DESIGN OF LARGE WOODY DEBRIS STRUCTURES FOR CHANNEL REHABILITATION

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Foreward: This paper was prepared and presented at the Seventh Federal Interagency Sedimentation Conference in March 2001. During the winter of 2001-2002, the project was subjected to at least 3 large flow events, with one near bankfull stage. During the first year following construction (2000-2001), stream bank erosion was checked by placement of the debris structures and deposition of sand berms adjacent to steep, concave banks. However, many of these deposits were scoured away during high flows and attendant bed degradation occurring 16 and 17 months following construction, resulting in progressive failure of ~30% of the structures and renewed erosion.

Abstract: Described is a project intended to restore habitats along 2 km of a sand bed stream severely damaged by channel incision. The project consists of placement of large woody debris (LWD) and planting native vegetation. Design and construction of large woody debris structures are described. If successful, this approach will offer significant cost savings over traditional approaches involving stone bank protection structures.

INTRODUCTION

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. Nationally, emphasis for stream and lake restoration has slowly increased over the last two to three decades. Additionally, restoration of aquatic systems to a functional state is the primary goal of the Total Maximum Daily Load (TMDL) approach to water quality now being applied nationally. The end-point of current federal water quality goals and new upcoming nutrient criteria is return to a functional ecological state, i.e. an aquatic ecosystem with ecological integrity. Thus, implementation plans focus on remediation of specific impairments. In many severely incised streams, primary impairments are lack of stable habitat including shifting bottom substrate, shallow depths with a lack of pools, and limited woody debris. Canopy and carbon are at a minimum since the stream is separated from its floodplain. Stabilization can improve both habitat potential and water quality.

Current practice for stabilizing watersheds destabilized by channel incision is based on combinations of grade control drop structures, in-channel stone structures, drop pipes, small reservoirs (floodwater retarding structures), and land treatment. Costs for treating an entire watershed range as high as \$750 ha^{-1}, and costs for channel stabilization as high as \$300 m^{-1} for the affected stream reach. Described herein are design and construction of a demonstration rehabilitation project with projected cost less than \$100 m^{-1}. The project is intended to quantify ecological effects of the low-cost measures, which were selected and designed with consideration of existing habitat deficiencies. Plans call for monitoring physical and biological response for up to five years.

STUDY SITE

The study site is located along 2 km of Little Topashaw Creek, a fourth-order stream in the Yalobusha River watershed in north central Mississippi. Contributing drainage area is about 37 km^2. Floodplain stratigraphy is characterized by dispersive silt and clay soils underlain by sand that overlies the consolidated cohesive material (Adams 2000). Sandy deposits are often found along the bank toe. The channel is tortuous, with an average sinuosity of 2.1, an average width of about 35 m, and an average depth of 6 m. At least two abandoned meanders suggest recent natural neck cutoffs. Channel bed materials are comprised primarily of sand with median sizes between 0.2 and 0.3 mm. However, cohesive materials occur as massive outcrops and as gravel-sized particles. Available evidence suggests mean width has increased by a factor of 4 to 5 since 1955. A geomorphic evaluation performed immediately prior to construction (Wallerstein 2000) indicated that the downstream end of the reach was in the aggradational stage V of the Simon (1989) conceptual model of incised channel evolution, while the middle part of the reach was stage IV, and the upstream fourth of the reach was still degrading (stage III). A knickpoint was located between zones classified as stage IV and stage III, with thalweg slopes ~0.003 upstream of the knickpoint and ~0.002 downstream. In general, concave banks on the outside of meander bends are failing by mass wasting subject to basal endpoint control, and sand is accreting on large point bars opposite failing banks (Figure 1). Outside of bends, eroding banks frequently invade adjacent cultivated fields, while inside bends and abandoned sloughs are vegetated with a diverse mixture of hardwood trees and associated species.

Large woody debris naturally occurring in the channel was mapped in the Spring of 1999 and 2000 using a differentially-corrected global positioning system. Debris 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 (Figure 2) indicated that the channel contained more debris in 2000, perhaps because the 2000 map included smaller logs. Reach-mean debris density was 40.5 logs km^{-1} in 1999 and 60.5 logs km^{-1} in 2000 (formations omitted). Debris density was greatest in channel segments immediately downstream from the knickpoint. Debris stability during the period between the two maps was related to LWD orientation and channel evolution. Only about 29% of the debris mapped in 1999 remained in the same location in 2000, but about 70% of this debris was oriented roughly parallel to the flow direction with the butt pointing upstream. Debris stability was generally higher in stage V segments than in actively evolving stage III or IV segments.

Hydrologic data for the study reach is limited. A large storm in June 1999 produced overbank flooding along the reach, and a USGS gage (07282075) located on a larger stream about 1 mile downstream recorded a peak 11 m above base stage. Stage records obtained since this project was initiated indicate that storm hydrographs are typically brief (< 1 day) and have rise times on the order of 6 hours.

DESIGN AND CONSTRUCTION

Structural measures for stream corridor rehabilitation must be selected and designed to harmonize with the dominant geomorphic processes. For ecosystem rehabilitation, they must address the major factors inhibiting natural recovery. Accordingly, this project was designed 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). Bank stabilization structures made from large woody debris instead of stone were placed along the toe of eroding banks. The large woody debris structures (LWDS) were designed to resist displacement by interlocking, keying-in to banks, anchoring, and by inducing sediment deposition. The LWDS were intended to accrete and retain sediment and organic matter input both from adjacent mass wasting and material transported into the reach from upstream. Crest elevations were set high enough to stabilize existing near-vertical banks failing by mass-wasting (Simon 1998) by building a berm at the toe and preventing episodic cleanout of failure blocks. Since these structures will rapidly decompose in the humid, temperate climate, they are intended to provide suitable habitat for invasion of sediment deposits by plants that will secure and stabilize the channel margins over the longer term (Jacobson *et al.* 1999). In addition, since studies of degraded streams across the region have shown that habitat diversity (Shields and Smith 1992), invertebrate species richness and abundance (Cooper and Testa 1999), and fish species richness (Shields *et al.* 1998a) are associated in a positive fashion with LWD density, addition of LWDS should improve aquatic habitat and facilitate ecological recovery. Additional elements of the project include planting selected native plant materials to rapidly stabilize accreted deposits and gullies formed by runoff passing over the top of banks.

Design of LWDS was based on concepts from Edminster *et al.* (1949), Mott (1994), Abbe *et al.* (1997), Derrick (1997) and others adapted to our region (Figure 3). Structures simulate stable configurations of naturally-occurring debris (Wallerstein *et al.* 1997). Bed material gradations and thalweg profiles were available for design, as were limited cross-section survey data collected in 1997 and 1999.

About 1500 m of eroding banks were selected for LWDS protection. LWDS were constructed using either woody debris (~10%) or living trees (~90%) harvested from designated areas including the channel. Living trees were larger than 200 mm diameter at breast height (DBH). Living trees were harvested by grubbing in order to retain root balls and crowns intact. LWDS were constructed by stacking trees as shown in Figure 3. Members running across the flow direction ("key members") were ~9 m long and were keyed into the bank toes when bank slopes were gradual enough to permit key trench excavation. LWDS crest elevations were specified as either 2.4 m or 3.6 m above the adjacent streambed based on eroding bank height and channel alignment, but constructed LWDS were slightly lower. An average of 16 trees were used per LWDS. Structures were spaced to create nonuniformity, which is valuable for physical habitat recovery (Shields *et al.* 1998b), but aligned to enhance log stability and sediment deposition. In general, structures extended about 15 m in the streamwise direction, about 5 m transverse to the stream, and were spaced about 14 m apart. About one LWDS was constructed to protect each 20 m of eroding bank (Figure 2), which represented an order of magnitude increase in LWD loading.

For design, forces acting on the LWDS were partitioned into buoyancy and fluid drag. The buoyant force acting on each LWDS was computed using the formula:

$$F_b = \{\gamma_w (S_{wood}\ \Sigma \text{ volume of LWD} - \Sigma \text{ volume of displaced water})\} \qquad (1)$$

Where F_b = net buoyant force in N, S_{wood} = specific gravity of wood, and γ_w = specific weight of water in N m^{-3}. LWD stems were assumed to have volumes equal to cylinders with diameters equal to the mean DBH. This assumption overestimates LWD volume because it neglects stem tapering, but this factor is balanced by the volume of branches. The specific gravity of LWD was determined by collecting 89 samples of naturally-occurring debris prior to construction. Samples were weighed and volumes were determined by measuring the volume of water displaced by submerging each sample. Specific gravities were determined for *in-situ* conditions, after soaking in water for ten days, and after drying in an oven at 50^o C for ten days. *In-situ* S_{wood} varied from 0.30 to 1.39 for dead trees and from 0.67 to 1.14 for living trees. Means and standard deviations for dead and living trees were 0.82 ± 0.21 and 0.96 ± 0.16, respectively. Dried samples averaged about 73% lighter and soaked samples about 137% heavier than in-situ conditions.

For design, the depth of flow required for the LWDS to float (treating the structure as a unit) was computed by setting the weight of displaced water equal to the weight of wood. The volume of displaced water was determined by integrating the submerged volume of LWD using an approach similar to that of Braudrick and Grant (2000). Root balls were treated as cylindrical disks for key members, but neglected for racked members. The weight of soil within root balls was neglected in order to be conservative.

These depths were compared to those predicted by a steady flow model (Copeland *et al.* 1998) for typical cross sections using discharges determined for the two- and five-year return interval events using regional regression formulas (Landers and Wilson 1991). Results (Figure 4) indicated that LWDS stability is sensitive to wood density. Flow depths for frequent events are not adequate to submerge the upper portions of the structure, where the heavier parts of the members are concentrated. LWDS comprised of typical materials should be stable during frequent events. Discharges equivalent to the two-year event are required to float the LWDS if the specific gravity of wood = 0.75. Buoyant forces will be counteracted initially by the weight of fill in key trenches and by four earth anchors placed on opposite corners of each structure and load tested to a minimum of 4.4 kN. Anchors on opposite corners are attached by 6 mm wire cable. After a few flow events, buoyant forces should also be counteracted by the weight of sediments deposited on LWDS members.

The drag force on the LWDS was computed by:

$$F_d = 0.5\ V^2 A \rho_w C_D \qquad (2)$$

Where F_d = drag force in N, V = approach flow velocity in m s^{-1}, A = area in m^2 of LWDS projected in the plane perpendicular to flow, ρ_w = density of water in kg m^{-3}, and C_D = drag coefficient. Approach velocities for the two-year event were computed using the Manning equation (V_{mean} = 1.0 m s^{-1}) and verified using output from SAM (Copeland *et al.* 1998) and typical cross-sections (V_{mean} = 0.6 m s^{-1}). For design, the mean velocity of 1.0 m s^{-1} was increased by a factor of 1.5 to allow for higher velocities on the outside of bends. Drag coefficients were computed using the empirical formula for LWD formations presented by Shields and Gippel (1995), and ranged from ~0.7 to 0.9. 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.*, In Review). Results of LWDS force analysis for five-year discharge conditions are summarized in Table 1.

Materials available for LWDS construction were limited to LWD presently in the channel and trees growing in patchy stands on the floodplain. 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 ha^{-1} 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 1500 m of eroding bank, which would require a total of about 1,200 trees harvested from 5 to 10 ha of forest. The finished project consisted of 72 structures built with about 1,200 trees, but these were obtained by clearing only about 3.4 ha. Cleared areas were primarily zones such as fencerows and ditches that landowners wanted cleared for cultivation.

Table 1. Computed Forces Acting on Submerged 2.4-m high LWDS (discharge = 57 $m^3 s^{-1}$ racked member diameter = 30 cm, key member diameter = 40 cm, S_{wood} = 0.75).

Quantity	Magnitude, kN
Total weight of LWD	115
Weight of displaced water	126
Submerged weight of backfill in key trenches	7
Force due to earth anchors	18
Drag force	14

Effects of rehabilitation measures on bed-material sediment transport were estimated by applying the SAM computer routine (Copeland *et al.* 1998) to a data set comprised of 11 cross sections. The total force option was used for determination of composite hydraulic properties, and the Yang equation was used to compute bed-material sediment load. Manning n values were set at 0.07 for vegetated banks and 0.04 for the central portion of the channel. These values reflect increases of about 30% to allow for effects of sinuosity (Chow 1959). At the estimated two-year discharge, the computed sediment transport capacity of the existing channel upstream from the project was about 1,200 kg s^{-1}, increased in the reach containing a 0.8-m high headcut, and then declined to about 800 kg s^{-1}. This pattern is consistent with the channel evolution model proposed by Simon (1989). The influence of LWDS was simulated by increasing the Manning n values to 0.15 for segments of the cross section covered by LWDS. Resulting composite n-values computed by SAM were consistent with values obtained using the approach of Shields and Gippel (1995). This modification influenced only a small fraction of the wetted perimeter, but reduced computed sediment transport for the reach by 50%. Effects for greater discharges were slightly less.

MONITORING

The Little Topashaw Creek corridor is being used as a study site for a variety of projects, all of which should provide insight into rehabilitation and response. Precipitation, stage and discharge and routine water quality parameters are continuously monitored. Thalweg profile and 39 strategically located cross sections are surveyed each winter. Fish, macroinvertebrates, and physical aquatic habitat information are collected from zones located upstream, within, and downstream from the study reach in Fall and Spring. Special studies are proceeding to describe the effects of local dewatering on stability of steep banks, the effects of LWDS on flow depths and velocities, and the effects of planting large native grasses on streamside gullies. A census of terrestrial plants was performed prior to construction, and bank soils data were collected to confirm a recently developed protocol for prediction of willow planting success.

CONCLUSIONS

LWDS hold considerable potential as low-cost measures for rehabilitating small (drainage area < 200 km^2) sand-bed streams damaged by channel incision. Successful application will result in decelerated erosion and ecosystem recovery. However, the structures are vulnerable after they are installed but before sufficient sediment has deposited within the woody debris matrix to counteract buoyant forces. Another hazardous period will occur when the structures decompose and disintegrate if colonization of the sediment deposits by woody vegetation is not rapid. Finally, the long term outlook depends upon a watershed-wide strategy to control grade and upstream sediment sources so that the new morphology developed by the LWDS will approach dynamic equilibrium with water and sediment inputs.

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Figure 1. Typical bank erosion in study reach, 1999.

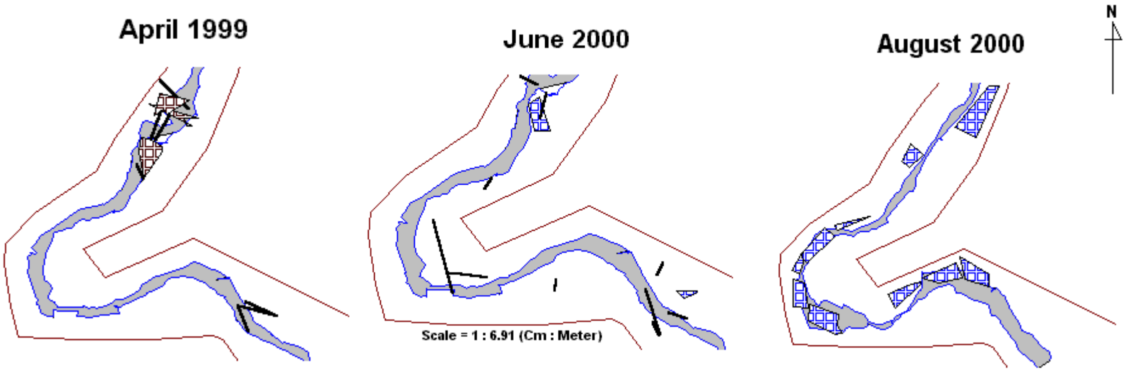

Figure 2. Map of selected segment of study reach showing top banks, water's edge at base flow, LWD formations and individual logs (April 1999 and June 2000) and LWDS (August 2000).

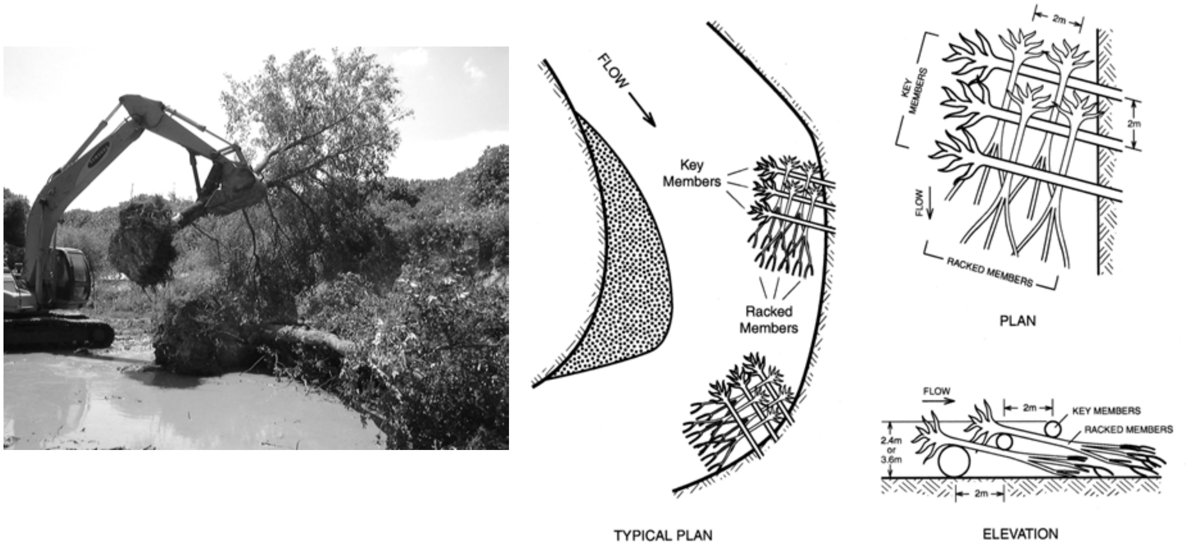

Figure 3. Typical plan and elevation of large woody debris structures. Inset photo shows LWDS under construction**.**

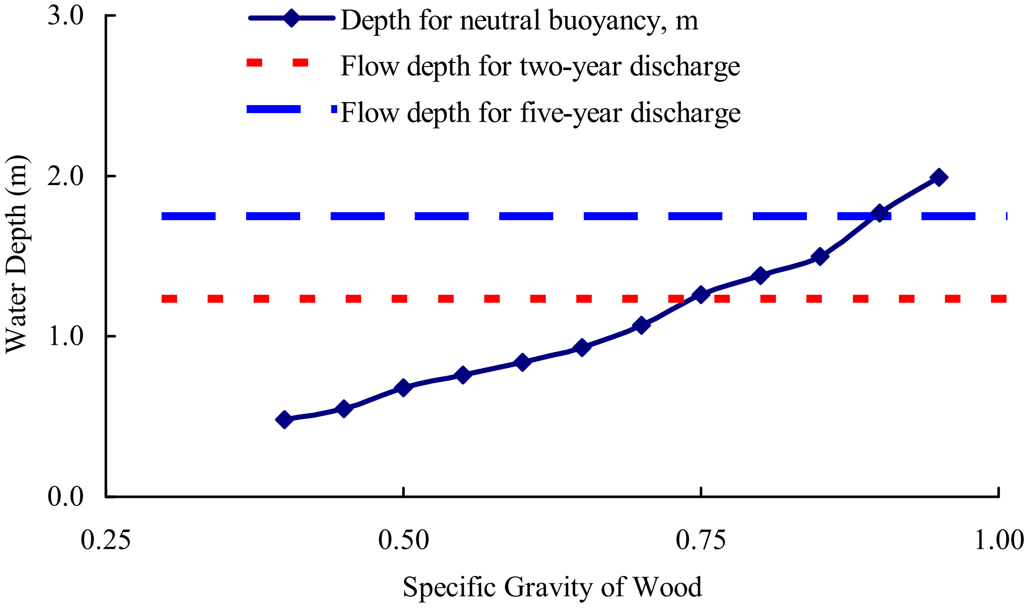

Figure 4. Flow depth required for buoyant force on large woody debris structure to equal weight of wood as a function of flow depth.