EXPERIMENT IN STREAM RESTORATION

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ABSTRACT: Aquatic habitats in a deeply incised sand-bed channel were modified by adding 1,380 t of stone and planting dormant willow posts. Restoration structures (groin extensions and longitudinal toe protection) were designed as complements to existing channel stabilization works. Prior to restoration, base-flow aquatic habitats were characterized by uniform conditions, little woody debris or riparian vegetation, shallow depths, and sandy bed material. The stage-discharge relationship, channel geometry, and bed material size were unaffected by restoration, but the average depth of scour holes adjacent to extended groins increased from 32 cm to 72 cm, and pool habitat in the lower half of the study reach increased from 2.9% to 14% of water surface area. Median water depth at base flow increased from 9 cm to 15 cm. Woody vegetation cover on one side of the channel increased from 38% to 78%. Fish numbers tripled, median fish size increased by 50%, and the number of species increased from 14 to 19. Groin extensions experienced partial failure due to erosion of sand from underneath stones.

INTRODUCTION

Hydraulic engineers are increasingly becoming involved in environmental restoration projects. One particularly challenging type of project involves modification of an alluvial channel to restore habitat or aesthetic values lost due to earlier water projects or poor watershed land management. The need for restoration is especially acute in regions such as the immediate drainage of the lower Mississippi River, where 25,000 km of 142,000 km of bank line are eroding (U.S. Army Corps of Engineers 1981), and rainfall-runoff relations have been transformed. Ecological significance of stream restoration efforts hinges on the fact that many watersheds have only a few unimpacted segments remaining in small tributaries. Additional significance must be placed on restoration in areas where the majority of stream ecosystems have been damaged.

Restoration design criteria are especially needed for small-to-medium sized incised channels (watersheds $< \sim 1{,}000$ km^2). Such a project requires inputs from several disciplines, use of the latest guidance (e.g., *Restoration* 1985; Brookes 1988; *River* 1992, *Alternatives* 1989), and considerable professional judgment. Hydraulic analysis of restoration projects has received little attention (Heiner 1991). Since primary benefits of environmental restoration efforts are usually intangible or very difficult to quantify, economic constraints on these projects are often very strong. The scale of restoration projects in these watersheds precludes costly, elaborate investigations for planning and design. Available data sets often do not support mathematical simulation studies, and empirical approaches based on assumptions of dynamic equilibrium are of limited use due to continuing complex responses to previous channel and watershed perturbations.

Channel incision occurs when sediment transporting capacity exceeds sediment supply and bed level controls (e.g., erosion-resistant strata) are weak or absent. Sediment transporting capacity can be increased by channel straightening or removal of large roughness elements, while sediment supply can be restricted by urbanization or upstream impoundments. Physical changes in channel systems undergoing incision have been described by many workers (Galay 1983; Grissinger and Murphey 1983; Piest et al. 1977; Simon 1989; Simon and Robbins 1987; Harvey and Watson 1986). In many cases erosion of the bed (channel lowering) is initially dominant over channel widening, but when a critical threshold is passed, widening can be explosively rapid, and increases in channel cross-sectional area of up to 1,000% within a few years have been reported (Harvey and Watson 1986). Incision of a channel lowers base level for all of its tributaries, thus destabilizing the entire watershed. Ecological impacts are also severe. Incision severs a stream from its traditional land-water interface, the floodplain, depriving the stream of carbon and nutrients. Aquatic habitats in unstable channels are typically of low quality due to frequent extreme temporal variations in hydraulic variables (Carline and Klosiewski 1985), lack of woody debris, continually shifting bed material, shallow, uniform base-flow depths (Shields et al. 1994), elevated sediment loads (Simon 1989), and the isolation of instream aquatic habitats from the floodplain due to channel incision and widening.

Since incision results in long-term morphologic transformation at the landscape scale, its potential for degrading biotic integrity is greater than point-source or non–point-source pollution (Karr 1991), and unassisted ecosystem recovery can be expected to be slow (Yount and Niemi 1990). Although a large body of literature addresses placement of simple structures in stream channels to improve aquatic habitats (Swales 1989; Wesche 1985; Shields 1983), relatively little hydraulic design guidance is available. Salmonid habitat restoration projects in the Pacific Northwest have been widely described (e.g., Kauffman et al. 1993; Beschta et al. 1993), but similar information is less plentiful for warmwater streams of the Southeast and Midwest, despite their higher levels of biological diversity. Furthermore, restoration of unstable, incised warmwater streams has received little attention (Shields et al. 1992). For example, classification systems advanced by Rosgen (1985, 1994) for developing restoration prescriptions do not include categories for these types of channels. Design for warmwater-stream restoration is complicated by channel instability, large fluctuations in discharge (Carline and Klosiewski 1985; Fajen 1981), and more complex ecology than that of coldwater streams.

The purpose of the present paper is to describe short-term results of experimental restoration of an incised warmwater sand bed stream. The objective of the restoration project was to improve aquatic habitats by accelerating natural processes promoting recovery of channel equilibrium, riparian vegetation, and stream-floodplain interaction. Project planning and design are summarized, and physical conditions before and after restoration are described. Biological response to

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restoration, which included an order of magnitude increase in fish biomass and doubling of the number of fish species and average fish length has been described elsewhere (Shields et al. 1993).

STUDY SITE

Hotophia Creek, an incised channel in the hills of northwest Mississippi, was selected for experimental restoration. The reach selected for restoration was immediately upstream of a grade control structure and was relatively stable (Swanson 1989; Shields et al. 1992). Site location is shown in Fig. 1, a typical view of the upper end of the study reach is shown in Fig. 2, and physical characteristics of the study reach are summarized in Table 1. At the time of this study (1991–1993), only 8% of the watershed was cultivated, while 40% was idle or pasture, and 52% was forested or water area. In general, cultivated areas were limited to valley bottoms. Historically, much of the watershed has been cultivated or timbered. European settlement of the area, which began about 1830, was followed by deforestation, cultivation, rapid erosion of hillsides, and accelerated valley sedimentation (Happ et al. 1940). Between about 1840 and 1930 individual landowners and drainage districts attempted to reclaim valley lands by channelizing streams. A second round of channelization by federal agencies occurred between about 1930 and 1965. Flood control reservoirs were built on major rivers draining the hill region between 1940 and 1954.

The study reach responded to channelization and reduction of flood stages on its receiving stream by rapid incision and accelerated bank erosion. Incision often occurred by upstream progression of knickpoints ("headcutting"), as described by Whitten and Patrick (1981) and Smith and Patrick (1991), and averaged about 5 m throughout the basin (Whitten and Patrick 1981; Soil Conservation Service 1991). Aerial photographs taken in 1937, 1953, 1957, 1963, 1968, 1975, 1977, 1979, and 1985 show instability advancing on the study reach from downstream beginning in 1957. Channel widening accelerated after the channel was cleared and snagged in 1961 and channelized in 1963, when the sinuosity of the 1-km study reach was reduced from 1.8 to 1.2 by cutting off five bends. Mean channel top width increased from 17 m to 42 m between 1953 and 1985, and comparison of a 1976 profile (U.S. Army Corps of Engineers, undated) with data collected for this study indicated about 1.2 m of bed degradation between 1976 and 1991.

Channel response was characteristic of systems described by the incised channel evolution model (ICEM) (Harvey and Watson 1986; Simon 1989), a conceptual framework that correlates channel morphology with bed degradation processes. According to the ICEM, channels incise following channel straightening or lowering of base level by headward progression from the mouth to the watershed divides. Channels initially deepen as small waterfalls (headcuts) or oversteepened zones (knickzones) migrate upstream, and then rapidly widen after bank heights exceed a critical threshold. The ICEM recognizes five or six distinct stages of channel evolution, with the latter stages (V and VI) characterized by deposition and gradual revegetation of large sandbars within channels enlarged by erosion. Downstream reaches within an incising watershed often are in the latter stages of evolution while upstream and tributary reaches are in earlier stages, still actively enlarging, and producing large volumes of sediment.

Study reach morphology was typical ICEM stage V: base flow channels flanked by lightly vegetated sandy berms occurred within the enlarged main channel, creating a two-stage cross section. Base flow was characterized by shallow, uniform flow over a sand bed. Concave banks of the main channel were steep, high, and protected by short riprap spur dikes [similar to hard points described by Petersen (1986)] placed at roughly 25-m intervals. These dikes, also referred to in the following as groins, did not project far enough into the baseflow channel to create significant scour holes.

Efforts to halt channel incision and restore watershed stability began at least as early as the 1970s and continue to the present. Projected expenditures for watershed stabilization

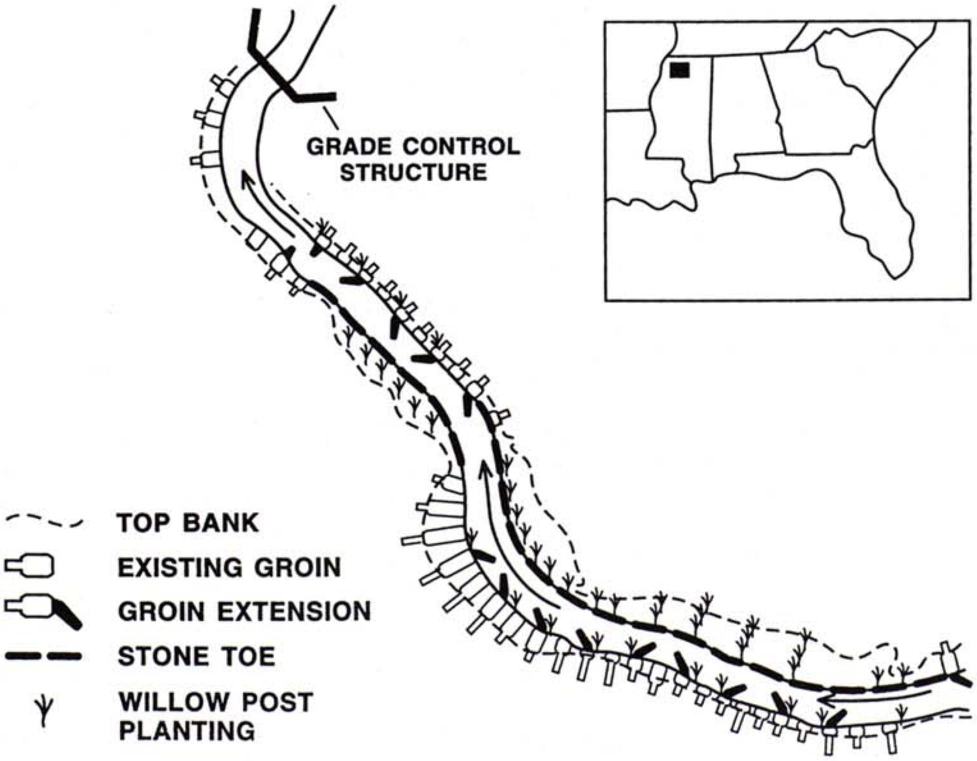

FIG. 1. Location and Layout of Study Reach

FIG. 2. Prerestoration Conditions

TABLE 1. Hotophia Creek Study Reach Characteristics

Parameter (1)	Value (2)
Drainage area	91 km^2
Length	1 km
Sinuosity	1.2
Thalweg slope	0.0011
Channel top width	44–77 m
Channel depth	3–4 m
Median bed material size	0.20–0.56 mm
Average discharge	1.91 m^3 s^{-1}
Annual suspended sediment yield	985 t km^{-2}

exceed \$132,000 km^{-2}. A grade-control structure was placed immediately downstream from the study reach in about 1980, and the aforementioned groins were constructed during 1986–1990. During 1984–1993, numerous grade-control structures, bank protection devices, and drop inlet pipes were placed in the watershed upstream of the study reach.

RESTORATION DESIGN AND CONSTRUCTION

A step-by-step approach for stream habitat restoration design (Shields 1983; Brookes 1990) was used. First, aquatic-habitat deficiencies were defined using preconstruction data collected as is described. Base-flow conditions were characterized by shallow (generally <20 cm), swift (generally >30 cm s^{-1}) flow over a sandy bed with minimal woody debris and cover due to riparian vegetation. Previous studies of similar channels have shown that grade-control weirs and spur dikes that created deep (say >0.5 m), low-velocity scour holes at base flow supported more species of fish and larger fish than surrounding channel habitats without structures (Shields and Hoover 1991; Knight and Cooper 1991; Knight and Cooper 1987). Based on this evidence, and biological studies finding that pool availability is a key component of fish-habitat quality in warmwater streams (Schlosser 1987; TerHaar and Herricks 1989; Ebert et al. 1991; Lobb and Orth 1991; Foltz 1982), scarcity of pool habitat was identified as the primary habitat deficiency. Work by others showed that water quality was adequate for maintenance of healthy aquatic life (Slack 1992).

Design considerations included economics and channel stability. Costs were held low in order to develop techniques that would be feasible for integration with larger-scale watershed stabilization activities elsewhere; meander restoration was therefore rejected. Furthermore, restoration features had to be virtually maintenance free and durable enough to withstand the high energy and varying sediment transport conditions typical of this (Rebich 1993) and other (Simon 1989) incised channels. Major changes in channel slope were avoided because the two-stage cross section developing in the prerestoration channel was relatively stable and met Brookes' (1990) specific stream-power criterion (bank-full discharge stream power was 23–41 Wm^{-2}).

Next, structural types for restoration were selected and laid out. Spur dikes are the most durable of the four types of structures commonly used for stream restoration (bank covers, randomly placed boulders, and weirs being the other three), particularly in sand-bed channels (Shields et al. 1992; Babcock 1982). Stone was used for construction due to its ability to conform to changes in bank-line geometry, long-term durability, appearance, and the capabilities of the constructing agency. Restoration spurs were designed as extensions to the existing groins. Opposing spurs (Brookes 1992) would have been attractive for developing thalweg sinuosity and forcing scour-hole formation, but with the exception of the extreme downstream end of the study reach, the structures were limited to one bank. Placement of dikes on the sandbar opposite the existing groins was avoided due to the hazard of flanking. Extensions were spaced to create a scour-hole ("pool") spacing equal to roughly three times the prerestoration base-flow channel width. This spacing was based on the idea that the gradual reduction of base-flow width and simultaneous increase in channel sinuosity and length would lead to a pool spacing approaching that for natural streams (five to seven widths) (Keller 1978). Extensions were alternately angled upstream and downstream to promote thalweg meandering (Fig. 1). To prevent the channel from migrating away from the extensions, the sandbar opposite them was protected using longitudinal stone toe protection and dense plantings of dormant willow posts just landward of the stone.

Finally, stone gradation and structural dimensions were selected. Stone gradation was based on the one used by the U.S. Army Corps of Engineers for the existing groins and other channel stabilization projects in similar settings. Median stone size was checked against standard hydraulic design criteria (U.S. Army Corps of Engineers 1991). However, to enhance physical-habitat diversity, the gradation was specified to contain a slightly larger fraction of smaller stones than the standard: 100%, 50%, and 15% of the stone by weight were smaller than 90–36 kg, 36–18 kg, and 18–0.2 kg, respectively. Extensions were sized to produce scour holes, but to have minimal effects on high flow conveyance and sediment transport. Extensions were 12-m long and made an angle of 45° with the approach flow, and thus constricted the existing 21-m-wide base-flow channel by 8.5 m. Crest elevations ranged from 0.3–1 m (sloping downward toward riverward tip) above the existing streambed (Bulkley et al. 1976; Klingeman et al. 1984; Wesche 1985). More sophisticated approaches for designing dikes and simulating channel response (i.e., numerical simulation) were not used due to the paucity of prototype data for model calibration and verification. In addition, costs for a major simulation effort would have approached construction costs—a pitfall not unheard of in habitat restoration work (Beschta et al. 1993).

Native willow (*Salix* spp.) was specified for plantings because of qualities documented by others working in similar environments (Fowells 1965; Bowie 1981, 1982). Furthermore, several small willows were already growing at the study site, indicating habitat conditions were suitable for established plants. Plantings were intended to initially stabilize the bar and provide shade and carbon input to the channel. Over the longer term, willow posts were intended to speed riparian-zone recovery by inducing sediment deposition and fostering conditions for colonization by other woody species. A more fully functional riparian zone would remove nutrients from shallow ground water and provide large woody debris to the

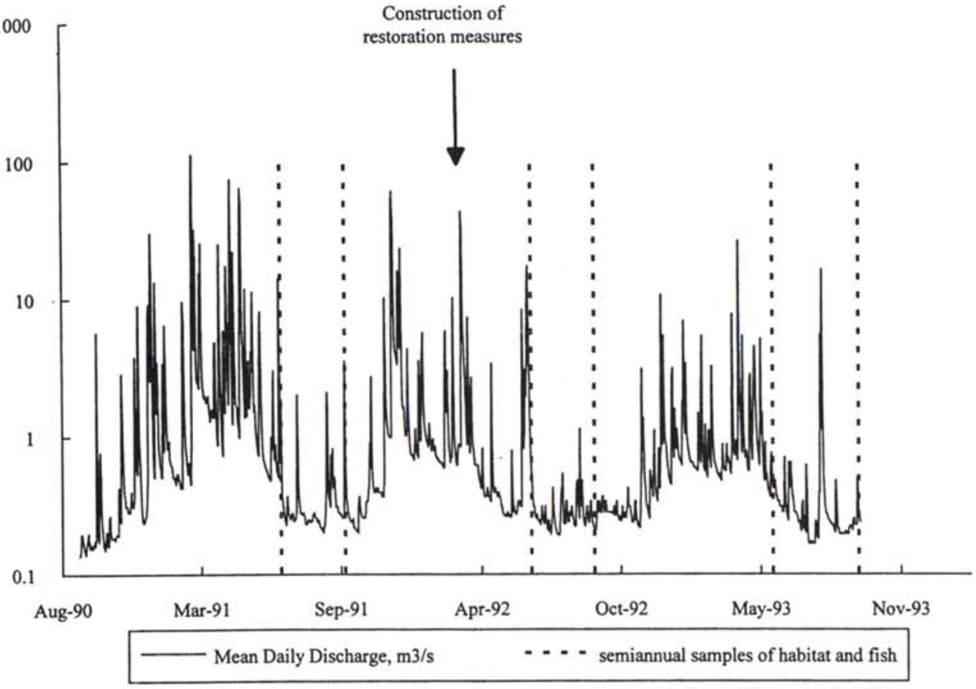

FIG. 3. Mean Daily Discharge Hydrograph for Study Site

TABLE 2. Hydrologic Conditions before and after restoration

Condition (1)	Dates (2)	Max (3)	Min (4)	Median (5)	Mean (6)	Std. Dev. (7)
(*a*) Mean Daily Discharge ($m^3\ s^{-1}$)						
Prerestoration	Mar. 91–Feb. 92	75	0.20	0.77	2.76	7.89
Postrestoration	Mar. 92–Feb. 93	44	0.19	0.37	1.02	3.23
(*b*) Sediment Load ($t\ day^{-1}$)						
Prerestoration	Mar. 91–Feb. 92	21,192	0	3	392	1,975
Postrestoration	Mar. 92–Feb. 93	12,184	0	1	147	782

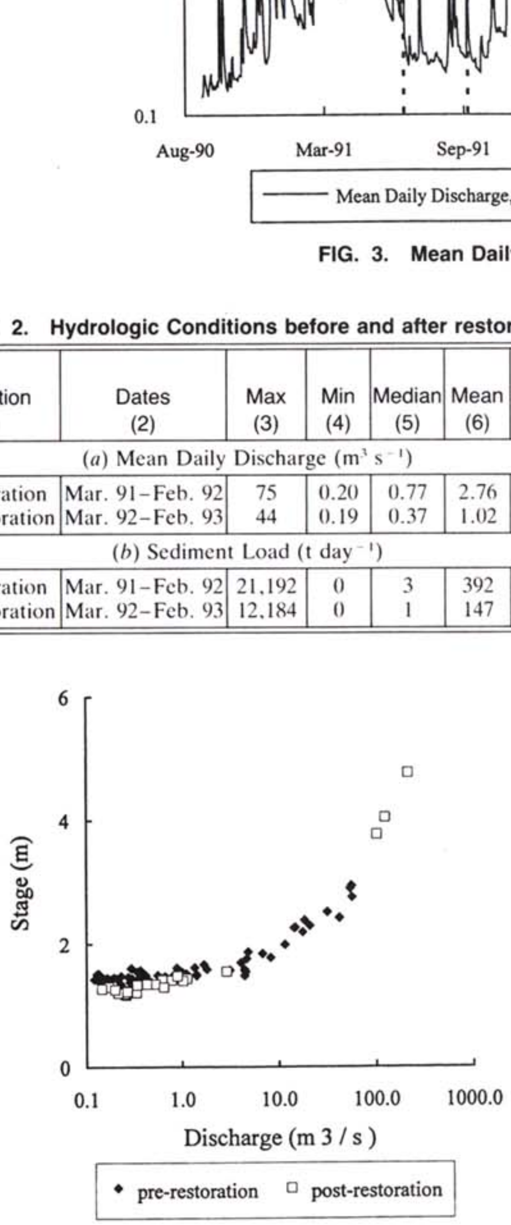

FIG. 4. Manual Discharge and Stage Measurements Obtained by U.S. Geological Survey for Midpoint of Study Reach

channel that would gradually supersede the stone habitat structures (Sedell and Beschta 1991).

Postsize cuttings were used to obtain high rates of survival and bank stabilization during establishment (Shields et al. 1993; Bhowmik 1993). A total of 3,445 dormant posts were planted. Posts were 2–25 cm in diameter and 150–180 cm long, and were harvested from a thicket within 1 km of the planting site on the same day they were planted. Three planting techniques were used, none of which involved bank shaping or grading (Fig. 1):

1. 1,680 posts were placed in a single row of 1–1.5 m deep holes excavated by a 1-m-wide hydraulic hoe bucket just landward of the longitudinal stone toe (Fig. 1). Twelve posts were placed around the perimeter of each hole, and holes were dug on ~4-m centers.
2. 600 posts were placed in five 1-m-deep by 2-m-wide trenches excavated across the bar perpendicular to the channel.
3. 1,165 posts were planted in holes created in cohesive banks adjacent to groin extensions (White 1991) using a 1.3-m-long 10-cm-diameter metal ram mounted on the hydraulic hoe. Posts were placed on ~1 m centers in three to five rows parallel to the channel.

Approximate mean planting densities for the three techniques were 2.8, 2.2, and 10.0 posts m^{-2}, respectively. Areas supporting native woody vegetation were avoided, and are not included in density calculations. Sandbar plantings (methods 1 and 2) were on gradual slopes (0–15°), while cohesive banks (method 3) were steep (30° to near vertical). With the possible exception of the posts planted using the second method, all posts were planted deeply enough so that at least the lower 30 cm was in contact with dry-season ground water.

Construction of restoration structures required addition of about 1,380 t of stone to the study reach, which amounted to 10% of the quantity previously placed for channel stabilization. Costs for willow planting per unit of bank line treated were roughly an order of magnitude less than conventional stone stabilization.

DATA COLLECTION

Restoration construction occurred in February 1992. Water stage and suspended sediment concentration were monitored continuously by the U.S. Geological Survey at a gauge located

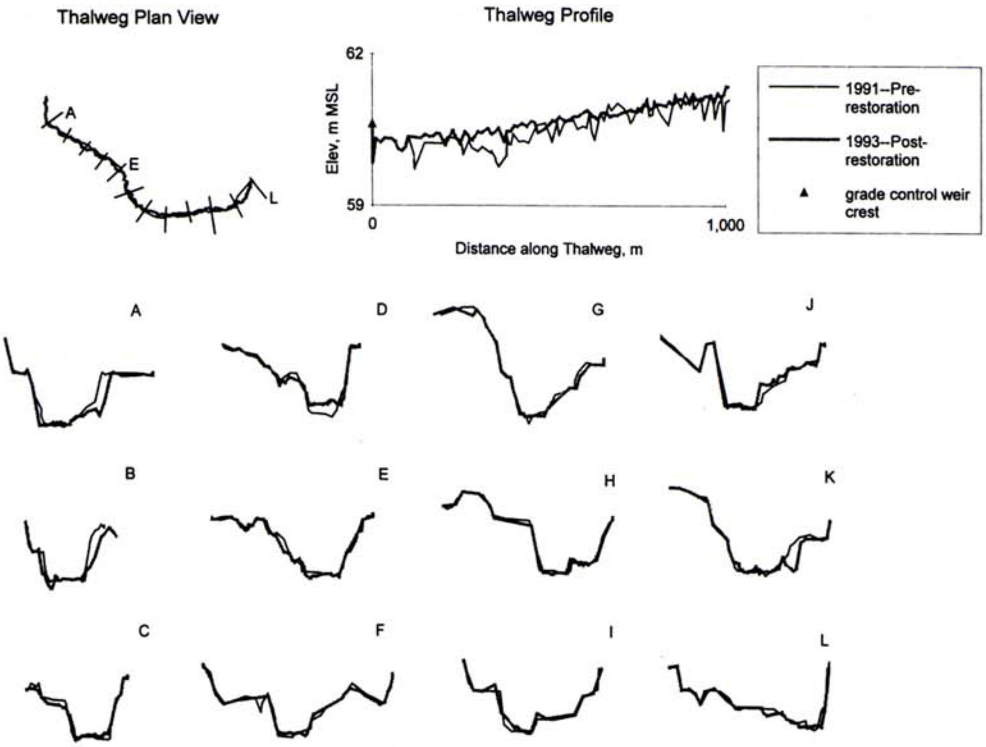

FIG. 5. Pre- and Postrestoration Thalweg Plan and Profile and Channel Cross Sections

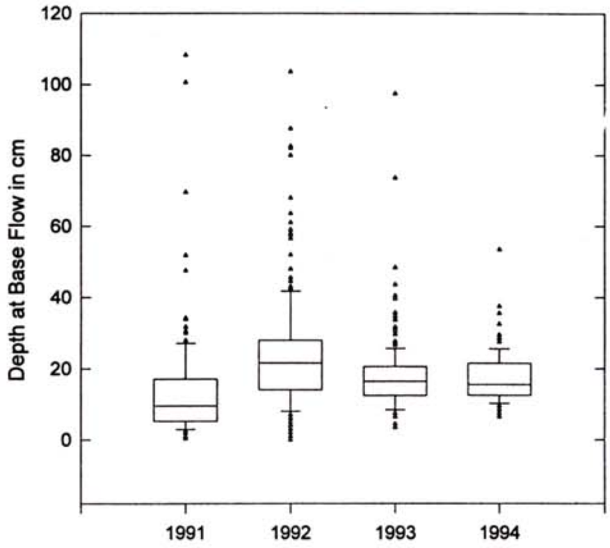

FIG. 6. Distribution of Base-Flow Depth before (1991) and after (1992–1994) Restoration. Depths Were Measured in Spring (May–June) and Fall (September) each Year (Only Spring Data Were Available for 1994); Restoration Was Completed in February 1992 (Upper Limit, Central Line, and Lower Limit of Boxes Represent the 75th, 50th, and 25th Percentiles, while Error Bars Show 10th and 90th Percentiles, and Triangles Show Outliers)

TABLE 3. Base-Flow Depths before and after Habitat Restoration [Medians in Boldface Are Not Significantly Different ($p < 0.05$)]

Condition (1)	Date (2)	Median depth (cm) (3)	Mean depth ± Std. Dev. (cm) (4)
Prerestoration	1991	9	14 ± 16
Postrestoration	1992	22	24 ± 16
Postrestoration	1993	**16**	18 ± 10
Postrestoration	1994[a]	**15**	17 ± 7

[a] Includes only spring data. Other rows include data from spring and fall.

in the middle of the study reach throughout the study. Discharge and stage were measured manually at the gauge site periodically to maintain the rating curve. Geometry of 12 cross sections located at roughly 100-m intervals and thalweg profiles were obtained using standard surveying techniques in May 1991 and July 1993. The postrestoration survey included profiles of the deflector crests. The spatiotemporal distribution of pool habitat in the incised reaches was assessed using cross-section surveys, stage-duration curves provided by the U.S. Geological Survey for 1986–1991 (water years), and observed water-surface slopes. Bed material was grab-sampled from the center and quarterpoints of 12 cross sections during midsummer base flow in 1991 and 1993, and maximum depth of scour holes adjacent to all spur dikes were measured using a wading rod at midsummer base flow in 1991–1993.

Fish were sampled from the study reaches during base flow in spring and fall before (1991) and after (1992 and 1993) construction of the restoration project as described by Shields et al. (1993). Concurrent with 1991–1993 fish sampling and in late May 1994, physical aquatic habitat characteristics were delineated by sampling depth, velocity, and bed type at ~100–137 regularly spaced grid points. Depth was measured with a wading rod, and velocity was measured at 0.6 of the depth using a current meter. These data provided much more detail about base-flow physical characteristics than the cross-section and thalweg surveys because the spatial density of the points was much greater. Typically, five to seven grid points were located at uniform intervals along cross sections running from water's edge to water's edge 15–20 m apart. Grid-point depth and velocity were used to compute local Froude numbers, since the local Froude number has been shown to be an indicator of aquatic habitat quality in streams of this size (Statzner et al. 1988). The percentage of stream surface area overlying pool habitat was computed by defining pool habitat in two ways: (1) area with depth ≥ 20 cm and velocity ≤ 10 cm s^{-1}; and, somewhat less restrictively (2) area with local Froude Number ≤ 0.15. Though somewhat arbitrary, these definitions of pool habitat were necessary to quantify changes due to restoration. The numerical criteria were based on values successfully used by others working in this and similar streams to explain differences in fish populations (Gorman and Karr 1978; Shields and Hoover 1991; Shields et al. 1994).

Periodic observations were made of planted willows throughout the first growing season, and the condition of the plantings was assessed at the end of the first and second growing seasons (October 1992 and October 1993). Numbers of surviving and dead individuals were counted twice by two observers, and the lengths of bank segments with and without woody vegetation cover within 1.5 m of the base-flow water's edge were measured with a tape.

RESULTS

A near bank-full discharge occurred just 11 days after construction was completed (380 $m^3 s^{-1}$; 9 March 1992), but significant damages to restoration structures and plantings did not occur. The mean of mean daily discharges for 12 months before restoration was more than twice that for the 12 months after restoration, primarily due to several large events in 1991 (Fig. 3 and Table 2). Data for the 12 months before and after restoration indicated that prerestoration suspended sediment loads were also higher. Rebich (1993) used trend analysis to detect an upward trend in water discharge and a downward trend in flow-adjusted sediment concentration at this site for the period of water years 1985–1991. Examination of manually collected stage-discharge data obtained by the U.S. Geological Survey before and after restoration reveal no pronounced shifts in channel conveyance (Fig. 4). Low flow ($Q < 1$ m^3 s^{-1}) stages were slightly lower following restoration than before.

Comparison of channel surveys taken before and after restoration showed minimal changes (Fig. 5). Mean cross-sectional area changed less than 5%. Thalweg sinuosity increased slightly (from 1.34 to 1.39), and about 20 cm of aggradation occurred along the thalweg profile. Visual observations indicate that this level of aggradation is typical of episodic, cyclical behavior driven by antecedent hydrology or spatiotemporal variations in sediment availability. The two cross sections immediately upstream from the grade-control structure displayed 1–6 m of bank recession, but the other 10 sections were very stable. Based on computation of depths using the cross-section surveys and stage-duration curves, pool-habitat availability was similar before and after restoration: about 60% of the water area was shallower than 40 cm for the stage equaled or exceeded 20% of the time. Computations were performed using more frequently observed stages (i.e., the 80% duration stage), but were judged unrealistic as episodic scour and fill of the sand bed creates instability in the lower end of the stage-discharge relationship and, at times, nonuniform water-surface slopes.

Measurements of base-flow depth and velocity at regularly spaced grid points detected changes following restoration that were beyond the resolution of the channel surveys. Stages varied about 31 cm across sampling dates, so depths were adjusted to a common stage in the middle of the range. Corrected depths less than zero were not used in computing statistics for comparison. Depths were not normally distributed, so a distribution-free test (Kruksal-Wallis one way analysis of variance on ranks) was used to compare annual median values. Median depth, corrected for stage variation, increased from 9 cm to 22 cm during the first year after restoration, but fell to 15 cm (2 years after restoration (Fig. 6 and Table 3). Depths generally increased more in the downstream half of the study reach than upstream, possibly due to the effects of local acceleration as flow approached the sharp-crested weir of the grade-control structure (Fig. 1).

Effects of restoration on pool-habitat quantity were determined by comparing grid-point measurements taken at comparable discharges and stages in the downstream half of the study reach (data for similar hydraulic conditions before and after restoration were unavailable elsewhere). Restoration had little impact on mean water width (taking stage variation into account), but pool habitat increased three- to fivefold (Table 4). Depths were not adjusted for stage differences when computing pool-habitat availability.

Repeated visual observations of scour holes adjacent to groins following restoration showed that scour and deposition patterns at a given structure fluctuated through time. Several structures exhibited cycles of deposition: deep scour holes adjacent to extension would alternate with dry sandbars. However, in general, groin extensions forced development of larger, deeper scour holes (Table 5). Four months after construction, the average maximum scour-hole depth for structures with extensions increased from 32 cm to 84 cm. Scour-hole length and width also increased, but were not measured due to the difficulty of establishing definite downstream boundaries. Scour holes adjacent to extensions angled downstream were deeper than for those angled upstream ($p = 0.0007$, analysis of variance). A year later (16 months after construction), average maximum scour-hole depth for groins with extensions was 72 cm, 125% greater than before restoration.

The slight decrease in mean scour-hole depth mirrored the trends in reachwide depth described earlier. Declining scour-hole depths reflected the gradual failure of the groin extensions: by 16 months after construction, the 12-m-long angled extensions were only 8–10 m long. Failure of groin extensions appeared to be caused by leaching or winnowing of sand from underneath stones. Stones generally subsided in place rather than launching into scour holes. In contrast to the angled extensions, the straight extensions placed on opposite banks at the downstream end of the restored area (Fig. 1) were shortened by about 6 m when they failed in the first major event following construction.

Bed material size is an important indicator of aquatic-habitat quality (Shields and Milhous 1992). Restoration had little effect on bed material size in the channel proper: median size (D_{50}) was 0.40 mm before restoration and 0.35 mm afterward. The upper end of the gradation curves also showed little variation (D_{90} was 0.68 mm before restoration and 0.58 mm afterward). Despite visual observation of isolated veneers of fine material on the sandbar, willow planting did not accelerate deposition of fine sediments. Surficial sediments on the sandbar bordering the channel contained 12% (by weight) of material finer than 0.063 mm (hereinafter, "fines") prior to restoration, and a similar amount (10%) after restoration. However, development of scour holes adjacent to groin extensions increased the amount of cohesive bottom available to aquatic species: postrestoration samples of sediments from these areas contained an average of 9% fines, which was two orders of magnitude greater than for channel sediments. Although the biological response has not yet been quantified, retention of cohesive sediments in scour holes and the addition of stone to the base-flow channel represent improvements in study reach macroinvertebrate habitat (Cooper et al. 1993; Shields and Milhous 1992).

After restoration, fish populations increased sharply (Table 6). The number of fish species and the size of fish found in the study reach increased by about 50%. The difference in fish length was statistically significant at $p < 0.001$ (Mann-Whitney rank sum test for nonnormally distributed data). The addition of larger fish was particularly notable (Fig. 7). These changes are consistent with observations of other workers studying warmwater streams: Foltz (1982) found that fish population was correlated with the cube of mean depth in a South

TABLE 4. Base-Flow Channel Geometry and Pool Habitat at Similar Discharges before and after Habitat Restoration

Condition (1)	Date (2)	Relative stage (cm) (3)	Discharge, ($m^3 s^{-1}$) (4)	Mean width (m) (5)	Mean depth (cm) (6)	Percent local Froude numbers (≤0.15) (7)	Percent pools[a] (8)
Prerestoration	25 Sept. 1991	12	0.71	17.7 ± 4.4	17 ± 10	20%	2.9%
Postrestoration	16 June 1992	2	0.66	16.6 ± 2.9	25 ± 18	58%	14.0%
Postrestoration	28 May 1993	0	0.50	16.3 ± 2.3	14 ± 14	59%	8.2%

[a] Pools were defined as areas with depth ≥ 20 cm and velocity ≤ 10 cm s^{-1}.

TABLE 5. Average Maximum Scour Hole Depth (cm)

Structure type (1)	Year 1991 (2)	 1992 (3)	 1993 (4)
All groins[a]	32	58	49
Without extensions	32	37	30
With extensions[b]	—	84	72
Downstream extensions	—	98	88
Upstream extensions	—	58	55

[a] None of the entries include the upstream-angled structure at the extreme upstream end of the restoration reach (Fig. 1).

[b] Includes two straight extensions at lower end of reach not included in either of the two following rows.

TABLE 6. Summary of Fish Sampling Results [All Medians Are Significantly Different ($p < 0.05$)]

Condition (1)	Date (2)	Number of fish (3)	Number of species (4)	Maximum fish length (cm) (5)	Median fish length (cm) (6)
Prerestoration	1991	324	14	44	3.6
Postrestoration	1993	638	23	59	5.0
Postrestoration	1994	1,086	19	70	5.5

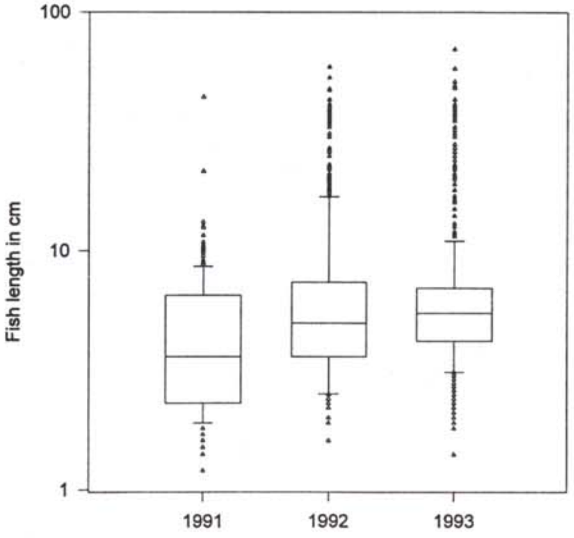

FIG. 7. Distribution of Fish Length before (1991) and after (1992 and 1993) Restoration. Fishes Were Sampled in Spring (May–June) and Fall (September) each Year. Restoration Was Completed in February 1992 (See Fig. 6 for Meaning of Symbols)

Carolina watershed, while Schlosser (1987) documented the strong positive association of fish size, total biomass, and number of species with the presence of pool habitat in a second-order Illinois stream. Shields and Hoover (1991) observed associations between fish species diversity and pool-habitat availability in incised Mississippi streams.

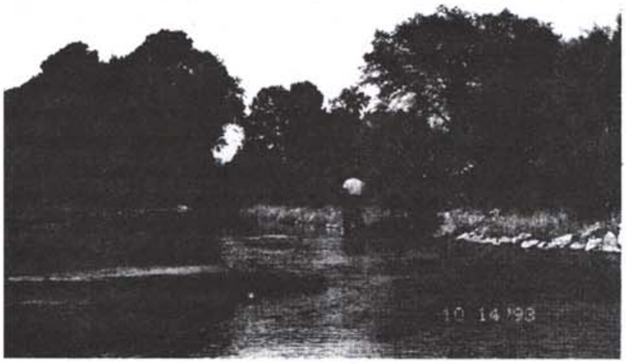

FIG. 8. Willow Posts Two Growing Seasons after Planting

Labor requirements for harvesting and planting willow posts averaged five posts per man-hour. A storm event produced near bank-full stages 11 days after planting was completed, but less than 1% of the posts were washed away. Green buds appeared on all remaining posts within 1 month of planting, and dense foliage, with limbs reaching an average height of about 2 m above the adjacent ground surface developed (Fig. 8). Most of this growth occurred during the first growing season. Signs of beaver (*Castor canadensis*) activity and herbivory were plentiful, but did not seem to affect willow survival, as plants resprouted vigorously after cutting by beaver. The stone toe and willow posts have prevented channel migration in response to the groin extensions, and the stone toe has protected existing stands of natural woody vegetation.

The two-season survival rate for all willow posts was about 30%. Post survival rates were controlled by competition from kudzu and soil moisture, but not bank height or angle. Although only 50–60% of the posts planted on the sandbar margin survived two growing seasons, because of the high planting density the percentage of sandbar bank line supporting woody vegetation more than doubled, increasing from 38% to 78%. Only 23% of posts planted in trenches survived two growing seasons. Trench plantings were denser and higher relative to the water table than the posts planted with the other two techniques. Posts planted in cohesive banks were entirely covered and killed by the exotic vine, kudzu (*Pueraria lobata*).

SUMMARY AND CONCLUSIONS

Aquatic habitats along a 1-km reach of the incised channel of Hotophia Creek, Mississippi were partially restored by adding extensions to existing spur dikes, placing stone-toe protection on a sandbar opposite the extensions, and by planting willow posts. Major changes in channel characteristics did not occur following restoration. Channel geometry, channel sinuosity, bed material size, and hydraulic roughness remained fairly stable. However, the fraction of sandbar bank line supporting vegetation more than doubled, and pool-habitat availability increased fivefold, principally due to the enlargement of scour holes adjacent to groin extensions. Fish populations have responded by growing larger, more diverse, and by retaining larger individuals.

Performance of the groin extensions has been somewhat disappointing. Groins have tended to gradually subside and shorten. Groin extensions should have been designed with broader crests to allow for sacrifice (2 m instead of 1 m, based on subsequent observations of similar structures). The stone toe placed along the margin of the sandbar has performed without failure, and has been mostly covered by deposition. Preliminary results of a subsequent experiment in a nearby channel indicate that the stone toe may not be necessary to retain willow posts if they are planted deeply enough ($\sim$1.5 m) in the sandbar to withstand removal by local scour during the period of root establishment.

Physical-habitat restoration should not be attempted unless water quality is adequate to support aquatic life (Kern 1992). Restoration efforts in incising channels should be focused in lower reaches that are aggradational. The goal of restoration should be to accelerate natural processes of berm formation, base-flow-channel narrowing and deepening, and recovery of riparian vegetation. Aquatic-habitat objectives may be addressed within orthodox incised channel-erosion control projects with little additional cost. When handled and planted carefully, willow posts are cost-effective materials for stabilizing bars and restoring riparian zones along the lower reaches of incising channels. However, when posts are planted in droughty soils (sandbars), densities lower than the $2\ \text{m}^{-2}$ used in this effort might improve survival rates. Posts must be planted deeply enough to remain in contact with ground water during dry portions of the growing season. Kudzu must be absent or eradicated before willow posts are planted if they are to survive.

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