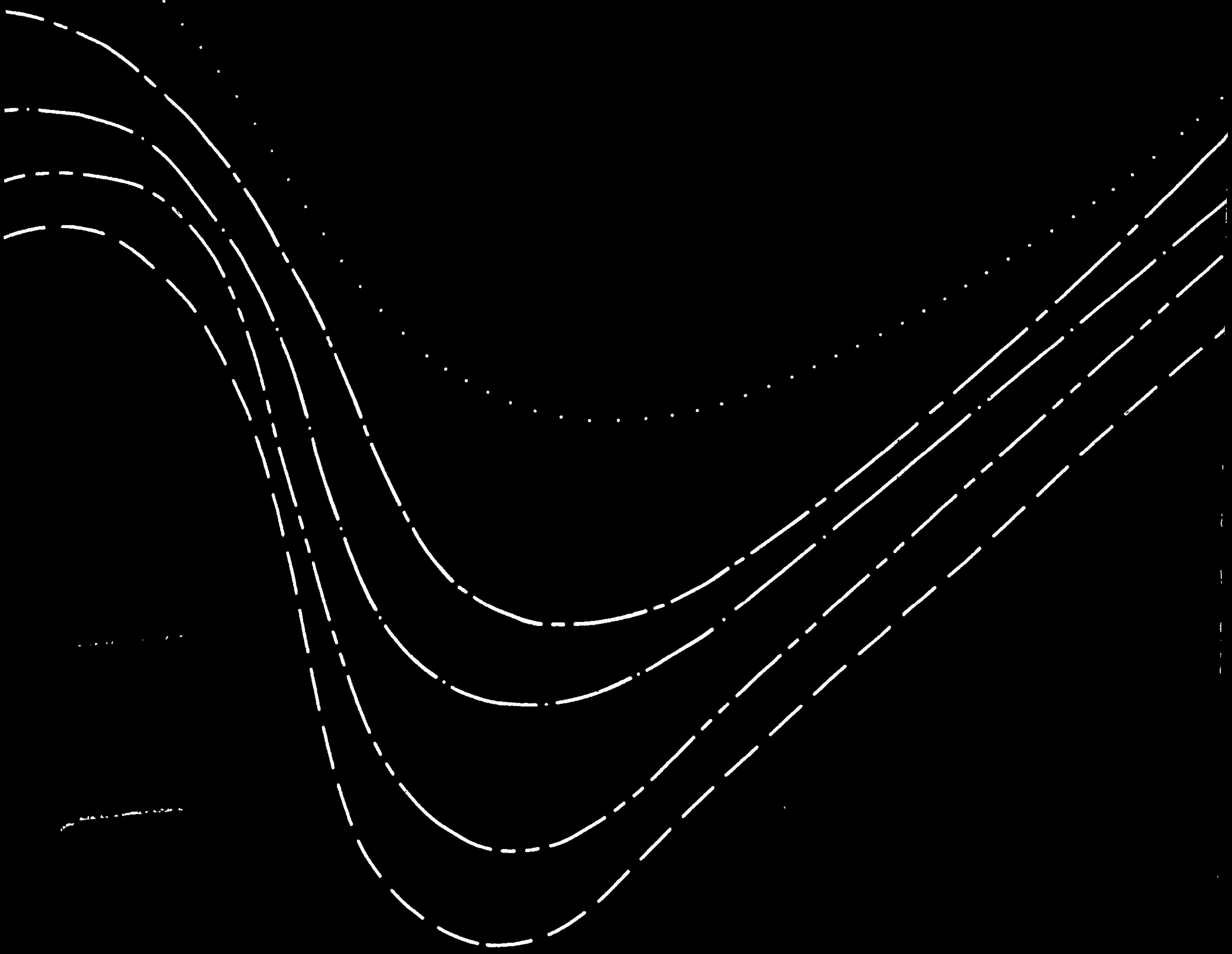
Open-File Report 91-502

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



Prepared by the
U.S. GEOLOGICAL SURVEY

in cooperation with the
TENNESSEE DEPARTMENT OF TRANSPORTATION

U.S. DEPARTMENT OF THE INTERIOR
March 3 1849

Bank Evolution--General

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

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

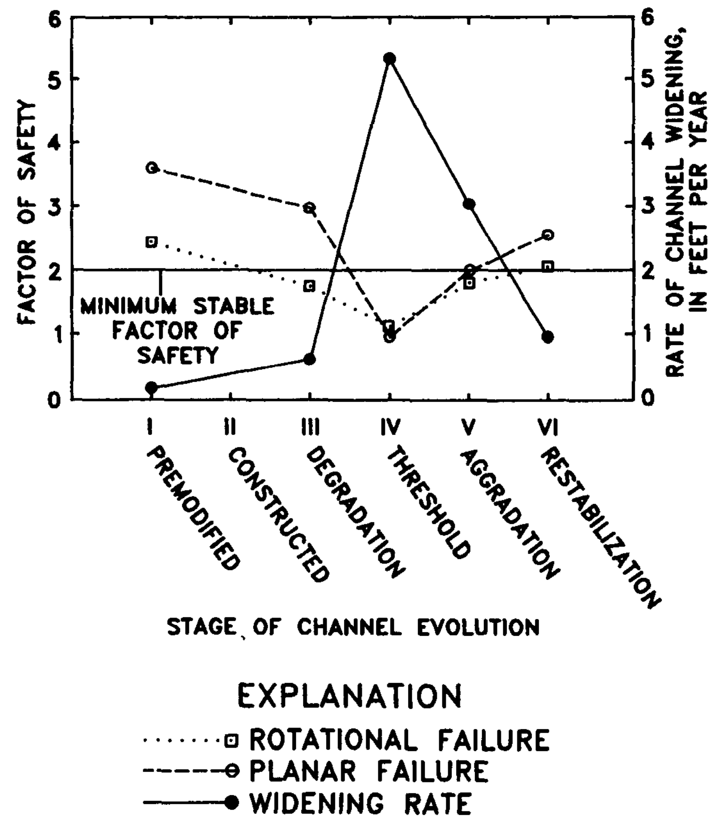


Figure 29.--Factors of safety for mass-bank failures and rate of channel widening by stage of channel evolution.

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

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

Stage I - Premodified

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

Stage II - Constructed

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

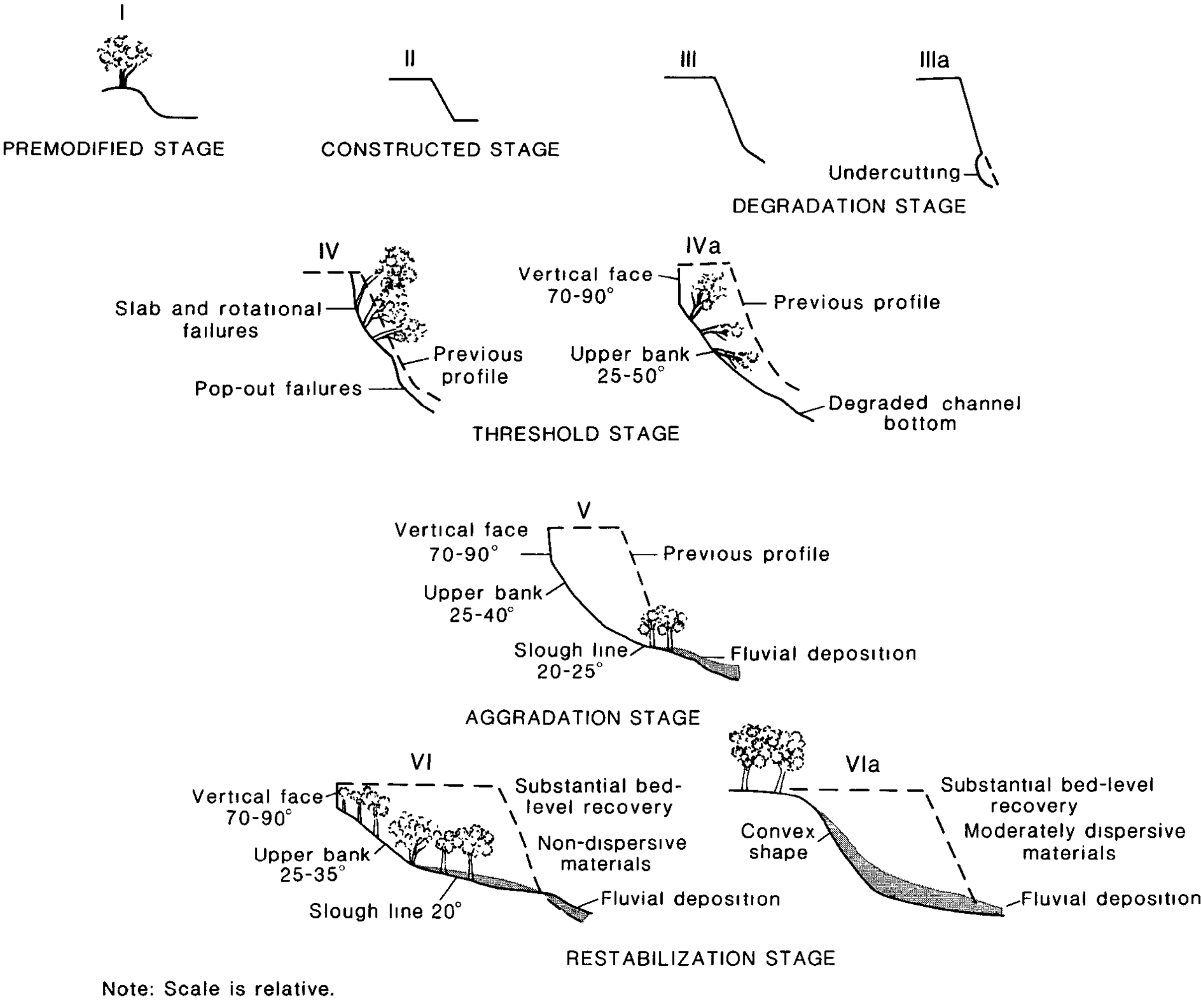


Figure 30.--Six-stage model of bank-slope development in disturbed channels. (From Simon, 1989.)

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

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

Stage III - Degradation

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

Stage IV - Threshold

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

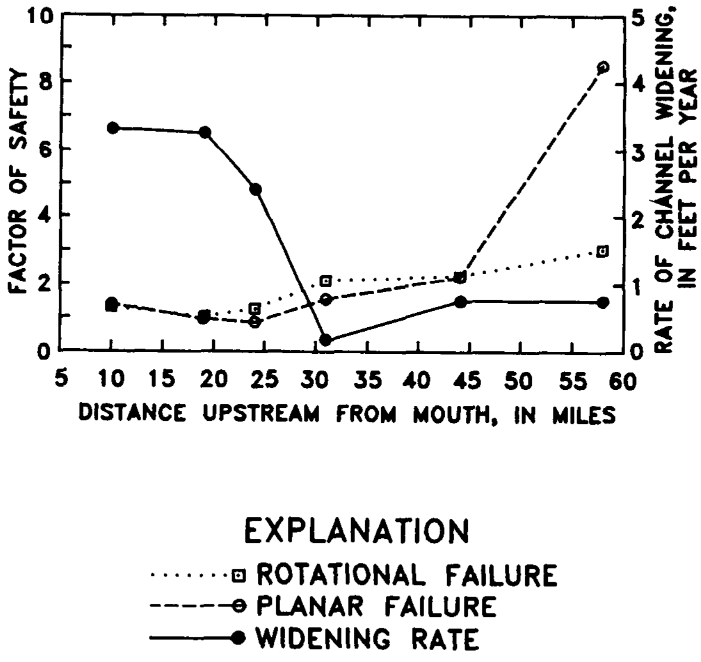


Figure 31.--Factors of safety and recent widening rates along the Wolf River.

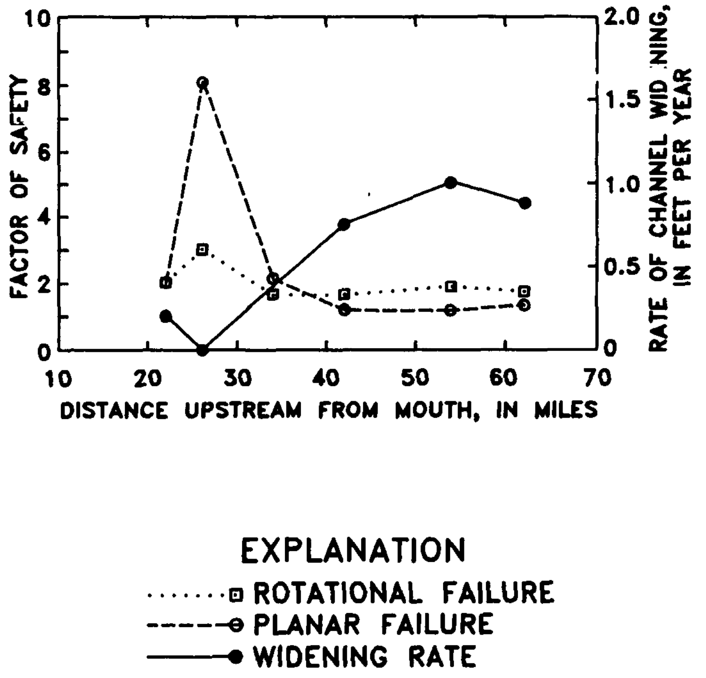


Figure 32.--Factors of safety and recent widening rates along the Obion River main stem.

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

Rotational Compared Against Planar Failures

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

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

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

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

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

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

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

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

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

Stage V - Aggradation

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

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

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

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

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

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

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

Possible explanations include:

1. bank heights are still very high owing to the slow rate of aggradation relative to previous degradation,
2. bank angles are constantly being reduced by rotational failures, causing the orientation of the principal plane to be variable and the failure plane curved, and
3. there are fewer steep segments on stage V banks making conditions less favorable for planar failures.

Stage VI - Restabilization

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

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

Critical Bank Conditions

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

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

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

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

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

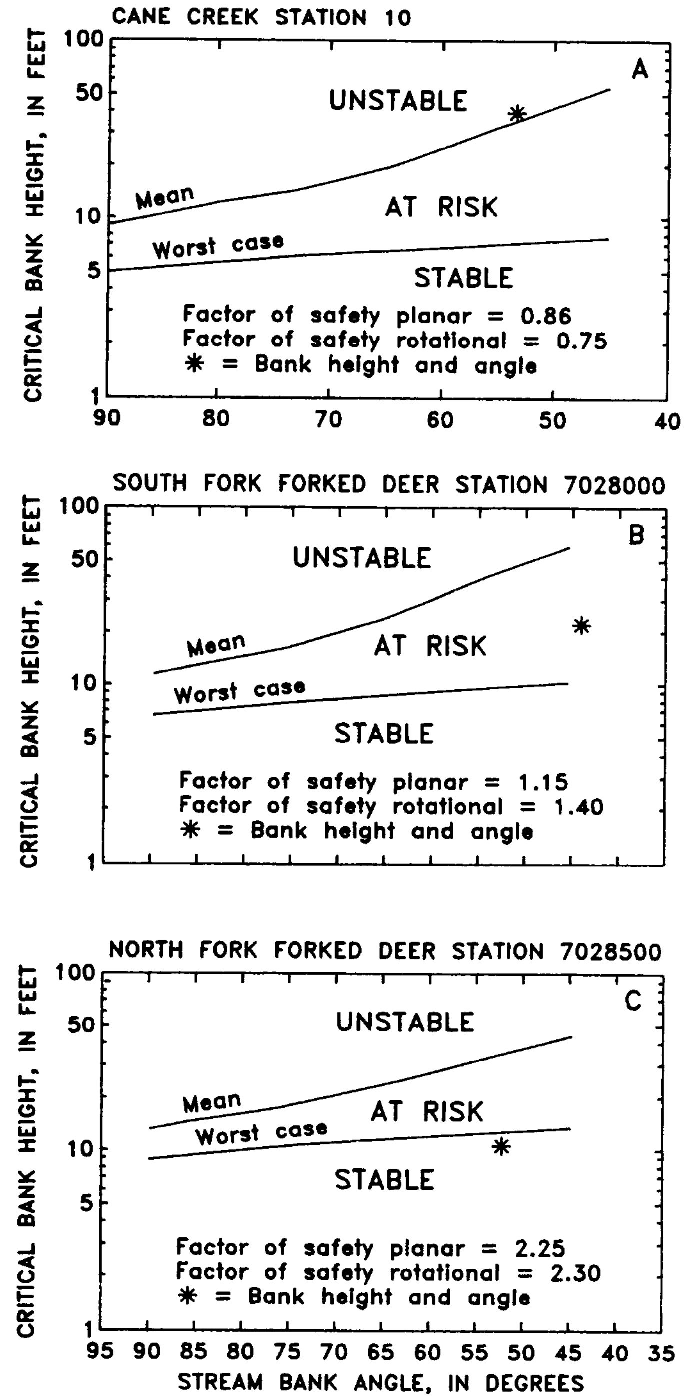


Figure 35.--Slope-stability charts for (A) unstable, (B) at risk, and (C) stable bank-slope configurations.

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

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

1. presence of a coarse sediment load,

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

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

4. time since channel response began.

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

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

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

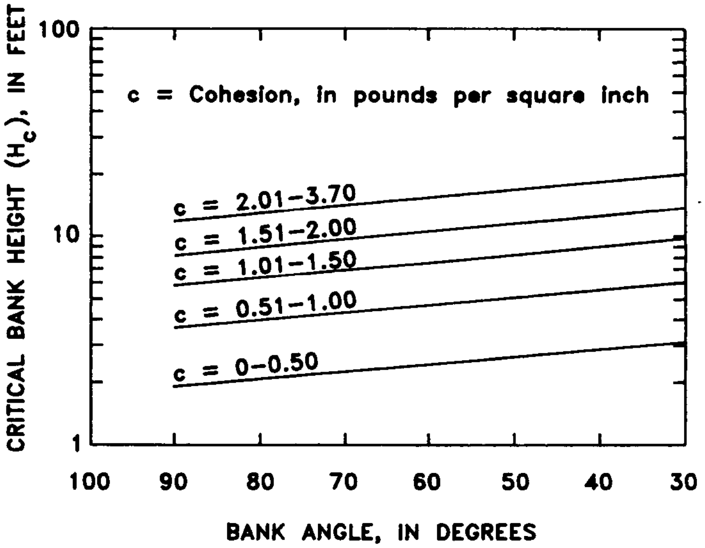


Figure 36.--Critical bank-slope configurations for various ranges of cohesive strengths under saturated conditions.

Channel Widening

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

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

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

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

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

Recent Widening

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

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

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

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

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

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

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

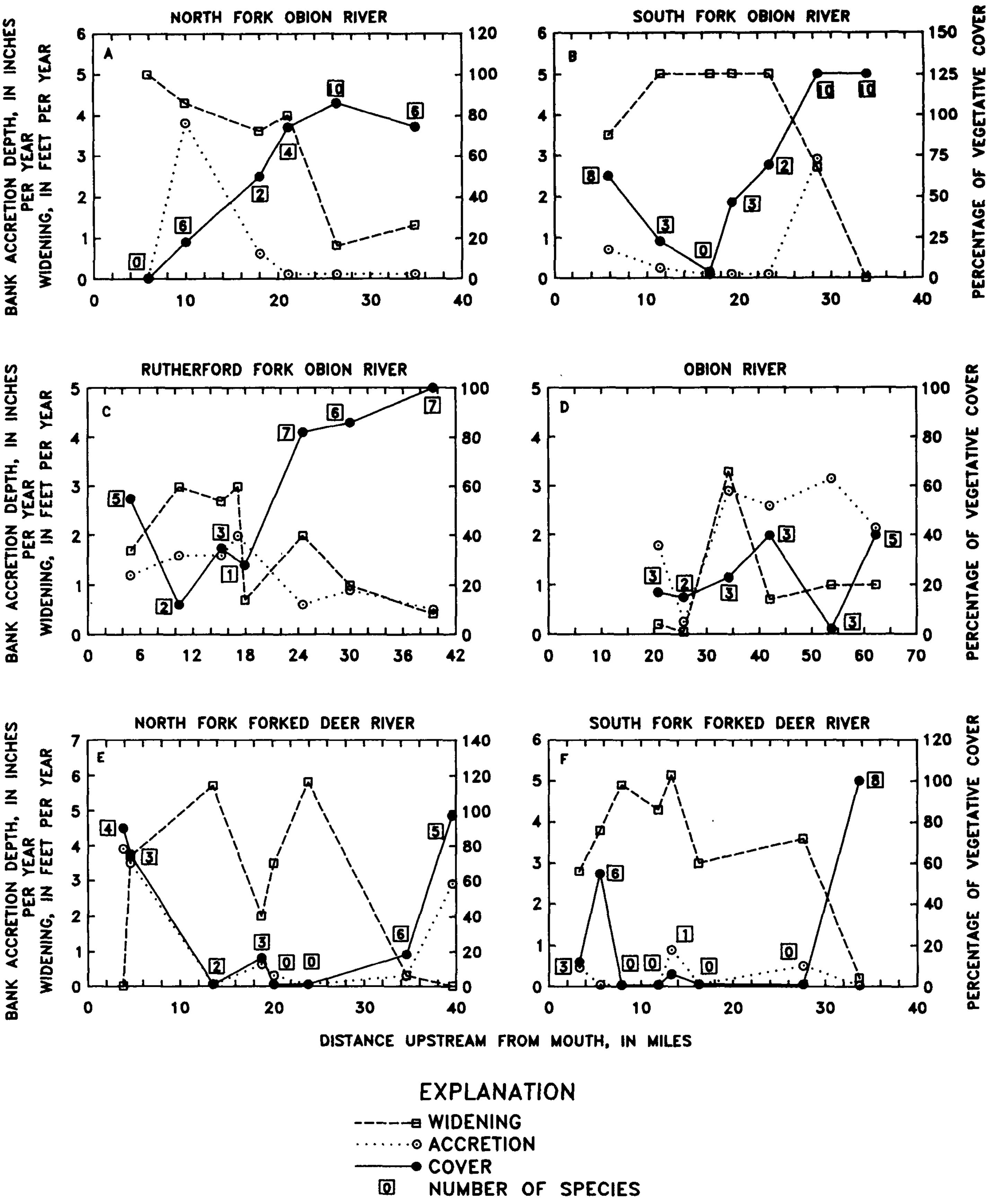


Figure 37.––Channel widening, bank accretion depth, and percentage of vegetative cover at selected locations in the (A to D) Obion River system and (E to F) the Forked Deer River system.

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

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

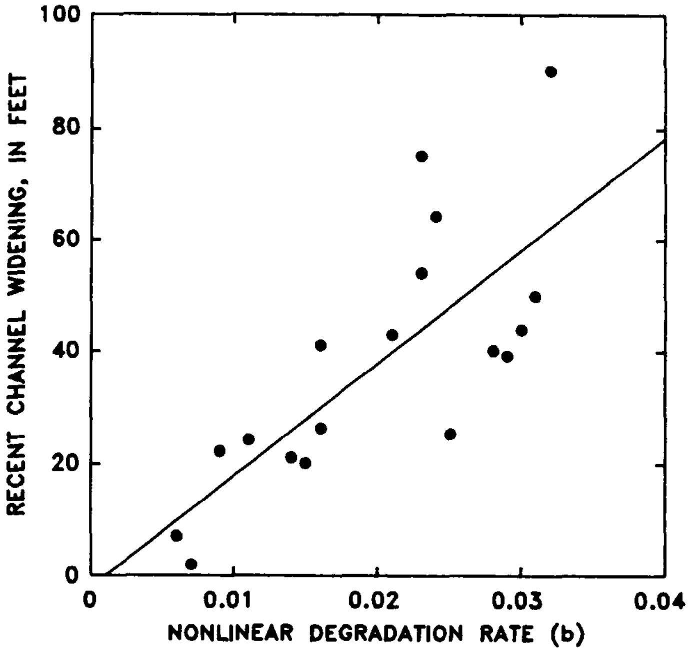


Figure 38.—Relation between bed degradation (b) and recent channel widening, Cane Creek.

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

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

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

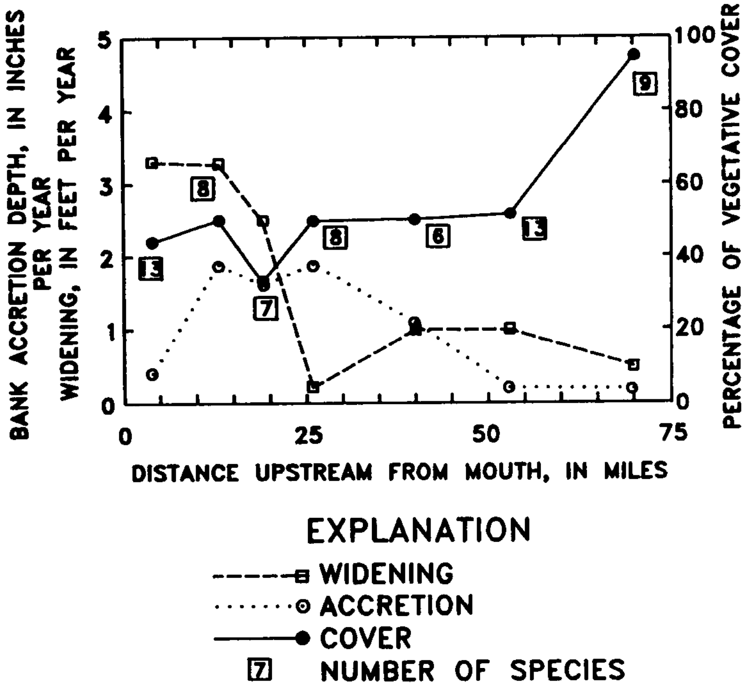


Figure 39.—Channel widening, bank accretion depth, and percentage of vegetative cover at selected locations along the Wolf River.

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

Total Widening

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

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

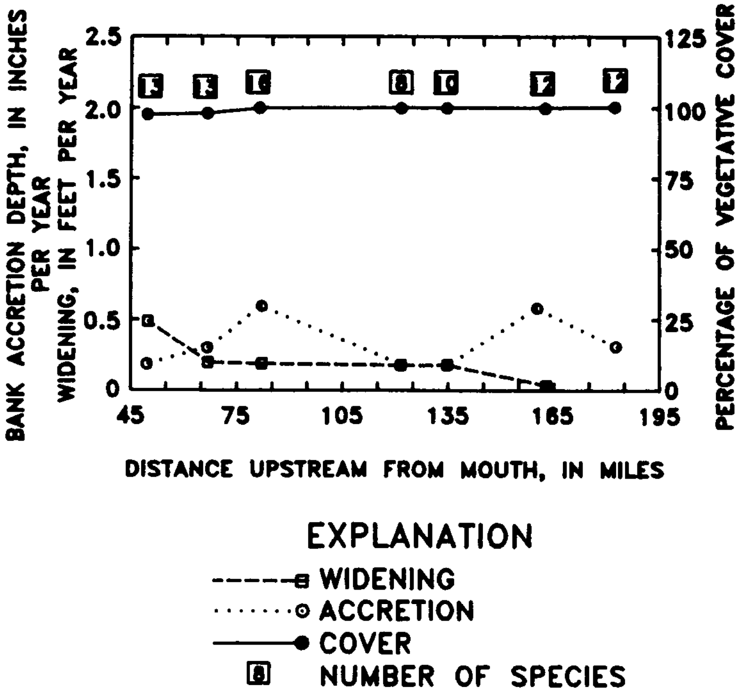


Figure 40.—Channel widening, bank accretion depth, and percentage of vegetative cover at selected locations along the Hatchie River.

Volumes of Bank Erosion

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

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

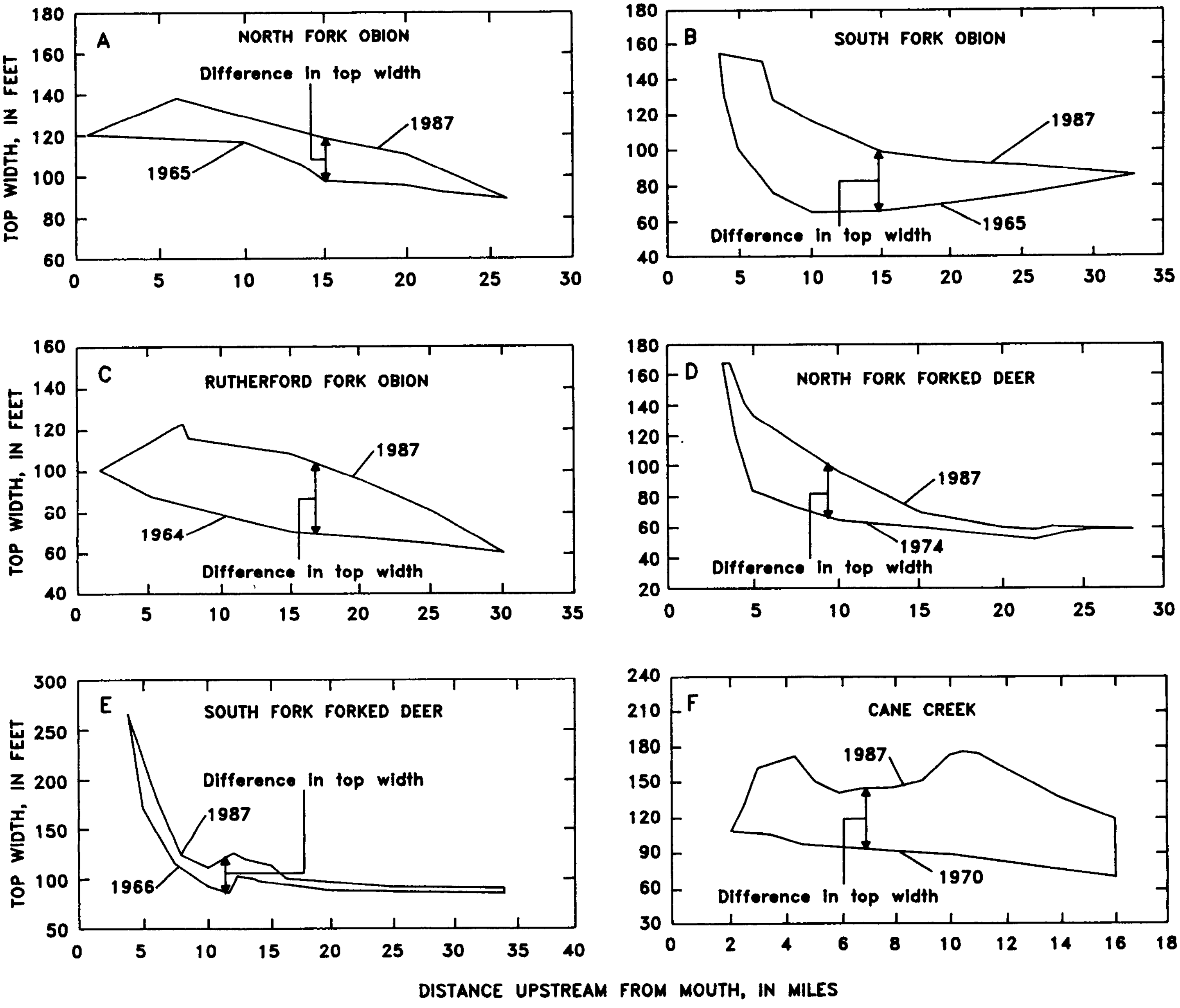


Figure 41.--Changes in channel top width along the (A) North Fork Obion, (B) South Fork Obion, (C) Rutherford Fork Obion, (D) North Fork Forked Deer, (E) South Fork Forked Deer Rivers, and (F) Cane Creek.

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

[-- = No data]

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

[1] Estimated data.

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

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

Projected Widening

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

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

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

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

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

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

Obion-Forked Deer River Forks

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

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

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

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

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

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

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

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

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

Obion River Main Stem

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

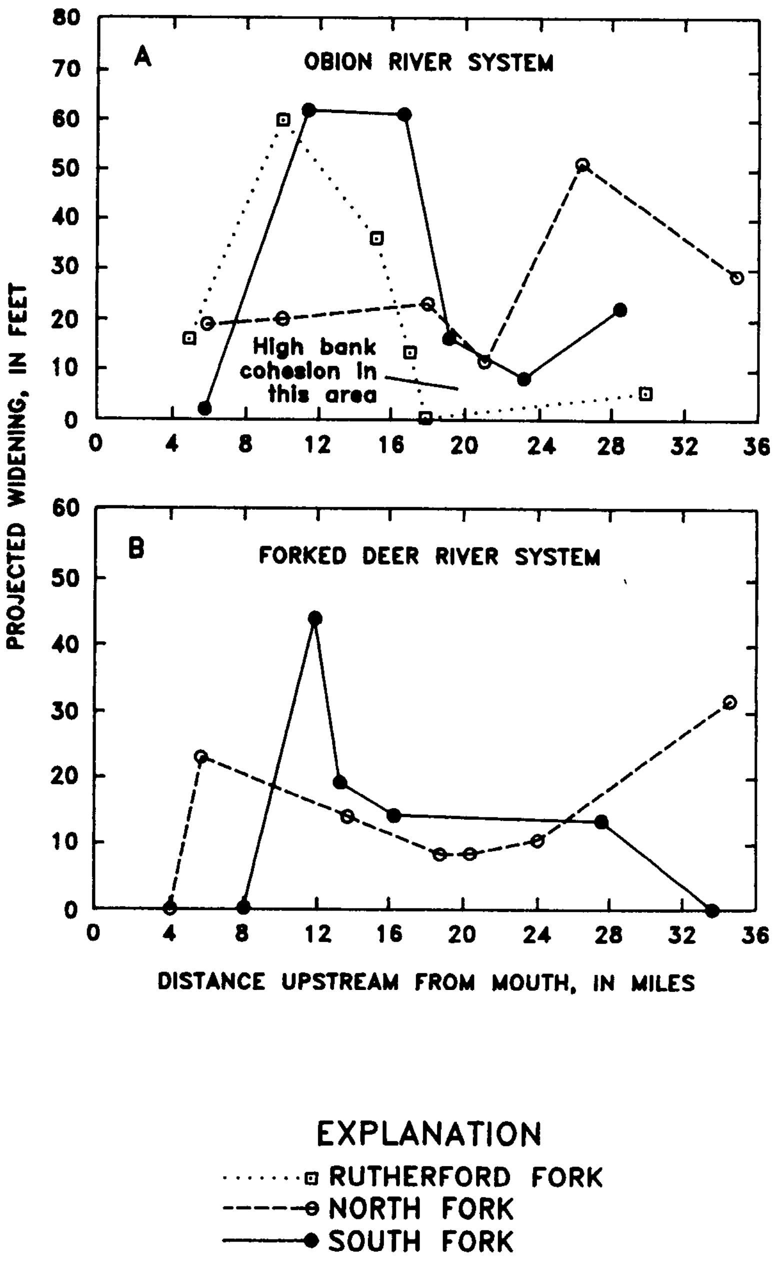


Figure 42.--Projected widening along the (A) Obion River and (B) Forked Deer River systems.

Cane Creek

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

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

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

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

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

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

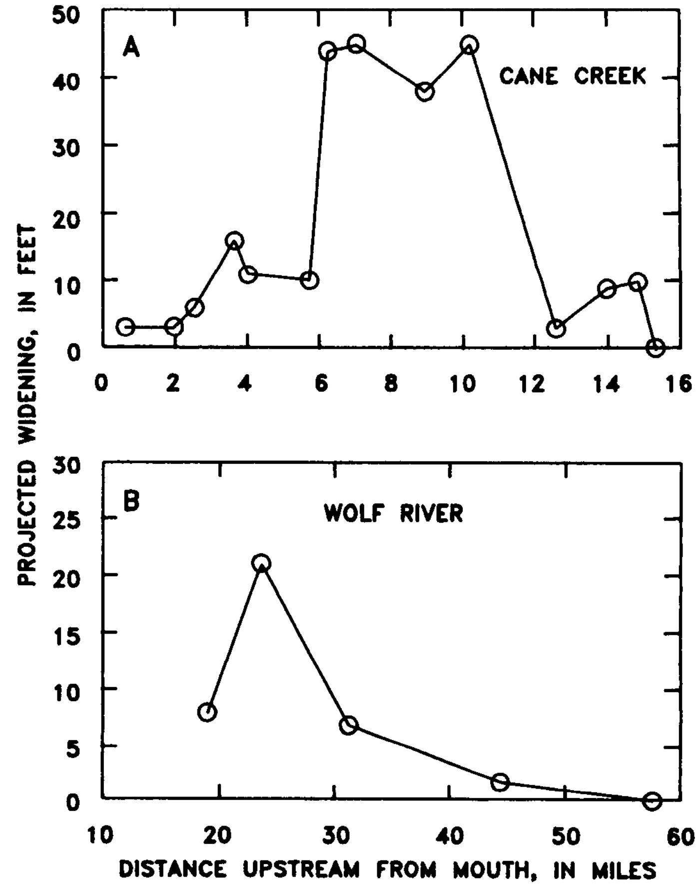


Figure 43.--Projected widening along (A) Cane Creek and (B) Wolf River.

Wolf River

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

Cub and Porters Creeks

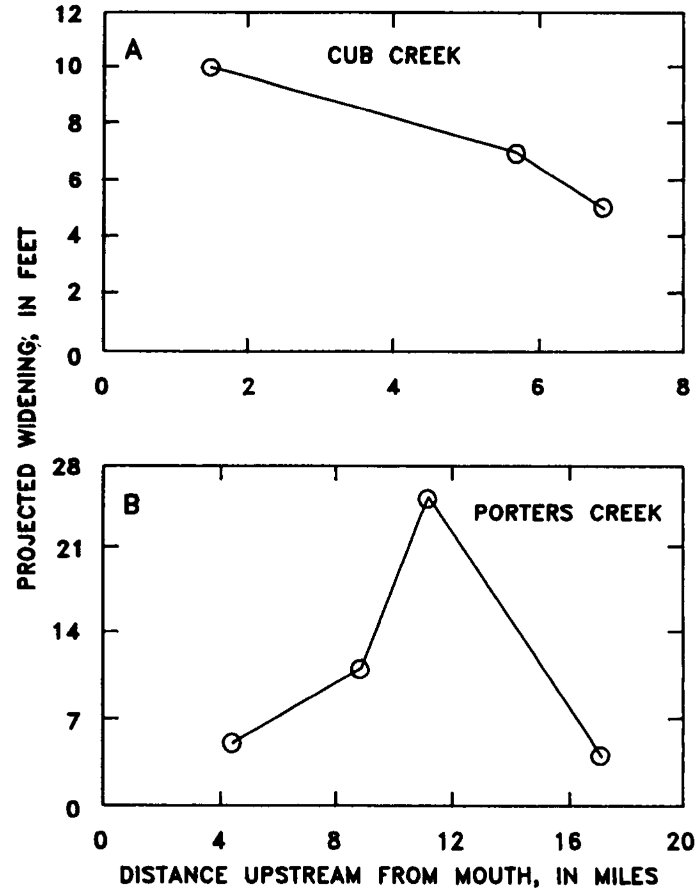


Figure 44.--Projected widening along (A) Cub and (B) Porters Creeks.

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

Hoosier and Pond Creeks

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

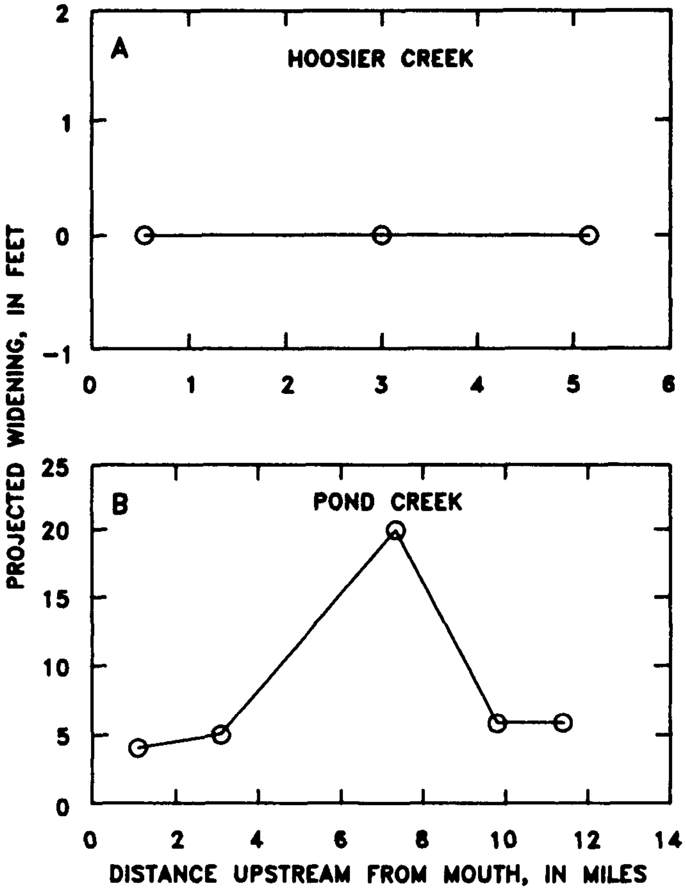


Figure 45.--Projected widening along (A) Hoosier and (B) Pond Creeks.

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

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

Systematic trends of channel adjustment begin immediately after modifications to reduce channel gradient and stream power (Simon and Robbins, 1987). Channel bed, bank, and vegetative processes vary through the course of fluvial adjustment and are diagnostic in determining the stage of channel evolution (table 5). The relative roles of channel-bed degradation, channel widening, and shear strength on morphologic changes have been addressed in previous sections. These processes and variables have been shown to vary according to the stage of adjustment, and to yield quantitative information regarding