Gradation Processes and Channel Evolution in Modified West Tennessee Streams: Process, Response, and Form

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Prepared in cooperation with the Tennessee Department of Transportation

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By ANDREW SIMON

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CONVERSION FACTORS AND VERTICAL DATUM

For readers who may prefer to use inch-pound units rather than the International System of Units (SI), the conversion factors are listed below:

Multiply	By	To obtain
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
meter per year (m/yr)	3.281	foot per year (ft/yr)
meter per second (m/s)	3.281	foot per second (ft/s)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	0.3861	square foot (ft^2)
kilopascal (kPa)	0.1450	pound per square inch (lb/in^2)
cubic meter per meter (m^3/m)	10.76	cubic foot per foot (ft^3/ft)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

SYMBOLS

Symbol	Definition
AGI	Area-gradient index, in cubic meters per meter
AMD	Area of maximum disturbance, by river kilometer
b	Dimensionless exponent indicative of the nonlinear rate of change on the channel bed
c	Cohesion, in kilopascals
CL	Percentage of clay in sample, by weight
d_{50}	Median grain size, in millimeters
d_{84},d_{16}	Diameter of particle by which 84 and 16 percent of the sample, by weight, are finer, in millimeters
DSLR	Imposed gradient change in reach, in percent
DSLT	Imposed total gradient change relative to mouth, in percent
DW	Change in top width from premodified state to 1983, in meters
E	Elevation of channel bed or specific-gage elevation, in meters
G	Gradation index of sediment, dimensionless measure of sediment sorting
H_c	Critical bank height, in meters
H'_c	Critical bank height with tension cracks, in meters
IMAGI	Imposed area-gradient index, used as a surrogate for stream power, in cubic meters per meter
LL	Liquid limit, in percent
ϕ	Angle of internal friction, in degrees
PERS	Sand content, by weight, in percent
PI	Plasticity index
PL	Plastic limit, in percent
PMW	Premodified channel top width, in meters
PV	Maximum noneroding pinhole velocity, in meters per second
Q	Water discharge, in cubic meters per second
Q_s	Bed-material discharge, in cubic meters per second
r	Correlation coefficient
r^2	Coefficient of determination
RKM	Distance above mouth of stream, in kilometers
RSH	Imposed shortening of reach, in percent
$\|\Delta S\|$	Absolute value of the yearly change in gradient in a reach, in meters per meter
S_E	Standard error of the mean
SC	Percentage of silt plus clay in sample, by weight
SCR	Silt-clay ratio
SYNAG	Synthesized aggradation exponent
t_0	Year prior to start of gradation process
TSH	Imposed total shortening from mouth to site, in percent
$W83$	1983 surveyed top width
y	Depth of tension crack, in meters
γ	Unit weight of soil, in kilograms per cubic meter

GRADATION PROCESSES AND CHANNEL EVOLUTION IN MODIFIED WEST TENNESSEE STREAMS: PROCESS, RESPONSE, AND FORM

By Andrew Simon

ABSTRACT

Channelization of alluvial channels in West Tennessee has increased energy conditions along main stems and tributaries and initiated systematic trends in channel adjustment. Gradation processes and adjustment trends are a function of the magnitude and extent of an imposed disturbance on a stream channel and the location of the adjusting reach in the fluvial network.

Degradation at a site is described by power-decay equations. Exponents denoting the nonlinear rate of downcutting with time decrease with distance upstream from the area of maximum disturbance, and generally range from −0.002 to −0.04.

Aggradation occurs in reaches immediately downstream from the area of maximum disturbance and in upstream reaches following overadjustment by degradation, and also can be described by power equations. Aggradation rates increase linearly with distance downstream and reach a maximum of 0.12 meters per year.

Adjustment of channel width by mass-wasting processes follows degradation and continues through the aggradational phases. Bank instabilities are induced after downcutting creates bank heights and angles that exceed the critical conditions of the material. Piping in the loess-derived bank materials enhances bank-failure rates.

Development of the bank profile is defined in terms of three dynamic and observable surfaces: vertical face (70° to 90°), upper bank (25° to 50°), and slough line (20° to 25°). Both the vertical face and upper bank sections represent major failure planes, and masses of failed bank material often come to rest on the upper bank. The slough line develops from additional flattening and downslope movement by low-angle slides and fluvial reworking, and is the initial site of reestablishing riparian vegetation and stable bank conditions.

A six-stage, semiquantitative model of channel evolution in disturbed channels is developed by quantifying gradation trends, by interpreting process-response relations during stages of bank-slope development, and by interpreting changes over space as changes over time.

INTRODUCTION

Alluvial channels are dynamic geomorphic features that naturally adjust to altered environmental conditions. This ability to adjust implies that a change imposed on a fluvial system, be it natural or manmade, will cause channel adjustments in an attempt to offset the change for some distance upstream and downstream.

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

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

where

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

Under natural conditions of change, channel adjustments may occur at such low rates and over such extended periods of time that they are virtually imperceptible. When natural stream conditions are altered by dredging, or straightening (shortening), both bankfull Q and channel gradient S can be dramatically increased. By equation 1, this results in a proportionate increase in bed-material discharge (Q_s) and (or) grain size of the bed material (d_{50}) such that rapid and observable morphologic changes occur. These changes include upstream degradation, downstream aggradation, and bank instabilities along the altered rivers and adjacent tributaries.

Man-induced changes can occur more quickly than "naturally" induced adjustments and thus provide an important opportunity to examine adjustment processes over a reasonable amount of time. Channelization is a common and controversial engineering practice aimed at controlling flooding or draining wetlands. Quantification of channel responses can be a valuable tool for mitigating the effects on river-crossing structures and lands adjacent to these channels. This study deals with channel adjustments and channel evolution following substantial modifications to alluvial channels in the Obion, Forked Deer, and upper and lower Hatchie River basins of West Tennessee (fig. 1).

PURPOSE OF STUDY

The objectives of this study were to

1. Determine rates and durations of gradation processes (aggradation and degradation) in 13 modified alluvial streams of West Tennessee;
2. Characterize various physical and mechanical properties of the channel alluvium;

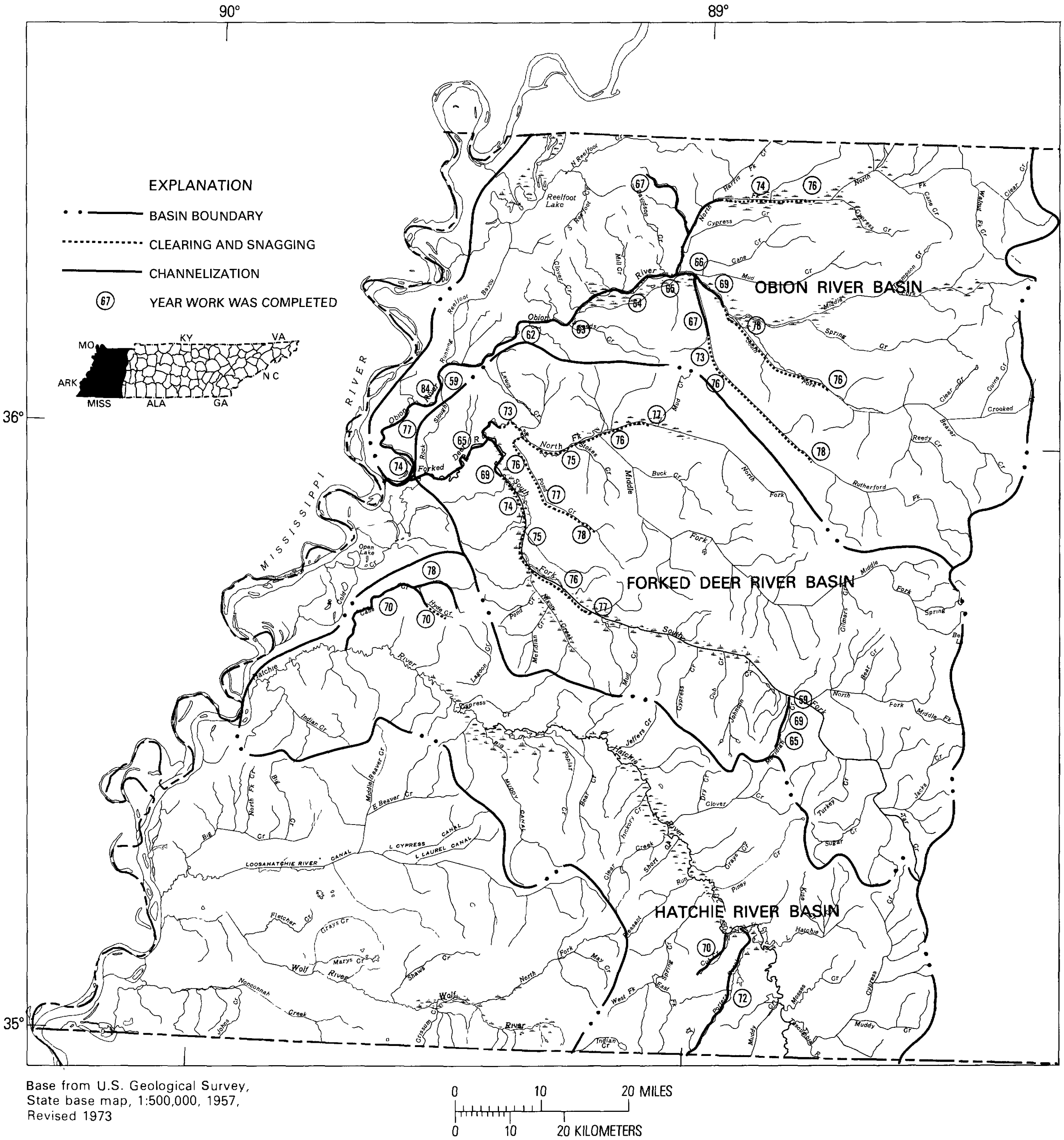

FIGURE 1.—Geographical extent of recent channel modifications in West Tennessee.

3. Determine imposed changes from channel modifications and subsequent adjustments in unit stream power in gaged reaches;
4. Establish process and response relations among parameters that describe the magnitude and extent of the imposed disturbance, rates of bed-level change, and bed-material properties;
5. Document and compile changes in channel width due to channel modification, and develop field and analytical techniques to characterize width adjustment;

TABLE 1.—*Drainage basins, drainage areas, and dominant surficial geologic units of studied area*
[km², square kilometers]

Drainage basin	Drainage area (km^2)	Dominant surficial geologic units
Obion River[1]	[2]6330	Loess.
North Fork Obion River	1550	Loess.
Hoosier Creek	88.8	Loess.
South Fork Obion River	1100	Loess.
Rutherford Fork Obion River	717	Loess.
Forked Deer River[1]	5390	Holocene alluvium.
North Fork Forked Deer River[1]	2460	Loess.
Pond Creek	180	Loess.
South Fork Forked Deer River[1]	2750	Loess, Claiborne and Wilcox Formations.
Meridian Creek	80.0	Claiborne and Wilcox Formations.
Hatchie River[1]	6760	Loess, Claiborne and Wilcox Formations.
Cane Creek	224	Loess.
Hyde Creek	27.2	Loess.
Cub Creek	43.2	Midway Group.
Porters Creek	165	Midway Group.

[1]Larger streams also flow through substantial deposits of Holocene alluvium.
[2]Above mouth of Forked Deer River.

6. Use techniques developed in this and previous studies to estimate channel response to channel modifications in ungaged and (or) unsurveyed reaches of the region; and
7. Develop a conceptual model of channel evolution in modified streams from the premodified condition, through modification and stages of adjustment, to relative stability.

The purpose of this report is to provide detailed empirical evidence of the dominant processes and trends controlling channel evolution in 13 channelized streams of West Tennessee. The time period covered by this report is from the late 1950's through 1983. Documentation and quantification of aggradation and degradation trends in gaged reaches serve as examples for establishing similar trends in ungaged, but periodically surveyed, reaches. Identification of these trends as a systematic pattern of bed-level response throughout much of the region establishes a framework for the development of a quantitative model of longitudinal adjustment. A direct relation between the rates of degradation and widening is established and combined with observed trends of bank-slope development to provide a conceptual model of channel evolution over time and space.

AREA AND SCOPE OF STUDY

STUDY AREA AND GEOLOGY

The study area includes approximately 27,500 km^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 from the Obion, Forked Deer, and Hatchie River basins (fig. 1, table 1). These rivers are cut into unconsolidated and highly erosive units (U.S. Department of Agriculture, 1980), predominantly of Quaternary age. There is a total lack of bedrock control of base level, so that following a disturbance such as dredging, the alluvial channels of West Tennessee are free to systematically adjust their profiles.

The Obion and Forked Deer Rivers flow through Mississippi River alluvial deposits in their most downstream reaches and through loess-derived alluvium farther upstream and in their forks (fig. 2). Most tributary streams throughout the area flow across deposits of loess that thin eastward from 30 m along the bluffs of the Mississippi River, to approximately 1 m at the outcrop of the Claiborne and Wilcox Formations of Tertiary age (Miller and others, 1966) (fig. 2). These formations, composed predominantly of sand, are interbedded with a relatively stiff, gray to white clay and are found in the Meridian Creek basin (fig. 1) as well as along some of the uppermost reaches of the forks of the Obion and Forked Deer Rivers (fig. 2).

Some tributaries to the Hatchie River, including Porters and Cub Creeks (fig. 1), flow on a relatively resistant massive and blocky clay deposit of the Midway Group of Tertiary age, known as the Porters Creek Clay (fig. 2). The sandy lower formation of the Midway Group (the

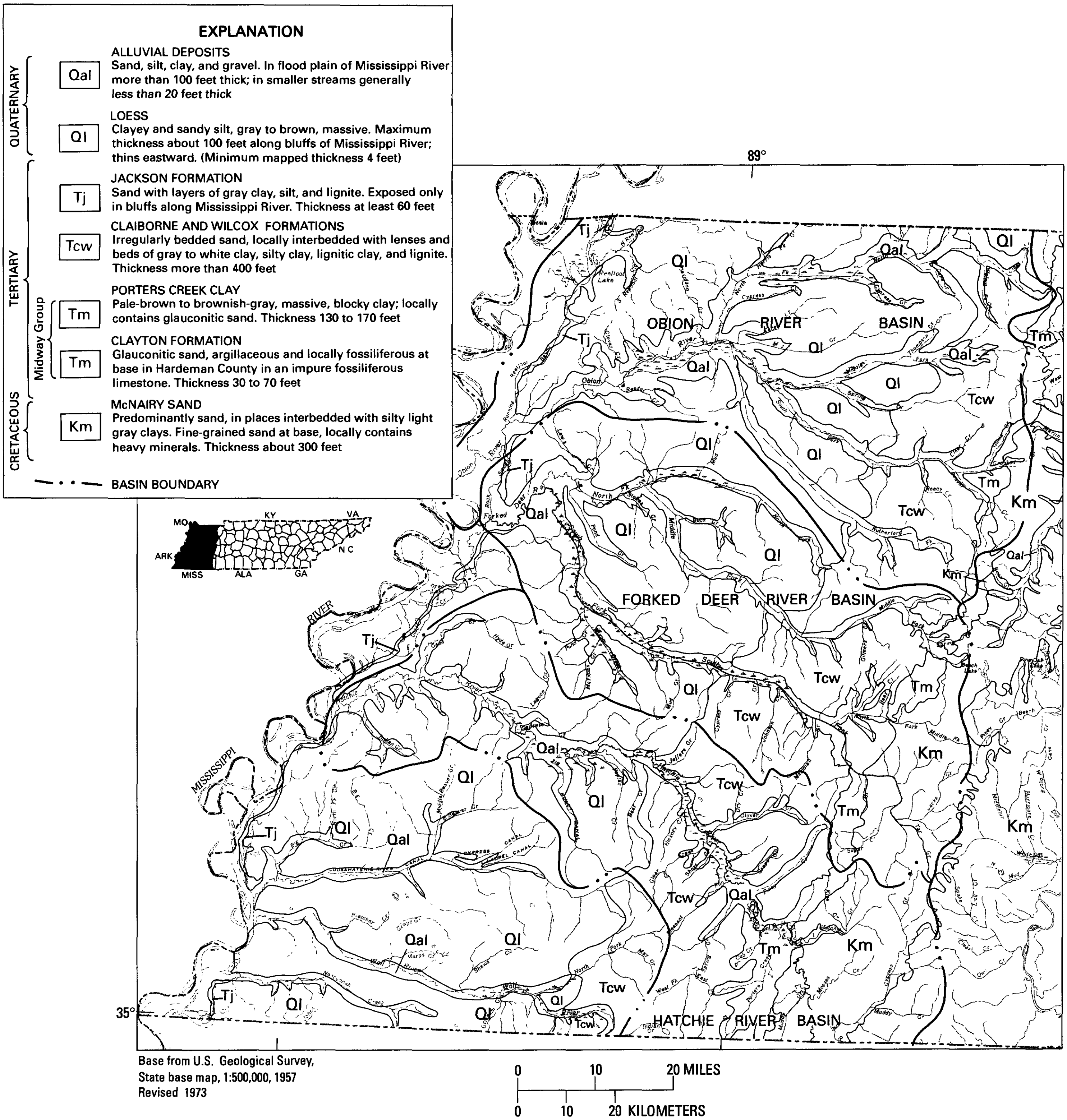

FIGURE 2.—Surficial geology of West Tennessee region.

Clayton Formation) also crops out in these areas of the Hatchie River basin, as well as along other reaches east of the loess contact (fig. 2). Only upper reaches of the Hatchie (near the Mississippi State line) and South Fork Forked Deer Rivers cut through the McNairy Sand of Cretaceous age (Miller and others, 1966).

PREMODIFIED DRAINAGE CONDITIONS

Prior to major deforestation of the region following the Civil War, rivers "flowed with good depths year round" (Ashley, 1910). Clearing of large tracts of land and the consequent reduction in storage and increase in runoff rates led to erosion of the uplands and gullying in fields. Eroded material was deposited on the flood plains (Maddox, 1915) and in the stream channels, resulting in a general loss of channel capacity (Ashley, 1910). Channels were extremely sinuous, choked with sediment and debris, and subject to frequent and prolonged flooding (Morgan and McCrory, 1910). Early surveys (circa 1910) of the Obion and South Fork Forked Deer Rivers disclosed mild channel gradients of approximately 1.14×10^{-4} meter per meter (m/m) and broad flood plains 1.6 to 4.8 km 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 floodwaters. Conservation measures were proposed to protect and reclaim the gullied landscape (Maddox, 1915).

CHANNELIZATION AND SUBSEQUENT DRAINAGE CONDITIONS

By 1926, most stream channels in West Tennessee, with the exception of the Hatchie River main stem, had been dredged and straightened to increase drainage rates (Speer and others, 1965). Further enlargement of the channels was caused by increases in velocity and channel capacity (Ramser, 1930). Subsequent accumulation of drift (trees and stumps) from failed banks was of sufficient magnitude to cause backwater and sedimentation at the downstream ends of the forks of the Obion and Forked Deer Rivers (Speer and others, 1965). Continued aggradation and drift accumulation through the 1930's necessitated the clearing and snagging of approximately 270 km of main stem, forks, and tributaries of the Obion River system in the late 1930's and 1940's. When this work was finished, the cycle simply repeated, 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 channelize further many of the drainage systems in West Tennessee. Channel work on the Hatchie River during the period 1938–52 was limited to channel snagging, thereby preserving 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 27.2 to 6,330 km^2 (tables 1, 2; fig. 1). The West Tennessee Tributaries Project, which provided for the enlargement and straightening of 190 km of the Obion River system and 170 km of the Forked Deer River System, was temporarily halted by court order in 1970 when it was approximately one-third complete (Robbins and Simon, 1983). At that time, channelization in the Obion River system had extended into the lower reaches of the forks (table 2, fig. 1). Bed level was lowered by approximately 5.2 m at the upstream terminus of the Obion River main stem (site 07025900). Where the downstream modified channel met the upstream "natural" channel, a "transition slope," steeper than either reach, was constructed to offset the differences in bed elevations (Robbins and Simon, 1983). Similar transition slopes were constructed on the South Fork and North Fork Forked Deer Rivers at the upstream ends of the channel work. Knickpoints progressed headward from these sites, causing degradation upstream. Degradation migrated upstream at a rate of 2.6 km per year (km/yr) on the South Fork Forked Deer River, causing 3.1 m of downcutting at 07028100 and 1.7 m of downcutting 13.5 km upstream at 07027800 through 1983 (Robbins and Simon, 1983). Approximately 2.6 m of incision occurred as a result of degradation at the most downstream site on the South Fork Obion River (07024800) between 1966 and 1967. Similar headward degradation occurred on all tributaries subjected to the lowering of their trunk streams (fig. 3).

As was the case following earlier channel modifications, the most downstream reaches of the constructed channels began to fill with accumulated sediment and drift emanating from degrading reaches upstream (Robbins and Simon, 1983). The entire length of the Obion River main stem became (1970's and 1980's) a depository for materials eroded from upstream. Rates of aggradation along this river range from 0.03 m/yr at the confluence of the forks to 0.12 m/yr, 13.7 km downstream at Obion (fig. 1). The most downstream site on the South Fork Forked Deer River (07028200) experienced 2.2 m of infilling over a 12-year period following channelization. Clearing operations were undertaken from 1973 to 1978 along approximately 82 km of the Obion River basin channels and 108 km of the Forked Deer River basin channels. Additional dredging and straightening activities on the lower Obion main stem were carried out in the late 1970's and early 1980's.

Channelization projects of lesser extent than the West Tennessee Tributaries Project also were included in this study (table 2, fig. 1). Because the only direct alterations to the Hatchie River main stem involved snagging and clearing between 1938 and 1952 and no alteration to plan or profile, it can be considered to have had an almost "natural" fluvial development. It is one of the few sinuous channels remaining in West Tennessee and has shown relative stability in plan and profile (Robbins and Simon, 1983). Therefore, it was excluded from the quantitative analysis of adjustment trends. The Hatchie, however, cannot be interpreted as representing pre-

TABLE 2.—*Type, extent, and dates of recent channel modifications on studied streams (1959–78)*
[—, data not available; km, kilometers]

Basin	Stream	Type of modification	Length (km)	Dates
Obion	Obion River	Enlarging and straightening[1]	75.1	1959–66
	......do	Clearing and snagging	6.8	1976
	......do	Enlarging and straightening[1]	—	1974–77
	North Fork Obion River	Enlarging and straightening[1]	17.5	1967
		Clearing and snagging.	17.4	1974–76
	Hoosier Creek	Enlarging and straightening[1]	11.9	1967
	Rutherford Fork Obion River	Enlarging[1]	11.9	1967
		Clearing and snagging.	28.8	1973–78
	South Fork Obion River	Enlarging[1]	9.6	1967, 1969
		Clearing and snagging.	28.8	1976–78
Forked Deer	North Fork Forked	Enlarging and straightening[1]	6.9	1973
	Deer River.	Clearing and snagging.	31.5	1974–77
	Pond Creek	Clearing and snagging	21.1	1976–78
	South Fork Forked	Enlarging and straightening[1]	7.1	1969
	Deer River.	Clearing and snagging.	36.5	1973–77
	Meridian Creek	Enlarging and straightening	2.6	1959?
	......do	Enlarging and straightening	8.4	1969
	......do	Enlarging	2.6	1969
Cane (lower Hatchie)	Cane Creek	Enlarging and straightening	52.0	1970
	......do	Enlarging and straightening	20.9	1978
	Hyde Creek	Enlarging and straightening	1.3	1970
Upper Hatchie	Cub Creek	Enlarging and straightening	15.6	1970
	Porters Creek	Enlarging and straightening	34.4	1972

[1]Part of the West Tennessee Tributaries Project.

settlement conditions because of post–Civil War deforestation and because its tributary basins are intensely farmed and channelized.

Analysis of the adjustment of West Tennessee alluvial channels presented in this report is limited to the consideration of channelization work from the late 1950's through the 1970's.

PREVIOUS INVESTIGATIONS

ADJUSTMENT BY NONLINEAR DECAY

A common concept in all the approaches to channel adjustment is that following a disturbance of sufficient magnitude, the channel will respond and attempt to return to its predisturbed state. Irrespective of the approach used, adjustment trends through time can be described mathematically by nonlinear decay functions, which asymptotically approach minimum values and therefore can potentially be used to estimate the time it will take for the channel to return to quasi-equilibrium conditions (Schumm and Lichty, 1965; Schumm, 1973; Bull, 1979; Robbins and Simon, 1983; Williams and Wolman, 1984; Simon, 1989; and others).

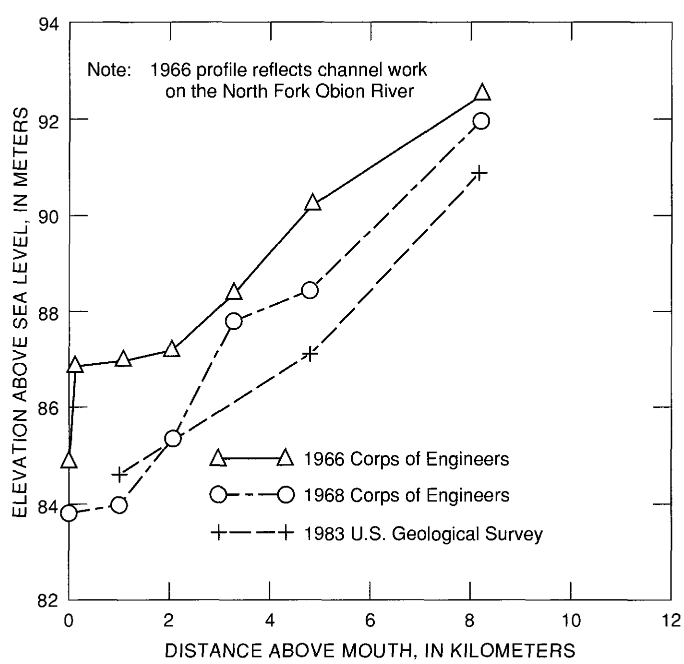

FIGURE 3.—Incision on Hoosier Creek due to bed-level lowering on the North Fork Obion River.

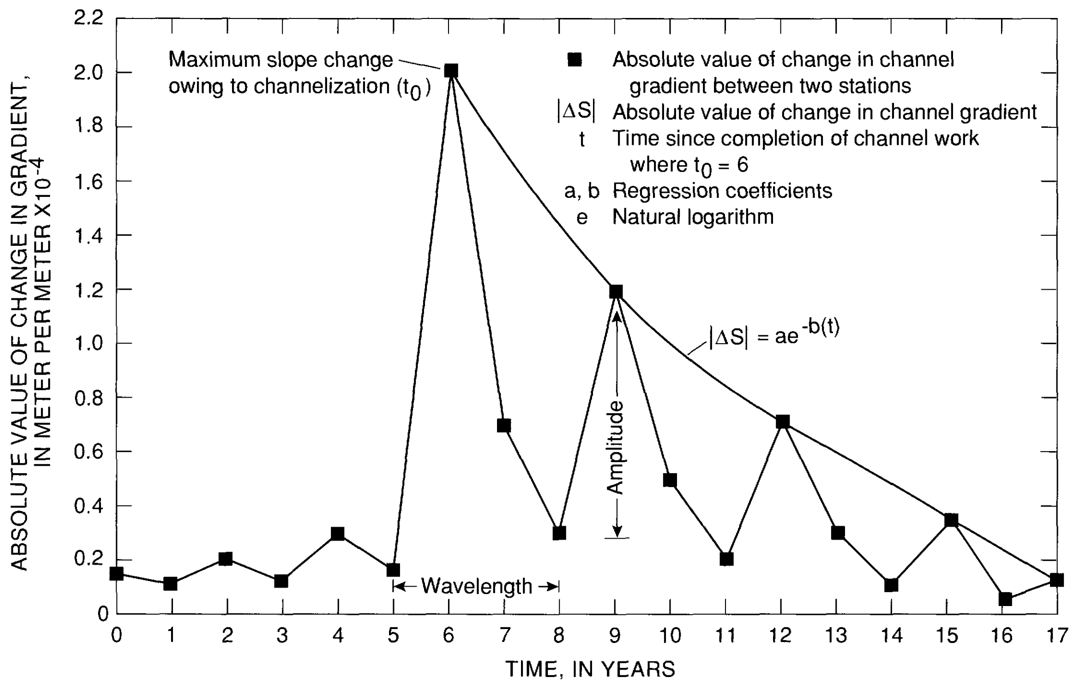

FIGURE 4.—Idealized representation of gradient adjustment as an oscillatory response and by nonlinear decay. (Modified from Robbins and Simon, 1983.)

Robbins and Simon (1983) used nonlinear decay functions to establish empirical relations of gradient adjustment with time along some West Tennessee channels. Exponential decay functions were developed to describe the initially rapid, and then gradual, reduction in channel gradient following channelization. The absolute value of the yearly change in channel gradient $|\Delta S|$ was found to have the most potential in determining response times because it represents the magnitude of the annual change in gradient. Plots of $|\Delta S|$ delineate a series of oscillations (episodic response) with the height of successive peaks generally declining with time (Simon and Robbins, 1987) (fig. 4).

CONSEQUENCES OF CHANNELIZATION

AGGRADATION AND DEGRADATION

It is well documented that upstream progressing degradation and downstream aggradation are common attributes of channelized streams and are due to increases in channel gradient and capacity. Additional consequences of degradation, including bank failure (from overheightening and oversteepening) and undermining of hydraulic structures, such as bridges, are also commonly reported.

Daniels (1960) reports that straightening of the Willow River, southwestern Iowa, led to approximately 9 m of degradation in some reaches. Canyon-type gullies formed and extended into the surrounding countryside, disrupting 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 southwest Mississippi caused up to 5.8 m of degradation, accelerated bank caving, and led to the collapse of several bridges (Wilson, 1979). Following channelization of the Blackwater River in Missouri, degradation and widening increased channel cross-sectional area as much as 1,000 percent, causing several bridge failures (Emerson, 1971). Bed level dropped approximately 5.2 m in 10 years along some reaches of Cane Creek, West Tennessee, as a response to channelization activities (Simon and Hupp, 1986).

Sediment, eroded from degrading reaches and tributaries upstream, will generally be deposited along the gentler sloping downstream reaches (Simon, 1989). Aggradation initiated in this manner leads to a loss of channel capacity and increased frequency of flooding, thereby countering the purpose of the channelization (Parker and Andres, 1976). The downstream reaches of Cub and Porters Creeks, Hardeman County, Tenn., similarly filled with sediments just 2 years after these streams were channelized.

BANK FAILURE AND CHANNEL WIDENING

Bed-level lowering may create an unstable, overheightened bank profile. Continual basal erosion undercuts and removes support for the top part of the bank, causing “slab failure” (Thorne and others, 1981) or wedge-type failure. Lower-angle slopes may fail along a circular arc as "deep-seated rotational slides" due to prolonged wetting and (or) incision (Bradford and Piest, 1980). Fluvial erosion of bank material does not contribute significantly to bank retreat in the loess-derived materials that characterize streams of the West Tennessee study area (Bradford and Piest, 1980; Little and others, 1982). Channel widening in these materials can therefore be considered a mass-wasting process that occurs when critical conditions are exceeded (Lohnes and Handy, 1968). The critical bank height (H_c) is a function of debris at the slope base, the slope angle, and moisture and soil conditions (Bradford and Piest, 1980). A complete discussion of bank-stability analyses is given in Lohnes and Handy (1968) and Thorne and others (1981).

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

Tension cracking and piping are common in loess soils. Tension cracking develops from the ground surface (Thorne and others, 1981) and serves to destabilize the bank. Piping, an erosion process initiated by the percolation of water through a soil mass, further serves to weaken banks composed of loess (Simon and Hupp, 1986).

Channel widening following degradation is well documented. Increases in top-bank width 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), Robbins and Simon (1983), and others. Simon and Hupp (1986) report 46 m of widening between 1970 and 1980 in some parts of Cane Creek, West Tennessee, following channelization (fig. 5).

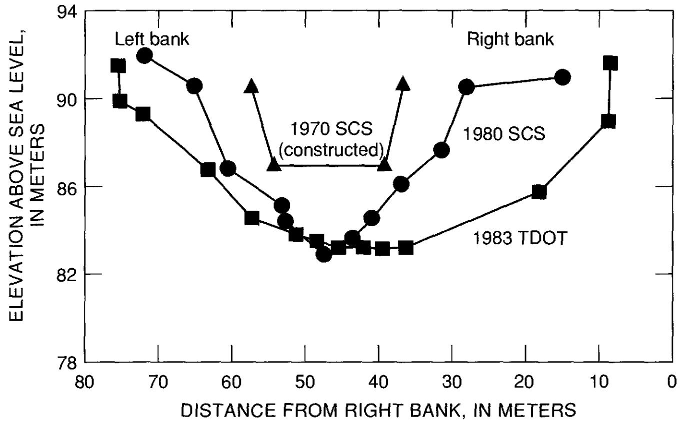

FIGURE 5.—Example of severe widening following channelization and degradation, Cane Creek, 30 m downstream from Hunter Road, Lauderdale County, Tenn. SCS, Soil Conservation Service; TDOT, Tennessee Department of Transportation. (Modified from Simon and Hupp, 1986.)

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METHOD OF STUDY

SITE SELECTION

The streams studied herein reflect varying degrees and types of channel modifications from 1959 through the 1970's (table 2). A sufficient number of sites were selected along a given stream system to delineate the range of adjustment processes and to facilitate the development of a conceptual model of channel evolution. At least two previous channel cross sections, a premodified cross section and the constructed cross section, are required for the analysis of adjustment trends. An attempt was also made to include channels representative of the various geologic units that outcrop 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. Where a bridge exerted a profound influence on site hydraulics and geometry, and yet the site was needed because of its position in the fluvial network, a section away from the effect of the structure was used.

DATA COLLECTION, COMPILATION, AND SOURCES

Channel-geometry measurements, and bed- and bank-material samples were collected in 1983 and early 1984 at the sites indicated in figure 6.

CHANNEL MORPHOLOGY

Channel-geometry data were used to determine the degree of morphologic change and to trace channel

FIGURE 6.—Sampling and surveying sites in West Tennessee.

evolution over time and space. Data included bed (thalweg) elevation, channel gradient, channel width, bank height, and type of geomorphic surface.

WATER-SURFACE AND BED ELEVATIONS

The mean annual water-surface elevation for a selected discharge and at a given gaging station is termed “specific-gage elevation” (Blench, 1973). The discharge selected for calculation of specific-gage elevation at all gaged sites was close to the 50-percent flow duration. By use of gaging station records from the U.S. Geological Survey and the U.S. Army Corps of Engineers, a simple linear regression analysis between discharge (20 percent above and below the selected discharge) and its corresponding water-surface elevation was made for each year of record. This resulted in a regression equation for each year of record. A specific-gage elevation was then obtained by substituting the selected discharge into the resulting regression equation and by solving the equation for water-surface elevation. Thus a specific-gage elevation was obtained for each year of record for all gaging stations included in the study. Changes in specific-gage elevation imply similar changes on the channel bed, can be used to document trends of degradation and aggradation, and serve as a basis for computations of channel gradient.

Bed elevation was obtained from measured cross sections of the channel at all sites. Data for premodified and constructed cross sections also were obtained from the U.S. Geological Survey (Geological Survey), Corps of Engineers, Soil Conservation Service (SCS), and Obion-Forked Deer Basin Authority (OFBA) dredging plans. All ungaged sites were surveyed again in 1983 during low-flow conditions.

Bed (thalweg) elevation in the vicinity of the bridges is defined for this study as the mean of the minimum nonscoured channel elevations on the upstream and downstream sides of the bridge. The differences between elevations on the upstream and downstream sides were generally minimal and further served as a reference for assessing the potential hydraulic influences of the bridge.

Channel Gradient

A channel gradient for each year was calculated by dividing the difference in bed elevations between two sites by the distance between the sites. Where a stream was straightened, both premodified and constructed channel lengths were measured and applied to gradient computations for the appropriate years. Historical channel gradients in some cases were obtained from plotted profiles (U.S. Army Corps of Engineers, 1907; Hidinger and Morgan, 1912).

Channel Width and Bank Height

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

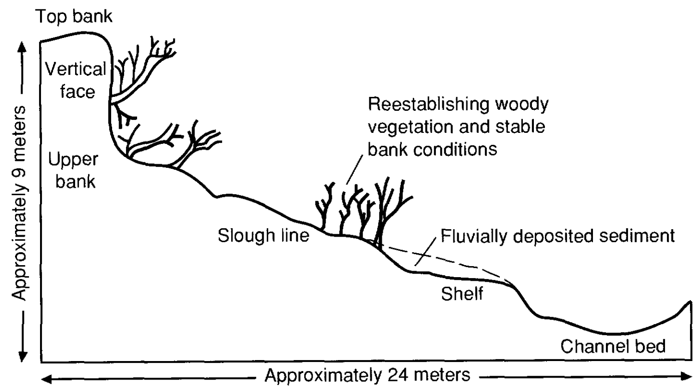


FIGURE 7.—Idealized geomorphic surfaces during channel adjustment and bank-slope development. (Modified from Simon and Hupp, 1986.)

some cases, from Corps of Engineers and Geological Survey gaging-station records.

Bank height information was derived from measured cross sections by subtracting the bed elevation (as previously defined) from the elevation of the flood plain. In cases where a levee is an integral part of the bank, bank height is calculated from the top of the levee.

Geomorphic Surfaces and Geobotanical Evidence

The identification and dating of various geomorphic surfaces (fig. 7) can be diagnostic in determining the relative stability of a reach and the status of bank-slope development (Hupp, 1983; Simon and Hupp, 1986). Acquisition of this type of data collection from field reconnaissance was carried out in early 1984 for approximately one-half of the reaches. This data collection involved locating and dating riparian vegetation on (1) newly stabilized surfaces (that is, the slough line) to determine the timing of initial stability for that surface, and on (2) unstable bank surfaces to estimate rates of bank retreat (fig. 7).

STREAM POWER

A term similar to that of specific-gage elevation, “specific velocity” is defined as the mean annual flow velocity at the same discharge (close to the 50-percent flow duration) used to calculate specific-gage elevation. By use of mean velocity values obtained from discharge measurements, a linear regression analysis of mean velocity and water discharge (20 percent above and below the selected discharge value) was made for each year of record. As with the calculation of specific-gage elevation, the selected discharge was substituted into the resulting regression equation, and the equation was solved for flow velocity. This resulted in a specific velocity for each year of record. This value was multiplied by the gradient between the selected site and the next site upstream to obtain values of unit stream power (the velocity-gradient product).

Because discharge records are available for only a limited number of sites, the area-gradient index (AGI, or the product of channel gradient and drainage area) was used as a surrogate for stream power (Schumm and others, 1981). AGI values (expressed in meters cubed per meter) that represent imposed conditions (IMAGI) address the extent and magnitude of channel disturbance.

CHANNEL MATERIALS AND LABORATORY ANALYSIS

Data on bed and bank materials were collected and compiled for the purposes of characterizing the channel alluvium and to address the question of erodibility. Much bank-material information was acquired from boring logs furnished by the U.S. Army Corps of Engineers, Memphis District. Some bed- and bank-material data were also available from the SCS and the TDOT and from previous investigations of the Geological Survey. Each bed-material sample collected during the study is a composite of three evenly spaced samples taken by conventional methods (Guy and Norman, 1970) along the channel bottom. Site locations of available data are shown in figure 6.

NONCOHESIVE MATERIALS

Noncohesive (sand) channel materials are generally found as recent deposits on bank surfaces, as bed material, and less frequently, as interbedded lenses within cohesive banks. A standard particle-size analysis (Guy, 1969) was performed on samples from each site.

COHESIVE MATERIALS

Data on cohesive materials indicate some of the physiochemical properties of these sediments. In addition to standard particle-size analysis, the SCS Soil Mechanics Laboratory, Fort Worth, Tex., classified the materials and determined plasticity (PI) and pinhole dispersion. Due to a lack of shear-strength data, PI values were applied to two nomographs (U.S. Department of Agriculture, 1969) to estimate the material's cohesion (c) and angle of internal friction (ϕ) (F. Cousins, Soil Conservation Service, written commun., 1984). Both of these nomographs were based on 325 tests of fine-grained soil materials and were fit to the following equations (Simon and Hupp, 1986): if PI≤27, then

$$c=13.3+(0.99\ \text{PI}), \qquad (2a)$$

or if PI>27, then

$$c=60.3-(0.86\ \text{PI}) \qquad (2b)$$

and

$$\phi=34.54e^{-0.0520\ (\text{PI})} \qquad (3)$$

Calculated values of c and ϕ agree reasonably well with values obtained in West Tennessee by the U.S. Army Corps of Engineers using more expensive, conventional methods such as the traxial-shear and unconfined-compression tests.

The pinhole-dispersion test is a relatively new technique developed to assess the potential for erosion by dispersion or deflocculation in cohesive materials (Sherard and others, 1976; Grissinger and others, 1981; Acciardi, 1982). Using the pinhole-dispersion technique, Grissinger and others (1981) calculated a maximum noneroding pinhole velocity (PV) and successfully related it to average erosion rates in undisturbed bank materials of West Tennessee and northern Mississippi. For this study, relatively undisturbed samples were collected for the pinhole-dispersion test with a split-spoon sampler in order to maintain as much of the material's in situ characteristics as possible (E.H. Grissinger, U.S. Department of Agriculture, Agricultural Research Service, oral commun., 1983). Unit soil weights used in the calculation of critical bank height H_c were compiled from Corps of Engineers' boring logs. Similar data for the Cane Creek basin were obtained by Lohnes and Handy (1968).

CHARACTERISTICS OF THE CHANNEL ALLUVIUM

Three hundred and sixty-six samples of channel alluvium were grouped as follows: bank material (244 samples), bed material (100 samples), and recent deposits (22 samples) (supplement A). Generalizations regarding noncohesive deposits are based largely on comparisons of median grain size (d_{50}) and the degree of sorting (Osterkamp and others, 1982). Mean d_{50} values for most of the sand-bed channels in West Tennessee fall within the medium-sand-size class (0.25–0.50 mm). Sorting can be equated by the gradation index (G) (Schumm and Khan, 1972):

$$G=1/2\frac{d_{84}}{d_{50}}+\frac{d_{50}}{d_{16}} \qquad (4)$$

where d_{84}, d_{50}, and d_{16} are particle sizes for which 84, 50, and 16 percent, by weight, of the sample is of finer diameter. In this report, a well-sorted sand is considered to have a gradation index of 2.00 or less. Erodibility of the loess-derived materials may be indicated by a lack of plasticity, low percentages of clay, and low pinhole velocities.

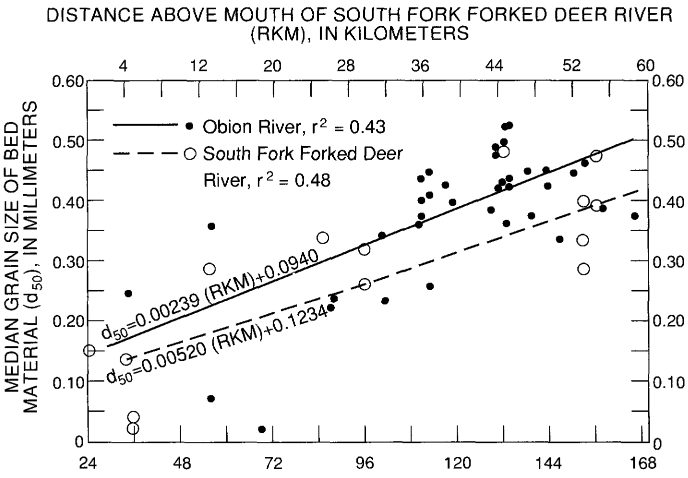


FIGURE 8.—Downstream decrease in grain size of bed material on the main stem and forks of the Obion River and South Fork Forked Deer River.

BED MATERIAL

Most bed material of West Tennessee channels is unconsolidated and highly mobile. Exceptions occur in places along Cub, Porters, and Meridian Creeks, where beds of relatively stiff clay crop out from the Claiborne and Wilcox Formations, and the Porters Creek Clay of the Midway Group. Bed-material sample statistics for each of the 14 streams studied are listed in supplement B.

OBION RIVER BASIN

Bed material of the major rivers in the Obion River basin, including the main stem and the North, South, and Rutherford Forks, is virtually devoid of fine material. Only the most downstream reaches of the Obion River main stem contain any clay (5 percent of the samples) or more than 1 percent of silt plus clay (SC; 13 percent of the samples). The relation between median grain size of the bed material and distance along the Obion River system portrays the theoretical, progressive downstream decrease in grain size (fig. 8). Mean d_{50} values for the forks of the Obion River fall in the medium-sand-size class, and no sample has a d_{50} coarser than 0.53 mm (supplement B). Bed material in these streams is well sorted and the mean gradation index is 1.51 (S_E=0.03). The lack of fine-grained material on the beds of the forks of the Obion suggests that stream power is sufficient, even in aggrading reaches, to transport silt and fine sand delivered from eroding banks and upstream discharges.

The bed material of Hoosier Creek, a tributary to the North Fork Obion River, can be considered typical of the smaller streams draining loess deposits in West Tennessee. Mean d_{50} (0.021 mm, n=3) is within the medium-silt-size class, the average clay content is 16 percent, and the plasticity index (PI) is low (≤9).

FORKED DEER RIVER BASIN

The relation between median grain size and river kilometer in the Forked Deer River system is somewhat obscured by bimodal particle-size distributions. In contrast to the Obion River system, two-thirds of the 21 bed-material samples include more than 1 percent SC. These fine particles are relatively unrelated to hydraulic conditions in a given reach (Leopold and others, 1964) and make comparisons between particle size and sediment transport difficult. Nevertheless, a downstream reduction of median grain size is indicated on the South Fork Forked Deer River by the available data (fig. 8). No such trend could be established for the North Fork owing to the greater number of samples containing fine material (fig. 9). The North Fork Forked Deer River is the only major river studied whose headwaters do not extend into the outcrop areas of the sandier Tertiary formations (fig. 2). Mean d_{50} values for the North and South Forks still fall close to the fine- to medium-sand boundary at 0.24 mm (n=12) and 0.27 mm (n=8), respectively.

Pond Creek flows across Quaternary loess and into the North Fork Forked Deer River at river kilometer 16.1. Like Hoosier Creek in the Obion River basin, bed-material characteristics reflect the creek's geologic setting, namely, a mean d_{50} in the medium-silt range (0.023 mm; n=5), a mean clay content of 15 percent, and a mean silt-plus-clay content of 87 percent. Other sample statistics are listed in supplement B.

Meridian Creek drains to the South Fork Forked Deer River near Jackson and is cut into the Tertiary Claiborne and Wilcox Formations. The sands are well sorted (G≤1.64) and the mean d_{50} is approximately 0.35 mm. A relatively stiff gray clay occurs in several places along the channel bottom and may serve as a local control of bed level. A sample of this material contained 40 percent clay, had a plasticity index of 13, and was estimated to be moderately cohesive (c=26.3 kPa).

HATCHIE RIVER BASIN

The four tributary streams studied in the Hatchie River basin can be separated into two groups on the basis of geographic location and the geologic units into which they cut (fig. 2). Cane Creek and one of its tributaries, Hyde Creek, are located in the lower Hatchie River basin and flow across loess deposits of Quaternary age. Cub Creek and Porters Creek occupy adjacent watersheds in the Hatchie River basin near the Mississippi State line and flow through the Porters Creek Clay and Clayton Formation of Tertiary age (fig. 2).

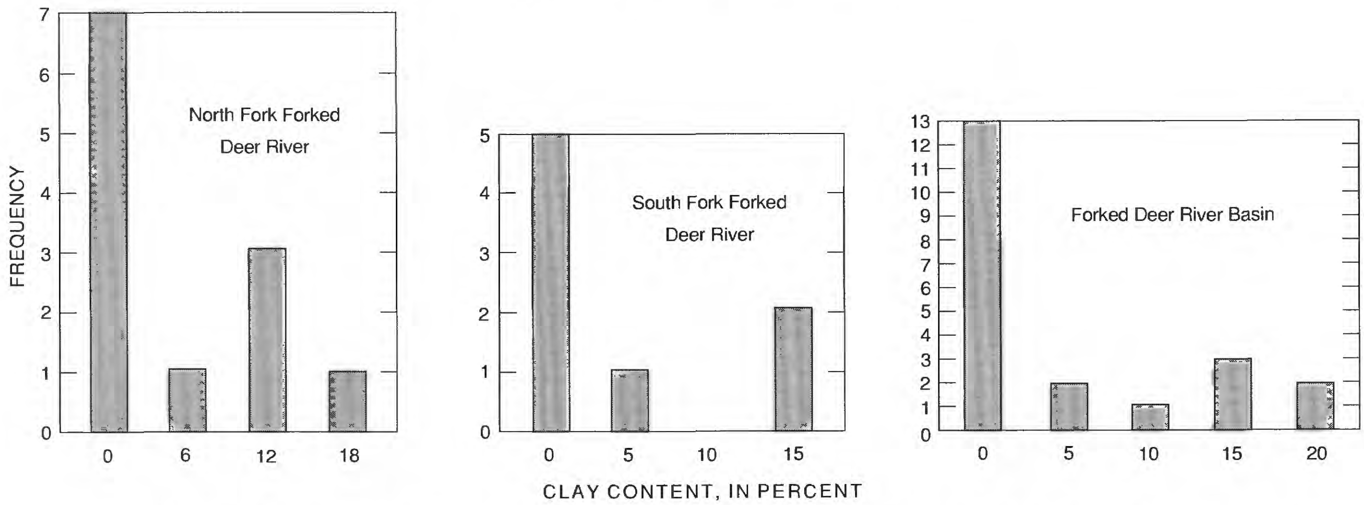


FIGURE 9.—Frequency histograms of clay content in bed-material samples of the Forked Deer River basin.

Mean d_{50} on the Hatchie River main stem is medium sand (0.35 mm), similar to the other large rivers of the region. Values for the gradation index and the sand-plus-clay content appear to be quite variable, ranging from 1.42 to 21.8, and from 0 to 46 percent, respectively. It is assumed from field observation and discharge records that this highly sinuous channel is of low energy and maintains the ability in some reaches to deposit fine-grained material on the bed.

Sixteen bed-material samples were collected from Porters and Cub Creeks. In heavily degraded reaches such as upper Porters Creek, resistant clay beds of the Porters Creek Clay have been exposed. This material tends to erode from the bed as chips, or small blocks, and abrades to rounded sand-sized particles. Fluvial transport of these clay balls is probably governed by hydraulic forces, and in this regard, the clay balls do not behave as a typical suspension of deflocculated clays. Samples of this material have PI values up to 20, implying greater plasticity and cohesion than other fine-grained material making up the channel alluvium of West Tennessee streams. Estimated values of cohesion are at least 74 percent greater (33.3 kPa) than the mean cohesion value for the loess of the Cane Creek basin (19.1 kPa). In aggrading and transporting reaches, bed material is composed primarily of well-sorted ($G \leq 2.12$), medium-to-coarse sand from the Clayton Formation.

Bed material of Cane and Hyde Creeks typifies that of other tributary basins of the lower Hatchie River. It is predominantly medium silt and the mean d_{50} is 0.026 mm ($n=7$). Mean PI is low (5.8). This lack of plasticity, which is characteristic of both the bed and bank material, indicates an increased potential for erosion when saturated. The striking similarity among bed-material properties of small loess-bed streams throughout the region is demonstrated in table 3.

TABLE 3.—*Mean bed-material properties for loess-bed creeks with less than 260-square-kilometer drainage area*

[mm, millimeters]

Stream	Basin	d_{50} (mm)	Clay (percent)	Silt + clay (percent)	Plasticity index
Cane Creek	Hatchie	0.028	17	85	6.0
Hoosier Creek	Obion	.021	16	93	9.0
Hyde Creek	Hatchie	.024	15	93	5.7
Pond Creek	Forked Deer	.023	15	87	8.5

BANK MATERIAL

Bank material of West Tennessee channels is dominated by extensive deposits of loess-derived alluvium and, to a much lesser degree in the eastern part of the region, by Tertiary clay beds. In contrast to the sandy beds of the majority of the channels studied, West Tennessee bank material is predominantly fine grained (see supplement C). General characteristics can be derived from frequency histograms (fig. 10). Class intervals of 10 and 20 percent clay (fig. 10*C*), plasticity index intervals of 8 and 16 (fig. 10*D*), and a maximum non-eroding pinhole velocity class of 0.8 m/s (fig. 10*E*) are representative of the loess-derived sediments. The interbedded clays of the eastern Tertiary formations characteristically are more plastic and have greater percentages of clay and greater pinhole velocities (figs. 10*C*–10*E*).

Banks of Cane, Hyde, Hoosier, and Pond Creeks that are loess derived tend to be the most erodible and subject to failure. Materials of the Cane Creek basin tend to be the least plastic and are highly dispersive, possibly because of high concentrations of sodium in the pore water (Grissinger and others, 1981). Mean pinhole veloc-

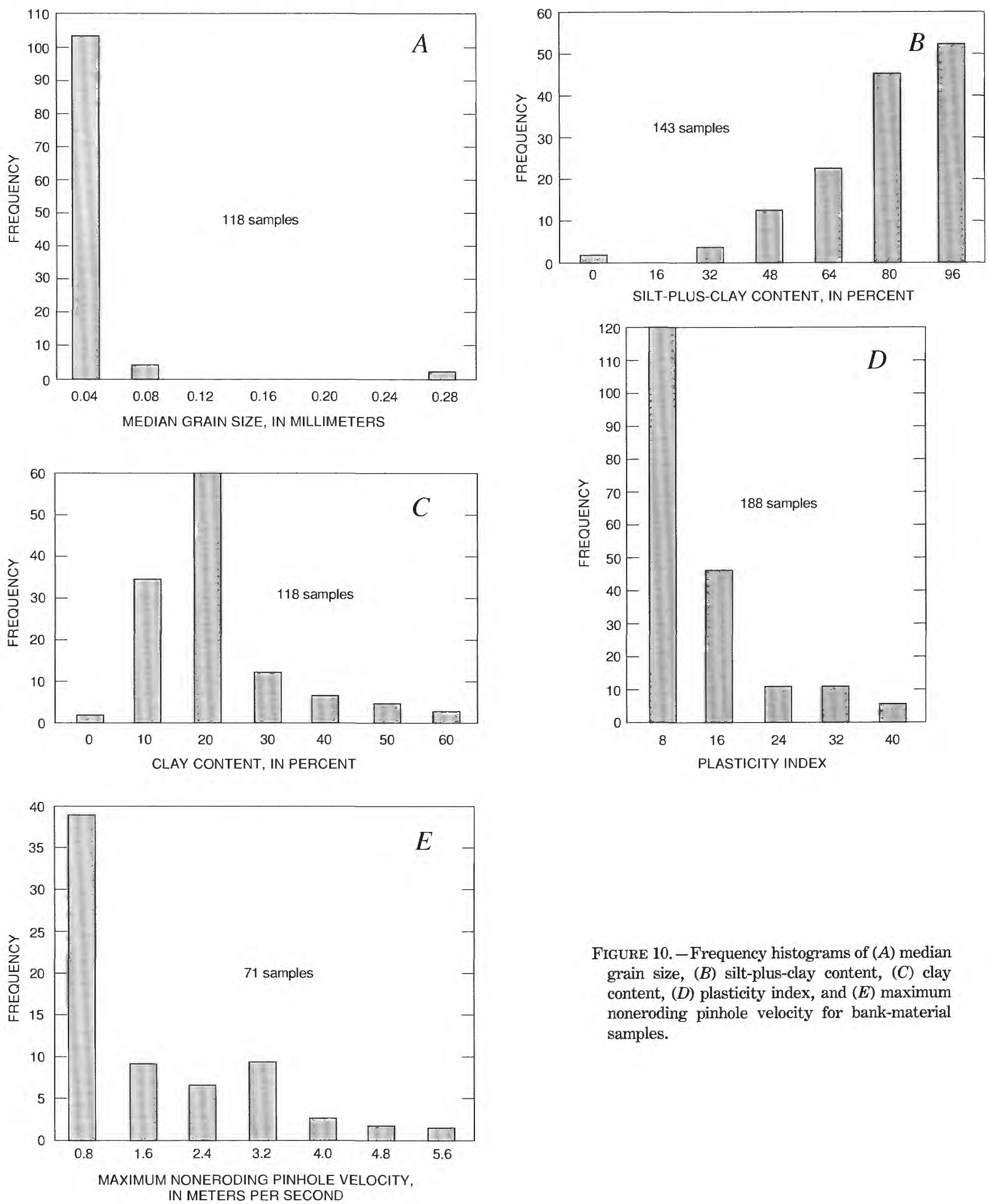


FIGURE 10.—Frequency histograms of (*A*) median grain size, (*B*) silt-plus-clay content, (*C*) clay content, (*D*) plasticity index, and (*E*) maximum noneroding pinhole velocity for bank-material samples.

ities for Cane and Hyde Creeks are the lowest in the region: 0.56 m/s (n=8) and 0.53 m/s (n=3), respectively. Samples from Hoosier and Pond Creeks are also somewhat dispersive (mean PV=0.93 m/s) but not as strongly as those from the Cane Creek basin. Mean pinhole velocity rates of 0.93 m/s (n=5) and 0.98 m/s (n=9) for the South and North Forks Forked Deer River also suggest the presence of some dispersive bank material.

In contrast to the relatively dispersive nature of the loess-derived alluvium, pinhole velocity rates obtained from Cub and Porters Creeks indicate the nondispersive tendencies of deposits from the Tertiary Midway Group. Mean pinhole velocity rates for these two creeks are the highest recorded in this study and are both greater than 3.0 m/s (supplement C). The distribution of mean pinhole velocity rates among the streams studied is shown in figure 11.

West Tennessee bank material is generally low to moderately plastic, the mean PI values ranging from 5.6 (Cane Creek) to 18.1 (Obion River). The general relations between percent clay and plasticity index, and between percent clay and calculated cohesion for West Tennessee streams are shown in figure 12. In many bank samples plasticity index was indeterminate due to a lack of clay.

RECENT DEPOSITS

Twenty-two samples of recent fluvial deposits were collected from accreting bank surfaces on eight sand-bed streams (see supplement D). Such materials on banks and flood plains are not found in degrading reaches and are diagnostic of aggrading conditions on the bed. Samples were devoid of clay, and mean silt-plus-clay values did not exceed 11 percent, indicating that most fine-grained material is transported through the aggrading reaches. As expected, the mean d_{50} value for recent deposits for each stream is finer than the corresponding mean d_{50} value for bed material. Mean d_{50} for the 22 samples is 0.22 mm (fine sand), and the deposits are very well sorted (mean G=1.62).

Recent deposits on Cane, Hoosier, Hyde, and Pond Creeks are composed of silt. However, much of the silt- and clay-size fractions are apparently transported through the system, thereby maintaining large channel capacities and stream power. Reestablishment of stable conditions along these loess-type streams can be somewhat delayed because of suppressed rates of aggradation and bank accretion. Geobotanical evidence from aggrading reaches on Cane and Cub Creeks, and on the Rutherford Fork Obion River, indicates rates of bank accretion ranging from 0.05 to 0.07 m/yr (Hupp and Simon, 1986).

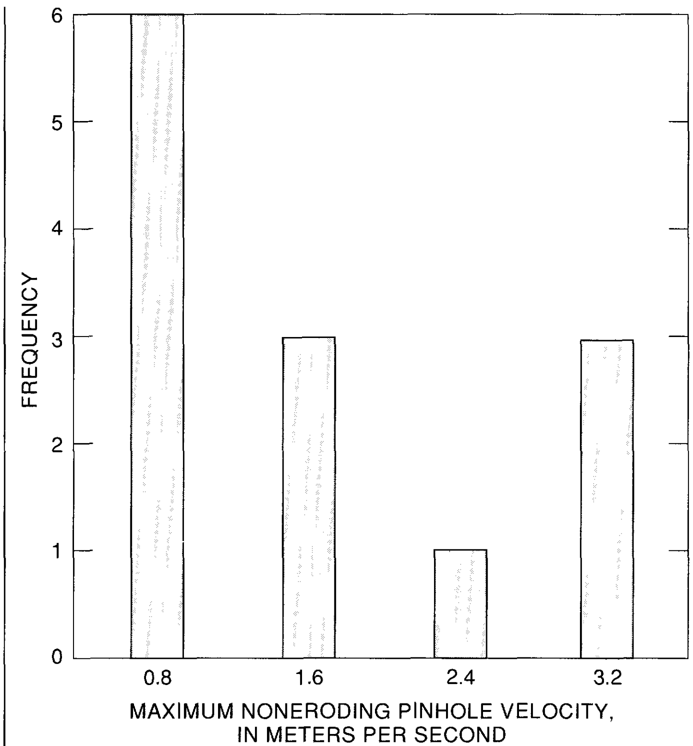


FIGURE 11.—Frequency histogram of mean maximum noneroding pinhole velocity for studied streams (see supplement C).

BED-LEVEL ADJUSTMENT PROCESSES AND TRENDS

Channel adjustment in modified West Tennessee streams refers to channel changes that take place in response to imposed increases in energy conditions. Observed adjustments in these channels and their tributaries include incision, headward degradation and resulting bank instabilities, and downstream aggradation. The results of this study focus on gradation processes and identify longitudinal trends of channel response that may be useful to predict channel changes over time and space.

Bed-level adjustments at gaged sites are determined from specific-gage elevation data for the period just prior to and following channelization activities (Blench, 1973). Trends in specific-gage elevation with time based on annual data serve as examples for the ungaged, but periodically surveyed sites. Gradation processes at a site, through time, can be described by power-decay equations that take the general form

$$E=a(t)^b, \tag{5}$$

where

E =elevation of the bed or water surface for a given year, in meters above sea level;

a =premodified elevation of the bed or water surface, in meters above sea level;

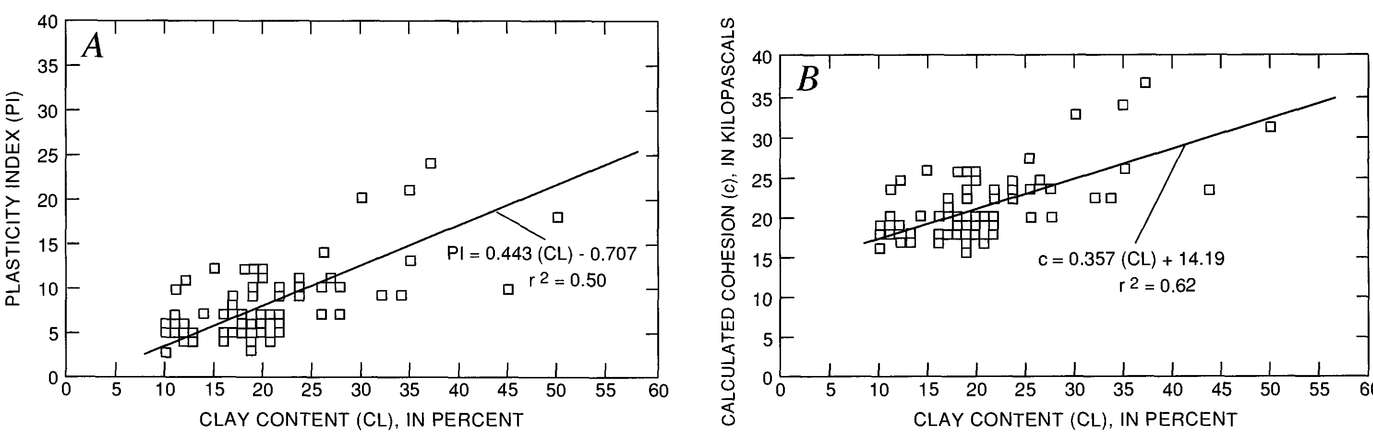


FIGURE 12.—Derived relations (*A*) between clay content and plasticity index and (*B*) between clay content and calculated cohesion for bank-material samples containing more than 10 percent clay.

t = time since the year prior to start of the gradation process (t_0), in years, where t_0=1.0; and

b = dimensionless exponent determined by power regression, indicative of the nonlinear rate of change on the bed.

Adjustment rates obtained by using equation 5 are initially rapid and then diminish as the slope of the curve becomes flat with increasing time (fig. 13). The sign of b denotes the particular gradation process that occurs over the period of time: negative for degradation and positive for aggradation. The effect of the datum (a in equation 5) is found not to affect the statistical significance of b at the 0.001 level. If a different datum were used, individual b values would change. However, trends of b over time and space would remain consistent.

Periodic bed-level data from ungaged sites are consistent with equation 5 (fig. 14). To facilitate channel gradient computations between a gaged and an ungaged site, values of a (equation 5), representing the premodified water-surface elevation, are discarded and replaced with the premodified elevation of the bed. These predisturbed bed elevations are obtained either from dredging plans or from other channel surveys that predated the channel work.

The magnitude of b in equation 5 reflects the nonlinear rate of degradation or aggradation at a site, through time. As such, it is used as the dependent variable in regression analyses for determination of systematic bed-level adjustments along the fluvial networks of West Tennessee. A summary of nonlinear gradation rates

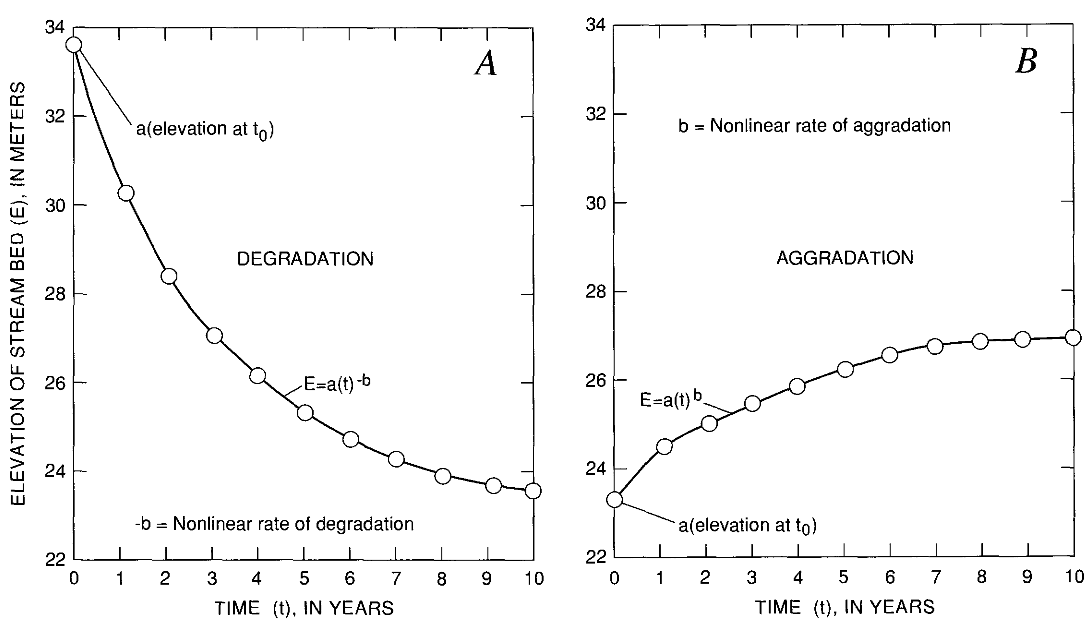


FIGURE 13.—Idealized representation of the applicability of power equations to describe (*A*) degradation and (*B*) aggradation through time.

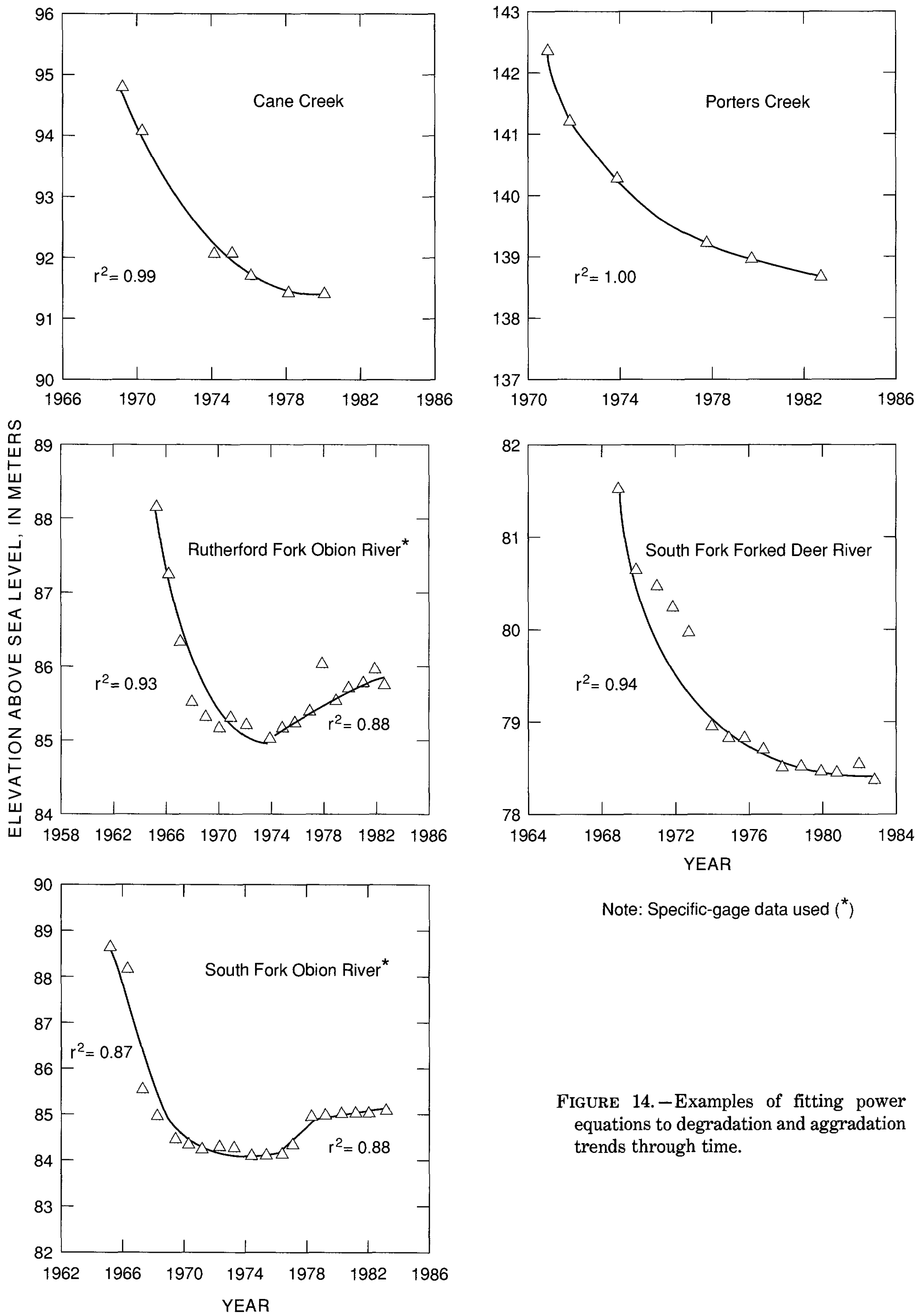


FIGURE 14.—Examples of fitting power equations to degradation and aggradation trends through time.

calculated by regression of a power function, and equation statistics is given in table 4. Relations that are not significant at the 95 percent confidence limit are included in table 4 to increase the geographical distribution of the data set.

DEGRADATION

In modified West Tennessee channels, degradation is induced primarily by downstream increases in channel gradient and capacity and, to a lesser degree, by the

TABLE 4.—*Sites with calculated gradation rates*

[b, nonlinear gradation rate; n, number of observations; r^2, coefficient of determination; RKM, river kilometer; t_O, start of observed gradation process; —, data not available; Do, ditto]

Stream	b	n	r^2	RKM	t_O
Cane Creek	−0.00989	6	0.91	26.60	1969
Do.	−.01620	7	.99	23.89	1969
Do.	.00168	2	—	23.89	1980
Do.	−.02022	4	1.00	20.24	1969
Do.	.01052	2	—	20.24	1980
Do.	−.03300	3	1.00	14.46	1969
Do.	.00770	2	—	14.46	1980
Do.	−.03131	2	—	10.09	1969
Do.	.00352	2	—	10.09	1980
Do.	−.04126	3	.91	6.53	1969
Do.	−.02011	4	.92	4.06	1969
Do.	.00835	2	—	4.06	1980
Cub Creek	−.00243	3	.69	11.13	1969
Do.	−.00342	3	.87	9.22	1969
Do.	−.00565	4	.88	3.48	1969
Do.	−.00905	5	.91	2.48	1969
Do.	.00272	2	—	2.48	1976
Hoosier Creek	−.00843	3	1.00	8.29	1967
Do.	−.01130	4	.94	4.81	1966
Do.	−.02081	3	.67	.88	1965
Do.	.00274	2	—	.88	1968
Do.	−.02630	3	.99	.02	1965
Hyde Creek	.00281	2	—	3.81	1975
Do.	−.00737	2	—	3.81	1969
Do.	−.01070	4	.92	2.22	1969
Do.	−.01380	3	.99	1.19	1969
Do.	−.02050	4	1.00	.02	1969
Meridian Creek	−.00326	3	.99	5.94	1965
Do.	−.00580	4	.98	4.73	1964
Do.	−.00341	3	.99	2.41	1969
Do.	−.00190	3	.99	1.54	1967
North Fork					
Forked Deer River	−.00740	4	.95	38.46	1977
Do.	−.01076	5	.52	32.47	1974
Do.	−.00839	4	.96	30.28	1978
Do.	−.01720	10	.95	8.53	1973*
Do.	−.02297	3	.87	6.16	1972
North Fork					
Obion River	.00111	15	.69	59.37	1969*
Do.	−.00206	2	—	42.48	1979
Do.	−.00490	2	—	33.95	1975
Do.	−.00372	13	.80	28.96	1972*
Do.	−.01240	6	.93	15.83	1965*
North Fork Obion River—Continued					
Do.	−.02470	4	0.85	9.49	1965*
Do.	.00303	5	.89	9.49	1967*
Obion River	−.02220	10	.95	110.22	1965*
Do.	.00463	10	.74	110.22	1974*
Do.	−.04030	4	.81	100.08	1965*
Do.	.00235	16	.76	100.08	1968*
Do.	.00908	19	.93	86.40	1965*
Do.	.00518	15	.84	55.03	1963*
Do.	.00585	16	.74	33.47	1960*
Pond Creek	−.00828	5	.81	18.29	1977
Do.	−.00799	4	.84	15.80	1977
Do.	−.01233	4	.97	11.78	1977
Do.	−.00900	5	.79	1.71	1977
Porters Creek	−.01069	7	1.00	27.51	1971
Do.	−.01320	7	.99	18.02	1971
Do.	−.00578	6	1.00	14.30	1971
Rutherford Fork					
Obion River	.00149	19	.60	48.11	1965*
Do.	−.00317	4	.91	28.80	1977
Do.	−.00493	3	1.00	24.46	1977
Do.	−.00991	4	.79	16.73	1972
Do.	.00356	4	.99	16.73	1977
Do.	−.01728	9	.93	7.88	1965*
Do.	.00433	9	.88	7.88	1974*
South Fork					
Forked Deer River	−.00895	6	.59	44.41	1976
Do.	−.00950	10	.92	26.23	1974*
Do.	−.00978	5	.76	21.40	1969
Do.	−.01264	5	.96	19.15	1969
Do.	−.01630	15	.94	12.71	1969*
Do.	.01180	13	.92	5.31	1969*
South Fork					
Obion River	−.02430	11	.87	9.33	1965*
Do.	.00544	9	.88	9.33	1975*
Do.	.00133	13	.90	55.35	1969*
Do.	−.00054	4	.26	45.70	1972
Do.	−.00238	6	.50	37.33	1972
Do.	−.00661	7	.90	30.89	1977*
Do.	−.00573	5	.87	27.03	1972
Do.	−.00932	4	.94	18.34	1972

*Specific gage data used; where n is low, statistical significance may be limited.

removal of riparian vegetation. These changes result in a stream power that is more than sufficient to transport the bed material delivered from upstream. Thus, the bed of the channel degrades headward to increase bed-material transport and to reduce channel gradient.

All reaches of a fluvial network do not degrade simultaneously; rather, the gradation process moves upstream from the disturbance episodically, as threshold conditions along the bed are exceeded. At some distance downstream of the advancing knickpoint, the critical-

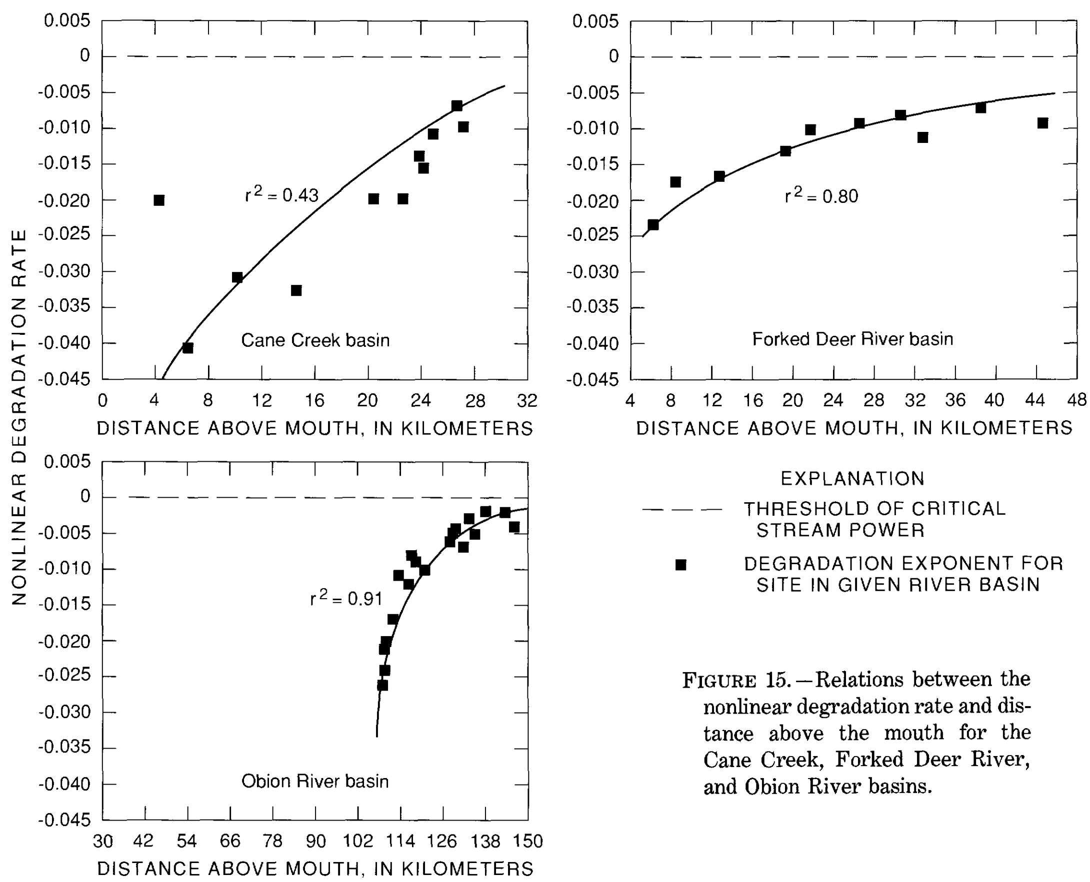


FIGURE 15.—Relations between the nonlinear degradation rate and distance above the mouth for the Cane Creek, Forked Deer River, and Obion River basins.

power threshold (Bull, 1979) may become less than 1.0 through gradient reduction and enhanced sediment delivery from upstream. If the trunk stream is not degrading, aggradation becomes the dominant gradation process in the most downstream reaches. Although no specific time lag between degradation and aggradation in a given downstream reach is implied, aggradation can occur almost immediately downstream from a knickpoint if stream power is insufficient to transport the increased loads. A given upstream reach, however, does display a lag between the two gradation processes. A phase of degradation first takes place for a period of time (10–15 years) as the knickpoint moves upstream through the reach and reduces channel gradient. Migration of the erosion zone farther upstream supplies the reach with heightened loads that cannot be transported through the flattened reach. Aggradation then begins, and bed level recovers.

LOCATION IN FLUVIAL NETWORK

Values of $-b$ and river kilometer (RKM) data are regressed by basin to (1) test the hypothesis that longitudinal degradation trends can be defined throughout a basin network by site-specific power-decay equations and (2) maximize the spatial applicability of a single equation. Some values of $-b$ are not statistically significant but are included to show consistency of trends. Degrading sites are divided into the Cane Creek, Forked Deer River, and Obion River basins to establish degradation trends throughout these three fluvial networks. River kilometer is calculated for each of the basins from the mouth of the trunk stream except in the case of the Forked Deer River basin, for which it is calculated from the confluence of the North and South Forks. Streams of the upper Hatchie River basin are not included in this analysis because they are not tributary to one another.

Plotted trends indicate the nonlinear decrease in degradation with distance upstream for sites in each of the three basins as values of $-b$ approach 0.0 (fig. 15). Linear relations are derived from these trends by logarithmic transformation and regression, resulting in predictive equations for the Cane Creek, Forked Deer River, and Obion River basins. Comparisons of observed and predicted log $|-b|$ values, the downstream limit of applicability for each of these equations, streams included in each analysis, and regression statistics are shown in figure 16. Equations for the Cane Creek and Forked Deer River basins are valid for determining degradation exponents and rates along main stem and tributary channels for most downstream reaches. In contrast to the Cane Creek and Forked Deer River basins, aggra-

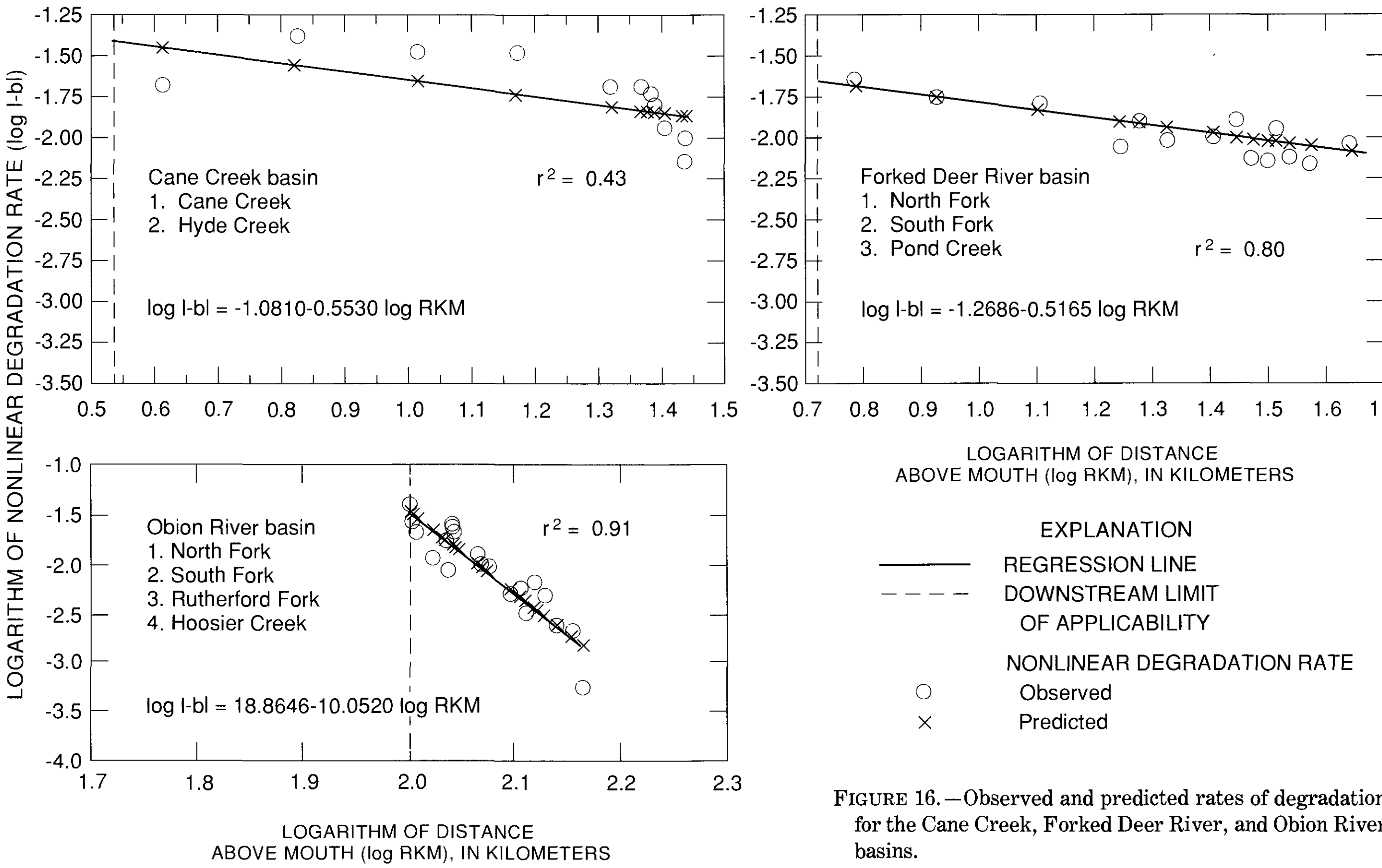


FIGURE 16.—Observed and predicted rates of degradation for the Cane Creek, Forked Deer River, and Obion River basins.

dation along the entire main stem of the Obion River restricts the use of the Obion River basin equation to reaches and tributaries above RKM 101.

To establish whether longitudinal degradation trends exist for given streams within basin networks, values of $-b$ are plotted against the corresponding distance of each site above the mouth. Examples of these plots for streams of the Obion, Forked Deer, and upper and lower Hatchie River basins again indicate that a nonlinear relation exists between $-b$ and distance upstream from the mouth (fig. 17). Regression equations describing the longitudinal variation in nonlinear degradation rates are obtained (table 5). Although the number of observations is small, systematic trends are clear, irrespective of the differences in bed-material characteristics (fig. 17, table 5).

Relations derived for Cane, Pond, Meridian, and Porters Creeks indicate relatively low r^2 values and have a small number of sites. Cane, Pond, and Meridian Creeks are responding to multiple disturbances (table 2) and complex response, making relations between $-b$ and distance upstream obscure. Sheet-pile, grade-control structures along Porters Creek serve to disrupt the longitudinal continuity of the adjustment by retarding the rate of headward degradation. This does not imply that degradation just downstream of the structure is stopped, but only that the headward migration of downcutting is temporarily halted (fig. 18).

The exclusion of Cane, Pond, Meridian, and Porter Creeks improves the mean r^2 value of the equations in table 5 to 0.87 and substantiates the nonlinear decrease in degradation with distance upstream. Thus, the nonlinear degradation rate $(-b)$ for a site can be estimated by substituting RKM into the appropriate equation (table 5) and by multiplying the absolute value of the result by -1.0. This value $(-b)$ then can be applied to b in equation 5 to estimate annual bed-level change at a site over the degradation phase of adjustment. To obtain mean rates of degradation in meters per year at a site, equation 5 is solved using the predisturbed elevation for a and is solved over a given period of time. The resulting elevations can then be subtracted from one another, and the difference divided by the span of time in years. It should be noted that actual degradation rates at a site are nonlinear with time, and mean values calculated in this fashion are only approximations. Care must be exercised that the equations in table 5 are used only for specified reaches and tributaries entering those reaches. Statistics regarding the range of nonlinear degradation rates $(|b|)$ for each stream are given in table 6.

Longitudinal trends of degradation for main stem and tributary channels are evident. The location of a partic-

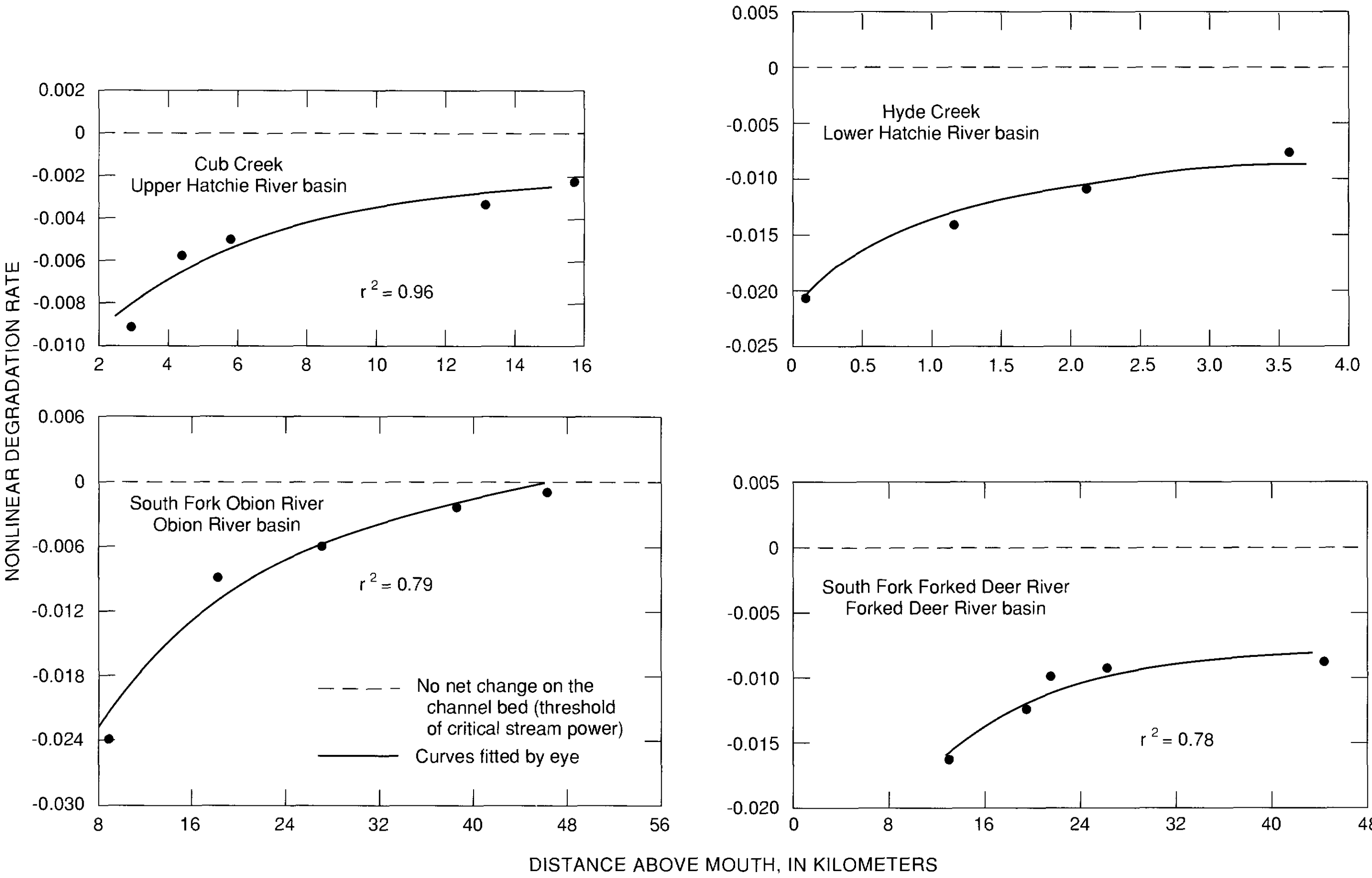


FIGURE 17.—Examples of relations between the nonlinear degradation rate and distance above the mouth for selected streams.

ular site in the fluvial network partly determines degradation rates and amounts. Refinement of predictive equations to include variables that delineate the area and magnitude of imposed disturbances is required to add further to the physical significance of the relations.

LOCATION RELATIVE TO IMPOSED DISTURBANCE

The downstream limit of applicability for the basin equations in figure 16 generally coincides with the upstream limit of dredging. Upstream migration of degradation in the Forked Deer and Obion River basins originates from these areas of maximum disturbance (AMD) in the system. On the North and South Fork Forked Deer Rivers the AMD is in downstream reaches, near RKM 4.8 and RKM 9.7, respectively, and adjacent to the upstream limit of channelization. In the Obion River system, this area is near the confluence of the North Fork and South Fork Obion Rivers, and also at the upstream end of the channelization (fig. 1). The Cane Creek channel was dredged and straightened to a relatively uniform gradient throughout its length, implying that the AMD is in the most downstream reaches, where water discharge (Q) is greatest. Streams of the upper Hatchie River basin were similarly channelized, the greatest disturbance occurring in the lower reaches. Maximum imposed changes (AMD) for the Obion and Forked Deer River basins are denoted by peak values of the imposed area-gradient index (IMAGI; a surrogate for stream power) that fall in the vicinity of the upper limit of channel work (figs. 19*B*, 19*C*). Maximum IMAGI values are recorded in the most downstream reaches of the Cane Creek and upper Hatchie River basins (figs. 19*A*, 19*D*), thereby supporting the contention that the AMD in these fully channelized streams is far downstream.

Values of the IMAGI are at their maximum either at the upstream end of channel work, or far downstream (if the entire stream was channelized). The apparent nonlinear associations between the IMAGI and RKM (figs. 19*A*–19*D*) are similar to the nonlinear associations between the resulting nonlinear degradation rate (-b) and RKM (fig. 15).

The greatest downcutting occurs either in downstream areas or in reaches just upstream of the original disturbance, depending on the geographic extent of channelization. Downcutting then diminishes asymptotically upstream (figs. 15, 17). As the knickpoint (or knick area)

TABLE 5.—*Regression equations and statistics describing the relation between nonlinear degradation rates* (|−b|) *and distance above the mouth (RKM) of studied streams*

[Although *n* values are apparently low, each data point (*n*) represents a given site along a stream and the culmination of a number of years of data at that site; r^2, coefficient of determination; —, data not available]

Stream	Equation	r^2	*n*	Approximate downstream limit (RKM)
Cane Creek	$\lvert -b \rvert = 0.0602(\mathrm{RKM})^{-0.3918}$	0.32	7	0
Cub Creek	$\lvert -b \rvert = 0.0167(\mathrm{RKM})^{-0.7685}$	.96	4	2.4
Hoosier Creek	$\lvert -b \rvert = 0.0148(\mathrm{RKM})^{-0.1679}$	.81	4	0
Hyde Creek	$\lvert -b \rvert = 0.0114(\mathrm{RKM})^{-0.1151}$	.81	4	0
Meridian Creek	$\lvert -b \rvert = 0.0018(\mathrm{RKM})^{0.5291}$	.51	4	0
North Fork Forked Deer River	$\lvert -b \rvert = 0.0591(\mathrm{RKM})^{-0.5456}$	.93	5	4.8
North Fork Obion River	$\lvert -b \rvert = 0.8950(\mathrm{RKM})^{-1.5738}$	.95	5	0
Obion River[1]	—	—	—	—
Pond Creek	$\lvert -b \rvert = 0.0095(\mathrm{RKM})^{-0.0104}$	.003	4	0
Porters Creek	$\lvert -b \rvert = 0.0010(\mathrm{RKM})^{0.7629}$	.35	3	7.2
Rutherford Fork Obion River	$\lvert -b \rvert = 0.2570(\mathrm{RKM})^{-1.2503}$	.93	4	0
South Fork Forked Deer River	$\lvert -b \rvert = 0.0501(\mathrm{RKM})^{-0.4815}$	.78	5	9.7
South Fork Obion River	$\lvert -b \rvert = 0.3160(\mathrm{RKM})^{-2.0222}$	.79	6	0

[1]All reaches aggrading.

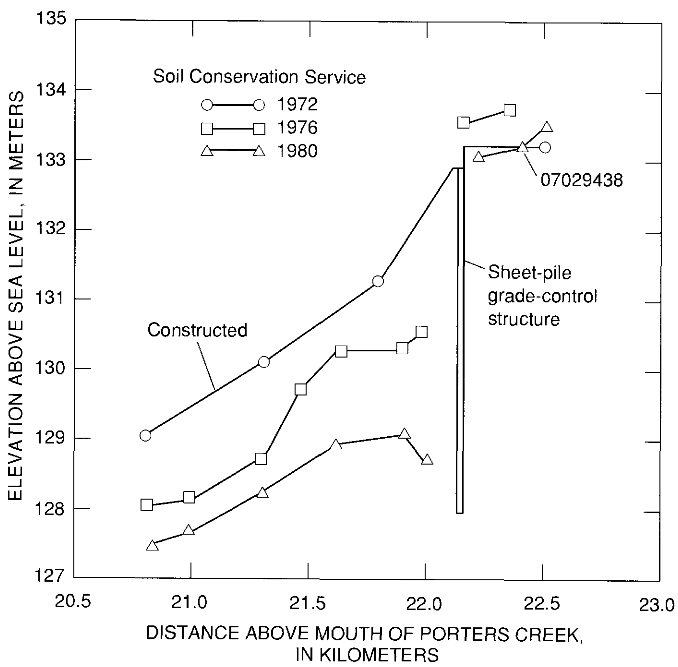


FIGURE 18.—Example of degradation just downstream from grade-control structure, on Porters Creek following channelization.

TABLE 6.—*Range of nonlinear degradation rates by stream*

[Values are negative; —, data not available; Min., minimum; Max., maximum; *n*, number of observations]

Stream	Mean	Min.	Max.	*n*
Cane Creek	0.02457	0.00989	0.04126	7
Cub Creek	.00514	.00243	.00905	4
Hoosier Creek	.01671	.00843	.02630	4
Hyde Creek	.01309	.00737	.02050	4
Meridian Creek	.00359	.00190	.00580	4
North Fork Forked Deer River	.01334	.00740	.02297	5
North Fork Obion River	.00956	.00206	.02470	5
Obion River[1]	—	—	—	—
Pond Creek	.00940	.00799	.01233	4
Porters Creek	.00989	.00578	.01320	3
Rutherford Fork Obion River	.00882	.00317	.01728	4
South Fork Forked Deer River	.01143	.00895	.01630	5
South Fork Obion River	.00815	.00054	.02430	6

[1]All reaches aggrading.

proceeds upstream, the stream progressively erodes less material from the channel bed but still reduces channel gradients downstream from the knickpoint. Stream power, although heightened near the knickpoint, is similarly less intense with distance upstream. A point is reached some distance upstream where the increase in stream power due to the advancing knickpoint (available stream power) is insufficient to overcome bed resistance (critical stream power) and the threshold of critical power. Degradation is thereby abated. The threshold and quasi-equilibrium conditions are apparently approached asymptotically during the waning stages of degradation at a site (fig. 14) and with distance upstream (figs. 15, 17). The observed data demonstrate that quasi-equilibrium conditions, with respect to degradation, are temporally and spatially approached asymptotically. This is in general agreement with the more theoretical discussions of the threshold of critical stream power (Bull, 1979) and channel adjustment.

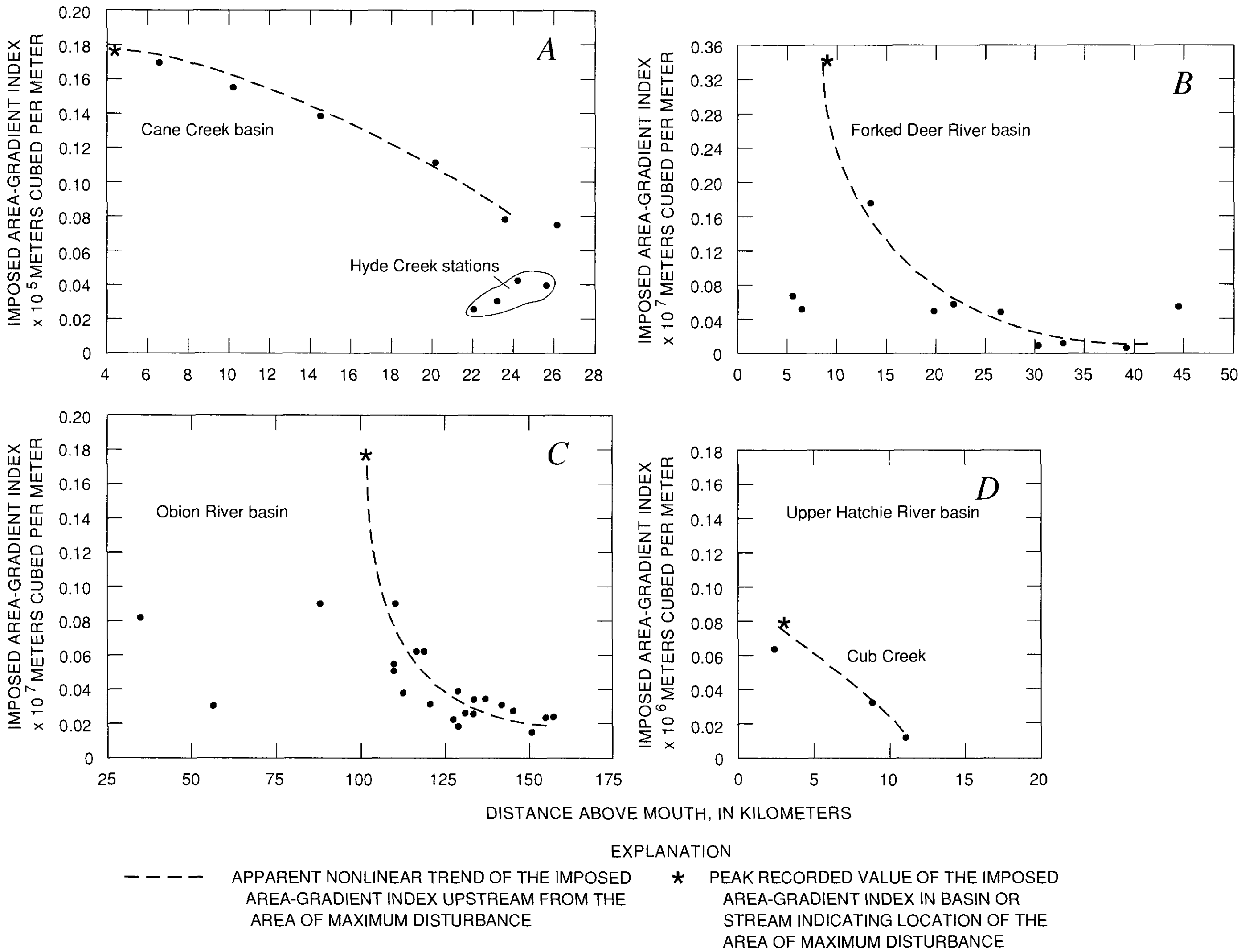


FIGURE 19.—Longitudinal variation in the imposed area-gradient index, indicating area of maximum disturbance, for (*A*) Cane Creek, (*B*) Forked Deer River, (*C*) Obion River, and (*D*) upper Hatchie River basins (see supplement E).

MAGNITUDE OF IMPOSED DISTURBANCE AND DISTURBANCE PARAMETERS

Channel gradient is an important dependent variable to channel adjustment (Mackin, 1948; Lane, 1955) and, as such, can be used as a measure of the magnitude of imposed changes. Percent increase in gradient and percent shortened (also a gradient increase) are used as the two primary measures of channel disturbance. Because not all adjusting reaches have been channelized directly but are still responding to changes imposed downstream, these two parameters are each further subdivided to describe two types of imposed disturbance as follows: (1) those made directly to a particular reach (type I) and (2) those made to downstream reaches and therefore serving as an indirect inducement to upstream adjustment (type II).

Type I disturbances are represented by variables that describe the percent change of gradient in a reach (DSLR) and the percent shortening in a reach (RSH) as a direct result of channel modifications. Type II disturbances depict changes imposed only on downstream reaches of channels and are calculated from the mouth of the channel to the site in question. Variables describing type II disturbances are termed "total gradient change" (DSLT) and "total shortening" (TSH). All four parameters (DSLR, RSH, DSLT, and TSH) are expressed as percentages and are merely a comparison of channel gradients and channel lengths before and after channel alteration (table 7). The minimum and maximum values of imposed gradient and length changes have been summarized for each stream (table 8). Disturbance-parameter data for all sites are listed in supplement E.

TABLE 7.—*Types, definitions, and applications of various disturbance parameters*
[do and Do, ditto]

Disturbance type	Parameters	Expressed as	Type of modification	Extent of modification	Calculated
I	RSH	Percent shortened	Dredging and straightening.	All reaches.............	Within each reach.
	DSLR	Percent increase in gradient.	Dredging...........	......do...............	Do.
II	TSH	Percent shortened	Dredging and straightening.	Only downstream reaches.	From mouth to given site.
	DSLT	Percent increase in gradient.	Dredging...........	......do...............	Do.

TABLE 8.—*Range of disturbance-parameter values by stream*
[DSLR, gradient change in reach; DSLT, gradient change from mouth; RSH, shortening in reach; TSH, shortening from mouth; all parameter values expressed as percent; —, data not available; Max., maximum; Min., minimum; *n*, number of observations]

Stream	DSLR		DSLT		RSH		TSH		*n*
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	
Cane Creek	−1.4	168	49	168	6.7	43.8	30.8	38.8	7
Cub Creek	1.6	23	5.6	11	1.7	18.9	7.4	18.9	4
Hoosier Creek.......................	−11	606	72	228	0	3.6	1.9	3.6	4
Hyde Creek..........................	−.8	107	12	53	6.7	38.8	13.4	38.8	4
Meridian Creek[1]	—	—	—	—	—	—	—	—	4
North Fork Forked Deer River	−23	198	−23	74	0	34.9	8.2	34.9	5
North Fork Obion River.............	0	142	26	177	0	3.4	.6	3.4	6
Obion River.........................	−47	161	−13	2.0	0	42.4	0	18.8	5
Pond Creek	0	0	0	0	0	0	0	0	4
Porters Creek.......................	34	86	50	86	24.1	38.0	33.8	38.9	3
Rutherford Fork Obion River.........	0	60	16	60	0	0	0	0	5
South Fork Forked Deer River	0	181	22	67	0	42.1	8.9	42.1	6
South Fork Obion River.............	0	476	−13	476	0	0	0	0	7

[1]Multiple disturbances.

The type and longitudinal extent of channel modifications along a given stream or basin network determine the applicability of particular disturbance parameters to depict mathematically the degree of disruption and subsequent adjustment to the fluvial system. Linear regression analysis of disturbance-parameter data with degradation data (log $|-b|$) suggests that percent-shortening indices result in less scatter (higher r^2 values) than when using gradient-change indices as independent variables for those streams that have been shortened.

Percent shortening of a reach (RSH) would be expected to be the most significant disturbance parameter for Cane, Cub, Hyde, and Porters Creeks, where channels were straightened throughout their lengths. This is supported by r^2 values of 0.85 for Cane Creek and 0.84 for Cub Creek (table 9). A relation for Porters Creek could not be established due to the presence of sheet-pile, grade-control structures located between sites. The lack of significant correlation between log $|-b|$ and RSH, or between log $|-b|$ and any other disturbance parameter for Hyde Creek is attributed to its small drainage area (27.2 km^2). The most upstream site (07030104) drains only 17.4 km^2, some of which is located upstream from retention structures. The small drainage area suggests that imposed disturbances on Hyde Creek may be inconsequential relative to those on Cane Creek, the trunk stream. In fact, the maximum IMAGI along Hyde Creek (4.51×10^4 m^3/m) is less than the minimum IMAGI for Cane Creek (8.21×10^4 m^3/m) and is less than the mean IMAGI for any stream studied (supplement E). The Hyde Creek channel apparently is responding to changes imposed on Cane Creek that have migrated up the tributary.

Degradation trends along streams experiencing type II straightening disturbances are best described by percent shortening relative to the mouth (TSH). These streams include Hoosier Creek, North Fork Forked Deer River, North Fork Obion River, and the South

TABLE 9.—*Appropriate disturbance parameters and selected statistics for estimating the dependent variable log* |−b| *for degrading streams*

[Appropriate disturbance parameter as determined by type and extent of channel modification (table 7); r^2, coefficient of determination; n, number of observations; —, data not available]

Basin and stream	Appropriate disturbance parameter	log [|−b|] r^2	n
Cane Creek	RSH	0.58	11
Cane Creek	RSH	.85	7
Hyde Creek	—	—	—
Forked Deer River	TSH	.92/[1].81	10/[1]14
North Fork Forked Deer River	TSH	.93	5
South Fork Forked Deer River	TSH	.86	5
Obion River	TSH	.86	19
Hoosier Creek	TSH	1.00	4
North Fork Obion River	TSH	.91	5
Rutherford Fork Obion River	DSLT	.92	4
South Fork Obion River	DSLT	.64	6
Upper Hatchie River	RSH	.54	7
Cub Creek	RSH	.84	4
Porters Creek	—	—	—

[1]Includes Pond Creek data.

TABLE 10.—*Statistical properties of multiple-regression analyses to estimate dependent variable log* |−b| *(degradation rates)*

[r^2, coefficient of determination; n, number of observations; RKM, river kilometer; Do, ditto]

Basin	Independent variables used	r^2	n	Approximate downstream limit (RKM)
Cane Creek	log RKM			
Do	log RSH	0.87	7	0.0
Do	log CL			
Do	log RKM	.63	11	.0
Do	[1]log RSH			
Forked Deer River[2]	log RKM			
Do	log TSH	.79	10	4.8
Do	log d_{50}			
Do	log RKM	.80	14	4.8
Do	[1]log TSH			
Obion River	log RKM			
Do	log TSH	.94	16	101
Do	log d_{50}			
Do	log RKM	.91	19	101
Do	[1]log TSH			

[1]Denotes group of parameters used.
[2]Excludes Meridian Creek data.

Fork Forked Deer River, where dredging and straightening took place only in the lower reaches (table 9). Similar direct relations between log |−*b*| and TSH were established for the Forked Deer River (excluding Meridian and Pond Creeks) and Obion River basins (table 9).

Gradient change relative to the mouth (DSLT) was most useful for describing induced degradation trends along streams that have been dredged but not altered by straightening. The Rutherford Fork and South Fork Obion Rivers are representative of type II dredged streams, and direct relations between log |−*b*| and DSLT were established for these two rivers (table 9). It is assumed that local gradient change (DSLR) would be equally appropriate for type I dredged streams, but none were available for study.

PREDICTIVE MULTIPLE-REGRESSION EQUATIONS

Independent variables that describe location in a stream or fluvial network (RKM; fig. 16) and degree of disturbance have been individually related with log |−*b*| by linear regression (table 9). To establish equations of increased reliability and applicability, multiple-regression techniques have been used.

Predictive equations are generally considered useful if they can account for a wide range of conditions over a large area. By concentrating on basinwide relations rather than relations for individual streams, greater bed-material and adjustment variability, and longer channel lengths were included in a single equation. Bed-material data, in addition to location and disturbance data, were used initially in multiple-regression analysis of degradation variability within basins, but because Cub and Porters Creeks in the upper Hatchie River basin are not tributary to one another, those analyses were performed individually.

Two- and three-parameter multiple regressions for the Cane Creek, Forked Deer River, and Obion River basins all include the appropriate basin RKM data, the specified disturbance parameter (tables 7, 9), and a bed-material term as independent variables (table 10).

The lack of clear-cut improvement in r^2 values using the additional bed-material parameter may be a matter of incongruous sediment and degradation data and (or) due to a different number of data points. Bed-material samples collected in 1983 reflect the gradation processes ongoing at that time. In contrast, the degradation data represent a range of stream-power conditions through time—from the stream-power peaks of the early stages of the degradation phase to moderating conditions that approach the threshold of critical power as degradation subsides. During the adjustment, the capacity and competence of the stream to transport bed material obviously change with changes in stream power. Some sites included in the analysis of degradation trends that were degrading through the 1970's were aggrading in the 1980's. Bed-material data at different sites, therefore,

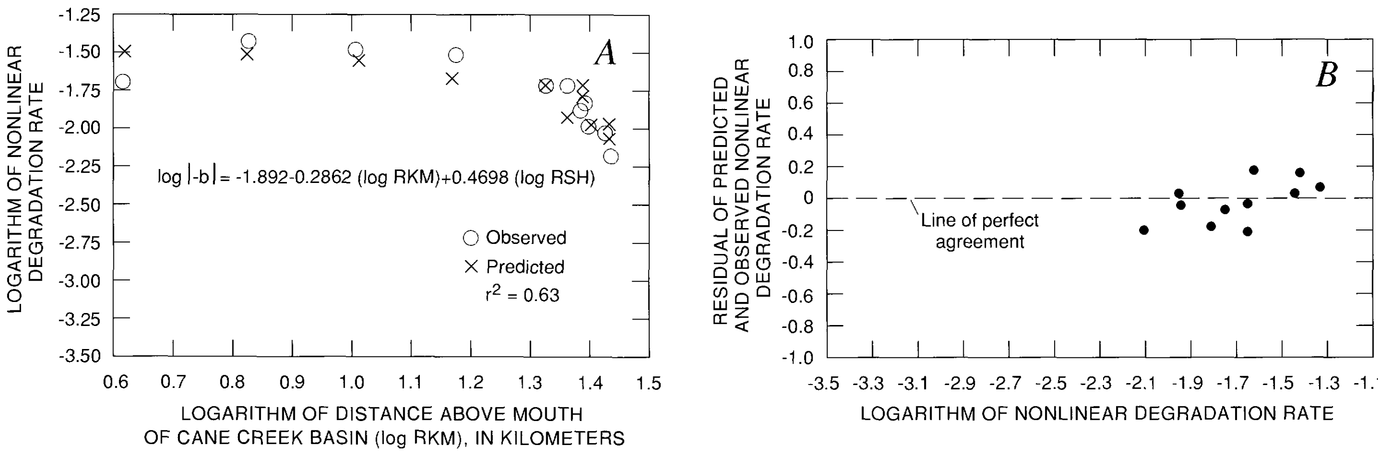


FIGURE 20.—Predicted and observed (*A*) rates of degradation and (*B*) residuals in the Cane Creek basin determined by multiple regression.

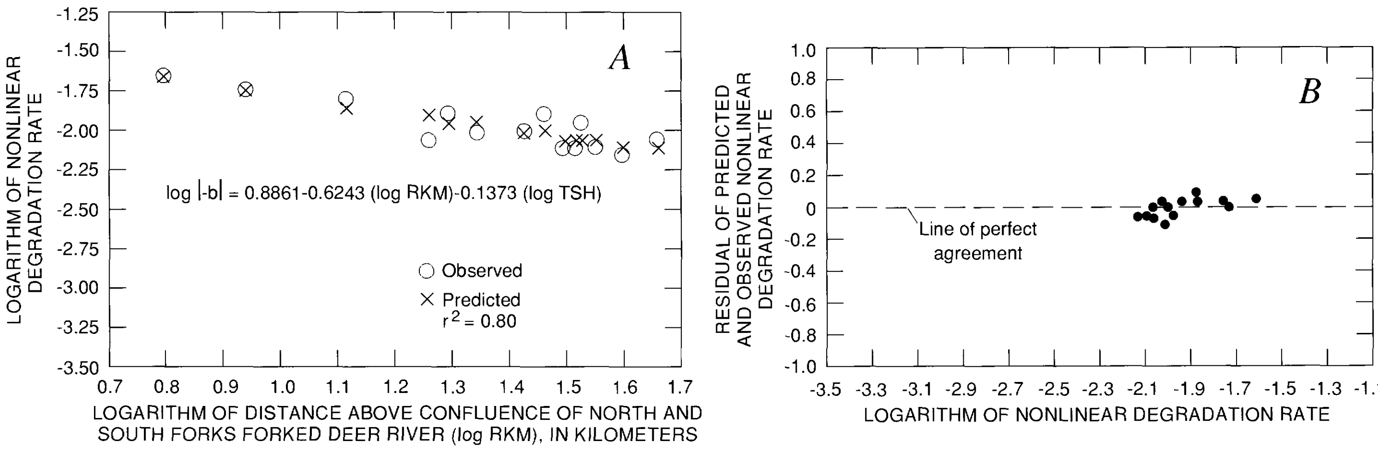


FIGURE 21.—Predicted and observed (*A*) rates of degradation and (*B*) residuals in the Forked Deer River basin determined by multiple regression.

represent different parts of the degradation and aggradation curves (fig. 14), depending on the stage of adjustment occurring in 1983. Because channels at many of the sites included in these regressions either are currently (1983) in the latter stages of degradation or have shifted to aggradation, the use of 1983 bed-material data to describe degradation trends becomes tenuous. In addition, there is a limited range in available particle sizes; therefore, for most sand-bed channels, d_{50} in equation 1 is almost constant, leaving Q_s (bed-material discharge) to absorb most of the effects of gradient change. In streams with coarser bed material (gravel and cobbles) bed-material particle size may play an important role in determining trends of bed-level adjustment.

Two-parameter multiple regressions of log $|-b|$ for the Cane Creek, Forked Deer, and Obion River basins, therefore, are used to estimate degradation trends along main stem and tributary channels (figs. 20, 21, 22, respectively). These plots (figs. 20–22) depict the degree of reliability of each basin regression with (1) a comparison of predicted and observed log $|-b|$ data by basin river kilometer and (2) a plot of residual and observed log $|-b|$ data. Regression statistics for these equations and the approximate downstream limit of applicability are listed in table 10. Degradation exponents can be generated for any location in the fluvial networks situated above the downstream limit of applicability (figs. 20–22). If disturbance-parameter data are not available, or cannot be obtained, degradation exponents can be derived from the equations in figure 16, using only RKM data.

Similar two-parameter (log RKM and log RSH) multiple-regression equations for individual streams and regression statistics are listed in table 11. The multiple-regression equations (table 11) are more useful than the simple-linear regression equations (table 5), which use only RKM data. The inclusion of the disturbance term places greater emphasis on the physical basis of degradation trends by indicating the degree of adjustment needed to return the channel to quasi-equilibrium conditions. Again, prediction of degradation exponents using

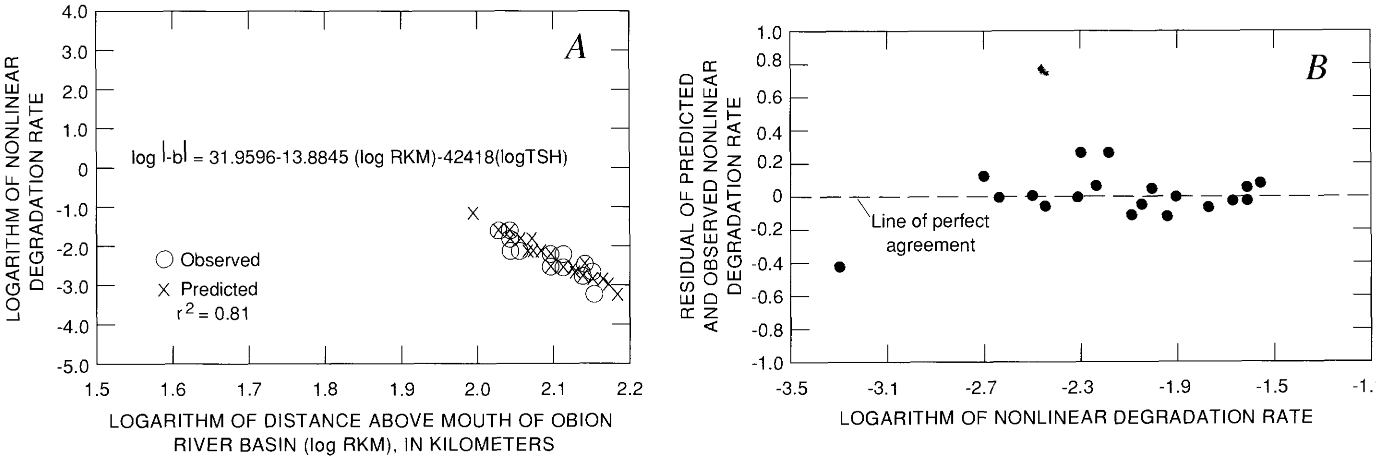


FIGURE 22.—Predicted and observed (*A*) rates of degradation and (*B*) residuals in the Obion River basin determined by multiple regression.

TABLE 11.—*Multiple-regression equations for calculation of degradation rates by stream*

[Although *n* values are apparently low, each data point (*n*) represents a given site along a stream and the culmination of a number of years of data at that site; r^2, coefficient of determination; —, data not available]

Stream	Equation	r^2	n	Approximate downstream limit (RKM)
Cane Creek	log |−*b*|= −2.4132−0.0925 (log RKM)−0.6023 (log RSH)	0.76	7	0
Cub Creek	log |−*b*|= −2.3439−0.3260 (log RKM)+0.3400 (log RSH)	1.00	4	2.4
Hoosier Creek	log |−*b*|= −2.4731−0.0339 (log RKM)+1.5003 (log TSH)	1.00	4	0
Hyde Creek	log |−*b*|= −2.2672−0.1610 (log RKM)+0.2633 (log RSH)	.92	4	0
North Fork Forked Deer River	log |−*b*|= 0.5443−1.1923 (log RKM)−0.8113 (log TSH)	.94	5	4.8
North Fork Obion River	log |−*b*|= 6.1043−5.5859 (log RKM)−4.1739 (log TSH)	.96	5	0
Obion River[1]	—	—	—	—
Pond Creek[2]	log |−*b*|= −8.4988+1.2631 (log RKM)+4.7917 (log TSH)	.86	4	0
Porters Creek[3]	log |−*b*|=−16.2501+4.7142 (log RKM)+5.4216 (log RSH)	1.00	3	7.2
Rutherford Fork Obion River	log |−*b*|= −3.1169−0.7006 (log RKM)+1.1138 (log DSLT)	1.00	4	0
South Fork Forked Deer River	log |−*b*|= 15.6765−6.5906 (log RKM)−7.2369 (log TSH)	.93	5	9.7
South Fork Obion River	log |−*b*|=−14.1491+3.0941 (log RKM)+3.5588 (log DSLT)	.86	6	0

[1]All reaches aggrading.
[2]LTSH data reflect straightening on North Fork Forked Deer River.
[3]Use with caution due to unrealistic regression statistics.

the equations in table 11 is restricted to those streams and their tributaries above the specified downstream limit of applicability. These equations represent observed longitudinal trends of degradation throughout the studied streams. For each site studied and included in the analysis, 2–19 observations of bed level over time were incorporated. Therefore the relatively low n values in table 11 are somewhat misleading.

After log $|-b|$ is obtained for a given site, degradation trends at the site can be calculated by the following procedure:

1. Multiply the antilog of log $|-b|$ by −1.0,
2. Substitute for b in equation 5,
3. Assign the predisturbed elevation of the bed to a in equation 5, and
4. Calculate E (elevation) in equation 5 for the period of interest.

Rates of downcutting in meters per year can be approximated using the previously specified procedure. The equations are useful in determining expected bed-level lowering for a given disturbance and at a particular location in the fluvial network, irrespective of the timing of initial degradation at the site.

The predictive degradation equations based solely on location (log RKM) are valid if no additional channel modifications are imposed on the channels. However, the two-parameter multiple-regression equations (figs. 20–22, table 11) should be applicable for future disturbances, owing to the presence of the disturbance parameter.

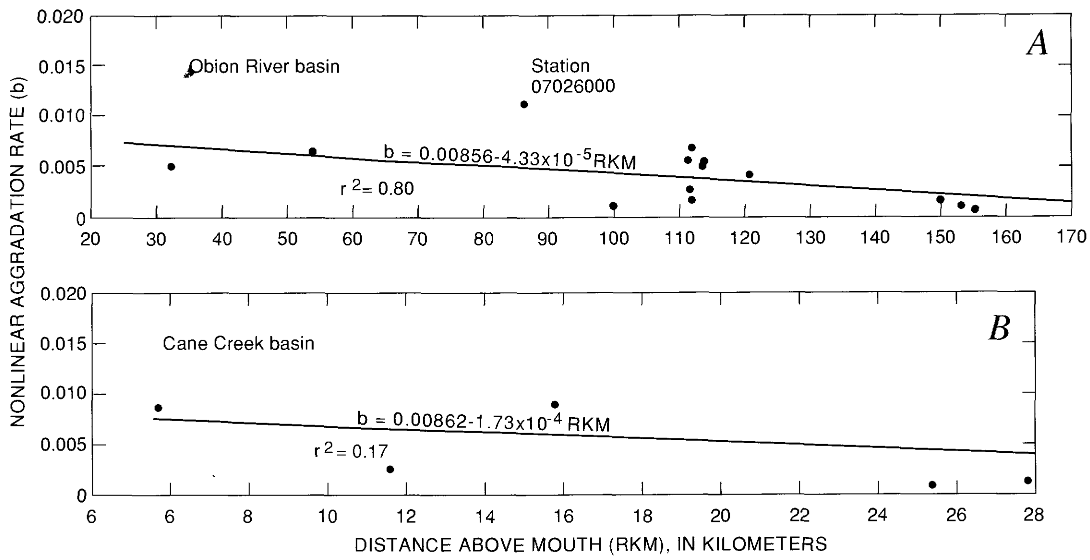


FIGURE 23.—Trends of aggradation in the (*A*) Obion River basin and (*B*) Cane Creek basin.

AGGRADATION

Aggradation occurs when the available stream power at a location is not sufficient to transport the sediment load delivered from upstream. In adjusting fluvial networks such as those in West Tennessee, these conditions are met almost immediately following channelization in the most downstream reaches. Aggradation occurs in upstream reaches of the basin network following the adjustment to much gentler slopes by degradation. This secondary response to channelization occurs as headward infilling and indicates that the initial adjustment by degradation overcompensates for the imposed increases in total stream power (QS). Aggradation then becomes the dominant trend, and channel gradients can increase.

Aggrading conditions on the channel bed can often be recognized during site inspection by the presence of recently deposited sand on bank and flood-plain surfaces. Limited information is available concerning aggradation trends along the streams of West Tennessee because

1. The time involved for maximum degradation to occur at a site is relatively long (up to 10–15 years) (fig. 14), and
2. Aggradation follows degradation and in many reaches has not yet occurred.

OBSERVED AGGRADATION

Ongoing aggradation trends at a site are based on observed data and are calculated using equation 5, where b becomes positive (fig. 14). Positive b is indicative of the nonlinear rate of aggradation at a site and is used similarly to log $|-b|$ to determine longitudinal variation. Because of the geographical distribution of $+b$ data, longitudinal aggradation trends using observed data can only be established for the Obion River basin. However, aggradation trends for presently degrading sites can be synthesized and are discussed in detail later.

Observed rates of aggradation decrease with distance upstream in the Obion River basin (fig. 23*A*). An anomalous rate of aggradation farther upstream at site 07026000 on the Obion River main stem is indicated by the plotted data in figure 23*A*. Infilling at this site, 0.12 m/yr (S_E=0.02, b=0.0091), is the greatest in the basin and is at least partly due to the proximity of the site to the area of maximum disturbance at the confluence of the North and South Fork Obion Rivers (fig. 1). Plentiful sand deposits are observed on bank surfaces along nearby reaches.

The three most upstream data points (located near RKM 150–153) in figure 23*A* represent sites on the North, South, and Rutherford Fork Obion Rivers that have not degraded as part of the integrated basin response. Ongoing aggradation at these sites reflects "natural" land-use and channel processes and serves as a fundamental site type in the development of a quantitative model of bed-level adjustment.

The poor relation obtained with the Cane Creek aggradation data (fig. 23*B*) is attributed to (1) limited data, (2) limited reliability in calculated $+b$ (table 4), (3) complex responses caused by the second phase of channelization along the upstream reaches of Cane Creek (table 2), and (4) the small amount of hydraulic control over the fine-grained sediments being transported.

SYNTHESIZED AGGRADATION (SYNAG)

Because of the paucity of observed aggradation data, a method was developed for estimating future aggradation

TABLE 12.—*Sites and values used in determining rate reduction from degradation to aggradation*

[Do, ditto]

Stream	Station	Rate reduction (percent)	
Cane Creek[1]	07030100	−89.6	
Do	07030129	−76.7	
Do	07030133	−88.8	
Do	07030140	−58.5	
Cub Creek	07029450	−69.9	
Hoosier Creek	07025690	−86.8	
Hyde Creek	07030104	−66.4	$\bar{x}$=78.2
North Fork Obion River	07025600	−87.7	[3]S_E=6.16
Obion River[2]	07025900	−94.2	
Do	07026000	−80.9	
Do	07026300	−78.7	
Rutherford Fork Obion River	07025050	−64.1	
Do	07025100	−74.9	
South Fork Obion River	07024800	−77.6	

[1]Site 07030123 not included due to multiple disturbances.
[2]Values based on rates of bed-level lowering during channelization.
[3]S_E adjusted for small n at 5 percent critical probability.

rates at sites that are currently degrading. A comparison of the rates of degradation and subsequent aggradation at 14 sites throughout the region disclosed a mean rate reduction of 78.2 percent (S_E=6.16; table 12). That the bed aggrades at a rate roughly 22 percent of the preceding rate of degradation may reflect the magnitude of the basin's initial overcompensation by incision. The small standard error relative to the mean suggests that aggradation trends representing a secondary phase of adjustment on the bed can be approximated at a site from the original degradation rate. Like degradation rates ($-b$), the rate of aggradation on the channel bed ($+b$) decreases in a nonlinear fashion with time (fig. 13*B*). Although the relation between nonlinear degradation rates and RKM is also nonlinear (table 5; figs. 15, 17), the relation between nonlinear aggradation rates and RKM is apparently linear (fig. 23). The synthesized aggradation variable (SYNAG) is, therefore, related to RKM by linear regression. The difference between the absolute values of $-b$ and $+b$ can be considered relatively constant. Prospective nonlinear aggradation rates for sites that have degraded, or are currently degrading, are calculated by the following equation:

$$\text{SYNAG}=|-b|-0.782(|-b|), \qquad (6)$$

where SYNAG is the synthesized aggradation exponent for use as b in equation 5.

Longitudinal trends of the synthesized aggradation rate agree reasonably well with those of observed aggradation data for both the Obion River and Cane Creek basins (fig. 24). Equations are developed for the Cane Creek, Forked Deer River, and Obion River basins that relate synthesized aggradation to RKM and quantitatively depict the longitudinal variation of the secondary aggradation phase (table 13). These equations produce reasonably good results for secondary-aggradation sites upstream from the area of maximum disturbance that have been or are degrading. Upstream extrapolation of the basin equations into unaffected reaches can be done with confidence, but extrapolation to sites downstream from the area of maximum disturbance in the Obion and Forked Deer River basin produces increasing error with distance downstream. Longitudinal variability in aggradation rates for individual streams is determined from synthesized data because of the limited amount of observed aggradation data. Regression equations and statistics are provided in table 13.

AGGRADATION SITE TYPES

Aggradation trends along the Obion River system serve as an example of the significance and applicability of a space-for-time substitution. All sites can be grouped into one of three aggradation categories on the basis of location and time relative to when disturbance took place. The characteristics of each site type are as follows:

1. Downstream-imposed aggradation:
   a. directly channelized
   b. located downstream from imposed knickpoint
   c. maintains highest aggradation rates
   d. linear decrease in aggradation with distance upstream
   e. aggrades immediately following channel work upstream
2. Secondary aggradation:
   a. some directly channelized
   b. located in areas of migrating knickpoint
   c. aggradation rates approximately 78 percent less than degradation rates
   d. linear decrease in aggradation with distance upstream
   e. aggrades following degradation phase of adjustment
3. Premodified aggradation:
   a. not channelized
   b. located upstream from migrating knickpoint
   c. maintains lowest aggradation rates
   d. relatively constant aggradation rates
   e. aggrades prior to, during, and following channel work.

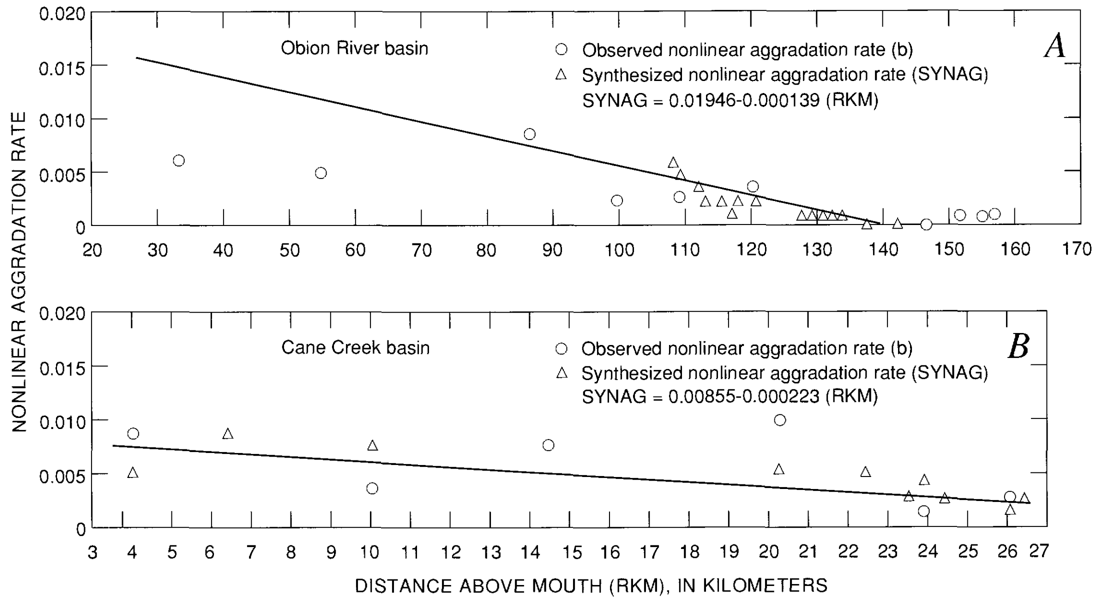


FIGURE 24.—Observed and synthesized rates of aggradation in the (*A*) Obion River basin and (*B*) Cane Creek basin.

TABLE 13.—*Relations describing the nonlinear, synthesized aggradation rate (SYNAG) by basin and stream*

[Although n values are low in some cases, each data point (n) represents a given site along a stream and the culmination of a number of years of data at that site; r^2, coefficient of determination; —, data not available]

Basin and stream	Equation	r^2	n
Cane Creek	SYNAG=0.00855−0.000223 (RKM)	0.66	11
Cane Creek	SYNAG= .00822− .00019 (RKM)	.48	7
Hyde Creek	SYNAG= .00418− .00073 (RKM)	.94	4
Forked Deer	SYNAG= .00427−6.98×10^{-5}(RKM)	.66	14
Meridian Creek	SYNAG= .00043− .00009 (RKM)	.30	4
North Fork Forked Deer River	SYNAG= .00505− .00009 (RKM)	.90	5
Pond Creek	SYNAG= .00219− .00001 (RKM)	.04	4
South Fork Forked Deer River	SYNAG= .00354− .00004 (RKM)	.57	5
Obion River	SYNAG= .01946− .000139 (RKM)	.80	20
Hoosier Creek	SYNAG= .00523− .00045 (RKM)	.92	4
North Fork Obion River	SYNAG= .00570− .00014 (RKM)	.83	5
Obion River[1]	—	—	—
Rutherford Fork Obion River	SYNAG= .00482− .00015 (RKM)	.99	4
South Fork Obion River	SYNAG= .00540− .00013 (RKM)	.82	6
Cub Creek	SYNAG= .00203− .00014 (RKM)	.85	4
Porters Creek	SYNAG= .00108+ .00005 (RKM)	.20	3

[1]No data due to aggrading conditions.

Sites below RKM 101 are located on the Obion River main stem and represent downstream-imposed aggradation (B, fig. 25). Secondary-aggradation sites (D, fig. 25) include the forks and tributaries of the Obion River that have been, or are being, degraded. Reaches upstream of RKM 150 continue to aggrade at premodified levels (E, fig. 25).

Data points included in sections B, D, and E in figure 25 depict the three aggradation categories and can be fit to a single trend line that represents advancing time and decreasing aggradation with distance upstream. Thus, channel conditions far upstream represent not only the moderate adjustment processes and premodified aggradation rates at those sites, but also conditions that will be attained in downstream reaches as the channel network approaches quasi-equilibrium. Similar space-for-time substitutions of aggradation trends along the Cane Creek and Forked Deer River basin streams are implied by

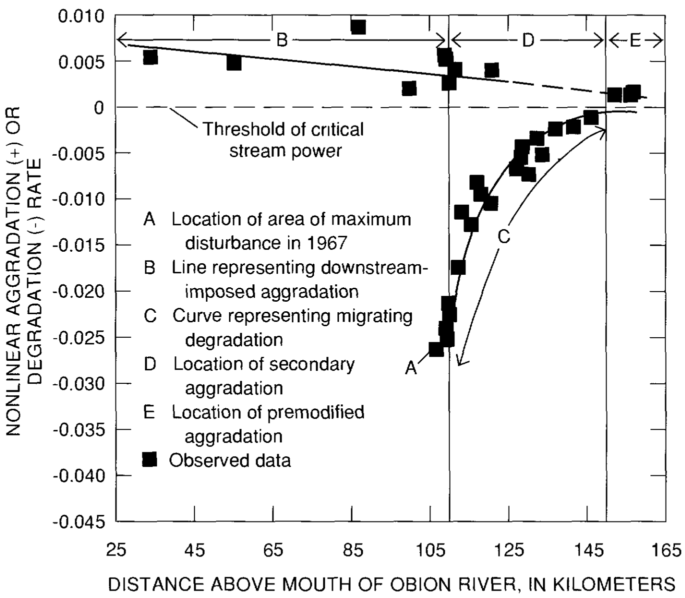


FIGURE 25.—Model of bed-level adjustment in the Obion River system.

extrapolating the appropriate equations upstream beyond their measured limits. Equations describing aggradation trends can be used in conjunction with the corresponding two-parameter multiple regressions describing degradation to produce a quantitative model of bed-level adjustment.

MODEL OF BED-LEVEL ADJUSTMENT

Bed-level adjustment, as a response to the increases in energy conditions imposed by channelization, occurs as degradation and aggradation. The distribution of these gradation processes over time and space is a function of location in the fluvial network relative to the area of maximum disturbance. The longitudinal variations in the rates of degradation and aggradation were combined to establish a model of bed-level adjustment.

ADJUSTMENT AT A SITE

DOWNSTREAM AGGRADATION

Sites downstream from the most disturbed area, such as those on the Obion River main stem, aggrade nonlinearly over time, as material is delivered from eroding reaches upstream. These sites do not degrade and are synonymous with the "downstream-imposed" site type. Aggradation rates are derived from the appropriate observed and synthesized regressions (fig. 23, table 13).

MIGRATING DEGRADATION AND SECONDARY AGGRADATION

Sites located upstream from the area of maximum disturbance undergo at least a two-stage process of bed-level adjustment. Channel beds in this general locale initially degrade at a rate commensurate with the magnitude of the imposed disturbance and the site's distance upstream from the AMD. The two-parameter multiple regressions are used to determine the degradation rate at these sites (figs. 20–22, table 11). Gradients are reduced as degradation progresses farther upstream. This degradation apparently causes an overadjustment until a point is reached when the gentler gradients can no longer provide sufficient stream power to transport the delivered sediment loads, resulting in a shift to aggradation. This secondary-aggradation phase indicates that the two gradation processes may alternate in the form of oscillations of decreasing amplitude (Alexander, 1981). Secondary-aggradation rates at a given site are calculated from the appropriate observed and synthesized regressions (fig. 23, table 13).

PREMODIFIED AGGRADATION

At some distance upstream from the migrating knickpoint, sites remain unaffected by degradation and aggrade at low rates (mean $+b=0.0013$) prior to, during, and after channel modifications. This type of site is referred to as "premodified." Infilling is due to the interaction of "natural" land-use practices and channel processes.

LONGITUDINAL ADJUSTMENT

A plot of b-value data and distance above the mouth of a major trunk stream (fig. 25) shows the distribution of site types and the longitudinal variability of their corresponding gradation processes. The Obion River basin was used as an example of systematic longitudinal adjustment because of available data for each site type. A representation of completed and ongoing gradation processes and rates as a response to the imposed changes in the Obion River network is shown in figure 25. Nonlinear aggradation and degradation rates (b values) are represented by the y-axis, the 0.00 line signifying quasi-equilibrium conditions and, therefore, no net change on the channel bed. Deviations from the 0.00 line denote the crossing of the threshold of critical stream power, either by imposed disturbances or by subsequent channel responses.

The modifications imposed on the Obion River system can be perceived as a rejuvenation of the fluvial network that caused a condition of peak disequilibrium when major channelization was completed in 1967 (table 2). Point A in figure 25 denotes the location of this peak disturbance (AMD) in the Obion River system, represents maximum rates of degradation, and serves as a starting time (1967) for a space-for-time substitution. Incision migrates upstream from the AMD (according to

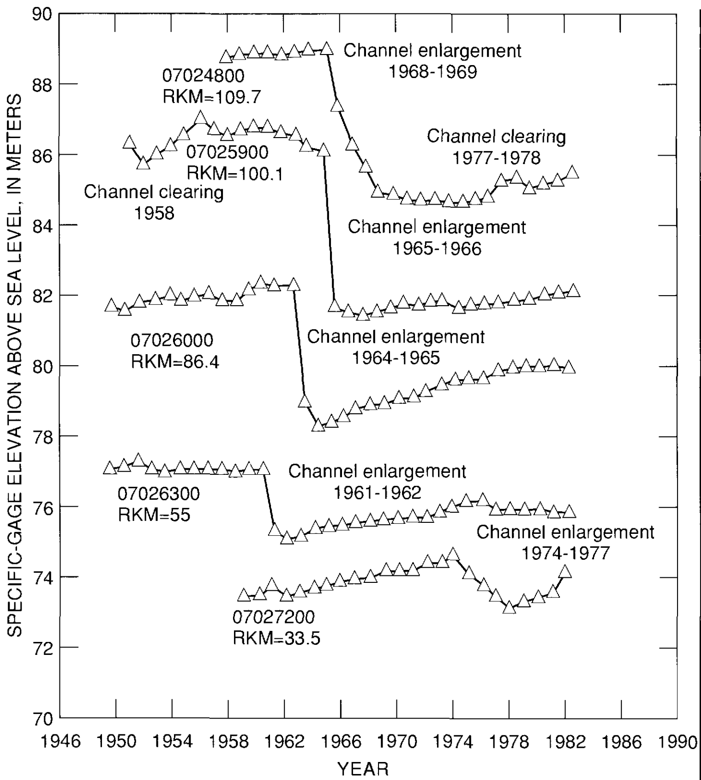


FIGURE 26.—Specific-gage elevations for stations on the Obion River.

curve C), and aggradation occurs downstream from the AMD at rates represented by line B (fig. 25). In fact, the downstream aggradation commenced prior to 1967 as the channel work progressed upstream past each site (fig. 26). Immediate degradation at the AMD is represented by the cluster of points at A (fig. 25) and can be characterized by station 07024800 (fig. 26). There, channel work to within 0.6 km of the site caused 2.6 m of degradation over a 2-year period (1966–67). Continued downcutting at decreased rates migrated upstream according to curve C (figs. 25, 27). This headward propagation of knickpoints along the forks of the Obion River at approximately 1.6 km/yr is represented in figures 27*A*–27*C*.

Gradation-rate data (*b* values) for the most downstream sites on the forks of the Obion River (figs. 27*A*–27*C*) and specific-gage elevation data for sites 07025900 and 07024800 on the Obion River main stem (fig. 26) display the shift to secondary aggradation due to overadjustment to much gentler gradients by degradation processes. This shift from degradation to aggradation is discussed with regard to the South Fork Forked Deer River by Simon and Robbins (1987). The nonlinear aggradation rate is about 22 percent of the previous degradation rate, indicating an initial overcompensation of 22 percent. Point D (fig. 25) denotes the location of ongoing headward infilling, characteristic of the secondary-aggradation phase. Data points near D represent the period 1969–78, signifying the beginning of secondary aggradation at various downstream sites on the forks of the Obion River. The migration of degradation upstream leads the onset of aggradation in both time and space (fig. 27*A*–27*C*). Expected shifts to secondary aggradation at sites farther upstream that are currently degrading are provided by the inclusion of synthesized data; this serves to extend the trend line from D, toward E in time (fig. 28*A*).

This process of headward infilling (line D–E, fig. 28*A*) tends to increase channel gradients and, in conjunction with progressive decreasing sediment loads from upstream (curve C, fig. 28*A*), may eventually lead to another overadjustment. That the channel aggrades at all in the period following adjustment by degradation confirms the idea of overcompensation and oscillatory channel response (Alexander, 1981). To counteract this potential imbalance between increasing gradients and decreasing loads (equation 1), and assuming that the threshold of critical power is again surpassed, the channel will again degrade, but at an even lesser rate. Given the recorded reductions in gradation rates (degradation to aggradation) and the oscillation across the threshold of critical power to aggradation, a pattern of peaks, each declining 78 percent in amplitude over a given time interval and representing alternating phases of aggradation and degradation, can be proposed (fig. 28*B*). With the magnitude of gradation processes reflecting the imbalance in the stream power equation (equation 1) (Lane, 1955) and the deviation from the threshold of critical power, bed-level adjustment can then be considered as oscillations around the threshold of critical stream power (fig. 28*B*). The bed stabilizes, and quasi-equilibrium is asymptotically approached as the oscillations are minimized with time (fig. 28*C*).

With stream power conditions becoming asymptotic to the threshold of critical stream power (fig. 28*C*), pattern adjustment would occur at this time by lateral cutting (Bull, 1979). The time interval for shifts between degradation and aggradation would tend to be greatest (10–15 years) close to the area of maximum disturbance and to decrease upstream because of the upstream attenuation of the degradation process. Similarly, the amplitude of the initial peak and the peaks thereafter would be less with distance upstream from the AMD (figs. 28*D*, 28*E*). For each site, a "threshold diagram" could be used to describe changes in stream power and to estimate the rates of alternating gradation processes over the long term (40–60 years). Observed and synthesized rates of bed-level adjustment reported in this study may represent only the two largest of a number of oscillating responses.

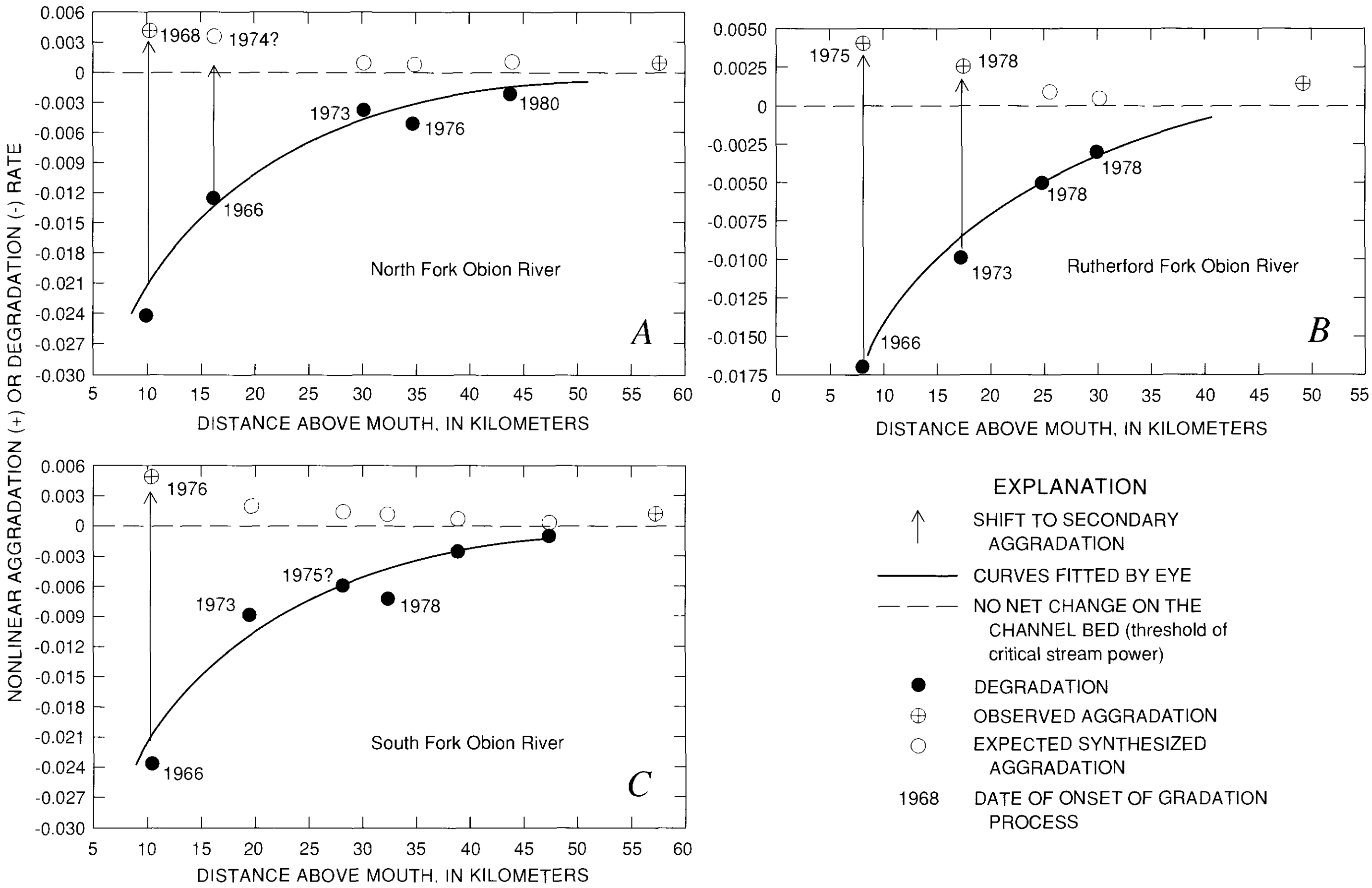


FIGURE 27.—Headward propagation of the degradation process and shifts to secondary aggradation on the forks of the Obion River.

The wavelength of each oscillation in figure 28*B* represents the time period in which a single gradation process is occurring at a site. This period may be as long as 10–15 years. Unit stream power data from gaged stations throughout West Tennessee in the vicinity of an AMD indicate that smaller oscillations occur within these larger ones. Plots delineating the annual change (positive or negative) in unit stream power for sites on various streams reflect these smaller oscillations (fig. 29). The short dashed lines superimposed on figure 29 signify the domination of the particular gradation process (large oscillation) and encompass unit stream power flux. A similarity between figures 28*B* and 29*A*–29*D* is evident, the primary exception being that of time scale. The change in unit stream power during a particular gradation process apparently represents short-term (2–5 years) overcompensations in unit stream power following the initial shock imposed by downstream rejuvenation. Station 07029100 on the North Fork Forked Deer River represents a completed degradation phase (fig. 29*A*), the aggradation beginning in 1983. Oscillations of changing unit stream power through the degradation phase (1976) at site 07024800 are somewhat distorted because of additional clearing operations near the site in the mid-1970's (fig. 29*B*). Oscillations representing the secondary-aggradation phase are also shown in figure 29*B* (1977–83). Figures 29*C* and 29*D* also suggest the small oscillations in unit stream power amidst the larger shifts in gradation processes and are similarly misshaped because of clearing activities (table 2). In all cases (figs. 29*A*–29*D*), the secondary-aggradation phase results in net positive changes in unit stream power. With aggradation causing decreases in channel capacity, net increases in unit stream power are assumed to be due to the increasing of gradients by headward infilling. Trends of changing unit stream power for downstream-imposed sites 07026300 and 07026000 on the Obion River main stem also show small oscillations of declining amplitudes during a single adjustment phase (fig. 30).

Where curve C and line D–E approach the 0.00 line (fig. 28*A*), gradation processes due to downstream modifications are minimized, and sites will not degrade. This is estimated to take place near RKM 150 in the Obion River system. Upstream from the intersection of the 0.00 line at E, premodified aggradation continues to take place at low rates according to basin and "natural"

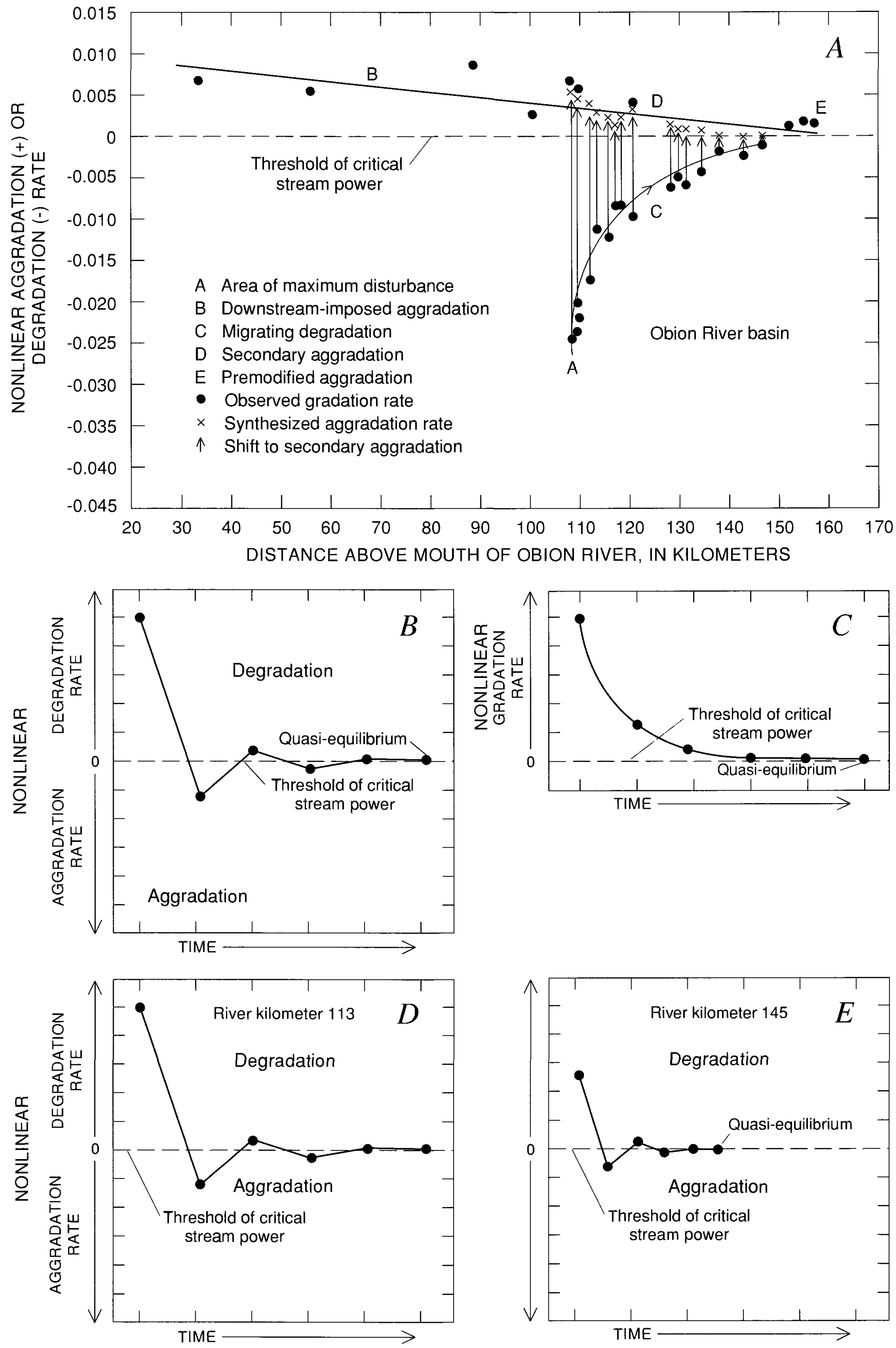


FIGURE 28.—Conceptual model of oscillatory channel response showing (*A*) shifts to secondary aggradation by headward infilling, (*B*) alternating processes of degradation and aggradation at a site with a 78-percent rate reduction with each shift in process, (*C*) absolute values of gradation rates and the approaching of quasi-equilibrium conditions asymptotically, and examples of oscillatory channel response at (*D*) river kilometer 113 and (*E*) river kilometer 145 in the Obion River basin.

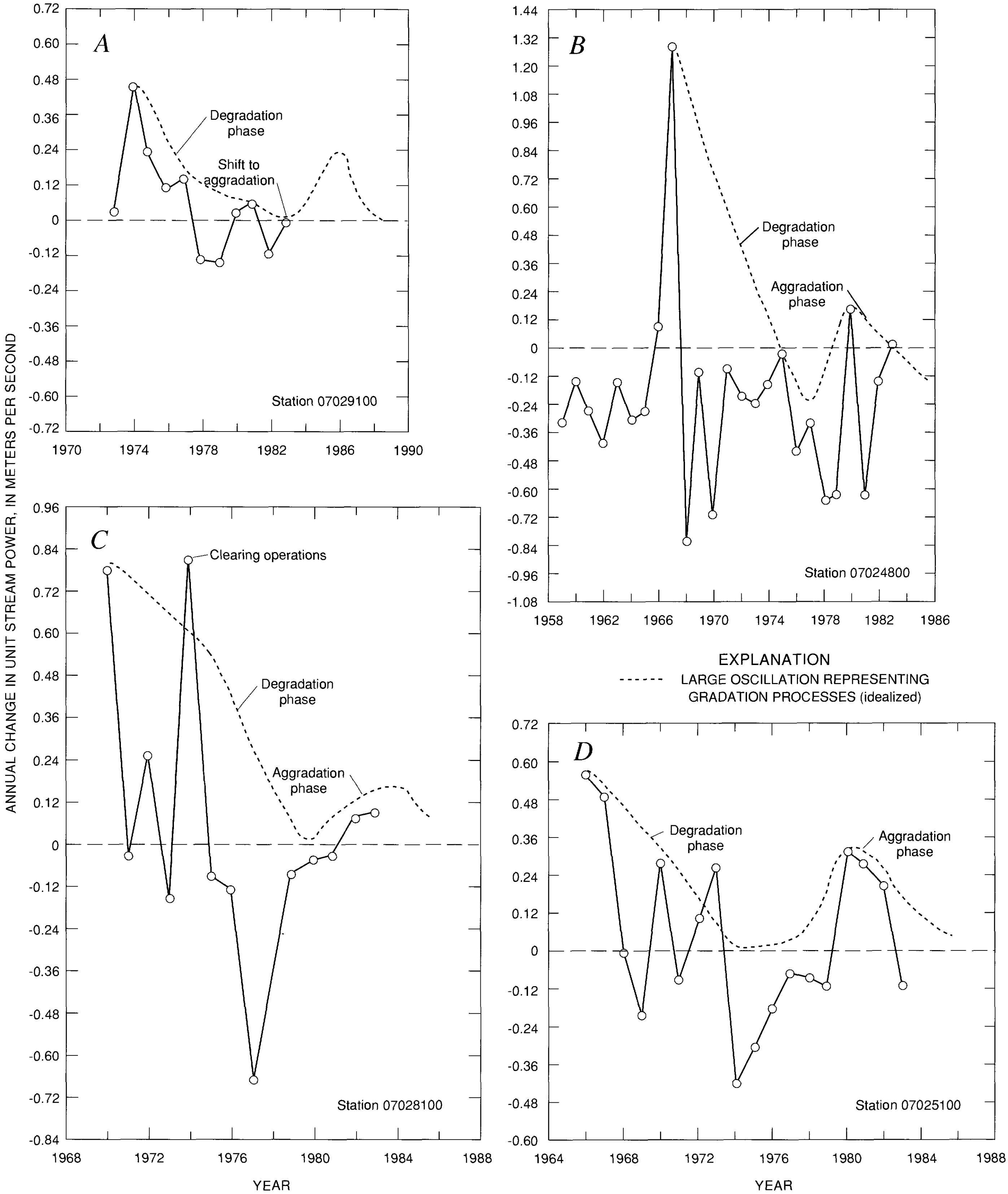


FIGURE 29.—Variation in unit stream power displaying short-term oscillations within larger oscillations that represent changes in gradation processes for sites on the (*A*) North Fork Forked Deer River, (*B*) South Fork Obion River, (*C*) South Fork Forked Deer River, and (*D*) Rutherford Fork Obion River.

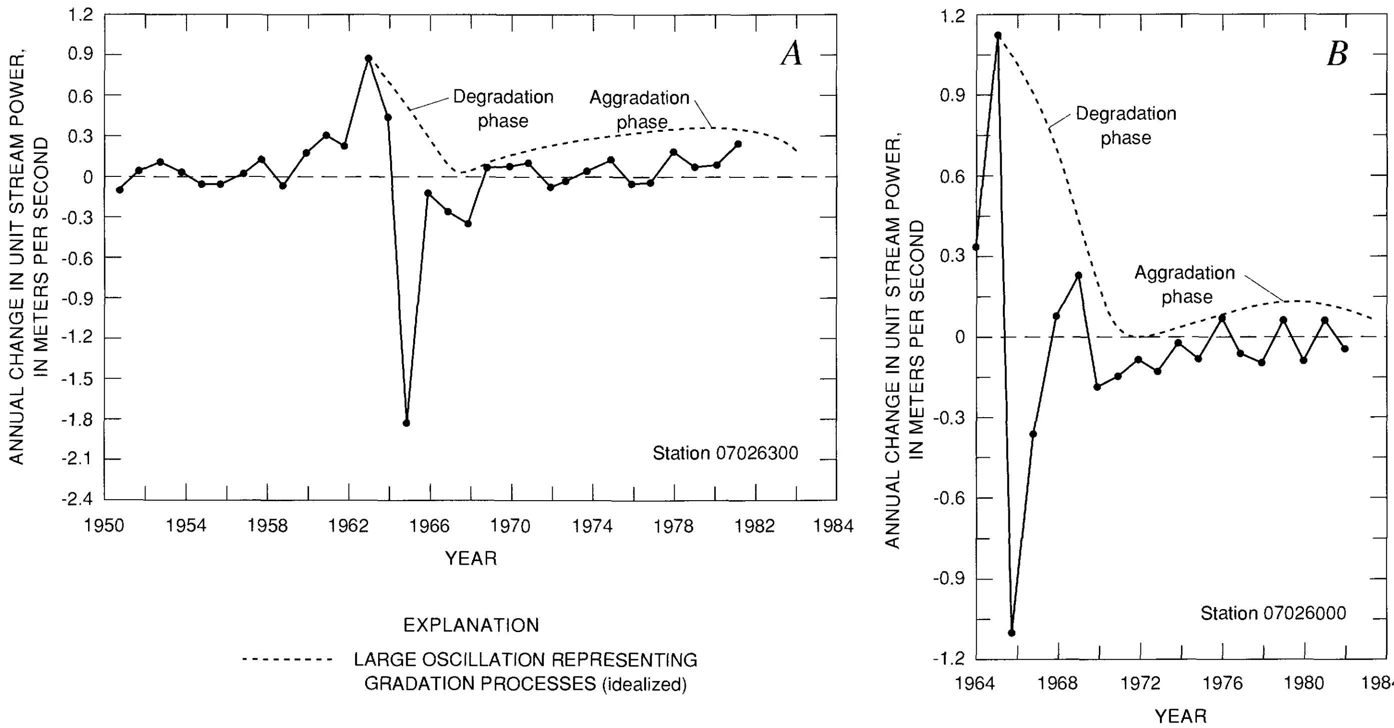


FIGURE 30.—Variation in unit stream power displaying oscillatory channel response for sites on the Obion River main stem: (*A*) station 07026300 and (*B*) station 07026000.

channel characteristics. Line BDE (fig. 28*A*) thus corresponds to the regression representing nonlinear aggradation rates (fig. 23*A*) and denotes bed-level recovery throughout the Obion River basin through time.

Bed-level adjustment rates along the channels of the Obion River basin can be calculated using the predefined regression equations.

Degradation:

$$\log |-b| = 31.9596 - 13.8845(\log \text{RKM}) - 4.2418 (\log \text{TSH}) \quad (7)$$

Aggradation:

$$+b = 0.00856 - 4.33\times10^{-5}(\text{RKM}) \quad (8)$$

To calculate the actual change on the channel bed, derived values of log $|-b|$ (after transformation) and $+b$ are substituted for b in equation 5.

Development of the bed-level adjustment model for other streams and basins is based on identical site types and space-for-time substitutions. Application of the model for determining the systematic channel response along the Cane Creek and Forked Deer River basin streams, as well as various other streams, is presented in figure 31. The geographical distribution of ongoing (1983) gradation processes and the downstream terminus of unaffected zones (premodified site types) is given in figure 32.

WIDTH ADJUSTMENT PROCESSES AND TRENDS

Channel widening and bank failure by mass-wasting processes are common occurrences in adjusting channels in West Tennessee. Channel widening occurs as an indirect result of imposed increases in energy conditions once the shear strength of the bank material has been exceeded. Bank-material properties and bank geometry determine a bank's resistance to failure and its maximum stable height. The impetus for bank failure is created by an overheightened and oversteepened bank profile from degradation and by undercutting of the bank toe. A threshold between bank height and H_c (critical bank height) or H_c' (H_c with tension cracks) can be used to indicate the potential for failure.

Assuming that banks are "stable" prior to channelization, the concept of the bank-failure threshold implies that a certain amount of downcutting is required before the critical bank height is exceeded. Bank failures and width adjustment, therefore, generally do not occur with the onset of degradation but exhibit a time lag until downcutting is sufficient to surpass the critical bank height. Widening by mass-wasting processes then occurs concurrently with degradation and continues through aggradational phases until bank heights are reduced. The concept of the bank-failure threshold further suggests that widening by mass wasting will not occur in those reaches that experience only limited degradation.

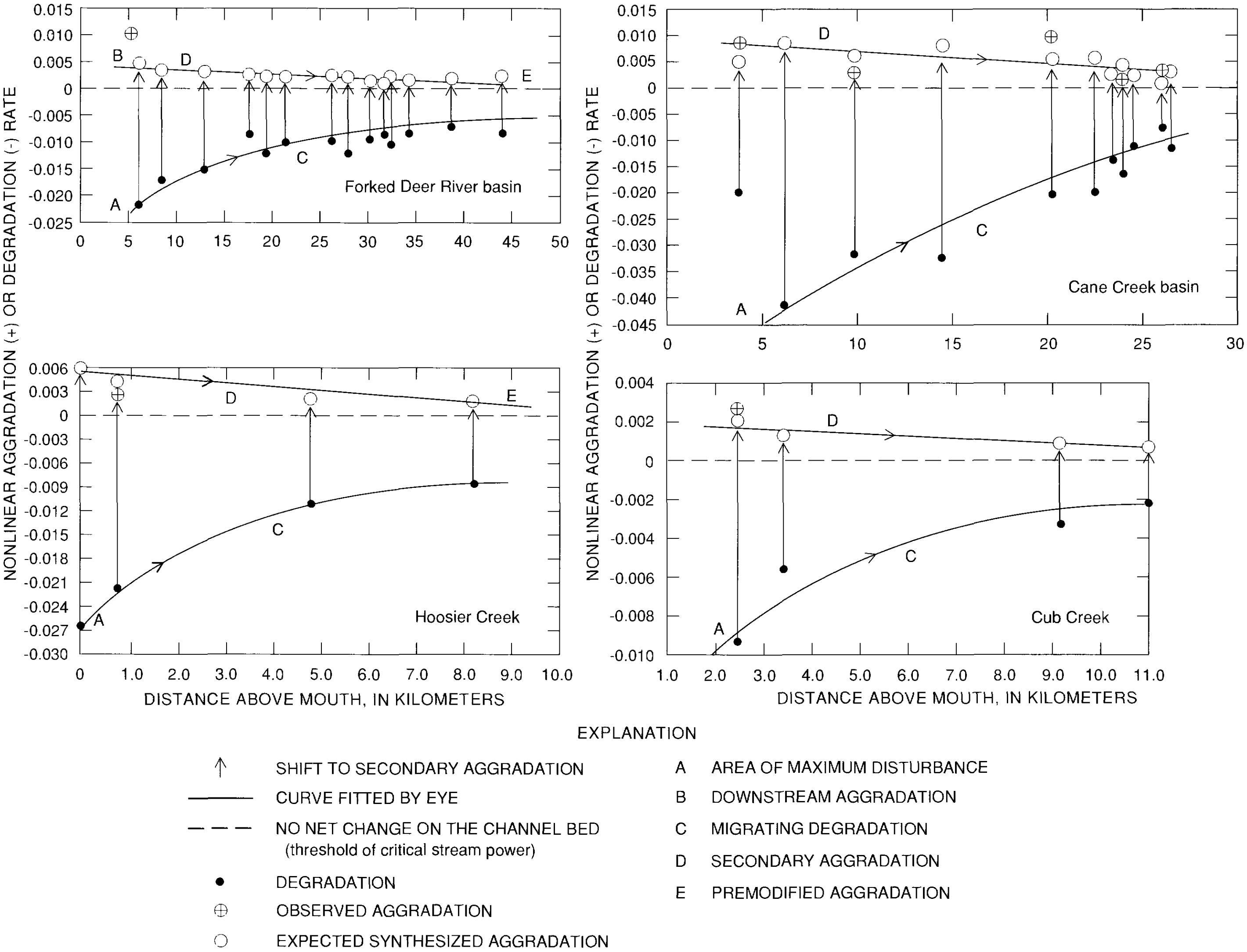
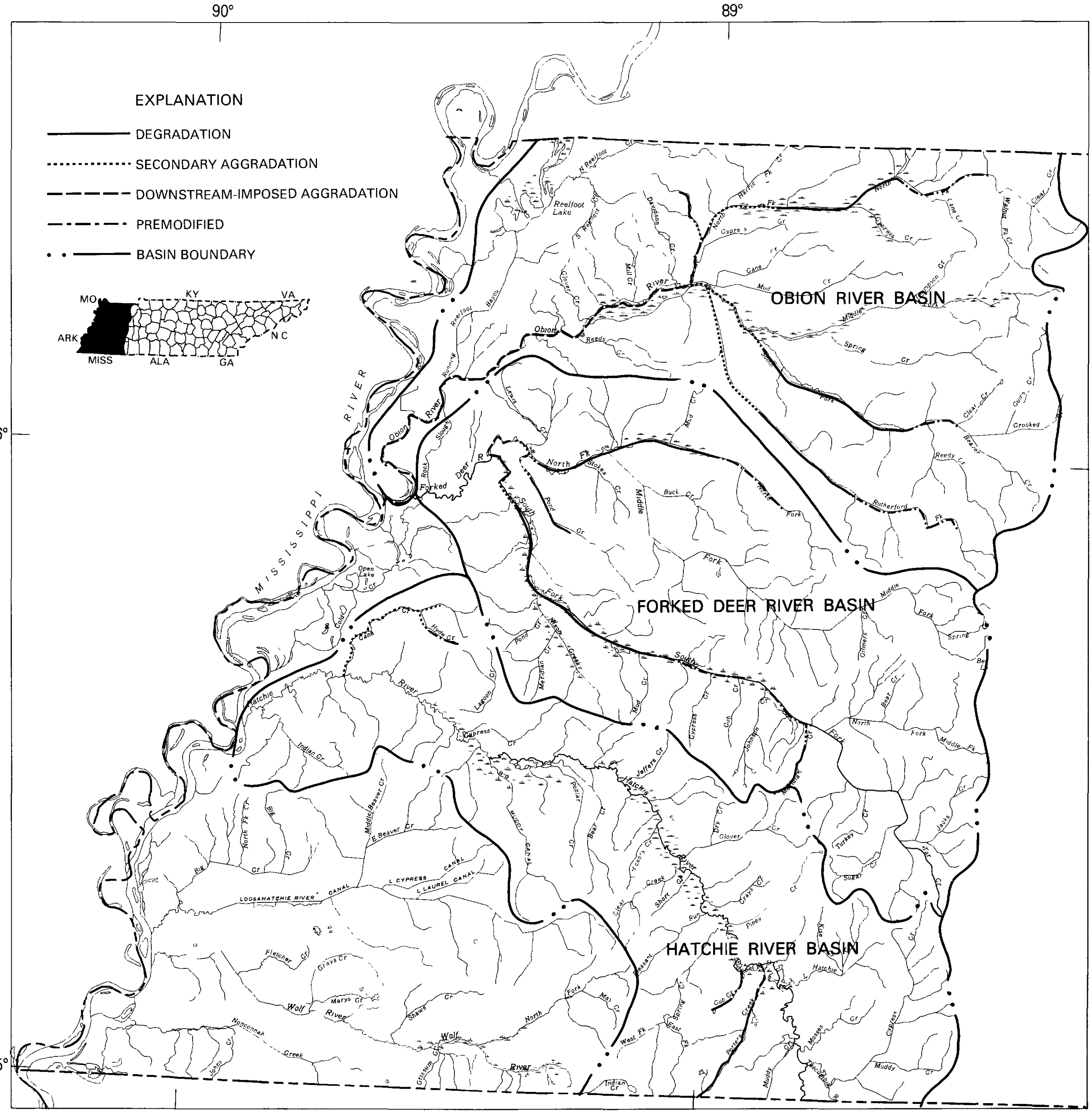


FIGURE 31.—Examples of application of the bed-level adjustment model for individual streams and basin networks.

Local site conditions such as flow deflection, obstructions to flow, and location of the section relative to a channel bend further influence bank-failure rates. The deflection of flow is significant at moderate and high flows when shear forces are directed at a given location on a bank and cause excessive undercutting and the removal of toe material. Drift accumulation may lead to backwater conditions just upstream of the obstruction that tend to keep banks saturated and, as a result, cause a loss of shear strength. Flows are usually deflected toward the opposite bank a short distance downstream from the obstruction, leading to excessive undercutting and, potentially, to planar and rotational failures (fig. 33*A*). A site located on the outside of a channel bend can be affected similarly by flow deflection. Greater shear forces are exerted by flows at these bank sections, causing undercutting and oversteepening. High flows impinge on alternating sides of the channel, causing excessive widening in the outside bends of the high-flow thalweg (fig. 33*B*). This is particularly evident along the incipient meanders of Cane Creek and have resulted in bank failures up to 60 m long and 6 m wide (fig. 33*C*).

The frequency and duration of bankfull discharges also play a role in determining bank-failure recurrence. High flows keep bank materials wet, causing a loss of shear strength and greater bank-material weight (Little and others, 1982). Failure generally occurs following the recession of the discharge hydrograph (rapid drawdown condition) because of the loss of support afforded by the water in the channel and the removal of toe material that can oversteepen the bank (Thorne and others, 1981; Simon and Hupp, 1986).

Critical bank heights for all sites are calculated from equations derived from SCS nomographs (F. Cousins,



Base from U.S. Geological Survey, State base map, 1:500,000, 1957, Revised 1973

0 10 20 MILES
0 10 20 KILOMETERS

FIGURE 32.—Geographical distribution of ongoing gradation processes along studied streams of West Tennessee.

Soil Conservation Service, written commun., 1984) (equations 2*a*, 2*b*, 3) and from the following equation:

$$H_c = \frac{4c}{\gamma}\tan\left(45+\frac{\phi}{2}\right) \qquad (9)$$

where

ϕ = angle of internal friction, in degrees,

γ = unit weight of the soil mass, in kilograms per cubic meter, and

c = cohesion, in kilopascals.

TABLE 14.—*Mean critical bank height (H_c) and maximum noneroding pinhole velocity (PV), illustrating potential unreliability of* H_c *data*

[Max., maximum; Min., minimum; S_E, standard error of the mean; n, number of observations; —, data not available]

Stream	H_c, in meters					PV, in meters per second				
	Mean	Max.	Min.	S_E[1]	n	Mean	Max.	Min.	S_E[1]	n
Cane Creek	7.80	8.93	7.07	0.30	18	0.56	0.81	0.34	0.12	8
Cub Creek	6.92	7.65	6.28	.37	10	3.41	6.28	.55	3.75	4
Hoosier Creek	7.44	—	—	—	1	.94	1.95	.08	1.24	4
Hyde Creek	7.71	7.71	7.71	—	2	.53	.66	.45	.26	3
Meridian Creek	6.89	7.50	6.28	.46	6	—	—	—	—	—
North Fork Forked Deer River	7.13	8.87	5.91	.36	29	.98	2.86	.38	.60	9
North Fork Obion River	7.83	9.69	6.61	.60	13	1.61	2.76	.51	.73	8
Obion River	7.44	9.94	5.27	.27	35	2.44	4.67	.42	3.69	4
Pond Creek	7.83	8.84	7.16	.59	6	.93	1.36	.47	1.12	3
Porters Creek	7.89	9.66	6.34	.92	10	3.12	3.49	2.76	4.57	2
Rutherford Fork Obion River	6.61	7.59	5.97	.26	17	1.42	3.39	.42	1.15	7
South Fork Forked Deer River	7.13	8.72	6.10	.27	26	.93	3.08	.25	1.50	5
South Fork Obion River	7.65	8.84	6.46	.43	14	1.56	3.25	.17	1.05	7

[1]S_E corrected for small n at 5 percent critical probability of $n \leq 30$.

Mean critical bank height for studied streams ranges from 6.6 to 7.9 m (table 14), indicating a relative homogeneity in the region's bank material. The pinhole velocity data, however, serve to illustrate a shortcoming of the sole use of critical bank height data to assess bank stability. As stated earlier, internal erosion by dispersion and piping within loess-channel banks commonly causes a loss of stability, increases potential for failure, and serves to reduce critical bank heights. Mean pinhole dispersion data reflect the physiochemical properties of the fine-grained material and the bank's potential to develop pipes. However, pinhole velocity data do not account for certain mechanical properties of the material, such as cohesion and the angle of internal friction, which are included in the critical bank height equations and help determine shear strength. Because of the relative homogeneity among the physical properties of West Tennessee bank materials, the lack of variability in values of mean critical bank height is not surprising. It is clear from the pinhole velocity data, though, that these banks do indeed behave differently, and information concerning the physiochemical properties of the bank material must be used to assess bank stability adequately. A good example of this apparent inconsistency can be obtained by comparing critical bank height and pinhole velocity data for Cane Creek and the Rutherford Fork Obion River (table 14). Cane Creek displays one of the highest mean H_c values of the streams studied (7.8 m), yet because of the highly dispersive nature of its banks (low PV rates) and the consequent development of many pipes, it has widened 46 m in some severely affected locations (Simon and Hupp, 1986). This can be partly attributed to the great amounts of degradation along this stream (Simon and Hupp, 1986). Although the Rutherford Fork Obion River has the lowest mean H_c value of the streams studied, bank widening is not nearly as intense as it is along Cane Creek.

Width adjustment can be perceived as an imbalance between the forces and conditions that tend to instigate bank failure and those that tend to resist it. Processes and conditions that remove toe material and increase bank heights, bank angles, moisture content of bank material, and dispersion represent imposed, destabilizing factors. Factors that promote bank resistance are low bank angles, low bank heights, and those properties of the bank material that decrease dispersion and increase cohesion and shear strength.

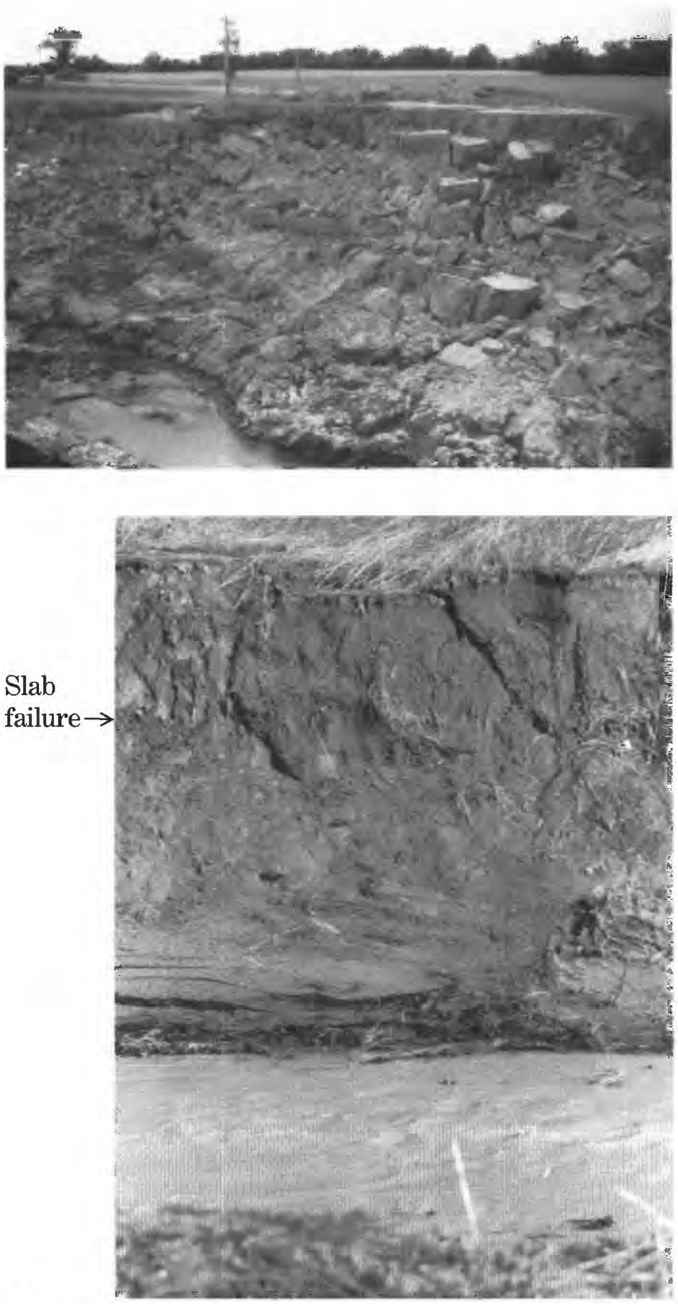
TRENDS AND RELATIONS

The adjustment of channel width (in meters) is described using the following three parameters:

1. PMW=premodified top width,
2. W83=1983 surveyed top width, and
3. DW=change in top width from premodified to 1983.

A summary of these data is given in table 15.

The 1983 surveyed width generally decreases with distance upstream except along Meridian and Pond Creeks, where multiple disturbances have occurred. Rivers such as the Obion and the South Fork Forked Deer are narrowing because of bank accretion in heavily aggrading areas downstream from the area of maximum disturbance. This narrowing process is more marked on the Obion River main stem, where aggradation and bank accretion are dominant processes. In addition, along the lower Obion River main stem a decreasing tendency for channel widening exists as bed level recovers and bank



A

B

FIGURE 33.—Examples of induced bank failures due to downcutting and (*A*) flow deflection and (*B*,*C*) location on the outside of a bendway, including (*C*) particularly large rotational failures at Cane Creek.

heights are reduced. Linear regression of 1983 surveyed top widths and RKM data indicate that relations between these parameters are tenuous. Only four coefficients of determination shown in table 16 are significant at the 95 percent confidence limit. All regressions represent direct relations except for Meridian and Pond Creeks, which are inversely related. The 1983 surveyed top widths are shown plotted against basin RKM in figure 34.

C

FIGURE 33.—Continued.

IMPOSED DESTABILIZING FORCES

Channel widening due to imposed increases in energy conditions and subsequent gradation processes can be assessed in terms of DW (change in top width from premodified state to 1983). The majority of the sites studied have been widened to varying degrees, by man. Assuming that the adjustment of channel width proceeds from a stable condition toward a value commensurate with the adjusting gradient, total changes in width can be appropriately measured from the premodified state, using DW.

Bed-level lowering by degradation increases bank heights and serves to create the impetus for bank failures. The role of the degradation process in controlling channel widening is mildly reflected by an r^2 value of 0.50 (n=49) between the absolute value of the degradation exponent ($|-b|$) and widening (DW) for all sites. It is assumed that a greater r^2 value would have been obtained if DW represented channel widening only by adjustment processes. The effect of degradation as a destabilizing force is individually assessed for each basin in table 17. All relations represented in table 17 are significant at the 95 percent confidence limit. The magnitude and effect of degradation as a force in instigating failures and, therefore, channel widening are reduced with distance upstream.

Changes in channel width (DW) as a result of the most recent major channel modifications imposed on West Tennessee streams are summarized in table 18. Mean DW values for each stream should be regarded as merely a point of reference and not as a precise average of width adjustment. Minimum and maximum values of DW, however, do reflect a realistic range of width changes throughout the stream lengths studied.

Minimum changes in channel width on the forks of the Obion River (table 18) represent the stable bank conditions of the most upstream premodified sites. In contrast, sites with maximum values of DW for these rivers tend to be close to the AMD, where degradation is greatest. With the exception of the Obion River main stem, the Cane Creek channel has both the highest mean and the highest minimum values of width change. This is not surprising, considering the extensive channel shortening and the highly dispersive loess materials making up the Cane Creek banks. The Hoosier Creek data also indicate that substantial changes in channel width have occurred in the dispersive-loess banks. Minimum DW values for Cub and Hyde Creeks (0 and 0.3 m, respectively) represent upstream locations where corresponding drainage areas may be insufficient to effect the necessary amount of downcutting to cause bank instabilities. The large changes in channel width on the Obion River main stem (table 18) are primarily the result of the direct removal of bank material by man. Mean DW for this river is 37.8 m.

Rates of channel widening, in meters per year, are difficult to determine from available data because of the time lag involved in surpassing critical bank height following the onset of degradation. The lack of annual channel surveys during the adjustment period signifies a need for geobotanical data to supplement periodically observed changes in channel width. A combination of channel geometry and geobotanical data at sites on Cane Creek and the Rutherford Fork Obion River aided in estimating mean rates of channel widening of approximately 2.4 and 1.1 m/yr, respectively (Hupp and Simon, 1986) (figs. 5, 35). The product of recent (5 to 10 years) failure recurrence (as determined from tree-ring data) and mean failure-block widths was used to calculate these rates (Simon and Hupp, 1986).

The reduced tendency for channel widening with distance upstream is represented by plots for the Cane Creek, Forked Deer River, and Obion River basins

TABLE 15.—*Premodified width (PMW), 1983 surveyed top width (W83), and changes in top width (DW) for studied sites*

[In meters; —, data not available; Do, ditto]

Stream	Station	PMW	W83	DW
Cane Creek	07030097	—	—	—
Do	07030100	10.4	30.5	20.1
Do	07030123	17.1	32.0	14.9
Do	07030129	26.2	39.9	13.7
Do	07030133	24.4	38.7	14.3
Do	07030137	16.4	41.1	25.0
Do	07030140	18.0	39.6	21.6
Cub Creek	07029447	8.2	8.2	0
Do	07029448	7.9	8.5	.6
Do	07029449	18.3	25.0	6.7
Do	07029450	16.8	18.0	1.2
Hoosier Creek	07025660	24.4	32.9	8.5
Do	07025690	15.8	43.0	27.1
Do	07025691	—	—	—
Hyde Creek	07030104	11.3	11.6	.3
Do	07030107	6.1	11.6	5.5
Do	07030110	14.9	18.6	3.7
Do	07030111	—	—	—
Meridian Creek	07027478	18.0	22.2	4.3
Do	07027480	—	20.1	—
Do	07027483	—	19.8	—
Do	07027485	15.8	18.3	2.4
North Fork Forked Deer River	07028820	12.8	15.8	3.0
Do	07028835	—	—	—
Do	07028840	13.1	16.5	3.4
Do	07029100	25.0	34.7	9.8
Do	07029105	25.6	50.6	25.0
North Fork Obion River	07025320	21.9	22.6	.6
Do	07025340	31.4	32.0	.6
Do	07025375	—	—	—
Do	07025400	27.4	37.8	10.4
North Fork Obion River—Continued.	07025500	32.6	47.5	14.9
	07025600	25.3	50.9	25.6
Obion River	07024800	24.7	60.4	35.7
Do	07025900	9.8	69.2	59.4
Do	07026000	31.1	67.7	36.6
Do	07026300	43.3	63.1	19.8
Do	07027200	—	—	—
Pond Creek	07029060	9.8	14.0	4.3
Do	07029065	9.8	11.9	2.1
Do	07029070	15.2	18.3	3.0
Do	07029080	11.6	13.7	2.1
Porters Creek	07029437	13.4	21.3	7.9
Do	07029439	10.7	22.2	11.6
Do	07029440	22.6	26.2	3.7
Rutherford Fork Obion River	07024900	22.9	22.9	0
Do	07025000	28.0	28.6	.6
Do	07025025	26.5	32.3	5.8
Do	07025050	24.1	35.7	11.6
Do	07025100	15.8	34.1	18.3
South Fork Forked Deer River	07027720	23.2	28.0	4.9
Do	07027800	27.4	38.1	10.7
Do	07028000	25.6	36.6	11.0
Do	07028005	14.6	35.4	20.7
Do	07025100	26.5	53.6	27.1
Do	07028200	32.9	39.9	7.0
South Fork Obion River	07023350	22.6	22.6	0
Do	07024430	18.3	29.3	11.0
Do	07024460	19.8	26.2	6.4
Do	07024500	24.1	38.4	14.0
Do	07024525	24.4	27.7	3.4
Do	07024550	23.8	36.9	13.1
Do	07024800A	24.7	60.4	35.7

(figs. 36*A*–36*C*). A similar plot for the upper Hatchie River basin (fig. 36*D*) shows no discernible relation between longitudinal distance and channel widening. This could be due to the presence of grade-control structures on Porters Creek, outcroppings of the resistant Porters Creek Clay, and the small drainage area of the Cub Creek sites (2.6 to 39 km^2).

RESISTING FORCES

Bank-material properties data offer the best means of describing a bank's resistance to failure. However, the erodibility of cohesive materials is extremely difficult to determine and is largely a function of pore-water chemistry and electrochemical forces (Carey and Simon, 1984). The pinhole-dispersion test is used in this study as an empirical means of assessing the role of the electrochemical bond between cohesive particles in determining dispersion and bank erodibility.

PREDICTIVE EQUATIONS

Relations for estimating width adjustment were developed using multiple-regression analyses. The nonlinear degradation rate ($|-b|$) represents the force mechanism in instigating bank failure, and the degree of dispersion (PV) denotes bank-material properties. Trends in channel narrowing in the heavily aggrading downstream-imposed reaches are not included in these multiple-regression analyses because the degradation term restricts the inclusion of data to only those sites that have been downcut. Estimates of induced increases in channel width can be obtained from the following regressions:

TABLE 16.—*Relations between 1983 surveyed top width (W83) and river kilometer*

[r^2, coefficient determination; n, number of observations; Max., maximum; Min., minimum]

Stream	r^2	W83, in meters		n
		Min.	Max.	
Cane Creek	0.79	30.5	41.4	6
Cub Creek	.77	8.2	25.0	4
Hoosier Creek	.94	32.9	43.0	3
Hyde Creek	.64	11.6	18.6	3
Meridian Creek	.85	18.3	22.2	4
North Fork Forked Deer River	.86	15.8	50.6	4
North Fork Obion River	1.00	22.6	50.9	5
Obion River	.0004	60.4	69.2	4
Pond Creek	.10	11.9	18.3	4
Porters Creek	.69	21.3	26.2	3
Rutherford Fork Obion River	.88	22.9	35.7	5
South Fork Forked Deer River	.48	28.0	53.6	6
South Fork Obion River	.67	22.6	60.4	7

Cane Creek basin:

$$DW=601.4(|-b|)+28.9(PV)-16.2 \quad (10)$$

where r^2=0.57 and n=7.

Forked Deer River basin:

$$DW=1{,}583(|-b|)-3.1(PV)-7.0 \quad (11)$$

where r^2=0.70 and n=10.

Obion River basin:

TABLE 17.—*Statistical properties of relations between changes in top width and degradation rate*

[r^2, coefficient determination; n, number of observations]

Basin	Degradation rate r^2	n
Cane Creek	0.49	9
Forked Deer River	.60	13
Obion River	.80	18
Upper Hatchie River	.64	7

$$DW=989.7(|-b|)+3.1(PV)-1.3 \quad (12)$$

where r^2=0.86 and n=16.

Upper Hatchie River basin:

$$DW=960.4(|-b|)+0.3(PV)-4.5 \quad (13)$$

where r^2=0.75 and n=5.

Predicted and observed values of channel widening (equations 10–13) for the period prior to modification to 1983 are shown for the four basins by RKM in figure 37. Again, it should be noted that the relations (equations 10–13) represent channel widening in degraded reaches and do not account for narrowing by accretion in the heavily aggrading, downstream-imposed reaches. Interpretation of width-adjustment trends in the downstream aggrading reaches is limited to a conceptual model because of a general lack of these types of sites in each

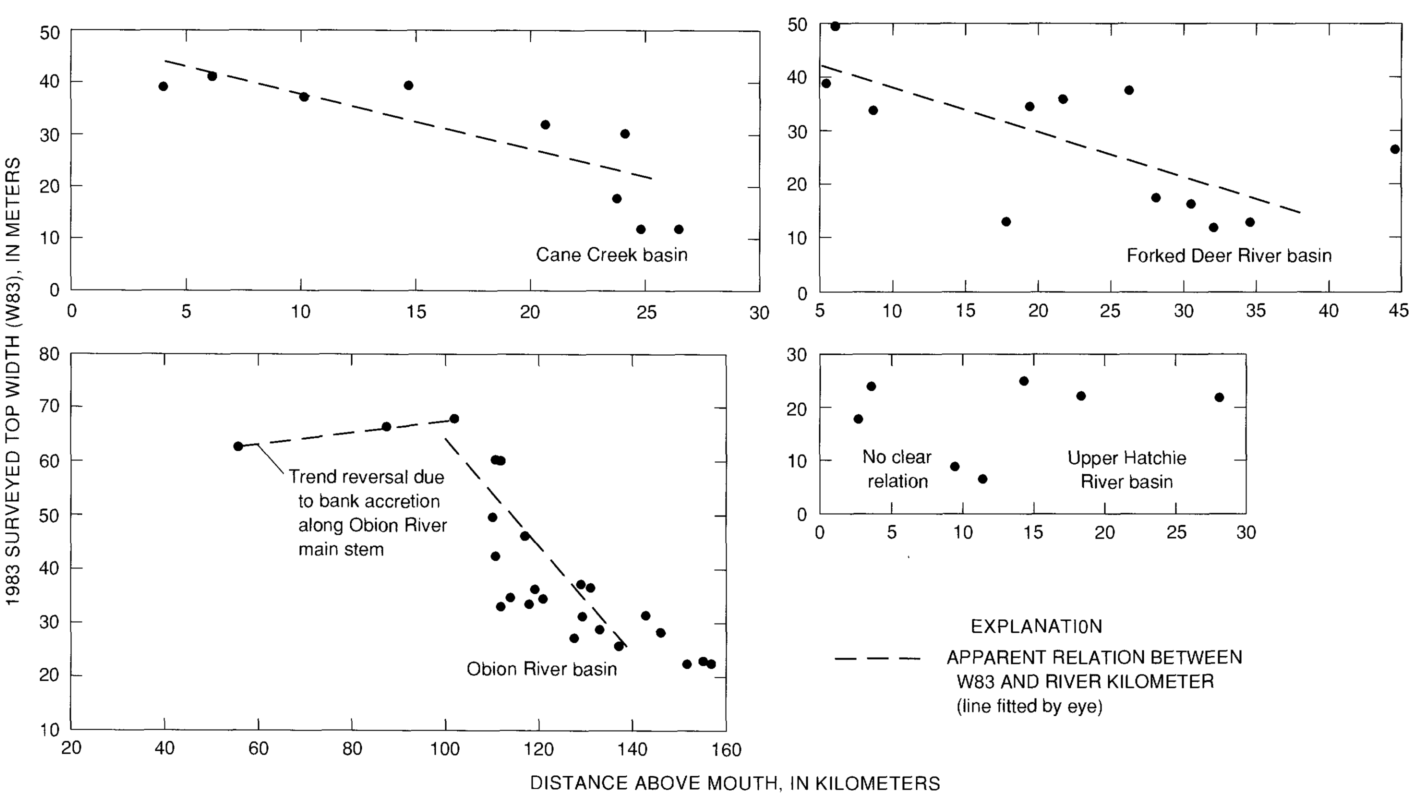


FIGURE 34.—Surveyed top width (1983), by river kilometer, for studied basin networks.

TABLE 18.—*Range of changes in channel top width (DW) by stream*
[Max., maximum; Min., minimum; *n*, number of observations]

Stream	DW, in meters			*n*	Years since most recent major channelization (from 1983)
	Mean	Min.	Max.		
Cane Creek	18.3	13.7	46.0	6	13
Cub Creek	2.1	0	6.7	4	13
Hoosier Creek	14.2	7.0	27.1	3	16
Hyde Creek	3.1	.3	5.5	3	18
Meridian Creek	3.4	2.4	4.3	2	16
North Fork Forked Deer River	10.3	3.0	25.0	4	10
North Fork Obion River	10.4	.6	25.6	5	16
Obion River	37.8	19.8	59.4	4	17
Pond Creek	2.9	2.1	4.3	4	5
Porters Creek	7.7	3.7	11.6	3	11
Rutherford Fork Obion River	7.3	0	18.3	5	14
South Fork Forked Deer River	13.6	4.9	27.1	6	14
South Fork Obion River	11.9	0	35.7	7	14

basin. However, potential widening can be estimated by equations 10–13 at sites undergoing the milder secondary aggradation, such as the lower ends of the forks of the Obion and Forked Deer Rivers.

PROCESSES AND STAGES OF BANK RETREAT AND SLOPE DEVELOPMENT

Interpretations of the processes and successive forms of bank retreat and bank-slope development reflect the

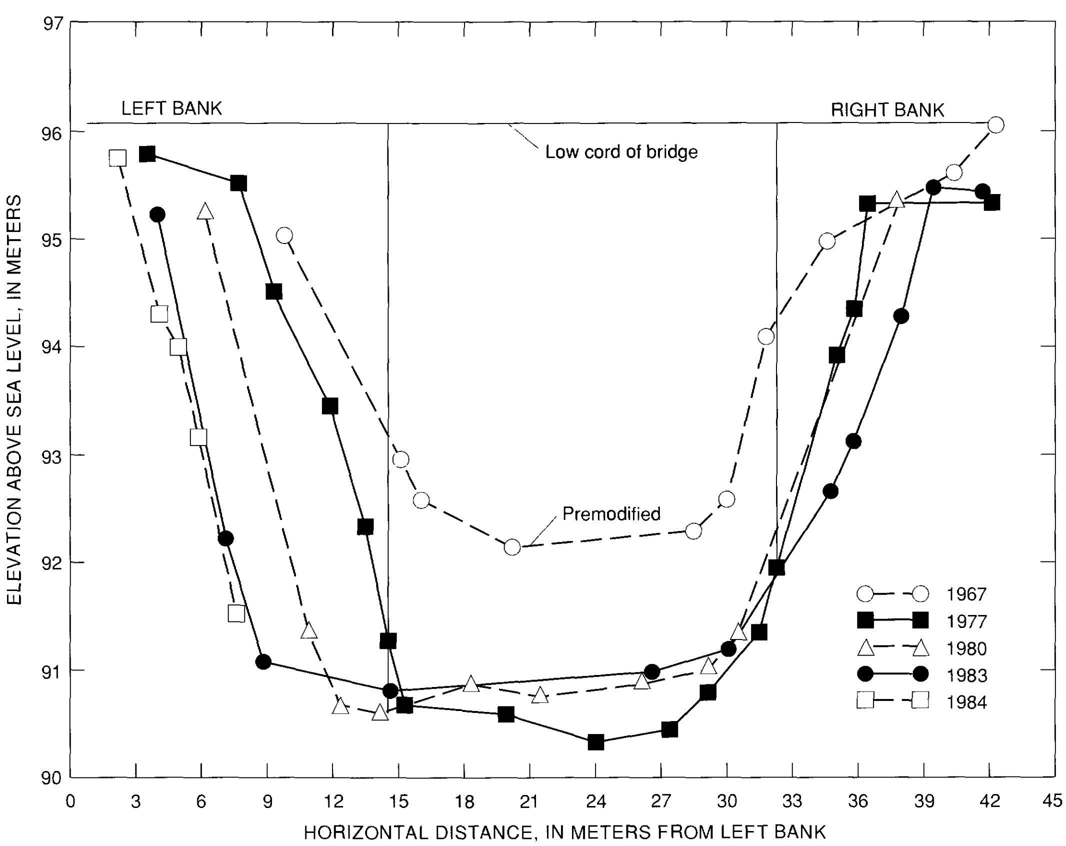


FIGURE 35.—Channel widening on the Rutherford Fork Obion River (station 07025050).

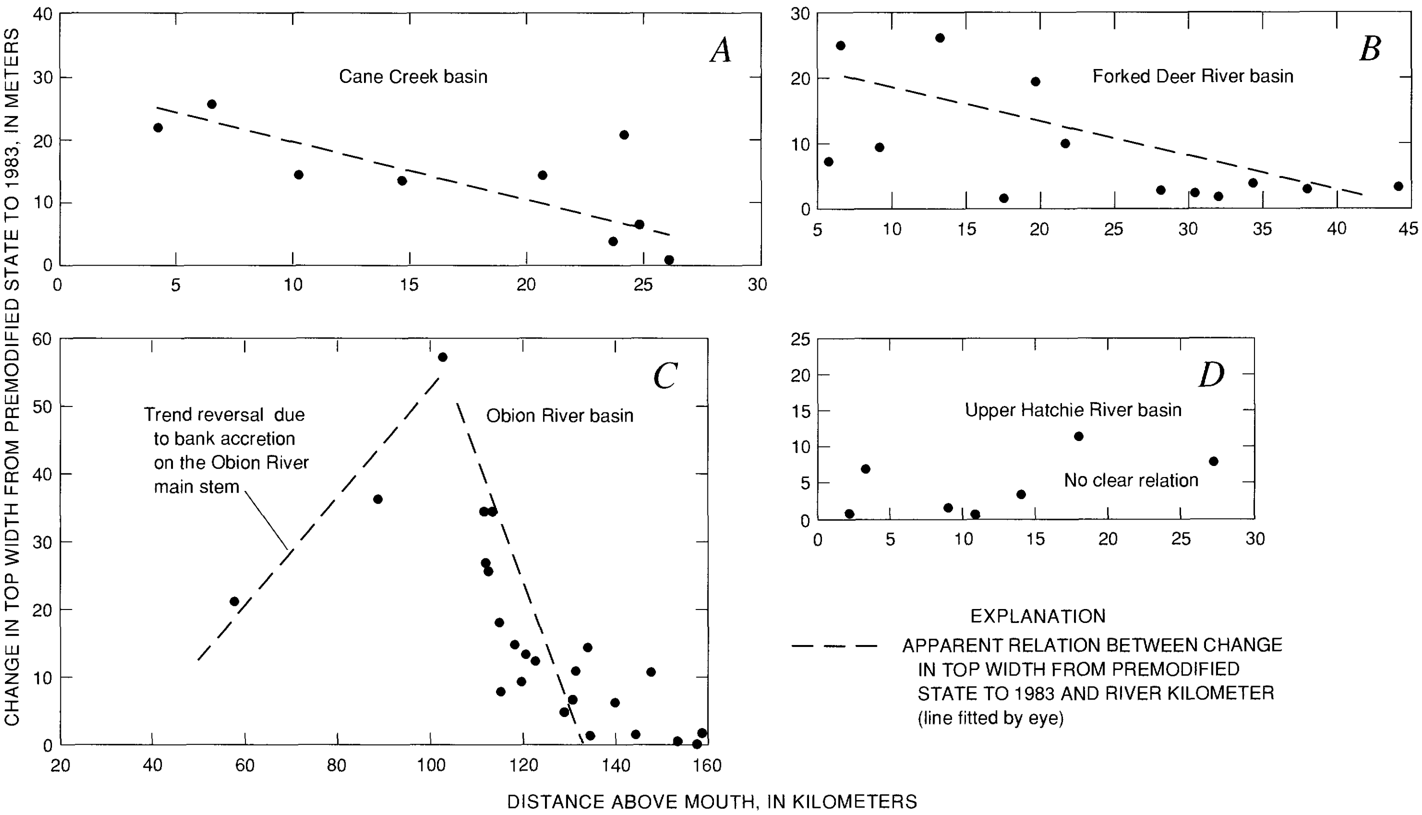


FIGURE 36.—Relation between changes in channel width and river kilometer for studied basin networks: (*A*) Cane Creek basin, (*B*) Forked Deer River basin, (*C*) Obion River basin, and (*D*) upper Hatchie River basin.

interaction of hillslope and fluvial processes and are based largely on bed-level adjustment trends, field observations, and geobotanical evidence. A complete "cycle" of bank-slope development from the premodified conditions through stages of adjustment to the eventual reestablishment of stable bank conditions assumes that degradation is of sufficient magnitude to instigate unstable bank conditions and a prolonged period (20–40 years) of mass wasting. This "cycle" assumes further that successive processes are not interrupted by an additional disturbance. An idealized representation of the six stages of bank retreat and bank-slope development is provided in figure 38. The stages represent distinguishable bank morphologies characteristic of the various site types that describe bed-level adjustment (that is, downstream-imposed aggradation, migrating degradation, secondary aggradation, and premodified aggradation). Varying intensities of gradation processes among the four types of bed-level adjustment are used to identify the six stages of bank-slope development (table 19). By applying a space-for-time substitution, longitudinal variation in bank-slope development can be used to denote morphologic change through time. Based on field observations and historical data, it will take 20–40 years for channel adjustment to pass through the first five stages of the model. A total of 50–100 years is assumed necessary for the restabilization of the channel banks (stage VI) and the initial development of meander bends (pattern adjustment).

PREMODIFIED STAGE (I)

Premodified bank conditions can be assumed to be the result of natural land-use practices and fluvial processes. Bank failure by mass-wasting processes generally does not occur, and banks are considered stable. Data referring to stable bank conditions along West Tennessee channels are available from the literature, agency work plans, the most upstream reaches of present-day (1983) adjusting networks, and the nonchannelized Hatchie River.

Premodified bank conditions (stage I in fig. 38) are characterized generally by low-angle slopes (20°–30°), convex upper bank and concave lower bank shapes, and established woody vegetation along the top bank and downslope toward the low-flow channel (fig. 39). Channels having these characteristic bank conditions generally have width-to-depth ratios (as measured from the flood-plain surface) between 6.0 and 10.0 and narrow slowly with time owing to mild aggradation and bank accretion. Sand is commonly found deposited on bank

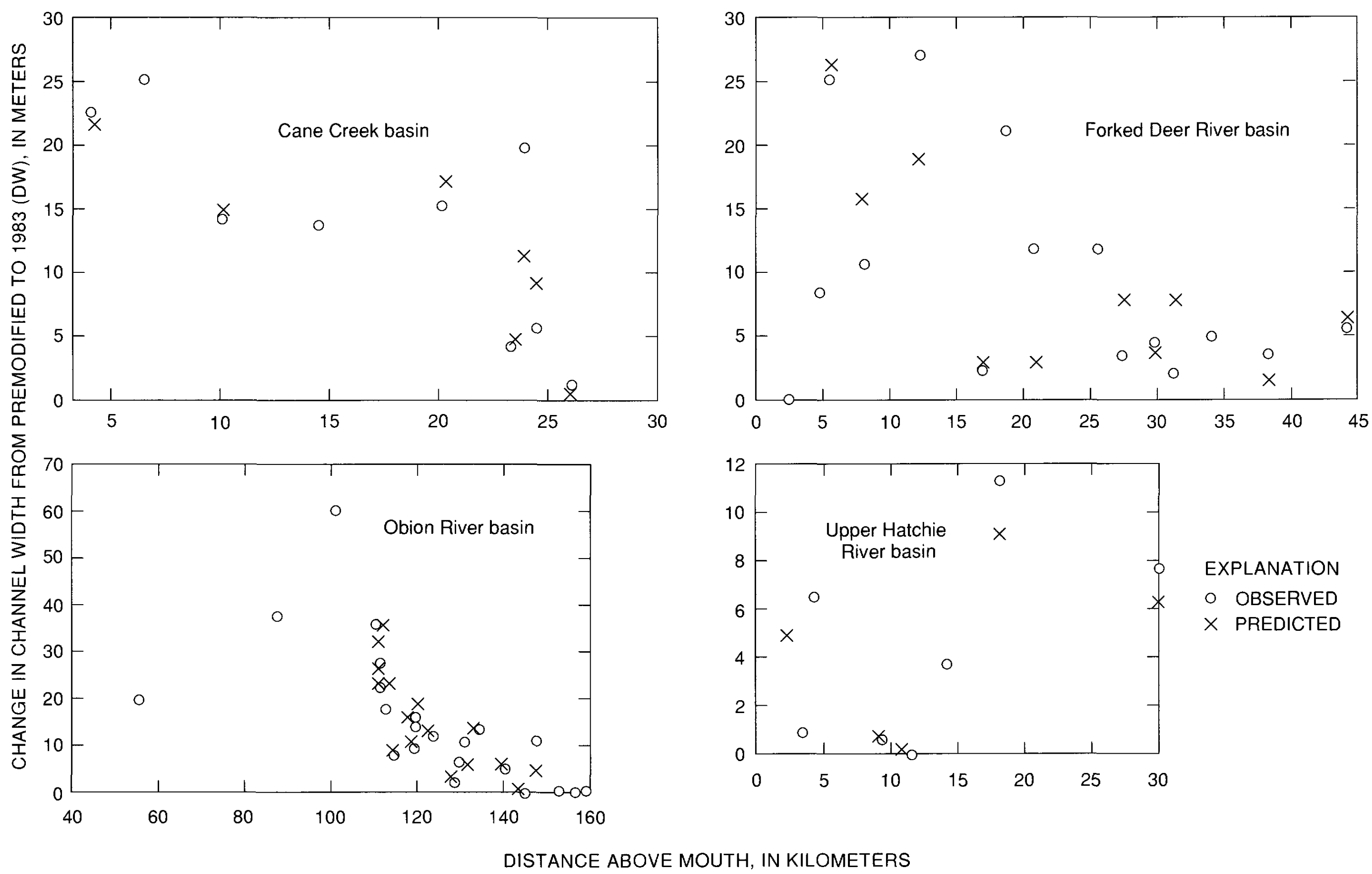


FIGURE 37.—Predicted and observed values of channel widening for studied basin networks.

surfaces, and limited channel widening occurs on some outside meander bends.

Premodified channel widths (prior to 1915) along the lower ends of the forks of the Obion and Forked Deer Rivers ranged from 15 to 27 m, depending on the stream's drainage area (Morgan and McCrory, 1910; Hidinger and Morgan, 1912). The present-day (1983) "premodified sites" (most upstream) on the forks of the Obion River are approximately 23 m wide (table 15).

CONSTRUCTED STAGE (II)

Construction of a new channel may involve reshaping of the existing channel banks or the repositioning of the entire channel. In either case, the banks are generally steepened, heightened, and made linear (stage II in fig. 38). West Tennessee channels are generally constructed as trapezoids, the bank slopes ranging from 18° to 34°, depending on soil conditions and the location of the site in the stream system. Channel widths are increased and vegetation is removed in order to convey greater discharges within the channel banks. Examples of constructed channels are shown in figure 40.

The combination of increased bank heights and angles and the removal of stabilizing vegetation leaves the channel banks more susceptible to erosion. The initiation of changes in channel width during this stage would be a function of the amount of bed-level lowering by man relative to the critical bank height. It is more appropriate, however, to consider the constructed condition (stage II) as a transition from the stable, premodified state to the more unstable degradation stage, when further heightening and steepening of the banks occur by fluvial processes.

DEGRADATION STAGE (III)

The degradation stage (stage III in fig. 38) is characterized by the lowering of the channel bed and the consequent increase in bank heights. Downcutting generally does not steepen bank slopes directly but maintains bank angles close to the angle of internal friction (Skempton, 1953; Carson and Kirkby, 1972; Simon and Hupp, 1986). Steepening occurs as moderate and high flows attack basal surfaces and remove toe material (stage IIIa in fig. 38). The bank profile remains linear through stage III but begins to steepen as undercutting takes place during stage IIIa. Widening by mass wasting does not occur because the critical bank height has not been exceeded.

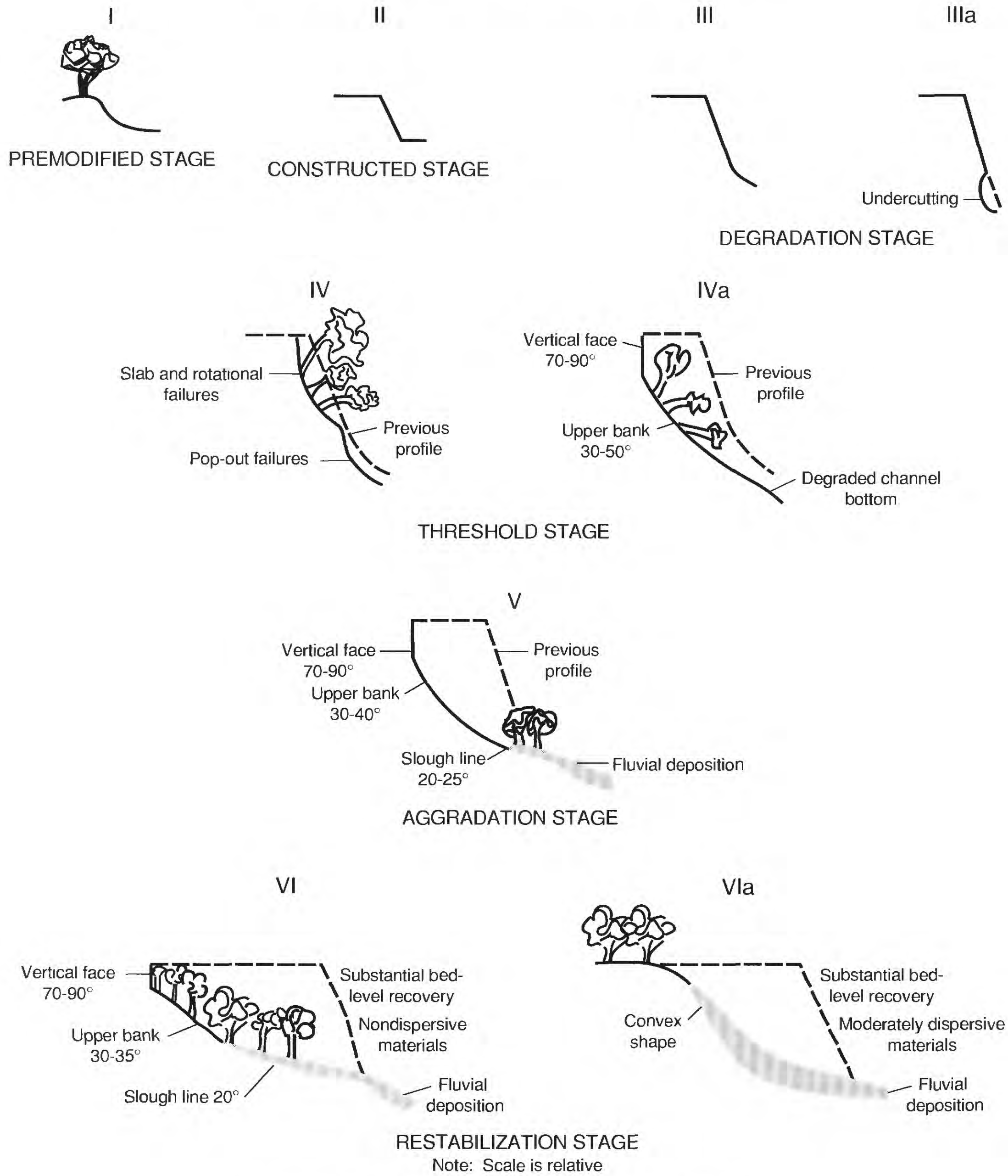


FIGURE 38.—The six stages of bank-slope development.

The degradation stage is probably the most important in determining the magnitude of channel widening that will occur because the amount of incision partly controls the bank-failure threshold. This is in agreement with the relations between degradation and widening developed previously and provides a framework for the reduction of channel widening with distance upstream. Sites close to the AMD are therefore expected to widen appreciably. Examples of West Tennessee channels undergoing degradation (stage III) and basal erosion (stage IIIa) as a preliminary condition to channel widening are shown in figure 41. The degradation stage ends when the critical bank height of the material is reached.

THRESHOLD STAGE (IV)

Stage IV (fig. 38) is the result of continued degradation and basal erosion that further heightens and steepens channel banks. The critical bank height is exceeded, and bank slopes and shapes become the product of mass-wasting processes. Slab- and wedge-type (planar) failures occur because of excessive undercutting and the loss of support for the upper part of the bank. Pop-out

TABLE 19.—*Stages of bank-slope development*
[AMD, area of maximum disturbance]

Stage No.	Stage Name	Type of bed-level adjustment	Location in network	Process on channel bed	Active widening	Failure types	Bank surfaces present	Approximate bank angles (degrees)
I	Premodified....	Premodified.....	Most upstream 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	Slab, rotational, pop-out.	Vertical face upper bank.	70–90 25–50
V	Aggradation....	Secondary aggradation.	Upstream of the AMD.	Aggradation ...	Yes	Slab, rotational, pop-out, low-angle slides.	Vertical face upper bank slough line.	70–90 25–40 20–25
VI	Restabilization..	Downstream-imposed aggradation.	Downstream of the AMD.	Aggradation ...	No	Low-angle slides, pop-out.	Vertical face upper bank slough line.	70–90 25–35 15–20

FIGURE 39.—Examples of premodified bank conditions (stage I of bank-slope development).

failures at the base of the bank due to saturation and excess pore-water pressure (Thorne and others, 1981) similarly oversteepen the upper part of the bank and can lead to further slab- and wedge-type failures.

Deep-seated rotational failures shear along a circular arc, and bank material often becomes detached from the top-bank surface by tension cracking. These fialures can involve a saturated mass of bank material that can leave 1- to 3-m slickensides along the failure plane (often a pipe) that come to rest in a lobate form at the base of the bank (fig. 42*A*). The failed material loses shear strength and, in its saturated state, can then be removed easily by moderate flows. Saturated rotational failures observed on the Rutherford Fork and South Fork Obion Rivers and on Cane Creek tend not to reduce bank angles as much as drier, rotational failures (fig. 42*A*).

Large, nonsaturated rotational failures along Cane Creek (up to 60 m long and 6 m wide) appear to occur along a series of pipes that form in the bank mass and intersect the flood-plain surface. Individual piping holes on the flood-plain surface form in rows parallel to the channel, 0.6 to 1.8 m apart, and are joined by cracks. These rows often coincide with the depressions formed between rows of crops that have been planted parallel to

FIGURE 40.—Examples of constructed channels (stage II of bank-slope development).

the channel. Water drains into the bank mass along the pipes, causing a reduction in shear strength and an increase in pore-water pressure along the potential failure planes. The bank then fails as a series of plates 0.6–3 m in width and 3–15 m long (fig. 42*B*). The width of the plates is partly a function of the extent of internal erosion along each row of pipes. These failure mechanisms can be considered worst case conditions in highly dispersive materials, such as in the Cane Creek basin.

Nonsaturated rotational failures also occur in less dispersive materials, where piping is not as prevalent. The bank fails as a single mass of material along a circular arc and may crumble to some extent during transport downslope (fig. 42*C*). Elliptical scars from these failures, commonly 15 m long, have been observed along many reaches of the adjusting streams of West Tennessee.

When failed material does not come to rest at the base of the bank, a definable surface forms higher on the bank profile at slopes ranging from 25° to 50° (stage IV in fig. 38). This surface is termed the "upper bank" (Simon and Hupp, 1986) (fig. 7) and can often be identified on field inspection by tilted and fallen vegetation. A second definable surface, termed the "vertical face" and representing the top section of the major failure plane, also is developed during the threshold stage (stage IV in fig. 38). The slope of the vertical face actually may range from 70° to 90° and represents the primary location of top-bank retreat.

Bank retreat by planar and rotational failures continues through the threshold stage, developing the vertical face and upper bank as two distinguishable bank forms (stage IV in figs. 38 and 43). The threshold stage is the first of two that are dominated by active channel widening. Failed material generally is carried off by moderate to high flows, thereby retaining the overheightened and oversteepened bank profile and giving the banks a scalloped appearance (fig. 44).

FIGURE 41.—Examples of degrading channels prior to the onset of channel widening (stage III of bank-slope development).

AGGRADATION STAGE (V)

Stage V (fig. 38) is marked by the onset of aggradation on the channel bed and can often be identified by deposited sand on bank surfaces. Bank retreat dominates the vertical face and upper bank sections because bank heights still exceed the critical height of the material. The failed material on the upper bank undergoes a reduction in shear strength to its residual strength (Thorne and others, 1981) and is subject to low-angle slides, which may produce a concave surface. These failures are partly the result of continued wetting of the material by rises in stage. The low-angle failures serve to reduce the angle of the upper bank and to extend it downslope (stage V in fig. 38).

Older masses of failed material on the upper bank also move downslope by low-angle slides (fig. 45*A*) and show evidence of fluvial reworking and deposition. This combination of mass-wasting and fluvial processes creates a low-angle surface (20°–25°), termined the "slough line," extending downslope from the upper bank (fig. 45*B*) (Simon and Hupp, 1986). This bank form can indicate the beginning of stable bank conditions. Samples of woody vegetation reestablishing on the slough line show only mild eccentricity in their rings and can be used to date the timing of renewed bank stability (stage V in fig. 38). A rate of deposition on the slough line can also be obtained by dividing the depths of burial above the root collar of trees by the age of the trees. These dating techniques have been used on some reaches of Cane Creek to estimate the beginning of lower-bank stability (Simon and Hupp, 1986).

Bank stability, as indicated by establishing vegetation on the slough line, extends upslope, away from the channel, with time. Bank angles on the upper bank and slough-line surfaces continue to flatten through stage V because of high moisture content of the banks, low-angle slides, and fluvial reworking. The shape of the bank, when composed of the vertical face (70°–90°), upper bank (25°–50°), and slough-line surfaces (20°–25°) in stage V, represents a characteristic profile of recovering channels in West Tennessee (stage V in fig. 38).

The break in slope between the upper bank and the vertical face may remain distinct for some time (fig. 43). Moderate and high flows may no longer spread out over the flood plain in the enlarged channels but are contained within the channel and impinge upon bank surfaces. As the channel bed rises with time during stage V, the vertical face is subjected to greater flow frequencies. The introduction of fluvial processes to the vertical face implies that undercutting and increased moisture contents can occur along this surface. Assuming that the critical bank height is still exceeded and (or) that dispersion and tension cracking continue to weaken the vertical face, parallel retreat along the vertical face and flattening of the upper bank and slough line may continue as the channel creates a new flood plain at an elevation lower than the previous one. The original flood plain will then become a fluvial remnant, or terrace. This condition of flood-plain development is not applicable to all of the adjusting channels in West Tennessee but probably is appropriate for the highly disturbed channels cut through deposits of dispersive loess, such as Cane Creek. Channels like Cane Creek tend to aggrade very slowly following the degradation phase of adjustment because of the lack of hydraulic control of the fine-grained sediments in transport and because of the paucity of coarse-grained materials in the basin. The lack of bed-level recovery may lead to an extended period during which bank heights exceed the critical bank height, allowing for continued bank retreat and the start of flood-plain development. It is estimated that the development of a new and typical broad flood plain on an adjusting channel such as Cane Creek will occur over geomorphic time (1,000 years or more). Stage V would then represent the final stage of bank-slope development in these types of channels.

In adjusting channels that have sand beds, aggradation may be of sufficient magnitude to stabilize the vertical face through a reduction in bank height below the critical height. Bank-slope development can occur in sand-bed channels where rising bed levels have effectively reduced bank heights below the critical height. These developments can result in the onset of stage VI conditions over time spans that approximate 20–40 years (based on the duration of the individual gradation processes).

The aggradation stage (stage V) of bank-slope development occurs first in downstream reaches and progresses upstream with trends of secondary aggradation. A meandering thalweg also begins to develop during stage V. Various downstream reaches characterized by stage V of bank-slope development are shown in figure 46.

RESTABILIZATION STAGE (VI)

The restabilization stage is marked by a significant reduction of bank heights by aggradation on the channel bed and fluvial deposition on the upper bank and slough-line surfaces. Bank retreat along the vertical face subsides because of the lack of bank height relative to the critical height.

Banks composed of strongly nondispersive, cohesive materials such as Porters and Cub Creeks and areas of the Obion River system could maintain the vertical face even though the surface would be frequently wet by rises in stage. Woody vegetation extends to the base of the vertical face in these cases, and the old flood-plain surface again becomes a terrace (stage VI in fig. 38).

In channels where bank materials are only moderately dispersive and where bed level has sufficiently recovered to cause more frequent wetting of the vertical face, the uppermost section of the bank may take a convex shape due to fluvial reworking and deposition (stage VI in fig. 38). In heavily aggrading reaches of the Obion and North Fork and South Fork Forked Deer Rivers, the flood-plain surface continues to function as a conduit for moderately high flows, as woody vegetation becomes reestablished at the top of the bank and on the flood-plain surface (fig. 47). Young riparian vegetation reestablishing on the slough-line and upper bank surfaces can be buried by the deposition of sands or washed off by moderate and high flows (fig. 47).

The interpretation of stage VI of bank-slope development assumes either significant bed-level recovery such as occurs along downstream-imposed reaches, or limited initial downcutting, as along Meridian Creek and other upstream reaches close to and including the premodified areas (fig. 32). Flattening of the upper bank and slough-line surfaces can continue in both the nondispersive and moderately dispersive materials due to weakened residual strengths, increased moisture conditions, and the additional weight of fluvially deposited material. A relatively permanent angle of stability below the vertical face still cannot be estimated. However, the conceptual framework of the simultaneous retreat of the vertical face, and flattening along surfaces below it, is supported by the observations of other investigations reported in Carson and Kirkby (1972, p. 184).

The six stages of bank-slope development represent a conceptual model of channel adjustment. Stages (premodified, constructed, degradation, threshold, aggradation, and restabilization) are induced by a succession of interactions between gradation and hillslope processes (fig. 38, table 19). The model does not imply that each adjusting reach will undergo all six stages over the course of the adjustment, but that specific trends of bed-level response will result in a series of mass-wasting processes and definable bank forms.

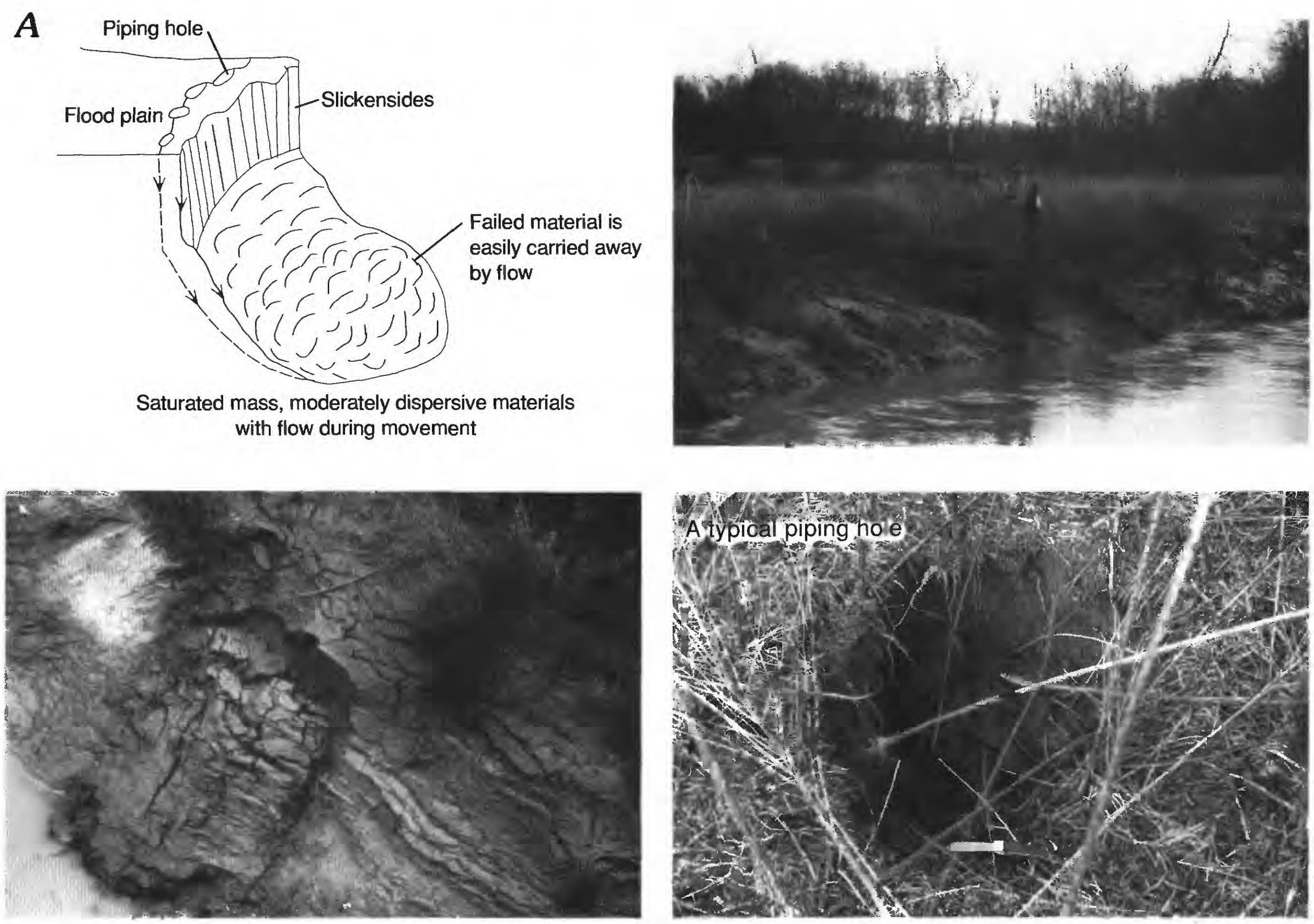


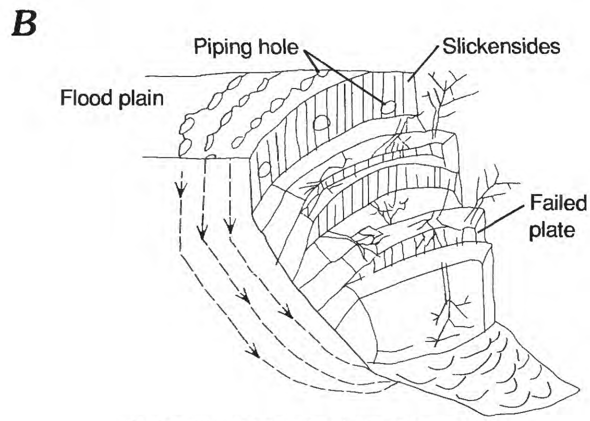
FIGURE 42.—(*A*) Saturated and (*B*,*C*) nonsaturated deep-seated rotational failures.

CHANNEL EVOLUTION

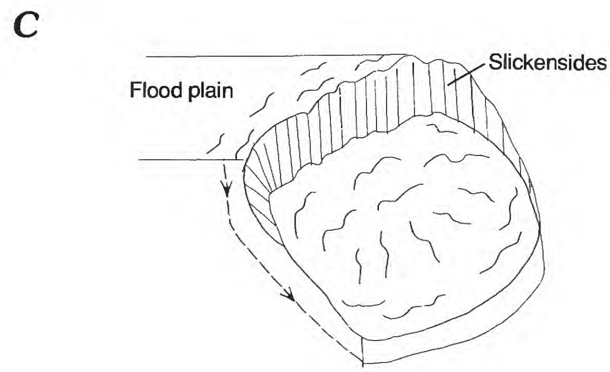
A sequence of channel evolution over a 100-year time period is developed from the trends of bed level and width adjustment discussed earlier. The approach is similar to that used by Harvey and others (1983), in that channel morphology observed along the lengths of the studied channels is arranged in an order that denotes change through time. The six-stage model proposed here differs in scope and detail from the channel evolution model recently developed along approximately 6.4 km of Oaklimiter Creek, northern Mississippi, by Harvey and others (1983). The six stages of channel evolution following major disruption of West Tennessee fluvial systems are determined by the dominant hillslope and fluvial processes, characteristic forms, and diagnostic geobotanical evidence (table 20).

The development of a meandering thalweg and alternate channel bars indicates the initial healing of the channel (stage V, and fig. 48). Failures along the vertical face and upper bank leave scallops along the flood-plain surface that tend to extend downstream and enlarge with time. These scallops serve to aid in the development of a meandering high-flow thalweg and, ultimately, a meandering pattern.

The six-stage model of channel evolution is based on documented trends of channel response following channelization throughout much of West Tennessee (fig. 49). The succession of observed bank morphologies can be directly related to changes on the channel bed and to various mass-wasting processes. Similar bank-failure mechanisms and bank forms have been observed in other areas of the Mississippi embayment as well as along streams cut into loess deposits in the Central United States (Piest and Bowie, 1974; Bradford and Piest, 1980; Thorne and others, 1981). Skempton (1953) and Carson and Kirkby (1972) also report similar combinations of processes, as well as successions of bank forms, along fine-grained channels in Great Britain. Reported bank angles characteristic of each stage and surface are a function of the bank-material properties but are in general agreement with those reported by Carson and Kirkby (1972) and Thorne and others (1981). The concept



Nonsaturated, highly dispersive materials moving as a series of plates



Nonsaturated, mildly dispersive materials moving as a single mass

FIGURE 42.—Continued.

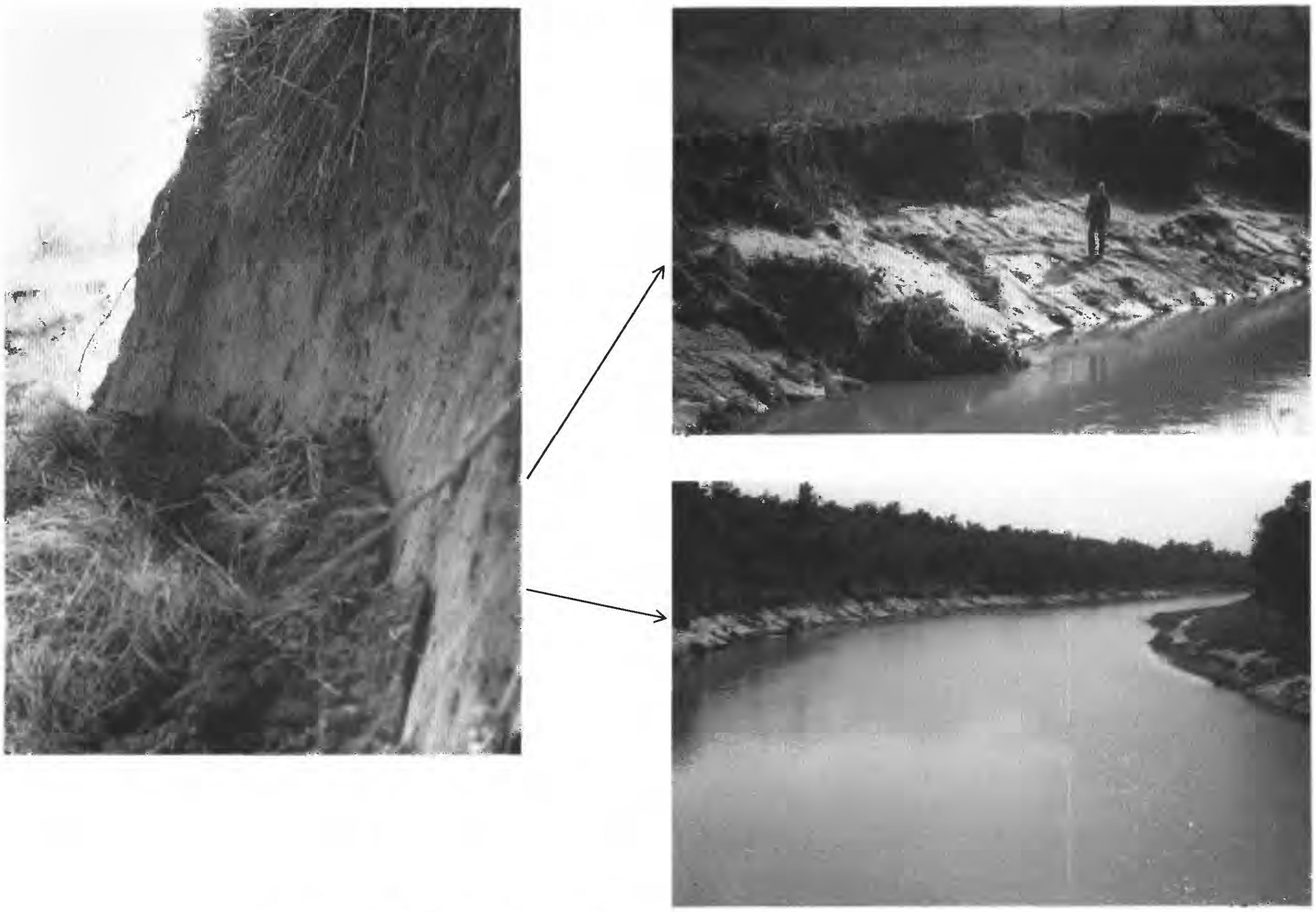


FIGURE 43.—The vertical face and upper bank as two distinguishable bank forms.

of initial overadjustment by degradation and consequent secondary aggradation has been verified earlier in this report and is an integral part of the channel-evolution model. Infilling of the channel serves to reduce bank heights and, ultimately, to stabilize the channel banks. For the purpose of simplicity, it is assumed that if secondary aggradation also overcompensates for the lowering of the channel bed, the next phase of degradation (oscillation) will not be of sufficient magnitude to destabilize the channel banks.

The model is apparently applicable to adjusting channels whose bank heights have increased beyond their critical height in West Tennessee and to areas of similar materials in the Mississippi embayment and the Central United States. It is suggested that extrapolation of the model into other geographical areas is justifiable on the basis that similar processes can result in similar forms. Variations in time scales and forms from the idealized model will occur because of local bedrock control, and differences in relief, soil properties, and climatic conditions. Still, the six-stage model of channel evolution is useful in determining expected changes in alluvial channel morphology over the course of fluvial adjustment.

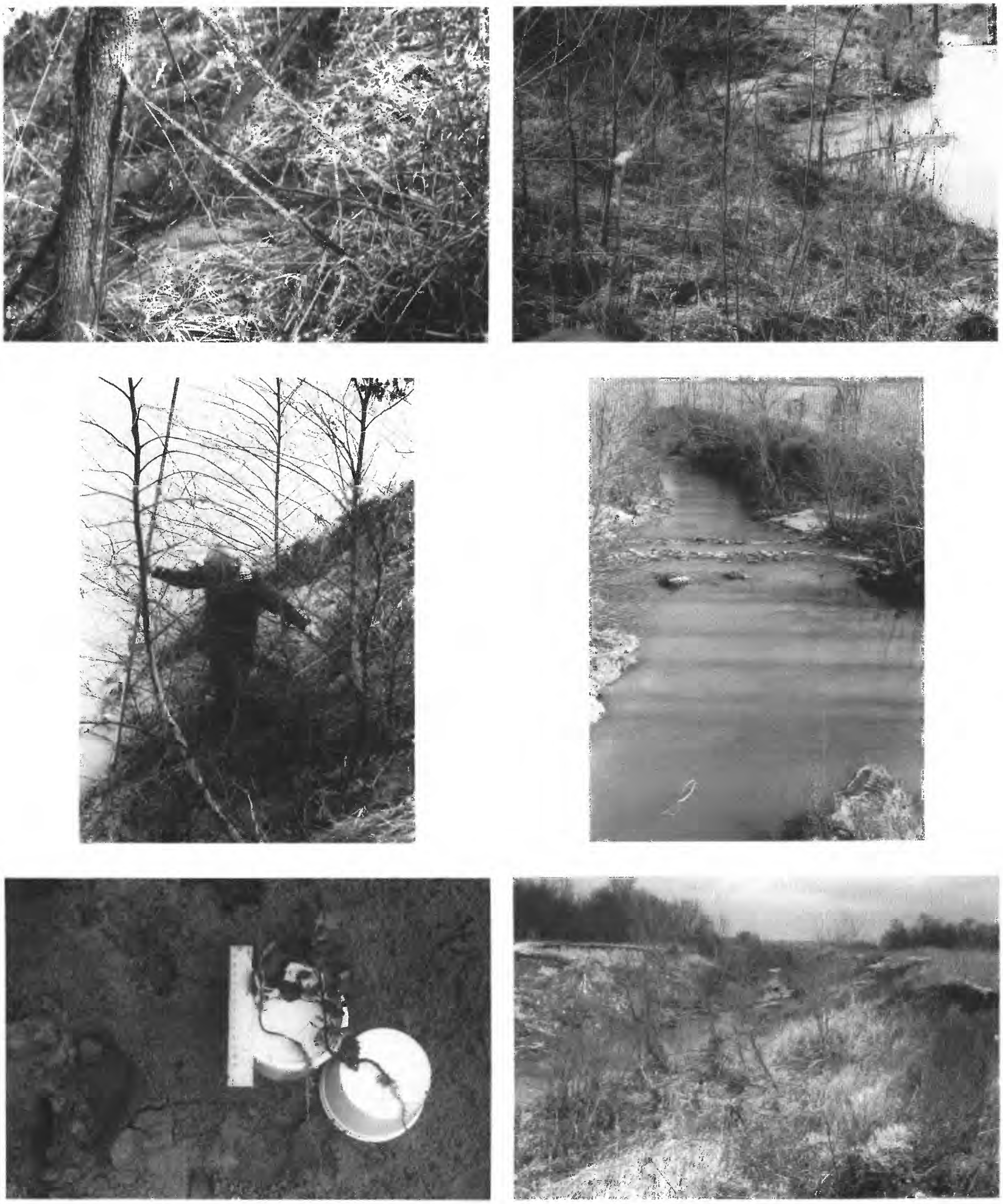
SUMMARY AND CONCLUSIONS

Channelization projects from the late 1950's through the 1970's initiated systematic trends of bed-level and width adjustment throughout four fluvial networks in West Tennessee. Data from 13 modified streams, where there is no bedrock control, were compiled and used to interpret channel response over time and space due to imposed increases in energy conditions. Bed material in these channels can be described generally as being either medium sand or medium silt.

The nonlinear rates of aggradation and degradation on the channel bed are described by a power equation of the general form $E=a(t)^b$. The sign of b indicates the particular gradation process operative over the time period, that is, negative for degradation and positive for aggradation.

Nonlinear degradation rates decrease nonlinearly with distance upstream from the AMD and can be described in

FIGURE 44.—Examples of the threshold stage of bank-slope development (stage IV).



A *B*

FIGURE 45.—Examples of (*A*) secondary downslope movement on the upper bank by low-angle slides and (*B*) establishing vegetation on the slough line.

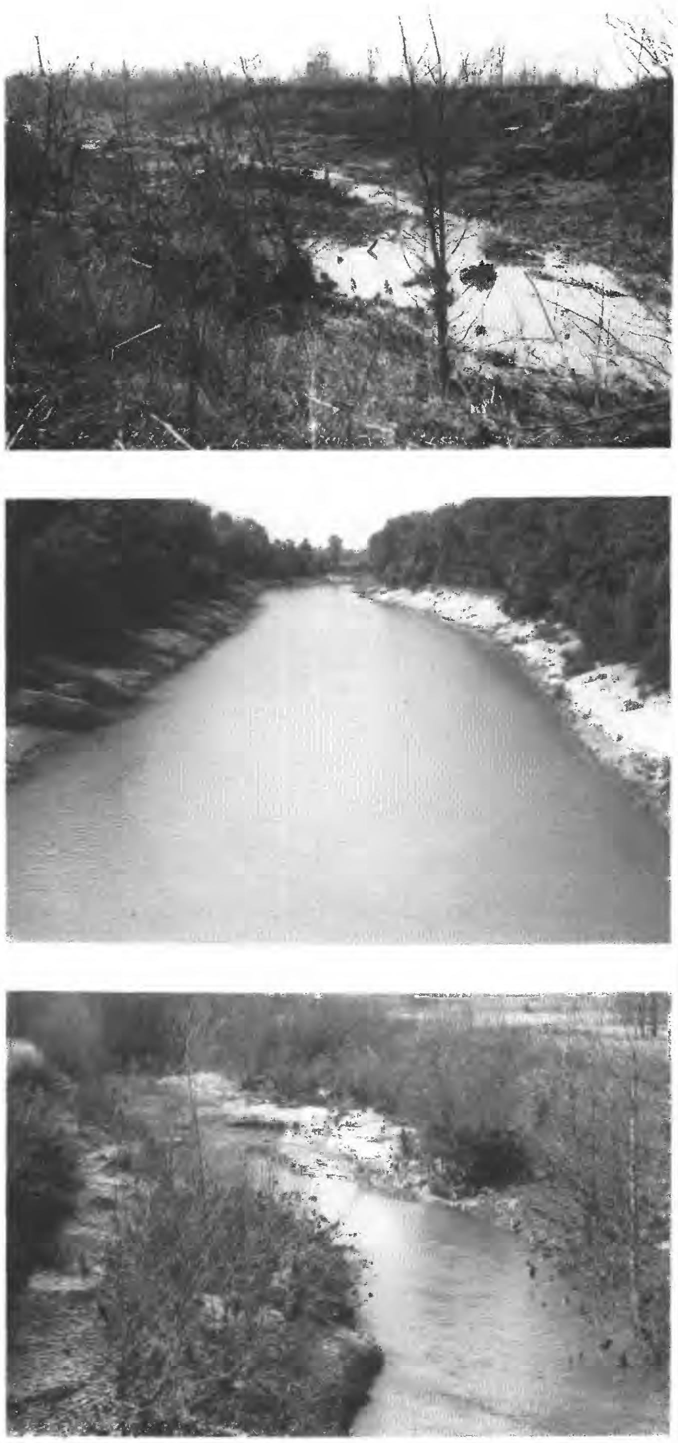


FIGURE 46.—Examples of the aggradation stage of bank-slope development (stage V).

FIGURE 47.—Examples of the restabilization stage of bank-slope development showing characteristic deposition on bank surfaces and established vegetation (stage VI). ▶

TABLE 20.—*Stages of channel evolution*

Stage		Dominant processes		Characteristic forms	Geobotanical evidence
No.	Name	Fluvial	Hillslope		
I	Premodified	Sediment transport; mild aggradation; basal erosion on outside bends; deposition on inside bends.		Stable, alternate channel 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	Heightening and steepening of banks; alternate bars eroded; flow line lower relative to top bank.	Riparian vegetation high relative to flow line and may lean toward 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 blocks 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; flattening of bank angles; flow line low relative to top bank; development of new flood plain(?).	Tilted and fallen riparian vegetation; reestablishing vegetation on slough line; deposition of material above root collars of slough-line vegetation.
VI	Restabilization	Aggradation; further development of meandering thalweg; further deposition of alternate bars; reworking of failed material; some basal erosion on outside bends; deposition on flood plain and bank surfaces.	Low-angle slides; some pop-out failures near flow line.	Stable, alternate channel bars; convex-short vertical face on top bank; flattening of bank angles; development of new flood plain(?); flow line high relative to top bank.	Reestablishing vegetation extends up slough line and upper bank; deposition of material above root collars of slough line and upper bank vegetation; some vegetation establishing on bars.

terms of the location of the site and the magnitude of the imposed disturbance. If a channel has been straightened by the construction of cutoffs, parameters that describe the percent shortened are used to denote the degree of disturbance. For channels modified only by dredging, the percent increase in gradient accounts for the amount of disruption by man. Nonlinear degradation rates upstream from the AMD following channelization can then be estimated using two-parameter multiple-regression equations. These equations are applicable to unsurveyed tributary channels and main-stem reaches. If disturbance-parameter data are not available, rates of downcutting can be approximated along main-stem and tributary channels from RKM data alone. These relations must not be used downstream from the stipulated limit of applicability. Once the nonlinear degradation rate (log $|-b|$) is obtained for a given site, bed-level change over the period of interest can be estimated.

Aggradation occurs immediately following channelization downstream from the AMD and in the uppermost reaches because of the interaction of natural land-use practices and channel processes (premodified). Degradation upstream from the AMD overcompensates for the imposed increases in energy conditions and results in channel gradients that cannot transport the increased sediment loads from degrading reaches farther

FIGURE 48.—Initial development of meandering thalweg and point bars during stage VI of the conceptual model of channel evolution.

upstream. These conditions initiate a phase of secondary aggradation following 10–15 years of downcutting at a site.

Data from 14 sites on eight streams in West Tennessee where there has been a shift from degradation to secondary aggradation indicate that nonlinear aggradation rates are 22 percent of the initial nonlinear degradation rates. This indicates that there is approximately 22 percent overadjustment by degradation. If it is assumed that the phase of secondary aggradation overadjusts similarly, channel response can be envisioned as alternating and diminishing phases of aggradation and degradation.

Data concerning secondary-aggradation rates are limited because of the span of time required for degradation at a site to be completed (10–15 years). To alleviate this problem, secondary-aggradation rates were synthesized from established degradation data, using the 78-percent reduction value. Longitudinal trends of synthesized aggradation rates agree reasonably well with trends of observed data and can be used to estimate bed-level change through time. Bed-level trends among the three aggradation site types (downstream-imposed, secondary, and premodified) are represented by a single linear equation that describes the reduction in aggradation with distance upstream. Maximum recorded rates of infilling may exceed 3 cm/yr on the Obion River main stem.

Trends in degradation and aggradation throughout the four fluvial networks were represented in models of longitudinal bed-level adjustment through time and space. The AMD denotes time zero and the location of initial channel responses in the river system. Degradation progresses upstream with time according to established trends, reducing channel gradients and inducing aggradation downstream. Following further migration of degradation upstream, sites begin to aggrade in the vicinity of the AMD where significant reductions in gradient have taken place. This secondary aggradation occurs as headward infilling and increases channel gradients in order to transport material delivered from degrading reaches upstream. With time, each degraded reach will begin to aggrade as a secondary response. It is believed that numerous shifts (oscillations) between degradation and aggradation occur before quasi-equilibrium is attained on the channel bed. Presumably, these oscillations around the threshold of critical power will diminish with time until quasi-equilibrium is approached.

The adjustment of channel width and bank-slope development due to channelization is directly related to induced changes on the channel bed. Heightening and steepening of the bank profile by degradation and undercutting serve initially to destabilize the bank. When the critical bank height of the material is exceeded, bank failures by mass-wasting processes can be expected. Mean values of critical bank height for the 13 studied streams range from 6.6 to 7.8 m, suggesting relatively homogeneous bank-material properties. However, pinhole dispersion tests of West Tennessee bank material indicate a broader range of characteristics and the potential for internal destabilization of the banks by piping. This process exerts a major influence in determining the susceptibility of a bank to fail and sheds doubt on use of critical bank height data as the only indicator of bank stability. The means of the maximum noneroding pinhole velocities for Cane and Hyde Creeks are 0.56 and 0.53 m/s, respectively; these values reflect the highly dispersive nature of the loess-bank materials on these creeks, and the great potential for piping. In contrast, outcroppings of the relatively resistant beds of the Porters Creek Clay are identified by high values of maximum noneroding pinhole velocity (3.0 m/s) in the Cub and Porters Creek basins. There are currently no means of

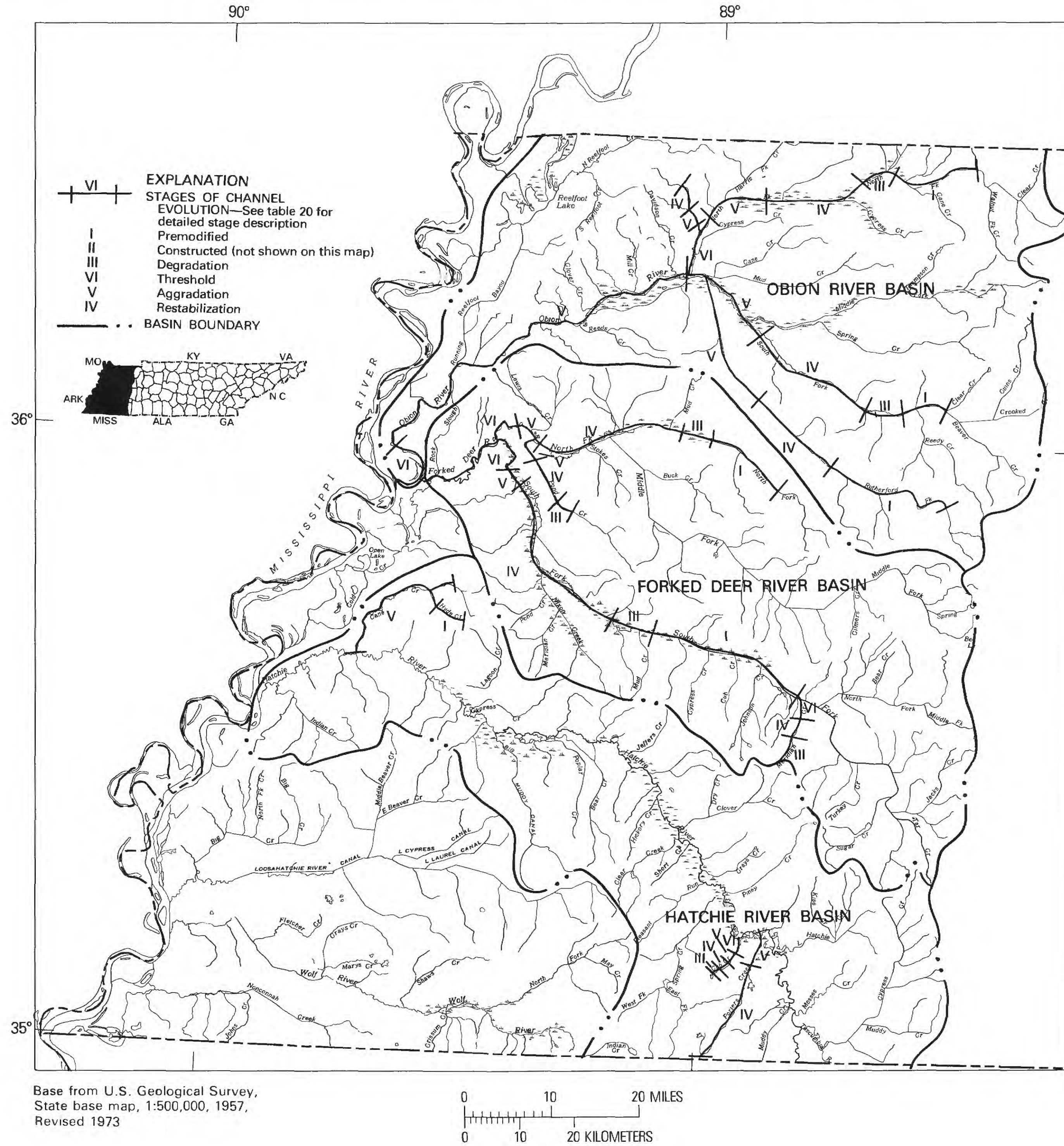


FIGURE 49.—Geographical distribution of stages of channel evolution.

mathematically accounting for the effects of dispersion characteristics in the calculation of critical bank height.

Increases in channel width upstream from the AMD are described in terms of downcutting, the predominant mechanism that tends to induce bank failure. The inclusion of bank-material properties data (percent clay and maximum noneroding pinhole velocity) into multiple-regression analyses results in greater coefficient of determination (r^2) values but decreasing values of statistical significance.

A six-stage model of bank retreat and bank-slope development was generated from bed-level adjustment trends and geobotanical evidence at each of the site types (that is, downstream-imposed aggradation, migrating degradation, secondary aggradation, and premodified aggradation). A space-for-time substitution was used to arrange the longitudinal variations in bank morphology such that they denote change through time. The six stages of bank retreat and bank-slope development, their location in the network, the dominant process on the channel bed, and the state of active widening (presence or absence) are listed below:

I. Premodified
   a. most-upstream reaches
   b. transport of sediment or mild aggradation
   c. absence of widening

II. Constructed
   a. where applicable
   b. dredging
   c. widening by man

III. Degradation
   a. upstream from the area of maximum disturbance
   b. migrating degradation
   c. absence of widening

IV. Threshold
   a. just upstream from the area of maximum disturbance
   b. migrating degradation
   c. active widening

V. Aggradation
   a. secondary aggradation
   b. upstream from the area of maximum disturbance
   c. active widening

VI. Restabilization
   a. downstream-imposed aggradation
   b. downstream from the area of maximum disturbance
   c. absence of widening

The threshold stage (stage IV) marks the beginning of intense mass-wasting processes such as planar and deep-seated rotational failures due to exceeding of the critical bank height by degradation. The vertical face (70°–90°) and the upper bank (25°–50°) develop during this stage as two distinguishable surfaces. The vertical face represents the location of top-bank retreat, and the upper bank represents parts of failure planes and masses of failed material.

Bank retreat by mass-wasting processes continues through the aggradation stage (stage V), and the upper bank surface flattens somewhat owing to low-angle slides. Stage V also marks the development of the slough line from the transport of previously failed materials farther downslope and from fluvial deposition. This surface (20°–25°) represents the initial location of renewed bank stability, as indicated by the reestablishment of woody vegetation. Greatly disturbed channels, which cut into highly dispersive fine-grained materials such as Cane Creek, may continue to widen for extended periods of time and may create a new flood plain at a lower elevation because of the lack of bed-level recovery. Sand-bed channels, however, may sufficiently reduce their bank heights by aggradation to a value less than the critical bank height within 20–40 years. In these cases, intense mass wasting subsides, and bank stability extends farther upslope along the slough line and upper bank surfaces. In the case of the development of a new flood plain, 1,000 years or more may be needed before a typically broad flood plain is constructed by the stream.

The six stages of bank-slope development incorporate vertical changes on the channel bed and can therefore be used to propose a model of channel evolution. The six stages of the channel evolution are similar to the stages of bank-slope development. However, incipient meandering and the development of alternate channel bars are included in stages V and VI of the channel-evolution model to address pattern adjustment.

Models described in this report assume that there is overadjustment and secondary response, that the bed and banks are free to adjust to imposed changes, and that there is no local bedrock control of channel geometry. Extrapolation of the six-stage conceptual models of bank-slope development and channel evolution should be particularly appropriate for areas of the Mississippi embayment and the Central United States. Application over a broader geographical area is conceptually justified on the basis that similar processes can create similar forms. Variations in time scales and forms from the idealized models will occur because of local bedrock control, variations in relief, soil properties, and climatic conditions. Still, the models reflect the overadjustments inherent in fluvial response and are useful in determining expected changes in alluvial-channel morphology over the course of a major adjustment cycle.

Reported predictive equations are regional in scope (West Tennessee and northern Mississippi), but could be applicable in similar geologic and topographic settings. Additional information is needed to assess the role of dispersion in effectively reducing the critical bank height and thereby controlling rates of widening. Additional geobotanical surveys throughout channels of the region would aid in determining rates of widening, bank-slope development, and fluvial deposition. Once this is accomplished, a six-stage quantitative model of channel evolution could be developed.

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SUPPLEMENTAL DATA

SUPPLEMENT A
Characteristics of the channel alluvium

[G, gradation index; CL, percent clay; SC, percent silt plus clay; LL, liquid limit; PL, plastic limit; PV, pinhole velocity, in meters per second]

Stream and station	Date	Type	d_{95}	d_{84}	d_{50}	d_{16}	d_5	G	CL	SC	LL	PL	PV
Cane Creek													
07030140	1983	BANK	0.230	0.110	0.059	0.0062	0.0011	5.69	12	80	--	--	0.81
07030133	1983	BANK	.070	.050	.026	.0070	.0015	2.82	10	96	--	--	.49
07030133	1983	BANK	.068	.044	.024	.0066	.0002	2.73	12	96	--	--	.62
07030123	1983	BANK	.066	.038	.016	.0014	.0003	6.90	22	96	34	25	.68
07030123	1983	BANK	.130	.041	.016	.0008	.0002	11.28	28	92	36	26	--
07030100	1983	BANK	.150	.054	.024	.0026	.0003	5.74	18	89	30	24	.57
07030090	1983	BANK	.064	.047	.024	.0046	.0010	3.59	15	99	--	--	--
07030125	1980	BANK	--	--	.020	--	--	--	12	96	30	19	--
07030125	1980	BANK	--	--	.022	--	--	--	11	95	30	20	--
07030127	1984	BANK	--	--	--	--	--	--	--	--	31	24	--
07030127	1984	BANK	--	--	--	--	--	--	--	--	31	25	--
07030127	1984	BANK	--	--	--	--	--	--	--	--	30	28	--
07030127	1984	BANK	--	--	--	--	--	--	--	--	32	27	--
07030127	1984	BANK	--	--	--	--	--	--	--	--	31	26	--
07030127	1984	BANK	--	--	--	--	--	--	--	--	30	26	--
07030127	1984	BANK	--	--	--	--	--	--	--	--	29	27	--
07030127	1984	BANK	--	--	--	--	--	--	--	--	28	26	--
07030127	1984	BANK	--	--	--	--	--	--	--	--	28	26	--
07030127	1984	BANK	--	--	--	--	--	--	--	--	33	27	--
07030127	1984	BANK	.060	.046	.028	.0073	.0024	2.74	10	97	--	--	--
07030127	1984	BANK	.092	.054	.026	.0067	.0004	2.98	11	92	29	24	.34
07030127	1984	BANK	.070	.051	.028	.0067	.0026	3.00	10	96	28	25	.57
07030127	1984	BANK	.070	.053	.028	.0067	.0025	3.04	10	96	29	24	.38
07030140	1983	BED	.370	.230	.037	.0120	.0004	4.65	10	76	--	--	--
07030133	1983	BED	.180	.090	.030	.0020	--	9.00	16	80	24	18	--
07030123	1983	BED	.074	.050	.024	.0007	.0001	18.18	25	95	30	24	--
07030100	1983	BED	.150	.054	.020	.0040	.0008	3.85	16	89	32	26	--
Cub Creek													
07029450	1983	BANK	.150	.042	.010	.0023	.0010	4.27	24	89	30	20	2.97
07029450	1976	BANK	.550	.360	.030	.0029	.0008	11.17	19	55	26	17	--
07029450	1976	BANK	.500	.275	.025	.0024	.0007	10.71	20	65	28	17	--
07029450	1976	BANK	.400	.197	.027	.0024	.0007	9.27	20	63	29	17	--
07029449	1976	BANK	.250	.100	.020	.0033	.0016	5.53	19	81	29	19	--
07029449	1976	BANK	.330	.210	.068	.0056	.0012	7.62	13	51	20	16	--
07029448	1983	BANK	.290	.205	.053	.0060	.0016	6.35	13	59	20	15	6.28
07029448	1983	BANK	.185	.092	.032	.0060	.0016	4.10	12	78	23	19	--
07029448	1976	BANK	.074	.045	.014	.0030	.0016	3.94	22	95	28	22	--
07029447	1983	BANK	.122	.068	.018	.0052	.0015	3.62	12	86	25	19	3.86
07029447	1983	BANK	1.130	.790	.261	.0230	.0079	7.19	2	29	--	--	.55
07029450	1983	BED	1.150	.800	.460	.3150	.2200	1.60	0	0	--	--	--
07029450	1976	BED	1.540	.970	.505	.2700	.1400	1.90	0	2	--	--	--
07029449	1983	BED	1.060	.740	.378	.2170	.1490	1.85	0	0	--	--	--
07029448	1983	BED	.123	.066	.021	.0056	.0016	3.45	13	86	28	22	--
07029448	1983	BED	1.350	.940	.570	.3400	.2150	1.66	0	1	--	--	--
07029448	1977	BED	1.600	.760	.460	.2900	.2200	1.62	0	2	--	--	--
07029450	1983	DEP.	.520	.390	.275	.1860	.1380	1.45	0	1	--	--	--

SUPPLEMENT A—Continued

Stream and station	Date	Type	d_{95}	d_{84}	d_{50}	d_{16}	d_5	G	CL	SC	LL	PL	PV
Hatchie River													
07030050	1983	BANK	0.290	0.084	0.015	0.0037	0.0005	4.83	17	80	26	17	3.17
07030000	1983	BANK	.280	.078	.015	.0040	.0007	4.48	16	83	30	23	2.46
07029500	1983	BANK	.190	.072	.019	.0019	.0004	6.89	22	85	30	20	--
07029400	1983	BANK	1.050	.058	.010	.0018	.0002	5.68	24	90	35	24	3.18
07029270	1983	BANK	.355	.230	.044	.0039	.0013	8.25	16	52	--	--	--
07030050	1983	BED	--	--	--	--	--	--	--	--	--	--	--
07030000	1983	BED	1.050	.640	.290	.0070	.0002	21.82	11	46	--	--	--
07029500	1980	BED	.717	.590	.450	.2910	.1950	1.43	0	0	--	--	--
07029400	1983	BED	1.000	.550	.305	.0600	.0025	3.44	8	20	--	--	--
07029270	1983	BED	.770	.540	.340	.2700	.2000	1.42	0	0	--	--	--
07025690	1983	BANK	.160	.048	.021	.0060	.0004	2.89	13	92	--	--	1.00
Hoosier Creek													
07025666	1983	BANK	.060	.039	.023	.0072	.00110	2.45	12	98	--	--	.74
07025666	1981	BANK	--	--	.020	--	--	--	15	95	31	19	.08
07025660	1983	BANK	.160	.047	.023	.0070	.00130	2.66	12	92	--	--	1.95
07025690	1983	BED	.074	.041	.019	.0033	.00090	3.96	18	95	33	24	--
07025666	1983	BED	.100	.048	.021	.0031	.00120	4.53	19	92	30	21	--
07025660	1983	BED	.160	.047	.023	.0070	.00200	2.66	11	92	--	--	--
Hyde Creek													
07030110	1983	BANK	.330	.100	.028	.0035	.00060	5.79	17	82	--	--	.45
07030107	1983	BANK	.420	.066	.029	.0040	.00005	4.76	16	85	30	25	.49
07030104	1983	BANK	.105	.042	.022	.0033	.00064	4.29	18	94	30	25	.66
07030110	1983	BED	.100	.048	.025	.0046	.00020	3.68	15	91	30	25	--
07030107	1983	BED	.090	.052	.025	.0040	.00030	4.17	16	94	32	25	--
07030104	1983	BED	.110	.048	.022	.0050	.00010	3.29	15	93	29	24	--
Meridian Creek													
07027485	1983	BANK	.565	.030	.028	.0048	.00030	7.02	6	72	--	--	--
07027485	1983	BANK	.160	.049	.018	.0030	.00010	4.36	19	91	28	22	--
07027483	1984	BANK	.320	.240	.094	.0110	.00270	5.55	9	44	--	--	--
07027483	1984	BANK	.190	.054	.005	.0020	.00140	6.65	45	90	31	21	--
07027483	1983	BANK	.220	.120	.018	.0012	.00020	10.83	24	80	27	16	--
07027480	1983	BANK	.105	.050	.013	.0014	.00040	6.56	14	90	27	20	--
07027480	1983	BANK	.520	.220	.020	.0005	.00010	25.50	26	66	22	15	--
07027478	1983	BANK	.350	.230	.037	.0025	.00030	10.50	19	60	--	--	--
07027478	1983	BANK	.330	.170	.019	.0040	.00240	6.85	16	75	22	18	--
07027485	1983	BED	1.000	.480	.310	.1800	.13800	1.63	0	1	--	--	--
07027483	1984	BED	.730	.530	.365	.2100	.13000	1.59	0	0	--	--	--
07027483	1983	BED	.800	.500	.340	.2100	.15200	1.54	0	1	--	--	--
07027480	1983	BED	.460	.360	.250	.1580	.13000	1.51	0	1	--	--	--
07027478	1983	BED	.160	.060	.007	.0005	.00020	11.29	40	87	35	22	--
07027478	1983	BED	5.000	.740	.470	.3000	.24000	1.57	0	0	--	--	--
07027483	1983	DEP.	.330	.260	.150	.0920	.05800	1.68	0	7	--	--	--
07027483	1984	DEP.	.380	.280	.200	.0620	.02000	2.31	0	17	--	--	--
07027483	1984	DEP.	.380	.300	.210	.1300	.04000	1.52	0	8	--	--	--

SUPPLEMENT A—Continued

Stream and station	Date	Type	d_{95}	d_{84}	d_{50}	d_{16}	d_5	G	CL	SC	LL	PL	PV
North Fork Forked Deer River													
07029105	1983	BANK	0.070	0.050	0.021	0.0044	0.00080	3.58	15	96	--	--	1.08
07029105	1964	BANK	--	--	--	--	--	--	--	--	40	24	--
07029105	1964	BANK	--	--	--	--	--	--	--	--	36	22	--
07029105	1964	BANK	--	--	--	--	--	--	--	--	37	22	--
07029105	1964	BANK	--	--	--	--	--	--	--	--	34	23	--
07029105	1964	BANK	--	--	--	--	--	--	--	--	31	26	--
07029105	1964	BANK	--	--	--	--	--	--	--	--	26	20	--
07029105	1964	BANK	--	--	--	--	--	--	--	--	23	20	--
07029100	1983	BANK	.270	.052	.025	.0024	.00050	6.24	20	92	22	17	.38
07029100	1983	BANK	.130	.077	.026	.0024	.00030	6.90	19	81	26	23	2.86
07029100	1964	BANK	--	--	--	--	--	--	--	--	34	26	--
07029100	1964	BANK	--	--	--	--	--	--	--	--	35	26	--
07029100	1964	BANK	--	--	--	--	--	--	--	--	37	24	--
07029100	1964	BANK	--	--	--	--	--	--	--	--	29	23	--
07029100	1964	BANK	--	--	--	--	--	--	--	--	30	24	--
07029100	1964	BANK	--	--	--	--	--	--	--	75	26	21	--
07029040	1983	BANK	.115	.067	.027	.0042	.00060	4.45	16	86	--	--	.64
07029040	1964	BANK	--	--	--	--	--	--	--	72	36	15	--
07029040	1964	BANK	--	--	--	--	--	--	--	--	62	24	--
07029040	1964	BANK	--	--	--	--	--	--	--	--	45	17	--
07028840	1983	BANK	.086	.039	.020	.0023	.00070	5.32	21	93	32	25	.38
07028840	1983	BANK	.068	.053	.022	.0035	.00110	4.35	17	96	31	26	1.39
07028840	1964	BANK	--	--	--	--	--	--	--	--	53	23	--
07028840	1964	BANK	--	--	--	--	--	--	--	--	41	20	--
07028840	1964	BANK	--	--	--	--	--	--	--	--	56	20	--
07028840	1964	BANK	--	--	--	--	--	--	--	--	39	23	--
07028820	1983	BANK	.147	.037	.018	.0011	.0001	9.21	22	91	28	23	.47
07028820	1964	BANK	--	--	--	--	--	--	--	--	33	22	--
07028820	1964	BANK	--	--	--	--	--	--	--	--	30	24	--
07028820	1964	BANK	--	--	--	--	--	--	--	--	30	23	--
07028820	1964	BANK	--	--	--	--	--	--	--	--	38	20	--
07028500	1983	BANK	.310	.170	.032	.0042	.0008	6.47	16	77	--	--	.79
07028410	1983	BANK	.088	.077	.026	.0042	.0006	4.58	16	81	--	--	.81
07029105	1983	BED	3.000	.890	.480	.2850	.0620	1.77	0	5	--	--	--
07029100	1983	BED	.480	.110	.031	.0050	.0012	4.87	14	81	--	--	--
07029100	1973	BED	4.600	3.800	.210	.0140	.0030	16.55	7	37	--	--	--
07029040	1983	BED	.443	.365	.278	.2000	.1450	1.35	0	1	--	--	--
07028840	1983	BED	.079	.041	.019	.0018	.0005	6.36	22	94	27	21	--
07028840	1983	BED	.375	.285	.220	.1500	.0150	1.38	1	8	--	--	--
07028820	1983	BED	.680	.410	.275	.1800	.1100	1.50	0	4	--	--	--
07028820	1983	BED	.320	.260	.083	.0120	.0003	5.02	10	34	--	--	--
07028500	1983	BED	.275	.074	.029	.0056	.0011	3.86	13	84	27	22	--
07028500	1983	BED	1.250	.850	.550	.3350	.2700	1.59	0	1	--	--	--
07028500	1973	BED	1.100	.710	.430	.2700	.1800	1.62	0	1	--	--	--
07028410	1983	BED	.615	.445	.320	.1940	.1250	1.52	0	3	--	--	--
07029105	1983	DEP.	.385	.290	.198	.1400	.0460	1.44	0	7	--	--	--
07029100	1983	DEP.	.330	.217	.150	.1250	.0320	1.32	0	10	--	--	--
07028500	1983	DEP.	.375	.280	.180	.1300	.1100	1.47	0	2	--	--	--

SUPPLEMENT A—Continued

Stream and station	Date	Type	d_{95}	d_{84}	d_{50}	d_{16}	d_5	G	CL	SC	LL	PL	PV
North Fork Obion River													
07025600	1983	BANK	.086	0.077	0.028	0.0072	0.0003	3.31	13	81	--	--	2.04
07025600	1983	BANK	.260	.048	.013	.0009	.0004	9.07	35	92	32	19	.68
07025600	1964	BANK	--	--	--	--	--	--	--	--	32	21	--
07025600	1964	BANK	--	--	--	--	--	--	--	--	30	20	--
07025600	1964	BANK	--	--	--	--	--	--	--	--	31	16	--
07025600	1964	BANK	--	--	--	--	--	--	--	--	31	17	--
07025600	1964	BANK	--	--	--	--	--	--	--	--	40	14	--
07025600	1964	BANK	--	--	--	--	--	--	--	--	--	--	--
07025500	1983	BANK	.074	.042	.004	.0008	.0004	7.75	50	95	39	21	2.76
07025500	1961	BANK	--	--	--	--	--	--	--	--	32	20	--
07025500	1961	BANK	--	--	--	--	--	--	--	--	47	19	--
07025500	1961	BANK	--	--	--	--	--	--	--	--	44	20	--
07025500	1961	BANK	--	--	--	--	--	--	--	--	36	28	--
07025400	1983	BANK	.068	.045	.012	.0016	.0006	5.62	26	96	30	23	2.72
07025400	1983	BANK	.068	.036	.008	.0011	.0005	5.89	34	96	30	21	.51
07025400	1946	BANK	--	--	--	--	--	--	13	62	--	--	--
07025400	1946	BANK	--	--	--	--	--	--	49	85	--	--	--
07025340	1983	BANK	.140	.082	.031	.0045	.0006	4.77	15	82	--	--	1.36
07025340	1946	BANK	--	--	--	--	--	--	43	86	--	--	--
07025340	1946	BANK	--	--	--	--	--	--	42	89	--	--	--
07025320	1983	BANK	.540	.062	.027	.0033	.0004	5.24	17	87	--	--	1.91
07025310	1983	BANK	.295	.190	.050	.0046	.0010	7.33	15	59	--	--	.91
07025600	1983	BED	.820	.580	.440	.3200	.2600	1.35	0	0	--	--	--
07025600	1973	BED	.670	.540	.400	.3100	.2450	1.32	0	0	--	--	--
07025500	1983	BED	.860	.620	.430	.3100	.2600	1.41	0	0	--	--	--
07025400	1983	BED	2.000	.760	.480	.3250	.2700	1.53	0	0	--	--	--
07025400	1980	BED	.977	.667	.490	.3730	.2970	1.34	0	0	--	--	--
07025340	1983	BED	1.000	.610	.420	.2800	.2100	1.48	0	0	--	--	--
07025340	1981	BED	1.570	.785	.455	.3200	.2315	1.57	0	0	--	--	--
07025320	1983	BED	1.000	.610	.390	.2600	.1780	1.53	0	0	--	--	--
07025310	1983	BED	2.000	.610	.380	.2600	.1750	1.53	0	0	--	--	--
07025600	1983	DEP.	.320	.270	.200	.1550	.1300	1.32	0	1	--	--	--
07025500	1983	DEP.	.360	.280	.210	.1400	.0370	1.42	0	6	--	--	--
07025500	1983	DEP.	.420	.340	.250	.1700	.1350	1.41	0	1	--	--	--
07025400	1983	DEP.	.355	.290	.222	.1530	.1050	1.38	0	3	--	--	--
07025340	1983	DEP.	.380	.300	.230	.1600	.1350	1.37	0	0	--	--	--
Obion River													
07027200	1983	BANK	.064	.043	.023	.0035	.0010	4.22	17	96	--	--	.42
07027200	1970	BANK	--	--	--	--	--	--	--	--	54	19	--
07027200	1970	BANK	--	--	--	--	--	--	--	--	57	21	--
07027200	1970	BANK	--	--	--	--	--	--	--	--	94	25	--
07027200	1970	BANK	--	--	--	--	--	--	--	--	67	23	--
07027200	1970	BANK	--	--	--	--	--	--	--	--	53	22	--
07027200	1970	BANK	--	--	--	--	--	--	--	--	38	19	--
07027200	1970	BANK	--	--	--	--	--	--	--	--	28	19	--
07027200	1970	BANK	--	--	--	--	--	--	--	--	33	20	--
07027200	1970	BANK	--	--	--	--	--	--	--	--	38	23	--

SUPPLEMENT A—Continued

Stream and station	Date	Type	d_{95}	d_{84}	d_{50}	d_{16}	d_5	G	CL	SC	LL	PL	PV
Obion River--Continued													
07027200	1970	BANK	--	--	--	--	--	--	--	--	54	24	--
07026300	1983	BANK	0.070	0.051	0.023	0.0066	0.0002	2.85	11	96	28	21	--
07026300	1961	BANK	--	--	--	--	--	--	--	--	36	20	--
07026300	1961	BANK	--	--	--	--	--	--	--	77	37	20	--
07026300	1961	BANK	--	--	--	--	--	--	--	54	23	15	--
07026300	1961	BANK	--	--	--	--	--	--	--	56	31	17	--
07026250	1983	BANK	.066	.039	.021	.0050	.0007	3.03	14	96	--	--	4.20
07026250	1961	BANK	--	--	--	--	--	--	--	--	46	21	--
07026250	1961	BANK	--	--	--	--	--	--	--	--	38	21	--
07026250	1961	BANK	--	--	--	--	--	--	--	--	53	25	--
07026250	1961	BANK	--	--	--	--	--	--	--	53	23	17	--
07026250	1961	BANK	--	--	--	--	--	--	--	56	--	--	--
07026250	1946	BANK	--	--	--	--	--	--	12	43	--	--	--
07026250	1946	BANK	--	--	--	--	--	--	23	57	--	--	--
07026250	1946	BANK	--	--	--	--	--	--	60	97	--	--	--
07026000	1983	BANK	.290	.180	.046	.0092	.0002	4.46	11	52	--	--	--
07026000	1983	BANK	.180	.077	.028	.0070	.0014	3.38	10	83	28	22	4.67
07026000	1961	BANK	--	--	--	--	--	--	--	--	34	22	--
07026000	1961	BANK	--	--	--	--	--	--	--	--	31	25	--
07026000	1961	BANK	--	--	--	--	--	--	--	70	--	--	--
07026000	1961	BANK	--	--	--	--	--	--	--	--	33	24	--
07026000	1961	BANK	--	--	--	--	--	--	--	--	32	22	--
07026000	1961	BANK	--	--	--	--	--	--	--	--	26	20	--
07026000	1961	BANK	--	--	--	--	--	--	--	--	30	21	--
07026000	1961	BANK	--	--	--	--	--	--	--	--	39	26	--
07025900	1983	BANK	.350	.225	.057	.0050	.0022	7.67	14	55	--	--	.47
07025900	1961	BANK	--	--	--	--	--	--	--	58	--	--	--
07025900	1961	BANK	--	--	--	--	--	--	--	--	28	24	--
07025900	1961	BANK	--	--	--	--	--	--	--	--	29	22	--
07025900	1961	BANK	--	--	--	--	--	--	--	--	32	24	--
07025900	1961	BANK	--	--	--	--	--	--	--	--	29	23	--
07025900	1961	BANK	--	--	--	--	--	--	--	--	32	18	--
07025900	1961	BANK	--	--	--	--	--	--	--	--	47	18	--
07025900	1961	BANK	--	--	--	--	--	--	--	--	61	23	--
07025900	1961	BANK	--	--	--	--	--	--	--	--	34	18	--
07027200	1983	BED	1.750	.690	.250	.0480	.0110	3.98	0	18	--	--	--
07026300	1983	BED	1.400	.420	.080	.0150	.0028	5.29	8	49	--	--	--
07026300	1973	BED	.570	.445	.360	.2700	.2000	1.28	0	1	--	--	--
07026250	1983	BED	.066	.042	.021	.0050	.0007	3.10	14	96	30	23	--
07026000	1983	BED	.480	.330	.224	.0900	.0140	1.98	0	15	--	--	--
07026000	1980	BED	.353	.293	.235	.1917	.1503	1.24	--	--	--	--	--
07026000	1973	BED	.430	.400	.320	.2500	.2000	1.27	0	0	--	--	--
07025900	1983	BED	.420	.315	.220	.1500	.0950	1.45	0	4	--	--	--
07026300	1983	DEP.	.660	.380	.225	.1600	.1300	1.55	0	2	--	--	--
07026000	1983	DEP.	.240	.190	.150	.0310	.01000	3.05	0	26	--	--	--
07025900	1983	DEP.	.240	.204	.167	.1300	.06200	1.25	0	6	--	--	--

SUPPLEMENT A—Continued

Stream and station	Date	Type	d_{95}	d_{84}	d_{50}	d_{16}	d_5	G	CL	SC	LL	PL	PV
Pond Creek													
07029080	1983	BANK	0.110	0.048	0.018	0.0028	0.00040	4.55	19	93	33	21	1.36
07029075	1983	BANK	.054	.040	.017	.0027	.00060	4.32	19	99	31	19	--
07029070	1983	BANK	.036	.027	.013	.0011	.00030	6.95	26	99	32	18	.95
07029070	1970	BANK	--	--	--	--	--	--	--	--	34	22	--
07029070	1970	BANK	--	--	--	--	--	--	--	--	47	18	--
07029065	1983	BANK	.100	.046	.023	.0120	.00030	1.96	7	93	--	--	.47
07029060	1983	BANK	.043	.032	.012	.0017	.00060	4.86	24	99	32	23	--
07029080	1983	BED	.110	.048	.025	.0058	.00160	3.12	13	93	30	20	--
07029075	1983	BED	1.000	.056	.014	.0024	.00110	4.92	24	87	--	--	--
07029070	1983	BED	.094	.046	.020	.0056	.00130	2.94	12	93	--	--	--
07029065	1983	BED	.100	.056	.022	.0048	.00080	3.56	14	92	28	21	--
07029060	1983	BED	3.800	1.100	.036	.0064	.00170	18.09	11	72	--	--	--
Porters Creek													
07029445	1983	BANK	.085	.070	.023	.0037	.00180	4.62	17	86	28	20	--
07029445	1983	BANK	1.000	.250	.037	.0033	.00060	8.98	18	70	29	17	--
07029440	1975	BANK	.560	.330	.033	.0005	.00010	38.00	30	60	40	20	--
07029440	1975	BANK	.380	.290	.022	.0002	.00004	61.59	35	64	43	22	--
07029440	1975	BANK	.500	.270	.020	.0002	.00004	56.75	37	73	50	26	--
07029440	1975	BANK	--	--	.016	.0003	.00007	--	--	77	46	23	--
07029440	1975	BANK	.590	.295	.004	.0005	.00025	40.88	54	69	94	55	--
07029439	1983	BANK	.480	.410	.295	.2000	.16000	1.43	0	0	--	--	--
07029439	1983	BANK	.125	.046	.010	.0012	.00060	6.47	32	89	34	25	3.49
07029438	1983	BANK	.440	.350	.090	.0053	.00160	10.44	12	42	21	15	--
07029438	1983	BANK	.330	.175	.014	.0033	.00060	8.37	18	77	23	16	2.76
07029437	1983	BANK	.600	.390	.088	.0072	.00200	8.33	12	42	--	--	--
07029445	1983	BED	1.150	.760	.500	.3400	.27500	1.49	0	0	--	--	--
07029440	1983	BED	.980	.760	.430	.2800	.21500	1.65	0	1	--	--	--
07029440	1975	BED	1.160	.850	.420	.2800	.23000	1.76	0	0	--	--	--
07029439	1983	BED	.640	.480	.360	.2800	.18000	1.31	0	1	--	--	--
07029439	1983	BED	.074	.040	.007	.0004	.00010	11.61	40	95	44	24	--
07029438	1983	BED	1.250	.760	.450	.2900	.19000	1.62	0	0	--	--	--
07029438	1977	BED	.820	.550	.375	.2550	.10500	1.47	--	5	--	--	--
07029437	1983	BED	.210	.059	.017	.0028	.0005	4.77	19	89	29	20	.85
07029437	1983	BED	1.000	.750	.510	.3100	.2300	1.56	0	0	--	--	--
07029437	1977	BED	.810	.590	.330	.1350	.0420	2.12	0	8	--	--	--
07029445	1983	DEP.	.460	.380	.260	.1620	.1050	1.53	0	2	--	--	--
Rutherford Fork Obion River													
07025100	1983	BANK	.230	.120	.027	.0044	.0006	5.29	16	77	--	--	1.61
07025100	1983	BANK	.094	.050	.011	.0016	.0074	5.71	28	92	26	19	3.39
07025100	1961	BANK	--	--	--	--	--	--	--	--	27	15	--
07025100	1961	BANK	--	--	--	--	--	--	--	--	28	21	--
07025100	1961	BANK	--	--	--	--	--	--	--	--	28	16	--
07025100	1961	BANK	--	--	--	--	--	--	--	--	26	14	--
07025050	1984	BANK	.165	.084	.028	.0026	.0009	6.88	21	80	22	18	--
07025050	1983	BANK	.185	.108	.035	.0050	.0007	5.04	15	73	--	--	.42
07025050	1961	BANK	--	--	--	--	--	--	--	--	30	24	--
07025050	1961	BANK	--	--	--	--	--	--	--	--	31	24	--

SUPPLEMENT A—Continued

Stream and station	Date	Type	d_{95}	d_{84}	d_{50}	d_{16}	d_5	G	CL	SC	LL	PL	PV
Rutherford Fork Obion River--Continued													
07025050	1961	BANK	--	--	--	--	--	--	--	--	30	23	--
07025050	1961	BANK	--	--	--	--	--	--	--	--	23	17	--
07025050	1961	BANK	--	--	--	--	--	--	--	--	30	20	--
07025050	1961	BANK	--	--	--	--	--	--	--	--	31	17	--
07025050	1961	BANK	--	--	--	--	--	--	--	--	27	18	--
07025025	1984	BANK	0.250	0.110	0.020	0.0044	0.0007	5.02	16	82	24	20	--
07025025	1961	BANK	--	--	--	--	--	--	--	--	27	20	--
07025025	1961	BANK	--	--	--	--	--	--	--	38	--	--	--
07025020	1983	BANK	.170	.070	.025	.0044	.0006	4.24	15	85	--	--	0.46
07024900	1983	BANK	.096	.080	.029	.0044	.0003	4.67	16	78	--	--	.45
07024880	1983	BANK	.130	.049	.019	.0018	.0004	6.57	22	94	28	22	.70
07024880	1983	BANK	.330	.220	.035	.0027	.0006	9.62	19	63	20	16	2.89
07025100	1983	BED	.900	.580	.415	.2950	.2300	1.40	0	0	--	--	--
07025100	1973	BED	1.000	.650	.450	.3300	.2700	1.40	0	1	--	--	--
07025100	1980	BED	.450	.370	.265	.1750	.1250	1.46	0	0	--	--	--
07025050	1983	BED	2.000	.780	.390	.2850	.1900	1.68	0	0	--	--	--
07025020	1983	BED	2.900	1.000	.520	.3100	.2400	1.80	0	1	--	--	--
07025020	1980	BED	.720	.497	.365	.2800	.2350	1.33	0	0	--	--	--
07025020	1981	BED	1.030	.680	.420	.3250	.2450	1.46	0	0	--	--	--
07025000	1983	BED	4.000	1.000	.530	.3300	.2650	1.75	0	0	--	--	--
07025000	1973	BED	.850	.600	.440	.3200	.2600	1.37	0	0	--	--	--
07024900	1983	BED	1.200	.750	.460	.3200	.2250	1.53	0	0	--	--	--
07024880	1983	BED	2.800	.800	.400	.2600	.1750	1.77	0	1	--	--	--
07025050	1983	DEP.	.670	.540	.425	.2800	.1400	1.39	0	3	--	--	--
07025020	1983	DEP.	.385	.305	.210	.1050	.0540	1.73	0	8	--	--	--
South Fork Forked Deer River													
07028200	1983	BANK	.078	.055	.035	.0048	.0019	4.43	14	94	--	--	--
07028200	1964	BANK	--	--	--	--	--	--	--	--	32	24	--
07028200	1964	BANK	--	--	--	--	--	--	--	--	35	22	--
07028200	1964	BANK	--	--	--	--	--	--	--	--	29	20	--
07028200	1964	BANK	--	--	--	--	--	--	--	76	25	18	--
07028100	1983	BANK	.062	.039	.021	.0046	.0019	3.21	14	98	--	--	.47
07028100	1964	BANK	--	--	--	--	--	--	--	--	34	24	--
07028100	1964	BANK	--	--	--	--	--	--	--	--	34	22	--
07028100	1964	BANK	--	--	--	--	--	--	--	--	33	22	--
07028100	1964	BANK	--	--	--	--	--	--	--	--	36	23	--
07028000	1983	BANK	.180	.055	.021	.0028	.0006	5.06	20	88	27	22	3.08
07028000	1983	BANK	.180	.055	.021	.0028	.0006	5.06	20	88	28	22	.47
07028000	1964	BANK	--	--	--	--	--	--	--	--	30	20	--
07028000	1964	BANK	--	--	--	--	--	--	--	--	28	22	--
07028000	1964	BANK	--	--	--	--	--	--	--	--	26	21	--
07028000	1964	BANK	--	--	--	--	--	--	--	--	34	21	--
07028000	1964	BANK	--	--	--	--	--	--	--	--	40	20	--
07028000	1964	BANK	--	--	--	--	--	--	--	60	22	18	--
07027800	1983	BANK	.120	.048	.016	.0020	.0010	5.50	27	91	33	22	--
07027800	1964	BANK	--	--	--	--	--	--	--	--	40	24	--
07027800	1964	BANK	--	--	--	--	--	--	--	--	37	21	--
07027800	1964	BANK	--	--	--	--	--	--	--	--	37	22	--
07027800	1964	BANK	--	--	--	--	--	--	--	72	35	20	--
07027800	1964	BANK	--	--	--	--	--	--	--	63	25	15	--
07027720	1983	BANK	.250	.100	.021	.0027	.0007	6.27	20	78	25	19	.25

SUPPLEMENT A—Continued

Stream and station	Date	Type	d_{95}	d_{84}	d_{50}	d_{16}	d_5	G	CL	SC	LL	PL	PV
South Fork Forked Deer River--Continued													
07027720	1964	BANK	--	--	--	--	--	--	--	67	25	14	--
07027720	1964	BANK	--	--	--	--	--	--	--	39	20	12	--
07027680	1983	BANK	0.042	0.032	0.022	0.0030	0.0019	4.39	20	99	30	23	0.40
07028200	1983	BED	.460	.325	.039	.0038	.0019	9.30	17	65	20	16	--
07028200	1973	BED	.060	.036	.017	.0025	.0006	4.46	20	98	--	--	--
07028100	1983	BED	.520	.390	.275	.0400	.0070	4.15	3	17	--	--	--
07027800	1983	BED	.520	.420	.334	.1900	.0270	1.51	0	7	--	--	--
07027720	1983	BED	.900	.660	.480	.3400	.2750	1.39	0	0	--	--	--
07027680	1983	BED	.610	.420	.278	.1850	.1250	1.51	0	3	--	--	--
07027680	1973	BED	.840	.580	.400	.3100	.2400	1.37	0	1	--	--	--
07027680	1980	BED	.580	.435	.334	.2450	.1930	1.33	0	0	--	--	--
07028200	1983	DEP.	.320	.248	.186	.0590	.0210	2.24	0	18	--	--	--
07028100	1983	DEP.	.330	.260	.180	.0620	.0140	2.17	0	17	--	--	--
07027800	1983	DEP.	.430	.350	.290	.2200	.1600	1.26	0	0	--	--	--
07027680	1983	DEP.	.600	.450	.340	.2600	.1900	1.32	0	0	--	--	--
South Fork Obion River													
07024800	1983	BANK	.066	.042	.010	.0013	.0005	5.95	28	96	31	24	3.25
07024800	1961	BANK	--	--	--	--	--	--	--	--	36	18	--
07024800	1961	BANK	--	--	--	--	--	--	--	--	29	17	--
07024800	1961	BANK	--	--	--	--	--	--	--	--	33	16	--
07024550	1983	BANK	.240	.135	.035	.0044	.0010	5.91	15	73	--	--	--
07024550	1983	BANK	.215	.098	.021	.0024	.0014	6.71	26	72	25	15	2.00
07024550	1961	BANK	--	--	--	--	--	--	--	--	28	19	--
07024550	1961	BANK	--	--	--	--	--	--	--	--	30	18	--
07024550	1961	BANK	--	--	--	--	--	--	--	--	50	19	--
07024525	1961	BANK	.200	.120	.026	.0018	.0004	9.53	22	76	25	18	.17
07024525	1961	BANK	--	--	--	--	--	--	--	--	33	24	--
07024525	1961	BANK	--	--	--	--	--	--	--	--	31	20	--
07024525	1961	BANK	--	--	--	--	--	--	--	--	50	21	--
07024525	1961	BANK	--	--	--	--	--	--	--	--	32	17	--
07024500	1983	BANK	.300	.078	.029	.0046	.0010	4.50	15	83	--	--	2.58
07024500	1961	BANK	--	--	--	--	--	--	--	--	30	25	--
07024460	1983	BANK	.200	.110	.036	.0044	.0010	5.62	15	77	--	--	1.26
07024460	1983	BANK	.210	.082	.024	.0080	.0002	3.21	11	79	--	--	.30
07024430	1983	BANK	.190	.086	.050	.0100	.0024	3.36	8	64	--	--	--
07024430	1983	BANK	.096	.060	.026	.0044	.0012	4.11	15	85	--	--	1.34
07024800	1983	BED	.680	.475	.357	.2680	.2000	1.33	0	0	--	--	--
07024800	1973	BED	.800	.530	.380	.2700	.2200	1.40	0	1	--	--	--
07024550	1983	BED	1.000	.680	.400	.2800	.2400	1.56	0	0	--	--	--
07024525	1983	BED	1.000	.640	.390	.2850	.2550	1.50	0	0	--	--	--
07024500	1983	BED	1.000	.720	.425	.2900	.2300	1.58	0	0	--	--	--
07024500	1980	BED	1.620	.597	.430	.3370	.2200	1.33	0	0	--	--	--
07024500	1973	BED	1.650	.860	.500	.3350	.2700	1.60	0	0	--	--	--
07024460	1983	BED	1.300	.680	.375	.2750	.2300	1.59	0	0	--	--	--
07024460	1981	BED	1.130	.683	.455	.3270	.2450	1.45	0	0	--	--	--
07024430	1983	BED	1.700	.660	.340	.1800	.1400	1.92	0	1	--	--	--

SUPPLEMENT B

Sample statistics of bed-material properties data

[d_{50}, median grain size in millimeters; MEAN, mean grain size in millimeters; SCR, silt-clay ratio; SC, silt plus clay in percent; CL, clay in percent; PERS, sand in percent; PI, plasticity index; PV, maximum noneroding pinhole velocity in meters per second; G, gradation index]

Variable	N	Mean	Standard deviation	Minimum value	Maximum value	Standard error of mean
			Cane Creek			
d_{50}	4	0.028	0.007	0.020	0.037	0.004
MEAN	4	.046	.032	.025	.093	.016
SCR	4	4.49	1.59	2.80	6.60	.793
SC	4	85.0	8.60	76.0	95.0	4.30
CL	4	16.8	6.19	10.0	25.0	3.09
PERS	4	15.0	8.60	5.00	24.0	4.30
PI	3	6.00	0	6.00	6.00	0
PV	0	--	--	--	--	--
G	4	8.92	6.58	3.85	18.2	3.29
			Cub Creek			
d_{50}	6	.399	.196	.021	.570	.080
MEAN	6	.450	.214	.031	.617	.087
SCR	1	5.62	--	5.62	5.62	--
SC	6	15.2	34.7	0	86.0	14.2
CL	6	2.17	5.31	0	13.0	2.17
PERS	6	84.8	34.7	14.0	100	14.2
PI	1	6.00	--	6.00	6.00	--
PV	0	--	--	--	--	--
G	6	2.01	.713	1.60	3.45	.291
			Hatchie River			
d_{50}	4	.346	.072	.290	.450	.036
MEAN	4	.361	.065	.305	.444	.033
SCR	2	2.34	1.19	1.50	3.18	.841
SC	4	16.5	21.8	0	46.0	10.9
CL	4	4.75	5.62	0	11.0	2.81
PERS	4	83.5	21.8	54.0	100	10.9
PI	0	--	--	--	--	--
PV	0	--	--	--	--	--
G	4	7.03	9.91	1.42	21.8	4.95
			Hoosier Creek			
d_{50}	3	.021	.002	.019	.023	.001
MEAN	3	.024	.002	.021	.026	.001
SCR	3	5.16	1.92	3.84	7.36	1.11
SC	3	93.0	1.73	92.0	95.0	1.00
CL	3	16.0	4.36	11.0	19.0	2.52
PERS	3	7.00	1.73	5.00	8.00	1.00
PI	2	9.00	0	9.00	9.00	0
PV	0	--	--	--	--	--
G	3	3.72	.956	2.67	4.53	.552
			Hyde Creek			
d_{50}	3	.024	.002	.022	.025	.001
MEAN	3	.026	.001	.025	.027	.001
SCR	3	5.05	.163	4.88	5.20	.094
SC	3	92.7	1.53	91.0	94.0	.882
CL	3	15.3	.577	15.0	16.0	.333
PERS	3	7.33	1.53	6.00	9.00	.882
PI	3	5.67	1.16	5.00	7.00	.667
PV	0	--	--	--	--	--
G	3	3.71	.438	3.29	4.17	.253

SUPPLEMENT B—Continued

Variable	N	Mean	Standard deviation	Minimum value	Maximum value	Standard error of mean
			Meridian Creek			
d_{50}	6	0.290	0.157	0.007	0.470	0.064
MEAN	6	.304	.160	.022	.503	.065
SCR	1	1.18	--	1.18	1.18	--
SC	6	15.0	35.3	0	87.0	14.4
CL	6	6.67	16.3	0	40.0	6.67
PERS	6	85.0	35.3	13.0	100	14.4
PI	1	13.0	--	13.0	13.0	--
PV	0	--	--	--	--	--
G	6	3.19	3.97	1.51	11.3	1.62
			North Fork Forked Deer River			
d_{50}	12	.244	.181	.019	.550	.052
MEAN	12	.356	.365	.021	1.34	.105
SCR	6	4.53	1.63	2.40	7.00	.664
SC	12	29.4	36.6	1.00	94.0	10.6
CL	12	5.58	7.54	0	22.0	2.18
PERS	12	70.6	36.6	6.00	99.0	10.6
PI	2	5.50	.707	5.00	6.00	.500
PV	0	--	--	--	--	--
G	12	3.95	4.34	1.35	16.5	1.25
			North Fork Obion River			
d_{50}	9	.432	.039	.380	.490	.013
MEAN	9	.460	.045	.417	.522	.015
SCR	0	--	--	--	--	--
SC	9	0	0	0	0	0
CL	9	0	0	0	0	0
PERS	9	100	0	100	100	0
PI	0	--	--	--	--	--
PV	0	--	--	--	--	--
G	9	1.45	.098	1.32	1.57	.033
			Obion River			
d_{50}	8	.214	.113	.021	.360	.040
MEAN	8	.236	.108	.023	.358	.038
SCR	2	5.49	.518	5.13	5.86	.366
SC	7	26.1	35.1	0	96.0	13.3
CL	7	3.14	5.64	0	14.0	2.13
PERS	7	73.9	35.1	4.00	100	13.3
PI	1	7.00	--	7.00	7.00	--
PV	0	--	--	--	--	--
G	8	2.45	1.53	1.24	5.29	.540
			Pond Creek			
d_{50}	5	.023	.008	.014	.036	.004
MEAN	5	.097	.159	.024	.381	.071
SCR	5	5.33	1.59	2.63	6.75	.711
SC	5	87.4	8.96	72.0	93.0	4.01
CL	5	14.8	5.26	11.0	24.0	2.35
PERS	5	12.6	8.96	7.00	28.0	4.01
PI	2	8.50	2.12	7.00	10.0	1.50
PV	0	--	--	--	--	--
G	5	6.52	6.51	2.94	18.1	2.91

SUPPLEMENT B—Continued

Variable	N	Mean	Standard deviation	Minimum value	Maximum value	Standard error of mean
			Porters Creek			
d_{50}	10	0.340	0.182	0.007	0.510	0.058
MEAN	10	.372	.196	.016	.533	.062
SCR	2	2.53	1.63	1.38	3.68	1.16
SC	10	19.9	38.1	0	95.0	12.1
CL	9	6.56	14.0	0	40.0	4.68
PERS	10	80.1	38.1	5.00	100	12.1
PI	2	14.5	7.78	9.00	20.0	5.50
PV	1	.850	--	.850	.850	--
G	10	2.94	3.21	1.31	11.6	1.02
			Rutherford Fork Obion River			
d_{50}	11	.423	.073	.265	.530	.022
MEAN	11	.472	.097	.270	.620	.029
SCR	0	--	--	--	--	--
SC	11	.273	.467	0	1.00	.141
CL	11	0	0	0	0	0
PERS	11	99.7	.467	99.0	100	.141
PI	0	--	--	--	--	--
PV	0	--	--	--	--	--
G	11	1.54	.175	1.33	1.80	.053
			South Fork Forked Deer River			
d_{50}	8	.270	.163	.017	.480	.058
MEAN	8	.281	.155	.018	.493	.055
SCR	3	3.80	.926	2.82	4.67	.535
SC	8	23.9	37.1	0	98.0	13.1
CL	8	5.00	8.44	0	20.0	2.98
PERS	8	76.1	37.1	2.00	100	13.1
PI	1	4.00	--	4.00	4.00	--
PV	0	--	--	--	--	--
G	8	3.13	2.82	1.33	9.30	.995
			South Fork Obion River			
d_{50}	10	.405	.048	.340	.500	.015
MEAN	10	.447	.057	.367	.565	.018
SCR	0	--	--	--	--	--
SC	10	.200	.422	0	1.00	.133
CL	10	0	0	0	0	0
PERS	10	99.8	.422	99.0	100	.133
PI	0	--	--	--	--	--
PV	0	--	--	--	--	--
G	10	1.527	.171	1.331	1.915	.054

SUPPLEMENT C
Sample statistics of bank-material properties data

[d_{50}, median grain size in millimeters; MEAN, mean grain size in millimeters; SCR, silt-clay ratio; SC, silt plus clay in percent; CL, clay in percent; PERS, sand in percent; PI, plasticity index; PV, maximum noneroding pinhole velocity in meters per second; G, gradation index]

Variable	*N*	Mean	Standard deviation	Minimum value	Maximum value	Standard error of mean
			Cane Creek			
d_{50}	13	0.026	0.011	0.016	0.059	0.003
MEAN	11	.029	.011	.018	.058	.003
SCR	13	6.49	2.17	2.29	8.70	.600
SC	13	93.8	4.90	80.0	99.0	1.39
CL	13	13.9	5.56	10.0	28.0	1.54
PERS	13	6.15	4.90	1.00	20.0	1.36
PI	18	5.56	2.92	2.00	11.0	.687
PV	8	.557	.154	.340	.810	.055
G	11	4.59	2.67	2.74	11.3	.805
			Cub Creek			
d_{50}	11	.051	.072	.010	.261	.022
MEAN	11	.091	.096	.018	.358	.029
SCR	11	4.29	3.31	1.90	13.5	1.01
SC	11	68.3	19.6	29.0	95.0	5.92
CL	11	16.0	6.29	2.00	24.0	1.90
PERS	11	31.7	19.6	5.00	71.0	5.92
PI	10	7.70	3.02	4.00	12.0	.955
PV	4	3.42	2.37	.550	6.28	1.18
G	11	6.71	2.74	3.62	11.2	.826
			Hatchie River			
d_{50}	5	.021	.013	.010	.044	.006
MEAN	5	.043	.028	.023	.093	.013
SCR	5	3.15	.781	2.25	4.19	.349
SC	5	78.0	15.0	52.0	90.0	6.70
CL	5	19.0	3.74	16.0	24.0	1.67
PERS	5	22.0	15.0	10.0	48.0	6.70
PI	4	9.25	1.71	7.0	11.0	.854
PV	3	2.94	.413	2.46	3.18	.238
G	5	6.03	1.56	4.48	8.26	.696
			Hoosier Creek			
d_{50}	4	.022	.002	.020	.023	.001
MEAN	3	.025	.001	.023	.026	.001
SCR	4	6.31	.789	5.33	7.17	.395
SC	4	94.3	2.87	92.0	98.0	1.44
CL	4	13.0	1.41	12.0	15.0	.707
PERS	4	5.75	2.87	2.00	8.00	1.44
PI	1	12.0	--	12.0	12.0	--
PV	4	.942	.775	.080	1.95	.388
G	3	2.67	.224	2.45	2.89	.129
			Hyde Creek			
d_{50}	3	.026	.004	.022	.029	.002
MEAN	3	.033	.011	.022	.044	.006
SCR	3	4.12	.260	3.82	4.31	.150
SC	3	87.0	6.25	82.0	94.0	3.61
CL	3	17.0	1.00	16.0	18.0	.577
PERS	3	13.0	6.25	6.00	18.0	3.61
PI	2	5.00	0	5.00	5.00	0
PV	3	.533	.112	.450	.660	.064
G	3	4.95	.765	4.29	5.79	.442

SUPPLEMENT C—Continued

Variable	N	Mean	Standard deviation	Minimum value	Maximum value	Standard error of mean
			Meridian Creek			
d_{50}	9	0.028	0.026	0.005	0.094	0.009
MEAN	9	.061	.035	.020	.115	.012
SCR	9	3.87	3.01	1.00	11.0	1.00
SC	9	74.2	15.8	44.0	91.0	5.27
CL	9	19.8	11.4	6.00	45.0	3.81
PERS	9	25.8	15.8	9.00	56.0	5.27
PI	6	7.50	2.59	4.00	11.0	1.06
PV	0	--	--	--	--	--
G	9	9.32	6.43	4.36	25.5	2.14
			North Fork Forked Deer River			
d_{50}	9	.024	.004	.018	.032	.001
MEAN	9	.032	.015	.019	.069	.005
SCR	9	3.97	.735	3.14	5.40	.245
SC	11	85.5	8.69	72.0	96.0	2.62
CL	9	18.0	2.55	15.0	22.0	.850
PERS	11	14.5	8.69	4.00	28.0	2.62
PI	29	13.0	9.79	3.00	38.0	1.82
PV	9	.978	.780	.380	2.86	.260
G	9	5.68	1.73	3.58	9.21	.576
			North Fork Obion River			
d_{50}	8	.022	.015	.004	.050	.005
MEAN	8	.032	.022	.015	.082	.008
SCR	12	2.54	1.56	.735	5.23	.451
SC	12	84.1	12.2	59.0	96.0	3.52
CL	12	29.3	14.5	13.0	50.0	4.20
PERS	12	15.8	12.2	4.00	41.0	3.52
PI	13	15.0	6.98	7.00	28.0	1.94
PV	8	1.61	.883	.510	2.76	.312
G	8	6.12	1.84	3.32	9.07	.649
			Obion River			
d_{50}	6	.033	.015	.021	.057	.006
MEAN	6	.047	.032	.022	.096	.013
SCR	9	4.10	2.49	.617	7.73	.830
SC	16	68.7	19.1	43.0	97.0	4.78
CL	9	19.1	15.8	10.0	60.0	5.28
PERS	16	31.3	19.1	3.00	57.0	4.78
PI	35	18.1	14.0	4.00	69.0	2.37
PV	4	2.44	2.31	.420	4.67	1.16
G	6	4.27	1.79	2.85	7.67	.730
			Pond River			
d_{50}	5	.017	.004	.012	.023	.002
MEAN	5	.020	.005	.014	.027	.002
SCR	5	5.27	3.97	2.81	12.3	1.77
SC	5	96.6	3.29	93.0	99.0	1.47
CL	5	19.0	7.38	7.00	26.0	3.30
PERS	5	3.40	3.29	1.00	7.00	1.47
PI	6	14.7	7.20	9.00	29.0	2.94
PV	3	.927	.445	.470	1.36	.257
G	5	4.53	1.78	1.96	6.95	.794

SUPPLEMENT C—Continued

Variable	*N*	Mean	Standard deviation	Minimum value	Maximum value	Standard error of mean
			Porters Creek			
d_{50}	12	0.054	0.081	0.004	0.295	0.023
MEAN	11	.113	.076	.019	.302	.023
SCR	10	2.01	1.23	.278	4.06	.389
SC	12	62.4	24.6	0	89.0	7.09
CL	11	24.1	15.1	0	54.0	4.55
PERS	12	37.6	24.6	11.0	100	7.09
PI	10	16.9	10.5	6.00	39.0	3.31
PV	2	3.13	.516	2.76	3.49	.365
G	11	22.4	22.4	1.43	61.6	6.76
			Rutherford Fork Obion River			
d_{50}	9	.025	.008	.011	.035	.003
MEAN	9	.043	.019	.021	.086	.006
SCR	9	3.45	.830	2.29	4.67	.277
SC	10	76.2	16.1	38.0	94.0	5.10
CL	9	18.7	4.36	15.0	28.0	1.45
PERS	10	23.8	16.1	6.00	62.0	5.10
PI	17	7.88	3.10	4.00	14.0	.752
PV	7	1.42	1.26	.420	3.39	.475
G	9	5.90	1.64	4.24	9.62	.546
			South Fork Forked Deer River			
d_{50}	7	.022	.006	.016	.035	.002
MEAN	7	.027	.008	.019	.041	.003
SCR	7	3.96	1.39	2.37	6.00	.524
SC	13	77.9	17.6	39.0	99.0	4.87
CL	7	19.3	4.42	14.0	27.0	1.67
PERS	13	22.1	17.6	1.00	61.0	4.87
PI	26	10.3	4.08	4.00	20.0	.799
PV	5	.934	1.20	.250	3.08	.538
G	7	4.85	.966	3.21	6.27	.365
			South Fork Obion River			
d_{50}	9	.029	.011	.010	.050	.004
MEAN	9	.041	.012	.018	.058	.004
SCR	9	4.12	1.74	1.77	7.00	.580
SC	9	78.3	9.08	64.0	96.0	3.03
CL	9	17.2	6.70	8.00	28.0	2.24
PERS	9	21.7	9.08	4.00	36.0	3.03
PI	14	13.7	7.85	5.00	31.0	2.10
PV	7	1.56	1.14	.170	3.25	.430
G	9	5.43	1.96	3.21	9.53	.654

SUPPLEMENT D
Sample statistics of recent-deposits properties data

[d_{50}, median grain size in millimeters; MEAN, mean grain size in millimeters; SCR, silt-clay ratio; SC, silt plus clay in percent; CL, clay in percent; PERS, sand in percent; PI, plasticity index; PV, maximum noneroding pinhole velocity in meters per second; G, gradation index]

Variable	*N*	Mean	Standard deviation	Minimum value	Maximum value	Standard error of mean
			Cub Creek			
d_{50}	1	0.275	--	0.275	0.275	--
MEAN	1	.284	--	.284	.284	--
SCR	0	--	--	--	--	--
SC	1	1.00	--	1.00	1.00	--
CL	1	0	--	0	0	--
PERS	1	99.0	--	99.0	99.0	--
PI	0	--	--	--	--	--
PV	0	--	--	--	--	--
G	1	1.45	--	1.45	1.45	--
			Meridian Creek			
d_{50}	3	.187	0.032	.150	.210	0.019
MEAN	3	.187	.024	.167	.213	.014
SCR	0	--	--	--	--	--
SC	3	10.7	5.51	7.00	17.0	3.18
CL	3	0	0	0	0	0
PERS	3	89.3	5.51	83.0	93.0	3.18
PI	0	--	--	--	--	--
PV	0	--	--	--	--	--
G	3	1.84	.418	1.52	2.31	.241
			North Fork Forked Deer River			
d_{50}	3	.176	.024	.150	.198	.014
MEAN	3	.190	.023	.164	.209	.014
SCR	0	--	--	--	--	--
SC	3	6.33	4.04	2.00	10.0	2.33
CL	3	0	0	0	0	0
PERS	3	93.7	4.04	90.0	98.0	2.33
PI	0	--	--	--	--	--
PV	0	--	--	--	--	--
G	3	1.41	.077	1.32	1.47	.045
			North Fork Obion River			
d_{50}	5	.222	.019	.200	.250	.009
MEAN	5	.225	.018	.208	.253	.008
SCR	0	--	--	--	--	--
SC	5	2.20	2.39	0	6.00	1.07
CL	5	0	0	0	0	0
PERS	5	97.8	2.39	94.0	100	1.07
PI	0	--	--	--	--	--
PV	0	--	--	--	--	--
G	5	1.38	.040	1.32	1.42	.018

SUPPLEMENT D—Continued

Variable	*N*	Mean	Standard deviation	Minimum value	Maximum value	Standard error of mean
			Obion River			
d_{50}	3	0.181	0.039	0.150	0.225	0.023
MEAN	3	.182	.067	.124	.255	.039
SCR	0	--	--	--	--	--
SC	3	11.3	12.9	2.00	26.0	7.42
CL	3	0	0	0	0	0
PERS	3	88.7	12.9	74.0	98.0	7.42
PI	0	--	--	--	--	--
PV	0	--	--	--	--	--
G	3	1.95	.965	1.25	3.05	.557
			Porters Creek			
d_{50}	1	.260	--	.260	.260	--
MEAN	1	.267	--	.267	.267	--
SCR	0	--	--	--	--	--
SC	1	2.00	--	2.00	2.00	--
CL	1	0	--	0	0	--
PERS	1	98.0	--	98.0	98.0	--
PI	0	--	--	--	--	--
PV	0	--	--	--	--	--
G	1	1.53	--	1.53	1.53	--
			Rutherford Fork Obion River			
d_{50}	2	.317	.152	.210	.425	.107
MEAN	2	.311	.147	.207	.415	.104
SCR	0	--	--	--	--	--
SC	2	5.50	3.54	3.00	8.00	2.50
CL	2	0	0	0	0	0
PERS	2	94.5	3.54	92.0	97.0	2.50
PI	0	--	--	--	--	--
PV	0	--	--	--	--	--
G	2	1.56	.235	1.39	1.73	.166
			South Fork Forked Deer River			
d_{50}	4	.249	.079	.180	.340	.039
MEAN	4	.242	.092	.164	.350	.046
SCR	0	--	--	--	--	--
SC	4	8.75	10.1	0	18.0	5.06
CL	4	0	0	0	0	0
PERS	4	91.3	10.1	82.0	100	5.06
PI	0	--	--	--	--	--
PV	0	--	--	--	--	--
G	4	1.75	.532	1.26	2.24	.266

SUPPLEMENT E

Disturbance-parameter values by site and stream

[DSLR, change in gradient in reach in percent; DSLT, change in gradient from mouth in percent; RSH, shortening in reach in percent; TSH, shortening from mouth in percent; IMAGI, imposed area-gradient index in meters cubed per meter]

Stream	Station	DSLR	DSLT	RSH	TSH	IMAGI
Cane Creek						
	07030097	26.9	50.9	6.70	32.5	82131
	07030100	65.2	52.6	26.8	34.6	88426
	07030100	65.2	52.6	26.8	34.6	88426
	07030123	50.5	49.5	33.5	35.8	125221
	07030123	50.5	49.5	33.5	35.8	125221
	07030129	-1.40	49.1	32.7	36.7	162510
	07030129	-1.40	49.1	32.7	36.7	162510
	07030133	139	87.4	41.5	38.3	179652
	07030133	139	87.4	41.5	38.3	179652
	07030137	10.1	66.0	43.8	36.4	198408
	07030140	168	168	30.8	30.8	209037
	07030140	168	168	30.8	30.8	209037
Cub Creek						
	07029447	1.60	9.40	1.70	7.40	12373
	07029448	11.0	11.3	3.50	8.50	38558
	07029449	22.8	10.8	6.10	15.6	86049
	07029450	5.60	5.60	18.9	18.9	73512
	07029450	5.60	5.60	18.9	18.9	73512
Hoosier Creek						
	07025660	54.5	71.8	0	1.90	42560
	07025666	-11.3	103	0	2.40	46902
	07025690	606	228	0	3.30	205903
	07025690	606	228	0	3.30	205903
	07025691	173	173	3.60	3.60	55839
Hyde Creek						
	07030104	107	47.7	12.4	22.8	39844
	07030104	107	47.7	12.4	22.8	39844
	07030107	-.800	28.8	12.3	28.9	45094
	07030110	20.6	43.5	38.8	38.8	31138
	07030111	12.2	12.2	13.4	13.4	26426
Meridian Creek						
	07027478	--	--	--	--	--
	07027480	--	--	--	--	--
	07027483	--	--	--	--	--
	07027485	--	--	--	--	--
North Fork Forked Deer River						
	07028820	0	18.7	0	8.20	125590
	07028835	0	22.2	0	9.60	226873
	07028840	0	24.0	0	10.2	122598
	07029100	198	74.0	5.20	28.7	3968441
	07029105	-23.3	-23.3	34.9	34.9	578836

SUPPLEMENT E—Continued

Stream	Station	DSLR	DSLT	RSH	TSH	IMAGI
North Fork Obion River						
	07025320	0	25.8	0	0.600	279767
	07025340	0	40.7	0	.800	373721
	07025375	0	64.0	0	1.00	426425
	07025400	25.1	70.6	0	1.20	476594
	07025500	51.3	177	0	2.10	741869
	07025600	142	142	3.40	3.40	618572
	07025600	142	142	3.40	3.40	618572
Obion River						
	07024800	161	-12.9	.300	17.4	1088988
	07024800	161	-12.9	.300	17.4	1088988
	07025900	142	-11.4	42.4	18.8	2080412
	07025900	142	-11.4	42.4	18.8	2080412
	07026000	85.6	2.00	22.4	13.1	1051603
	07026000	85.6	2.00	22.4	13.1	1051603
	07026300	-47.3	-12.0	15.6	6.80	383334
	07026300	-47.3	-12.0	15.6	6.80	383334
	07027200	0	0	0	0	997668
Pond Creek						
	07029060	0	0	0	0	59247
	07029065	0	0	0	0	48760
	07029070	0	0	0	0	42343
	07029080	0	0	0	0	157439
Porters Creek						
	07029437	34.7	49.6	24.1	33.8	68324
	07029439	33.7	62.4	36.2	38.9	133157
	07029440	86.0	86.0	38.0	38.3	129754
Rutherford Fork Obion River						
	07024900	0	15.7	0	0	175681
	07025000	0	30.1	0	0	303298
	07025025	0	39.0	0	0	246383
	07025050	43.7	59.3	0	0	367100
	07025050	43.7	59.3	0	0	367100
	07025100	60.2	60.2	0	0	462446
	07025100	60.2	60.2	0	0	462446
South Fork Forked Deer River						
	07027720	0	21.7	0	8.9	638009
	07027800	0	26.9	0	14.2	555769
	07028000	0	46.1	0	16.9	676122
	07028005	0	51.6	0	18.5	576096
	07028100	181	67.1	6.10	25.5	2063840
	07028200	26.8	26.8	42.1	42.1	737357
South Fork Obion River						
	07024350	0	36.2	0	0	265512
	07024430	0	49.8	0	0	327851
	07024460	0	67.0	0	0	429238
	07024500	0	98.2	0	0	344571
	07024525	0	123	0	0	282961
	07024550	168	228	0	0	744786
	07024800A	476	476	0	0	662587
	07024800A	476	476	0	0	662587

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