Channel Evolution in Modified Alluvial Streams

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Modification of alluvial channels in western Tennessee has created increased energy conditions along main stems and tributaries and initiated longitudinal channel adjustment. Changes in bed level are functions of the magnitude and extent of the imposed disturbance and the location of the adjusting reach in the fluvial network. Streambed degradation is described by simple power equations. Computed exponents define the magnitude of downcutting with time and decrease nonlinearly with distance upstream from the area of maximum disturbance (AMD). Aggradation begins immediately in reaches downstream of the AMD and in upstream reaches after overadjustment by the degradation process. Aggradation rates increase linearly with distance downstream from the AMD and can be estimated from local degradation rates. Channel widening by mass wasting follows degradation and continues through aggradational phases. Piping in the loess-derived bank materials enhances bank failure rates by internally destabilizing the bank. Development of the bank profile is defined in terms of three dynamic and observable surfaces: (*a*) vertical face (70 to 90 degrees), (*b*) upper bank (25 to 50 degrees), and (*c*) slough line (20 to 25 degrees). The slough line develops through additional flattening by low-angle slides and fluvial reworking and is the initial site at which riparian vegetation and stable bank conditions are reestablished. A six-step, semiquantitative model of channel evolution in disturbed channels was developed by quantifying bed level trends and recognizing qualitative stages of bank slope development.

Alluvial channels adjust to imposed changes so as to offset the effects of those changes and approach quasi-equilibrium. Lane (*1*) describes this general balance in terms of the stream power expression

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

where

Q = water discharge, in cubic meters per second;
S = channel gradient, in meters per meter;
Q_s = bed material discharge, in kilograms per cubic meter; and
d_{50} = median grain size of bed material load, in millimeters.

Dredging and straightening (shortening) alter both channel cross-sectional area and channel gradient (S) such that they are increased. By Equation 1, this results in a proportionate increase in either bed load discharge (Q_s), or bed material size (d_{50}), or both, such that rapid and observable morphologic changes occur.

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Channelization (dredging and straightening) is a common engineering practice for controlling flooding or draining wetlands. Quantification of subsequent channel responses can be valuable in estimating the effects on river-crossing structures and lands adjacent to these channels. The purposes of this study are (*a*) to assess the channel changes and network trends of bed level response after modifications between 1959 and 1972 of alluvial channels in western Tennessee (Figure 1) and (*b*) to develop a conceptual model of bank slope development to qualitatively assess bank stability and potential channel widening. Such a model will be useful in identifying trends of alluvial channel stability.

STUDY AREA

Western Tennessee is an area of approximately 27,500 km^2 bounded by the Mississippi River on the west and the Tennessee River on the east (Figure 1). All of the stream systems studied drain to the Mississippi River via the Obion, Forked Deer, and Hatchie river basins. These rivers are cut into unconsolidated and highly erosive formations (*2*), predominantly of Quaternary age. Wisconsin loess dominates the surficial geology of the region, and a majority of the channels have medium-sand beds. These alluvial channels are free to systematically adjust their profiles after a disturbance because of the lack of bedrock control of local base level.

DATA COLLECTION

Channel morphology data were collected and compiled from previous surveys to determine channel change with time. These data consisted of bed elevations and gradients; channel top widths; and channel lengths before, during, and after modification. If they were available, gauging station records were used to record annual changes in water surface elevation at a given discharge (*3*). Changes in water surface elevation at the given discharge imply similar changes on the channel bed and can be used to document bed level trends (*3, 4*).

Identification and dating of various geomorphic surfaces can be useful in determining the relative stability of a reach and the status of bank slope development (*5, 6*). Data collection involved locating and dating riparian vegetation on (*a*) newly stabilized surfaces to determine the timing of initial stability for that surface and (*b*) unstable bank surfaces to estimate rates of bank retreat.

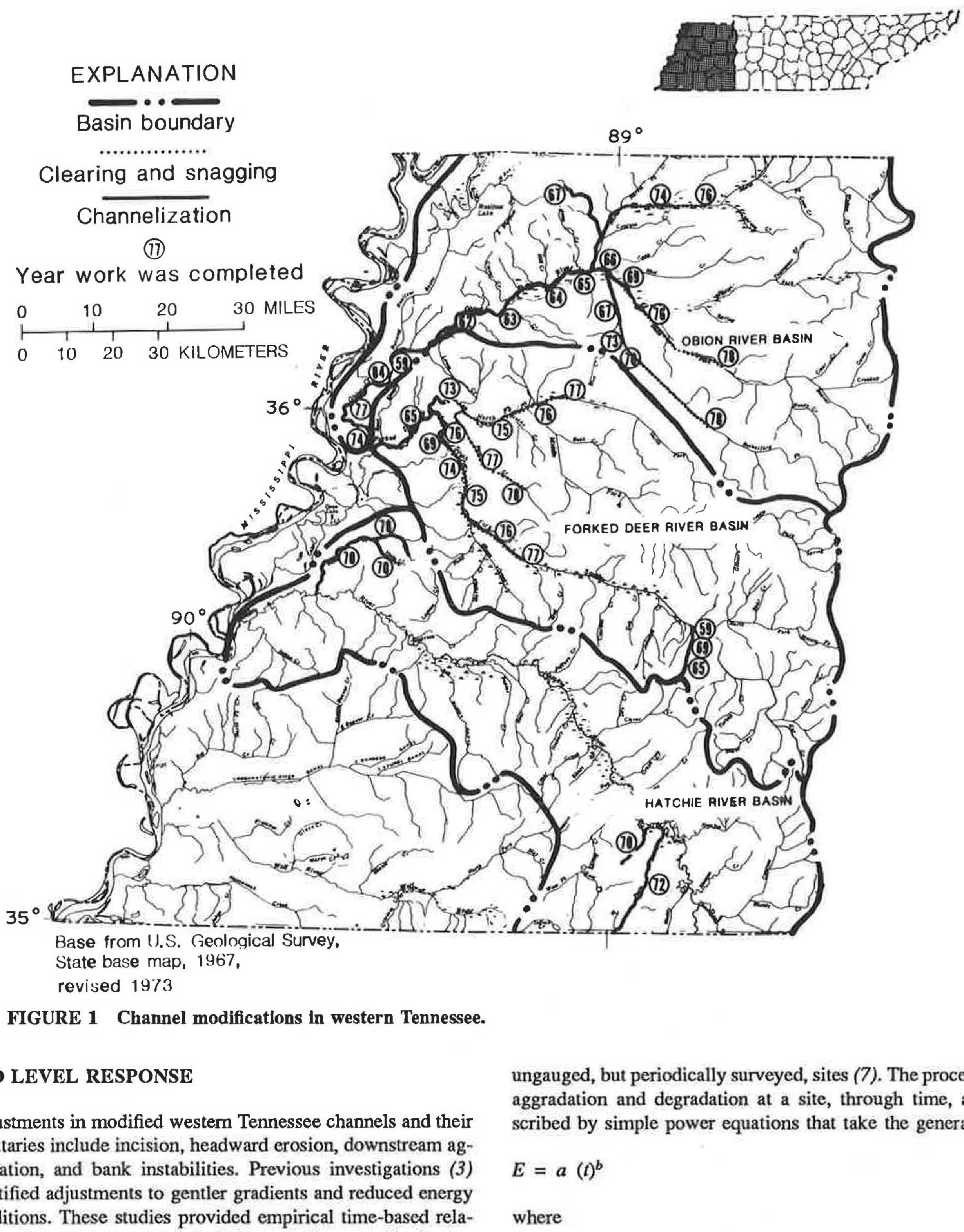

FIGURE 1 Channel modifications in western Tennessee.

BED LEVEL RESPONSE

Adjustments in modified western Tennessee channels and their tributaries include incision, headward erosion, downstream aggradation, and bank instabilities. Previous investigations *(3)* identified adjustments to gentler gradients and reduced energy conditions. These studies provided empirical time-based relations of site-specific gradient adjustment. These studies further determined that the bed of the Hatchie River had remained stable during the period when streams of the Obion and Forked Deer river basins were undergoing drastic morphologic changes.

Bed level adjustment trends at gauged sites are determined by calculating the mean annual specific-gauge elevation for the period just before and following channelization activities *(3, 4)*. Specific-gauge trends serve as examples for the ungauged, but periodically surveyed, sites *(7)*. The processes of aggradation and degradation at a site, through time, are described by simple power equations that take the general form

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

where

- E = elevation of the bed or specific gauge for a given year, in meters above sea level;
- a = premodified elevation of the bed or specific gauge, in meters above sea level;
- t = time since channel work, in years, where $t_0 = 1.0$; and
- b = exponent determined by regression, indicative of the nonlinear rate of change on the bed.

TABLE 1 SITES WITH CALCULATED GRADATION RATES (*b*)

Stream	b	n	r2	RKM	TO	DA
Cane Creek						
	-0.01620	7	0.99	23.89	1969	87.8
	0.00168	2	1.00	23.89	1980	87.8
	-0.02022	4	1.00	20.24	1969	130
	0.01052	2	1.00	20.24	1980	130
	-0.03300	3	1.00	14.46	1969	169
	0.00770	2	1.00	14.46	1980	169
	-0.03131	2	1.00	10.09	1969	187
	0.00352	2	1.00	10.09	1980	187
	-0.04126	3	0.91	6.53	1969	207
	-0.02011	4	0.92	4.06	1969	217
	0.00835	2	1.00	4.06	1980	217
Cub Creek						
	-0.00243	3	0.69	11.13	1969	2.8
	-0.00342	3	0.87	9.22	1969	17.1
	-0.00565	4	0.88	3.48	1969	37.0
	-0.00905	5	0.91	2.48	1969	38.9
	0.00272	2	1.00	2.48	1976	38.9
Hoosier Creek						
	-0.00843	3	1.00	8.29	1967	39.4
	-0.01130	4	0.94	4.81	1966	69.4
	-0.02081	3	0.67	0.88	1965	84.7
	0.00274	2	1.00	0.88	1968	88.8
	-0.02630	3	0.99	0.02	1965	88.8
Hyde Creek						
	0.00281	2	1.00	3.81	1975	16.6
	-0.00737	2	1.00	3.81	1969	16.6
	-0.01070	4	0.92	2.22	1969	23.1
	-0.01380	3	0.99	1.19	1969	26.2
	-0.02050	4	1.00	0.02	1969	27.7
Meridian Creek						
	-0.00326	3	0.99	5.94	1965	38.3
	-0.00580	4	0.98	4.73	1964	39.6
	-0.00341	3	0.99	2.41	1969	49.2
	-0.00190	3	0.99	1.54	1967	50.2
North Fork Forked Deer River						
	-0.00740	4	0.95	38.46	1977	448
	-0.01076	5	0.52	32.47	1974	479
	-0.00839	4	0.96	30.28	1978	552
	-0.01720	10	0.95	8.53	1973*	2432
	-0.02297	3	0.87	6.16	1972	2440
North Fork Obion River						
	0.00111	15	0.69	59.37	1969*	422
	-0.00206	2	1.00	42.48	1979	741
	-0.00490	2	1.00	33.95	1975	922
	-0.00372	13	0.80	28.96	1972*	963
	-0.01240	6	0.93	15.83	1965*	1243
	-0.02470	4	0.85	9.49	1965*	1303
	0.00303	5	0.89	9.49	1967*	1303
Obion River						
	-0.02220	10	0.95	110.22	1965*	1948
	0.00463	10	0.74	110.22	1974*	1948
	-0.04030	4	0.81	100.08	1965*	4496
	0.00235	16	0.76	100.08	1968*	4496
	0.00908	19	0.93	86.40	1965*	4797
	0.00518	15	0.84	55.03	1963*	5265
	0.00585	16	0.74	33.47	1960*	6229
Pond Creek						
	-0.00828	5	0.81	18.29	1977	96.9
	-0.00799	4	0.84	15.80	1977	117
	-0.01233	4	0.97	11.78	1977	140
	-0.00900	5	0.79	1.71	1977	176
Porters Creek						
	-0.01069	7	1.00	27.51	1971	37.8
	-0.01320	7	0.99	18.02	1971	92.7
	-0.00578	6	1.00	14.30	1971	105
Rutherford Fork Obion River						
	0.00149	19	0.60	48.11	1965*	285
	-0.00317	4	0.91	28.80	1977	521
	-0.00493	3	1.00	24.46	1977	557
	-0.00991	4	0.79	16.73	1972	616
	0.00356	4	0.99	16.73	1977	616
	-0.01728	9	0.93	7.88	1965*	692
	0.00433	9	0.88	7.88	1974*	692
South Fork Forked Deer River						
	-0.00895	6	0.59	44.41	1976	1992
	-0.00950	10	0.92	26.23	1974*	2414
	-0.00978	5	0.76	21.40	1969	2598
	-0.01264	5	0.96	19.15	1969	2616
	-0.01630	15	0.94	12.71	1969*	2639
	0.01180	13	0.92	5.31	1969*	2727
South Fork Obion River						
	0.00133	13	0.90	55.35	1969*	528
	-0.00054	4	0.26	45.70	1972	811
	-0.00238	6	0.50	37.33	1972	914
	-0.00661	7	0.90	30.89	1977*	922
	-0.00573	5	0.87	27.03	1972	1020
	-0.00932	4	0.94	18.34	1972	1093
	-0.02430	11	0.87	9.33	1965*	1948
	0.00544	9	0.88	9.33	1975*	1948

Note: b, nonlinear gradation rate; n, number of observations; r2, coefficient of determination; RKM, river kilometer; TO, start of observed gradation process; DA, drainage area in square kilometers; *, specific gauge data used.

Equation 2 reflects bed level response at a site (Table 1) and implies that adjustment rates are initially rapid and then diminish as the bed elevation asymptotically approaches a condition of no net change (Figure 2). The magnitude of *b* denotes the nonlinear rate of degradation (negative *b*) or aggradation (positive *b*) and is used as the dependent variable in regression analyses for determination of longitudinal adjustment trends.

Degradation exponents ($-b$) generally range from −0.005 to −0.040 with the greatest rates of change occurring near the upstream side of the area of maximum disturbance (AMD), usually the upstream terminus of the channel work. Increases in downstream channel gradient and cross-sectional area by man result in a stream power that is more than sufficient to transport the bed material delivered from upstream. The bed of the channel therefore erodes headward to increase bed material transport or reduce channel gradient, or both. Typically, degradation occurs for 10 to 15 years at a site and can deepen the channel as much as 6.1 m.

Aggradation rates ($+b$) are less than their degradation counterparts and generally range from 0.001 to 0.009 with the greatest rates occurring near the stream mouth. This process begins immediately after channelization downstream of the AMD, may reach 0.12 m/year, and can continue for more than 20 years. As degradation proceeds upstream from the AMD to reduce channel gradient, aggradation downstream of the AMD similarly flattens gradients as part of an integrated basin response to the man-induced increases in energy conditions *(7)*.

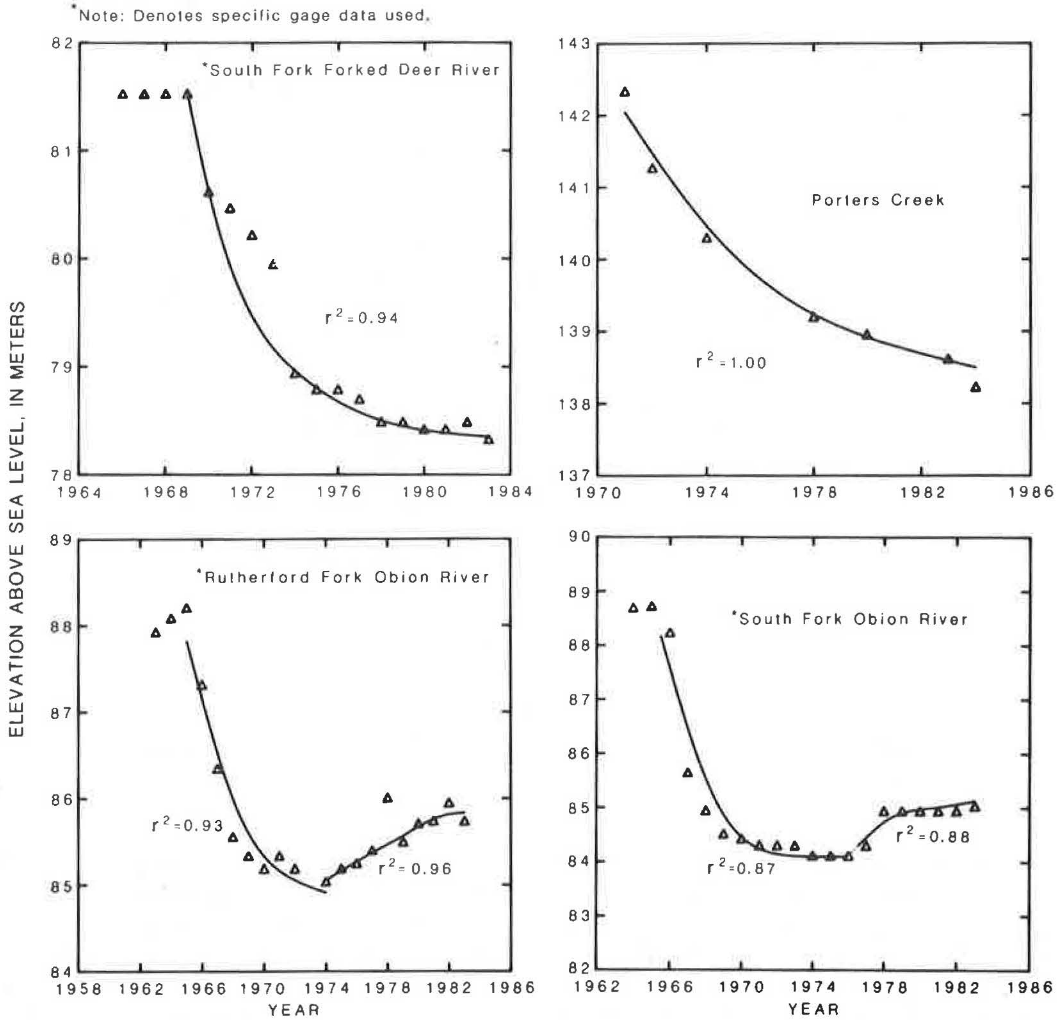

FIGURE 2 Examples of fitting power equations to degradation and aggradation trends through time.

Aggradation also occurs at sites upstream of the AMD that have been previously degraded and suggests an initial overadjustment by degradation. This secondary aggradation occurs as headward infilling. The rate of infilling at a site is approximately 78 percent less (S_E = 2.85) than the initial rate of degradation at that site *(7)*. Expected aggradation rates at sites upstream of the AMD can therefore be estimated at approximately 22 percent of the degradation rate at the site in question. Equations have been developed to calculate aggradation rates in the Cane Creek and Forked Deer and Obion river systems and are reported in Simon *(7)*.

Degradation rates decrease nonlinearly with distance upstream from the AMD in the Cane Creek and Forked Deer and Obion river basins as values of *b* become less negative and approach 0.0 (Figure 3). Linear relations are derived from these trends and used to predict degradation rates in the three basins *(7)*. The shapes of the curves that represent areal trends of degradation are functions of the magnitude and extent of the imposed disturbance.

Completed and ongoing rates of bed level change as a function of distance upstream from the mouth of the Obion River are shown in Figure 4. Rates of bed level change are plotted on the *y*-axis; the horizontal 0.00 line represents the threshold of critical power and, theoretically, no net change on the channel bed *(8)*. Deviations from the 0.00 line denote a period of bed level change caused by the imposed disturbance or by subsequent channel responses. The Obion River is used as a typical example of bed level response. Similar models have been documented for other streams and basins in western Tennessee *(7)*.

The modifications imposed on the Obion River can be considered to have caused a rejuvenation of the fluvial network. Peak disequilibrium occurred at the upstream end of the channel work after its completion in 1967. Point A in Figure 4 denotes the location of this peak disturbance (AMD), represents maximum rates of degradation, and serves as a starting time (1967) for a space-for-time substitution. Incision upstream according to Line C and aggradation downstream according to Line B progress from this point in time and space.

Degradation for 10 to 15 years at sites just upstream of A reduces gradients to such an extent that the river can no longer transport the loads delivered from degrading reaches further upstream. These sites then experience secondary aggradation due to the overadjustment by degradation processes (D in

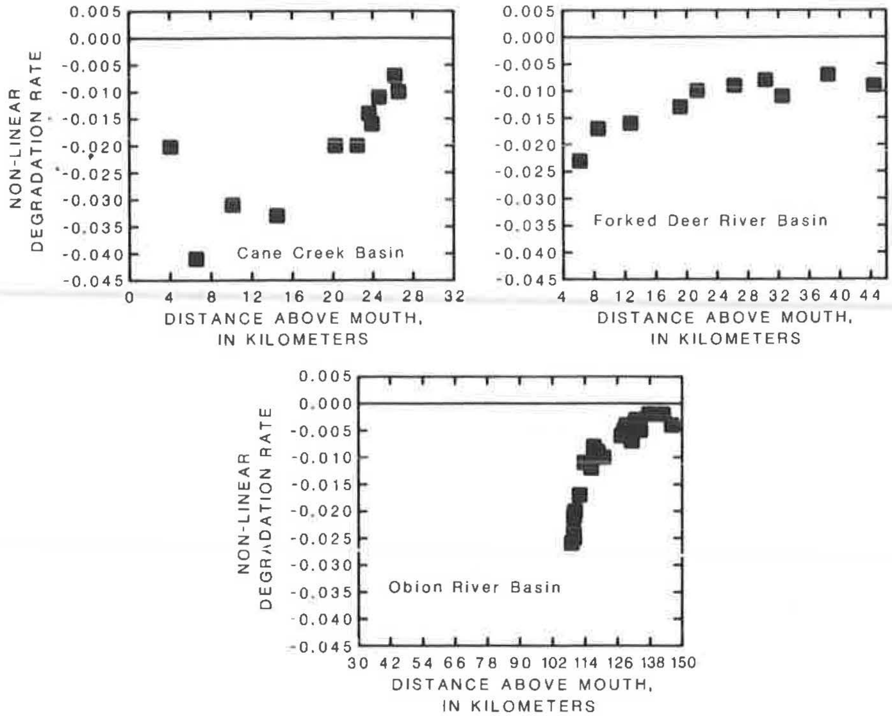

FIGURE 3 Longitudinal trends of degradation in three networks in western Tennessee.

Figure 4). This headward infilling occurs at magnitudes 78 percent less than the previous degradation rate, which suggests an overcompensation of 22 percent and oscillatory channel response. Expected shifts to secondary aggradation at sites further upstream that are presently degrading are provided by the inclusion of estimated data and serve to extend Line B-D in time and space. The bed level response model allows prediction of degradation and aggradation over time and space at any site along these river systems and is therefore extremely useful for the design of river-crossing structures.

Where Lines C and D approach the 0.00 line, gradation due to downstream modifications is minimized, and these sites will

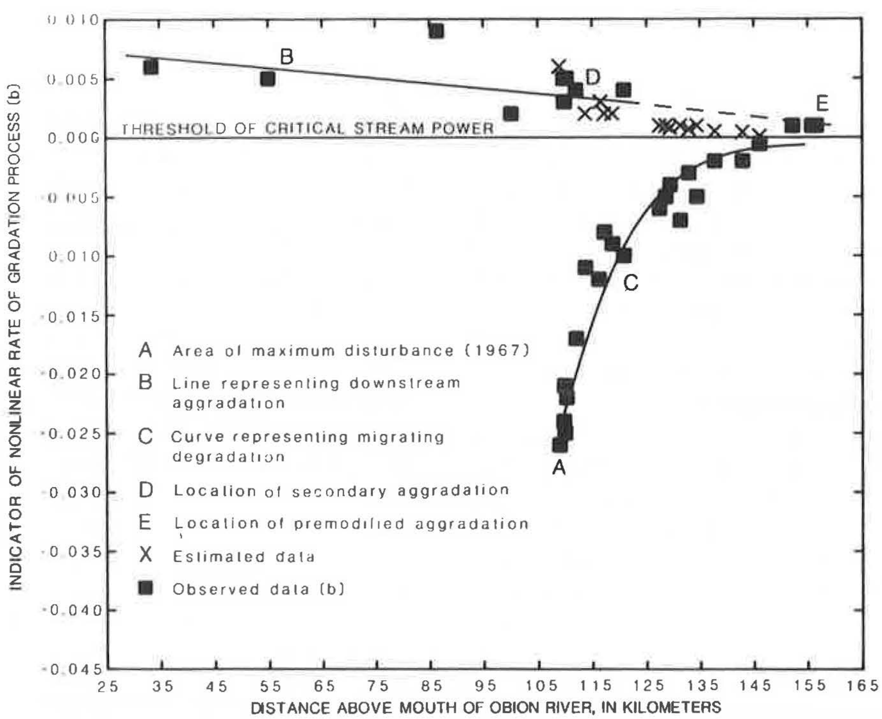

FIGURE 4 Model of bed level response for the Obion River system.

not degrade. This is estimated to take place near river kilometer 145 in the Obion River system. Upstream of the estimated intersection of the 0.00 line at E, aggradation continues to take place at low, premodified rates, according to "natural" basin and channel characteristics. Channel conditions far upstream of the AMD near E represent not only moderate adjustment processes and premodified aggradation rates but also conditions that will be attained by downstream reaches in the future as the channel network approaches quasi-equilibrium.

WIDTH ADJUSTMENT AND BANK SLOPE DEVELOPMENT

Channel widening (DW) and bank failure by mass-wasting processes are common attributes of adjusting channels in western Tennessee. Bank failure is induced by the overheightening and oversteepening of the bank by degradation and by undercutting at the toe of the bank *(9)*. Piping in the loess-derived bank materials enhances bank failure by internally destabilizing the bank.

The effect on channel widening of bed level lowering by degradation is reflected by the following direct correlation between the degradation exponent ($-b$) and DW where $r^2 = 0.50$, $S_L = 0.0001$, and $n = 49$. This relation implies that lower headward degradation rates reduce the tendency for channel widening upstream *(7)*. A summary of changes in channel width (DW) after the most recent major channel modifications of western Tennessee streams is given in Table 2. Mean DW-values for each stream are merely a point of reference and not a precise average of width adjustment because of the variability of gradation processes and the relative location of sites along a given stream. Minimum and maximum values of DW, however, do reflect a realistic range of width changes along the stream lengths studied.

PROCESSES AND STAGES OF BANK RETREAT AND SLOPE DEVELOPMENT

The processes and successive forms of bank retreat and bank slope development reflect the interaction of hillslope and fluvial processes. Interpretations of these processes and forms are based largely on bed level adjustment trends and botanical evidence *(7)*. An idealized representation of six stages of bank retreat and bank slope development is shown in Figure 5. The stages represent distinguishable bank morphologies that are characteristic of the various types of sites that describe bed level adjustment (Table 3).

Premodified Stage

Premodified bank conditions are assumed to be the result of "natural" land use practices and fluvial processes. Bank failure by mass wasting generally does not occur, and banks are considered stable. Premodified bank conditions (Stage I in Figure 5) are generally characterized by low-angle slopes (20 to 30 degrees), convex upper bank and concave lower bank shapes, and established woody vegetation along the top bank and downslope toward the low-flow channel. Stage I channel widths may narrow slowly with time as a result of mild aggradation and bank accretion. Sand often is found deposited on bank surfaces. Limited channel widening caused by bank caving and fluvial erosion may occur on some outside meander bends.

Constructed Stage

Construction of a new channel involves reshaping the existing channel banks or repositioning the entire channel. In either case, the banks are generally steepened, heightened, and made linear (Stage II in Figure 5). Modified western Tennessee channels generally are constructed as trapezoids with bank slopes ranging from 18 to 34 degrees. Channel widths are increased and vegetation is removed so that greater discharges can be conveyed within the channel banks.

Degradation Stage

The degradation stage (Stage III in Figure 5) is characterized by the lowering of the channel bed and the consequent increase in bank heights. Downcutting generally does not steepen bank slopes directly but maintains bank angles close to the angle of internal friction *(5, 10, 11)*. Steepening occurs when moderate flows attack basal surfaces and remove toe material along

TABLE 2 RANGE OF CHANGES IN CHANNEL TOP WIDTH (DW) BY STREAM

	DW, in meters					Years since most recent major channelization (from 1983)
	Mean	n	S	Min	Max	
Cane Creek	18.2	6	6.2	14	25	13
Cub Creek	2.1	4	5.1	0	6.7	13
Hoosier Creek	14.2	3	21.2	7.0	27	16
Hyde Creek	3.1	3	5.0	.3	5.4	18
Meridian Creek	3.4	2	3.0	2.4	4.3	16
North Fork Forked Deer River	10.3	4	16.9	3.0	25	10
North Fork Obion River	10.4	5	15.4	.6	25	16
Obion River	37.8	4	26.8	20	59	17
Pond Creek	2.9	3	1.7	2.1	4.3	5
Porters Creek	7.7	3	7.5	3.7	12	11
Rutherford Fork Obion River	7.2	5	11.4	0	18	14
South Fork Forked Deer River	13.6	6	11.5	4.9	27	14
South Fork Obion River	11.9	6	14.5	0	36	14

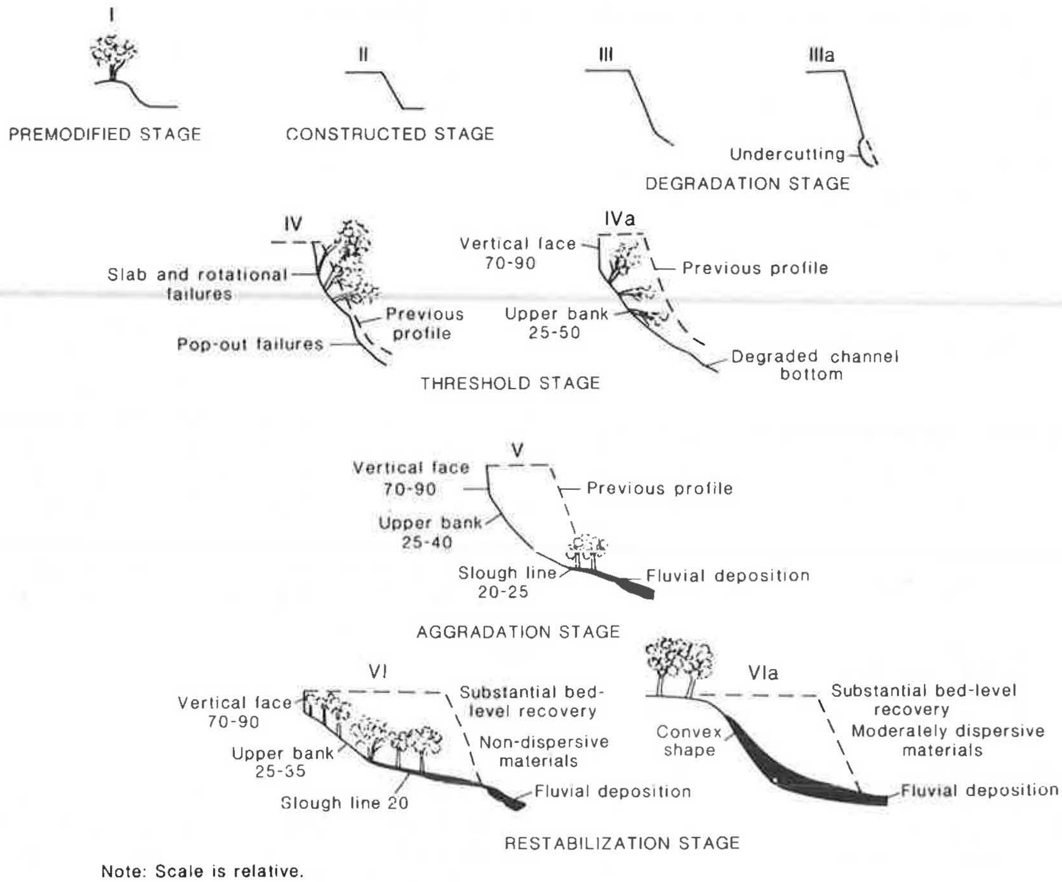

FIGURE 5 Six stages of bank slope development.

the heightened banks (Stage IIIa in Figure 5). Ideally, widening by mass wasting does not occur because the critical bank height has not yet been exceeded. The degradation stage ends when the critical height of the material is reached.

Threshold Stage

Stage IV (Figure 5) is the result of continued degradation and basal erosion that further heighten and steepen the channel banks. The critical bank height is exceeded, and bank slopes and shapes become the product of mass-wasting processes. Slab failures occur as a result of excessive undercutting and loss of support for the upper part of the bank. Pop-out failures at the base of the bank caused by saturation and pore water pressure *(9)* similarly oversteepen the upper part of the bank. Deep-seated rotational failures shear along a circular arc and often become detached from the top bank surface by piping and tension cracking. These failures can leave 1.8- to 3-m-long

TABLE 3 STAGES OF BANK SLOPE DEVELOPMENT

Stage No.	Stage Name	Bed Level Adjustment Type	Location in Network	Process on Channel Bed	Active Widening	Failure Types	Bank Surfaces Present	Approximate Bank Angles (degrees)
I	Premodified	Premodified	Upstream-most reaches	Transport of sediment or mild aggradation	No	N/A	N/A	20–30
II	Constructed	N/A	Where applicable	Dredging	By man	N/A	N/A	18–34
III	Degradation	Migrating degradation	Upstream from AMD	Degradation	No	N/A	N/A	20–30
IV	Threshold	Migrating degradation	Close to AMD	Degradation	Yes	Slab rotational pop-out	Vertical face Upper bank	70–90 25–50
V	Aggradation	Secondary aggradation	Upstream of AMD	Aggradation	Yes	Slab rotational pop-out, low-angle slides	Vertical face Upper bank Slough line	70–90 25–40 20–25
VI	Restabilization	Downstream-imposed aggradation	Downstream of AMD	Aggradation	No	Low-angle slides, pop-out	Vertical face Upper bank Slough line	70–90 25–35 15–20

NOTE: AMD = area of maximum disturbance.

slickensides along the failure plane and have been observed to be as much as 60 m long and 6 m wide *(5)*. The bank also can fail as plates along a series of pipes that form in the bank mass and intersect the flood plain surface *(7)*. Occasional debris avalanching occurs as well. These failure mechanisms are most intense in highly dispersive loess materials, such as are found in the Cane Creek basin.

The failed material that comes to rest on the bank forms a definable surface at slopes ranging from 25 to 50 degrees (Stage IV in Figure 5). This surface is termed the "upper bank" *(5)* and can often be identified on field inspection by tilted and fallen vegetation. The "vertical face," representing the top section of the major failure plane, is developed concurrently. The vertical face may range from 70 to 90 degrees and represents the primary location of top bank retreat.

The threshold stage is the first of two that are dominated by active channel widening. Failed material may be carried off by moderate to high flows, thereby retaining the overheightened and oversteepened bank profile and giving the banks a scalloped appearance.

Aggradation Stage

Stage V (Figure 5) is marked by the onset of aggradation on the channel bed and often can be identified by deposited sand on bank surfaces. Bank retreat dominates the vertical face and upper bank sections because bank heights still exceed the critical height of the material. The failed material on the upper bank is subject to low-angle slides resulting from continued wetting of the material by rises in stage. This process flattens and extends the upper bank downslope. Older masses of failed material on the upper bank also move downslope by low-angle slides. Such masses show evidence of fluvial reworking and deposition low on the upper bank and create a low-angle surface (20 to 25 degrees) termed the "slough line," extending downslope from the upper bank *(5, 6)*. Reestablishment of woody vegetation on the slough line has been used to date renewed bank stability along several streams *(6)*.

A slow and prolonged period of bed level recovery (as with the loess bed channels) maintains bank heights greater than the critical height of the material for extended periods. Dispersion and tension cracking continue to weaken the vertical face. Parallel bank retreat along the vertical face, and flattening of the upper bank and slough line, may continue as the channel creates a new flood plain at an elevation lower than the previous one. The previous flood plain would then become a fluvial remnant, or terrace, over geologic time. This scenario of flood plain development is probably appropriate only for the most highly disturbed channels that are cut through deposits of dispersive loess, such as Cane Creek *(5)*. Stage V would then represent the final stage of bank slope development for these types of channels.

Restabilization Stage

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

Cohesive banks along Porters and Cub creeks, and areas of the Obion River system that are composed of strongly nondispersive materials, can maintain a vertical face even though the surface is frequently wet by rises in stage. Woody vegetation extends to the base of the vertical face in these cases, and the old flood plain surface becomes a terrace (Stage VI, Figure 5). In channels the bank materials of which are only moderately dispersive and the bed level of which has sufficiently recovered to cause greater flow frequencies on the vertical face, the uppermost section of the bank may take a convex shape due to fluvial reworking and deposition (Stage VI, Figure 5). In some extensively aggrading downstream reaches, such as along the Obion River main stem, the flood plain surface maintains its role as a conduit for moderately high flows, and woody vegetation becomes reestablished at the top of the bank and on the flood plain surface *(6)*.

The six stages of bank slope development represent a conceptual model of width adjustment. Stages are induced by a succession of interactions between gradation and hillslope processes (Table 3). The model does not imply that each adjusting reach will undergo all six stages during the course of adjustment but that specific trends of bed level response result in a series of mass-wasting processes and definable bank forms. The conceptual framework of the simultaneous retreat of the vertical face, and flattening along surfaces below it, is supported by the observation of other investigators reported by Carson and Kirkby (*11*, p. 184).

CONCLUSIONS

Channel dredging and straightening between 1959 and 1972 in western Tennessee caused a series of morphologic changes along modified and adjacent reaches and tributaries. Simple power equations accurately describe bed degradation and aggradation over time. Degradation occurs for 10 to 15 years at sites upstream of the AMD and can lower bed level by as much as 6.1 m. Aggradation downstream of the AMD can reach 0.12 m/year with the greatest rates near the mouth. Distance upstream or downstream from the AMD is a principal independent variable in determining trends of bed level response. Initially degraded sites experience a secondary aggradation phase in response to excessive incisement and gradient reduction.

Adjustment of channel width is characterized by six stages of bank slope development: premodified, constructed, degradation, threshold, aggradation, and restabilization. Characteristic forms and processes of the six stages can be extrapolated to other river systems to ascertain the relative stability of an alluvial channel. Downcutting and toe removal during the degradation stage cause bank failure by mass-wasting processes when the critical height of the bank material is reached (threshold stage). Top bank widening continues through the aggradation stage as the slough line develops as an initial site of lower bank stability. The development of the bank profile is defined in terms of three dynamic surfaces: (*a*) vertical face (70 to 90 degrees), (*b*) upper bank (25 to 50 degrees), and (*c*) slough line (20 to 25 degrees).

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