Geomorphic and vegetative recovery processes along modified Tennessee streams: an interdisciplinary approach to distributed fluvial systems

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ABSTRACT The sand-bed stream channels of the Obion-Forked Deer River basin periodically have been dredged and straightened since the turn of the century to reduce flood magnitude and frequency. Channel bed, banks, and flood plains are systematically adjusting their form and vegetative patterns over time and space in response to the latest episode of major channel modifications (1959-1973). Headward-progressing degradation heightens and steepens the loess-derived banks and causes channel widening (up to 1-4 m year⁻¹) by mass-wasting processes. With time, aggradation reduces bank heights and continued mass failures reduce bank angles causing low-bank surfaces to stabilize and become revegetated. Riparian species characterize various stages of channel adjustment and are associated with specific geomorphic processes. Through ordination techniques, a predescribed six-stage model of channel evolution is supported by species presence data.

Processus de rétablissement géomorphique et végétatif le long de cours d'eau du Tennessee: une approche interdisciplinaire aux perturbations de systèmes fluviaux

RESUME Depuis le début du siècle, les thalwegs sur lit de sable du bassin Obion-Forked Deer River ont été dragués et redressés périodiquement de façon à réduire la fréquence et l'intensité des crues. Les lits, rives et plaines d'inondation ajustent encore leur forme et leur couvert végétal dans le temps et dans l'espace suite au dernier épisode de modification majeure du thalweg (1959-1973). La progression vers l'amont de la dégradation élève et accentue la pente des berges loessiques et entraîne l'élargissement du thalweg (1-4 m an⁻¹) par l'affouillement des berges. Avec le temps, la sédimentation et l'affouillement réduisent la hauteur et la pente des berges, y entraînant la stabilisation et l'établissement de la végétation. Les espèces ripariennes caractérisent les différentes étapes de l'ajustement du thalweg et sont associées à des processus géomorphiques spécifiques. Un modèle pré-établi à six stades d'évolution du thalweg est
INTRODUCTION

The sand-bed stream channels of the Obion-Forked Deer River basin (11 800 km²) have been periodically dredged and straightened since the turn of the century to reduce out-of-bank flooding and to improve flood plain drainage (Fig.1). Previous investigations by the authors resulted in the development of a quantitative model of bed-level adjustment and six-stage conceptual models of bank-slope development and channel evolution (Simon & Hupp, 1986a; and Simon, in press). The purposes of this study are (1) to determine the relative roles of bed processes, soil properties, and riparian vegetation on streambank stability; and (2) to assess the spatial and temporal trends of vegetation establishment in terms of its potential as a diagnostic tool in evaluating channel stability.

FIG. 1 Location of study streams in West Tennessee.

Dredging and straightening of alluvial stream channels was carried out between 1959 and 1967 in the Obion basin, between 1968 and 1969 in the South Fork Forked Deer basin, and between 1970 and 1973
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in the North Fork Forked Deer basin. These channel modifications caused a series of channel adjustments along modified reaches and tributary streams (Simon, in press). Degradation occurred for 10 to 15 years at sites upstream of the area of maximum disturbance (AMD) and lowered bed levels by as much as 5 meters ('C' in Fig.2). Following degradation, reaches upstream of the AMD experienced a secondary aggradation phase in response to incision and gradient reduction ('D' in Fig.2). Aggradation downstream of the AMD reached 0.12 m year\(^{-1}\) with the greatest rates generally occurring near the stream mouths ('B' in Fig.2).

Channel-bank material of West Tennessee streams is completely alluvial; comprised of loess-derived Quaternary sediments which are predominantly nonplastic, dispersive silts of low cohesion (Simon, in press). These alluvial channels, without bedrock control, are free to systematically adjust in plan and profile.

The adjustment of stream channel geometry and phases of channel evolution are characterized by six process-oriented stages of morphologic development - premodified, constructed, degradation, threshold, aggradation, and restabilization (Simon, in press; and Table 1). Downcutting and toe removal during the degradation stage causes bank failure by mass wasting when the critical height and angle of the bank material is exceeded (threshold stage). Top-bank widening continues through the aggradation stage and the 'slough
<table>
<thead>
<tr>
<th>Stage No.</th>
<th>Name</th>
<th>Stages of channel evolution</th>
<th>Dominant processes</th>
<th>Hillslope Characteristic forms</th>
<th>Geobotanical evidence</th>
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<tr>
<td>I</td>
<td>Premodified</td>
<td>Sediment transport-mild aggradation; basal erosion on outside bends; deposition on inside bends.</td>
<td>--</td>
<td>Stable, alternate bars, convex top-bank shape; flow line high relative to top bank; channel straight or meandering.</td>
<td>Vegetated banks to flow line</td>
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<td>II</td>
<td>Constructed</td>
<td>--</td>
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<td>Trapezoidal cross section; linear bank surfaces; flow line lower relative to top bank.</td>
<td>Removal of vegetation (?)</td>
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<td>III</td>
<td>Degradation</td>
<td>Degradation; basal erosion on banks.</td>
<td>Pop-out failures</td>
<td>Heightening and steepening of banks; alternate bars eroded; flow line lower relative to top bank.</td>
<td>Riparian vegetation high relative to flow line and may lean towards channel.</td>
</tr>
<tr>
<td>IV</td>
<td>Threshold</td>
<td>Degradation; basal erosion on banks.</td>
<td>Slab, rotational and pop-out failures.</td>
<td>Large scallops and bank retreat; vertical-face and upper-bank surfaces; failure blocks on upper bank; some reduction in bank angles; flow line very low relative to top bank.</td>
<td>Tilted and fallen riparian vegetation.</td>
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<tr>
<td>V</td>
<td>Aggradation</td>
<td>Aggradation; development of meandering thalweg; initial deposition of alternate bars; reworking of failed material on lower banks.</td>
<td>Slab, rotational and pop-out failures.</td>
<td>Large scallops and bank retreat; vertical face, upper bank, and slough line; flattening of bank angles; flow line low relative to top bank; development of new flood plain (?)</td>
<td>Tilted and fallen vegetation; re-establishing vegetation on bank; deposition of material above root collars of slough-line vegetation.</td>
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<tr>
<td>VI</td>
<td>Restabilization</td>
<td>Aggradation; further development of meandering thalweg; further deposition of alternate bars; reworking of failed material; some basal erosion on outside bends; deposition on</td>
<td>Low-angle slides; some pop-out failures near flow line.</td>
<td>Stable, alternate channel bars; Convex-short vertical face, on top bank; flattening of bank angles; development of new flood plain (?) ; flow line line high relative to top bank.</td>
<td>Re-establishing vegetation extends up slough-line and upper-bank; deposition of material above root collars of slough line and upper-bank vegetation; some vegetation establishing on bars.</td>
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line' develops as an initial site of lower-bank stability. Alternate channel bars form during the restabilization stage and represent incipient meandering of the channel.

Riparian vegetation is that group of plants that grow on the channel banks below flood-plain level, and are strongly affected by channel responses to modification. Pioneer species may proliferate after channel work on banks as long as growth is not precluded by active mass wasting (Hupp & Simon, 1986). Once bank failure begins, largely in the form of rotational, pop-out and slab failures, riparian vegetation is tilted, scarred, or killed through slope instability. Rates of bank retreat range from 1.0 to 4.0 m year$^{-1}$ along unstable reaches and are characterized by minimal vegetative cover and number of species present.

Active mass wasting slows as bank heights and angles lessen through bed aggradation and bank failures. Bank accretion usually begins when the bed starts to aggrade (stage V) and low bank surfaces are stable enough to again support woody plants (Simon & Hupp, 1986a; Hupp & Simon, 1986). Pioneer plants survive moderate accretion and shallow low-angle slides, common on accreting surfaces. Black willow and river birch appear most tolerant of rapid sedimentation above their root collars. Woody vegetation improves bank stability by checking low-angle slides through root-mass development and slows streamflow velocity by increasing bank roughness (Gray & Leiser, 1982). Woody plants also increase the rate of bank accretion (Hupp & Simon, 1986).

Methods

Changes in channel morphology and the sequence of channel forms were determined from channel surveys and field reconnaissance (1981-1986), construction plans, and specific gage data (Blench, 1973; Robbins & Simon, 1983). Dendrochronologic and dendrogeomorphic analyses of riparian vegetation yielded information about channel widening, bank accretion, and timing of initial bank stability.

Channel widening, as described in this paper, refers to average increases in distance between top banks. Estimates of channel widening are made by determining ages of stem deformation associated with bank failure, then measuring the width of the slump block or the distance between affected stems and the present top-bank edge. Species presence and cover were estimated at each site by tallying the number of species presented and noting the areal canopy coverage over a bank, respectively.

Stems that remain buried for at least a growing season form root tissue instead of stem tissue, with adventitious roots sprouting in what was once stem wood. Exhuming buried stems to the depth of the original germination point, measuring the depth of burial, and determining the age of the stem through cores or cross section provide an estimate of sediment-accretion rate.

Samples of alluvium were analyzed for particle-size distribution, plasticity index, moisture content, density, cohesion, and angle of internal friction. The latter two parameters were determined with the Iowa Borehole Shear Tester, an instrument that allows for in situ testing of shear-strength (Lutenegger & Hallberg, 1981).
Critical-bank conditions for given shear-strength properties, bank heights, and angles were determined by a method reported in Thorne et al. (1981) using nondimensional stability numbers (\(N_s\); Chen, 1975). Critical bank heights can be obtained graphically for any slope angle after solving a dimensionless stability equation (Chen, 1975; Thorne et al., 1981).

System-wide data on channel widening, bank accretion, and vegetal cover combined with species-presence data were analyzed with multivariate statistical methods including binary discriminant, BDA (Strahler, 1978; Hupp, in press), and detrended correspondence analyses, DCA (Hill & Gauch, 1980). Standardized residuals (D-values) from the BDA were computed in terms of standard deviations (from contingency tables) that indicate species "preference" (positive values) or "avoidance" (negative values) for particular site parameters. DCA is an ordination technique that clusters similar sites (based on morphologic characteristics) according to species presence-absence data. Ordination thus allows for the interpretation of relations among geomorphic characteristics and riparian vegetation.

RESULTS AND DISCUSSIONS

In situ shear-strength tests show the bank materials are highly erodible silts of low cohesion, generally less than 14 kPa. Ambient, total shear-strength along failure surfaces of unit-width range from 16-158 kPa along the forks of the Forked Deer River, and from 17-270 kPa along the Obion River system. Mean effective unit-strengths are greater in the Obion (79.3 kPa; 49 tests) than the Forked Deer system (53.3 kPa; 26 tests).

![Figure 3](image-url)  
**FIG. 3** Example of slope-stability giving critical bank-heights for various bank angles, North Fork Obion River.
Although shear-strength values of this magnitude may appear sufficient to resist mass movement, the angle of internal friction and therefore the frictional component of shear strength becomes minimal at saturation (Lutton, 1974), leaving only the cohesion component to resist failure. Cohesive forces, on the average, make up only 8% of the total strength of the channel banks and generate limited resistance to mass failures under saturated conditions. Furthermore, the mean degree of saturation for studied channel banks is 91% even though most samples were taken during periods of low flow and well above the elevation of the free-water surface. Moderate rises in river stage are sufficient to complete saturation of the silty banks, and result in mass failures upon recession of river stage. An example bank-stability graph is shown in Fig.3.

Degraded reaches of the Obion-Forked Deer River system have mean bank-angles generally ranging from 55 to 65 degrees. However, toe removal often creates almost vertical banks. Given the low cohesive strengths and the ambient high-moisture contents of the channel banks, critical bank heights at saturation rarely exceed 5 m and are generally about 3 m. Degraded reaches of the studied streams, with bank heights commonly in excess of 8 m, therefore fail readily.

According to pre-described models of bank-slope development and channel evolution (Simon & Hupp, 1986a; Simon, in press) bank instabilities and channel widening occur following sufficient degradation (stages III and IV; Table 1), and continue through the aggregation stage (stage V; Table 1). These stages are not static over time or space. Channel widening, like bed degradation, migrates upstream of the AMD over time, yet lags behind degradation because it requires a sufficient increase in bank height to instigate bank failures.

Overlain plots of bank widening, bank accretion, and number of riparian species versus river kilometre are used to identify trends of channel response. Along the forks of the Obion and Forked Deer River basins, peak rates of channel widening coincide with minima of species numbers (Fig.4). In the Obion River system, this presently (1986) occurs near river kilometre 130 (Fig.4a). This area is 20 km upstream of the imposed AMD of 1967 (Fig.2) and reflects the headward migration of the widening process. Reaches downstream of this area, below the AMD represent stage V conditions and are aggrading (Fig.4a). Riparian trees 6-8 years old are now common here along the Obion River main stem, and reflect the stabilizing low-bank conditions characteristic of stage V.

Distinct trends of channel widening, bank accretion and species presence occur on the North and South Forks Forked Deer River (Fig.4b). High widening rates preclude high numbers of species present while high accretion rates do not limit species presence. Species presence and accretion rates increase in reaches above river kilometre 45 where degradation and widening have been negligible (Fig.4b). These stage I reaches coincide with sites located near "E" in Fig.2 and represent upstream reaches that remain unaffected by downstream channel modifications and aggrade at low rates due to natural fluvial processes and land-use practices (Fig.2 and Table 1). Similar trends of widening, accretion, and species presence occur in the upstream-most reaches of the Obion River system as well (Fig.4b).
Channel widening has migrated upstream at rates approximating 1 km year\(^{-1}\). The more rapid migration rates of bed degradation (2.6 km year\(^{-1}\) on the South Fork Forked Deer, Simon & Robbins, 1987; and 1.6 km year\(^{-1}\) on the Obion River Forks, Simon, in press) support the aforementioned time lag between bed degradation and channel widening.

Ages of riparian trees give minimum ages for the surface on which they germinate. The oldest riparian plants usually occur in the

FIG. 4 Trends of channel widening, accretion, and number of riparian species for (A) Obion River system, and (B) Forked Deer River system.
upstream-most (stage I) reaches, where bank clearing has not been recent. Riparian tree ages range from 25 to 45 years, perhaps reflecting channel work in the 1940's. Along lower reaches, pioneer woody plants range in age from 5 to 9 years, reflecting the onset of low-bank stability. Plant ages decrease upstream of the AMD to 1-2 years just downstream from the area of present greatest widening, where no woody plants grow.

Pioneer tree ages indicate the time required for reaches to proceed from stage III to stage V were 14 years on the forks of the Obion, 11 years on the South Fork Forked Deer and 7 years for the North Fork Forked Deer (Fig. 4a). These periods to initial bank-stability as determined from species ages are in complete agreement with the 10-15 year range specified by Simon & Hupp (1986) using geomorphic techniques. Reaches of the North Fork Forked Deer were among the fastest to reach stage V, probably due to the input of large quantities of bed-material from the Middle Fork Forked Deer River at river kilometre 25. This sediment input suppressed bed degradation, widening, and ultimately, the period required to regain low-bank stability.

Patterns of riparian species distribution is strongly associated with the geomorphic stage of adjustment (Table 1). The most common pioneer species in both river systems are black willow, river birch, silver maple, sycamore, green ash, and box elder. The older vegetation of the upper reaches (typically stages I and VI) is considerably more diverse and includes many species normally associated with flood plains such as bald cypress and various species of oak, in addition to the pioneer species.

Stages I and VI cannot be clearly separated on a botanical basis and have usually had 40 or more years to recover from the last cycle of channel work. Top banks are low relative to mean water levels and riparian surfaces support a relatively diverse species assemblage (13 species). Banks of stages I and VI tend to be gentle and aggradational as opposed to the higher and steeper banks of stage III and IV.

Stage III is the most vegetatively diverse (21 species) including many riparian species normally associated with natural bank conditions such as ironwood, sweetgum, overcup oak, willow oak, bald cypress, basswood, and various elm species. Banks along stage III reaches usually have been stable for many years because degradation has not yet been sufficient to cause widening (Table 1).

Stage IV reaches are characterized by highly unstable banks; nearly 50% of all stage IV sites have no woody species (Table 1), although a tangle of herbaceous species including knotweeds, brambles, and giant ragweed may be common on slump block surfaces of the upper bank. Only five woody species, all pioneers, occur on stage IV reaches and then only in protected areas such as on relict inside-bends where the thalweg is diverted. Stage V reaches are characterized by distinct zones of proliferating pioneer woody species (nine species), on low- to mid-bank surfaces, indicating the initiation of low-bank stability.

D-values for six selected species, silver maple, river birch, and black willow representing pioneer species and willow oak, bald cypress, and ironwood representing species of stable sites are shown in Fig. 5. Note that all species have positive associations for low
widening rates and a negative association with high widening rates, suggesting a pervasive influence of widening characteristics in patterns of species distribution. The pioneer species (Fig.5a) have positive values for medium widening rates and medium cover as would be expected in species that initially occupy disturbed areas. Conversely, the natural site species (Fig.5b) cannot tolerate even medium widening rates and as components of the mature forest are positively associated with only high cover values. Black willow, perhaps the most pioneering of all species, is strongly associated with bank accretion; a testament to this species ability to survive the rapidly aggrading low-bank areas. The distinct site preference or avoidance pattern of selected species suggests that they are indicators of specific bank conditions, which allows simple vege-
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Vegetative reconnaissance of an area to be used for at least preliminary estimation of site conditions.

The results of the multivariate DCA of species presence versus site conditions are shown in Fig. 6, where the site-parameter categories are ordinated by significant principal-components, DCA axes I and II. This ordination, based entirely on species presence, accurately reflects the hydrogeomorphic characteristics outlined in the six-stage model of channel adjustment (Table 1). Note that site conditions naturally cluster in groups that can be identified with specific stages of the model (Fig. 6). Thus, the independent vegetation ordination fully supports the conceptual framework of the bank-slope model; and strongly suggests that patterns of species distribution may be used to infer ambient bank-stability.

FIG. 6 DCA ordination of site parameters based on species presence data alone (V = very low, L = low, M = medium, H = high, W = widening, A = accretion, C = cover).

REFERENCES

Hupp, C.R. (in press) Determination of bank widening and accretion rates and vegetation recovery along modified West Tennessee


