Large Woody Debris Structures for Sand-Bed Channels

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Abstract: Described is a method for channel erosion control and habitat rehabilitation featuring intermittent placement of structures made of large woody debris. This method is expressly tailored to address severe problems typical of incised channels with little sediment coarser than sand. In these types of environments, buoyancy forces are typically more important factors in woody debris stability than fluid drag. Buoyant forces are counteracted by the weight of the structure, earth anchors, and sediment deposits. Design concepts were tested in a demonstration project constructed along 2 km of channel draining a 37-km^2 watershed. Large woody debris structures reduced velocities in the region adjacent to the bank toe and induced sediment deposition and retention. Construction costs per unit channel length were 23–58% of costs for recent stone bank stabilization projects within the same region. During the second year following construction, 31% of the structures failed during high flows, probably due to inadequate anchoring.

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Introduction

Channel incision is a worldwide problem (Wang et al. 1997; Darby and Simon 1999). In the absence of geological controls, incision triggers explosive channel erosion, with width increasing three- to sixfold in a short time, and elevating watershed sediment yield by 1 order of magnitude (Shields et al. 1995b), with associated ecological degradation (Shields et al. 1994). In many severely incised sand bed streams, primary ecological impairments are shifting bottom substrate, shallow depths with a lack of pools, and limited woody debris (Shields et al. 1994, 1995c; Warren et al. 2002). Stabilization of incising channels and their stream corridors can have major, positive ecological effects, particularly when the structures and methods used are designed to address habitat-limiting factors (Shields et al. 1998b). Current practice for stabilizing watersheds experiencing channel incision consists of applying a combination of grade control structures, in-channel stone structures, small reservoirs (floodwater retarding structures), and land treatment (Shields et al. 1995b). Costs for treating an entire watershed in northwestern Mississippi range as high as \$750 ha^{-1}, and current (1998–1999) costs for channel stabilization with riprap structures range up to \$400 m^{-1} of treated bank. Such costs are often prohibitive, except when special public funding is available. More cost-effective habitat rehabilitation might be obtained by emphasizing approaches that rely on natural processes (Brookes and Shields 1996). For example, channel erosion might be controlled by increasing woody debris loading and patterns of woody vegetation along channel margins (McKenney et al. 1995).

Large woody debris (LWD) exerts major influence over stream channel hydraulics and morphology in unmanaged fluvial systems (Sedell and Frogatt 1984; Triska 1984; Maser and Sedell 1994; Manga and Kirchner 2000; Brooks and Brierly 2002), and a lesser, but still important influence in systems where debris and riparian vegetation is periodically cleared (Smith et al. 1993; Piegay and Gurnell 1997). In incising channels, large amounts of debris are input to channels by bank failure processes, and in-channel debris accumulations are associated with sediment retention (Potts and Anderson 1990; Diehl 1997; Wallerstein et al. 1997; Downs and Simon 2001), in some cases reversing incision (Shields et al. 2000). Large woody debris is an important component of aquatic habitat in warmwater streams, retaining particulate organic matter (Bilby and Likens 1980), providing substrate for biomass production by benthic macroinvertebrates (Benke et al. 1985), and fostering higher levels of invertebrate species richness and abundance (Cooper and Testa 1999). Debris formations create zones of flow acceleration and deceleration that provide higher levels of physical diversity (Shields and Smith 1992; Gippel 1995), which are important to fish (Hickman 1975; Angermeier and Karr 1984; Scott and Angermeier 1998; Tillma et al. 1998; Warren et al. 2002). Pool habitat is often in short supply in sandy, incised streams (Shields et al. 1994), and addition of aggregations of LWD has been shown to enhance pool formation (Bilby and Ward 1989; Carlson et al. 1990).

Stabilization of eroding banks using structures composed entirely or partially from LWD has been described for streams in Vermont (Edminster et al. 1949); Arkansas (Mott 1994); Washington (Abbe et al. 1997); Illinois (Derrick 1997b); and Australia (Brooks et al. 2001). Stream aquatic habitat rehabilitation or enhancement using LWD addition has been described for a small gravel-bed stream in Virginia (Hilderbrand et al. 1998), for small rivers in British Columbia (D'Aoust and Millar 2000) and Washington (Larson et al. 2001), and for a large, regulated river in

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Table 1. Design Criteria for Bank Stabilization Measures (Large Woody Debris Structures) for Little Topashaw Creek

Category	Specific criteria
Economic	Cost per unit length of bank treated must be less than cost for traditional stone structures
Environmental	Materials must be locally available components of lightly degraded or pristine regional stream corridor ecosystems
	Structures must contribute to and accelerate natural recovery of riparian zone habitats and plant communities
	Measures must address key impairments in aquatic habitat: shortage of pool habitats, woody debris, and stable substrate
Structural	Structures should withstand the 5-year return interval flow without failure
Hydraulic	Structures should trap and retain sand-size sediments
	Flood stages may be increased, but duration of overbank flooding during the growing season should not be significantly increased
	Structures should be sized to promote berm formation that creates a two-stage compound channel with width and depth relative to watershed area similar to stable Stage V or VI channels within the region
Geotechnical	Some additional mass wasting of near-vertical banks is allowed, but structures should trap and retain materials resulting from bank caving. Structures should be high enough so that bank heights will be reduced to stable levels when structures are filled with sediments
Construction	Minimal requirements for specialized training and equipment
	Structures should be constructed using equipment operating from within the channel with minimal additional clearing and disturbance required

British Columbia (Goldberg et al. 1995). In order to maximize structure reliability with limited artificial anchoring, large woody debris structures (LWDSs) may be designed to emulate stable naturally occurring LWD formations (Gippel 1995; Abbe et al. 1997; Hilderbrand et al. 1998). In general, log length and orientation appear to be important determinants of stability, and logs longer than bankfull width oriented parallel to the flow appear to be most stable (Bilby 1984; Lienkaemper and Swanson 1987; Cherry and Beschta 1989; Robison and Beschta 1990; Abbe and Montgomery 1996; Braudrick and Grant 2000). Hilderbrand et al. (1998) reported that channel scouring was associated with LWD oriented transverse to flow while sediment deposition occurred adjacent to LWD oriented more nearly parallel to the current. Field studies indicate that smaller LWD has limited influence on channel morphology and aquatic habitat, but larger pieces can be important (Berg et al. 1998; Urabe and Nakano 1998). Controlled flume experiments indicate the stability of single logs is a function of orientation, the presence of a rootwad, wood density, and log diameter, but that log length is not important for logs shorter than channel width (Braudrick and Grant 2000).

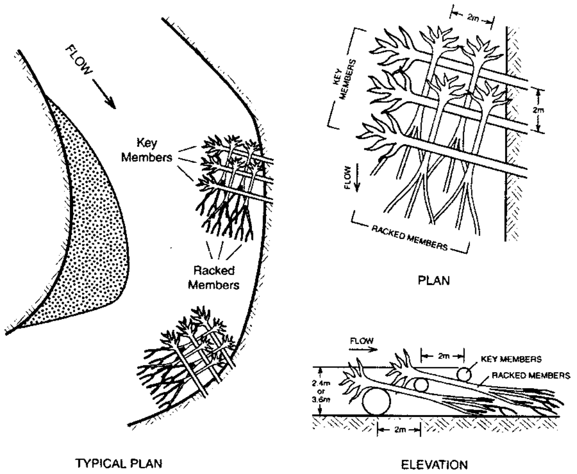

Fig. 1. Typical plan and elevation for large woody debris structures constructed along Little Topashaw Creek, Mississippi. Note definition for terms, "key member" and "racked member" which differ from those used by Abbe and Montgomery (1996) and Abbe et al. (1997)

Design of Large Woody Debris Structures

Key aspects of the design problem include: (1) use of buoyant materials, (2) use of materials that gradually decay, and (3) dual objectives of channel stabilization and habitat rehabilitation. In some cases conveyance issues and sediment budgets are important; these may be addressed using standard procedures [e.g., using standard one-dimensional models and increasing Manning n values for LWDS-covered segments of cross sections using approaches described by Arcement and Schneider (1989) or Kouwen and Fathi-Moghadam (2000)], and will not be discussed further here. Design of LWDS for controlling erosion and restoring aquatic habitat has been described for gravel-bed rivers and streams in the Pacific Northwest (Abbe et al. 1997; Drury et al. 1999; D'Aoust and Millar 2000). Placing structures in incised, sand-bed channels of smaller streams typical of the Midwestern and southeastern U.S. presents a different set of challenges. In addition to basic differences in ecology (Winger 1981), available wood tends to be smaller, material coarser than fine gravel for ballast is unavailable, and channel erosion rates (relative to channel width) are higher. Channel width–depth ratios are 1 order of magnitude smaller (typically <10), so storm flows tend to be deep, and structures are more frequently submerged. Bed slopes and current velocities are typically lower in sand-bed systems.

The purpose of LWDS placed in an incised sand-bed stream is to accelerate evolution of the existing system toward a sinuous two-stage channel with wooded berms that could be classified as Stage VI (Simon 1989). The LWDS thus amplify dominant geomorphic processes, perhaps emulating natural geomorphic and ecological recovery (Shields et al. 2000; Downs and Simon 2001). Proposed design criteria are outlined in Table 1. Large woody debris structures may be designed to resist displacement by interlocking, keying-in to banks, anchoring, and by trapping sediment and organic matter input both from adjacent mass wasting and material transported into the reach from upstream. Initial success of LWDS depends upon their ability to resist flotation. The main body of the LWDS should provide stem density great enough to reduce velocities and turbulence adjacent to the bank toe, encouraging sediment deposition and retention (Lopez and Garcia 1998; Nepf 1999). Since LWDS rapidly decompose in humid, temperate climates (Roni et al. 2002), long-term success is contingent upon their creation of suitable habitat for plants that will secure and stabilize the channel margins over the longer term (Jacobson et al. 1999).

In view of the factors above, an LWDS architecture (Fig. 1) similar in some respects to that tested in gravel-bed rivers in the Pacific Northwest (Abbe et al. 1997; Drury et al. 1999) was adopted. Large woody debris structure geometry may be specified by crest angle, length, elevation and spacing. The crest angle (angle between a line normal to the approach flow vector and the weir crest) was set at 15° upstream to promote deflection of overtopping flow away from eroding banks (Derrick 1997a), although others have suggested angles between the bank and the weir crest of 25–30° based on straight channel flume tests (Johnson et al. 2001). Crest length may be based on regression of channel bottom width against drainage area for regional data sets comprised of channels approaching quasiequilibrium (Downs and Simon 2001); crest length will be the difference between current and equilibrium width times the cosine of the crest angle. Alternatively, crest length may be based on a target flow conveyance for the design cross section. Crest elevations must be high enough so that the sediment berms that form over the LWDS stabilize existing near-vertical banks. Stable bank heights and angles may be based on geotechnical analyses (Darby and Simon 1999) or empirical criteria based on regional data sets (Shields et al. 1995b). Spacing between LWDS is difficult to prescribe before construction because the dimension of each LWDS parallel to the flow direction is dependent upon the diameter and length of the LWD (Fig. 1). In general, though, LWDS placed along a given segment of eroding bankline should be spaced 1.5–2.0 times the crest length apart (Petersen 1986). Spacing should be great enough to provide segments of unprotected bankline between structures to reduce cost and to create physical habitat diversity (Shields et al. 1995a).

Force Balance

For design, forces acting on the LWDS were partitioned into buoyancy and fluid drag (D'Aoust and Millar 2000). Forces due to ice and impact by floating LWD were neglected. The buoyant force on a LWDS, F_b (in Newtons), is equal to the product of the difference between the specific weight of water, γ_w ($\mathrm{N\,m^{-3}}$), and woody debris, γ_d ($\mathrm{N\,m^{-3}}$), and the submerged volume of the logs (Braudrick and Grant 2000)

$$F_b=(\gamma_w-\gamma_d)\left[\sum_{i=1}^{i=n+1} V_{k_i}+\sum_{i=1}^{i=n} n_{r_i}V_{r_i}\right] \tag{1}$$

where V_{ki} and V_{ri}=submerged volumes (m^3) for the ith key member and for racked members in the ith layer, respectively, in a LWDS composed of $n+1$ key members and n layers of racked members. The terms "key member" and "racked member" are defined in Fig. 1, and these definitions may differ from those used by others (Abbe and Montgomery 1996; Abbe et al. 1997). The quantity n_{r_i}=number of racked members in layer i. It was assumed that all of the key members in a given structure have volumes approximated by cylinders with radius r_k and length L and that all racked members have cylindrical volumes with radius r_r and length L. The assumption of cylindrical volumes overestimates LWD volume because it neglects stem tapering, but this factor is balanced by the volume of branches. The volume of key member rootwads was approximated by a circular disk of radius r_{rw} and length L_{rw}, and the volume of racked member rootwads was neglected. The weight of soil within root balls was neglected in order to be conservative. When the LWDS is not fully submerged, the quantities V_{k_i} and V_{r_i} may be determined by integration as shown in the Appendix. When fully submerged, $V_{\mathrm{ki}}=(\pi r_k^2 L+\pi r_{\mathrm{rw}}^2 L_{\mathrm{rw}})$ and $V_{\mathrm{ri}}=\pi r_r^2 L$ where subscripts k, r, and rw refer to key member, rack member, and rootwad dimensions, respectively. A simple solution for the depth, d_{wn} at which the structure becomes neutrally buoyant (buoyant forces=gravitational forces) may be obtained if it is assumed that the LWDS behaves like a triangular prism with height h and uniform specific weight

$$\gamma_d/\gamma_w=\frac{d_{\mathrm{wn}}}{h}\left(2-\frac{d_{\mathrm{wn}}}{h}\right) \tag{2}$$

The assumption of uniform specific weight neglects the fact that thicker and heavier parts of the logs (e.g., rootwads, see Fig. 1) are concentrated near the crest of the LWDS, but this is appropriately conservative.

Table 2. Mean (±Standard Deviation) Density ($\mathrm{kg\,m^{-3}}$) of Wood Samples from Living Trees, Trees Felled and Used in Rehabilitation Structures, and Naturally Occurring Large Woody Debris in Little Topashaw Creek in Summer, 2000

Wood condition	Dry	In situ	Wet
Living $n=8$	760±50	960±160	1150±140
Intact $n=73$	630±130	860±160	1140±150
Partially decayed $n=12$	390±90	590±270	980±110

Note: Dry densities were determined after drying samples at 50°C for 10 days; wet densities after soaking in water for 10 days.

If permanently submerged, wood absorbs water and achieves negative or neutral buoyancy, but submergence along incised, sand bed streams is likely to be limited to short periods. A representative range for the density of LWD ($\rho_d=\gamma_d/g$) was determined by collecting 8 and 42 samples of wood from living trees and naturally occurring debris, respectively, and 43 samples of wood from LWDS 2 to 4 weeks following construction of the demonstration project described below. Although most samples were obtained with a 5.15 mm diameter increment borer, samples of older debris were too spongy to extract from the borer, and larger, disk-shaped samples were collected from older logs using a chain saw. Samples were weighed on a balance, and their volumes were determined by measuring the volume of water displaced by submerging each sample. Sample densities were determined for in situ conditions, after soaking in water for 10 days, and after drying in an oven at 50°C for 10 days (Wallace and Benke 1984; Thevenet et al. 1998).

Measured values for in situ ρ_d ranged from 300 to 1,390 $\mathrm{kg\,m^{-3}}$. Preliminary analyses using wood samples obtained with chain saw and increment borer from similar locations on recently felled trees indicated no significant difference in mean in situ density values for the two sampling methods. However, density after soaking was slightly greater for the smaller increment cores, perhaps because their higher surface area to volume ratio facilitated water absorption. Mean in situ density did not vary significantly with log diameter or with the location of the sample on the tree stem. The primary determinants of wood density were decay and moisture status (Table 2), consistent with findings of Thevenet et al. (1998). Analyses of variance were used to examine the influence of tree species for a subset of the data that were balanced with respect to decay class. There were no significant differences in density among the four species examined, and only sweetgum (*Liquidamber styraciflua*, mean density=760 $\mathrm{kg\,m^{-3}}$) and hickory (*Carya* spp., mean density

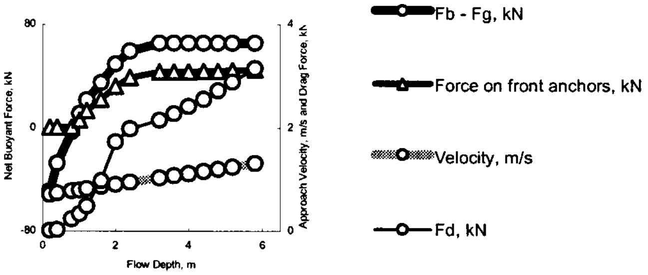

Fig. 2. Net buoyant force (left vertical axis) and approach velocity, drag force, and force on front anchors (al on right vertical axis) for large woody debris structure as function of flow depth. Net buoyant force computed using equations found in the Appendix and $\gamma_d/\gamma_w = 0.45$. Velocity rating is best fit regression based on observed data. Drag force was computed using Eq. (3) and C_D based on Shields and Gippel (1995). Force on front anchors was computed assuming that resultant of net buoyant force and drag force is resisted by submerged weight of fill in key trenches and four earth anchors.

$=980\ \mathrm{kg\,m^{-3}}$), displayed significant differences under in situ moisture conditions. Dry densities for samples from living or recently felled oak (*Quercus* spp.), sweetgum, elm (*Ulmus* sp.), and hickory were 610, 600, 680, 730 $\mathrm{kg\,m^{-3}}$, respectively, while published values for lumber obtained from these species were 550, 490, 480, 680 $\mathrm{kg\,m^{-3}}$, respectively [U.S. Department of Agriculture (USDA) 1999]. However, the latter values were obtained by dividing sample mass after oven-drying by "green" (in situ) volume, which likely depressed them.

Based on these findings, values of γ_d/γ_w suitable for design computations for environments similar to the project described below are between 0.4 and 0.5. Corresponding values of relative depth, d_{wn}/h, for neutral buoyancy ($F_b = 0$) as predicted by Eq. (1) vary from 0.2 to 0.3.

The drag force on the LWDS was computed by

$$F_d = \frac{\gamma_w V^2 A C_D}{2g} \tag{3}$$

where F_d = drag force (N); V = approach flow velocity ($\mathrm{m\,s^{-1}}$); A = area ($\mathrm{m^2}$) of LWDS projected in the plane perpendicular to flow; and C_D = drag coefficient. The LWDS may be treated as a single body, rather than as individual cylinders (Gippel et al. 1996). For design, the cross-section mean velocity should be increased by a factor of 1.5 to allow for higher velocities on the outside of bends (U.S. Army Corps of Engineers 1991). Drag coefficients for the LWDS may be computed using an empirical formula (Shields and Gippel 1995), and will typically range from ~0.7 to 0.9. Gippel et al. (1996) suggested that drag coefficients for logs may be assumed invariant with flow depth, but Wallerstein et al. (2002) showed that drag coefficients reach values as high as 1.5 for cylinders that are barely submerged due to forces associated with the formation of standing waves. Alonso (2004) presents a more complete review of applicable information regarding drag and lift on logs in streams. Drag forces are expected to rapidly diminish with time during the first few high flow events as patterns of scour and deposition reshape the local topography (Wallerstein et al. 2001).

Computed forces acting on an LWDS for flow velocities and depths observed at the demonstration project described below are plotted as a function of flow depth in Fig. 2. The rating curve for approach velocity in Fig. 2 is a regression curve fit to field data, and the observed depths and velocities are typical of maximum velocities observed in many incised, sand-bed streams. The net buoyant force is 1 order of magnitude greater than the drag force, which contrasts with findings of D'Aoust and Millar (2000) who found a ratio of computed buoyant force to computed drag force of about 1.25 for a single log anchored to the bed with rootwad upstream in a swifter, gravel-bed river despite their use of a lower drag coefficient (0.3). Buoyant and drag forces acting on the structures must be resisted using earth anchors, as large bed material for ballast (Abbe et al. 1997; D'Aoust and Millar 2000) is not available in sand-bed streams.

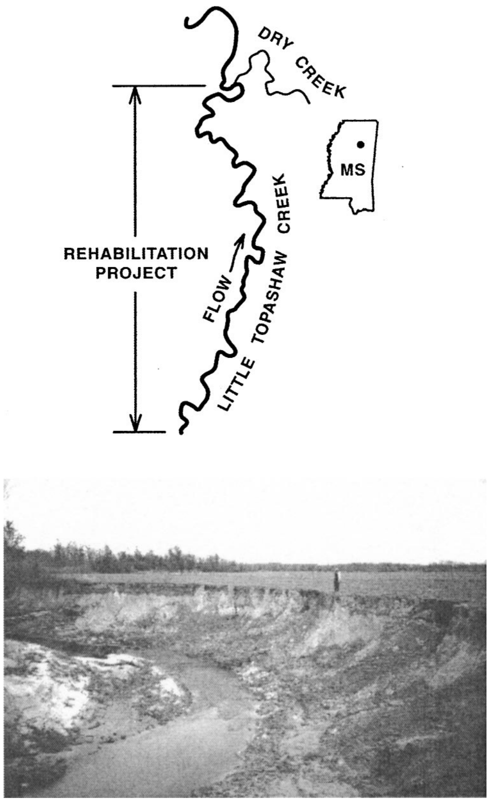

Fig. 3. Location and typical conditions prior to restoration, Little Topashaw Creek, Mississippi

Demonstration Project

A study site was selected to meet the criteria of rapid bank erosion driven by incision processes, sandy bed material, an abundant supply of bed material from upstream, advanced stage of channel evolution (Darby and Simon 1999), sources of LWD for construction, sufficient channel width to allow placement of the LWDS, nearby sources of native plant and animal colonists, and an aquatic ecosystem clearly limited by lack of pool and woody debris habitat components. The selected site is located along 2 km of Little Topashaw Creek, a fourth-order stream (1:24,000 topographic map) in north central Mississippi draining about 37 $\mathrm{km^2}$ (Fig. 3), contained within the larger watershed described by Simon and Thomas (2002). Floodplain stratigraphy was characterized by dispersive silt and clay soils overlying sand overlying consolidated cohesive material. Sandy deposits were often found along the bank toe. The channel had a single-thread planform with an average sinuosity of 2.1, an average slope of 0.002, an average top width of 35 m, and an average depth (cross-sectional area divided by top width) of 3.6 m. Channel bed materials were

Table 3. Dimensions and Orientation of Naturally Occurring Large Woody Debris Structures in Little Topashaw Creek before Construction of Large Woody Debris Structures

	May 1999	May 2000
Number of logs	81	121
Butt diameter [mean+standard deviation (cm)]	44+20	38+15
Length [mean+standard deviation (m)]	7.6+4.3	7.4+4.9
Number of LWD formations	13	6
Area of formations in horizontal plane [mean+standard deviation (m^2)]	27.3+18.7	30.7+26.5

Table 4. As-Built Dimensions for 72 Large Woody Debris Structures Constructed along Little Topashaw Creek, Mississippi

Quantity	Mean±standard deviation
Crest elevation (m)	2.1±0.5
Length of structure (m)	13.9±3.9
Width of structure (m)	5.3±1.9
Distance between structures (m)	13.0±10.8
Diameter of all members (cm)	32±5
Number of key members	4.4±1.0
Diameter of key members (cm)	45±14
Number of racked members	14.7±6.5
Length of racked members (m)	9.2±3.6
Diameter of racked members (cm)	26±10

Note: Statistics for structures are based on measurment of all 72 structures and statistics for individual members are based on measurement of members within 12 representative structures.

comprised primarily of 0.2–0.3 mm sand. However, cohesive materials occurred as massive outcrops and as gravel-sized aggregates. Available evidence suggests mean channel width had increased by a factor of 4–5 since 1955. Surveys of 13 cross sections before and after a flow of $55\ m^3\ s^{-1}$ that occurred 3 months prior to construction indicated an average increase in cross-sectional area of 10% with bank retreat as great as 7.6 m. This event, in which peak stages reached mid-bank elevation, triggered 60 m of upstream migration of a 0.6-m high headcut and produced two chute cutoffs across point bars.

Large woody debris naturally occurring in the channel was mapped in the spring of 1999 and 2000 using a differentially corrected global positioning system to record the endpoints of each log. Log diameter was measured using tree calipers, and in the 2000 census, orientation of tree boles with respect to flow direction was noted. When LWD formations were extremely complex, the perimeter of the formation was mapped rather than individual logs. Results (Table 3) indicated that the channel contained more debris in 2000, perhaps because a high flow event 2 months prior to the 2000 census resulted in 60 m of headward migration of a major knickpoint, triggering mass bank failure and debris inputs (Downs and Simon 2001). During both years, debris density was greatest in channel segments immediately downstream from the knickpoint. The stability of naturally occurring LWD was of interest as a design template. Only about 39% of the logs mapped in 1999 remained in the same location in 2000, but two-thirds of these were oriented roughly parallel to the flow direction with the butt pointing upstream, consistent with findings by Gippel et al. (1996). About two thirds of the logs and formations lodged in the center of the channel in 1999 had moved by 2000, but only about one third of those located along the banks moved. Stable logs were longer than those that moved, (mean lengths for stable and unstable logs = 11 and 7 m, respectively, $p < 0.0008$).

Construction

Large woody debris structures were constructed along 1,500 m of eroding bank using either woody debris (~10%) or living trees (~90%) harvested from designated areas including the channel. Living trees were larger than 0.20 m diameter at breast height. Living trees were harvested by grubbing in order to retain root balls and crowns intact. Materials available for LWDS construction were limited to LWD presently in the channel and trees growing in patchy stands on the floodplain, and no clearing was permitted within 10 m of top bank. There was considerable uncertainty prior to construction regarding the quantity of LWD required to complete the project, and the area needed for harvesting the required materials. Regional data collected by Downs and Simon (1999) indicated stem densities of about 100 and 800 ha^{-1} for trees with diameter >30 and >18 cm, respectively. Accordingly, given a minimum DBH of 20 cm and assuming an average DBH of 25 cm, we estimated about 50 LWDS would be needed to protect 1,500 m of eroding bank, which would require a total of about 1,200 trees harvested from 5–10 ha of forest. The finished project consisted of 72 structures built with about 1,168 trees, but these were obtained by clearing only about 3.4 ha. An average of 16 trees were used per LWDS (min=6, max=30). LWD source areas were primarily zones such as fencerows and ditches that landowners wanted cleared for cultivation.

Large woody debris structures were constructed by stacking trees as shown in Fig. 1. Members running across the flow direction (''key members'') were ~9 m long and were keyed into the bank toes (buried in trenches excavated in banks) when bank slopes were gradual enough to permit key trench excavation. Large woody debris structures crest elevations were specified as either 2.4 or 3.6 m above the adjacent streambed based on eroding bank height and channel alignment, but constructed LWDS were slightly lower, ranging from 1.1 to 3.2 m high (Table 4). Structures were spaced to create nonuniformity, which is valuable for physical habitat recovery (Shields et al. 1998a), but aligned to enhance log stability and sediment deposition. About 52% of the logs used in the LWDS had intact rootwads, with about 30% of the rootwads retaining a ball of soil. About two thirds of the key members were actually buried in the bank. Earth anchors were cabled to 58 (80%) of the completed LWDS. About one LWDS was constructed to protect each 25 m of channel, which represented a 1 order of magnitude increase in LWD loading. Costs for LWDS construction were about $80/m of treated bankline, which is 19–49% of recorded costs for recent stone bank stabilization projects in this region, and far less than similar costs from other regions. During the first winter following LWDS construction, about 4,000 willow (*Salix nigra*) cuttings were planted on point bars and in sediment deposits adjacent to selected LWDS using a water-jetting technique (Drake and Langel 1998) at a cost of about $30,000.

Effects of Large Woody Debris Structures on Local Velocity

The effects of the LWDS on local velocities are important because deposition of bed material within the structure changes the bank profile, stabilizing high, steep banks subject to mass wasting. In addition, much of the ecological value of LWDS is based on the velocity shelter they provide during high flows since

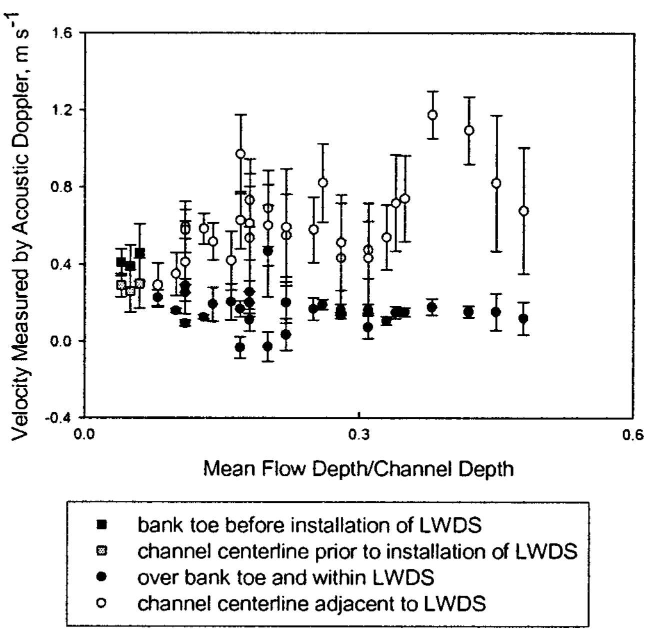

Fig. 4. Means of velocities measured by acoustic-doppler sensors versus ratio of flow depth to channel depth. Bank toe sensors (black circles) were within large woody debris structures, while channel center line sensors (white circles) were adjacent to same large woody debris structures. Means and standard deviations were computed using simultaneous measurements collected within and outside large woody debris structures during runoff event.

aquatic organisms in incised channels cannot retreat to the floodplain for velocity refuge except during rare events (Crook and Robertson 1999). Local depth and velocity within and adjacent to an LWDS were recorded at 5-min intervals during flow events using an array of ultrasonic acoustic–doppler velocity loggers installed along two cross sections about 7 m apart just downstream from the apex of a 180° bend as described by Shields et al. (2001). Data collected prior to LWDS placement show that the bank toe region experienced velocities about 1.5 times as great as those near the flow centerline, roughly consistent with field (Xia 1997) and laboratory (e.g., Odgaard and Bergs 1988; Hicks et al. 1990) observations. Similar data for 30 events following construction showed mean velocities within the region covered by the LWDS ranged from 0.03 to 0.25 m s^{-1} and were only 3–72% of the means of simultaneously measured velocities at adjacent points outside the LWDS (Fig. 4). Critical velocity for median bed material size was about 0.15 m s^{-1} [American Society of Civil Engineers (ASCE) 1975], and much higher for blocks of cohesive failed bank material (Simon et al. 2000).

Channel and Habitat Response

Channel surveys (thalweg and 38 cross sections) were obtained before and during the first two years following construction, and the baseflow channel planform was mapped using differentially corrected global positioning system. Rates of top bank retreat were measured for steep (>60°) banks using successive surveys. During the high flow season prior to construction, retreat rates were 1.1±1.7 m (mean+standard deviation) but declined to 0.44±0.66 m during the first year following construction, when only 4 of the 72 structures failed. At the end of the second year 31% of the structures were destroyed and 22% were damaged, and bank retreat rates increased to 1.6±4.9 m. After 3 years, 36% of the structures were destroyed and 35% were damaged. Cross sections impacted by a chute cutoff accounted for 37 and 59% of the total measured retreat during the preconstruction and post construction periods, respectively. Although the thalweg profile indicated about 0.5 m of degradation, mean channel depth increased only about 0.1 m because of the formation of sediment berms within LWDS at the toe of eroding banks (Fig. 5). Twenty-five bends in the baseflow channel were mapped during low flow seasons 1 and 2 years after construction. No change was evident in the location of 13 of the bends, while 9 exhibited slightly increased amplitude. Greatest changes were observed for three bends that lost amplitude due to erosion of the convex bank or chute cutoff, as described above. Decreasing amplitude and chute cutoff seems to be a typical feature of the evolution of incised channels with meandering planforms in this system, as it was observed in the study reach just prior to construction and in the untreated reach downstream.

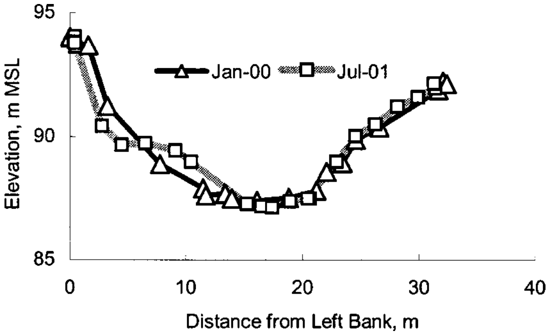

Fig. 5. Typical cross section showing formation of sediment berm at toe of left bank in response to construction of large woody debris structure in August 2000

Creation of stable pool habitats is a key component in restoration of incised stream corridors (Shields et al. 1994, 1998b), and pool habitats are often associated with LWD (House et al. 1991; Shields and Smith 1992; Larson et al. 2001). Local scour adjacent to structures (Gough 1991) and backwater from small beaver dams resulted in greater baseflow depths and higher levels of habitat heterogeneity following LWDS placement. About 100 water depth measurements (at equidistant points along 20 cross sections) at similar discharges before and during the first 2 years after construction showed mean water depth increased 40–100% and the standard deviation of depth increased by 70%. Fish community responses were consistent with previous observations of response to addition of pool habitats in incising warmwater streams—patterns of relative abundance shifted toward those typical of less-degraded streams (Shields et al. 2003), while macroinvertebrate community measures (Simpson index, Shannon index, and Evenness) showed positive response to LWDS, both within the treatment reach and downstream (Cooper and Testa 2002).

Large Woody Debris Structure Failures

Factors involved in LWDS failure included simplification of the LWD matrices due to breakage and decay, scour of sediments deposited within the structures, and failure of earth anchors. Structures located in sharp bends were most prone to fail. Damage rates were slightly higher for anchored LWDS (20/58) than for those without earth anchors (4/14). Forty-seven percent of the anchors were located upon inspection 2 years after construction,

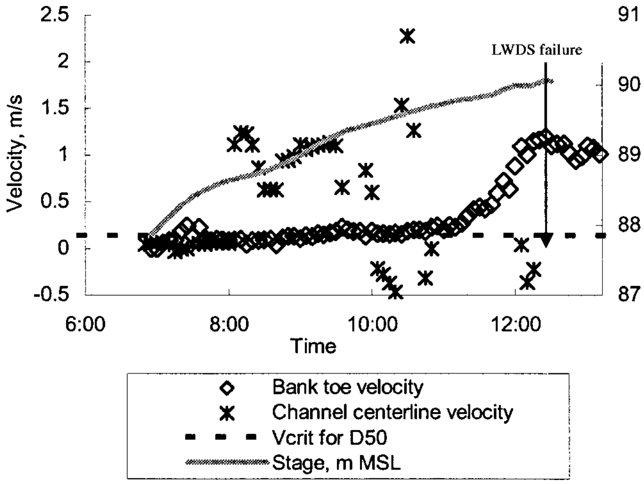

Fig. 6. Stage and velocities recorded within and adjacent to large woody debris structures No. 24, Little Topashaw Creek, Miss. during event of 20 November 2001

and 61% of those located were not functional. Evidently, the anchors, which were load tested when installed to 4.5 kN, were undersized. Anchor sizing was based on LWDS design dimensions and the assumption that critical conditions would occur shortly after construction. Accordingly, a relatively high value for wood density ($750\ \mathrm{kg\,m^{-3}}$) was used in Eq. (1). Retrospective computations using as-built dimensions and wood density $=450\ \mathrm{kg\,m^{-3}}$ indicate factors of safety well below unity.

It was assumed that sediments deposited within the LWDS would add ballast to counteract the increased buoyant force associated with drying of the wood as the structure aged. However, in many cases, sediments deposited during the first high flow season were scoured during the second. Acoustic Doppler velocity loggers recorded depth and velocity within and adjacent to an LWDS located at the apex of a bend with a ratio of top width to bend radius ~ 1.0. During the rising limb of a large flow event about 16 months after construction, apparently part of the structure shifted, allowing velocities within the structure to rapidly increase from 0.2 to $1.2\ \mathrm{m\,s^{-1}}$, greatly exceeding the critical level for the sandy bed material and approaching the velocity recorded at the adjacent channel centerline (Fig. 6). The structure failed shortly thereafter.

Conclusions

LWDS hold considerable potential as low-cost measures for rehabilitating reaches of small (drainage area$<200\ \mathrm{km}^2$) sand-bed streams in postdegradational stages of incised channel evolution. Successful application will result in decelerated erosion and ecosystem recovery. Performance depends on adequate anchoring and channel grade control. Application of this approach on a regional basis could trigger unprecedented recovery of stream corridor ecosystems at much lower cost than other practices.

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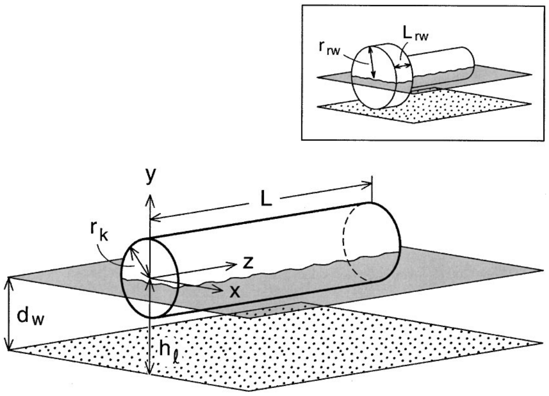

Fig. 7. Definition of variables used in computing submerged volume of key members

Appendix. Derivation of Volumes V_{r_i} and V_{k_i}

If $i=1$ for the lowest members, and if the radius and length of key members is given by r_k and L, the distance, h_{l_i}, from the streambed to the center of the ith key member will be (Fig. 7)

$$h_{l_i}=2(i-1)(r_k+r_r)+r_k \tag{4}$$

All quantities are in meters. Given a rectangular coordinate system with origin at the butt of the key member and depth of flow d_w

$$V_{k_i}=2L\int_{-r_k}^{d_w-h_{l_i}}\int_{0}^{\sqrt{r_k^2-y^2}}dx\,dy+V_{rw_i} \tag{5}$$

$$V_{k_i}-V_{rw_i}=2L\int_{-r_k}^{d_w-h_{l_i}}\sqrt{r_k^2-y^2}\,dy \tag{6}$$

$$=\frac{2L}{2}\left[y\sqrt{r_k^2-y^2}+r_k^2\sin^{-1}\left(\frac{y}{|r_k|}\right)\right]_{-r_k}^{d_w-h_{l_i}} \tag{7}$$

$$=L\left[(d_w-h_{l_i})[r_k^2-(d_w-h_{l_i})^2]^{1/2}+r_k^2\arcsin\left(\frac{d_w-h_{l_i}}{r_k}\right)+\frac{\pi r_k^2}{2}\right] \tag{8}$$

The same approach may be followed to obtain the submerged volume of the rootwad

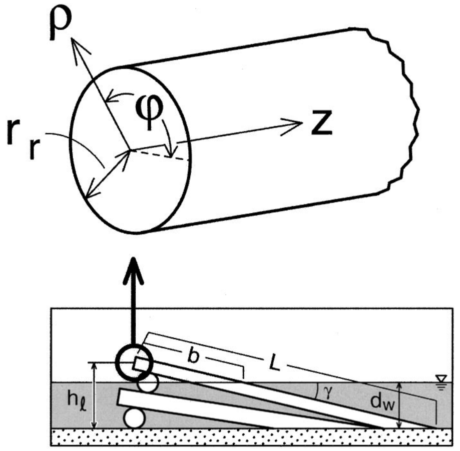

Fig. 8. Definition of variables used in computing submerged volume of racked members

$$V_{rw_i}=L_{rw}\left[(d_w-h_{l_i})[r_{rw}^2-(d_w-h_{l_i})^2]^{1/2}\right.$$
$$\left.+r^2\arcsin\left(\frac{d_w-h_{l_i}}{r_{rw}}\right)+\frac{\pi r_{rw}^2}{2}\right] \quad (9)$$

Eqs. (8) and (9) apply when the depth of water is less than needed for full submergence but great enough to wet the log

$$h_{l_i}-r<d_w<h_{l_i}+r \quad (10)$$

When a bole or rootwad is fully submerged $(d_w>h_{l_i}+r)$, then the submerged volume is simply $\pi r^2 L$. Here [and in Eq. (10)] the variable r refers to either r_k when applied to Eq. (8) or r_{rw} when applied to Eq. (9).

In order to compute the submerged volume of racked members, we adopt a cylindrical coordinate system ρ, σ, z with the z axis along axis of the log and the origin at the center of the butt (Fig. 8). The distance, h_{l_i}, from the streambed to the origin will be

$$h_{l_i}=\left(\frac{r_r}{\cos\phi}+2ir_k+2(i-1)r_r\right) \quad (11)$$

Since the angle ϕ is small, we may assume $\cos\phi\cong 1$. The equation of the water surface in this system will be $z=m\rho\sin\varphi+b$.

Therefore,

$$V_{r_i}=4\int_0^{\pi/2}\int_0^{r_r}\int_{m\rho\sin\varphi+b}^{L}\rho\,dz\,d\rho\,d\varphi \quad (12)$$

$$=\left[(L-b)\pi r_r^2-\frac{4mr_r^3}{3}\right] \quad (13)$$

This formula applies for $0<d_w<h_{l_i}+r_r/\cos\gamma$. When the entire racked layer is fully submerged, $d_w>h_{l_i}+r_r/\cos\gamma$, and then $V_{r_i}=\pi r_r^2 L$.

Notation

The following symbols are used in this paper:

d_w = depth of flow (m);
F_b = buoyant force on large woody debris structure (N);
F_d = fluid drag force on large woody debris structure (N);
F_g = gravitational force on large woody debris structure (N);
h_{l_i} = distance from streambed to axis of ith key member (m);
L = length of key and racked members (m);
L_{rw} = length (thickness) of key member rootwads (m);
n_{r_i} = number of racked members in ith layer of large woody debris structure;
r_k = radius of key members (m);
r_r = radius of racked members (m);
r_{rw} = radius of key member rootwads (m);
V_{k_i} = submerged volume for ith key member of large woody debris structure (m^3);
V_{r_i} = submerged volume for racked member of ith layer of large woody debris structure (m^3);
V_{rw_i} = submerged volume for rootwad of ith key member of large woody debris structure (m^3);
x = horizontal coordinate (m);
y = vertical coordinate (m);
γ_d = specific weight of woody debris (N m^{-3}); and
γ_w = specific weight of water (N m^{-3}).

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