Large Woody Debris Structures for Incised Channel Rehabilitation

F. Douglas Shields, Jr., Member, ASCE, S. S. Knight, C. M. Cooper and S. Testa

Research Hydraulic Engineer, Ecologist, Supv. Ecologist, and Biologist, respectively. USDA-ARS-National Sedimentation Laboratory, P.O. Box 1157, Oxford, MS 38655-1157
PH (662)232 2919; FAX (662) 232 2920; email: shields@sedlab.olemiss.edu

Abstract

Described is a project intended to restore habitats along 2 km of a sand bed stream severely damaged by channel incision. Structural measures are limited to placement of large woody debris and planting switchgrasses and woody vegetation. Assessment of pre-project channel stability and design 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. 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}. Described herein are planning and design of a demonstration rehabilitation project with projected cost less than \$100 m^{-1}. At this writing the project has been planned and designed, but not constructed. The proposed project will seek to quantify ecological effects of the proposed low-cost measures, which will be selected and designed with consideration of existing habitat deficiencies. The proposed experimental measures will include two major components:

- Bank stabilization structures made from large woody debris instead of stone will be placed along the toe of eroding banks. Debris structures will be designed to resist displacement by interlocking, keying-in to banks, anchoring, and by inducing sediment deposition.
- Selected plant materials representing native species will be used to rapidly stabilize accreted deposits and to create edge-of-field transition zones.

Hydraulic engineering aspects of the project include a pre-design stability assessment, analysis of forces acting on large woody debris structures, and sediment budgets for the existing and post-project conditions. Plans call for monitoring physical and biological response for up to five years.

Submitted to Proceedings of ASCE 2000 Joint Conference on Water Resources Engineering and Water Resources Planning and Management. To be published on CD-ROM, ASCE, Reston, VA. This version modified from published version (change in watershed size from 56 km^2 to 37 km^2).

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 (Figure 1). Contributing drainage area is about 37 km^2; and bed slope is about 0.002. 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. The reach was classified as Stage IV according to the Simon CEM (Simon 1998), and available evidence suggests mean width has increased by a factor of 4 to 5 since 1955. 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 2). Large woody debris is plentiful in the channel. 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.

Stability assessment

The existing stability of the project reach was assessed using five simple approaches (Shields et al. In Press) with results shown in Table 1. Reach slope was obtained from thalweg profiles surveyed in 1997 and 2000 (Figure 3), and bed-material size was obtained from sieve analyses of samples collected in 1997 and 1999 (Figure 4). Since the watershed is ungaged, a regression equation (Landers and Wilson 1991) was used to compute the peak discharges with two- and five-year average return intervals (29 and 60 m^{3}s^{-1}, respectively). Discharges obtained from the regression equation were within 12% of values computed by multiplying discharges determined for a downstream gage by the ratio of contributing drainage areas. Average stream power and bed shear stress were obtained by averaging outputs from the SAM software package (Copeland 1994) simulations of the hydraulics of each of three representative cross sections for a steady discharge equivalent to 150% of the computed two-year event.

The consensus of the stability assessment tools was that the existing channel is unstable. The Simon slope-area relationship indicates that the reach is about 30% steeper than needed for stage V stability, but this relationship was developed using data from straight reaches. If the concave banks of bends are well-protected, steeper slopes may be stable in this reach. In any case, the proposed rehabilitation measures are not likely to reduce channel slope enough to render it fully stable unless they are accompanied by construction of grade controls. However, the addition of the proposed large woody debris structures and revegetation of bars should dissipate much of the flow energy currently expended on bed and banks.

Ecological Assessment

Collections of invertebrate, fish, and physical habitat data were made at baseflow during June and September, 1999. Invertebrate and fish communities were typified by small populations of tolerant species. Assemblages were typical of highly degraded sites elsewhere in the region (Shields et al. 1995). Nineteen species of fish were found, but no fish was captured that was longer than 20 cm. A ranking based on rapid bioassessment habitat and macroinvertebrate collections placed this site 26th out of 29 sites located throughout the Yalobusha River watershed.

Discharge measurements on June 8 were 58, 31, and 56 L s^{-1} for transects located upstream, within, and downstream from the reach to be rehabilitated, perhaps indicating significant exchange between surface and groundwater. A similar pattern was observed in September, 1999. Initial measurements indicated that water quantity and quality should not be major impediments to restoration. Physical and chemical water quality parameters were within accepted limits. Low concentrations of persistent organochlorine pesticides were measurable, but this phenomenon is quite common within the region. Very low concentrations of some currently-used cotton insecticides have been measured. Most pesticides currently used in the watershed dissipated before reaching the stream. Coliform bacteria levels did not indicate any discrete sources.

Physical habitat conditions were marked by flow widths 10-15% of channel width, extremely shallow flow (mean depths 5-13 cm) and sand-dominated substrates (bottoms were 71-100% sand). The channel contained significant amounts of large woody debris relative to other channels in the region, but only a fraction (~1-5%) of what is needed to construct the rehabilitation structures. Rapid channel migration, shallow water depth at base flow (i.e., scarcity of pool habitat), and elevated sediment load will present major restoration challenges.

Table 1. Summary of Stability Assessment for Existing Conditions on Little Topashaw Creek, Mississippi. S= thalweg slope, A = drainage area in km^2, S_v = valley slope, Q_{bf} = channel-forming discharge in $m^3 s^{-1}$, D_{50} = median bed material size in m, and θ = dimensionless bed shear stress (Shields parameter).

Assessment Tool	Value for Existing Conditions	Value Required for Stability	Reference
Slope-drainage area relationship $S = 0.0042 A^{-0.282}$	0.002	0.0015	Simon (1998)
Stream power, W m^{-2}	29-53	< 35	Brookes (1990)
Potential specific stream power, W m^{-2} $2.1 S_v Q_{bf}^{0.5} < 843 D_{50}^{0.41}$	50-72	≤ 30 for meandering planform	van den Berg (1995)
Channel evolution model	Stage IV	Stage V or VI	Simon (1989 and 1998)
Average bed shear stress, N m^{-2} for θ = 1.8	24-34	7	For sand (active bed) channel stability

Design

Structures

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). Roughness elements are to be added along the toe of the eroding bank in the form of large woody debris structures (LWDS). The LWDS are intended to accrete and retain sediment and organic matter input from adjacent mass wasting and transported into the reach from upstream. Since these structures will rapidly decompose in our 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.

Design of large woody debris structures was based on concepts from Edminster et al. (1949), Missouri Department of Conservation (1993), Mott (1994), Abbe et al. (1997), Derrick (1997), Hilderbrand et al. (1998) and D'Aoust and Millar (In review) adapted to our region. The aforementioned bed material gradation and thalweg profiles (Figures 3 and 4) 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 will be constructed using either woody debris or living trees harvested from designated areas including the channel. Living trees must be larger than 200 mm diameter at breast height (DBH). Living trees will be harvested by grubbing trees in such a way as to retain root ball and crown intact. LWDS will be constructed by stacking trees as shown in Figure 5. Members running across the flow direction ("key members") will be 9 m long and will be keyed into the sediment deposits at the base of steep banks. Crest elevations will be either 2.4 or 3.6 m above the adjacent streambed based on eroding bank height and channel alignment. Structures will be spaced to create nonuniformity which is valuable for physical habitat recovery (Shields et al. 1998b), but aligned to enhance log stability and sediment deposition (Hilderbrand et al. 1998). In general, structures will extend about 20 m in the streamwise direction and will be spaced about 10 m apart.

For design, forces acting on the LWDS were partitioned into buoyancy and fluid drag. Based on SAM output, LWDS were assumed to be fully submerged at design discharge. Buoyant and drag forces will be balanced by forces exerted on the keyed-in portions of key members (Figure 5) by surrounding soils. Net buoyant force acting on each LWDS was computed using the formula:

$$F_b = \{(1.0 - S_{wood})\ \gamma_w\ (\Sigma \text{ volume of LWD members}) - \text{weight of fill in key trenches} \quad (1)$$

Where F_b = net buoyant force in N, 1.0 is the specific gravity of water, S_{wood} is the specific gravity of wood, and γ_w is the 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. The specific gravity of wood was assumed equal to 0.5, which was likely a conservative (low) value in light of results presented by Thevenet et al. (1998). The weight of soil within root balls was neglected in order to be conservative, but the weight of soil used as backfill in key trenches was computed by assuming typical dimensions for trenches (1 m wide x 1 m deep x 3 m long) and a dry density for backfill of 1,500 kg m^{-3}.

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 were computed using the Manning equation (V_{mean} = 1.9 m s^{-1}) and verified using output from SAM (Copeland 1994) and typical cross-sections (V_{mean} = 1.5 m s^{-1}). For design, the mean velocity of 1.9 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. Results of this analysis are presented in Table 2 below.

Table 2. Computed Forces Acting on Submerged LWDS at Design Discharge

Quantity, kN	2.4 m high LWDS	3.6 m high LWDS
Total weight of LWD	44	69
Weight of displaced water	87	118
Weight of backfill in key trenches	198	198
Drag force	17	34

Since the actual weight of backfill in key trenches will vary considerably due to variation in bank toe geometry (and thus trench depth) and bank material properties, four earth anchors will be installed at opposite corners of selected LWDS and connected with 6 mm wire cable passing over the top of the structure. Each anchor will be load tested when installed to insure a minimum holding capacity of 18 kN. 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). In addition, sediment deposition within the LWDS will provide additional ballast after a few high flow events.

Materials available for LWDS construction are limited to LWD presently in the channel and trees growing in patchy stands on the floodplain. A census of all LWD within the project reach indicated about 80 individual stems with mean length of 8 m and mean butt diameter of 43 cm. Additional data collected by Downs and Simon (1999) within the region 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, then about 40 of the 2.4-m -high LWDS will be required to protect 1200 m of eroding bank, and about 10 of the 3.6-m high structures will be required to protect 300 m of bank. This will require a total of about 1200 trees, which may be obtained from 5 to 10 ha of floodplain forest.

Effects of rehabilitation measures on bed-material sediment transport were estimated by applying SAM (Copeland 1994) 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} (Figure 6). 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% (Figure 6). Effects for greater discharges were slightly less.

Vegetative measures

About 3,900 willow cuttings 1.5 m long and $\geq$ 3 cm in diameter will be planted on 1-m centers in selected sediment deposits along the margins of the base flow channel. Approaches developed for planting dormant willow cuttings were based on Drake (1998), who presented a design for a pressure nozzle to be used with a small water pump to plant cuttings in alluvial soils by jetting. In addition, plans require that cuttings be immersed in water for 10 to 12 days prior to planting to improve growth and survival based on laboratory experiments by Schaff et al. (In review).

Additional vegetative measures include the use of hedges of switchgrass to control gullies formed in the banks of the incised stream channel by overland flow. Grass hedges will be formed by planting closely-spaced rows of sod at right angles to gully axes. Three gullies will be treated by planting sod and minimal shaping, and three will be treated by grading the existing gully into a shallow channel with a trapezoidal-shaped cross section and planting closely-spaced grass hedges at right angles to the flow direction.

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.

Acknowledgments

Construction of the Little Topashaw Creek Stream Corridor Rehabilitation Project is funded by the Demonstration Erosion Control Project, which is managed by Mr. Philip Haskins of the Vicksburg District of the U.S. Army Corps of Engineers. Preliminary channel surveys were conducted, and specifications were prepared by the Mississippi District of the U.S. Department of Agriculture Natural Resources Conservation Service (NRCS). The project engineer for the NRCS is Mr. Steve Wilson. Assistance with field data collection by Richard Lizotte, Terry Welch, Mark Griffith, Jon Maul, Dustin Rodgers, and Matt Moore is gratefully acknowledged.

References

Abbe, T. B., Montgomery, D. R., and Petroff, C. (1997). “Design of stable in-channel wood debris structures for bank protection and habitat restoration: An example from the Cowlitz River, WA.” *Proceedings From the Conference on Management of Landscapes Disturbed by Channel Incision*, 809-815.

Adams, F. A. (2000). “Geologic Investigation Report: Yalobusha River Subwatershed, LittleTopashaw Creek Stream Corridor Rehabilitation, Chickasaw County, Mississippi.” (unpublished report) U. S. Department of Agriculture, Natural Resources Conservation Service, Jackson, Mississippi.

Brookes, A. (1990). “Restoration and enhancement of engineered river channels, some European experiences.” *Regulated Rivers: Research and Management*, 5(1), 45-56.

Chow, V. T. (1959). *Open-Channel Hydraulics*. New York: McGraw-Hill Book Company.

Cooper, C. M., and Testa, S. (1999). “Examination of Revised Rapid Bioassessment Protocols in a Watershed Disturbed by Channel Incision.” *Bulletin of the North American Benthological Society*, 16(1), 198.

Copeland, R. R. (1994). “Application of channel stability methods-case studies.” *Technical Report HL-94-11*, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

D’Aoust, S. G., and Millar, R. G. (In review). “Stability of constructed LWD Habitat structures.” Revised Manuscript submitted to *Journal of Hydraulic Engineering*, ASCE, 24pp.

Derrick, D. L. (1997). “Harland Creek Bendway Weir/Willow Post Bank Stabilization Demonstration Project.” *Management of Landscapes Disturbed by Channel Incision*, 351-356.

Downs, P., and Simon, A. (1999). “The implications of large woody debris recruitment in the Yalobusha catchment: a summary of research in progress.” (report) University of Nottingham, Nottingham, NG7 2RD, UK.

Drake, L., Langel, R. (1998). “Deep-Palanting Willow Cuttings Via Water Jetting.” *Wetlands Engineering River Restoration Conference.*

Edminster, F. C., Atkinson, W. S., and McIntyre, A. C. (1949). “Streambank Erosion Control on the Winooski River, Vermont.” (837), 1-54.

Hilderbrand, R. H., Lemly, D. A., Dolloff, A. C., and Harpster, K. L. (1998). “Design Considerations for Large Woody Debris Placement in Stream Enhancement Projects.” *North American Journal of Fisheries Management*, (18), 161-167.

Jacobson, P. J., Jacobson, K. M., Angermeir, P. L., and Cherry, D. S. (1999). "Transport, retention, and ecological significance of woody debris within a large ephemeral river." *Bulletin of the North American Benthological Society*, 429-444.

Landers, M. N., and Wilson, K. V. (1991). "U. S. Geological Survey Water Resources Investigations Report." *Flood Characteristics of Mississippi Streams*, (91-4037), Mississippi State Highway Department, Jackson, Mississippi.

Missouri Department of Conservation of Fisheries Division (1993). "A Status Report of Stream Projects Installed in Missouri From 1987-1992." 1-229, (unpublished report) Jefferson City, Missouri.

Mott, D. N. (1994). "Streambank Stabilization/Riparian Restoration Action Plan: Buffalo National River Arkansas." 1-83, (unpublished report) National Park Service, Harrison, Arkansas.

Schaff, S. D., Pezeshki, R. S., Shields, F. D. Jr. (Paper in review). "Effect of pre-planting soaking on growth and survival of black willow cuttings." University of Memphis, Memphis, Tennessee, U. S. Department of Agriculture, Oxford, Mississippi.

Shields, F. D. Jr., Copeland, R. R., Klingeman, P. C., Doyle, M. W., and Simon, A. (paper in press) "Stream restoration." *Sedimentation Engineering,* Second Edition (9) ASCE Manuals and Reports on Engineering Practice (54) American Society of Civil Engineers, Reston, Virg.

Shields, F. D. Jr., and Smith, R. H. (1992). "Effects of large woody debris removal on physical characteristics of a sand-bed river." *Aquatic Conservation: Marine and Freshwater Ecosystems,* 2, 145-63.

Shields, F. D. Jr., and Gippel, C. J. (1995). "Prediction of Effects of woody debris removal of Flow Resistance." *Journal of Hydraulic Engineering,* 121(4), 341-354.

Shields, F. D. Jr., Knight, S. S., and Cooper, C. M. (1998a). "Rehabilitation of aquatic habitats in warmwater streams damaged by channel incision in Mississippi." *Hydrobiologia,* 382, 63-86.

Shields, F. D. Jr., Knight, S. S., and Cooper, C. M. (1998b). "Addition of Spurs to Stone Toe Protection for Warmwater Fish Habitat Rehabilitation." *Journal of the American Water Resources Association*, 34(6). 1427-1436.

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

Simon, A. (1998). "*Processes and Forms of the Yalobusha River system: a Detailed Geomorphic Evaluation*." U. S. Department of Agriculture, National Sedimentation Laboratory, Oxford, Mississippi.

Thevenet, A., Citterio, A., and Piegay, H. (1998). "A New Methodology for the Assessment of Large Woody Debris Accumulations on Highly Modified Rivers (Example of Two French Piedmont Rivers*)*." *Regulated Rivers: Research & Management,* 14, 467-483.

van den Berg (1995). "Prediction of channel pattern of alluvial rivers." *Geomorphology,* 12(1995), 259-279.

Wallerstein, N. P., Alonso, C. V., Bennett, S. J., and Thorne, C. R. (Paper in review). "Froude-Scaled Flume Analysis of Large Woody Debris." Department of Geology, University of Nottingham, Nottingham NG7 2RD, UK, U. S. Department of Agriculture, Oxford, Mississippi.

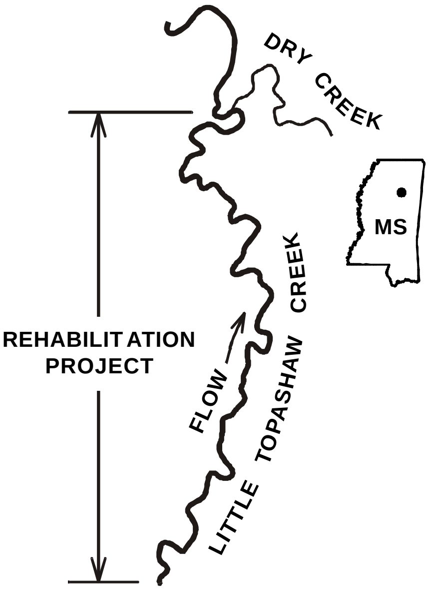

Figure 1. Study site location.

Figure 2. Bank erosion along study reach, 1999.

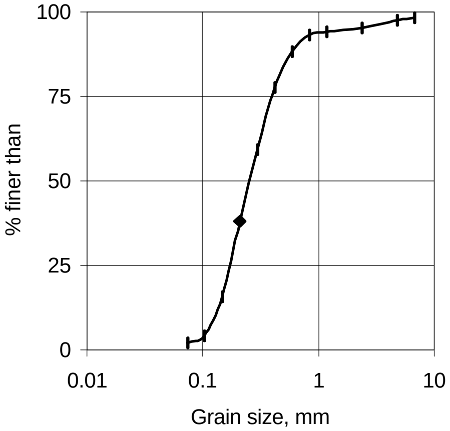

Figure 4. Bed material size gradation, 1999.

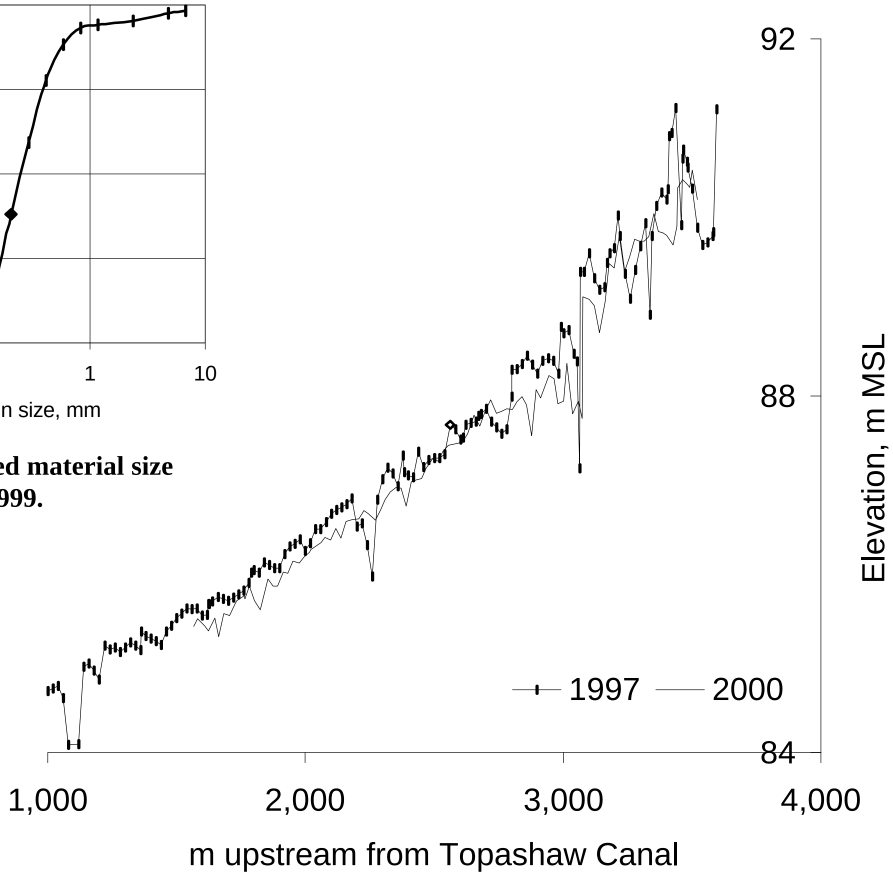

Figure 3. Thalweg profiles obtained in 1997 and 2000.

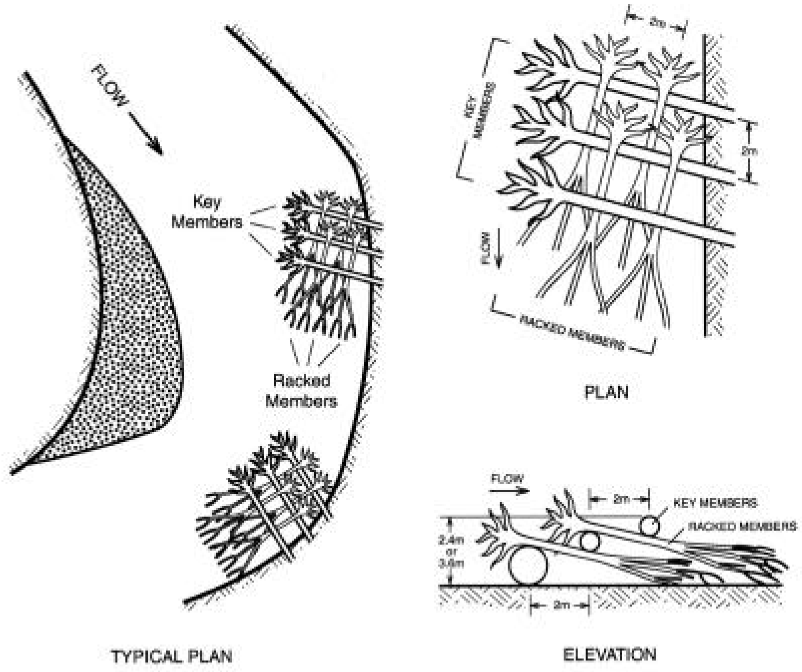

Figure 5. Typical plan and elevation of large woody debris structures.

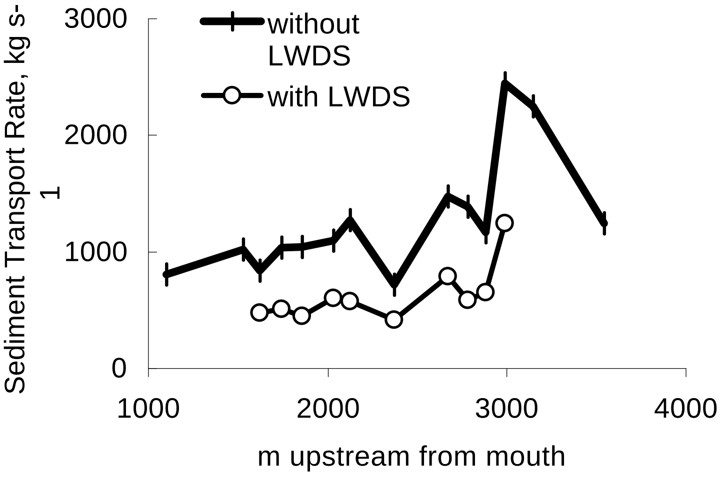

Figure 6. Effects of large woody debris structures on computed sediment transport capacity at design discharge.