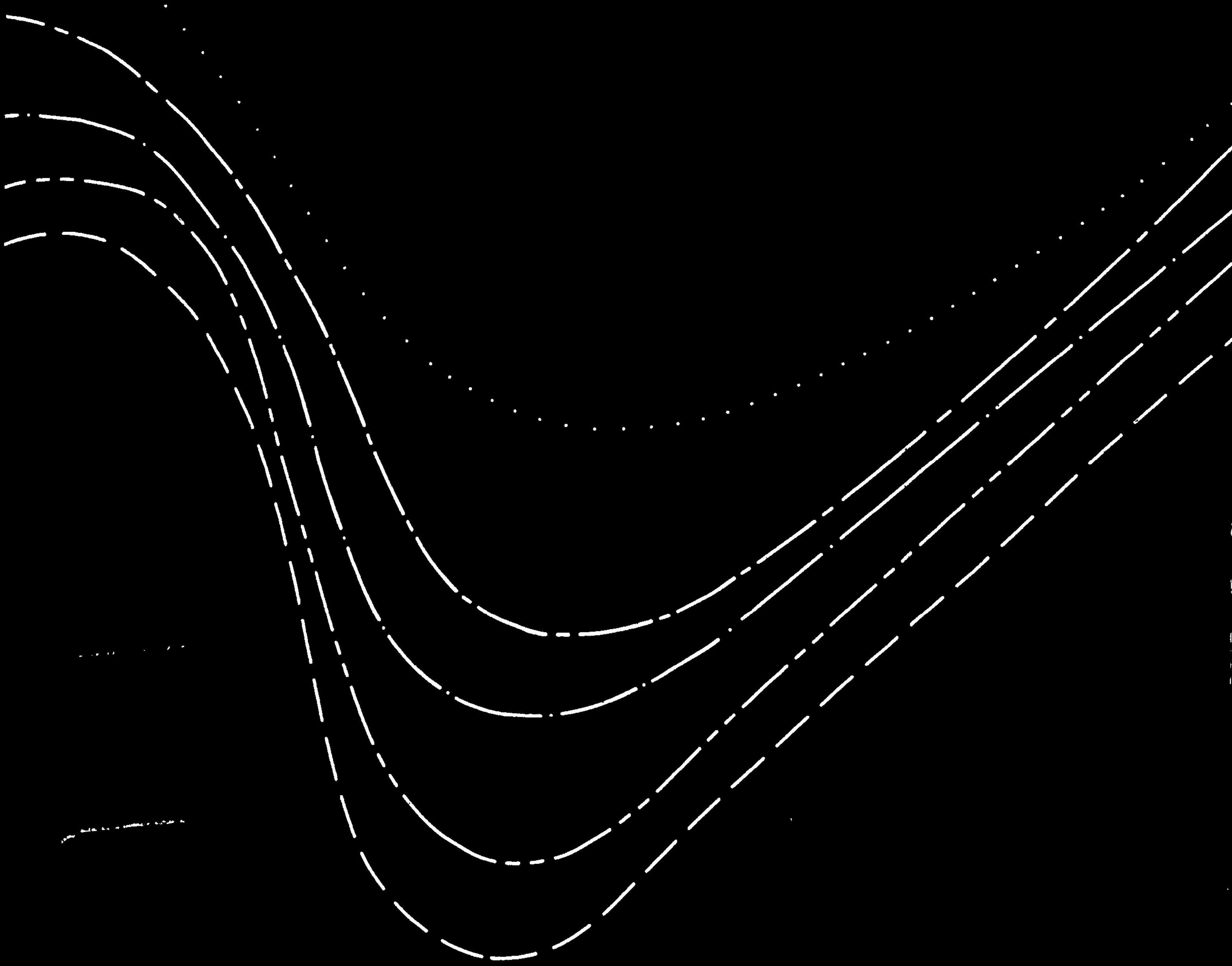
Open-File Report 91-502

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

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

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

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

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

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

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

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

where N_S = dimensionless stability number,
H = bank height, and
γ, c, ϕ, i = are as previously defined.

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

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

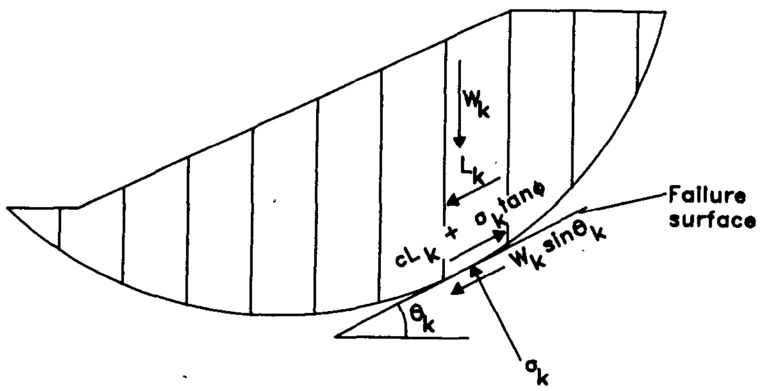


Figure 13.—Rotational failure surface. (Modified from Huang, 1983.)

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

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

Dendrogeomorphic Analyses

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

Channel widening

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

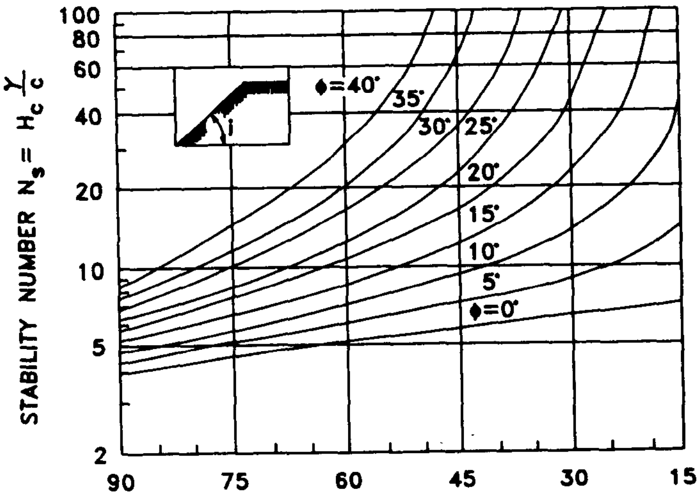


Figure 14.--Stability number (N_s) as a function of bank angle (i) for a failure surface passing through the toe. (γ=bulk unit weight; c=cohesion; ϕ=friction angle.) (Modified from Thorne and and others, 1981.)

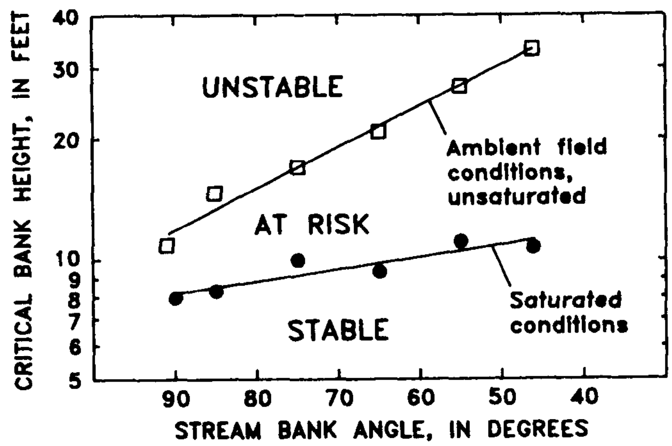


Figure 15.--Example of slope-stability chart giving critical-bank heights for various bank angles.

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

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

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

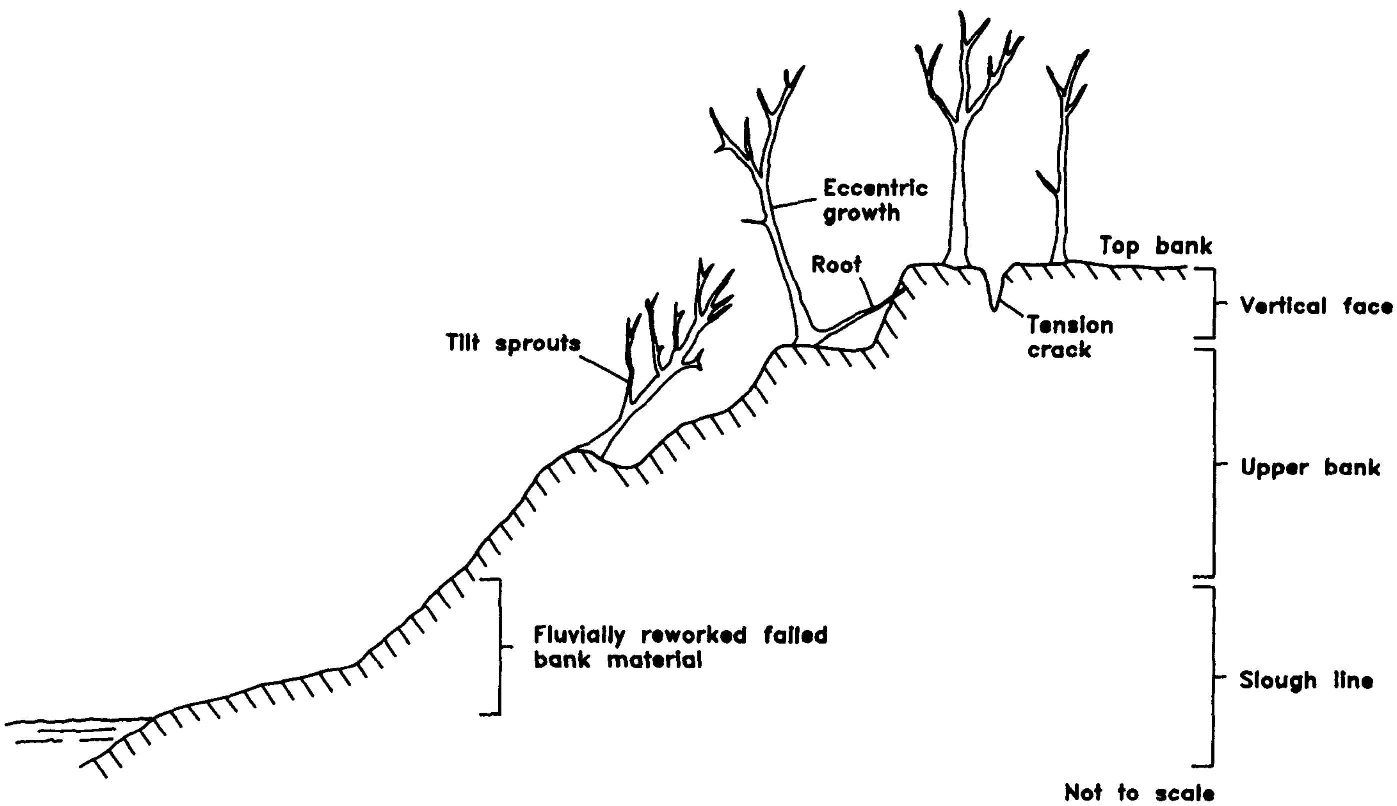


Figure 16.--Generalized bank cross section of modified channel after extensive channel-bed degradation and channel widening. Failure blocks and botanical evidence are shown. Note location of typical streambank forms, indicated on right.

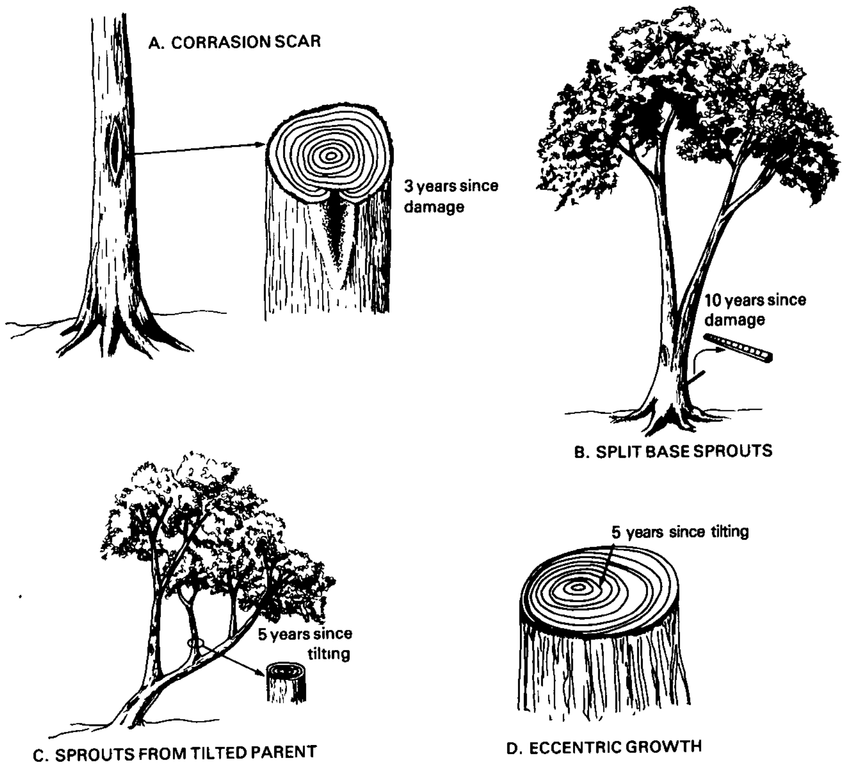


Figure 17.--Types of botanical evidence associated with typical geomorphic disturbances. (Modified from Hupp, 1988.)

Bank Accretion

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

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

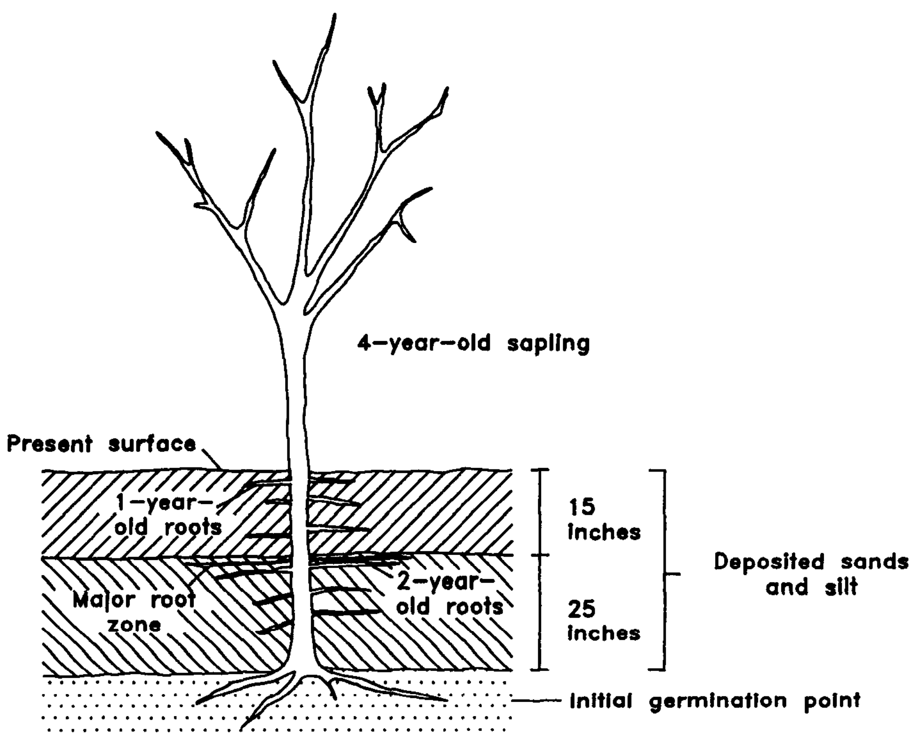


Figure 18.--Generalized buried sapling showing timing and depths of sediment deposition.

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

Woody Vegetative Cover

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

Timing of restabilizing bank conditions

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

Plant Ecology Analyses

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

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

Detailed Accretion Analyses

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

GEOMORPHIC AND VEGETATIVE RECOVERY PROCESSES

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

Channel Bed-Level Changes

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

Theoretical Considerations

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

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

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

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

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

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

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

Empirical Data by River Mile

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

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

Degradation

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

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

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

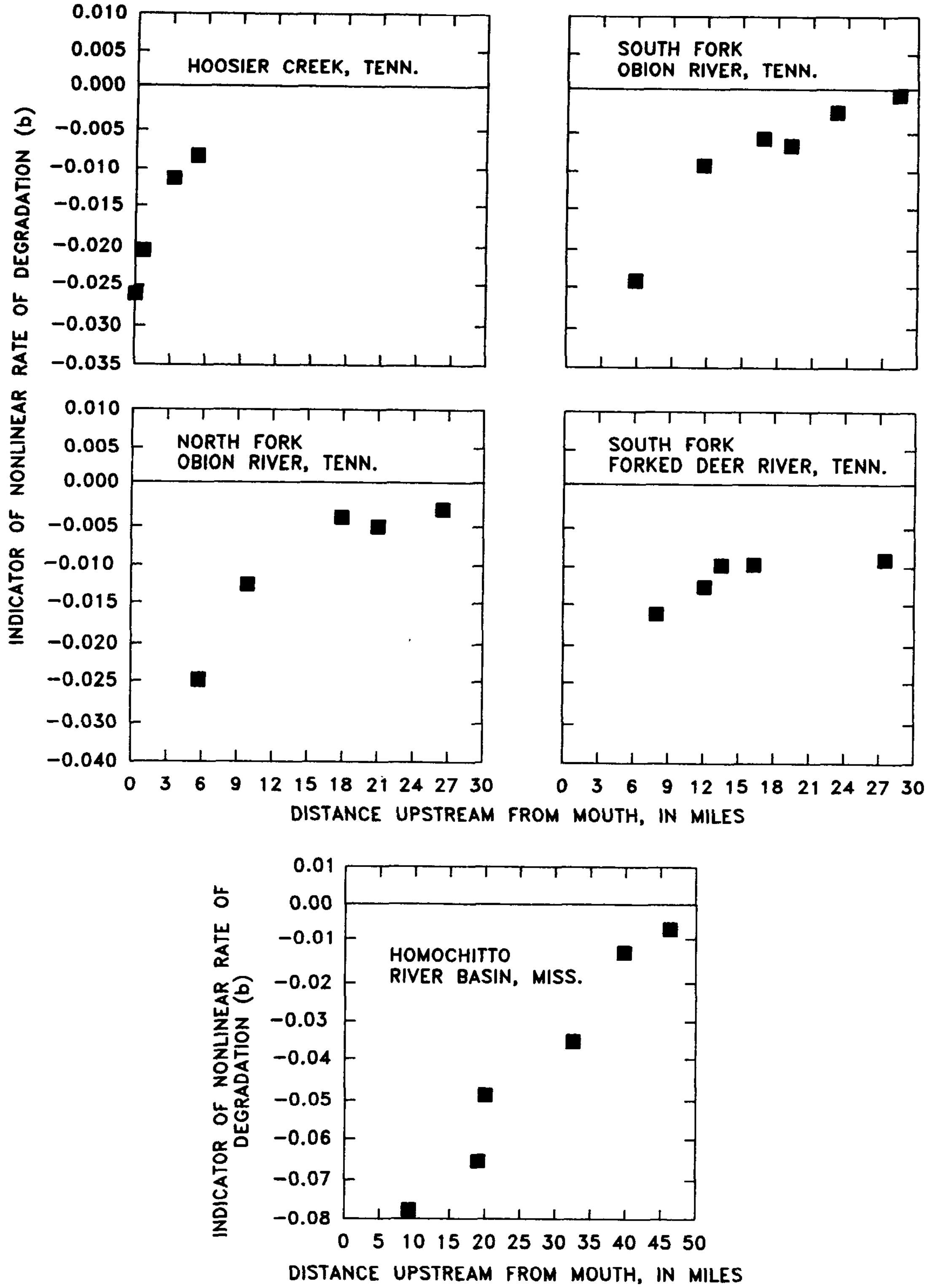


Figure 19.—-Relation between indicator of nonlinear rate of degradation (b) and river mile for selected streams in Mississippi and Tennessee. (Data for Homochitto River from Wilson, 1979.)

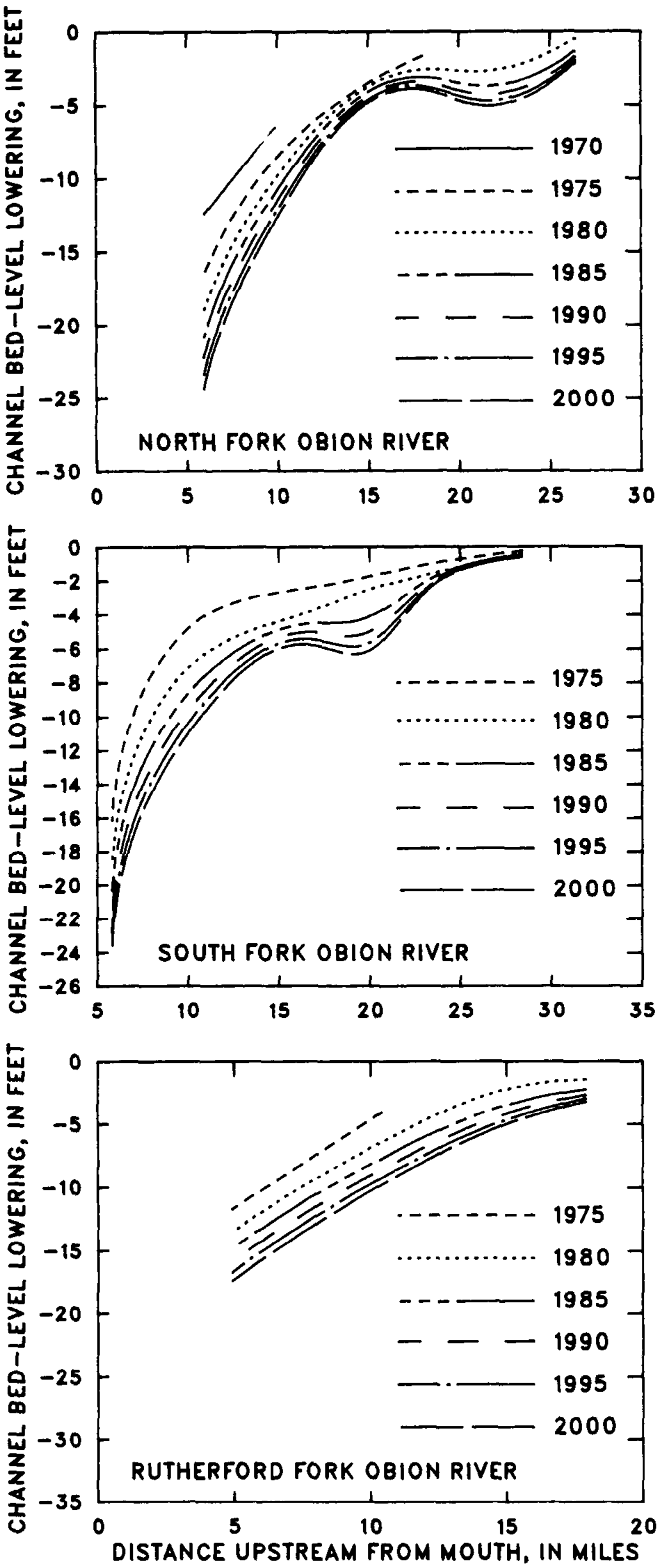


Figure 20.--Projected channel bed-level lowering for North Fork, South Fork, and Rutherford Fork of the Obion River.

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

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

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

Cane Creek was channelized throughout its length and shortened by approximately

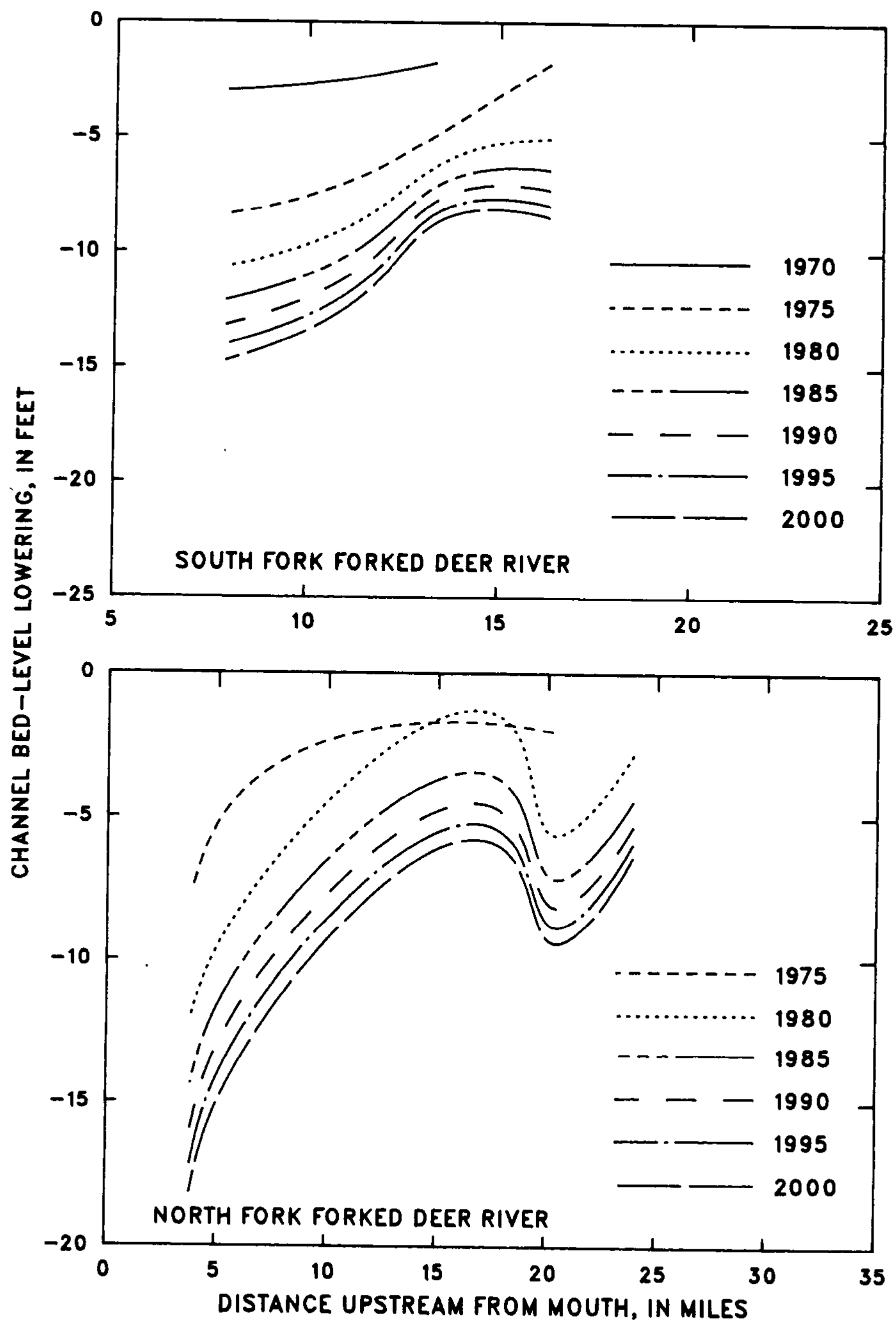


Figure 21.--Projected channed bed-level lowering for South Fork and North Fork of the Forked Deer River.

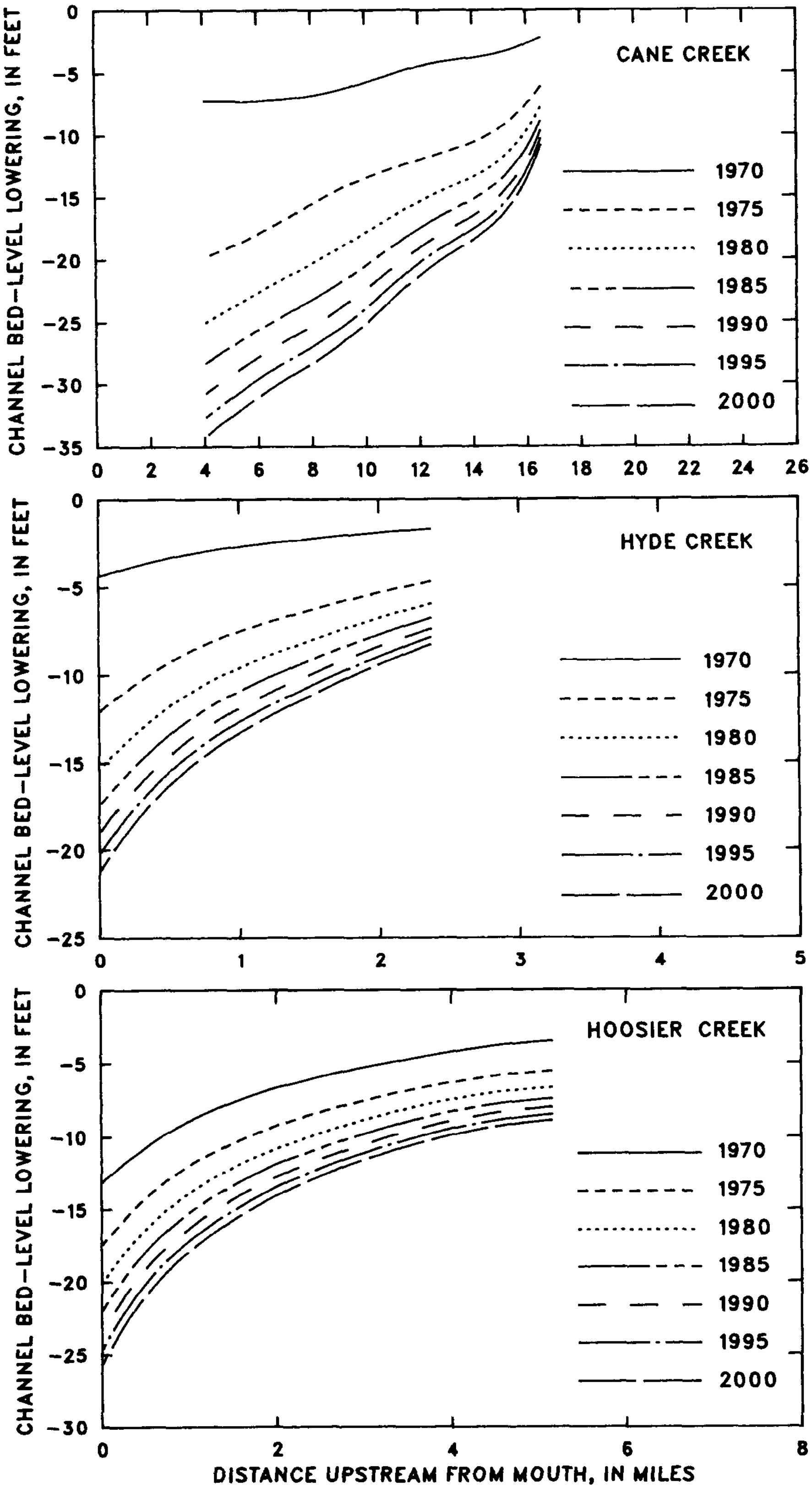


Figure 22.--Projected channel bed-level lowering for Cane Creek, Hyde Creek, and Hoosier Creek.

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

[. = no data]

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

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

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

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

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

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

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

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

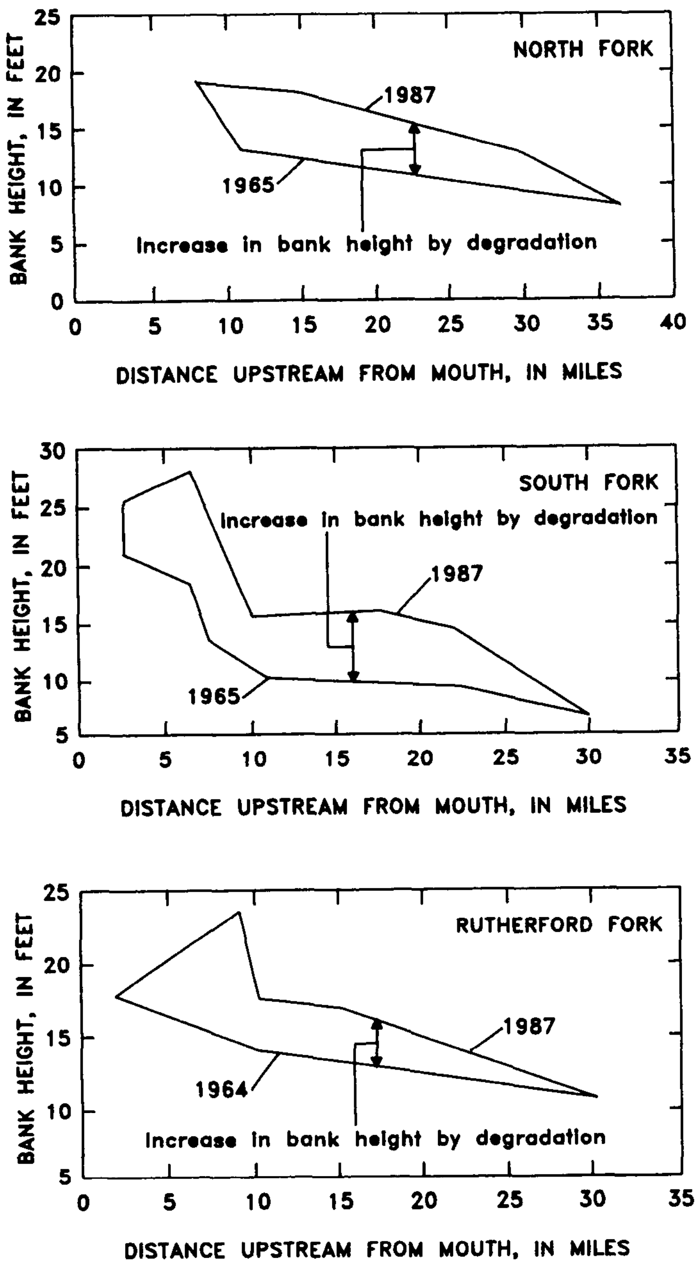


Figure 23.--Changes in bank heights by degradation along the North Fork, South Fork, and Rutherford Fork Obion River, 1964, 1965, and 1987.

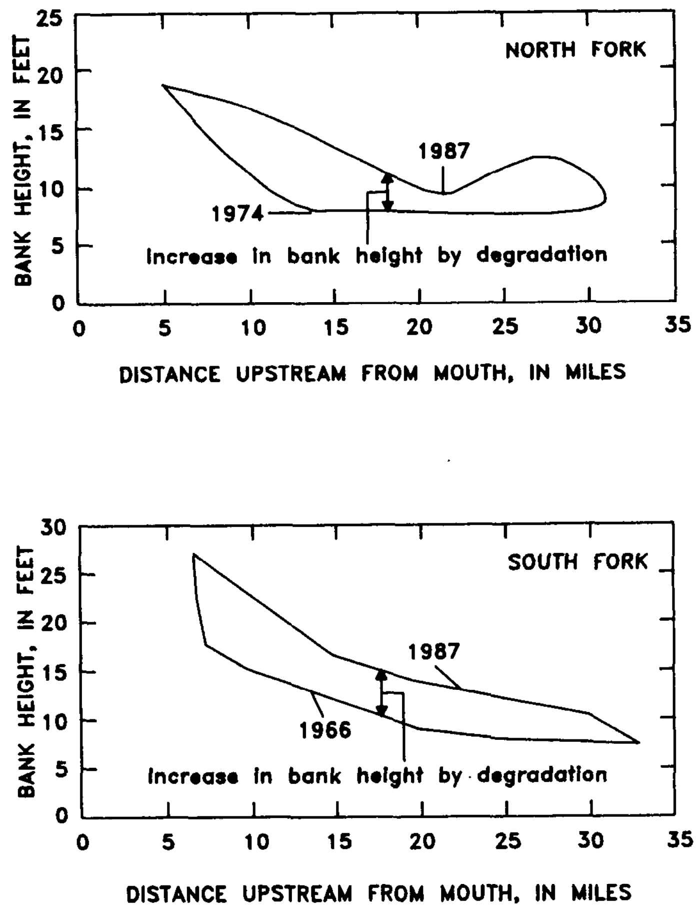


Figure 24.--Changes in bank heights by degradation along the North Fork and South Fork Forked Deer River, 1966, 1974, and 1987.

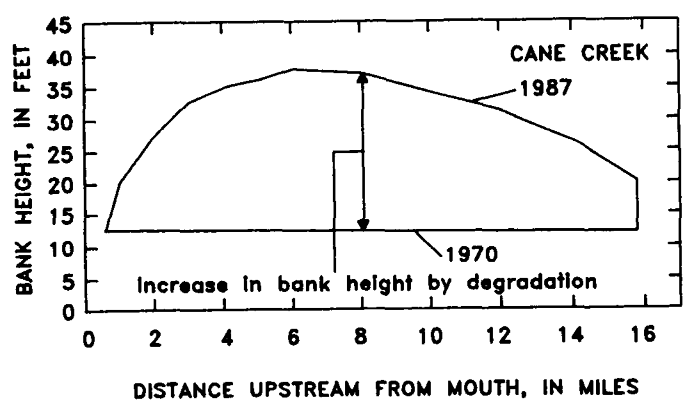


Figure 25.--Changes in bank heights by degradation along Cane Creek, 1970 and 1987.

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

[-- = Not applicable]

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

[1]Estimated data.

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

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

Aggradation

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

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

[AMD=Area of maximum disturbance]

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

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

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

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

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

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

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

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

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

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

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

[-- = Not applicable]

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

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

[-- = Not applicable]

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

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

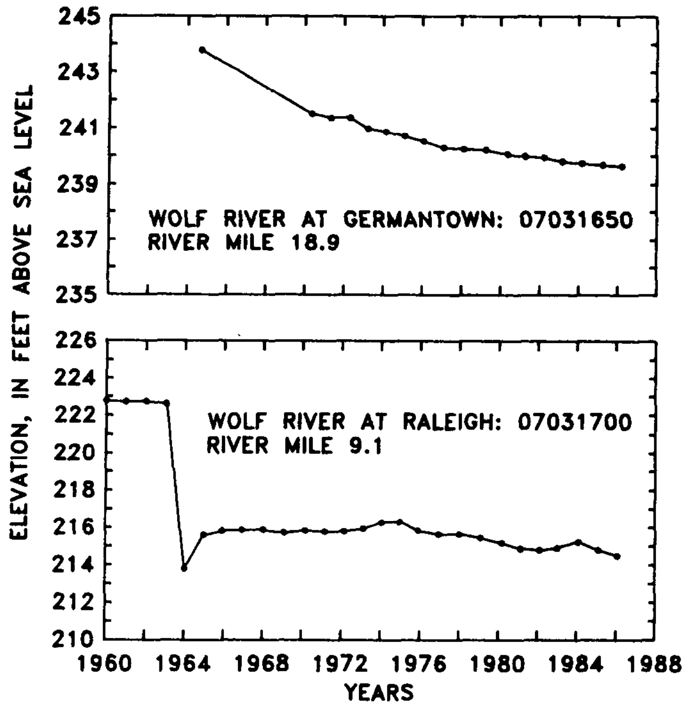


Figure 26.--Trends of channel-bed elevation with time for two sites on the lower Wolf River.

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

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

Bank Processes and Evolution

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

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

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

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

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

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

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

Bank-Material Properties

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

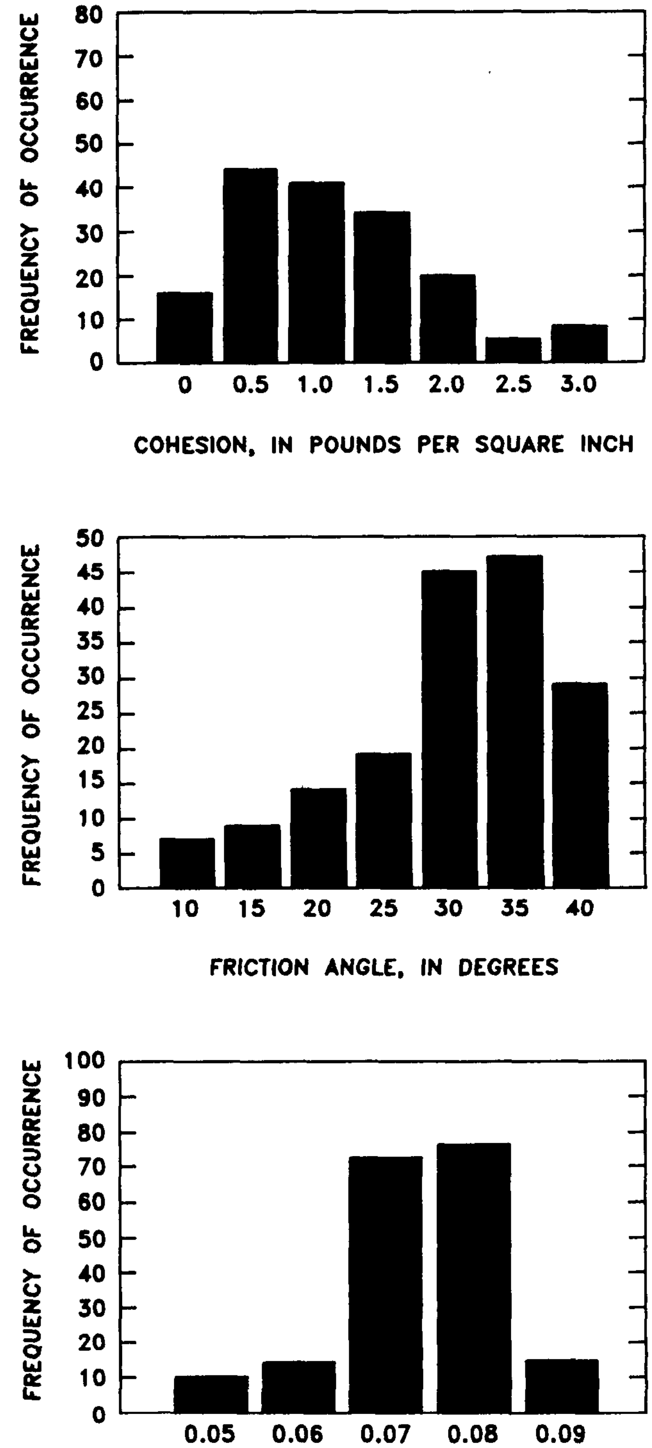


Figure 27.--Frequency histograms of soil-mechanics data.

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

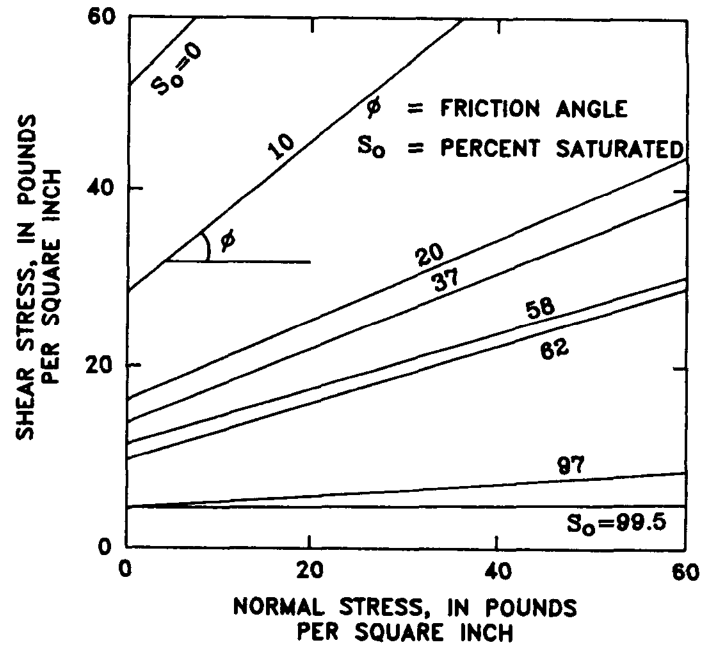


Figure 28.--Relation between normal stress and shear stress for loess at various degrees of soil saturation. (Modified from Lutton, 1974.) S_o values are in percent.

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

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

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