WATER RESOURCES BULLETIN
VOL. 31, NO. 3 AMERICAN WATER RESOURCES ASSOCIATION JUNE 1995

# CONTROL OF STREAMBANK EROSION DUE TO BED DEGRADATION WITH VEGETATION AND STRUCTURE[1]

*F. D. Shields, Jr., A. J. Bowie, and C. M. Cooper*[2]

ABSTRACT: Combinations of vegetation and structure were applied to control streambank erosion along incised stream channels in northwest Mississippi. Eleven sites along seven channels with contributing drainage areas ranging from 12-300 km$^2$ were used for testing. Tested configurations included eroding banks protected by vegetation alone, vegetation with structural toe protection, vegetation planted on re-graded banks, and vegetation planted on regraded banks with toe protection. Monitoring continued for up to 10 years, and casual observation for up to 18 years. Sixteen woody and 13 nonwoody species were tested. Native woody species, particularly willow, appear to be best adapted to streambank environments. Sericea lespedeza and Alamo switchgrass were the best nonwoody species tested. Vegetation succeeded in reaches where the bed was not degrading, competition from kudzu was absent, and bank slopes were stabilized by grading or toe protection. Natural vegetation invaded planted and unplanted stable banks composed of fertile soils. Designs involving riprap toe protection in the form of a longitudinal dike and woody vegetation appeared to be most cost-effective. The exotic vine kudzu presents perhaps the greatest long-term obstacle to restoring stable, functional riparian zones along incised channels in our region.

(KEY TERMS: vegetation; streambank protection; bioengineering; stream restoration; channel incision; riparian zone.)

## INTRODUCTION

The U.S. Army Corps of Engineers estimated 229,000 bank-km of waterways in the U.S. are in need of erosion protection at an annual cost of $1 billion (U.S. Army Corps of Engineers, 1981a), and Barnes (1968) estimated that 480,000 km of eroding streambanks in the U.S. produced an average of 450 million metric tons yr$^{-1}$ of sediments. In the Yazoo River basin of Mississippi alone, land loss due to streambank erosion averages 264 ha yr$^{-1}$ (U. S. Department of Agriculture, 1982). Extensive bank protection and channel stabilization works continue to be constructed on waterways of all sizes, and maintenance of existing structures is requiring increasing attention. One of the most difficult types of streambank erosion to combat is that caused by channel bed degradation, or incision. Channel incision is a widespread, worldwide problem often induced by cultural activities (Galay, 1983). Incision can trigger explosively rapid bank erosion that propagates throughout entire watersheds (Grissinger and Murphey, 1983; Piest *et al.*, 1977; Simon, 1989; Simon and Robbins, 1987; Harvey and Watson, 1986; Wilson and Turnipseed, 1989 and 1990; Smith and Patrick, 1991).

Erosion processes in incising channels have been studied extensively (Daniels, 1960; Little *et al.*, 1982; Grissinger and Bowie, 1984; Grissinger and Murphey, 1982, 1986, 1989; Grissinger *et al.*, 1991). Morphology of incising channels has been described in conceptual models of channel evolution that recognize five (Harvey and Watson, 1986) or six (Simon and Hupp, 1987) stages of channel response. Initially, channels are stable, with low gradients and stable, well vegetated banks (stage I). Stage II coincides with the short period of time immediately following channel straightening by man. In stage III, channels incise by deepening as discrete knickpoints (waterfalls) or less distinct knickzones that migrate from stream mouth to watershed divides. When bank heights exceed a critical threshold, stage IV commences, which is characterized by rapid channel widening as banks fail by mass wasting (Figure 1). Bank failure accelerates after a knickpoint passes because bank height is suddenly increased and because more erodible deposits may be uncovered at the bank toe. As knickzones and areas of

---

[1] Paper No. 94091 of the *Water Resources Bulletin*. **Discussions are open until February 1, 1996.**

[2] Respectively, Research Hydraulic Engineer, Research Hydraulic Engineer (retired), and Research Ecologist, USDA-ARS-NSL, P.O. Box 1157, Oxford, Mississippi 38655-1157.

Figure 1. Erosion Triggered by Channel Erosion. Channel shown drains only 16 $km^2$, but bank height is between 4 and 5 m. Photograph is looking upstream from downstream end of site VTS2.

most rapid erosion migrate upstream, downstream reaches experience aggradation (stage V). Banks become more stable as sediments derived from knickpoint progression upstream are deposited against the bank toe, reducing bank height and angle. Gradually bars form, become vegetated, and a meandering planform is regained (stage VI).

The critical bank height that marks the threshold between stages III and IV is a function of bank angle, tension crack depth, and soil properties (Little *et al.*, 1982). Soil properties (bulk density, friction angle, and cohesion) vary with soil moisture. Worst case conditions (highest likelihood of bank collapse) correspond to highest soil moisture levels. Bank failure is an episodic rather than a continuous process because of soil moisture variation and because accumulation of material at the bank toe following upper bank collapse effectively reduces bank angle. This material is removed by flow, thus steepening the bank and triggering new failure ("basal endpoint control," Thorne, 1982). Removal by flow during nonflood periods is dependent upon local hydraulic conditions that direct flows toward or away from a given bank. Bank failure is often further complicated and facilitated by piping processes (Simon and Hupp, 1986) and by development of tension cracks just landward of and roughly parallel to the top of the bank (Grissinger and Murphey, 1983).

Numerous methods are available to control bank erosion (Keown *et al.,* 1977; Petersen, 1986; Hemphill and Bramley, 1989). Interest in use of vegetation alone or in combination with structure to control bank erosion is increasing due to environmental and economic concerns. Woody riparian vegetation filters nutrients out of shallow ground water, thus reducing nonpoint source pollution (Pinay *et al.,* 1990; Lowrance *et al.,* 1984; Lowrance *et al.,* 1985). Engineers, their clients, and the general public are developing a stronger preference for stream and waterway designs that look natural and preserve or restore habitat values (Boon, 1992). Elmore and Beschta (1989) argue that restoration of riparian vegetation is a more effective approach to restoring stream habitats than adding instream structure. Hathaway (1986) describes how structures made from willow posts have been used for training gravel bed rivers in New Zealand. Despite higher levels of interest in vegetative control methods, design criteria for these methods are lacking (Spitz *et al.,* 1990). Schiechtl (1980), Hemphill and Bramley (1989), and Coppin and Richards (1990) are helpful texts but are frequently qualitative and emphasize European settings.

Amarasinghe (1992) provides fundamental results pertaining to control of bank erosion along a nonincised channel using herbaceous vegetation.

The purpose of this paper is to provide information useful for selecting plants and combinations of plants and structures for stabilizing and restoring banks of incised channels, particularly in the southeastern U.S. Results of a series of field experiments with durations ranging from 12 years to a single growing season are digested. Test sites were subjected to extreme floods and droughts during the periods of record. Site treatments included no protection, vegetation, vegetation with toe protection, and vegetation with bank shaping and toe protection.

## STUDY SITES

All study sites were located in the hills forming the eastern border of the lower Mississippi alluvial plain in northwest Mississippi. Site locations are shown in Figure 2, and salient characteristics are summarized in Table 1. Climate and rainfall were typical of the Southeastern coastal plain. Geology and fluvial geomorphology have been described by others (Whitten and Patrick, 1981; Schumm *et al.,* 1981; Grissinger and Murphey, 1983). Channels were straightened at various times between about 1910 and 1970, and thus they were repositioned away from original alluvial deposits. Valley-fill consisted of post-settlement alluvium overlying mid-Holocene meander belt alluvium and early Holocene deposits (primarily dense, semiconsolidated silts).

Relatively high rainfall (~1400 mm $\mathrm{yr^{-1}}$) and erodible bank materials coupled with the absence of channel bed geological controls produced rapid bank erosion typical of incising channels throughout the region. For example, Whitten and Patrick (1981) reported channel erosion that included incision-induced channel widening of 100-300 percent in 17 to 35 years. Wilson and Turnipseed (1990) reported incision-related channel widening of nearly 600 percent (from 7.6 to 45 m) during the period 1912-1988 for a section of Wolf Creek in northeast Mississippi. Simon and Hupp (1986) reported channel widening of 61 percent (reach mean) in just 10 years for an incising channel in West Tennessee. Little *et al.* (1982) reported that approximately 18 m of lateral bank retreat occurred in two months at a site on Johnson Creek roughly 4 km downstream of site VT2 (site numbers as shown in Figure 2). Channel width doubled in the reach containing sites V4 and V5 between 1968 and 1978 (Whitten and Patrick, 1981), and channel cross-sectional areas in this reach increased an average of 58 $\mathrm{m^2}$ (roughly 25 percent) between 1977 and 1983 (Murphey and Grissinger, 1985).

Sediment yield from incising channels in this area is large (Simon, 1989). Average channel erosion rates per unit channel length for selected reaches in the watersheds encompassing the study sites include 2,200 kg $\mathrm{m^{-1}\ yr^{-1}}$ for Pigeon Roost Creek (six years; Bowie and Mutchler, 1986), 2,900 kg $\mathrm{m^{-1}\ yr^{-1}}$ for Goodwin Creek (five year mean; Grissinger *et al.,* 1991), and 6,400 kg $\mathrm{m^{-1}\ yr^{-1}}$ for Hotophia Creek (18 years; Little and Murphey, 1981). Bowie (1987) determined that channel erosion produced 33 percent of the total sediment yield measured for Pigeon Roost Creek, and Grissinger *et al.* (1991) estimated that about 85 percent of the total sediment yield from Goodwin Creek originated from channel and gully banks and beds.

In the area containing the study sites, naturally occurring vegetation interacted with other factors to influence bank stability in complex ways. Woody species composition often reflected channel evolution, as described by Hupp (1992) and Hupp and Simon (1991). Bed degradation during stages III and IV produced high, steep banks (Figure 1); and gravity forces were more important influences than hydraulic forces. With the exception of local scour caused by fallen trees, modifications of the near-bank flow field by vegetation (e.g., shielding of bank by dense grasses or shrubby vegetation, or local scour adjacent to isolated tree trunks) was of relatively little importance. Because root mass increases soil strength (Coppin and Richards, 1990; Gray and Leiser, 1982), strategically located vegetation occasionally prevented tension crack development landward of steep banks and may have retarded erosion due to overbank drainage (Thorne *et al.,* 1981). However, plants were ineffective in preventing development of pipes, and the presence of large roots may have facilitated pipe initiation. Roots likely retarded bank collapse and subsidence over pipe voids, but they certainly did not prevent it. Furthermore, even the most vigorous stands of large trees could not prevent bank erosion and collapse following deep channel incision. Failure of well-vegetated banks was evident in the geologic record of periods when incision occurred in channels draining virgin forests (Grissinger and Murphey, 1983). When channel incision exposed bank materials far below the root zone, vegetation on top banks actually reduced bank stability because its weight served to increase loading on bank soils. Volny (1984) made similar observations in Europe. During latter stages of channel evolution (V and VI), pioneer woody species invaded aggradational surfaces that formed within channels enlarged by erosion. Some types of soils severely limited colonization and redevelopment of natural vegetation by their frequent failure (for banks

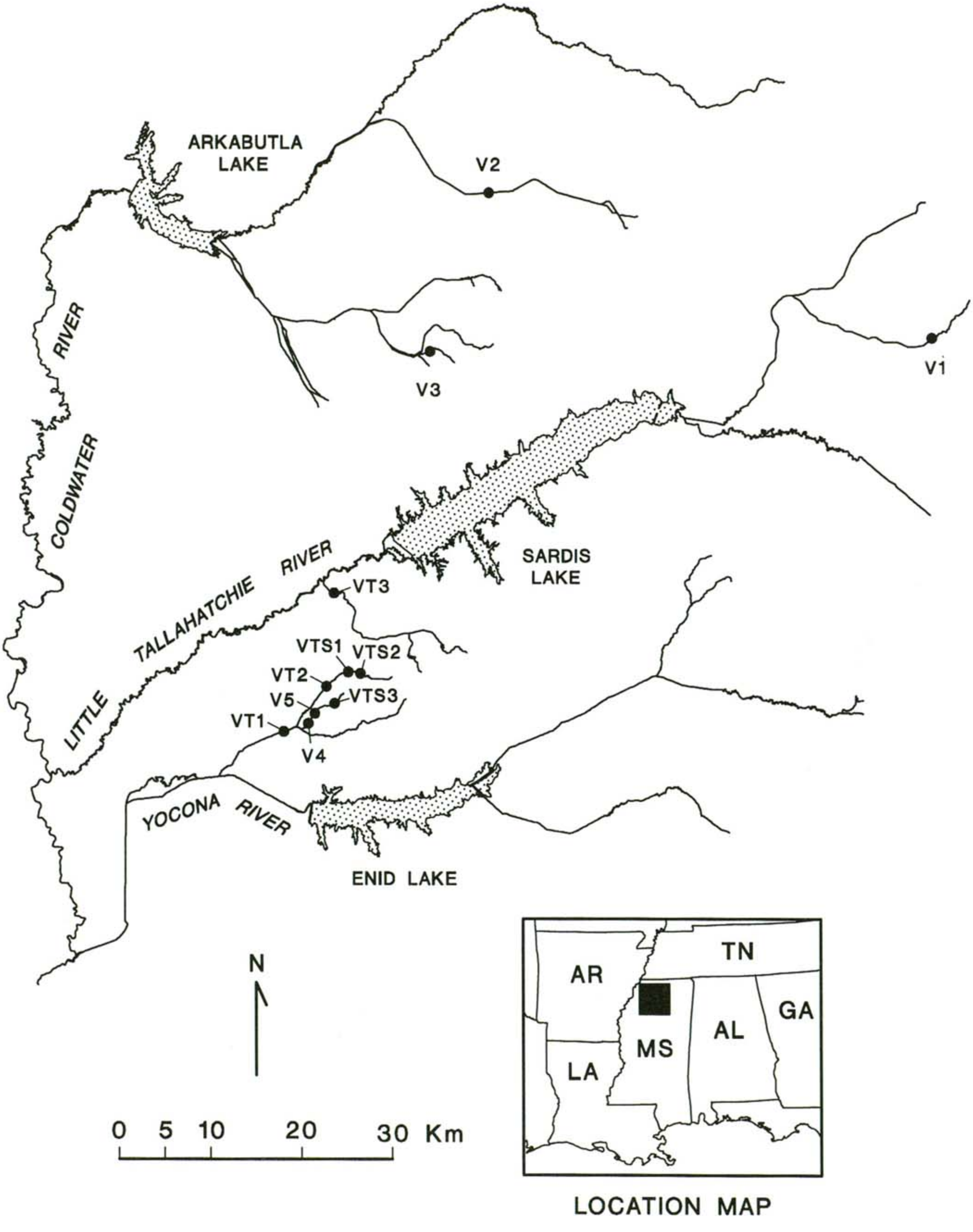

Figure 2. Location of Study Sites.

TABLE 1. Characteristics of Study Sites.

| Site Number | Stream | Drainage Area km² | Planform | Reach Length, m | Additional Erosion Controls | Channel Evolution Stage (Simon and Hupp, 1987) |
|---|---|---|---|---|---|---|
| | | | **Vegetation Alone** | | | |
| V1 | Oaklimiter | 29 | Straight | 100 | None | III/IV |
| V2 | Pigeon Roost | 300 | Straight | 3 reaches each 610 m long | None | IV/V |
| V3 | Martin Dale | 12 | Straight | 500 | Grade control structure at downstream end of reach | III |
| V4 | Goodwin | 21 | Convex point bar | 100 | Grade control structure ~ 1 km downstream | V |
| V5 | Goodwin | 21 | Straight | 100 | Grade control structure ~ 1 km downstream | V |
| | | | **Vegetation With Toe Protection** | | | |
| VT1 | Peters | 190-210 | Straight | Two 150-m-long and one 300-m- long plot in a ~2 km reach | None | V |
| VT2 | Johnson | 22 | Concave banks of bendways | 1,500 | None | IV |
| VT3 | Hotophia | 91 | Convex banks of gradual bendways | 750 | Grade control structure at downstream end of reach | V |
| | | | **Vegetation With Structure and Bank Shaping** | | | |
| VTS1 | Johnson | 16 | Straight | 490 | Grade control structure placed at downstream end of reach two years after construction | IV |
| VTS2 | Johnson | 16 | Bendway | 180 | Grade control structure 550 m downstream | IV |
| VTS3 | Goodwin | 14 | Bendway | 160 | Grade control structure downstream | IV |

composed primarily of meander belt alluvium), by their high density (which likely limited root penetration and water circulation), and by their tendency to fail along vertical planes (for banks composed primarily of the early Holocene silts) (Grissinger and Bowie, 1984). Natural invasion by woody species was also inhibited by competition from the exotic vine kudzu.

All study reaches had been affected by channel incision. Eroding banks were often near vertical and reached 4-5 m in height. A wide range of channel sizes was represented (Table 1). Protected banks were located in straight reaches and in bendways along channels with primarily sand beds. Channel slopes ranged from 1 to 5 m km$^{-1}$.

## METHODS

Tests were conducted using vegetation in three configurations on eroding banks: alone, in combination with structural protection at the bank toe, and in combination with structural toe protection on reshaped banks. Eleven sites were planted along seven stream channels. Planting methods are summarized below. Following planting, vitality was evaluated by counting living and dead individuals and computing survival percentages or by measuring the bare and vegetated lengths of bankline within the study reach. Channel stability was assessed visually for all sites and using repetitive surveys of selected cross sections and thalweg profiles at most sites. Stream stage, discharge, and precipitation records were obtained for most study sites. Costs for construction were recorded and compared to contemporaneous costs for standard riprap toe protection. Costs for work performed in the late 1970s and early 1980s were obtained from the U.S. Army Corps of Engineers (1981b), while more recent costs (1992-1993) were obtained from documents provided by the Vicksburg District of the U. S. Army Corps of Engineers.

### *Vegetation Alone*

Five tests were conducted using woody vegetation without supporting structural toe protection. Three of the five (V3, V4, and V5) were located upstream from grade control structures that limited bed degradation. Vegetation was planted along the toe of actively eroding, 4-5 m high banks at V1, V2, and V3 (Table 2). Stakes (1-3 cm diameter) or seedlings were planted manually at sites V1 and V2 by thrusting plant materials into soft soils or into holes made with planting bars. At V3, dormant willow posts (Evans *et al.*, 1992; Bhowmik, 1993) 1.5 m long by 8-30 cm diameter were planted 1.2 m deep in the face and along the toe of steep, slowly eroding banks by making holes using a metal ram mounted on an hydraulic hoe (Figure 3). Dormant posts were also used at V4 and V5, but they were planted in sandbars in an effort to restore riparian zones and canopy destroyed by incision-induced channel widening (Volny, 1984). Posts were planted in a series of 1.2-m-deep pits excavated in the sandbar just parallel to the base flow channel. Square pits (about 1.2 m x 1.2 m) were dug within 5 m of the water's edge with an hydraulic hoe, and 10 to 12 posts were placed vertically around the perimeter of each pit before refilling.

The test conducted at V2 was the most extensive in time and space. Both banks along three 610-m long reaches of a 40-m wide straight channel were divided into four plots, each 150 m long. Plots were then randomly assigned to one of four treatments: no planting, planting with black willow (scientific names given in Appendix I), planting with halbert willow, or planting with either basket willow or slender willow. Thus, there were 24 experimental plots, six for each of the four treatments. Initial planting occurred in June 1974, five years after the channel had been enlarged by dredging. Due to low survival rates for initial planting, all plots were replanted in March or April 1976.

TABLE 2. Tests of Vegetation Without Structure.

| Reach | Test Duration | Species Planted | Survival (percent) | Remarks |
|---|---|---|---|---|
| V1 | 1977-1980 | Slender Willow | 54 | Between 1981 and 1994, the reach containing the site was badly eroded, apparently by passage of a series of headcuts. |
| | | River Birch | 54 | |
| | | Hazel Alder | 37 | |
| | | Carolina Willow | 21 | |
| | | Gilg Willow | 12 | |
| V2 | 1974[1]-1986 | Black Willow | 32/67[2] | In 1986, 17 of the 24 plots were classified as stable, while seven were eroding. All stable plots supported stands of black willow and river birch 6-9 m tall. Kudzu was invading four plots. In 1994, banks remained mostly stable, and stands of large trees alternated with kudzu. |
| | | Halbert Willow | 23/0 | |
| | | Slender Willow | 15/0 | |
| | | Gilg Willow | 11/0 | |
| | | No Planting | - -/67 | |
| V3 | 1993-1994 | Black Willow | ~11 | Dormant posts. Mortality due to impermeable soils, competition by kudzu, and erosion. |
| V4 | 1993-1994 | Black Willow | 50 | Sandbar stabilization using dormant posts. Despite relatively low survival, percent of bankline covered with vegetation increased from about 0 to 80 percent. |
| V5 | 1993-1994 | Black Willow | 56 | Sandbar stabilization using dormant posts. Black willow survival was probably lower than for V4 because planting was later. |
| | | River Birch | 4 | |
| | | Sycamore | 2 | |
| | | Cottonwood | 1 | |

[1] Replanted in 1976.

[2] First number is three-year survival for second (1976) planting and represents percent of individuals surviving. Second number is based on 1986 assessment by plot.

Figure 3. Planting Dormant Willow Posts With Hydraulic Hoe and Ram at Site V3.

*Vegetation With Toe Protection*

Three experiments involved planted vegetation with toe protection (Table 3). Arrays of concrete jacks laced together with steel cables were used for toe protection for three separate plots along a straight channel at VT1. The VT2 site consisted of a sinuous reach with concave banks protected by placing a windrow of stone (Maynord, 1994) along the bank toe at rates of 1,500, 6,000, and 9,000 kg $m^{-1}$ to create windrows ~ 1 m high (Figure 4). Windrows were tied into banks at the upstream and downstream ends of each bendway. Alignment of stone toe was designed by an engineer experienced in river stabilization (B. R. Winkley) to minimize erosion by smoothing transitions between bends and slightly reducing curvature. Fourteen bends were treated. In every other bend, water elm seedlings were planted landward of the toe protection, and remaining bends were not planted.

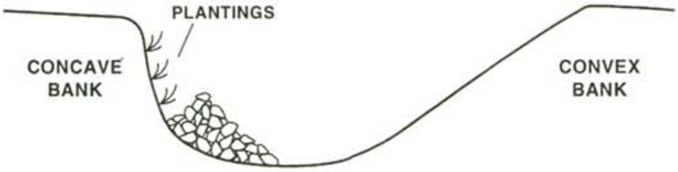

Figure 4. Stone Toe Protection Design Used at VT2 and VT3. Stone is placed in a windrow parallel to the channel. Windrow side slopes are equal to natural angle of repose.

VT3 involved planting dormant posts along the margin of convex bank sandbars as at V4 and V5. A stone windrow (1,500 kg $m^{-1}$) was placed along the margin of the sandbar, and posts 2-25-cm in diameter and 150-180-cm long were planted immediately landward of the stone. About 750 m of bankline was planted with 1,680 posts.

*Vegetation With Structure and Bank Shaping*

Three reaches along two channels were stabilized by grading banks to more gradual slopes, planting vegetation, and placing structure at the toe of concave banks (Figure 5). Shaped banks were graded so that the top of the finished bank sloped away from the channel to prevent drainage of runoff over the face of the slope. Full details of protection designs are provided by Bowie (1982). Two of the reaches (VTS2 and

TABLE 3. Tests of Vegetation With Toe Protection, No Bank Shaping.

| Reach | Toe Protection | Test Duration | Species Planted | Survival (percent) | Remarks |
|---|---|---|---|---|---|
| VT1 | Concrete Jacks | 1978-1980 | Black Willow<br>River Birch<br>Streamco Willow | 75<br>55<br>32 | Two of three plots were vegetated and stable in 1993. The third had been replaced by riprap revetment. |
| VT2 | Stone Toe Protection | 1978-1980 | Water Elm | 60 | By 1981 natural vegetation had taken over all areas landward of toe protection. Spitz *et al.* (1990) noted minor damages to stone structures in four bendways in 1989. No distinction could be made between planted and unplanted areas in 1993. |
| VT3 | Stone Toe Protection | 1992-1993 | Black Willow | 50-60 | Sandbar stabilization. Despite relatively low survival rate, the percent of bankline covered with vegetation was doubled. |

VTS3) were located in bendways, while VTS1 was located in a straight reach.

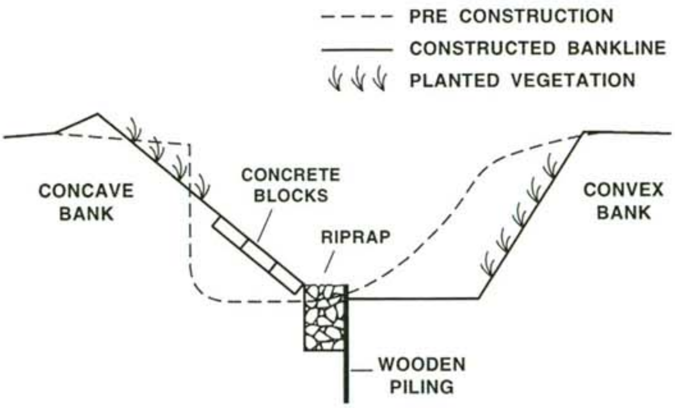

Figure 5. Typical Cross Section (simplified) of Design Involving Vegetation, Bank Shaping, and Structure.

**Straight Reach.** A 184-m long segment of the straight reach (VTS1) was treated by grading the banks to 1V:2.5H. The top 0.6 m of soil along both sides of the channel was stockpiled during bank shaping and later spread on the sloped middle and upper banks to a depth of 30 cm. These soils were limed, fertilized, and compacted prior to planting and mulching. Plant materials consisted of two woody and five nonwoody species (Table 4).

Banks on both sides of the remaining 306 m of the straight reach were regraded from near vertical slopes to a compound slope with segments of 1V:2H (lower bank), 1V:5H (2-m wide planting bench or middle bank), and 1V:2.5H (upper bank). The boundary between the lower and middle banks corresponded to the elevation of the maximum stage for 90-95 percent of estimated annual storm events. Bank toe was protected with riprap placed in 0.8-m deep by 0.8-m wide trenches, and the lower bank was covered with stone or concrete blocks placed on geotextile fabric. Topsoil was stockpiled, replaced, and prepared for planting as described above. Banklines were subdivided into six plots ranging from 62 to 143 m long, and the upper bank of each plot was planted with one of the five herbaceous species listed in Table 4. The middle bank of each plot was planted with a woody species (black willow, streamco willow, or indigo bush). Willows were planted by inserting 30 cm stakes at 75 cm intervals along the bank toe and were thinned to 1.5-m intervals at the beginning of the second growing season.

TABLE 4. Tests of Vegetation With Toe Protection and Bank Shaping.

| Reach | Test Duration | Toe Protection | Species Planted* | Survival (percent) | Remarks |
|---|---|---|---|---|---|
| VTS1 | 1979-1990 | Stone riprap, cellular block | Bristly Locust | 50-70 | Banks remained stable after planting even though 1 m of bed degradation occurred during the first two years after construction. |
| | | | Indigo Bush | 50-70 | |
| | | | Sericea Lespedeza | 80-100 | |
| | | | Alamo switchgrass | 70-90 | |
| | | | Pensacola Bahiagrass | 50-70 | |
| | | | Common Bermudagrass | 30-60 | |
| | | | Crownvetch | 50-70 | |
| VTS2 | 1981-1990 | Stone riprap, concrete cap block, treated wood piling, chain link fence | Black Willow | 60-80 | This site is depicted before and 13 years after construction in Figures 1 and 8, respectively. |
| | | | Bristly Locust | 30-60 | |
| | | | Indigo Bush | 30-60 | |
| | | | Multiflora Rose | 60-80 | |
| | | | Sericea Lespedeza | 80-100 | |
| | | | Pensacola Bahiagrass | 30-60 | |
| | | | Common bermudagrass | 60-80 | |
| | | | Crownvetch | 30-60 | |
| VTS3 | 1980-1990 | Stone riprap, cellular block, treated wood piling, chain link fence | Black Willow | 60-80 | By 13 years after construction, banks were stable and supported a lush mix of planted and native invader species. |
| | | | Multiflora Rose | 60-80 | |
| | | | Alamo switchgrass | 80-100 | |
| | | | Pensacola Bahiagrass | 30-60 | |
| | | | Common Bermudagrass | 30-60 | |
| | | | False Anil Indigo | 40-70 | |
| | | | Common Reedgrass | 30-60 | |

*The following species were tested on shaped banks without success (0-30 percent survival): Streamco willow, Appalow serecia, buffalograss, maidencane, reed canarygrass, subterranean clover, Boston ivy, and English ivy.

**Bendway Sites.** Bank shaping at the bendway sites was extensive enough to reduce channel curvature, flatten the near-vertical concave banks without infringing on adjacent farmland, and increase total cross-sectional area 25-45 percent (Figure 5). Convex banks were excavated to gradual slopes (1V:2H, VTS2; 1V:5H, VTS3), and excavated material was used to fill concave slopes to final grades ranging from 1V:2H to 1V:4H. Top soil was stockpiled and spread to a depth of 0.2 m on finished slopes, limed, and fertilized, before planting and mulching. A 0.9-m deep by 1.5-m wide trench was excavated along the toe of concave banks, and 0.2-m diameter treated wooden pilings were driven on 2.4-m centers along the streamward edge of the trenches. Pilings protruded 0.6-m above the adjacent streambed. Galvanized chain link fencing was attached to the bank sides of the pilings, and the toe trench was backfilled with stone to the top of the pilings. Lower banks were protected with an articulated matting made of concrete cap blocks and wire netting (VTS2) or cellular concrete blocks (VTS3).

Convex banks received less structural protection than concave banks (Figure 5). After shaping, convex banks were planted with annual ryegrass for temporary cover and bermudagrass for permanent cover. The toe of the convex bank at VTS2 was planted with black willow. Upper banks were planted with a variety of herbaceous and woody species including seven grasses, three trees, and two shrubs (Table 4).

## RESULTS

### *Vegetation Alone*

Short-term (1-3 growing seasons) survival rates for woody species varied from 0-56 percent (Table 2). Mortality was due to one or more reasons including drought, bank erosion, covering by sediment, abrasion by high velocity (>1 m $s^{-1}$) flows, poor soils, and competition by the exotic vine kudzu. At V3, 34 percent of the dormant posts were destroyed by erosion or deposition during the first year, and 56 percent were lost due to covering by kudzu or impermeable soils (Grissinger and Bowie, 1984). Native black willow was found superior to the hybrid varieties of willow in both survival and growth. With the exception of river birch at V1, short-term survival rates for species other than black willow were less than 40 percent. Short-term willow survival was sharply reduced when planting occurred after leaf buds began to swell (ca. 1 April).

Long-term results, which were available for V1 and V2, illustrate the importance of bed stability. Two of the five species planted at V1 had short-term survival rates > 50 percent, and the planted banks were stable over the short term. However, when V1 was inspected 17 years after planting, headcuts that Schumm *et al.* (1981) found downstream of V1 had evidently moved through the reach, causing considerable bed erosion and bank failure. In contrast, the initial planting failed at V2, and short term survival rates for the second planting were relatively low (Table 2). However, banks were generally stable over the long term. By 10 years after planting, native species had taken over all stable banklines. Five of the six unplanted plots were stable and supported dense woody vegetation, equaling or exceeding the performance of the treatments involving planting. Figure 6 depicts typical conditions in the V2 reach 20 years after initial planting and 18 years after replanting. Bank stability was likely related to the fact that the V2 bed was stable to slightly aggradational during the period of observation (Schumm *et al.*, 1981; Watson and Alexander, 1989; Fullerton and Grindeland, 1990).

Dormant willow posts showed promise for initial establishment of woody vegetation on sandbars as a riparian zone restoration measure. Species other than willow fared poorly when planted as dormant posts, with survival rates of only 1-4 percent (V5, Table 2). However, survival in the V5 experiment was likely depressed by a late planting date (mid April) and a midsummer drought following planting (July rainfall was only 17 percent of normal.) Willow posts planted two weeks earlier and slightly closer to the base flow channel at the adjacent V4 site fared much better in spite of the drought. Long-term performance of willow posts on sandbar margins will depend upon the ability of the plants to withstand high velocity flows and to function in droughty, infertile soils.

Three sites, which all involved the use of dormant posts, had costs ranging from \$8 to \$20 $m^{-1}$ of protected bankline, or about 5-14 percent of 1992 costs for riprap stone toe protection at 6,000 kg $m^{-1}$. Costs were unavailable for V1 and V2.

### *Vegetation With Toe Protection*

All three of the reaches protected by vegetation and structure at the bank toe remained stable in spite of rigorous environmental conditions (Figure 7). The survival rates shown in Table 3 for VT1 and VT2 were measured following a growing season (1980) for which precipitation was only 33 percent of normal (Bowie, 1982) and temperatures were an average of 1.8°C above normal (National Climatic Center, undated). Channel surveys showed 30-60-cm of bed degradation


3 23 '94

Figure 6. Site V2 About 18 Years After Vegetation Was Replanted. Stands of river birch and black willow 30-cm in diameter by 10-15-m high alternate with areas covered by kudzu. Note sand deposition at toe of opposite bank.

between 1985 and 1991 at VT1. At VT3, a near bankfull discharge occurred just 11 days after construction was completed, but significant damages to the stone toe and plantings did not occur.


3 28 '94

Figure 7. Typical View Within Site VT2 16 Years After Construction. Schematic of design is shown in Figure 4.

When inspected in 1993, two of the three VT1 plots were covered with a variety of commonly-occurring riparian trees (willow and river birch), while the third, which was adjacent to a bridge, had been replaced by a riprap revetment. At VT2, natural vegetation took over both the planted and the unplanted areas landward of the stone toe within three years. Evidently, banks landward of the stone toe caved to their angle of repose, and transport of caved material was prevented by the toe protection. In a short period of time, the caved material was vegetated, and active erosion was eliminated.

The period of record at VT3 is shorter than for the other two test sites. At this site, only 50-60 percent of the posts survived two growing seasons. Nevertheless, because of the high density of plantings, the fraction of the sandbar margin that supported woody vegetation increased from 38-78 percent after two growing seasons. Willow posts produced dense foliage, with limbs reaching an average height of about 2-m above the adjacent ground surface. Most of this growth occurred during the first growing season. Signs of beaver (*Castor canadensis*) activity and herbivory were plentiful, but that did not seem to affect willow survival, for plants resprouted vigorously after cutting by beaver. Comparison of cross-section surveys taken one year before and one year after construction showed that the sandbar margins protected by willow posts and stone were very stable.

Costs were unavailable for VT1, but costs for VT2 and VT3 were 96 percent and 28 percent, respectively, of costs for riprap stone toe protection (6,000 kg $m^{-1}$) without vegetation. Stone toe protection at VT2 was applied at rates of 1,500, 6,000, and 9,000 kg $m^{-1}$ (varying from bendway to bendway), while the application rate at VT3 was 1,500 kg $m^{-1}$.

### *Reaches With Bank Shaping*

Study reaches with shaped banks were subjected to severe climatic stresses during the 12-year period of observation, but they remained well-vegetated and stable (Figure 8). Planted and native species gradually invaded areas protected by rock and concrete blocks, colonizing deposited sediments and interstitial soils (Figures 7 and 8), and perhaps increasing the strength of the block revetments (Hewlett *et al.*, 1987). Rainfall for four of the growing seasons was extremely light, ranging from no rainfall for 30 consecutive days to an average of only 43 percent of normal. During these dry periods, temperatures were 4-7°C above normal levels for several successive days. Record low temperatures occurred in three consecutive winters, falling 3°C below normal for 28 successive days during 1985.

Figure 8. Site VTS2 13 Years After Construction. This photograph is taken from the same point as Figure 1. Schematic of design is shown in Figure 5.

At least 27 storm events producing peak stages more than 1-m above base flow elevations were observed at VTS1 and VTS2 during the first two years following construction. Storm hydrograph base widths ranged from 5.4 to 39.2 hours. Observed velocities exceeded 3.5 m $s^{-1}$ (channel centerline) and 0.8 m $s^{-1}$ (near bank). Record events producing bankfull flows occurred in the second and third years. About 1 m of bed degradation occurred at VTS1 during the first two years following construction. This bed lowering caused rock and cellular block revetment to slide down the bank, exposing the underlayer of geotextile. Nevertheless, banks in all three of the reaches subjected to shaping remained stable. Degradation was halted by completion of a grade control structure immediately downstream from VTS1.

Two of the 12 herbaceous species (Alamo switchgrass and sericea lespedeza) tested on shaped banks consistently performed well (60-100 percent ground cover, Table 4). Alamo switchgrass grew to a height of 1.5 m but reclined to form protective matting during high flows. Stands survived inundation and swift velocities with no appreciable damage, and induced sediment deposition along concave banks. Over time, the Alamo switchgrass produced heavy thatch which required controlled burning to prevent restriction of new growth. Other herbaceous species were intolerant of climatic extremes or were unsuccessful in competition against native species. Two of the seven woody species (black willow and multiflora rose) were consistent performers (60-80 percent survival of individuals). Black willow planted on 1.5 m centers grew rapidly, attaining average heights of 2.4 and 3.1 m at the ends of the second and third growing seasons, respectively. Multiflora rose was tolerant of inundation and climatic extremes and formed a dense shrub suitable for use as a hedge to exclude livestock as suggested by Edminster *et al.* (1949). However, others have noted that this species can become a pest in pastures and abandoned fields.

Construction costs for reaches with bank shaping were elevated by the "demonstration" nature of the planting designs. Construction costs, including excavation and fill, ranged from \$173-\$270 $m^{-1}$ of protected bankline, or about 173-270 percent of costs for riprap stone toe protection (6,000 kg $m^{-1}$) incurred at the same time (1979-1981).

## DISCUSSION

Banks along incising stream channels fail by several mechanisms. Perhaps the most important is catastrophic collapse that occurs when gravity forces exceed soil strength. Analyses by Osman and Thorne (1988) and others have shown that for a given bank height and soils, the ability of a bank to withstand this failure mechanism is inversely related to bank angle. Therefore, banks along an incised channel that is not growing deeper may be stabilized against gravity failure by either grading the bank to a more gradual slope or stabilizing the toe. If the toe is protected but the bank is not graded, the bank may fail landward of the toe to create a stable angle. The toe protection will then ensure that the angle will not be increased by erosion. Once stabilized, banks composed of soils that are suitable for vegetation will be dominated by native species (in our region, principally black willow and river birch) within a few years. If other mechanisms (e.g., piping, direct removal of material by flowing water, overbank drainage) are not significant, planting vegetation and placing additional structure will be superfluous. Our experience indicates that stands of species that are not native pioneers will require considerable maintenance if they are to avoid succession. Hupp (1992) observed similar patterns of woody species succession at 150 sites along incised channels in Western Tennessee. Amarasinghe (1992) found natural revegetation by herbaceous species to be effective in controlling bank erosion along a nonincised channel in Britain.

Accordingly, toe protection appears to be the most efficient approach for stabilizing banks along incised channels that are no longer actively downcutting. A short term study (< 6 years) of a wide variety of protection structures in 220 bendways throughout the Yazoo Basin of northwest Mississippi indicated that longitudinal stone dikes similar to the ones placed at VT2 and VT3 were the best forms of protection for incising channel banks (U. S. Army Corps of Engineers, 1981b). Spitz *et al.* (1990) inspected a large number of these and similar Yazoo basin bendways in 1989. Reaches containing 12 types of protection structures that were 8-18 years old were inspected, and longitudinal stone toe protection was found to be the most cost-effective structural type.

What then are the benefits of planting vegetation along incised channels? If a new wave of channel degradation passes through a reach, a healthy stand of natural or planted vegetation may retard bank collapse by imparting additional strength to bank soils as in the case of our VTS2 and VTS3, but if bank heights become great enough, even the best vegetation will prove inadequate. Furthermore, planted stands may establish and mature enough to protect a bank against erosion by direct abrasion in a shorter period of time than for natural invasion. Planted vegetation may be selected and placed to offer less resistance to flow than natural invaders, reducing frequency of overbank flooding. However, flow resistance due to bank vegetation is rarely an issue in wider channels (Volny, 1984) or in channels enlarged by incision.

Planted vegetation (in particular, dormant posts) can accelerate colonization of large bars that form within channels enlarged by erosion, storing sediments and creating a more natural stream corridor (as at V4, V5, and VT3). Colonization of these bars by natural invasion will necessarily be slower because the narrow range of conditions required by species like willow for germination and establishment (Maisenhelder and Heavrin, 1956) are unusual along straight, incised channels which tend to have flashy hydrology.

Evidence collected by other investigators suggests that dormant posts are more resistant to drought and erosion during the period of establishment than other types of planted vegetation (Slowikowski *et al.*, 1992). Our findings and work by others (Evans *et al.*, 1992; Bhowmik, 1993; personal communication, Mr. David Derrick, U. S. Army Engineer Waterways Experiment Station) suggests that costs for dormant willow posts are attractive relative to costs for stone structures. Coppin and Richards (1990) have noted that cost comparisons between vegetation and inert structures should consider life cycle costs. Vegetation typically has lower construction costs, higher maintenance costs, and perhaps less frequent requirements for rehabilitation or replacement.

## CONCLUSIONS

Bed stability is a necessary but not sufficient condition for bank stability in incised channels. If the channel bed is protected against degradation, banks may be stabilized against the effects of mass gravity failure by adequate structural toe protection but not vegetation. Alternatively, banks may be graded to a stable angle. In the humid southeast, stable banks composed of fertile soils will be rapidly colonized by native species. Planted vegetation is useful for protecting banks against erosion other than that driven by mass gravity failure (e.g., direct scour by current, overbank flow, and, to some extent, piping). Native species, particularly willow, appear best adapted to streambank environments. Sericea lespedeza and Alamo switchgrass were the best non-woody species tested.

Incremental costs for including middle and upper bank planting in structural toe protection designs are minimal. All bank protection schemes involving vegetation require considerable care in handling and installation of plant materials. Dormant willow posts have great potential for channel stabilization when adequate soils are present, and competition from kudzu is not a factor. Kudzu, which was unfortunately planted along channels by construction agencies, presents perhaps the greatest long-term obstacle to restoring stable, functional riparian zones along incised channels in our region.

## APPENDIX I
## PLANTS USED AT BANK PROTECTION STUDY SITES

| Common Name | Scientific Name |
|---|---|
| **Woody Species** | |
| black willow | *Salix nigra* |
| Arnot bristly locust | *Robinia fertilis* |
| Carolina willow | *Salix caroliniana* |
| cottonwood | *Populus deltoides* |
| false anil indigo | *Indigofera pseudotinctoria* |
| gilg willow | *Salix gilgiana* |
| halbert willow | *Salix hastata* |
| hazel alder | *Alnus rugosa* |
| indigo bush | *Amorpha fruticosa* |
| Halifax maidencane | *Panicum hemitomon* |
| multiflora rose | *Rosa multiflora* |
| river birch | *Betula nigra* |
| slender willow | *Salix gracilis* |
| Streamco willow | *Salix purpurea* |
| sycamore | *Platanus occidentalis* |
| water elm | *Planera aquatica* |
| **Nonwoody Species** | |
| Alamo switchgrass | *Panicum virgatum* |
| annual ryegrass | *Lolium multiflorum* |
| Appalow sericea | *Lespedeza cuneata* |
| Boston ivy | *Parthenocissus tricuspidata* |
| buffalograss | *Buchloe dactyloides* |
| common bermudagrass | *Cynodon dactylon* |
| common reedgrass | *Phragmites communis* |
| Penngift crownvetch | *Coronilla varia* |
| English ivy | *Hedera helix* |
| kudzu | *Pueraria lobata* |
| Pensacola bahiagrass | *Paspalum notatum* |
| reed canarygrass | *Phalaris arundinacea* |
| sericea lespedeza | *Lespedeza cuneata* |
| subterranean clover | *Trifolium subterraneum L.* |

### ACKNOWLEDGMENTS

Assistance provided by the U. S. Army Corps of Engineers and the U. S. Soil Conservation Service in constructing test sites is gratefully acknowledged. P. D. Mitchell prepared Figures 2, 4 and 5. Earl Grissinger, Steve Abt, Don Gray, Joe Snider, Randy Oswalt, and Cliff Hupp and two anonymous referees reviewed a draft of this manuscript and made many helpful comments.

### LITERATURE CITED

Amarasinghe, Ivan. 1992. Effects of Bank Vegetation In Waterways with Special Reference to Bank Erosion, Shear Strength, Root Density and Channel Hydraulics. Ph.D. thesis submitted to the Biology Department, the Open University, Milton Keynes, United Kingdom.

Barnes, R. C., Jr., 1968. Streambank Erosion. Soil Conservation 33(6):126-128.

Bhowmik, N. G., 1993. Evaluation and Utilization of Biotechnical Techniques and Willow Posts for Stabilizing Eroding Streambanks. Preprints of the International Riprap Workshop, Theory, Policy and Practice of Erosion Control Using Riprap, Armour Stone and Rubble, Delft Geotechnics, Netherlands, pp.163-192.

Boon, P. J., 1992. Essential Elements in the Case for River Conservation. *In:* River Conservation and Management, P. J. Boon, P. Calow, and G. E. Petts (Editors). John Wiley and Sons, Chichester, United Kingdom, Chapter 2, pp. 11-33.

Bowie, A. J., 1982. Investigations of Vegetation for Stabilizing Eroding Streambanks. Transactions of the American Society of Agricultural Engineers 25 (6): 1601-1606, 1611.

Bowie, A. J. and C. K. Mutchler, 1986. Sediment Sources and Yields from Complex Watersheds. *In:* River Sedimentation, S. Y. Wang, H. W. Shen and L. Z. Ding (Editors). University of Mississippi, University, Mississippi, Volume III, pp. 1223-1232.

Bowie, A. J.,1987. Stream Channel Erosion Contribution to Sediment Yields in Complex Watersheds. *In:* Proceedings of the 17th Mississippi Water Resources Conference, E. J. Hawkins (Editor). Mississippi Water Resources Research Institute, Mississippi State, Mississippi, pp. 55-61.

Coppin, N. J. and I. G. Richards (Editors), 1990. Use of Vegetation in Civil Engineering. Construction Industry Research and Information Association/Butterworths, London.

Daniels, R. B., 1960. Entrenchment of the Willow Drainage Ditch, Harrison County, Iowa. American Journal of Science 258:161-176.

Edminster, F. C., W. S. Atkinson, and A. C. McIntyre, 1949. Streambank Erosion Control on the Winooski River, Vermont. Circular No. 837, U.S. Department of Agriculture, Soil Conservation Service, Washington, D. C.

Elmore, W. and R. L. Beschta, 1989. The Fallacy of Structure and the Fortitude of Vegetation. Proceedings of the California Riparian Systems Conference. Pacific Southwest Forest and Range Experiment Station, 544, Berkeley, California, Gen. Tech. Rep. PSW-110, pp. 116-119.

Evans, J. L., B. Bennet, and D. Roseboom, 1992. Vegetative Streambank Protection in Court Creek Watershed. Presented at the 1992 International Summer Meeting of the American Society of Agricultural Engineers, Charlotte, North Carolina, Paper No. 922104, American Society of Agricultural Engineers, St. Joseph, Michigan.

Fullerton, William T. and Thomas R. Grindeland, 1990. Final Detailed Field Investigation Coldwater River and Tributaries: Coldwater River Watershed. Delivery Order No. 0003, Contract No. DACW-38-89-D-0113, for U.S. Army Corps of Engineers, Vicksburg, Mississippi; Lenzotti & Fullerton Consulting Engineers, Inc., Breckenridge, Colorado; and Simons, Li & Associates, Inc., Fort Collins, Colorado.

Galay, V. J., 1983. Causes of River Bed Degradation. Water Resources Research 19(5):1057-1090.

Gray, D. H. and A. T. Leiser, 1982. Biotechnical Slope Protection and Erosion Control. Van Nostrand Reinhold, New York, New York, pp. 173-177.

Grissinger, E. H. and A. J. Bowie, 1984. Material and Site Controls of Stream Bank Vegetation. Transactions of the American Society of Agricultural Engineers 27(6):1829-1835.

Grissinger, E. H. and J. B. Murphey, 1983. Present Channel Stability and Late Quaternary Valley Deposits in Northern Mississippi. Special Publication of the International Association of Sedimentologists 6:241-250.

Grissinger, E. H., A. J. Bowie, and J. B. Murphey. 1991. Goodwin Creek Bank Instability and Sediment Yield. Proceedings of the Fifth Federal Interagency Sedimentation Conference (FIASC), PS32-PS39, Las Vegas, Nevada, 1991, Federal Energy Regulatory Commission.

Grissinger, E. H. and J. B. Murphey, 1989. Goodwin Creek Channel Morphology and Stability. Sediment Transport Modeling Proceedings, International Symposium, New Orleans, Louisiana, 1989, USDA, National Sedimentation Laboratory, pp. 542-547.

Grissinger, E. H. and J. B. Murphey, 1982. Present "Problem" of Stream Channel Instability in the Bluff Area of Northern Mississippi. Journal of the Mississippi Academy of Sciences 27:117-128.

Grissinger, E. H. and J. B. Murphey, 1986. River Sedimentation *In:* Bank and Bed Adjustments in a Yazoo Bluffline Tributary, S. Y. Wang, H. W. Shen, and L. Z. Ding (Editors). Third International Symposium on River Sedimentation, The University of Mississippi, Oxford, Mississippi, Volume III, pp. 1003-1012.

Harvey, M. D. and C. C. Watson, 1986. Fluvial Processes and Morphological Thresholds in Incised Channel Restoration. Water Resources Bulletin 22(3):359-368.

Hathaway, R. L., 1986. Plant Materials for River Control and Bank Protection. *In:* Plant Materials Handbook for Soil Conservation Volume 1: Principles and Practices, C. W. S. Van Kraayenoord and R. L. Hathaway (Editors). Ministry of Works and Development, Wellington, New Zealand, Chapter 5, pp. 57-67.

Hemphill, R. W. and M. E. Bramley, 1989. Protection of River and Canal Banks. Construction Industry Research and Information Association/Butterworths, London.

Hewlett, H. W. M., L. A. Boorman, and M. E. Bramley. 1987. Design of Reinforced Grass Waterways, Report 116, Construction Industry Research and Information Association, London.

Hupp, C. R., 1992. Riparian Vegetation Recovery Patterns Following Stream Channelization: A Geomorphic Perspective. Ecology, 73(4):1209-1226.

Hupp, C. R. and A. Simon, 1991. Bank Accretion and the Development of Vegetated Depositional Surfaces along Modified Alluvial Channels. Geomorphology 4:111-124.

Keown, M. P., N. R. Oswalt, E. B. Perry, and E. A. Dardeau, Jr., 1977. Literature Survey and Preliminary Evaluation of Streambank Protection Methods. Technical Report No. H-77-9, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Little, W. C. and J. B. Murphey, 1981. Evaluation of Streambank Erosion Control Demonstration Projects in the Bluffline Streams of Northwest Mississippi. Appendix A of Stream Channel Stability Report to the Vicksburg District, U. S. Army Corps of Engineers, AD A101 386, National Technical Information Service, Washington, D. C.

Little, W. C., C. R. Thorne, and J. B. Murphey, 1982. Mass Bank Failure Analysis of Selected Yazoo Basin Streams. Transactions of the American Society of Agricultural Engineers 25(5):1321-1328.

Lowrance, R. R., R. L. Todd, J. J. Fail, O. J. Hendrickson, R. A. Leonard, and L. E. Asmussen, 1984. Riparian Forests as Nutrient Filters in Agricultural Watersheds. BioScience 34(6):374-377.

Lowrance, R. R., R. A. Leonard, and J. M. Sheridan, 1985. Managing Riparian Ecosystems to Control Nonpoint Pollution. Journal of Soil and Water Conservation 40(1):87-91.

Maisenhelder, L. C. and C. A. Heavrin, 1956. Silvics and Silviculture of the Pioneer Hardwoods – Cottonwood and Willow. Proceedings, Society of American Foresters; Memphis, Tennessee/Washington, D.C., pp. 73-75.

Maynord, S. T. 1994. Toe Scour Protection Methods. *In:* Hydraulic Engineering 94, G. V. Contronco and R. R. Rumer (Editors). American Society of Civil Engineers, New York, New York, pp. 1035-1039.

Murphey, J. B. and E. H. Grissinger, 1985. Channel Cross-section Changes in Mississippi's Goodwin Creek. Journal of Soil and Water Conservation 40(1):148-153.

National Climatic Center (undated). Climatological Data, Annual Summary, Mississippi, 1980. National Oceanic and Atmospheric Administration, Environmental Data and Information Service, Asheville, North Carolina, Volume 85, No. 13.

Osman, A. M. and C. R. Thorne, 1988. Riverbank Stability Analysis: I. Theory. Journal of Hydraulic Engineering 114(2):134-150.

Petersen, M. S., 1986. River Engineering. Prentice-Hall, Englewood Cliffs, New Jersey.

Piest, R. F., L. S. Elliot, and R. G. Spomer, 1977. Erosion of the Tarkio Drainage System, 1845-1976. Transactions of the American Society of Agricultural Engineers 20(3):485-488.

Pinay, G., H. Decamps, E. Chauvet, and E. Fustec, 1990. Functions of Ecotones in Fluvial Systems. *In:* The Ecology and Management of Aquatic-Terrestrial Ecotones, R. J. Naiman, and H. Decamps (Editors). United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris, France, Chapter 8, pp. 141-169.

Schiechtl, H. M. 1980. Bioengineering for Land Reclamation and Conservation. The University of Alberta Press, Hignell Printing Ltd., Winnipeg, Manitoba, Canada.

Schumm, S. A., M. D. Harvey, and C. C. Watson, 1981. Yazoo Basin Geomorphology, Part II: Geomorphic Studies of Oaklimiter Creek, Tippah River, and Pigeon Roost Creek, North-Central Mississippi. Final Report, Project SCS-23-MS-80, U. S. Soil Conservation Service, Jackson, Mississippi.

Simon, A., 1989. The Discharge of Sediment in Channelized Alluvial Streams. Water Resources Bulletin 25(6):1177-1188.

Simon, A. and C. H. Robbins, 1987. Man-Induced Gradient Adjustment of the South Fork Forked Deer River, West Tennessee. Environ. Geol. Water Sci. 9(2):109-118.

Simon, A. and C. R. Hupp, 1986. Channel Widening Characteristics and Bank Slope Development Along a Reach of Cane Creek, West Tennessee. Selected Papers in the Hydrologic Sciences 113-126.

Simon, A. and C. R. Hupp, 1987. Geomorphic and Vegetative Recovery Processes Along Modified Tennessee Streams: An Interdisciplinary Approach to Disturbed Fluvial Systems. International Association of Hydrological Sciences, Publication 167:251-262.

Slowikowski, James A., William C. Bogner, and Nani G. Bhowmik, 1992. An Evaluation of Streambank Stabilization Work on Richland Creek. Final Report for Illinois Department of Energy and Natural Resources, Springfield, Illinois, Illinois State Water Survey, Champaign, Illinois.

Smith, L. M. and D. M. Patrick, 1991. Erosion, Sedimentation, and Fluvial Systems. Geological Society of America Centennial Special Volume 3:169-181.

Spitz, William J., Lyle W. Zevenbergen, and Chester C. Watson, 1990. Re-Evaluation of the Streambank Erosion Control Evaluation and Demonstration Project. Delivery Order No. 0006, Contract No. DACW38-88-D-0099, for U. S. Army Corps of Engineers, Vicksburg, Mississippi, Water Engineering and Technology Inc., Fort Collins, Colorado.

Thorne, C. R., J. B. Murphey, and W. C. Little, 1981. Bank Stability and Bank Material Properties in the Bluffline Streams of Northwest Mississippi. Appendix D of Stream Channel Stability Report to the Vicksburg District, U. S. Army Corps of Engineers, National Technical Information Service, Washington, D.C.

Thorne, C. R., 1982. Processes and Mechanisms of River Bank Erosion (Chapter 9). *In:* Gravel-Bed Rivers: Fluvial Processes, Engineering and Management, R. D. Hey, J. C. Bathurst, and C. R. Thorne (Editors). John Wiley & Sons Ltd, Chichester, United Kingdom.

U.S. Army Corps of Engineers, 1981a. The Streambank Erosion Control Evaluation and Demonstration Act of 1974, Section 32, Public Law 93-251. Main Report of Final Report to Congress, Washington, D. C.

U.S. Army Corps of Engineers, 1981b. The Streambank Erosion Control Evaluation and Demonstration Act of 1974, Section 32, Public Law 93-251. Final Report to Congress, Appendix F, Yazoo Basin Demonstration Projects, Washington, D. C.

U.S. Department of Agriculture, 1982. Mississippi Water and Related Land Resources. Main Report - Phase I, U.S. Department of Agriculture, Soil Conservation Service, Jackson, Mississippi.

Volny, S., 1984. Riparian Stands. *In:* Developments in Agricultural and Managed Forest Ecology, O. Riedl and D. Zachar (Editors), Elsevier Scientific Publishing Company, Amsterdam, Chapter VIII, pp. 423-453.

Watson, Chester C. and William G. Alexander, 1989. Coldwater River Watershed Data Collection Preliminary Field Reconnaissance and Channel Assessment. Delivery Order No. 0003, Contract No. DACW38-88-D-0099, for U.S. Army Corps of Engineers, Vicksburg, Mississippi; Water Engineering & Technology, Inc., Fort Collins, Colorado.

Whitten, C. B., and D. M. Patrick, 1981. Engineering Geology and Geomorphology of Streambank Erosion (Report 2: Yazoo River Basin Uplands, Mississippi). Technical Report GL-79-7, Report 2 of a Series.

Wilson, K. V. and D. P. Turnipseed, 1989. Channel Stability of Selected Streams in Northern Mississippi. Proceedings of the Nineteenth Mississippi Water Resources Conference, Jackson, Mississippi, pp. 104-112.

Wilson, K. V. and D. P. Turnipseed, 1990. Channel and Bank Stability of Wolf Creek and a Tributary at U. S. Highway 45 near Wheeler, Prentiss County, Mississippi. Open File Report 90-110, U. S. Geological Survey, Jackson, Mississippi.