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RIPARIAN VEGETATION RECOVERY PATTERNS FOLLOWING STREAM CHANNELIZATION: A GEOMORPHIC PERSPECTIVE[1]

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Abstract. Hundreds of kilometres of West Tennessee streams have been channelized since the turn of the century. After a stream is straightened, dredged, or cleared, basin-wide ecologic, hydrologic, and geomorphic processes bring about an integrated, characteristic recovery sequence. The rapid pace of channel responses to channelization provides an opportunity to document and interpret vegetation recovery patterns relative to otherwise long-term, concomitant evolution of river geomorphology. Nearly 150 sites along 15 streams were studied in the Obion, Forked Deer, Hatchie, and Wolf River basins. Channels of these streams, except that of the Hatchie River main stem, have undergone major modifications along all or parts of their courses. This paper presents the eco-geomorphic analyses and interpretation of a large multidisciplinary study, with special reference to the interrelated hydrogeomorphic aspects of channel recovery. Quantitative plant ecological analyses were conducted to infer relative bank stability, to identify indicator recovery species, and to determine patterns of vegetation development through the course of accelerated channel evolution. Binary-discriminant and ordination analyses show that distinctive riparian-species patterns reflect a six-stage model of channel evolution and can be used to infer channel stability and hydrogeomorphic conditions. Woody vegetation initially establishes on low- and mid-bank surfaces at the same location and time that bank accretion begins, and corresponds to the site of initial geomorphic restabilization. The linkage of channel bed aggradation, woody vegetation establishment, and bank accretion all lead to recovery of the channel. Pioneer species are hardy and fast growing, and can tolerate moderate amounts of slope instability and sediment deposition; these species include river birch (*Betula nigra*), black willow (*Salix nigra*), boxelder (*Acer negundo*), and silver maple (*Acer saccharinum*). High stem densities and root-mass development appear to enhance bank stability. Tree-ring analyses suggest that on average 65 yr may be required for recovery after channelization.

Key words: bank accretion; bank stability; channel-evolution model; channelized streams; channel widening; dispersal; ecesis; geomorphic recovery; plant ecology; riparian vegetation; stream disturbance; stream models; succession; Tennessee; tree-ring analysis; vegetation patterns.

INTRODUCTION

Channelization is a common, although controversial, engineering practice aimed at controlling flooding and draining wetlands. Stream channelization in alluvial areas affects nearly all hydrogeomorphic characteristics and processes along and upstream of the channelized reach. The biotic environment is likewise severely affected, particularly in riparian areas but also on the adjacent flood plains. The geomorphic and plant ecological forms and processes described in this paper reflect the course of landscape development that would follow natural rejuvenation, such as tectonic uplift or base-level lowering. Geomorphic responses to channelization are rapid relative to most natural adjustments to rejuvenation. Here, we have the opportunity to study such processes because of the reduced time frames created by human channelization efforts.

Modifications during 1959–1978 throughout much of West Tennessee (Fig. 1) have created a natural laboratory for the study of environmental responses in rejuvenated fluvial networks. Streamside vegetation is directly removed during channelization or shortly afterward through channel responses to channelization. Preliminary results on the geomorphic and vegetation recovery in West Tennessee were reported by Hupp and Simon (1986) and Simon and Hupp (1987); these results described the use of dendrochronologic techniques to infer rates of channel widening and bank accretion. The purposes of the present paper are to describe and interpret woody-vegetation recovery patterns in relation to concomitant evolution of river geomorphology.

Vegetation analyses have been used to identify and interpret geomorphic features for many years (Cowles 1901, Gleason 1926, Hack and Goodlett 1960, Wharton et al. 1982). However, the use of vegetation analyses in the interpretation of fluvial geomorphic disturbance dynamics has been a relatively recent activity

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TABLE 1. Summary of geomorphic and ecologic attributes by stage of stream channel evolution following channelization. Cover values are for woody species only. Adapted from Simon and Hupp (1987).

Stage	Name and geomorphic attributes	Ecologic attributes and species presence	Stage duration
I	Premodified stage Aggrading bed and banks: meandering channel: low, convex upward banks, minimal mass wasting	Mature, diverse riparian community: 100% cover: Species: cypress, maple, hydric oaks, ash, birch	Stable
II	Constructed stage High gradient: straight channel: linear banks	All woody vegetation typically removed: 0% cover	Short-lived, usually <1 yr
III	Degradation stage Active bed degradation: minimal mass wasting; linear banks	Typically, woody vegetation unaffected by channel work, may be high and dry. Species as in Stage I. 100% cover.	Short-lived, 1–3 yr
IV	Threshold stage Active bed degradation: active mass wasting; concave upward banks: severe instability	Most woody species removed by bank-slope failure: Species: sumac, winged elm, herbaceous weeds: 0–5% cover	5–15 yr
V	Aggradation stage Aggrading channel bed: mild mass wasting; heavy bank accretion anastomosing thalweg; diverse bank forms	Initial active revegetation, at same site as initial bank accretion: Species: willow, birch, maple, boxelder: 10–50% cover	About 50 yr
VI	Recovery stage Meandering channel: low banks and gradient: convex upward banks: general mild aggradation: point-bar development	Diverse bank vegetation, growing down and into low water: Species: same as in Stage V plus cypress, hydric oaks, ash, elm: 90–100% cover	Stable

(Fig. 2) may proceed great distances upstream from the channel work.

Geomorphic rejuvenation refers to a drastic topographic uplift with respect to the base level of the water table. Channelization essentially accomplishes rejuvenation through a large increase in channel gradient. In stage III (Fig. 2), rejuvenation takes place almost immediately after channel work and induces a rapid degradation of the channel throughout much of the channelized reaches as well as reaches upstream where mature bank vegetation may remain. Vegetation is largely removed during the degradation response either directly by channel construction or through subsequent bank failure (stage IV), both along recently channelized reaches and above the channelization limit (Fig. 2). Aggradation may begin almost immediately in the farthest downstream reaches because of low gradients near base level and excess sediment loads entrained from rapidly degrading reaches. During subsequent aggradation, vegetation plays an important role in bank stabilization. This rapid ecogeomorphic response allows for intensive study of otherwise long-term geomorphic and ecologic processes.

Study area

The study area included most of West Tennessee, an area of ≈27 450 km^2, bounded by the Tennessee River on the east and by the Mississippi River on the west (Fig. 1). This area is entirely within the Mississippi embayment of the Gulf coastal plain physiographic province (Fenneman 1938).

The studied streams are in the Obion, Forked Deer, Hatchie, and Wolf River basins (Fig. 1). The unchannelized Hatchie River served as a control for the study. These streams flow on unconsolidated, erodible material, predominantly of Quaternary age (USDA 1980, Miller et al. 1966). The rivers flow on Mississippi River alluvium in their downstream reaches and on loess-derived alluvium farther upstream and in their forks (Table 2). Most tributaries flow on loess deposits that thin eastward from 30 m deep along the Mississippi bluffs to about 1 m near the outcrop of the Claiborne and Wilcox Formations of Tertiary age (Miller et al. 1966), at the eastern boundary of the study area (Fig. 1). The Claiborne and Wilcox Formations (Table 2), composed primarily of sand-size clasts, are the source of sand for the major drainages of the region, as well as for the eastern tributaries (Fig. 1). There is no bedrock control along any of the study streams.

The native vegetation in many West Tennessee bottomlands has been affected along channelized reaches directly or indirectly through lowered water tables and reduced hydroperiods (Miller 1985, Hupp and Simon 1986, Hupp 1987). The woody vegetation along modified channels or channels affected by downstream modification ranges from nearly absent to relatively natural, mature bottomland forests, composed of bottomland hardwoods and/or bald cypress (*Taxodium distichum*) and tupelo gum (*Nyssa aquatica*). Typically, previously degraded, now relatively stable, reaches support dense stands of black willow (*Salix nigra*), river birch (*Betula nigra*), or silver maple (*Acer saccharinum*). Other common constituents of these second-growth forests include boxelder (*Acer negundo*), green ash (*Fraxinus pennsylvanica*), and eastern cot-

TABLE 2. Geomorphology and engineering modification history of some West Tennessee streams. The extent of modification is given as distance above mouth.

Stream	Drainage area (km²)	Geologic unit*	Most recent modification†	Extent (km)	Dates
Obion River	61 966	L, HA	E, St C, Sn PE	75.0 6.8 ···	1959–1966 1976 1974–1988
North Fork of Obion River	2489	L, HA	E, St C, Sn	17.5 17.4	1967 1974–1976
Rutherford Fork of Obion River	1150	L, HA	E C, Sn	11.9 28.8	1967 1973–1978
South Fork of Obion River	1606	L, HA	E C, Sn	9.7 27.5	1967–1969 1976–1978
North Fork of Forked Deer R.	3950	L, HA	E, St	6.9	1973
Pond Creek	290	L	C, Sn	21.1	1976–1978
South Fork of Forked Deer R.	4416	L, C and W	E, St	7.1	1969
Cub Creek	69	MG	E, St	15.6	1970
Porters Creek	264	MG	E, St	34.4	1972
Wolf River	3388	L, C and W	E, St	35.1	1964

* Geologic abbreviations: L = loess, HA = Holocene alluvium, C and W = Claiborne and Wilcox Formations, MG = Midway Group.

† Modification abbreviations: E = enlarging, St = straightening, Sn = snagging, PE = periodic enlarging, C = clearing.

modifications occurred from 1959 through the 1970s. A sufficient number of sites were selected along a given stream to delineate channel adjustment trends; study sites, by basin, were located on the Obion River main stem, the North, South, and Rutherford Forks of the Obion River, Davidson Creek, the North and South Forks of the Forked Deer River, Pond Creek, the Hatchie River, Porters, Cub, and Cane Creeks, and the Wolf River (Fig. 1). Each site was categorized as to stage of channel evolution (Simon and Hupp 1986); most of the stages of the channel-evolution model are represented by many sampling sites. All study sites were located near bridges because of access limitations. Particular caution was used to avoid channel reaches that reflected strong hydraulic influences from the bridge. Sampling areas were at least 50 m upstream from the bridge and at least 100 m downstream from the bridge. Generally, a study site included a reach 1 to 2 km in length. Rod and level surveys of channel sections were developed for each site. Field work was conducted during 1984–1987.

METHODS

Dendrogeomorphic analyses

Field routine at each site included traversing bank slopes and noting the general condition of the bank (stability), presence of bank failures and toppled woody plants, presence of woody seedlings/saplings, and determination of bank-widening rates and bank accretion rates. Additional observations on bank form, bank heights, bank-slope angles, and hydrologic conditions were made to accompany the dendrogeomorphic analysis. Bank conditions along straight reaches were usually the same on both the left and right banks. However, along bends where incipient meanders had formed, there were distinct differences between banks on the inside and outside of the bend. Where differences were obvious, both banks were studied. The terms left and right banks always refer to a particular bank when looking downstream. More complete descriptions and interpretation of the physical and engineering attributes of the overall study may be found in Simon and Hupp (1992).

Dendrogeomorphic techniques were used to determine rates of channel widening and bank accretion. This methodology, as used in West Tennessee, has been described elsewhere (Hupp and Simon 1986, Hupp 1987). Channel widening refers to average increases in distance between top banks, typically accomplished by mass wasting (slump-block bank failure). Estimates of channel widening were made by tree-ring analysis of stem deformations associated with bank failure, and subsequent measurement of the width of the slump block or distance between affected stems and the present top-bank edge (Hupp 1987). Bank-accretion rate was determined by exhuming buried stems to the original germination point (major lateral roots), measuring the depth of burial, and determining the age of the stem from increment cores (Hupp 1987). Trees growing on various bank locations at each site were cored to determine the timing of stabilizing bank conditions relative to the site along the stream and to the location of geomorphic features of the bank. At least 10 trees

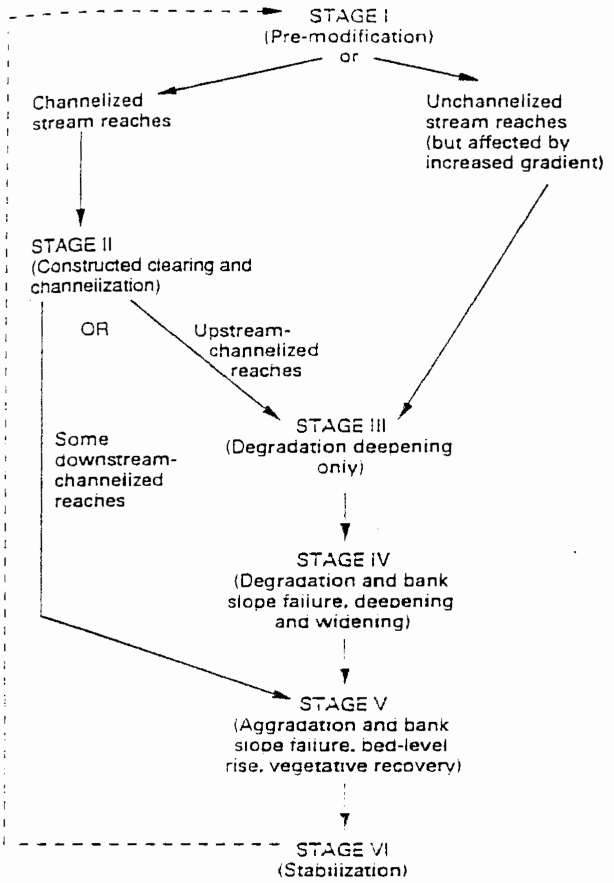

FIG. 3. Flow diagram of the six stages of channel evolution (see Fig. 2) following channelization. Only channelized reaches experience stage II; they then may either proceed to stage III or to stage V if aggradation rates are high, which may occur along downstream reaches away from the upstream limit of recent channelization.

stage IV), and the recovery stages (Fig. 3: stages V and VI). Many downstream channelized reaches, however, may proceed directly from stage II to stage V (Fig. 3) because of the almost immediate aggradation that results from heavy sediment loads derived from eroding upstream reaches.

Quantitative trends in plant ecological data (Fig. 4A), arranged by stage of channel recovery for 72 sites (Table 3), show that vegetative cover, tree age, and species numbers are generally low during stages characterized by high channel-widening rates (Fig. 4B: stages IV and V). Note the distinction between channelized and unchannelized reaches during stages II through IV (Figs. 3 and 4A). High widening rates are indicative of overall channel instability and, in general, preclude substantial vegetation establishment and high bank accretion (Fig. 4B: stage IV). However, from stage IV to stage V, as accretion increases and widening decreases, a site may have moderately high rates of both (Fig. 4B). Through the course of stage V, both widening and ultimately accretion decrease toward rates typical of pre-modified conditions; median cover, number of species, and tree ages increase from stage V to stage VI. Rate of bank widening is perhaps the most influential factor determining the type and abundance of riparian species.

The largest values of hardwood species cover (90–100%) and numbers (5–8 species), were attained during stages I, III, and VI, when widening rates are minimal. Stages III and VI reflect the longest periods of time since the last episode of major bank instability and, therefore, have vegetative characteristics most closely corresponding to natural banks (stage I). Reaches in stage I and III support the oldest trees (median age 33 and 41 yr, respectively; Fig. 4A). The tree ages for stages I and III may be more reflective of past land use than they are of recovery time. The oldest riparian trees ranged from 25 to 65 yr. Median tree ages along stage VI reaches are low (14 yr) relative to those in stages I and III (Fig. 4A). The median age of trees along stages IV, V, and VI reaches is a function of the recovery period as well as the timing of sampling relative to past channel work; all tree-age sampling was conducted during a 2-yr period.

Because of active mass wasting, stage IV reaches support trees whose median age is only 2 yr (Fig. 4A),

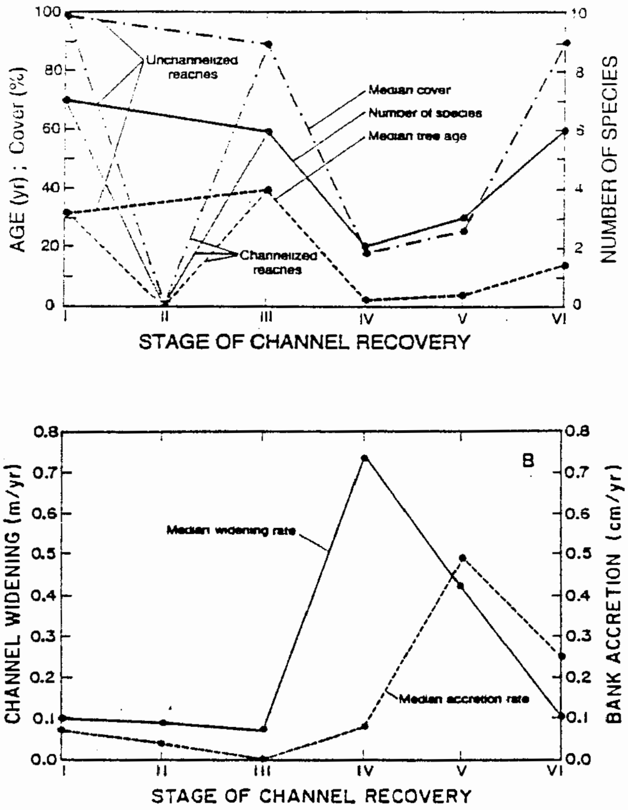

FIG. 4. Tree age, percentage of vegetation cover, and number of species (A), and widening rate and accretion rate (B), by stage of channel evolution. All values are medians except number of species, which has been multiplied by 10 to plot at same scale.

TABLE 3. Continued.

River	River kilometre	Percentage cover	Number of species	Maximum tree age	Median rate of accretion (cm/yr)
South Fork of Obion	18.3	19	3	2	1.0
South Fork of Obion	9.3	49	6	5	1.7
Wolf	112.5	95	7	35	0.5
Wolf	92.5	53	10	40	0.5
Wolf	71.4	50	6	17	3.0
Wolf	50.2	50	7	17	5.0
Wolf	38.0	33	4	6	4.0
Wolf	30.4	50	8	11	10.0
Wolf	14.6	48	7	8	1.0

and these grow only in protected areas. Successful woody vegetation establishment and initial bank recovery do not occur until stage V, during which time bed aggradation, bank accretion, and bank-slope reduction occur. The shift from degradation processes to aggradation processes is shown by the sharp increase in median accretion rates during stage V to 4.8 cm/yr (Fig. 4B). Channel process shifts, such as from degradation to aggradation or the initiation of severe bank instability through mass wasting, are examples of geomorphic thresholds (Schumm 1973) that punctuate the geomorphic evolution of channelized streams. These thresholds are important to the understanding of fluvial processes, and may be ultimately responsible for the shifting vegetation patterns observed through the course of channel recovery.

Median tree age in stage V (3 yr, Fig. 4A) is low because of the large numbers of 1- and 2-yr-old plants; active recruitment is characteristic of early stage V. Maximum ages of pioneer trees along stage V reaches are 14 yr on the forks of the Obion River, 11 yr on the South Fork Forked Deer and Wolf Rivers, and 7 yr on the North Fork Forked Deer River (Table 3). These time periods for the streams do not represent complete restabilization of the channel banks but only the time to low- and mid-bank stability. The relatively low value for the North Fork Forked Deer River possibly resulted from the input of large quantities of bed sediment from the Middle Fork Forked Deer River just above their confluence (Fig. 1). This suppressed the tendency for channel deepening and widening, and reduced the time to achieve low-bank stability. Conversely, low aggradation rates on the lowermost (stage V) reaches of Cane Creek, a tributary of the Hatchie River, resulted in initial recovery periods (early stage V) of >17 yr.

The particle sizes of channel-bed material may affect the time required for recovery. Excluding the North Fork Forked Deer River, sand-bed channels undergo ≈10–15 yr of widening processes (stage IV) before low- and mid-bank stability (stage V). The minimum time necessary for the sand-bed channels to reach stage VI is about 40 yr (determined from tree-age maxima along reaches that have only recently regained general bank stability). Thus, ≈65 yr (15 yr in stage IV and 40 yr in stage V) is necessary for recovery of sand-bed streams after initial, large-scale mass wasting of the banks. In contrast, degraded loess-bed channels may take considerably longer to recover because of the lack of coarse-grained material that facilitates bed aggradation. Cane Creek is a loess-bed stream that was channelized in 1970. As of 1990, Cane Creek was still experiencing massive bank failure; the stream has deepened and widened to ≈400% of its original cross-sectional dimensions.

The Obion River mainstem receives large volumes of both suspended sediments and bedload sediments from its forks. Since 1967, 6.3 × 10^6 m^3 of channel material have been delivered to the main stem (Simon, *in press*), causing high rates of bank accretion and aggradation, and necessitating repeated redredging. Rates of bank accretion are among the highest along the banks of the Obion River (Table 3); tree ages indicate that aggradation has occurred throughout the past 20 yr. A few plant species can tolerate relatively high accretion rates, including black willow, cottonwood, and boxelder. However, all species become severely limited along many reaches of the Obion River main stem. Apparently, the accretion rate is so rapid that most plants cannot elongate their stems and produce new roots fast enough to avoid burial and suffocation. Thus, cover values and tree ages along the main stem Obion River are less than along other stage V reaches.

VEGETATION PATTERNS

Thirty-eight species of woody, arboreal plants were identified along the study streams (Table 4). The most common species on disturbed West Tennessee streams is river birch, occurring in 63% of the study sites (Table 4). Also important are black willow, silver maple, sycamore, boxelder, cottonwood, and green ash (Table 4). Except for black willow and cottonwood, all of the above species and river birch are also common along unmodified reaches. This suggests—as might be expected—that many channel bank species are inherently adapted for fluvial disturbance. This vegetative assem-

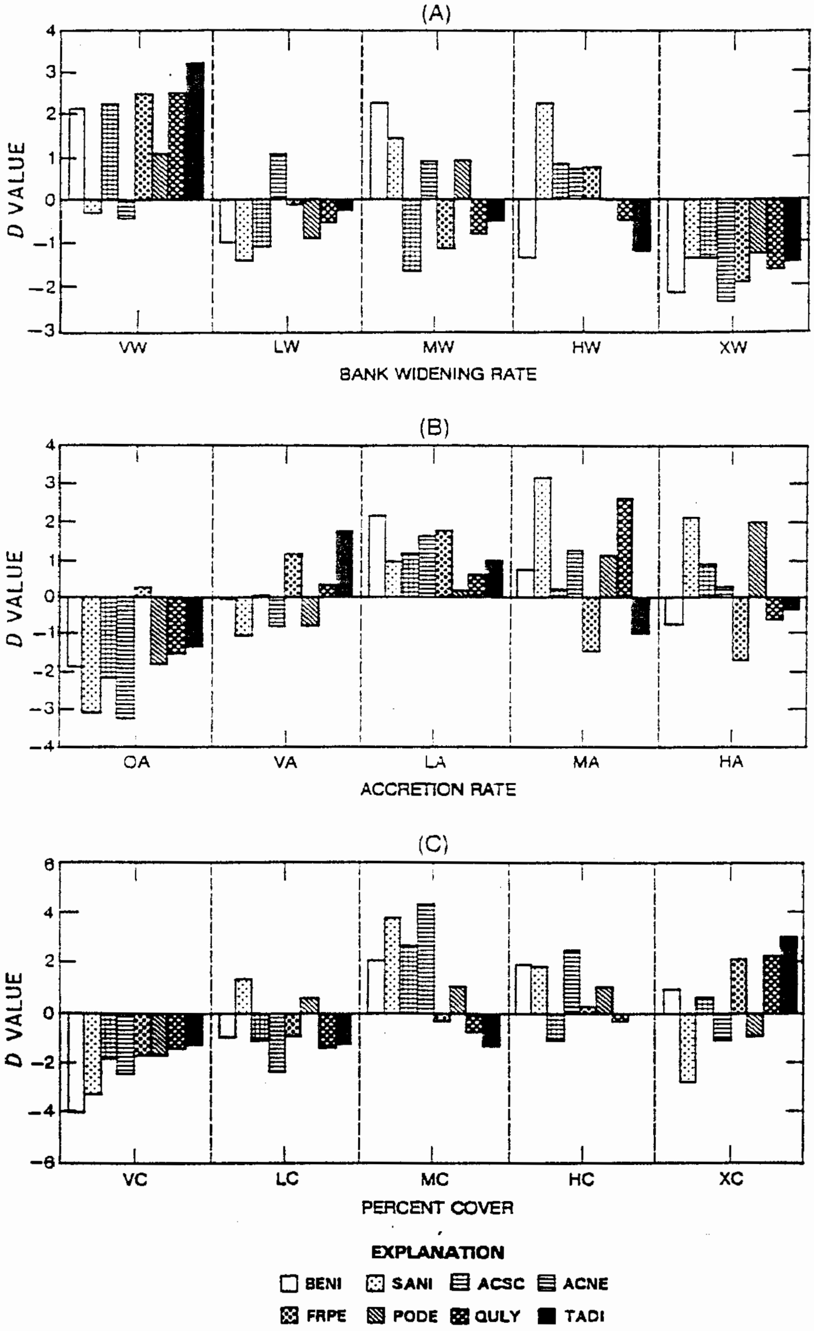

FIG. 5. *D* values (standardized residuals from contingency tables) of eight selected species for bank-widening rate (A), accretion rate (B), and percentage cover (C). Species and category abbreviations are explained in Tables 4 and 5, respectively.

Patterns of *D* values for eight selected species are illustrated in Fig. 5. D values of <1 are not considered to be reliable indications of species preference or avoidance (Strahler 1978); those >2 are considered distinct indications of preference or avoidance.

All species had rather substantial avoidance patterns for very high widening rates, whereas most showed distinct preference for very low widening rates. Distinct tolerances for medium or high widening rates were observed in black willow and river birch and, to a lesser degree, silver maple, boxelder, green ash, and cottonwood (Fig. 5A). Black willow and river birch are the most important initial colonizers after channelization, when widening rates are greatest. The lack of positive values in the low widening category may be an artifact of site selection and parameter categorization.

Species patterns relative to accretion rate show a clear trend from mostly negative values at zero accreturbed channels. They are fast growing and produce abundant seeds that are short-lived (a few days to a week) and dispersed by wind, water, or both, mostly during mid-to-late spring (Fowells 1965, Harlow and Harrar 1969). The timing of seed release coincides with the typical fall of water elevations in late spring. Thus, seeds from pioneer trees may deposit on fresh bank substrates created by mass wasting, bank accretion, fluvial reworking, or late-spring exposure. Dense layers of fine debris and seeds from pioneer species often are deposited, as waters recede in late spring, on the lower banks of the study streams. Here pioneer establishment is probable when the bank is relatively stable. Asexual reproduction by sprouting or rooting from broken branches is common in most of these species.

Because the establishment of the first suite of species is dependent on the rate of exposure of new substrates and the production, transport, and deposition of propagules, it can also be highly variable in time and space. Invasion of one species over others may be favored if, for example, conditions for optimal germination coincide with the seed release of that species. These unique events may account for much variation between sites in stages IV and V.

The second suite of species (Fig. 6B) does not normally function as invaders of degraded or newly aggraded substrates, yet these species are tolerant of bottomland conditions and have seed that is long-lived (up to 2 yr) and dispersed by wind or water (Fowells, 1965). Therefore these species are the best equipped to invade the bottomlands stabilized by the pioneer species of the first suite, and, accordingly, they occur in abundance only before channelization, or in the later stages of recovery (stages V and VI). Included here are ironwood, green ash, sweetgum, American elm, bald cypress, and tupelo, which are characteristic of southeastern bottomlands and represent the riparian plant community of relatively mature natural sites.

The third suite of species is composed of less invasive, shade-tolerant, longer-lived plants that have mostly short-lived, animal-dispersed seeds, and have little tolerance of either degradation or rapid aggradation. These species therefore characterize the final, stable s[illegible] as well as the pre-disturbance conditions [illegible] are the bottomland oaks: overcup [illegible] cherry bark oak, and willow oak (Fig. 6C). Most bottomland oaks tend to occur on natural and constructed levees, or slightly elevated parts of the bottomland; an exception is overcup oak, which may grow [illegible] outside of the very wet cypress–tupelo sloughs. Gradually increasing species richness is evident from stage IV to stage I/III (Fig. 6), inasmuch as only a few species tolerate the harsh conditions of late stage IV. As the banks stabilize, additional species may occupy a site. Thus, species richness generally increases with site stability.

Sites typically occupied by the hydric oaks (Fig. 6C) are generally high in elevation relative to the water table, such as swale ridges and levees. Natural levees may not form in the time it takes to reach stage VI; however, channel bed elevations rarely return to the pre-channelization elevation before stage VI processes and form are evident. Thus, top banks in stages V and VI, even though the original levee has been eroded by prior degradation processes (Fig. 2), are relatively dry sites and may support the hydric oaks. The patterns illustrated in Fig. 6 may be analogous to the bottomland vegetation zones described by Wharton et al. (1982), although it should be noted that most West Tennessee bottoms have been severely affected by agriculture, levee construction, channelization, and lumbering.

Ordination

Ordination allows for the classification of complex, multivariate data sets, in this case frequency data converted to standardized residuals. Ordination treats the presence data separately from the environmental data, leaving the environmental interpretation to a subsequent independent step. Results of the detrended correspondence analysis (DCA) ordination are shown in Figs. 7 and 8; individual species are plotted in Fig. 7 and site-characteristic categories are plotted in Fig. 8. Delineation of clusters in Figs. 7 and 8 is based on interpretation of *D* values and species loadings in the DCA.

The array of species in the DCA plots can be correlated with stages of channel evolution (Fig. 7). A distinct group in the upper right corner (Fig. 7) is composed of upland, largely disturbance-associated plants and is indicative of early to middle stage IV, when mass wasting is most active. Species of the central group are important in bank recovery. The dashed line (based on *D* values) separates the pioneer or late stage IV species from species associated with the more stable bank conditions in stages V and VI. This separation is somewhat arbitrary, as the geomorphic and vegetative processes on the banks operate without distinct thresholds from late stage IV to stage VI. Thus, a fluvial stability gradient is revealed in the central cluster (Fig. 7) from the upper-left (the most unstable) to the lower-right corner (the most stable). Topo- and hydrographic heterogeneity also increase along this same stability gradient, which increase species richness through habitat diversification.

The environmental gradients are perhaps best revealed in the site-characteristic ordination (Fig. 8). A general channel-stage pattern is shown in this ordination. Very high, high, and medium widening rates (Table 5) all plot in the unstable or pioneer areas of Fig. 8. High and medium accretion (Table 5) fall into the pioneer area, while the normal accretion falls, as expected, in the stable area. Cover values (Table 5) are accurately associated with anticipated site conditions; very low and low cover fall in the stage IV area where active mass wasting prevents substantial woody veg-

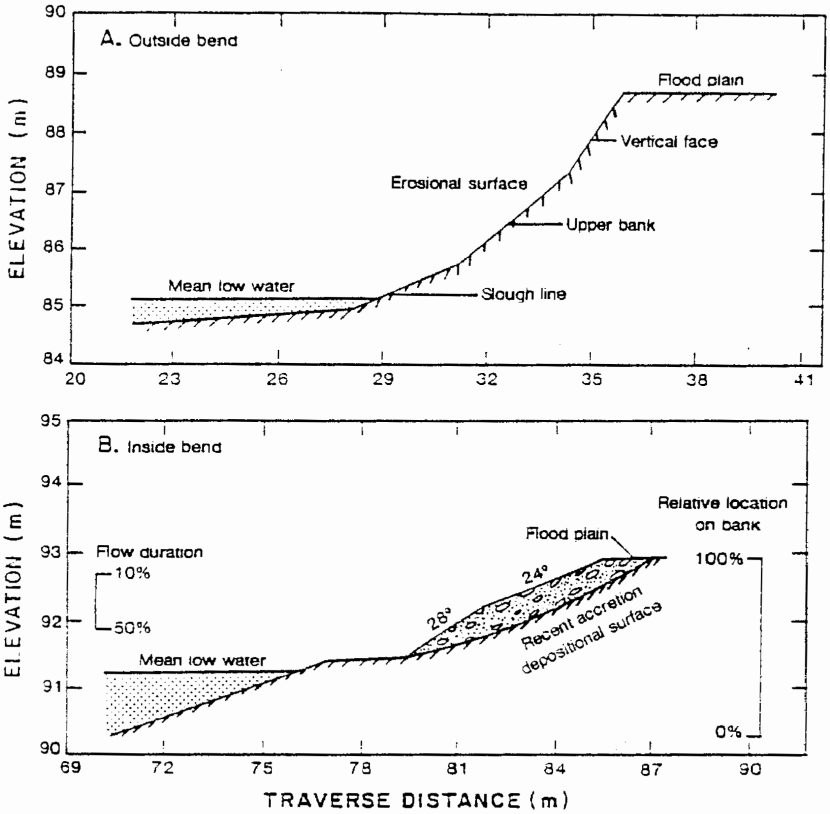

FIG. 9. Typical outside and inside banks at two sites on the South Fork of Forked Deer River. The typical bank features of a degraded channel are shown in A. Flow durations, relative locations, and locations of the depositional area are shown in B. Adapted from Hupp and Simon (1991).

nation accurately reflects hydrogeomorphic characteristics outlined in the channel-evolution model. Thus, the independent ordination of species-presence data fully supports the conceptual framework of the model and strongly suggests that species-presence data can be used to infer levels of bank stability.

VEGETATION AND ACCRETION RELATIONS

Revegetation of these highly disturbed channels, for the most part, begins in early stage V of the channel-evolution model. For this reason, detailed vegetation and accretion analyses were conducted at these sites. Typical outside and inside bends are depicted in Fig. 9. A depositional surface (Fig. 9B), determined dendrogeomorphically, typically ranges from the floodplain surface (100% of total bank height; the channel bed is the 0% location) to about the 50% location on the bank (Hupp and Simon 1991). Vegetation initially establishes on the depositional surface at about the same time the surface begins to form and, in following discussions, it is implied that the depositional surface supports newly established pioneer plants. During stages II and III of the channel-evolution model, and along outside bends, the depositional surface is largely absent (Fig. 9). The late phase of stage IV, in protected locations, shows the beginning of the depositional surface and vegetation establishment (Fig. 10). During stage V the depositional surface expands upslope from ≈70% of the total bank height to ≈85% (Fig. 10). Thus accretion begins low on the bank slope, with later upward expansion, which coincides with spreading vegetation

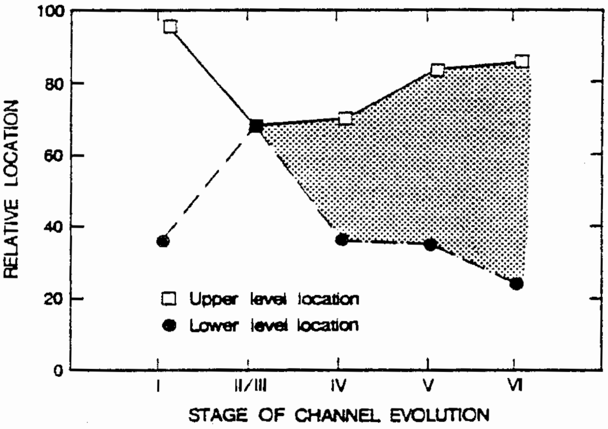

FIG. 10. Relative location on banks of the depositional surface and of established vegetation (shaded area) through the stages (see Fig. 2) of channel evolution in channelized streams in West Tennessee. Note the lower position of the depositional surface through the recovery period relative to stage I. There is no sediment deposition in stages II and III.

develop in response to varying stability conditions through the stages of this model, punctuated in places by important geomorphic thresholds.

Vegetation establishes in three distinct suites of species, separated in time and corresponding to middle and late stages of the bank-evolution model. The initial or pioneer species include black willow, river birch, boxelder, silver maple, and cottonwood. These species are hardy and fast growing, and produce seeds that are wind or water dispersed in the spring—a time that coincides with lowered streamflow elevations. These species tolerate moderate to high amounts of mass wasting and bank accretion; they establish in mid-stages of the bank-evolution model at the same time and location as initial bank stability and accretion. Species in the second suite are relatively stable-site species and establish in the late stages of bank recovery, after most mass wasting and high accretion rates have subsided; species in this suite include ironwood, green ash, sweetgum, American elm, and bald cypress and tupelo gum where previous channel-bed degradation has not been severe. The last suite of species establishes after bank recovery is complete and a meandering channel pattern returns. This suite is composed of bottomland oaks (overcup, water, cherrybark, and willow oak).

Detailed accretion analyses show that pioneer species establish low on the bank slope at the same point as initial bank accretion—at an elevation equivalent to that of the stream at about the 50% flow duration. (Flow duration is the percentage of time, annually, that flows at this elevation [stage] are equalled or exceeded.) Pronounced differences in geomorphi[illegible]d process occur on inside compared to outside [illegible]ends, producing pronounced vegetal differences [illegible] these two bank types, which in turn affect the cou[illegible] channel evolution. Stem densities are highest during the period of highest bank-accretion rate, suggesting that woody vegetation enhances sediment deposition on inside banks and deflects streamflow toward the opposite, eroding bank. Aggradation of channel beds, establishment of woody bank vegetation, and bank accretion, all of which signal the beginning of the recovery period, are intertwined environmental processes that are largely responsible for channel recovery following channelization.

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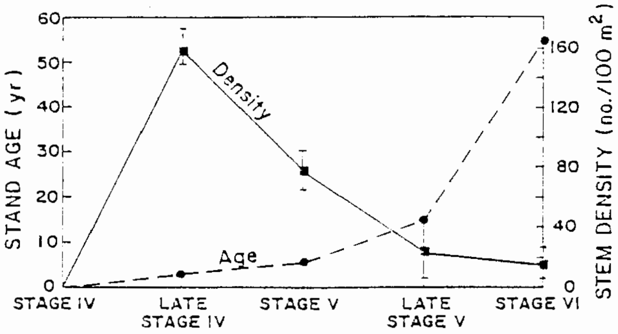


FIG. 11. Maximum stand age and stem density relation during the recovery stages of channel evolution in channelized streams in West Tennessee. Data are means ± 1 SE.

that establishes at the site of initial accretion (Fig. 9A: slough line). By stage VI the lower boundary extends down nearly to the 20% location (Fig. 10), which is substantially lower than the boundary of the natural Hatchie River, suggesting that a new equilibrium may establish below the pre-channelization elevation. The pronounced expansion of the lower boundary of the depositional surface relative to the upper boundary—unlike the stable Hatchie River depositional surfaces—may be due to the rapidly rising streambed and high sediment loads from upstream degradation. Continued expansion of the upper boundary in stage VI is also observed; it is expected that the upper boundary will slowly attach to the flood plain and ultimately resemble unaffected stage I sites. The sequence of depositional surface locations through the stages of channel evolution is most pronounced on inside bends. Straight reaches also follow this same pattern, albeit at a slower pace. Outside bends (Fig. 9A) experience little net accretion; however, active bank erosion slows to normal through the aggrading stages of channel evolution.

Differences between outside and inside banks (Fig. 9), which may be quite similar in stage IV, become more pronounced through the recovery stages (V and VI). The greater bank accretion and amount of vegetation on inside bends compared to outside bends provides a natural, physical explanation for increased flow deflection towards the opposite bank. This, in turn, leads to further point-bar development and concomitant vegetation establishment on the inside bend, accelerated bank retreat on the outside bend, and ultimately an increase in channel sinuosity as meanders develop. True meander development, which begins in early stage V with bank accretion and vegetation establishment, is characteristic of the final phase of recovery (stage VI). Control of channel gradient through sinuosity is a geomorphic hallmark of equilibrated channels in the Mississippi embayment of the Gulf coastal plain. This contrasts sharply with the initial geomorphic responses of severe upstream degradation and downstream aggradation. The most destabilizing effect of channelization is the drastic increase in channel gradient, which has been shown to be among the most important factors controlling fluvial geomorphic and riparian vegetation form and process (Kilpatrick and Barnes 1964, Hupp 1986). Thus, the channel initially reacts vertically to severe increases in gradient and then, through the course of stage V, returns to the largely lateral processes of meander-loop development.

Stem density is greatest within the first few years of establishment and declines with age of the stand through stage V (Fig. 11). This decline in density is probably associated with canopy closure and increasing competition for light and root space, providing an inverse relation between stand age and stem density (Fig. 11). Bank-accretion rate is also greatest in early stage V, when channel roughness is high, woody thickets are dense, and sediment loads from degrading areas upstream are large (Simon and Hupp 1986, 1987). Total volumes of bank accretion, however, do not show such a trend, given the general expansion, laterally, of the depositional area. Tree-age data show that the vegetated part of stage IV is short (3–4 yr) and is characterized by high stem densities (Fig. 11); the recovery period (stage V) lasts, on the average, ≈50 yr.

It is not clear whether bank accretion begins before, after, or at the same time that woody vegetation establishes on low bank slopes. Normal annual seed dispersal from suitable species deposits a large number of seeds on most riparian surfaces. It is probable, however, that some minimum amount of low-bank stability must be attained, geomorphically, before successful vegetation establishment occurs. Net bank accretion below the waterline may be the initial point of bank stabilization. Thorne and Osman (1988) suggest that bank stability is largely controlled by sediment fluxes in the lowest part of the bank. The earliest successful vegetation establishes low on the banks at the same location as initial (above-water) bank accretion, which corresponds to about the 50% flow duration (Fig. 9B). Establishing vegetation and accretion act in concert to increase bank stability through root-mass development and bank-slope angle reduction, respectively (Gray and Leiser 1982). Additionally, during high flows woody vegetation reduces velocities, which enhances bank accretion. Concomitant bed aggradation reduces bank heights, which also increase stability.

CONCLUSIONS

Patterns of woody vegetation recovery along modified alluvial channels develop in response to and, in turn, affect patterns of fluvial geomorphic recovery following human-induced rejuvenation. Bank widening, through mass wasting, and bank accretion are two important geomorphic processes that limit and affect woody vegetation patterns through the course of geomorphic recovery from channelization. This fluvial geomorphic recovery can be described in a six-stage model of bank evolution, which depicts landscape development over time. Distinctive vegetation patterns

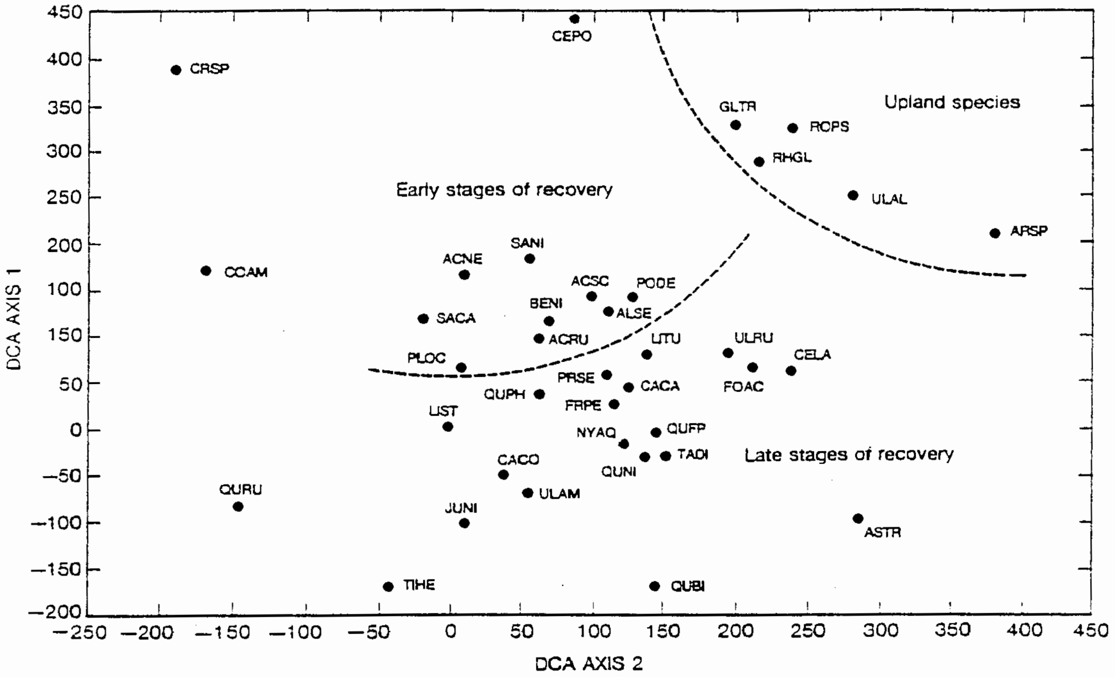


FIG. 7. Detrended correspondence analysis (DCA) species ordination for riparian hardwoods in West Tennessee. Upland species, in upper right, plot distinctly away from riparian species, which form a recovery gradient from upper left to lower right. Species abbreviations are explained in Table 4.

etation establishment; very high cover is in the most stable, stage I/VI, region of Fig. 8.

Two related environmental gradients are reflected in the DCA axes. DCA axis 1 is "stability," and the second axis is "time since disturbance," or degree of pioneer as a function of degree of maturity. The site characteristics can be clearly associated with various stages of bank-slope development (Fig. 8). This ordi-

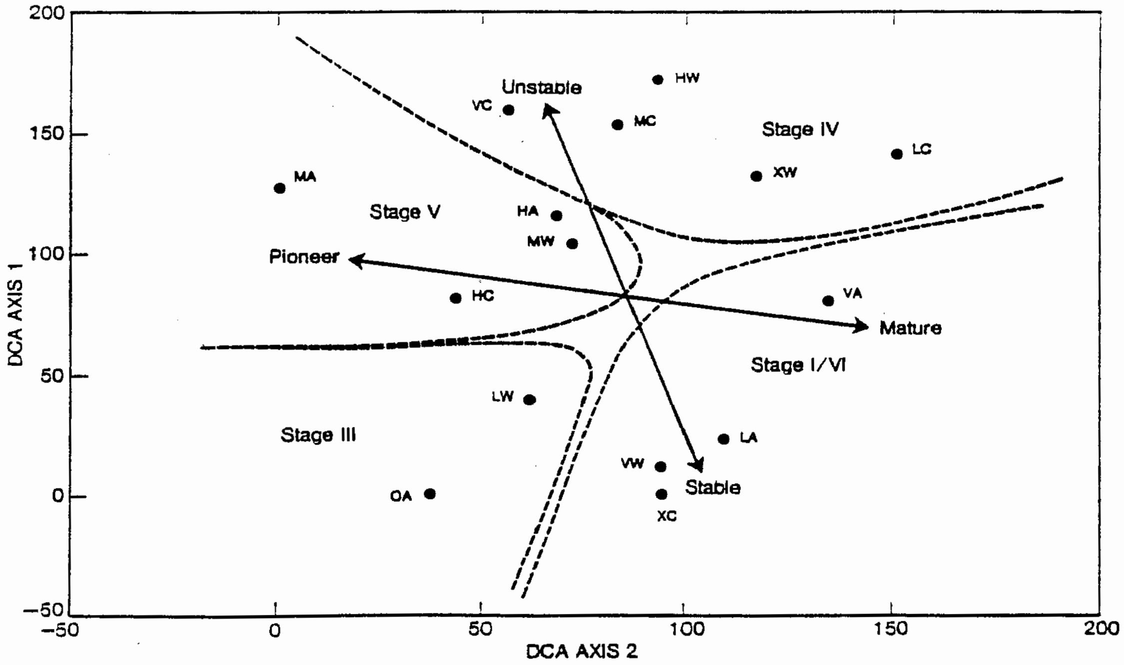


FIG. 8. Detrended correspondence analysis (DCA) parameter ordination for channelized streams in West Tennessee. Parameter clusters clearly depict the stages of channel evolution and two environmental gradients. Parameter abbreviations are explained in Table 5, and stages are explained in Fig. 2.

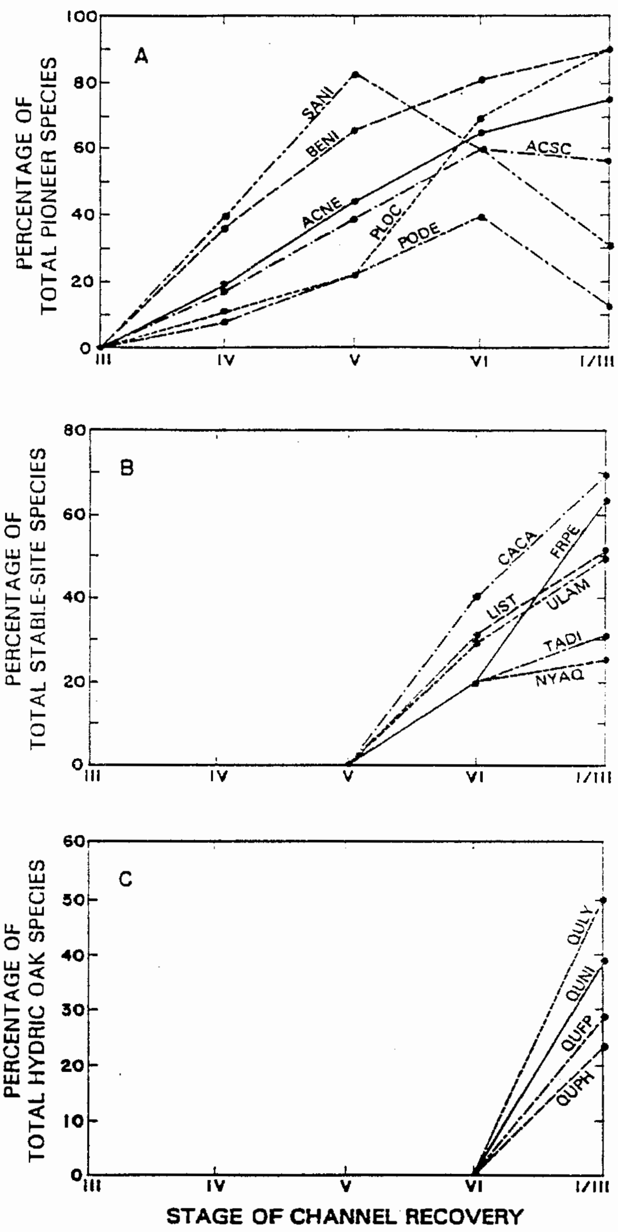


FIG. 6. **Recovery patterns by stage of channel evolution (see Fig. 2) for six pioneer species (A), six stable-site species (B), and four hydric oaks (C). Species abbreviations are explained in Table 4.**

tion to all positive value at low accretion, with some species avoiding medium and high accretion rates (Fig. 5B). The tendency for species to avoid the zero accretion condition may result from the trend for zero accretion to occur where there is a concomitant high widening rate, which removes both plants and possible accreted material through frequent mass wasting. Black willow, overcup oak, and cottonwood are particularly tolerant of moderate amounts of accretion; high accretion rates limit most species except black willow and cottonwood (Fig. 5B), which can produce roots from buried trunks and branches.

Species patterns relative to percentage of cover show that most of the selected species prefer medium to high cover (Fig. 5C); no species has a positive value for very low cover, as would be expected. Bald cypress, overcup oak, and green ash achieve their highest values in very high cover; all of these species are important components of the stable-site riparian forest. The other selected species are most common during the early and middle parts of the recovery period (stages IV and V). Black willow and to a lesser degree boxelder and cottonwood appear (or are) intolerant of closed canopy conditions. River birch remains important after canopy closure (high and very high cover percentages, Fig. 5A) and is part of the suite of species along unmodified West Tennessee streams, although it may share dominance with other stable-site species.

Green ash is a shade-tolerant species with many of the same *D*-value patterns of stable-site species (Fig. 5). Compared to black willow and river birch, green ash has a smaller ecological amplitude—a tendency that increases through the recovery process. In other words, the earliest pioneers have broad ecological amplitudes. Conversely, the stable-site species, bald cypress and overcup oak, have very similar strongly rigid preference patterns (Fig. 5C), having positive associations with only very low widening, very low accretion, low and medium accretion, and very high cover. The presence of these natural site species would suggest the natural or restabilized conditions associated with stage I or VI. The dominant presence of species like black willow and river birch suggests recent channel-bank instability, mass wasting, and subsequent high accretion rates associated with early and middle stage V. Cottonwood, like black willow, will grow under a wide range of environmental conditions; however, no *D* value exceeded 2 (Fig. 5B). Silver maple and boxelder (Table 4) are common species along recovery reaches. Although these species are present in natural, stable riparian forests, many banks in the later stages of recovery may support these two species singularly or together to the near exclusion of other species. Boxelder and silver maple site-parameter patterns (Fig. 5) typify species characteristic of middle to late bank recovery and have a tolerance for substantial accretion.

The tree species found along streams affected by channelization can be classified into three groups (or suites) on the basis of their response to channelization, and in particular to the stages at which they establish and reach peak abundance. The first suite is composed of species that establish on the exposed soils produced by the degrading channels of stage IV and the aggrading banks of stage V (Fig. 2). This group includes black willow, river birch, silver maple, boxelder, sycamore, and cottonwood (stage IV, Fig. 6A). The life-history characteristics of pioneer species make them particularly adapted for establishment and growth along dis-

TABLE 4. List of woody species and their abbreviations identified at 80 study sites along streams in West Tennessee. Species are listed in order of percentage of total sites at which they are present. Nomenclature follows Radford et al. (1968).

Binomial	Abbrev.	Proportion of sites where present (%)	Common name
Betula nigra	BENI	62.50	River birch
Salix nigra	SANI	53.88	Black willow
Acer saccharinum	ACSC	42.67	Silver maple
Platanus occidentalis	PLOC	41.38	Sycamore
Acer negundo	ACNE	36.64	Boxelder
Carpinus caroliniana	CACA	19.40	Ironwood
Liquidambar styraciflua	LIST	16.81	Sweetgum
Alnus serrulata	ALSE	15.95	Alder
Fraxinus pennsylvanica	FRPE	15.52	Green ash
Populus deltoides	PODE	15.52	Cottonwood
Ulmus americana	ULAM	14.22	American elm
Acer rubrum	ACRU	12.93	Red maple
Quercus lyrata	QULY	11.64	Overcup oak
Sambucus canadensis	SACA	11.64	Elderberry
Taxodium distichum	TADI	9.05	Bald Cypress
Nyssa aquatica	NYAQ	7.76	Tupelo gum
Quercus falcata var. *pagodaefolia*	QUFP	7.76	Cherrybark oak
Ulmus rubra	ULRU	7.76	Slippery elm
Forestiera acuminata	FOAC	6.47	Swamp forestiera
Quercus nigra	QUNI	6.47	Water oak
Quercus phellos	QUPH	6.47	Willow oak
Carya cordiformis	CACO	5.17	Bitternut
Ulmus alata	ULAL	5.17	Winged elm
Celtis laevigata	CELA	3.88	Sugarberry
Quercus bicolor	QUBI	3.88	Swamp red oak
Rhus glabra	RHGL	3.88	Staghorn sumac
Gleditsia triacanthos	GLTR	2.59	Honey locust
Juglans nigra	JUNI	2.59	Black walnut
Liriodendron tulipifera	LITU	2.59	Tulip tree
Quercus rubra	QURU	2.59	Red oak
Tilia heterophylla	TIHE	2.59	Basswood
Aralia spinosa	ARSP	1.29	Hercules club
Asimina triloba	ASTR	1.29	Pawpaw
Cephalanthus occidentalis	CEPO	1.29	Buttonbush
Cornus amomum	COAM	1.29	Silky dogwood
Crataegus spp.	CRSP	1.29	Hawthorn
Prunus serotina	PRSE	1.29	Black cherry
Robinia pseudoacacia	ROPS	1.29	Black locust

blage represents common "early successional" trees throughout the eastern United States and parts of the Great Plains. Also common along unmodified reaches are green ash, ironwood, sweetgum, overcup oak, cherrybark oak, water oak, and American elm; these species are more typical of middle to late recovery stages. Bald cypress and tupelo gum are common bank species in backwater–swampy reaches. Upland disturbance species like winged elm and honey locust (Table 4) are sometimes found on the most severely degraded (substantially lowered bed level) reaches, and suggest that some banks are now so high as to be above most fluvial activity; the presence of these species indicates a particularly disturbed site.

Standardized residuals (*D* values), computed from contingency tables, clearly show species preference or avoidance patterns (Fig. 5) for each of the 15 site-characteristic categories (Table 5). *D* values also indicate the plasticity of ecological amplitude; species with a few high *D* values are less plastic in their site requirements than those with several high *D* values.

TABLE 5. Site-characteristic categories, and number of sites in each category on 15 West Tennessee streams.

Abbreviation	Parameter category	Range	No. of sites
Channel widening rate (m/yr)			
VW	Very low	0.00–0.15	16
LW	Low	0.16–0.30	14
MW	Medium	0.31–0.91	17
HW	High	0.92–1.22	13
XW	Very high	>1.22	18
Bank accretion rate (cm/yr)			
OA	Zero	0	17
VA	Very low	0.03–1.24	21
LA	Low	1.25–2.50	12
MA	Medium	2.51–6.32	11
HA	High	>6.32	15
Bank vegetation coverage (%)			
VC	Very low	0–9	15
LC	Low	10–24	14
MC	Medium	25–49	16
HC	High	50–74	11
XC	Very high	75–100	22

TABLE 3. Dendrogeomorphic data for 72 sites along rivers in West Tennessee.

River	River kilometre	Percentage cover	Number of species	Maximum tree age	Median rate of accretion (cm/yr)
Cub Creek	11.1	25	5	8	0.8
Cub Creek	9.2	13	5	12	1.5
Cub Creek	3.5	36	4	11	7.0
Cub Creek	2.4	74	11	8	10.0
Hatchie	292.8	100	5	22	0.8
Hatchie	260.7	100	12	50	1.5
Hatchie	217.2	100	10	40	0.5
Hatchie	194.7	100	7	50	0.5
Hatchie	130.0	100	16	50	1.5
Hatchie	110.1	98	10	29	0.8
Hatchie	79.7	98	10	30	0.5
North Fork of Forked Deer	66.9	98	5	25	7.5
North Fork of Forked Deer	55.7	19	5	20	0.8
North Fork of Forked Deer	37.0	0	0	0	0
North Fork of Forked Deer	32.5	0	0	0	1.0
North Fork of Forked Deer	30.3	18	3	3	1.5
North Fork of Forked Deer	21.9	1	2	1	0
North Fork of Forked Deer	8.2	75	3	5	8.7
North Fork of Forked Deer	6.1	90	4	7	10.0
North Fork of Obion	56.2	75	6	45	0
North Fork of Obion	42.5	88	10	40	0
North Fork of Obion	34.0	75	2	4	0
North Fork of Obion	28.0	50	6	5	1.5
North Fork of Obion	16.1	19	1	3	10.0
North Fork of Obion	9.0	0	0	0	0
Obion	110.2	49	6	4	1.7
Obion	100.1	42	4	5	5.5
Obion	86.4	2	2	1	8.0
Obion	68.2	40	2	5	6.5
Obion	55.0	23	1	4	7.5
Obion	41.2	15	2	2	0.5
Obion	33.5	19	3	2	4.5
Pond Creek	18.3	20	1	2	7.5
Pond Creek	15.8	81	2	5	9.5
Pond Creek	11.8	21	1	3	6.5
Pond Creek	5.0	2	1	2	1.0
Pond Creek	1.8	75	2	5	1.0
Porters Creek	27.5	75	6	11	3.8
Porters Creek	22.4	95	6	12	2.5
Porters Creek	18.0	48	5	7	2.5
Porters Creek	14.3	68	6	9	5.3
Porters Creek	7.2	35	9	5	12.0
Rutherford Fork of Obion	69.7	75	7	20	1.2
Rutherford Fork of Obion	63.4	100	5	40	0.8
Rutherford Fork of Obion	48.1	88	4	30	2.0
Rutherford Fork of Obion	28.8	29	5	3	5.3
Rutherford Fork of Obion	39.4	81	3	41	1.5
Rutherford Fork of Obion	27.5	5	1	5	2.5
Rutherford Fork of Obion	24.5	35	3	6	4.0
Rutherford Fork of Obion	16.3	12	2	3	4.0
South Fork of Forked Deer	54.2	100	8	65	0
South Fork of Forked Deer	44.4	0	0	0	1.2
South Fork of Forked Deer	26.2	0	0	0	0
South Fork of Forked Deer	21.4	6	1	2	2.5
South Fork of Forked Deer	19.2	0	0	0	0
South Fork of Forked Deer	12.7	0	0	0	0
South Fork of Forked Deer	9.0	55	6	7	0
South Fork of Forked Deer	5.3	3	1	3	1.2
South Fork of Obion	54.4	100	3	35	1.0
South Fork of Obion	45.9	80	10	15	7.5
South Fork of Obion	37.3	55	2	2	0
South Fork of Obion	30.9	38	3	2	0
South Fork of Obion	27.0	2	1	2	0

(when present) were cored for age and/or accretion rate determinations at each site; in most cases many more than 10 trees were sampled. Dendrogeomorphic analyses have been reviewed by Shroder (1980), covering hillslope processes, and by Sigafoos (1964) and Hupp (1988), covering fluvial processes and paleohydrologic techniques.

Depositional surfaces (Hupp and Simon 1991) could be identified along many reaches that experience progressive accretion and vegetation establishment (Fig. 2: stages V and VI). At these sites accretion analyses were performed as described above. However, detailed information on accretion depth and rate was taken relative to specific locations on the bank, bank angles, and timing of vegetation establishment (Hupp and Simon 1991).

Among the most significant indicators of ambient bank stability is the amount of woody species coverage. 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-m reach at each site, and includes the area from top bank to low-water edge; all cover values were estimated by the author during the growing season. This percentage, along with rate of bank widening and rate of bank accretion, form the three principal dependent variables associated with environmental recovery along these channelized streams. These variables, as well as others, were analyzed relative to stage of channel evolution (Fig. 2).

Plant ecological analyses

Two types of plant ecological data were used: (1) simple presence–absence data for all woody species occurring at all sites, and (2) stem density data from plots along reaches where recently established plants were growing on new depositional surfaces. Rectangular plots, usually 5 × 20 m, were established normal to the cross section on depositional surfaces at each site that exhibited substantial accretion and distinct woody vegetation establishment. Thus most plots were established at sites in early, middle, and late phases of stage V and stage VI of the channel evolution model (Fig. 2). Within each plot, stems with a diameter of ≥1 cm at 1 m above the ground surface were tallied and converted to stems per 100 square metres; the site of the plot typically corresponds to the site of detailed accretion analyses (Hupp and Simon 1991).

Lists of woody species present were compiled by site. These data were collected at the same sites (72) where the dendrogeomorphic analyses were conducted; 8 sites were subsequently subdivided because of eco-geomorphic variation within the reach, so that a total of 80 sites are included in the species-presence analysis. Species carried onto bank locations through slumping were not included in the species-presence analysis. Binary data (presence–absence) are rapidly obtained, on the basis of site-specific vegetation patterns, and avoid possible complications that species interactions impose on abundance data (Hurlbert 1969, Zimmermann and Thom 1982). Binary vegetation data have been used with success in defining vegetation and geomorphic relations (Strahler 1978, Hupp and Osterkamp 1985).

Binary-discriminant analysis (BDA; Strahler 1978) was performed on the species-presence–absence data by site characteristics (bank-widening rate, bank-accretion rate, percentage of vegetative cover). Frequency data (number of occurrences as a function of number of possible occurrences) from the contingency tables were converted to standardized residuals, which places common and rare species on equal grounds (Haberman 1973). Standardized residuals (*D* values) are useful in identifying trends in species "preference" and "avoidance" for particular conditions.

The 80 study sites were categorized by stage of bankslope development and the site characteristics (widening rate, accretion rate, and percentage cover). Five classes were chosen for each characteristic to minimize differences among classes in the number of sites, which reduces the sample size bias in the statistical operations performed in the BDA where species-presence–absence data were used as the dependent variable. Two sites were omitted from the widening categorization, four sites in the accretion categorization, and two sites in the cover categorization because of unavailability of data. The descriptor terms of each site class lead to a proper interpretation of widening and accretion rates; however, "medium" cover may suggest a substantial amount of bank cover, but it includes values ranging from 25 to 49%.

Detrended Correspondence Analysis (DCA) (Hill and Gauch 1980) was performed on the species *D* values. The DCA was conducted using the DECORANA program (Hill 1979). DCA is a form of reciprocal averaging that has the "arch effect" (Gauch et al. 1977) removed (detrended), and uses a subroutine to preserve ecological distances through rescaling.

DENDROGEOMORPHIC TRENDS

Channelization may affect a stream both directly and indirectly. Reaches that are channelized are converted from stage I to stage II (Figs. 2 and 3) where the channel is dredged and straightened, and all woody vegetation is removed from the bank and typically also for a substantial distance from the river channel. However, reaches upstream of the limit of recent channelization are also affected; these channels proceed from stage I to stage III, obviously bypassing the constructed stage (Fig. 3: stage II). Severe increases in channel gradient through channelization will promulgate degradation significant distances upstream of the limit of channelization. Channelized reaches near the limit of channelization and upstream unchannelized reaches experience a period of degradation (Fig. 3: stage III), subsequent mass wasting on the banks (Figs. 2 and 3:

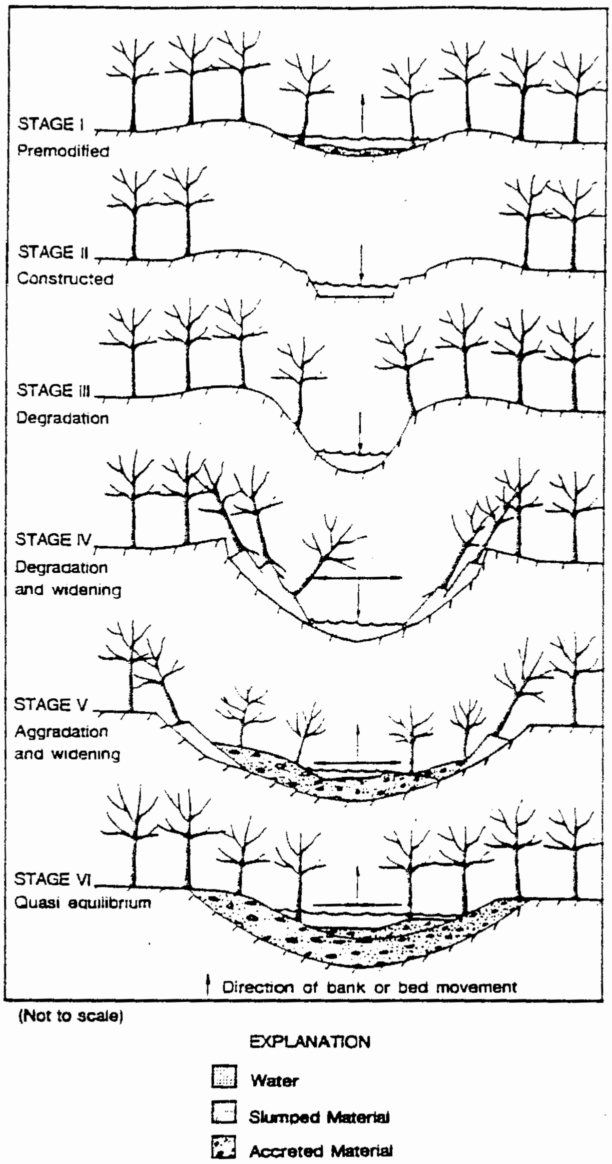


FIG. 2. Six-stage model of channel evolution following channelization. All stages are depicted for sites at or just above the limit of channel work. Note that stage III, as depicted above, could only occur above the limit of most recent channelization, where degradation is greatest. Arrows above channels indicate the direction of degradation or aggradation. Adapted from Hupp and Simon (1991).

tonwood (*Populus deltoides*); however, these species usually do not form dense, pure stands. Herbaceous vegetation is often dense, particularly on unshaded, unstable banks that do not support woody vegetation; common species include giant ragweed (*Ambrosia trifida*), knotweeds (*Polygonum* sp.), cocklebur (*Xanthium* sp.), and various grasses and sedges; catbriars (*Smilax* sp.) and blackberry (*Rubus* sp.) are also common. Nomenclature follows Radford et al. (1968).

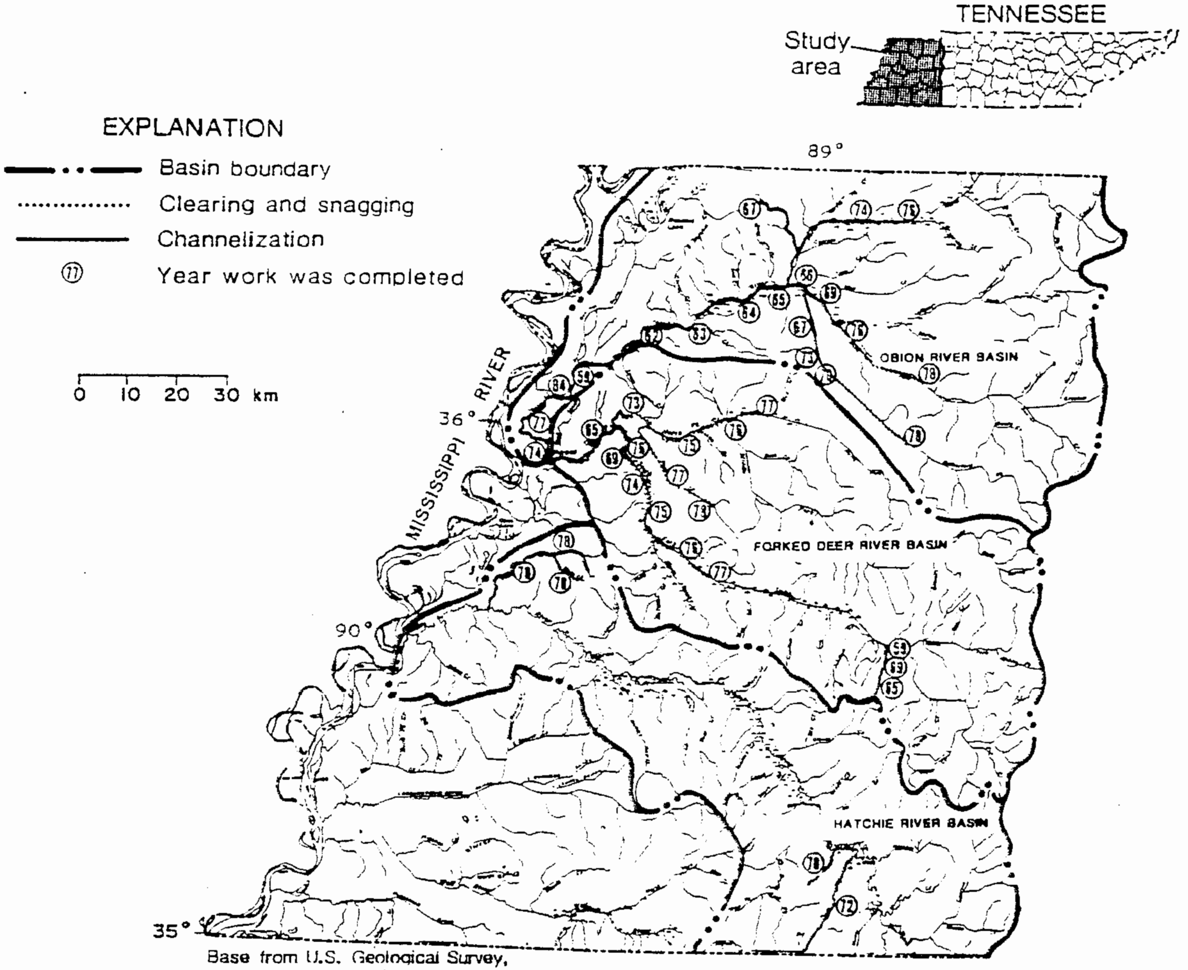
Channelization history

Prior to major deforestation of the West Tennessee region following the Civil War, "rivers flowed with good depths year round" (Ashley 1910). Clearing of large tracts of land and the consequent reduction in sediment storage and increase in runoff rates led to intense erosion of the uplands and gullying in fields. This material was deposited on the flood plains and in the stream channels (Maddox 1915), resulting in a general loss of channel capacity (Ashley 1910). Channels were extremely sinuous, choked with sediment and debris, and subject to frequent and prolonged flooding (Morgan and McCrory 1910). Early surveys (circa 1910) of the Obion and South Fork Forked Deer Rivers indicated mild channel gradients of $\approx 1.14 \times 10^{-4}$ m/m and broad flood plains 1.5–5.0 km wide (U.S. Army Corps of Engineers 1907, Hidinger and Morgan 1912).

Most stream channels in West Tennessee except the Hatchie River mainstem, by 1926, had been dredged and straightened to decrease the magnitude and frequency of out-of-bank flows (Speer et al. 1965). Further enlargement of the channels was caused by increases in velocity and channel capacity resulting from the channelization (Ramser 1930). Subsequent accumulation of drift (trees and stumps) from failed banks was of sufficient magnitude to cause backwater and sedimentation at the downstream ends of the forks of the Obion and Forked Deer Rivers (Speer et al. 1965). Continued aggradation and drift accumulation through the 1930s necessitated the clearing and snagging (stump removal) of ≈ 275 km of main stem, forks, and tributaries of the Obion River system in the late 1930s and 1940s. When this work was completed, the cycle was repeated, and channel filling occurred through the 1940s and 1950s (Robbins and Simon 1983). This resulted in the formulation of a regional program to further re-channelize many of the drainage systems in West Tennessee. Channel work on the Hatchie River during 1938–1952 was limited to snagging drift, thereby preserving its meandering course.

Various channelization projects were undertaken from the late 1950s through the 1970s (Table 2) in basins ranging in size from 28.1 to 61 966 km^2. The West Tennessee Tributaries Project (United States Army Corps of Engineers), which provided for the enlargement and straightening of 189 km in the Obion River system and 169 km in the Forked Deer River system, was temporarily halted by court order in 1970 when it was approximately one-third complete (Robbins and Simon 1983). At that time, channelization in the Obion River system had extended into the lower reaches of the forks (Fig. 1). As of 1989, all straightening and dredging by the United States Army Corps of Engineers in West Tennessee has been, more or less, abandoned.

The studied streams reflect varying degrees and types of channel modifications (Table 2); the most recent



Base from U.S. Geological Survey,
State base map, 1967,
revised 1973

FIG. 1. Location of study streams in West Tennessee.

(Graf 1977, White 1979, Cairnes 1980, Hupp and Osterkamp 1985, Hupp 1988, Nilsson et al. 1989). Analyses of riparian vegetation along streams affected by channelization have been very limited (McCall and Knox 1978, Miller 1985, Shields and Nunnally 1985, Simon and Hupp 1987). A few bottomland forests near channelized reaches have been studied; Bragg and Tatschi (1977) and Reily and Johnson (1982) suggest that bottomland forests along the Missouri River may be adversely affected by altered hydrologic regime in response to channel modification.

The term riparian, here, refers to channel banks and those areas subject to an annual hydroperiod; it does not include higher parts of the bottomland such as true flood plains or terraces (Osterkamp and Hupp 1984). The present study is concerned primarily with vegetation patterns near (within ≈ 50 m of) the stream channel; it generally does not include the active flood plain, swales, flats, and backswamps normally associated with the entire bottomland (Wharton et al. 1982). The typical vegetative, geomorphic, and hydrologic characteristics of these bottomland hardwood swamps (Wharton et al. 1982) have been substantially altered as a result of decades of channelization activity.

The present paper is devoted to the plant ecology of modified alluvial channels. Channelization, through drastic increases in stream gradient (profile slope), creates a cycle of rejuvenation response that can be likened to tectonic uplift. Simon and Hupp (1986) developed a conceptual model of channel evolution following channelization (Table 1, Fig. 2), which was later quantified (Simon, *in press*) and has been used in this and other papers to provide a spatial and temporal framework for several geomorphic and plant-ecologic analyses and interpretations. Not all reaches of a stream proceed through all stages of channel evolution, depending on the length and location of channelization relative to the site in question. Most streams are not channelized from mouth to drainage divide during one operation, although the effects beginning with stage III