table 5). Estimated channel geometries based on 100 years of aggradation, therefore, represent minimum channel depths. However, error margins should be small because extrapolation occurs in the very flat part of the curve generated by equation 2.

For the purposes of this study, long-term channel depths are calculated from equation 2 using a 15-year period of degradation (b-value from table 3) followed by aggradation (b-value from table 3 or calculated by $|-b| \times 0.22$) periods of 25 and 100 years. Calculated channel depths after 15 years of

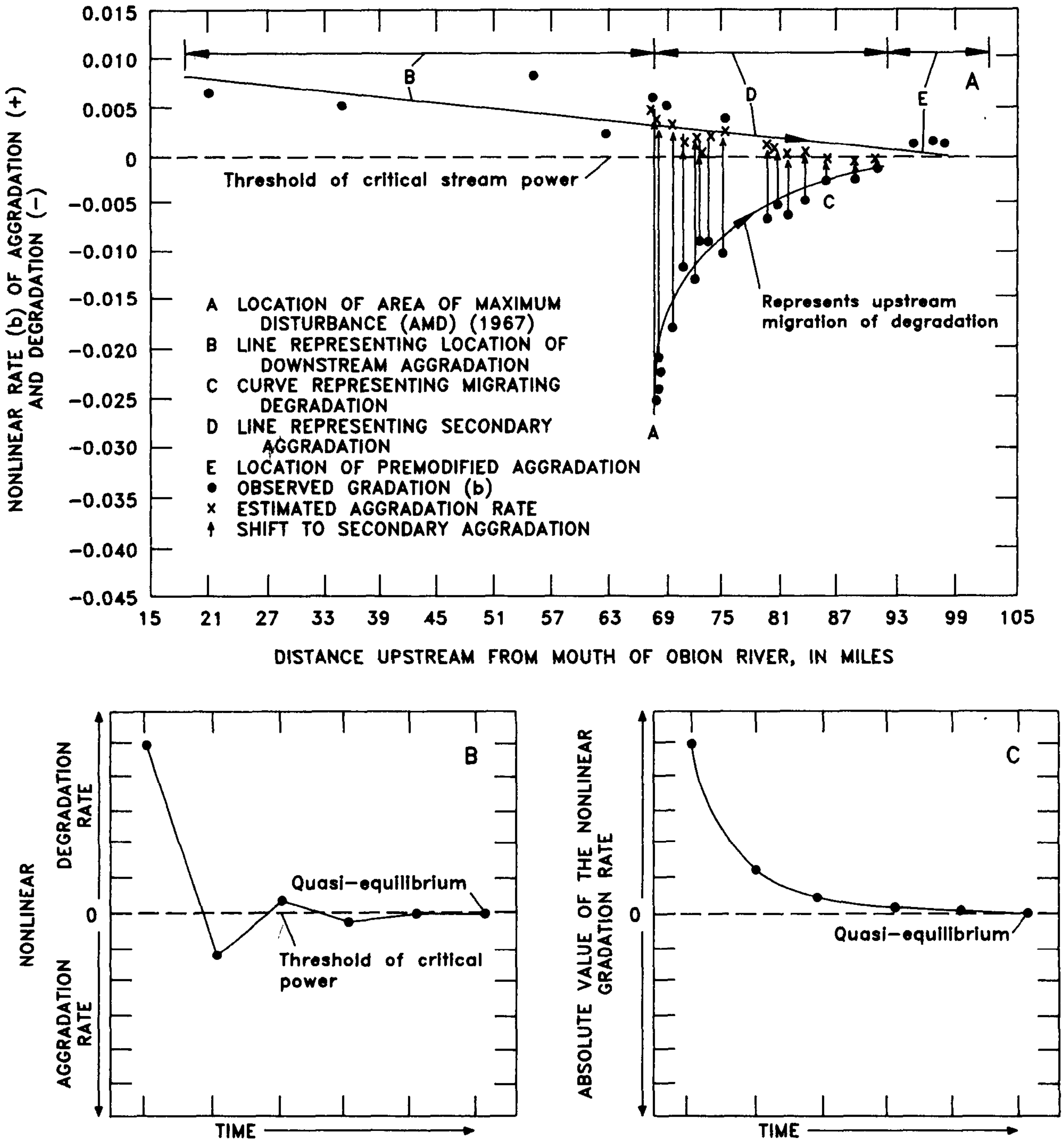



Figure 54.—–Representation of (A) channel–bed response to channel disturbance including secondary aggradation and (B and C) idealized oscillatory channel response. (Modified from Simon, in press.)

degradation and 25 years of aggradation, and after 15 years of degradation and 100 years of aggradation, are given in table 26. Thus the total amount of time represented for each of these estimates is 40 and 115 years, respectively.

Long-term channel widths are calculated using present (1987) channel widths and estimates of projected-channel widening (table 20). The values for long-term channel widths presented in table 27 are based on the assumption that there is no renewed phase of significant channel incision. The projection of long-term channel widths is based on values for a given cross section; using mean values of bank height, bank angle, and material properties between the left and right banks. If the site is in a straight reach, differences are generally minimal and the assumption of a trapezoidal shape is realistic. However, some differences between banks can exist for those reaches which exhibit incipient meandering of the thalweg. Estimates of long-term channel widths (top-bank width) do not account for channel narrowing which may take place in stage VI as the depositional surface attaches to the flood plain. In all cases, estimates in table 27 represent mean conditions for the entire cross section.

Long-term channel depths (table 26) and channel widths (table 27) should represent stable, stage VI conditions. This can be checked by taking the temporary stability angle (table 20) for a given site, and then selecting a channel depth for that site from table 26. Applying these values to a bank-stability chart for each site, it is found that most sites fall into the stable, or the lower part (more stable) of the at-risk category. This indicates bank stability and a general lack of mass-wasting processes.

Exceptions to this long-term stability are along Cane Creek. Throughout this report, Cane Creek has been used as the example of worst-case conditions in the region. Bank-stability charts developed for this stream indicate that a number of sites will still not be stable after 115 years of adjustment. This finding agrees with previous discussions of channel-adjustment trends in the Cane Creek channel and, potentially, of other severely degraded loess tributary streams.

A convenient means of discerning differences in controlling channel processes and channel morphology is the width-depth ratio. Low width-depth ratios indicate that bed degradation is dominant, whereas high values indicate mass wasting is dominant on the channel banks and (or) rapid infilling of the channel. Width-depth ratios for the studied sites are calculated by dividing the estimates of long-term channel widths by the estimates of long-term channel depths, after either 40 or 115 years of adjustment processes (table 28).

The minor differences between estimates of long-term width-depth ratios after 25 and 100 years of aggradation can be explained in terms of the time-dependent nature of channel adjustments. As with degradation, rates of change on the channel bed are relatively rapid at first as the aggradation threshold is crossed (due to low gradients and high tractive loads from upstream). The aggradation process

## Table 26.--*Estimated mean channel depths after 15 years of degradation and 25 and 100 years of aggradation*

[PDDH = Predisturbed depth; DH15 = Depth after 15 years of degradation; DHA25 = Depth after 15 years of degradation and 25 years of aggradation; DHA100 = Depth after 15 years of degradation and 100 years of aggradation]

| Stream and station No. | River mile | PDDH | DHA15 | DHA25 | DHA100 |
|---|---|---|---|---|---|
| Cane Creek | | | | | |
| 1 | 0.61 | 13.1 | 17.7 | 16.3 | 15.7 |
| 2 | 1.95 | 9.7 | 19.2 | 16.4 | 15.2 |
| 3 | 2.52 | 18.8 | 29.5 | 26.4 | 25.0 |
| 4 | 3.64 | 15.8 | 33.6 | 28.5 | 26.2 |
| 5 | 4.02 | 17.6 | 35.9 | 30.6 | 28.3 |
| 6 | 5.72 | 17.1 | 36.5 | 30.9 | 28.5 |
| 7 | 6.27 | 12.3 | 32.6 | 26.7 | 24.2 |
| 8 | 7.06 | 16.2 | 37.8 | 31.6 | 28.8 |
| 10 | 8.99 | 15.3 | 31.4 | 26.7 | 24.7 |
| 12 | 10.25 | 22.4 | 39.5 | 34.5 | 32.4 |
| 16 | 12.58 | 10.9 | 22.9 | 19.5 | 17.9 |
| 18 | 13.98 | 12.7 | 24.4 | 20.9 | 19.5 |
| 19 | 14.85 | 16.7 | 25.4 | 22.9 | 21.7 |
| 20 | 15.34 | 10.8 | 15.5 | 14.1 | 13.5 |
| Cub Creek | | | | | |
| 7029447 | 6.90 | 3.9 | 6.7 | 5.9 | 5.5 |
| 7029448 | 5.70 | 5.3 | 9.0 | 7.9 | 7.5 |
| 7029450 | 1.50 | 2.8 | 11.5 | 8.9 | 7.8 |
| Hoosier Creek | | | | | |
| 7025660 | 5.15 | 16.0 | 22.8 | 20.8 | 19.9 |
| 7025666 | 2.99 | 14.9 | 23.8 | 21.2 | 20.0 |
| 7025690 | .55 | 13.9 | 29.6 | 25.0 | 23.0 |
| Hyde Creek | | | | | |
| 7030002 | 1.20 | 6.6 | 18.1 | 14.7 | 13.3 |
| 7030004 | 1.90 | 9.3 | 18.5 | 15.8 | 14.6 |
| North Fork Forked Deer River | | | | | |
| 7028820 | 23.97 | 7.6 | 13.0 | 11.4 | 10.7 |
| 7028835 | 20.33 | 6.8 | 14.5 | 12.3 | 11.3 |
| 7028840 | 18.82 | 7.3 | 13.3 | 11.5 | 10.8 |
| 7029100 | 5.71 | 5.8 | 17.6 | 14.2 | 12.8 |
| 7029105 | 4.04 | 17.7 | 32.4 | 28.1 | 26.3 |
| North Fork Obion River | | | | | |
| 7025320 | 34.90 | 8.4 | -- | 7.1 | 6.5 |
| 7025340 | 26.40 | 14.0 | 15.8 | 15.3 | 15.1 |
| 7025375 | 21.10 | 16.9 | 21.1 | 19.9 | 19.3 |
| 7025400 | 18.00 | 13.6 | 16.7 | 15.8 | 15.4 |
| 7025500 | 10.00 | 6.1 | 15.8 | 12.9 | 11.7 |
| 7025600 | 5.90 | 12.0 | 30.3 | 24.9 | 22.6 |

| Stream and station No. | River mile | PDDH | DH15 | DHA25 | DHA100 |
|---|---|---|---|---|---|
| Obion River | | | | | |
| 7024800 | 68.5 | 4.0 | 20.6 | 15.8 | 13.7 |
| 7025900 | 62.2 | 22.8 | -- | 20.8 | 19.9 |
| 7026000 | 53.7 | 22.3 | -- | 14.8 | 11.5 |
| 7026300 | 34.2 | 27.0 | -- | 23.0 | 21.3 |
| 7027200 | 20.8 | 25.1 | -- | 20.7 | 18.8 |
| Pond Creek | | | | | |
| 7029060 | 11.4 | 7.9 | 14.1 | 12.3 | 11.5 |
| 7029065 | 9.8 | 7.8 | 13.6 | 11.9 | 11.2 |
| 7029070 | 7.3 | 5.7 | 14.6 | 11.9 | 10.9 |
| 7029075 | 3.1 | -- | -- | -- | -- |
| 7029080 | 1.1 | 6.6 | 12.8 | 11.0 | 10.2 |
| Porters Creek | | | | | |
| 7029437 | 17.1 | 3.9 | 17.2 | 13.3 | 11.6 |
| 7029439 | 11.2 | 7.0 | 21.5 | 17.2 | 15.4 |
| 7029440 | 8.9 | 7.8 | 13.9 | 12.1 | 11.3 |
| Rutherford Fork Obion River | | | | | |
| 7024900 | 29.9 | 10.7 | -- | 8.9 | 8.2 |
| 7025000 | 17.9 | 10.8 | 13.5 | 12.7 | 12.4 |
| 7025020 | 17.1 | -- | -- | -- | -- |
| 7025025 | 15.2 | 11.0 | 15.1 | 13.9 | 13.4 |
| 7025050 | 10.4 | 13.3 | 21.2 | 18.9 | 17.9 |
| 7025100 | 4.9 | 9.6 | 22.8 | 18.9 | 17.3 |
| South Fork Forked Deer River | | | | | |
| 7027720 | 27.6 | 11.9 | 18.7 | 16.7 | 15.8 |
| 7027800 | 16.3 | 7.1 | 13.9 | 11.9 | 11.0 |
| 7028000 | 13.3 | 11.9 | 18.9 | 16.7 | 15.9 |
| 7028050 | 11.9 | 15.1 | 23.9 | 21.3 | 20.2 |
| 7028100 | 7.9 | 15.1 | 26.1 | 22.9 | 21.5 |
| 7028200 | 3.3 | 30.9 | -- | 21.9 | 17.9 |
| South Fork Obion River | | | | | |
| 7024430 | 28.5 | 11.7 | 12.2 | 12.0 | 11.9 |
| 7024460 | 23.2 | 8.2 | 10.2 | 9.6 | 9.4 |
| 7024500 | 19.2 | 9.5 | 14.9 | 13.3 | 12.6 |
| 7024525 | 16.8 | 10.5 | 15.1 | 13.8 | 13.2 |
| 7024550 | 11.4 | 7.6 | 14.9 | 12.7 | 11.8 |
| 7024800 | 5.8 | 4.0 | 22.2 | 16.9 | 14.6 |

Table 27.--*Present (1987) and estimated mean long-term channel widths*

| Stream and station number | River mile | 1987 width | Long-term width |
|---|---|---|---|
| Cane Creek | | | |
| 1 | 0.61 | 91 | 94 |
| 2 | 1.95 | 109 | 112 |
| 3 | 2.52 | 155 | 161 |
| 4 | 3.64 | 162 | 178 |
| 5 | 4.02 | 160 | 171 |
| 6 | 5.72 | 148 | 158 |
| 7 | 6.27 | 160 | 204 |
| 8 | 7.06 | 152 | 197 |
| 10 | 8.99 | 141 | 179 |
| 12 | 10.25 | 165 | 210 |
| 16 | 12.58 | 109 | 112 |
| 18 | 13.98 | 143 | 152 |
| 19 | 14.85 | 124 | 134 |
| 20 | 15.34 | 114 | 114 |
| Cub Creek | | | |
| 07029447 | 6.90 | 25 | 30 |
| 07029448 | 5.70 | 29 | 36 |
| 07029450 | 1.50 | 62 | 72 |
| Hoosier Creek | | | |
| 07025660 | 5.15 | 109 | 109 |
| 07025666 | 2.99 | 118 | 118 |
| 07025690 | .55 | 146 | 146 |
| Hyde Creek | | | |
| 07030001 | .15 | 66 | 88 |
| 07030002 | 1.20 | 36 | 47 |
| 07030004 | 1.90 | 75 | 75 |
| North Fork Forked Deer | | | |
| 07028500 | 34.60 | 43 | 74 |
| 07028820 | 23.97 | 55 | 65 |
| 07028835 | 20.33 | 56 | 64 |
| 07028840 | 18.82 | 77 | 85 |
| 07029040 | 13.69 | 81 | 95 |
| 07029100 | 5.71 | 124 | 147 |
| 07029105 | 4.04 | 156 | 156 |
| North Fork Obion River | | | |
| 07025320 | 34.90 | 50 | 78 |
| 07025340 | 26.40 | 104 | 155 |
| 07025375 | 21.10 | 110 | 121 |
| 07025400 | 18.00 | 124 | 147 |
| 07025500 | 10.00 | 158 | 178 |
| 07025600 | 5.90 | 166 | 185 |
| Obion River | | | |
| 07024800 | 68.50 | 158 | 160 |
| 07025900 | 62.20 | 237 | 237 |
| 07026000 | 53.70 | 214 | 224 |
| 07026250 | 42.40 | 205 | 205 |
| 07026300 | 34.20 | 170 | 170 |
| 07027180 | 25.60 | 248 | 252 |
| 07027200 | 20.80 | 271 | 271 |
| Pond Creek | | | |
| 07029060 | 11.40 | 46 | 52 |
| 07029065 | 9.80 | 48 | 54 |
| 07029070 | 7.30 | 60 | 80 |
| 07029075 | 3.10 | 64 | 69 |
| 07029080 | 1.10 | 46 | 50 |
| Porters Creek | | | |
| 07029437 | 17.10 | 78 | 120 |
| 07029439 | 11.20 | 78 | 103 |
| 07029440 | 8.90 | 79 | 90 |
| 07029445 | 4.50 | 91 | 96 |
| Rutherford Fork Obion River | | | |
| 07024900 | 29.90 | 59 | 64 |
| 07025000 | 17.90 | 111 | 111 |
| 07025020 | 17.1 | 100 | 113 |
| 07025025 | 15.2 | 106 | 142 |
| 07025050 | 10.4 | 90 | 151 |
| 07025100 | 4.9 | 113 | 129 |
| South Fork Forked Deer River | | | |
| 07027680 | 33.7 | 115 | 115 |
| 07027720 | 27.6 | 94 | 107 |
| 07027800 | 16.3 | 109 | 123 |
| 07028000 | 13.3 | 105 | 124 |
| 07028050 | 11.9 | 117 | 161 |
| 07028100 | 7.9 | 146 | 146 |
| 07028200 | 3.3 | 112 | 112 |
| South Fork Obion | | | |
| 07024430 | 28.5 | 97 | 119 |
| 07024460 | 23.2 | 86 | 94 |
| 07024500 | 19.2 | 96 | 112 |
| 07024525 | 16.8 | 90 | 151 |
| 07024550 | 11.4 | 105 | 167 |
| 07024800 | 5.8 | 158 | 160 |
| Wolf River | | | |
| 07030395 | 57.5 | 100 | 100 |
| 07030500 | 44.4 | 105 | 107 |
| 07030600 | 31.2 | 115 | 122 |
| 07030610 | 23.6 | 142 | 163 |
| 07031650 | 18.9 | 170 | 178 |

Table 28.--*Estimated width-depth ratios after 15 years of degradation and 25 (WD25) and 100 (WD100) years of aggradation*

| Stream and station number | River mile | WD25 | WD100 |
|---|---|---|---|
| **Cane Creek** | | | |
| 1 | 0.61 | 5.75 | 5.97 |
| 2 | 1.95 | 6.81 | 7.35 |
| 3 | 2.52 | 6.10 | 6.43 |
| 4 | 3.64 | 6.25 | 6.79 |
| 5 | 4.02 | 5.59 | 6.04 |
| 6 | 5.72 | 5.11 | 5.55 |
| 7 | 6.27 | 7.64 | 8.44 |
| 8 | 7.06 | 6.24 | 6.83 |
| 10 | 8.99 | 6.70 | 7.25 |
| 12 | 10.25 | 6.08 | 6.49 |
| 16 | 12.58 | 5.76 | 6.25 |
| 18 | 13.98 | 7.26 | 7.81 |
| 19 | 14.85 | 5.86 | 6.16 |
| 20 | 15.34 | 8.07 | 8.42 |
| **Cub Creek** | | | |
| 07029447 | 6.90 | 5.08 | 5.41 |
| 07029448 | 5.70 | 4.54 | 4.83 |
| 07029450 | 1.50 | 8.06 | 9.19 |
| **Hoosier Creek** | | | |
| 07025660 | 5.15 | 5.23 | 5.46 |
| 07025666 | 2.99 | 5.57 | 5.88 |
| 07025690 | .55 | 5.84 | 6.34 |
| **Hyde Creek** | | | |
| 07030002 | 1.20 | 3.19 | 3.54 |
| 07030004 | 1.90 | 4.76 | 5.13 |
| **North Fork Forked Deer River** | | | |
| 07028820 | 23.97 | 5.68 | 6.04 |
| 07028835 | 20.33 | 5.22 | 5.67 |
| 07028840 | 18.82 | 7.36 | 7.89 |
| 07029100 | 5.71 | 10.38 | 11.61 |
| 07029105 | 4.04 | 5.54 | 5.93 |
| **North Fork Obion River** | | | |
| 07025320 | 34.90 | 10.98 | 11.92 |
| 07025340 | 26.40 | 10.13 | 10.28 |
| 07025375 | 21.10 | 6.09 | 6.26 |
| 07025400 | 18.00 | 9.31 | 9.55 |
| 07025500 | 10.00 | 13.75 | 15.20 |
| 07025600 | 5.90 | 7.41 | 8.17 |
| **Obion River** | | | |
| 07024800 | 68.5 | 10.13 | 11.69 |
| 07025900 | 62.2 | 11.38 | 11.87 |
| 07026000 | 53.7 | 15.10 | 19.41 |
| 07026300 | 34.2 | 7.38 | 7.99 |
| 07027200 | 20.8 | 13.09 | 14.44 |
| **Pond Creek** | | | |
| 07029060 | 11.4 | 4.24 | 4.53 |
| 07029065 | 9.8 | 4.53 | 4.83 |
| 07029070 | 7.3 | 6.67 | 7.37 |
| 07029080 | 1.1 | 4.54 | 4.89 |
| **Porters Creek** | | | |
| 07029437 | 17.1 | 9.01 | 10.33 |
| 07029439 | 11.2 | 5.97 | 6.69 |
| 07029440 | 8.9 | 7.44 | 7.95 |
| **Rutherford Fork Obion River** | | | |
| 07024900 | 29.9 | 7.13 | 7.78 |
| 07025000 | 17.9 | 8.71 | 8.96 |
| 07025025 | 15.2 | 10.20 | 10.60 |
| 07025050 | 10.4 | 7.99 | 8.44 |
| 07025100 | 4.9 | 6.80 | 7.46 |
| **South Fork Forked Deer River** | | | |
| 07027720 | 27.6 | 6.40 | 6.75 |
| 07027800 | 16.3 | 10.33 | 11.15 |
| 07028000 | 13.3 | 7.40 | 7.81 |
| 07028050 | 11.9 | 7.56 | 7.98 |
| 07028100 | 7.9 | 6.37 | 6.79 |
| 07028200 | 3.3 | 5.12 | 6.26 |
| **South Fork Obion River** | | | |
| 07024430 | 28.5 | 9.88 | 9.93 |
| 07024460 | 23.2 | 9.76 | 10.03 |
| 07024500 | 19.2 | 8.41 | 8.87 |
| 07024525 | 16.8 | 10.97 | 11.46 |
| 07024550 | 11.4 | 13.09 | 14.13 |
| 07024800 | 5.8 | 9.47 | 10.97 |

attenuates with time to a minimum and, in conjunction with reduced rates of channel widening, results in small variations in the width-depth ratio.

Variations in projected width-depth ratios also occur due to gross differences in the character of the channel alluvium. As indicated by Schumm (1960), channels cut through silt-clay alluvium tend to be narrower and deeper than those in sediments that contain greater percentages of coarse material. Although Schumm's "M" (percentage of silt-clay in the channel perimeter) was not calculated in this study, those channels that have been described as the "loess tributaries" display generally lower width-depth ratios than the sand-bed streams over the long term. Projected mean width-depth ratios for the loess tributaries and the sand-bed streams after 40 years of adjustment range from 4.0 to 6.4, and from 6.8 to 11.4, respectively. Similarly, after 115 years of adjustment, the estimated width-depth ratios for the fine-grained channels range from 4.3 to 6.8, and for the sand-bed channels, from 7.4 to 13.1. The discrete ranges given above are more a function of the lack of channel bed-level recovery along the loess tributaries (which keeps the channels deep) than of differences in widening rates due to greater cohesion in the channel banks. Furthermore, the loess tributaries have some of the greatest widening rates recorded during the study, and this is attributed to substantial amounts of channel bed-level lowering.

There are many uncertainties involved in projecting natural processes and forms 100 years into the future. Data presented in this section and tables 26 through 28 are estimates of the long-term channel geometry along adjusting channels in West Tennessee. The attenuation of processes such as bed-level change and channel widening have been accounted for through time and location within the general framework of the models of channel evolution and bank-slope development. However, variables such as further direct human intervention, land-use changes and low-frequency climatic events cannot be incorporated into this analysis and therefore create a degree of unreliability.

### *Riparian-Vegetation Recovery*

The most apparent characteristic of unstable bank conditions is a general lack of woody-riparian vegetation. The rate of bank widening is perhaps the most influential factor determining the type and abundance of riparian species. Bank accretion also affects species presence; high accretion rates appear to limit the presence of many species through suffocation of the root zone. Together, bank widening and accretion exert a pervasive influence on the riparian-vegetation community. The unstable banks are typically unshaded, which might also affect the early stages of revegetation; many stable-site species are relatively shade tolerant.

Natural or man-induced disturbance in vegetation systems have received considerable attention recently among students of plant ecology (White, 1979). Channel-bank responses to channelization (direct and indirect) are a major disturbance to riparian vegetation along West Tennessee channels. Little previous study has been directed toward the analysis and interpretation of plant ecological recovery on channelization-disturbed banks (Hupp and Simon, 1986).

Results of this part of the study pertain mostly to the bank forms and woody vegetation of strictly riparian zones (below the top-bank or flood-plain level). Along channelized reaches, the distinction between banks and flood plain is relatively clear. However, along some swampy, stable upstream reaches this topographic distinction may be blurred. Thirty-eight species of woody plants were identified along the channel banks of the study streams (table 29); this does not include vines such as blackberry and herbaceous perennial species. Seventy-seven species of trees and shrubs in total, that occur on riparian surfaces, flood plains, and fluvial wetlands were identified.

Table 29.--*List of woody riparian species in West Tennessee*

[This table provides explanation for species code in tables 30 and 31 and figures 57 and 58]

| Species code | Name: Scientific | Name: Common |
|---|---|---|
| ALSE | *Alnus serrulata* | Alder |
| ASTR | *Asimina triloba* | Pawpaw |
| ACNE | *Acer negundo* | Boxelder |
| ACRU | *Acer rubrum* | Red Maple |
| ACSA | *Acer saccharinum* | Silver Maple |
| ARSP | *Aralia spinosa* | Hercules Club |
| BENI | *Betula nigra* | River Birch |
| CACA | *Carpinus caroliniana* | Ironwood |
| CACO | *Carya cordiformis* | Bitternut |
| CELA | *Celtis laevigata* | Sugarberry |
| CEPO | *Cephalanthus occidentalis* | Buttonbush |
| COAM | *Cornus amomum* | Red Willow |
| CRSP | *Crataegus spp.* | Hawthorn |
| FOAC | *Forestiera acuminata* | Swamp Forestiera |
| FRPE | *Fraxinus pennsylvanica* | Green Ash |
| GLTR | *Gleditsia triacanthos* | Honey Locust |
| JUNI | *Juglans nigra* | Black Walnut |
| LIST | *Liquidambar styraciflua* | Sweetgum |
| MAPO | *Maclura pomifera* | Osage Orange |
| NYAQ | *Nyssa aquatica* | Water Tupelo |
| PLOC | *Platanus occidentalis* | Sycamore |
| PODE | *Populus deltoides* | Cottonwood |
| PRSE | *Prunus serotina* | Black Cherry |
| QUBI | *Quercus bicolor* | Swamp Red Oak |
| QUFP | *Quercus falcata* Var. *pagodaefolia* | Cherrybark Oak |
| QULY | *Quercus lyrata* | Overcup Oak |
| QUNI | *Quercus nigra* | Water Oak |
| QUPH | *Quercus phellos* | Willow Oak |
| QURU | *Quercus rubra* | Red Oak |
| RHGL | *Rhus glabra* | Staghorn Sumac |
| ROPS | *Robinia pseudoacacia* | Black Locust |
| SACA | *Sambucus canadensis* | Elderberry |
| SANI | *Salix nigra* | Black Willow |
| TADI | *Taxodium distichum* | Bald Cypress |
| TIHE | *Tilia heterophylla* | Basswood |
| ULAL | *Ulmus alata* | Winged Elm |
| ULAM | *Ulmus americana* | American Elm |
| ULRU | *Ulmus rubra* | Slippery Elm |

Several sites had woody vegetation that did not germinate in place; this includes sites where top-bank plants have been carried to mid-bank locations on slump blocks. Slumped vegetation is not included in species-presence analyses. Sites without in situ woody plants indicate substantial bank instability (Hupp and Simon, 1986). Species presence by site are listed in table 30. Eighty sites are included in species-presence analyses. The most common species on disturbed West Tennessee streams is river birch (*Betula nigra*), occurring in 75 percent of the study sites. Also important in re-establishment are black willow (*Salix nigra*, 68 percent), silver maple (*Acer saccharinum*, 55 percent), sycamore (*Platanus occidentalis*, 55 percent), boxelder (*Acer negundo*, 54 percent), cottonwood (*Populus deltoides*, 29 percent), and green ash (*Fraxinus pennsylvanica*, 26 percent). Common bank species along unmodified reaches include river birch, sycamore, silver maple, green ash, and boxelder mixed with ironwood (*Carpinus caroliniana*, 25 percent), sweetgum (*Liquadambar styraciflua*, 20 percent), overcup oak (*Quercus lyrata*, 14 percent), cherrybark oak (*Quercus falcata* var. *pagodaefolia*, 10 percent), water oak (*Quercus nigra*, 10 percent), and American elm (*Ulmus americana*, 8 percent). Bald cypress (*Taxodium distichum*, 13 percent) and tupelo gum (*Nyssa aquatica*, 10 percent), are common bank species in backwater swampy reaches. Black willow is conspicuously unimportant along undisturbed reaches with no mature forest while other species such as river birch and silver maple that are found along disturbed reaches, are relatively common along most West Tennessee stream reaches. The Hatchie River is used as an ecological measure of the undisturbed natural system (table 30); all sites along this stream are in stage I of the channel evolution model.

To test vegetative recovery through species response and establishment, dendrogeomorphic and species-presence data were compared. This analysis provides information concerning riparian environments that support specific species or suites of species. The 80 sites categorized by stage of bank-slope development and site variables (widening rate, accretion rate, percent vegetative cover; fig. 46) provide a set of dependent variables that is used in the following statistical analyses of species-presence data. Widening rates (total widening in ft/yr), accretion rates (mean rate of accretion in in/yr), and percent woody vegetative cover (mean percent cover) were each separated into 5 categories, for ease of statistical operations. The categories for the site variables are listed in table 23. All sites listed in table 30 were used in parts of the categorization. Because of missing data points, however, two sites were omitted in the widening categorization, four sites in the accretion categorization, and two sites in the vegetative cover categorization. The five categories for each of the main variables (widening rate, accretion rate, and percent vegetative cover; table 23) were chosen to avoid wide ranges in the number of possible sites per category, which tends to bias subsequent statistical operations performed on the contingency tables. The descriptor terms of each category lead to a proper interpretation of widening and accretion rates, however, the wide range of cover values may make the descriptors somewhat misleading. For example, medium cover would indicate a substantial amount of bank cover, but a value of only 26 percent would fall into this category. Likewise, a value of 51 percent, slightly better than half, falls into the high-cover category.

# Table 30.--*Summary of woody species present at selected stream sites*

[ALSE *Alnus serrulata*
ASTR *Asimina triloba*
ACNE *Acer negundo*
ACRU *Acer rubrum*
ACSA *Acer saccharinum*
ARSP *Aralia spinosa*
BENI *Betula nigra*
CACA *Carpinus caroliniana*
CACO *Carya cordiformis*
CELA *Celtis laevigata*
CEPO *Cephalanthus occidentalis*
COAM *Cornus amomum*
CRSP *Crataegus spp.*
FOAC *Forestiera acuminata*
FRPE *Fraxinus pennsylvanica*
GLTR *Gleditsia triacanthos*
JUNI *Juglans nigra*
LIST *Liquidambar styraciflua*
MAPO *Maclura pomifera*
NYAQ *Nyssa aquatica*
PLOC *Platanus occidentalis*
PODE *Populus deltoides*
PRSE *Prunus serotina*
QUBI *Quercus bicolor*
QUFP *Quercus falcata* Var. *pagodaefolia*
QULY *Quercus lyrata*
QUNI *Quercus nigra*
QUPH *Quercus phellos*
QURU *Quercus rubra*
RHGL *Rhus glabra*
ROPS *Robinia pseudoacacia*
SACA *Sambucus canadensis*
SANI *Salix nigra*
TADI *Taxodium distichum*
TIHE *Tilia heterophylla*
ULAL *Ulmus alata*
ULAM *Ulmus americana*
ULRU *Ulmus rubra*]

| Stream | Bank evolution stage | Station number | River mile | Number of species | Species code |
|---|---|---|---|---|---|
| North Fork Obion River | IV | 07025600 | 5.9 | 0 | |
| | V | 07025500 | 10.0 | 0 | |
| | IV | 07025400 | 18.0 | 6 | ACNE BENI CEPO FRPE SANI ULRU |
| | IV | 07025375 | 21.1 | 2 | BENI FRPE |
| | III | 07025340 | 26.4 | 10 | ACNE BENI CACA FRPE LIST PLOC QUPH TIHE ULRU |
| | VI | 07025320 | 34.9 | 6 | ACNE ACRU BENI CACO LIST PLOC |
| South Fork Obion River | V | 07024800 | 5.8 | 8 | ACNE ACSA BENI PLOC QUPH SACA SANI ULRU |
| | V | 07024550 | 11.4 | 3 | ACSA BENI SANI |
| | IV | 07024525 | 16.8 | 0 | |
| | IV | 07024500 | 19.2 | 3 | BENI SANI |
| | IV | 07024460 | 23.2 | 2 | BENI SANI |
| | VI | 07024430 | 28.5 | 10 | ACSA BENI JUNI NYAQ PLOC PODE QURU SANI TADI TIHE |
| | VI | 07024350 | 33.8 | 3 | BENI SANI TADI |
| Rutherford Fork Obion River | V | 07025100 | 4.9 | 5 | ACNE BENI SACA SANI |
| | V | 07025050 | 10.4 | 2 | BENI SANI |
| | IV | 07025025 | 15.2 | 3 | BENI RHGL SANI |
| | IV | 07025020 | 17.1 | 1 | BENI |
| | IV | 07025000 | 17.9 | 7 | ACNE ACSA BENI CRSP PLOC RHGL SANI |
| | IV | 07025001 | 24.5 | 3 | ACNE ACSA BENI |
| | VI | 07024900 | 29.9 | 6 | ACNE ACRU BENI CACA PLOC ULAM |
| | VI | 07024888 | 39.4 | 5 | BENI ACNE LIST PLOC ULAM |
| | VI | 07024880 | 43.3 | 7 | ALSE ACRU BENI CACA NYAQ PLOC ULAM |
| Obion River | V | 07027200 | 20.8 | 3 | ACSA PODE SANI |
| | II | 07027180 | 25.6 | 2 | PODE SANI |
| | V | 07026300 | 34.2 | 3 | ASTR PODE SANI |
| | V | 07026250 | 42.4 | 3 | ACSA PODE SANI |
| | V | 07026000 | 53.7 | 3 | ACNE ACSA SANI |
| | V | 07025900 | 62.2 | 5 | ACSA FRPE PLOC PODE SANI |
| | V | 07024800 | 68.5 | 8 | ACNE ACSA BENI PLOC QUPH SACA SANI ULRU |
| Davidson Creek | V | 07025917 | 2.2 | 4 | ACNE PODE SACA SANI |
| | IV | 07025913 | 5.8 | 3 | ACNE PODE SANI |
| | IV | 07025909 | 7.5 | 2 | ACNE SANI |
| | III | 07025905 | 9.0 | 9 | ACNE ACRU ACSA CELA FRPE MAPO PODE RHGL SANI |
| North Fork Forked Deer River | VI | 07029105 | 3.8 | 4 | ACSA BENI PODE SANI |
| | V | 07029100 | 5.1 | 3 | ACSA PLOC SANI |
| | IV | 07029040 | 13.6 | 2 | ACSA BENI |
| | V | 07028840 | 18.8 | 3 | ACSA BENI SANI |
| | IV | 07028835 | 20.2 | 0 | |
| | IV | 07028820 | 23.9 | 0 | |
| | I | 07028500 | 34.6 | 6 | ALSE ACNE ACRU BENI FRPE ULRU |
| | I | 07028410 | 41.6 | 5 | ACNE ACSA BENI PLOC SANI |
| South Fork Forked Deer River | V | 07028200 | 3.3 | 3 | ACSA BENI SANI |
| | IV | 07028150 | 5.6 | 6 | ACNE ACSA BENI PLOC SANI ULRU |
| | IV | 07028100 | 7.9 | 0 | |
| | IV | 07028050 | 11.9 | 0 | |
| | IV | 07028000 | 13.3 | 1 | ACSA |
| | IV | 07027800 | 16.3 | 0 | |
| | IV | 07027720 | 27.6 | 0 | |
| | III | 07027680 | 33.7 | 8 | ACSA CACA FRPE JUNI LIST PLOC ULAM |

Table 30.--*Summary of woody species present at selected stream sites*--Continued

| Stream | Bank evo-lution stage | Station number | River mile | Number of species | Species code |
|---|---|---|---|---|---|
| Pond Creek | IV | 07029080 | 1.1 | 2 | ACSA SANI |
| | IV | 07029075 | 3.1 | 1 | SANI |
| | IV | 07029070 | 7.3 | 1 | SANI |
| | IV | 07029060 | 11.4 | | SANI |
| Hatchie River | I | 07030025 | 49.5 | 13 | ACSA BENI CACA CACO CELA FOAC LIST PLOC QULY TADI ULAM QUFP QUBI |
| | I | 07030000 | 68.4 | 13 | ACSA BENI CACA CACO CELA FOAC QUPH PLOC QULY TADI ULAM QUFP QUBI |
| | I | 07029900 | 80.8 | 16 | ACSA BENI CACA CACO FOAC FRPE LIST PLOC PRSE QULY QUNI QUPH ULAM QUFP QUBI |
| | I | 07029650 | 121.1 | 8 | ASTR ACSA BENI CACA PLOC QULY QUNI QUFP |
| | I | 07029500 | 135.1 | 10 | ACNE ACSA BENI CACA FOAC FRPE LIST PLOC QUPH SANI |
| | I | 07029430 | 162.3 | 12 | ACSA BENI CACA FRPE LIST NYAQ PLOC QULY QUNI TADI ULAM QUFP |
| | I | 07029400 | 181.8 | 5 | ACSA BENI FRPE PLOC ULAM |
| Porter Creek | V | 07029445 | 1.5 | 9 | ALSE ACNE ACRU BENI LIST SACA SANI |
| | V | 07029440 | 8.8 | 9 | ALSE ACNE ACRU BENI LIST PLOC SACA SANI |
| | IV | 07029439 | 11.2 | 8 | ALSE ACNE BENI LIST PLOC PODE SANI |
| | VI | 07029438 | 13.9 | 6 | ALSE ACNE BENI FRPE PLOC SANI |
| | IV | 07029437 | 17.1 | 6 | ALSE ACRU BENI PLOC PODE SANI |
| Cub Creek | VI | 07029450 | 1.5 | 12 | ALSE ACNE BENI CACA COAM FRPE LIST PLOC PODE RHGL SANI |
| | VI | 07029449 | 2.2 | 6 | ALSE ACNE BENI CACA PODE SANI |
| | V | 07029448 | 5.7 | 5 | ALSE BENI CACA SANI ULAL |
| | IV | 07029447 | 6.9 | 6 | ALSE ACRU BENI ULAL ARSP |
| Cane Creek | IV | 4 | 3.6 | 8 | ACNE ACSA FOAC FRPE RHGL PLOC PODE SANI |
| | IV | 8 | 7.1 | 8 | ACNE ACSA FRPE PLOC PODE PRSE RHGL SANI |
| | IV | 12 | 10.2 | 5 | ACNE FRPE PLOC PODE SANI |
| | IV | 16 | 12.6 | 9 | ACNE ACSA FRPE GLTR MAPO PODE RHGL ROPS SANI |
| Wolf River | IV | 07031700 | 9.1 | 13 | ACNE ACSA BENI CELA FRPE GLTR PLOC PODE QULY ROPS SANI ULAL QUFP |
| | IV | 07031650 | 18.9 | 8 | ACNE ACSA BENI FOAC GLTR PLOC SANI ULAL |
| | IV | 07030610 | 23.6 | 6 | ACNE ACSA BENI PLOC SACA SANI |
| | I | 07030600 | 31.2 | 8 | ACNE ACRU ACSA BENI CACA PLOC SANI ULAM |
| | I | 07030500 | 44.4 | 6 | ACNE ACSA BENI PLOC SACA SANI |
| | I | 07030395 | 57.5 | 13 | ACNE ACRU BENI FRPE NYAQ PLOC PODE QULY QUNI QUPH SACA SANI TADI |
| | I | 07030392 | 69.9 | 9 | ACNE BENI CACA NYAQ QULY QUNI SACA TADI ULAM |

Standardized residuals as computed from contingency tables show species associations; positive and negative, for each of the 15 site categories. Positive associations are those with positive residual values, whereas negative associations are those with negative residual values. These values reflect species "preference" and "avoidance" patterns for the categorized site variables. Residual values between +1 and -1 are not considered particularly meaningful. A complete listing of all standardized residuals for 38 riparian species is given in table 31. Residual values for 12 selected species are graphically displayed in figure 55.

Black willow and river birch, the two most commonly occurring riparian species along disturbed reaches, tolerate moderate amounts of widening and accretion (fig. 55). Black willow in particular tolerates high accretion rates and is one of the few common species that does not have a positive association for very high cover (fig. 55). This suggests an important role in the initial stabilization of banks. However, after substantial cover occurs on the bank, closing canopies limit the continued dominance of black willow, due to its high light requirement (U.S. Department of Agriculture, 1965). River birch, a common pioneer, remains an important species after canopy closure (high and very high cover percentage, fig. 55) and is part of the suite of species along unmodified West Tennessee streams (Hatchie River; table 30).

Green ash and cottonwood are present in the early-to-middle stages of bank recovery. Both tolerate medium- or high-widening rates (fig. 55). Green ash is a shade-tolerant species (U.S. Department of Agriculture, 1965) with many of the same residual-value patterns of the "natural" species such as bald cypress and overcup oak (fig. 55). Cottonwood occurs in a wide range of environmental conditions, including sites with high-accretion rates like its relative, black willow (fig. 55). Cottonwood has no residual values with an absolute value much greater than 2; this suggests that its use as an indicator species is limited, with the possible exception of bank accretion.

Bald cypress and overcup oak characterize undisturbed banks or levees Hatchie River; table 30). Their residual-value patterns are strikingly similar (fig. 55). Water oak and American elm (fig. 55) are also "natural" bank or bottomland species. Note the rather striking associations (fig. 55) with only very high cover, very low widening, and low to medium accretion, with negative associations for all other site categories. This suggests rather "rigid" adaptations for stable sites, as opposed to the "elastic" adaptation pattern (large ecological amplitude) that appears to be characteristic of early- and mid-recovery species (pioneers). Thus the presence of these undisturbed site species indicate re-stabilized conditions associated with late stage V or VI. The dominant presence of species like black willow and river birch suggests previous channel-bank instability, mass wasting, and subsequent high-accretion rates associated with early- and mid-stage V. Absence or near absence of in situ woody plants indicates the general condition of bank instability associated with stage IV.

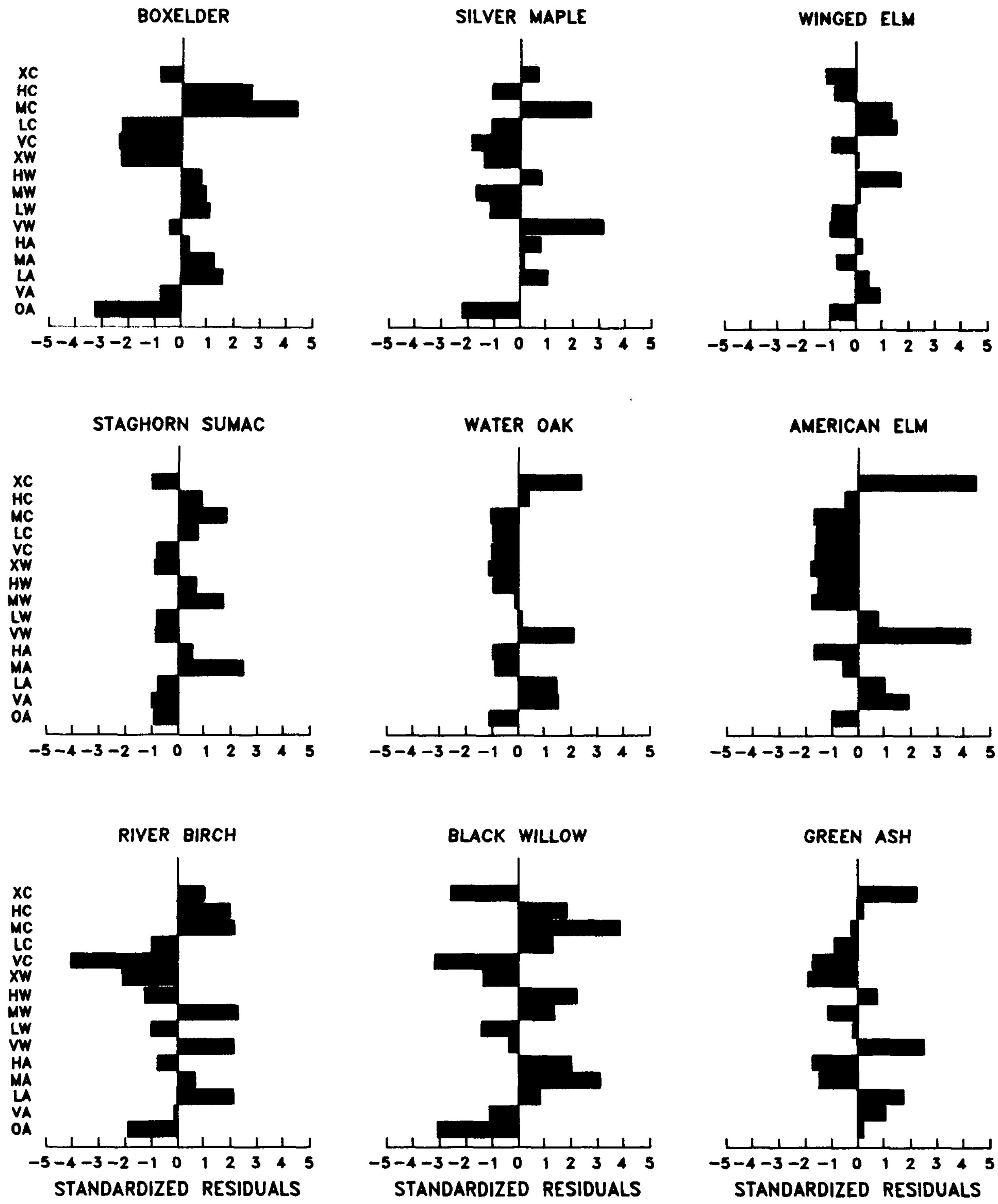
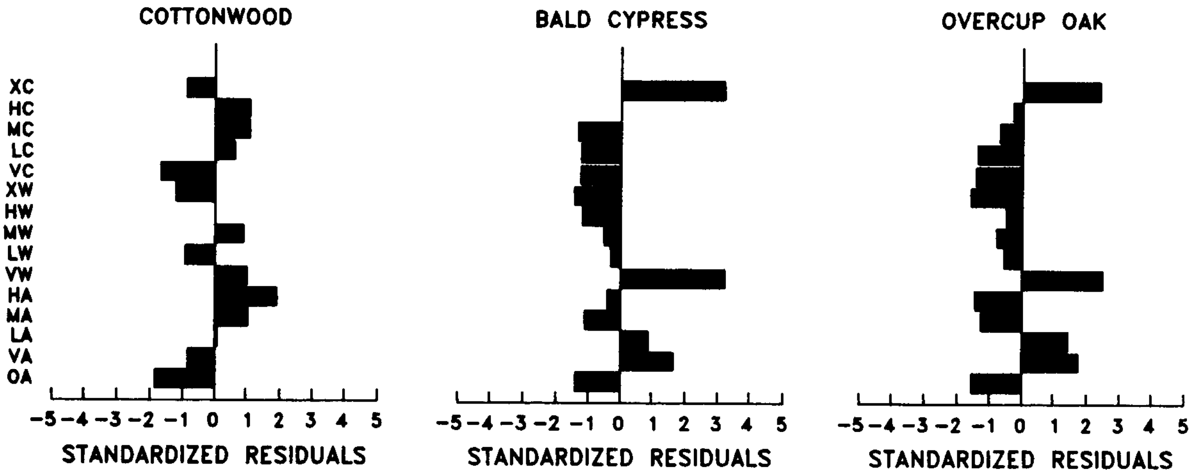



Figure 55.—Standardized residuals for each site-variable category showing site "preferences" for 12 selected riparian plants.




EXPLANATION

| | |
|---|---|
| XC | VERY HIGH COVER |
| HC | HIGH COVER |
| MC | MEDIUM COVER |
| LC | LOW COVER |
| VC | VERY LOW COVER |
| XW | VERY HIGH WIDENING |
| HW | HIGH WIDENING |
| MW | MEDIUM WIDENING |
| LW | LOW WIDENING |
| VW | VERY LOW WIDENING |
| HA | HIGH ACCRETION |
| MA | MEDIUM ACCRETION |
| LA | LOW ACCRETION |
| VA | VERY LOW ACCRETION |
| OA | ZERO ACCRETION |

Figure 55.--Standardized residuals for each site-variable category showing site "preferences" for 12 selected riparian plants--Continued.

Table 31.--*Standardized residuals for species association of 38 woody riparian species by bank condition and vegetation cover*
[Quantitative definitions of widening, accretion, and cover are provided in table 23]

| Species | | Percent[2] | Standardized residuals[1] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Bank widening | | | | | Bank accretion | | | | | Vegetation cover | | | | |
| Code | Name | occurrence | Very low | Low | Medium | High | Very high | Zero | Very low | Low | Medium | High | Very low | Low | Medium | High | Very high |
| BENI | Betula nigra | 62.50 | 2.14 | -1.00 | 2.28 | -1.25 | -2.15 | -1.89 | -0.06 | 2.14 | 0.72 | -0.76 | -4.07 | -1.00 | 2.14 | 1.99 | 1.04 |
| SANI | *Salix nigra* | 53.88 | -0.32 | -1.41 | 1.44 | 2.29 | -1.33 | -3.11 | -1.06 | 0.91 | 3.14 | 2.10 | -3.26 | 1.36 | 3.84 | 1.90 | -2.63 |
| ACSA | *Acer saccharinum* | 42.67 | 3.23 | -1.10 | -1.66 | 0.84 | -1.33 | -2.17 | 0.02 | 1.13 | 0.19 | 0.86 | -1.84 | -1.10 | 2.71 | -1.06 | 0.73 |
| PLOC | *Platanus occidentalis* | 41.38 | 3.36 | 0.12 | -1.04 | 0.36 | -2.71 | -1.55 | 0.14 | 1.22 | 1.54 | -0.65 | -3.36 | -3.24 | 1.78 | 2.79 | 1.77 |
| ACNE | *Acer negundo* | 36.64 | -0.46 | 1.07 | 0.93 | 0.73 | -2.34 | -3.26 | -0.80 | 1.60 | 1.26 | 0.28 | -2.49 | -2.36 | 4.38 | 2.55 | -0.96 |
| CACA | *Carpinus caroliniana* | 19.40 | 3.21 | 0.90 | -0.83 | -1.82 | -1.55 | -0.83 | 1.11 | 1.25 | -0.89 | -0.61 | -1.96 | -1.20 | -0.72 | -0.10 | 3.25 |
| LIST | *Liquidambar styraciflua* | 16.81 | 3.68 | -1.00 | 0.77 | -1.67 | -1.99 | 0.10 | 0.29 | 0.78 | -0.70 | -0.37 | -1.80 | -1.74 | -0.48 | 0.95 | 2.58 |
| ALSE | *Alnus serrulata* | 15.95 | 0.32 | 0.58 | 2.26 | -1.26 | -1.92 | -1.87 | 0.41 | 0.07 | 1.05 | 0.44 | -1.74 | 1.33 | -0.39 | 2.74 | -1.54 |
| FRPE | *Fraxinus pennsylvanica* | 15.52 | 2.52 | -0.13 | -1.14 | 0.77 | -1.89 | 0.25 | 1.10 | 1.75 | -1.46 | -1.72 | -1.72 | -0.89 | -0.24 | 0.25 | 2.22 |
| PODE | *Populus deltoides* | 15.52 | 1.09 | -0.89 | 0.95 | -0.01 | -1.22 | -1.84 | -0.80 | 0.11 | 1.10 | 1.97 | -1.72 | 0.63 | 1.09 | 1.10 | -0.88 |
| ULAM | *Ulmus americana* | 14.22 | 4.25 | 0.80 | -1.74 | -1.51 | -1.80 | -1.02 | 1.97 | 1.10 | -0.50 | -1.63 | -1.63 | -1.57 | -1.69 | -0.50 | 4.41 |
| ACRU | *Acer rubrum* | 12.93 | 0.72 | 0.16 | 1.35 | -1.43 | -0.97 | -0.90 | 0.88 | -0.49 | 1.45 | -0.75 | -1.54 | 0.16 | -0.83 | 4.21 | -1.23 |
| QULY | *Quercus lyrata* | 11.64 | 2.54 | -0.54 | -0.77 | -0.46 | -1.60 | -1.55 | 1.82 | 1.48 | -1.23 | -1.45 | -1.45 | -1.40 | -0.70 | -0.27 | 2.40 |
| SACA | *Sambucus canadensis* | 11.64 | -0.70 | 0.32 | 2.37 | -0.46 | -1.60 | -1.55 | -0.32 | 0.56 | 2.62 | -0.62 | -1.45 | -1.40 | 2.54 | 1.66 | -1.09 |
| TADI | *Taxodium distichum* | 9.05 | 3.21 | -0.26 | -0.47 | -1.17 | -1.39 | -1.35 | 1.67 | 0.94 | -1.07 | -0.33 | -1.26 | -1.22 | -1.31 | -0.01 | 3.13 |
| NYAQ | *Nyssa aquatica* | 7.76 | 1.70 | 0.94 | -0.30 | -1.08 | -1.28 | -1.24 | 1.17 | 1.18 | -0.99 | -0.16 | -1.16 | -1.12 | -1.20 | 1.32 | 1.92 |
| QUFP | *Quercus falcata* Var. *pagodaefolia* | 7.76 | 3.64 | -1.12 | -1.24 | -0.01 | -1.28 | -1.24 | 2.03 | 1.18 | -0.99 | -1.16 | -1.16 | -1.12 | -0.23 | -0.99 | 2.76 |
| ULRU | *Ulmus rubra* | 7.76 | -0.23 | -0.09 | -1.24 | 2.12 | -0.36 | 0.64 | -0.54 | 2.29 | -0.99 | -1.16 | -1.16 | -0.09 | 2.67 | -0.99 | -0.59 |
| FOAC | *Forestiera acuminata* | 6.47 | 3.12 | -1.01 | -1.13 | 0.19 | -1.16 | -1.13 | 1.53 | 0.27 | -0.89 | 0.03 | -1.05 | -1.01 | -0.04 | -0.89 | 2.35 |
| QUNI | *Quercus nigra* | 6.47 | 2.07 | 0.11 | -0.10 | -0.98 | -1.16 | -1.13 | 1.53 | 1.48 | -0.89 | -1.05 | -1.05 | -1.01 | -1.09 | 0.36 | 2.35 |
| QUPH | *Quercus phellos* | 6.47 | -0.04 | 0.11 | -0.10 | 1.35 | -1.16 | -0.10 | 0.60 | 1.48 | -0.89 | -1.05 | -1.05 | -1.01 | 1.02 | 0.36 | 0.53 |
| CACO | *Carya cordiformis* | 5.17 | 2.54 | -0.90 | 0.14 | -0.87 | -1.03 | 0.14 | 0.94 | 0.51 | -0.79 | -0.94 | -0.94 | -0.90 | -0.97 | 0.60 | 1.88 |
| ULAL | *Ulmus alata* | 5.17 | -0.97 | -0.90 | 0.14 | 1.71 | 0.08 | -1.00 | 0.94 | 0.51 | -0.79 | 0.27 | -0.94 | 1.59 | 1.37 | -0.79 | -1.15 |
| CELA | *Celtis laevigata* | 3.88 | 1.85 | -0.78 | -0.86 | 0.73 | -0.89 | -0.86 | 2.59 | -0.71 | -0.68 | -0.80 | -0.80 | -0.78 | 0.58 | -0.68 | 1.33 |
| QUBI | *Quercus bicolor* | 3.88 | 3.19 | -0.78 | -0.86 | -0.75 | -0.89 | -0.86 | 1.40 | 0.82 | -0.68 | -0.80 | -0.80 | -0.78 | -0.83 | -0.68 | 2.49 |
| RHGL | *Rhus glabra* | 3.88 | -0.83 | -0.78 | 1.75 | 0.73 | -0.89 | -0.86 | -0.97 | -0.71 | 2.52 | 0.58 | -0.80 | 0.78 | 1.85 | 0.92 | -0.99 |
| GLTR | *Gleditsia triacanthos* | 2.59 | -0.68 | -0.63 | -0.70 | 2.99 | -0.72 | -0.70 | 0.66 | -0.58 | -0.55 | 1.03 | -0.65 | -0.63 | 2.59 | -0.55 | -0.80 |
| JUNI | *Juglans nigra* | 2.59 | 2.59 | -0.63 | -0.70 | -0.60 | -0.72 | 0.89 | -0.78 | -0.58 | -0.55 | 1.03 | -0.65 | -0.63 | -0.68 | -0.55 | 2.02 |
| MAPO | *Maclura pomifera* | 2.59 | 0.96 | -0.63 | 0.89 | -0.60 | -0.72 | -0.70 | -0.78 | -0.58 | -0.55 | 2.71 | -0.65 | -0.63 | 0.96 | -0.55 | 0.61 |
| QURU | *Quercus rubra* | 2.59 | 0.96 | 1.11 | -0.70 | -0.60 | -0.72 | 2.48 | -0.70 | -0.58 | -0.55 | -0.65 | -0.65 | -0.63 | -0.68 | -0.55 | 2.02 |
| TIHE | *Tilia heterophylla* | 2.59 | 0.96 | 1.11 | -0.70 | -0.60 | -0.72 | 0.89 | -0.78 | -0.58 | 1.39 | -0.65 | -0.65 | -0.63 | -0.68 | -0.55 | 2.02 |
| ARSP | *Aralia spinosa* | 1.29 | -0.47 | -0.44 | 1.74 | -0.42 | -0.51 | -0.49 | 1.48 | -0.41 | -0.39 | -0.46 | -0.46 | 2.00 | -0.47 | -0.39 | -0.56 |
| ASTR | *Asimina triloba* | 1.29 | 1.82 | -0.44 | -0.49 | -0.42 | -0.51 | -0.49 | 1.48 | -0.41 | -0.39 | -0.46 | -0.46 | -0.44 | -0.47 | -0.39 | 1.42 |
| CEPO | *Cephalanthus occidentalis* | 1.29 | -0.47 | -0.44 | -0.49 | 2.10 | -0.51 | -0.49 | -0.55 | 2.22 | -0.39 | -0.46 | -0.46 | -0.44 | 1.82 | -0.39 | -0.56 |
| COAM | *Cornus amomum* | 1.29 | -0.47 | -0.44 | 1.74 | -0.42 | -0.51 | -0.49 | -0.55 | -0.41 | -0.39 | 1.90 | -0.46 | -0.44 | -0.47 | 2.35 | -0.56 |
| CRSP | *Crataegus spp.* | 1.29 | -0.47 | -0.44 | -0.49 | 2.10 | -0.51 | -0.49 | -0.55 | -0.41 | 2.35 | -0.46 | -0.46 | -0.44 | 1.82 | -0.39 | -0.56 |
| PRSE | *Prunus serotina* | 1.29 | 1.82 | -0.44 | -0.49 | -0.42 | -0.51 | -0.49 | -0.55 | 2.22 | -0.39 | -0.46 | -0.46 | -0.44 | -0.47 | -0.39 | 1.48 |
| ROPS | *Robinia pseudoacacia* | 1.29 | -0.47 | -0.44 | -0.49 | 2.10 | -0.51 | -0.49 | 1.48 | -0.41 | -0.39 | -0.46 | -0.46 | -0.44 | 1.90 | -0.39 | -0.56 |

[1]Positive values denote preference patterns; negative values denote avoidance patterns; and values between +1 and -1 are insignificant.

[2]Percentage of sites at which the indicated plant is present.

Winged elm (*Ulmus alata*) and staghorn sumac (*Rhus glabra*) are often found along reaches that have previously experienced severe degradation. These two species are not normally considered to be riparian plants and are mentioned here to illustrate how banks, now so high that their upper portions are above most fluvial activity can support upland species (fig. 55). Their low vegetative cover "preferences" and tolerance to substantial widening make these plants good indicators of bank-disturbance conditions that resemble upland mass-wasting conditions.

Silver maple (*Acer saccarhinum*) and boxelder (*Acer negundo*) are common along recovering reaches. Although these species are present in stable riparian forests, many banks in the later stages of recovery may support these two species singularly or in tandem to the near exclusion of other species. Boxelder and silver maple site-variable patterns (fig. 55) typify species characteristic of middle- to late-bank recovery.

## Species Distribution--Six-Stage Model

Data on species presence and site characteristics can be placed within the framework of the bank-slope-development model (Simon and Hupp, 1986a; Simon, 1989). The remainder of this discussion on species presence will be presented in relation to this six-stage bank-slope-development model (table 4, and, figure 30).

Species cover during stage I is always at or near 100 percent and the greatest number of species occurs here and along stage III reaches, which are vegetatively similar. Fourteen sites (table 30) were identified as stage I, principally along the Hatchie River and the upstream sites of the Wolf River. Stage I streams, in general, represent the "natural" geomorphic and botanical condition in West Tennessee. Stage II reaches are the constructed stage that have been recently straightened, dredged, and cleared of all woody-riparian vegetation. This stage is extremely short-lived; degradation or aggradation, depending on location in system, begins almost immediately.

Three sites are determined to be in stage III (table 30), although it undoubtedly exists in more areas not covered in our sampling scheme. Vegetatively, this stage resembles stage I areas, but geomorphically this stage is quite distinct. The banks are steeper and the channel bed has degraded considerably. This typically leaves mature riparian trees that were previously rooted at or below the low-water elevation, at mid-bank elevations now high and dry (fig. 56). Commonly a few trees have toppled into the channel. Imminent bank widening is apparent from the over-heightened and steepened banks and from the exposed and inclined old-tree bases and root systems. Vegetative-cover values drop dramatically as soon as mass wasting begins during stage IV.

Figure 56.--Upstream view of Davidson Creek near U.S. Highway 51; site is a typical reach during degradation stage (stage III).

Stage IV, the threshold stage, was investigated at 36 sites listed in table 30. The near absence of in situ vegetative cover is among the most striking characteristics of this stage. Vegetative cover values of approximately 20 percent represent maxima for this stage, and these values occur only in protected areas (typically on inside bends). Mean vegetative cover for this stage is just under 10 percent; 22 percent of the sites in stage IV are devoid of in situ woody plants. However, herbaceous species such as giant knotweed, cocklebur, and various grasses may form dense stands on these banks during the summer months. Such stands give the bank a falsely stable appearance. Reaches in late stage IV may support some of the early pioneer species in protected low-bank areas. The plants found here tolerate moderate amounts of bank instabilities and are present in low numbers. These numbers increase as widening subsides and low-bank areas of the reach move into stage V.

Stage V is the initial recovery stage. Eighteen sites were identified as stage V sites. This stage is characterized by relatively high accretion rates on the low- to mid-bank surfaces and relatively active widening on the vertical faces and upper bank. Mean vegetative cover for this stage is about

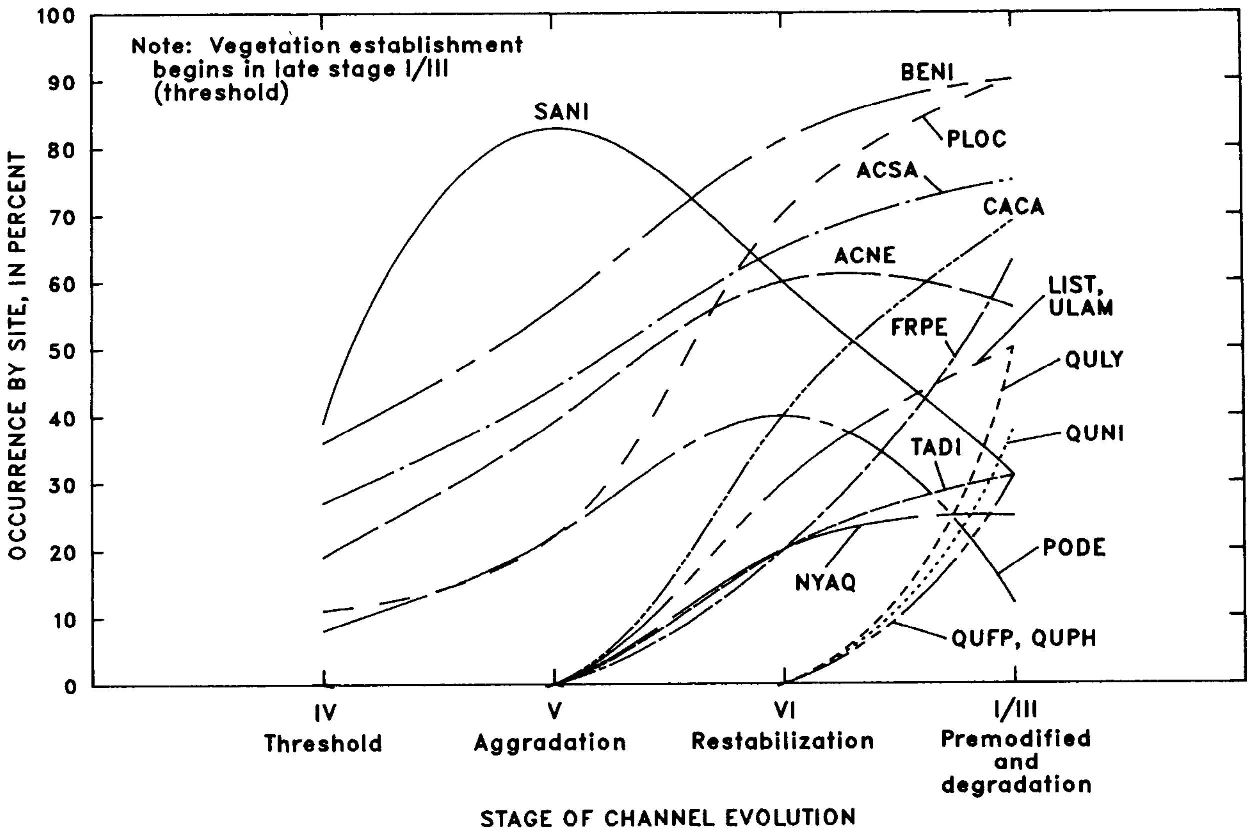
30 percent, and 6 percent of the sites lack in situ woody vegetation. There usually is less herbaceous vegetation here than in stage IV, owing to the high accretion rates and woody cover that may cause considerable shading. Black willow and river birch occur on more than 50 percent of these sites. Species richness increases in stage V. Mid-recovery species such as sycamore, green ash, cottonwood, and silver maple frequently invade areas adjacent to and upslope of the commonly dense thickets of black willow or river birch. All of these species tolerate relatively high accretion rates (fig. 55).

Stage VI reaches are largely recovered reaches with a meandering low-flow channel, relatively low banks, and tree-size vegetation occurring across the entire bank section down and into the low-flow channel. Ten sites were identified as stage VI; these are typically the most upstream sites and are the result of channel work at the turn of the century or in the 1940's. Species typical of stage I/III reaches begin to establish in stage VI including American elm (*Ulmus americana*), ironwood (*Carpinus caroliniana*), sweet gum (*Liquadambar styraciflua*), bald cypress (*Taxodium distichum*), and tupelo (*Nyssa aquatica*). Bottomland-oak species may be present on old levee surfaces, or areas of slightly higher elevations. Vegetative-cover values are at or near 100 percent at all sites. Outside bends suffer only from fluvial cutting, while inside bends are sites of point-bar development and subsequent vegetation establishment. Hydrologically, stage VI reaches can again have a prolonged hydroperiod (annual period of inundation) on the flood plains. The hydroperiod is often absent from this location along degraded reaches that are still recovering (stages III-V) because of increased channel capacity. The vegetation on stage VI reaches is not as mature or diverse as stage I. However, in all other aspects (vegetative, geomorphic, and hydrologic), stage VI reaches are basically recovered from channelization.

### *Vegetation Recovery and Life History*

Patterns of vegetative recovery after channelization can be estimated, when considered in terms of the six-stage model. Vegetation-recovery patterns for 16 species are shown in figure 57 (table 29). Stage II has been omitted from figure 57 because all vegetation typically is removed. Stages I and III, being vegetatively similar, are placed at the end of the stage scale (fig. 57) as, given enough time, stage VI reaches will closely approach stage I reaches. If subsequent downstream channel work takes place, the degradation and recovery processes will begin again.

The initial species to colonize channelization-affected reaches are willow, river birch, silver maple, box elder, sycamore, and cottonwood (stage IV, fig. 57). Asexual reproduction by runners or cuttings is common in most of these species. In addition, these species grow rapidly and produce abundant seeds that are short-lived. Dispersal in these species is by wind, water, or both, and all disseminate their seeds in middle to late spring (Fowells, 1965; Harlow and Harrer, 1969). The timing of seed dispersal coincides with the typical decrease in water levels in late spring. Thus, seeds from these trees may be deposited on fresh bank substrates created by mass wasting, bank accretion, fluvial reworking,




## EXPLANATION

### SPECIES CODE AND SCIENTIFIC NAME

| | |
|---|---|
| ACNE | ACER NEGUNDO |
| ACSA | ACER SACCHARINUM |
| BENI | BETULA NIGRA |
| CACA | CARPINUS CAROLINIANA |
| FRPE | FRAXINUS PENNSYLVANICA |
| LIST | LIQUIDAMBAR STYRACIFLUA |
| NYAQ | NYSSA AQUATICA |
| PLOC | PLATANUS OCCIDENTALIS |
| PODE | POPULUS DELTOIDES |
| QUFP | QUERCUS FALCATA |
| QULY | QUERCUS LYRATA |
| QUPH | QUERCUS PHELLOS |
| SANI | SALIX NIGRA |
| TADI | TAXODIUM DISTICHUM |
| ULAM | ULMUS AMERICANA |

Figure 57.--Vegetation-recovery patterns for 16 species by stage of channel evolution. Percent of occurrence is the total number of sites where species was present relative to the total number of sites in a given stage.

and late-spring exposure. The life-history characteristics of stage IV-V species make them particularly suited for establishment and growth along disturbed channels. If sites are relatively stable and accretion is not excessive, the successful establishment of these species is probable.

Variations in species patterns among stage IV-V sites may result from variations in the timing of water-elevation recession, rafting of viable seeds during high water, and the variability of seed release mechanisms among the individual species. The most successful pioneer species, black willow and river birch, are particularly tolerant of high accretion rates and shallow secondary sliding of accreted material, through layering and stem sprouting, respectively. Black willow and cottonwood (a related species) are the two species that reach maximums prior to stage I-III and have a substantial reduction of occurrence by stage I-III (fig. 57). These two species are probably limited by the low-light conditions of the subcanopy in mature "natural" riparian settings. All of the stage IV/V species are relatively short-lived and by stage VI, their dominance is substantially reduced due to sequential replacement by stable-site species (stage VI and I-III, fig. 57).

Stage I/III sites may have river birch present but the site may be a typical cypress-tupelo swamp, whereas an early stage V site may have river birch present to the near exclusion of all other species. Stage VI sites and some late stage V sites experience the gradual reduction of dominance by the "pioneer" species through the establishment of stable-site species (fig. 57). Thus, by stage I/III, two distinct suites of vegetation have become established, in addition to the initial suite in late stage IV (fig. 57). The second suite, which includes ironwood, green ash, sweetgum, American elm, bald cypress, and tupelo, is characteristic of southeastern bottomlands and represents the riparian plant community of relatively mature "natural" sites. All of these species, except sweetgum, are largely confined to bottomlands and have seeds that are dispersed by wind or water (Fowells, 1965). These plants have seeds that live up to 2 years as opposed to pioneer species whose seeds live only a few days to a week.

The last suite of vegetation includes the bottomland oaks, overcup oak, water oak, cherry bark oak (*Q. falcata* var. *pagodaefolia*), and willow oak (*Q. phellos*). Oaks produce heavy short-lived seeds that are normally animal-dispersed. The oaks tend to occur on natural and manmade levees, or on slightly elevated parts of the bottomland.

Thus, each of the three suites of tree species involved in vegetation recovery from channelization, have distinct life-history characteristics. The data suggest a trend from (1) fast-growing, short-lived trees with light, short-lived water- or wind-borne seeds, and a tolerance for bank disturbance and high-light conditions in the late stage IV and stage V part of bank recovery to, (2) long-lived, shade-tolerant trees with very specific growth requirements, long-lived water- or wind-borne seeds, and low tolerance to bank disturbance in stage VI to, (3) heavy-seeded, long-lived oak trees that share the bottomland with stage VI species after nearly complete ecologic and geomorphic recovery.

Perhaps the most important trend evident in figure 57 is the steadily increasing diversity of plants from stage IV to I/III. Species diversity has long been recognized to generally increase with physical site stability. Species-presence data by stage of bank-slope development are listed in table 32.

Table 32.--*Indicator species and percent presence for threshold (stage IV), aggradation (stage V), and restabilization (stage VI) stages*

| Species | Species code | Presence in percent |
|---|---|---|
| Species Tolerant of Bank-widening Disturbances (Late Stage IV Pioneers) | | |
| *Salix nigra* | SANE | 39 |
| *Betula nigra* | BENI | 36 |
| *Acer negundo* | ACNE | 19 |
| *Acer saccharinum* | ACSA | 17 |
| *Platanus occidentalis* | PLOC | 11 |
| *Populus deltoides* | PODE | 8 |
| *Alnus serrulata* | ALSE | 8 |
| ***Unvegetated*** | | 22 |
| Species Tolerant of High Deposition Rates (Stage V Pioneers) | | |
| *Salix nigra* | SANI | 83 |
| *Betula nigra* | BENI | 56 |
| *Acer saccharinum* | ACSA | 44 |
| *Acer negundo* | ACNE | 39 |
| *Sambucus canadensis* | SACA | 33 |
| *Platanus occidentalis* | PLOC | 22 |
| *Populus deltoides* | PODE | 22 |
| *Alnus serrulata* | ALSE | 17 |
| ***Unvegetated*** | | 6 |
| Recovery Species (Stage VI) | | |
| *Acer saccharinum* | ACRE | 65 |
| *Betula nigra* | BENI | 90 |
| *Plantanuss occidentalis* | PLOC | 70 |
| *Acer negundo* | ACNE | 60 |
| *Salix nigra* | SANI | 60 |
| *Alnus serrulata*[1] | ALSE | 50 |
| *Populus Deltoides* | PODE | 40 |
| *Carpinus caroliniana* | CACA | 40 |
| *Acer Rubrum* | ACRU | 30 |
| *Liquidambar styraciflua* | LIST | 30 |
| *Ulmus americana* | ULAM | 30 |
| *Betula Nigra* | BENI | 20 |
| *Nyssa aquatica* | NYAQ | 20 |
| *Taxodium Distichum* | TADI | 20 |
| *Fraxunus pennsylvanica* | FRPE | 20 |
| ***Unvegetated*** | | 0 |

[1]Only on sand/gravel bedded streams.

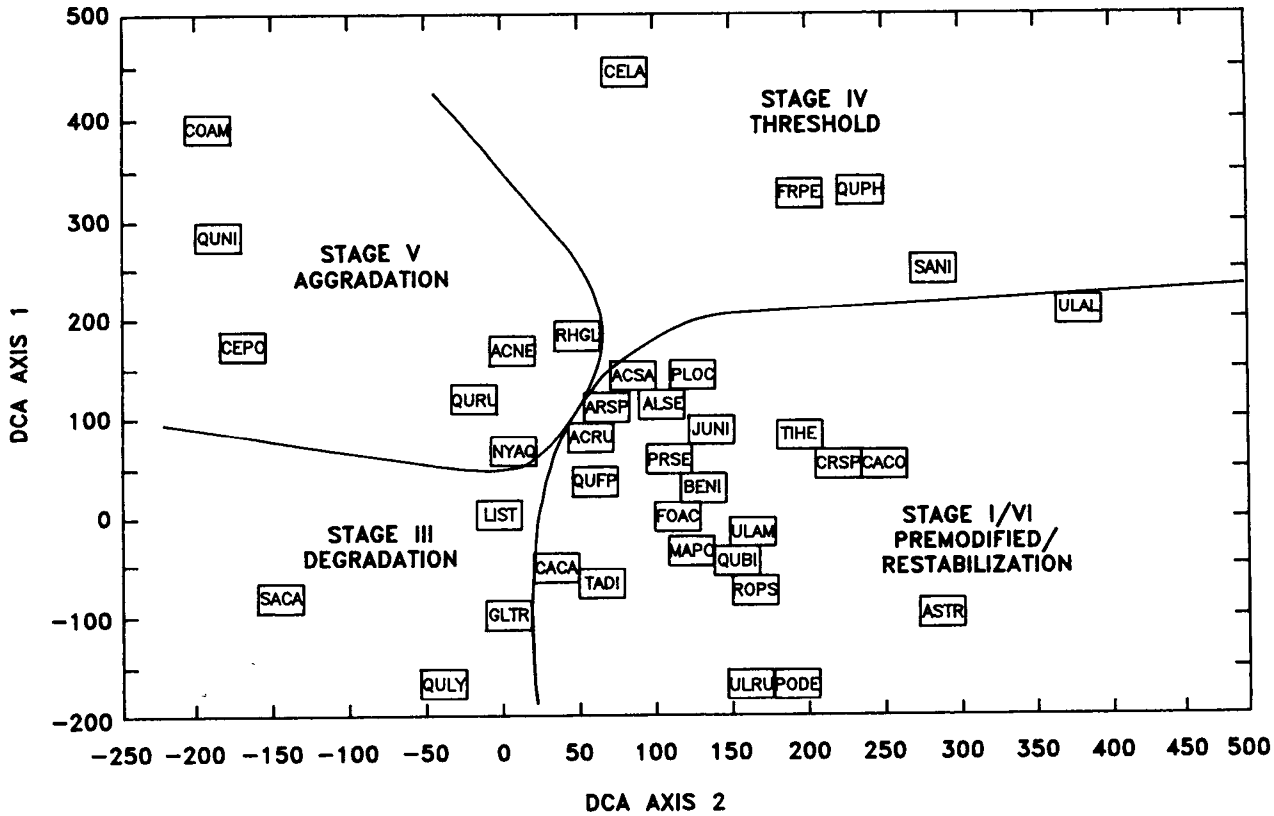
### *Species Ordination*

Ordination is a type of multivariate analysis that examines numerous variables simultaneously. Ordination allows for the classification of vegetation data, in this case frequency data converted to standardized residuals (table 31). This classification is based entirely on species-presence data, apart from environmental data, leaving environmental interpretation to a subsequent, independent step (Gauch, 1982). The result of ordination is a two-dimensional array such that the spatial arrangement of species, or site variables, places similar species or sites close by and dissimilar ones far apart.

Both the species and site ordinations were performed using the computer program DECORANA (Hill and Gauch, 1980)--a detrended correspondence analysis (DCA). Results of the species ordination are shown in figure 58; the site ordination is shown in figure 59. In both, the entities are spread across two multivariate axes. The distance between entities can be considered analogous to "ecological distance." For example, very high cover (XC) and very low widening (VW) group closely together (fig. 59) and, conversely, this group is ecologically distant from very low cover (VC) and very high widening (XW).

The ordination of species shows clusters of species in groups (fig. 58). Inspection of the pattern (fig. 58) allows for each group to be independently associated with a particular stage of bank-slope development. The boundary lines are placed on figure 58 on the basis of computed residual values for each species. DCA axis-1 is largely one of stability, and the second axis is largely one of time since disturbance, or pioneer versus mature (figs. 58, 59). The stage IV clusters of species, largely disturbance-associated plants, are easily separated from the other stage clusters. However, the separation between stage V and stage VI is largely one of interpretation, as would be expected. The difference between stage V and stage VI may be thought of as an environmental gradient beginning with stabilizing but relatively active banks, through to stable natural-bank conditions. Thus, a stability gradient is revealed in figure 59 with the upper left corner the most unstable, and the lower right corner, the most stable.

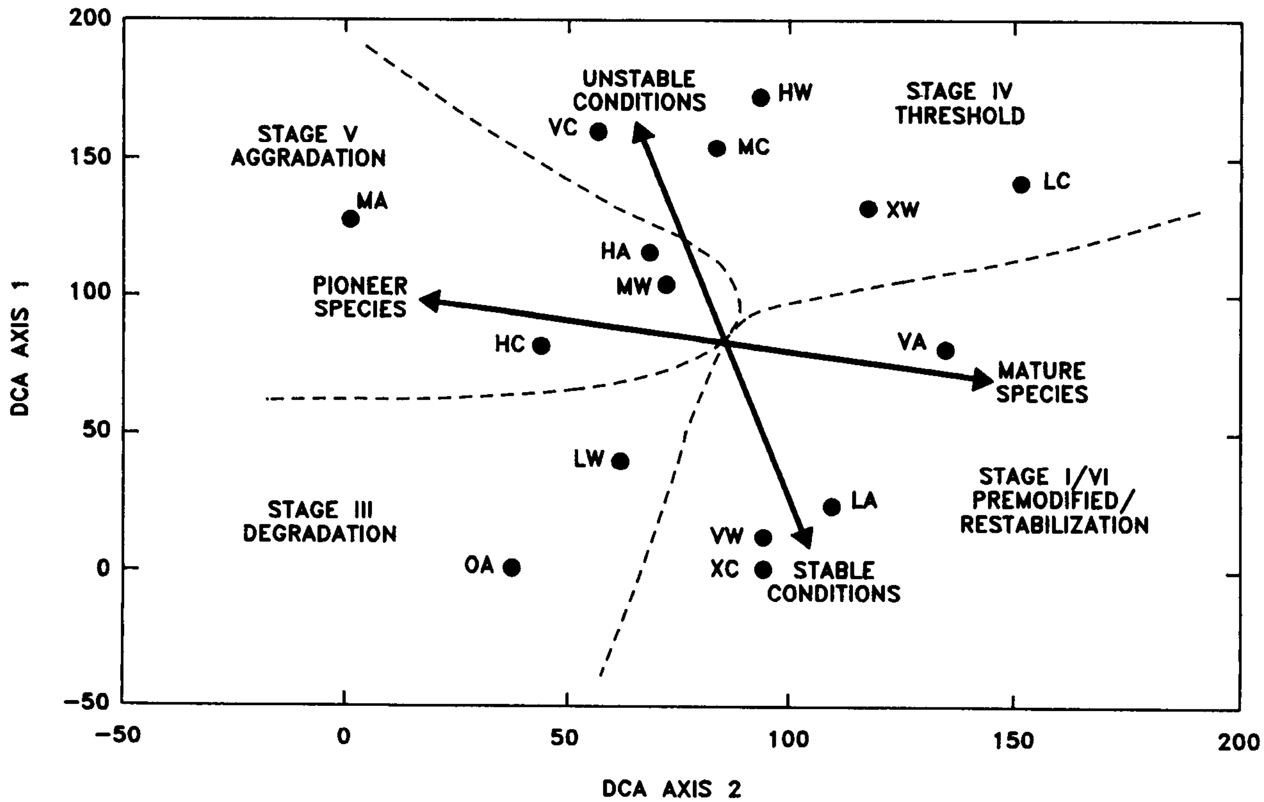
The environmental gradients are perhaps better revealed in the site-variable ordination (fig. 59). The same general bank-slope-development stage pattern is also shown for the species ordination. The site variables can be associated with the various stages of bank-slope development (fig. 59). This ordination reflects the geomorphic processes and characteristics outlined in the bank-slope-development model. Site conditions naturally cluster in groups that can be identified with specific stages of the model. Thus, the ordination of species-presence data supports the conceptual framework of the bank-slope-development and channel evolution models; and indicates that patterns of species distribution may be used to infer levels of ambient bank stability.




EXPLANATION
SPECIES CODE AND SCIENTIFIC NAME

| | | | |
|---|---|---|---|
| ALSE | ALNUS SERRULATA | NYAQ | NYSSA AQUATICA |
| ASTR | ASIMINA TRILOBA | PLOC | PLATANUS OCCIDENTALIS |
| ACNE | ACER NEGUNDO | PODE | POPULUS DELTOIDES |
| ACRU | ACER RUBRUM | PRSE | PRUNUS SEROTINA |
| ACSA | ACER SACCHARINUM | QUBI | QUERCUS BICOLOR |
| ARSP | ARALIA SPINOSA | QUFP | QUERCUS FALCATA |
| BENI | BETULA NIGRA | QULY | QUERCUS LYRATA |
| CACA | CARPINUS CAROLINIANA | QUNI | QUERCUS NIGRA |
| CACO | CARYA CORDIFORMIS | QUPH | QUERCUS PHELLOS |
| CELA | CELTIS LAEVIGATA | QURU | QUERCUS RUBRA |
| CEPO | CEPHALANTHUS OCCIDENTALIS | RHGL | RHUS GLABRA |
| COAM | CORNUS AMOMUM | ROPS | ROBINIA PSEUDOACACIA |
| CRSP | CRATAEGUS SPP. | SACA | SAMBUCUS CANADENSIS |
| FOAC | FORESTIERA ACUMINATA | SANI | SALIX NIGRA |
| FRPE | FRAXINUS PENNSYLVANICA | TADI | TAXODIUM DISTICHUM |
| GLTR | GLEDITSIA TRIACANTHOS | TIHE | TILIA HETEROPHYLLA |
| JUNI | JUGLANS NIGRA | ULAL | ULMUS ALATA |
| LIST | LIQUIDAMBAR STYRACIFLUA | ULAM | ULMUS AMERICANA |
| MAPO | MACLURA POMIFERA | ULRU | ULMUS RUBRA |

Figure 58.—Results of species ordination from detrended correspondence analysis (DCA). (Axes 1 and 2 are the first two principal components.)




EXPLANATION

VW VERY LOW WIDENING
LW LOW WIDENING
MW MEDIUM WIDENING
HW HIGH WIDENING
XW VERY HIGH WIDENING
OA ZERO ACCRETION
VA VERY LOW ACCRETION
LA LOW ACCRETION
MA MEDIUM ACCRETION
HA HIGH ACCRETION
VC VERY LOW COVER
LC LOW COVER
MC MEDIUM COVER
HC HIGH COVER
XC VERY HIGH COVER

*Figure 59.*—Results of site-variable ordination from detrended correspondence analysis (DCA). (Axes 1 and 2 are the first two principal components.)

## SUMMARY AND CONCLUSIONS

Dredging and straightening of alluvial channels in West Tennessee has caused significant adjustments in channel plan and profile. The removal of riparian vegetation during channel construction, and subsequent episodes of bank widening, resulted in increased streamflow velocities through a reduction in channel roughness. An interdisciplinary approach including geomorphology, soil mechanics and slope stability, dendrochronology, and plant ecology was used to determine geomorphic and vegetative-recovery processes along adjusting stream systems during the course of channel evolution.

A model of channel evolution was used to differentiate varying process-response mechanisms over the course of fluvial adjustment. Stage I, the premodified condition, is followed by the construction phase (stage II) where vegetation is removed, the channel deepened, and channel gradients and bank slopes steepened. Degradation (stage III) follows and is characterized by an increase in bank heights and angles until critical conditions of the bank material are exceeded, and the banks fail by mass-wasting processes (stage IV). Aggradation begins in stage V, and low-bank stability is achieved through a reduction in bank heights and bank angles. Stage VI (restabilization) is characterized by the relative migration of bank stability upslope (as determined by establishing woody-riparian species), point-bar development, and incipient meandering.

A quantitative model of bed-level adjustment over time and space was used to estimate amounts of bed degradation and aggradation at 5-year intervals, into the next century. A power equation relating channel-bed elevation to time used the exponent "b" as the primary indicator in describing the magnitude of channel bed-level changes. Maximum amounts of change occurred in reaches in the vicinity of the area of maximum disturbance (greatest imposed gradient change) and decreased nonlinearly with distance upstream. Aggradation took place downstream of this area of maximum disturbance, with the greatest rates occurring near stream mouths. Following a 10- to 15-year period of degradation, "secondary aggradation" occurred due to excessive incision and gradient reduction.

Channel-bank instabilities were induced by incision and undercutting of the bank toe, and resulted in channel widening by mass-wasting processes. Common failure types included rotational, planar, slab, and "pop out" (due to excess pore-water pressure). Failures generally occurred during or after recession of river stage due to bank saturation and the loss of support afforded by the flowing water (rapid drawdown condition). Highly degraded reaches, such as along Cane Creek, widened rapidly--up to 16 ft/y.

Drained shear-strength determinations were done on bank materials using a borehole-shear-test device that provides information on cohesion and the angle of internal friction of the material. Mean values of cohesion and the angle of internal friction for the loess-derived alluvium were 1.26 pounds per square inch and 30.1 degrees, respectively (168 tests). These direct-shear measurements were then used to calculate factors of safety and to construct bank-stability charts. Planar failures were found to be more critical in most cases, but rotational failures tended to produce higher rates of channel widening. An approximate threshold factor of safety of 2.0 was determined, indicating that for stream banks of loess-derived alluvium, the factor of safety of 1.50 commonly used in channel design, may be marginal. Factors of safety varied as expected with the stages of channel evolution. Critical bank conditions calculated for each site over a range of bank heights and bank angles were used to develop slope-stability charts for the purpose of assessing the relative bank stability of sites. These were based on ambient-field and saturated-bank conditions.

A nomograph was developed for the purpose of determining stable-bank configurations for worst-case conditions (saturation during rapid drawdown) at given cohesive strengths. Potential bank instabilities can also be estimated by using the nomograph and by noting possible changes in bank height as a result of channel-bed degradation.

Rates and amounts of channel widening calculated using dendrogeomorphic, soil mechanics, and survey techniques compared closely with each other. These values differed by the amount of channel-bed degradation, the strength of the bank materials, and the degree of fluvial undercutting (pronounced if on outside bends). Projections of future channel widening were based on the extension of a "temporary angle of stability" upslope, until it intersects the flood-plain surface. Estimates of further top-bank widening were then made by subtracting the distance between this point and the present top-bank edge. Initial stable-bank configurations were estimated from temporary angles of bank stability; obtained independently by soil mechanics, and dendrogeomorphic techniques. The two values were 23 and 24 degrees, respectively.

Estimates of long-term width/depth ratios for the loess tributary streams and for the sand-bed streams after 40 years of adjustment range from 4.0 to 6.4, and from 6.8 to 11.4, respectively. After 115 years of adjustment, estimated width-depth ratios for the fine-grained channels range from 4.3 to 6.8, and for the sand-bed channels, from 7.4 to 13.1. These estimates (with their inherent uncertainties) were determined from estimates of channel bed-level changes (from the power equation), and from estimates of projected channel widening. A 10- to 15-year period of degradation, followed by either 25 or 100 years of aggradation was assumed for each site.

Data from dendrogeomorphic and plant-ecologic analyses described trends of channel response and recovery. Patterns of riparian-species distributions are strongly associated with the stages of channel evolution. Vegetation re-establishment during late stage IV and stage V indicates ameliorating bank conditions and the inception of low-bank stability. The most common pioneer species in this study were black willow, river birch, silver maple, and boxelder. Dating of these species was used to determine the timing of initial bank stability. Stages I and III had the most diverse riparian species; stage IV banks often had no woody species due to the highly unstable nature of the channel banks.

Contingency-table and standardized-residual analyses indicated species "preference" or "avoidance" for particular site characteristics such as widening, accretion, and woody vegetative cover. Distinct differences exist between pioneer and mature species for specific site characteristics. This indicates that vegetative reconnaissance of an area can be used for at least preliminary estimation of bank-stability conditions.

Detrended-correspondence analysis displayed vegetation patterns and delineated species assemblages associated with the six stages of channel evolution. Ordination of site variables (channel widening, bank accretion and woody vegetative cover) based on species data alone reflected the hydrogeomorphic characteristics of the six-stage model of channel evolution. Site conditions clustered in groups that can be identified with specific stages of the model. This analysis supports the conceptual framework of the channel-evolution model, and it indicates that patterns of species distribution can be used to infer ambient channel stability.

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