WOODY VEGETATION AND DEBRIS FOR IN-CHANNEL SEDIMENT CONTROL

F. Douglas Shields, Jr. and C. M. Cooper[1]

ABSTRACT

Large woody debris and woody vegetation can exert a major influence on channel hydraulics and morphology, particularly in smaller (< 30 m wide) streams. Although debris and vegetation have long been used for channel erosion and sedimentation control, scientifically-based guidelines for designers are scarce. Recent advances in understanding vegetative effects on flow and sediment transport are reviewed. The effects of vegetation on the flow field leads to enhanced deposition within and adjacent to vegetated zones, and possibly erosion elsewhere. Site factors must be carefully evaluated when designing vegetative treatments.

Key Words: Woody debris, Woody vegetation, Channel erosion control, Sedimentation control

1 INTRODUCTION

Channel erosion and sedimentation are often problems in agricultural watersheds. For example, annual suspended sediment yield from 8 mixed cover watersheds with loessial soils in northwestern Mississippi, U.S.A. ranging in size from 21 to 622 km^2 was between 704 and 1673 tonnes (Shields et al. 1995). Control of channel bank erosion in the U.S. has traditionally been addressed with structures costing on the order of \$150 m^{-1} of bankline. Because of the ecological value and often lower cost (relative to nonliving structure) of vegetative treatments, we argue below that channel management systems of the future should focus on managing vegetation and large woody debris (LWD). Although plant materials are likely the oldest tools used by man to manage watercourses, and some of the best examples of stream rehabilitation with woody plant materials are several decades old (Edminster et al. 1949), few engineers have been trained to design with plant materials, and even the most widely recognized authorities and handbooks often resort to subjectivity in the absence of more scientific information. Accounts of existing projects usually contain few fundamental principles for universal application, and conflicting ideas often arise. Herein we review some key issues surrounding use of woody vegetation for stream corridor rehabilitation and recent advances. Due to the wide range of topics involved, this discussion is not comprehensive. Shields and Cooper (1998) provide a parallel paper containing observations regarding ecological implications of the issues discussed below.

2 HYDRAULICS

2.1 Flow structure

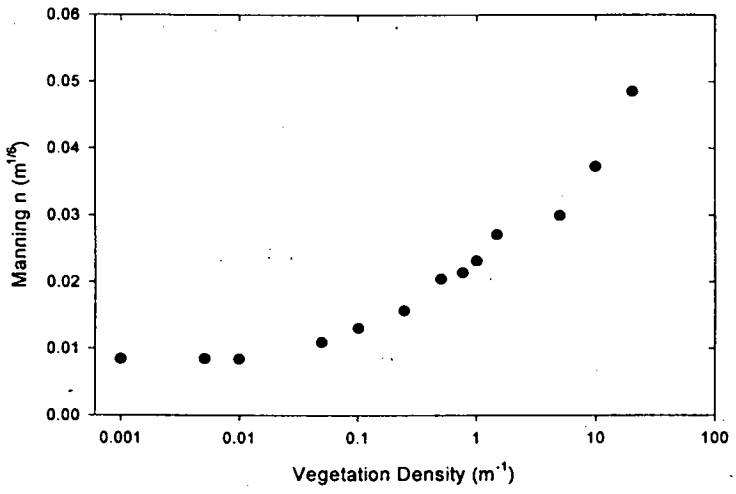
Vegetated banks and berms provide complex boundary conditions for open channel flows that set up intricate flow patterns. Work in this area is just beginning, with most research presently confined to the laboratory (e.g., Lopez and Garcia 1997, Fairbanks and Diplas 1998). Typically, woody vegetation is represented within laboratory flumes by plastic strips, wooden cylinders, or other objects that allow control of geometric and elastic properties and dynamic similitude. Velocity profiles within a field of rigid cylinders of nonuniform height indicate that streamwise velocities are greatly reduced by such vegetation, and that velocity within the array of cylinders is nearly constant with depth (Hodges et al. 1997). An important finding of these laboratory studies is that flow resistance and bed shear stress respond to vegetation density in a highly nonlinear fashion (Figure 1), likely indicating the importance of wake interference.

[1] Research Hydraulic Engineer and Supervisory Research Ecologist, respectively, U.S. Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory, Oxford Mississippi 38655-1157, shields@sedlab.olemiss.edu

Note: The manucript of this paper was received in March 1999, Discussion open until March 2001

2.2 Flow resistance

Extensive work has been done measuring effects of grasses on flow resistance, but data for woody vegetation (Volny 1984) and woody debris (Shields and Gippel 1995) are less common. Tables giving resistance coefficients (e.g., Manning n values) for various types of boundaries and vegetation are available, and schemes for computing composite flow resistance coefficients for channels and floodplains with spatial variations in vegetative conditions have been proposed (Arcement and Schneider 1989). Resistance due to rigid vegetation or woody debris may be computed given the vegetative density (Petryk and Bosmajian 1975, Shields and Gippel 1995), defined here as the fraction of flow area blocked by vegetation per unit channel length. Measurement or estimation of vegetative density is often difficult (Abt et al. 1998).



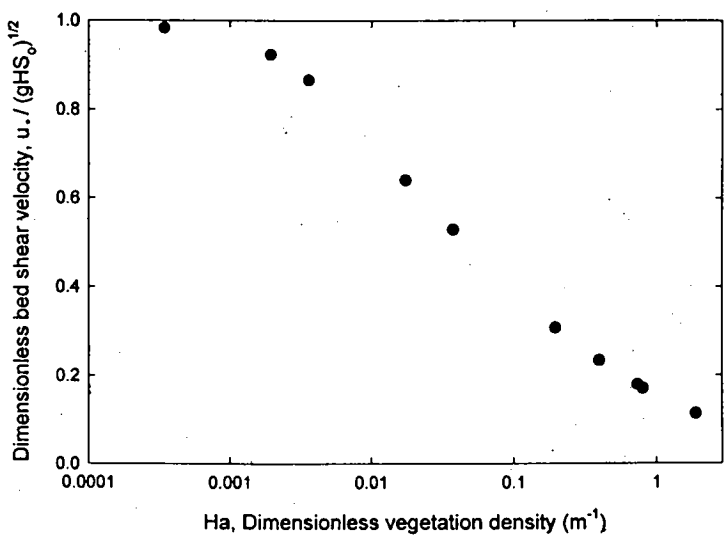


Fig. 1(a) Manning resistance coefficient as a function of vegetation density for flume experiments (b)Dimensionless bed shear stress as a function of dimensionless plant density for flume experiments. After Lopez and Garcia (1997).

Assuming that rigid vegetation acts as an array of uniform cylinders, increasing the product of vegetative density times flow depth from zero to 0.1 increases the normal depth for a given discharge by a factor of two(Garcia 1996). Field data indicate woody debris has little impact on flow conveyance if it occupies less than 10% of the flow cross-sectional area (Gippel et al. 1996). Measurements conducted in large (Shields and Gippel 1995) and small (Abt et al. 1998) natural channels indicate that flow resistance due to debris is a significant part of the total resistance at lower discharges, but that debris effects are drowned out at higher stages and discharges (Figure 2).

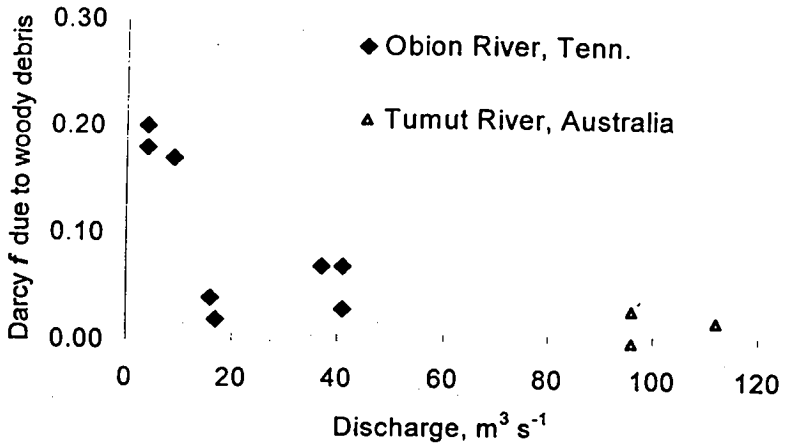


Fig. 2 Flow resistance due to woody debris in rivers (Shields and Gippel 1995). Resistance due to debris declines with increasing discharge as the fraction of the flow cross section occupied by debris and its hydraulic influence diminishes.

One procedure for predicting the flow resistance due to flexible vegetation involves computing a roughness height, k, analogous to the roughness height used for gravel beds and using this value in a Colebrook-White type resistance formula (Kouwen 1988). Roughness height of the vegetation has been empirically determined as a function of the ratio of stem stiffness to local boundary shear stress. For grasses, stem stiffness is a simple power function of stem height (Kouwen 1988). Simulation modeling indicates that channel boundaries covered by rigid vegetation are usually rougher than those covered by flexible vegetation, but that this difference diminishes as channel gradient is reduced and flexible vegetation is less likely to be bent over by the flow (Darby In Press). Regardless of the method used to predict the effect of bank vegetation on channel capacity, the influence of vegetation is closely related to the fraction of the wetted perimeter covered with vegetation. Therefore vegetation has more influence on the capacity of narrow channels than wide ones (Volny 1984).

2.3 Design issues

Even with the best tools for simulating the effect of vegetation on channel capacity, designers must solve several problems. Will the vegetation be washed away by high flows? Most types of vegetation will be extremely vulnerable to destruction by erosion during the period of establishment. Values for allowable shear stress for vegetation are hard to find in the literature. Eight projects on medium-sized streams involving well-designed vegetation treatments ("soil bioengineering") installed above stone toe protection withstood velocities of 1 to 3 m s^{-1} during floods with return intervals between 2 and 100 years without significant damage (Nunnally and Sotir 1997). Two others conveyed flows with centerline velocities of 3.5 m s^{-1} and near-bank velocities of 0.8 m s^{-1} (Shields et al. 1995). A digest of information from Eastern Europe is presented in Table 1.

Designs must not only consider what to plant and where to plant it, but also provisions for long-term maintenance. Effects of vegetation change radically with season (Sellin and Keast 1997) and over longer periods. A study of natural vegetation along rivers indicated that younger stands of woody vegetation provided greater flow resistance than older ones because stem density decreased as stands aged (McKenney et al. 1995).

Table 1 Allowable velocities and shear stresses for vegetation on river banks. After Volny (1984)

Vegetation type	Maximum velocity m s^{-1}	Maximum shear stress N m^{-2}
Turf	2	—
10 cm willows	5	—
Willows in combination with lath fence	6	—
Good quality willow covering with	---	50-70
a willow fence—1-2 years old	2.5	100
3-6 years old		
Riparian stand of predominantly ash and alder with receding shrub willow in the undergrowth	4.7	210

3 SEDIMENT TRANSPORT

3.1 Erosion and sedimentation

Some workers have observed coherent structures in riverine flows associated with riparian vegetation that are manifest in patterns of sediment movement and deposition (Fukuoka and Watanabe 1997). These findings, and study of the response of riverine systems to naturally occurring LWD accumulations (Hickin 1984; Abbe et al. 1997) suggest that well-designed plantations of woody cuttings and LWD structures might prove useful in stabilizing channels experiencing accelerated erosion or deposition.

One application of this concept would be in watersheds with incising channels. Channel networks experiencing incision tend to evolve in a generally predictable fashion. As upstream tributaries deepen and widen, downstream reaches experience accelerated sedimentation and lateral instability (Schumm et al. 1984 and Simon 1989). If riparian sediment accumulation can be triggered by planting woody vegetation, downstream problems created by large-scale sediment deposition may be ameliorated.

Sand deposition on bars that have formed in the lower reaches of incised streams has accelerated following planting rows of willow cuttings adjacent to the base flow channel (personal observation, Figure 3a and 3b). This depositional response to vegetation was similar to flume and numerical simulations by others (Yuuki and Okabe 1997). Bar revegetation speeds the evolution of the incised channel into a form that features a well-vegetated berm—the climax of the natural recovery process, according to a conceptual model of incised channel evolution (Simon 1989).

Fig. 3(a) Dormant willow posts planted in point bar along Goodwin Creek, Mississippi, 1993. Foot is on post. (b) Same site in 1995 showing deposition induced by willows, which are growing at water's edge in lower right of photo.

In order to specify vegetation type and density to achieve a certain pattern of sediment deposition, engineers need to understand the complex interactions among flow, sediment, and plant architecture. Initial progress has been made through flume studies. Although work by Abt et al. (1994) was limited to grass, results provide interesting insights. Plots of grass bordering a meandering flume channel significantly enhanced sediment deposition. The grass plots were subjected to sediment-laden flows for several hours and then were subjected to sediment-free flow to simulate the falling limb of the hydrograph. Vegetation retained from 30% to 70% of deposited sediments when subjected to sediment-

free flushing flows. At higher discharges, less deposition occurred in stands of grass with longer (20 cm) blades than in shorter (8 cm) grass, because the longer grass bent over and presented a smoother, more "armored" surface to the flow. On the other hand, the longer grass retained a greater percentage of the deposited sediments when subjected to flushing flows. These results generally agree with measurements of the effect of dimensionless plant density on shear stress at the bed (Lopez and Garcia 1997).

Additional progress has been reported from combinations of flume experiments and numerical simulation (Lopez and Garcia 1997, Tsujimoto and Kitamura 1997). Vegetation in open channels absorbs flow momentum via drag, thus reducing the shear on the channel bed.

3.2 Experiment

In order to visualize the interaction between vegetation and sediment transport in a small river, we conducted an experiment using a two-dimensional numerical model (Boss International, Inc. 1997) of an imaginary sand bed channel about 10 m wide, 2 m deep and carrying a discharge of 7 m^3s^{-1} and a sediment concentration of 500 mg L^{-1}. The cross section was a symmetric shallow V-shape, and average bed slope was 0.002. Bed sediment was medium sand (D_s = 0.3 mm). Patterns of scour and deposition for a gentle bend were simulated for two conditions: no vegetation within channel and for a channel with a dense stand of vegetation on the point bar. Manning n values (roughness coefficient) for the sand bed was assumed to be 0.025, while an n-value of 0.1 was assigned to cells containing vegetation, which is within the range of reported values for rivers obstructed by dense growths of trees, seasonal vegetation, or woody debris (Shields and Gippel 1995). Aside from the presence of vegetation, the two cases were identical. In both cases, a constant discharge of 4.6 hr duration was simulated.

Vertically-averaged current velocites were about 1 m s^{-1} across the point bar without vegetation, but about 0.6 m s^{-1} for the vegetated case. Resulting changes in bed topography reflected the influence of the vegetation (Figures 4 and 5). In both cases the inflow sediment load exceded transport potential, resulting in aggradation. The vegetated case resulted in retention of about 43 m^3 of sediment, while the reach without vegetation retained about 39 m^3. In both cases, deposition was greatest in the upstream limb of the bend, but patterns downstream were different. Downstream patterns were relatively uniform in the unvegetated case. In the case with vegetation, the resistance due to the vegetation increased deposition on the point bar and deflected higher velocities toward the concave bank, where a small amount of scour was detected. The added roughness due to vegetation apparently increased backwater effects in the upstream limb, further increasing deposition there for the vegetated case.

The model fell short of fully simulating the important processes involved because bend flow structure is three-dimensional. Future versions of this flow field model will include a correction term for effects of secondary currents in river bends (J.Letter, U.S. Army Engineer Waterways Experiment Station, personal communication). In addition, our simulation assumed sands were of uniform size, and did not consider transport or deposition of sizes finer than sand. In addition, the influence of vegetation on the vertical variation of shear stress was poorly represented. Although vertically-averaged shear stress may be higher than for unvegetated beds when flow overtops woody vegetation, bed shear stress will be much less.

3.3 Design issues

Although the benefits of using vegetation to enhance sediment deposition and storage are compelling, there are many uncertainties. Enhancing bar formation, stabilization, and growth by planting woody vegetation can accelerate erosion of adjacent concave banks (McKenney et al. 1995). In urban channels where flood control is important, a natural stream corridor with lush vegetation can trap large volumes of sediment in very short periods of time, reducing channel capacity and elevating flood hazards. Native plant species should be used because of their local adaptability as well as their predictable value as habitat. Use of exotic species should be avoided.

4 STABILITY OF BANKS AND RIPARIAN STRUCTURES

4.1 Banks

Vegetation directly protects banks from erosion by reducing near-bank shear stresses. Larger vegetation and woody debris deflect flows. These properties have been used to protect streambanks from erosion by using felled trees in structures referred to as "tree revetments," or woody debris in "engineered log jams" (Abbe et al. 1997). Use of living vegetation for bank protection offers the additional benefit of modifying

soil properties, increasing soil strength due to the reinforcing properties of roots, and lowering pore water pressures. The reduction in pore pressure is difficult to predict, because a stand of vegetation may enhance infiltration due to creation of macropores, or retard it due to the surficial organic layer associated with vegetation (Wu 1994). A stand of riparian vegetation can modify the microclimate, slightly reducing streamside temperatures and associated evaporation rates (Volny 1984). High, steep banks may be destabilized by large, heavy vegetation if roots do not grow deep enough to intercept failure planes. Wind loading due to forces on taller trees is also a negative factor in bank stability.

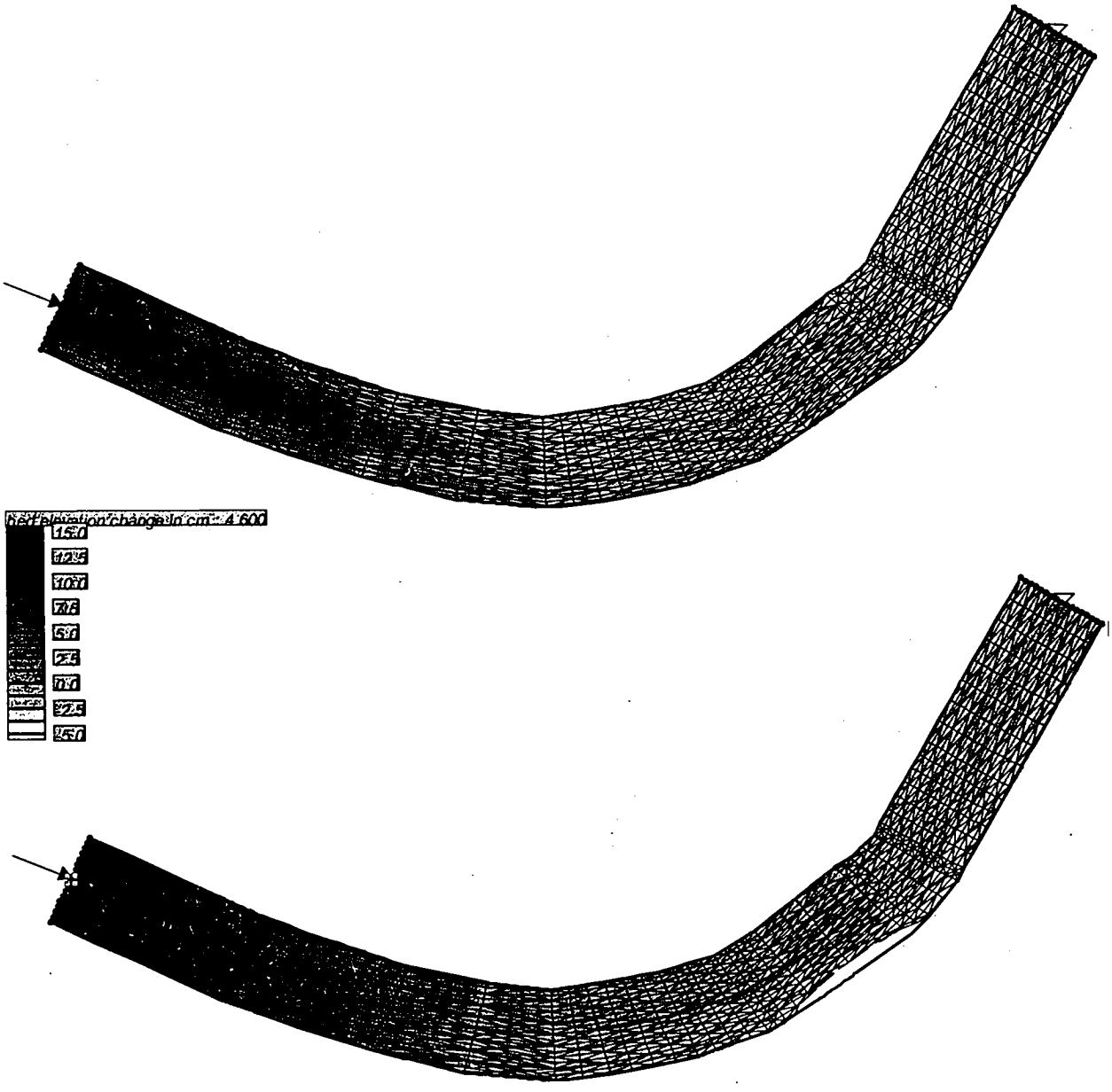


Fig. 4 (a) Simulated change in bed elevation of sand bed channel bend with uniform Manning coefficient of 0.025 following 4.6 hr discharge. (b) Simulated change in bed elevation of similar channel bend with Manning coefficient of 0.1 inside the dark black line on the convex bank following 4.6 hr discharge.

4.2 Effects of volunteer vegetation on riparian structures

Volunteer vegetation (that which occurs naturally in contrast to that planted by humans) on riparian structures provides ecological benefits similar to floodplain vegetation in natural settings by providing

cover, habitat, and a source of carbon (Dennis et al. 1984). Volunteer vegetation originates from local native flora and thus is generally well-suited to local conditions.

Due to uncertainties associated with the effects of vegetation on the durability of riprap revetments and earthen levees, maintenance regulations often require periodic removal of vegetation from structures by cutting, burning, or the use of herbicides. Additional objections to vegetation involve its contribution to flow resistance and the problems it creates for visual inspection of structures. Studies on revetments (Shields 1991) and levees (Shields and Gray 1992) along the Sacramento River indicated that volunteer woody vegetation was not detrimental to the performance of riprap revetments during large floods (Table 2), and that stands of woody vegetation on sandy levees actually enhanced their slope stability (Table 3). These studies did not consider erosion associated with piping or trees blown over by wind.

Work by Dwyer et al. (1997) established the value of forested buffers in protecting large river levees. The 1993 flood on the lower Missouri River was estimated to be a 500-year event, and the Corps of Engineers spent $36 million for levee repair as of 1995. Levee failures along the Missouri River in central Missouri during the 1993 flood were more common for levees with narrower bands of forest (woody corridor) between the levee toe and the riverbank. No failures were recorded for levees with woody corridors wider than 90 m, while 77% of observed levee failures occurred in levees with woody corridors less than 30 m wide. The width of levee breaks was inversely related to the width of the woody corridor.

Table 2 Effect of volunteer woody vegetation on revetments, Sacramento River km 136 to 192, September 1989. Significance of difference in damage rates, $p = 0.11$, Chi-Squared Test. After Shields (1991).

Condition of revetment	30-m segments damaged, %	Length of revetment examined, km
Vegetated	5	7.7
Unvegetated	3	68.8
Total	3	76.5

Table 3 Effect of roots on slope stability of sandy flood-control levees. After Shields and Gray (1992).

Root-area ratio	Factor of safety at 40 cm below soil surface	
	Average soil conditions	Worst-case soil conditions
0.01	3.7	0.8
0.1	4.4	1.1
1.0	12.6	7.7

5 SITE CONTROLS ON THE USE OF VEGETATION

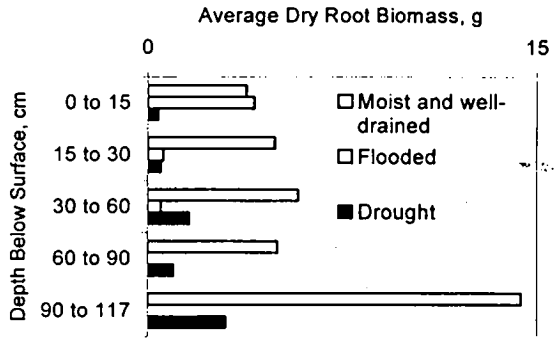
5.1 Riparian environment

Stream corridors subject to accelerated erosion and deposition can be extremely harsh environments for plants due to mechanical disturbance, abrasion, moisture gradients, soil infertility, flooding, and competition. Of 17 woody and 7 herbaceous species planted in a variety of microhabitats along an incised sand and gravel-bed stream draining a 21 km^2 northwest Mississippi watershed, only three of the woody species (*Salix* spp.) and one herbaceous species (*Arundo donax*) performed well (Snider 1996). Plant materials included sprigs, rhizomes, stakes and live fascines (bundles of stems). Live fascines and stakes were practical and inexpensive to install, but many washed away during floods before becoming fully established. Evidently even along smaller streams, high densities of plant materials are needed to provide adequate protection. Use of exotic species (such as *A. donax* and the vine *Pueraria lobata* in Mississippi) is not recommended, as they may develop into nuisances with no natural controls.

5.2 Willow post technique

Planting large willow (*Salix* spp.) cuttings (10 to 30 cm diameter, 2 to 4 m long) has been widely practiced in the U.S. for halting bank erosion and restoring riparian zones (Figure 6a) (Watson et al. 1997). However, success rates in some projects in the humid Southeastern U.S. have been disappointing (0 to 40%). Workers in the arid Southwestern U.S. recommended planting posts deeply in order to intercept groundwater tables (Swenson and Mullins 1985, York 1985). Field (Shields et al. 1998) and greenhouse (Pezeshki et al. 1998) studies of willow posts under environmental conditions typical of the Southeastern U.S. have revealed that posts are limited by surplus soil moisture as well as drought. Plant-available water for posts planted on streambanks is controlled by the elevation of the posts and soil texture. Posts planted at higher elevations are subject to drought-related stress, while those at lower elevations, particularly in soils containing silt and clay, are hindered by anaerobic soil conditions and flooding.

Although cuttings require adequate moisture for survival, any level of soil moisture leading to soil oxidation-reduction potential (Eh) less than about 200 mV is extremely detrimental. Ideal conditions for survival and growth involve abundant soil moisture, but well-drained conditions that produce levels of soil Eh > 350 mV. Posts grown under controlled greenhouse conditions developed masses of functional roots along the entire length of the post, while roots of posts subjected to continuous flooding displayed signs of severe stress and were limited to the top 60 cm of soil (Figure 6b). The average total dry biomass (roots + leaves + shoots + stem) for posts grown under ideal, flooded, and drought conditions were 110 g, 33 g, and 16.3 g, respectively.



5.3 Design issues

Designers must assess site suitability for any vegetative treatment. For willow posts, assessment should include soil classification, measurement of soil moisture, examination of typical stage hydrographs, and ideally, measurements of soil Eh at intervals throughout the growing season.

6 CONCLUSIONS AND RECOMMENDATIONS

Use of woody vegetation and LWD holds promise as a stream corridor rehabilitation and management technique, reducing costs and improving habitat functions and values. In order to fully exploit this potential, designers will need to absorb and synthesize findings of recent and ongoing research. Designers especially need to develop understanding of the engineering and biological performance of plant materials. Pitfalls await those who work with vegetative materials, as much is unknown about interactions with flow and bank properties. In our opinion, the safest course to follow is a three step process: (1) site evaluation using current state of science, (2) installation and monitoring of small pilot projects, and finally, (3) large scale implementation that includes monitoring and adaptive management.

ACKNOWLEDGMENTS

All programs and services of the U.S. Department of Agriculture are offered on a nondiscriminatory basis without regard to race, color, national origin, religion, sex, age, marital status, or handicap. Eddy

Langendoen and Joe Letter provided assistance with numerical simulations. Eddy Langendoen, Chang-xing Jin, and Joe Letter read an earlier version of this manuscript and made many helpful comments.

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, Washington, *Management of Landscapes Disturbed by Channel Incision,* Wang, S.Y., Langendoen, E. J., and Shields, F. D., Jr., eds., The University of Mississippi, pp. 809-815.

Abt, S. R., Dudley, S.J. and Fischenich, J.C. 1998. Woody debris influence on flow resistance. *Proceedings of the Wetlands Engineering and River Restoration Conference 1998*, American Society of Civil Engineers, New York.

Abt, S.R., Clary, W.P. and Thornton, C.I. 1994. Sediment deposition and entrapment in vegetated streambeds. *Journal of Irrigation and Drainage Engineering* 120(6), 1098-1111.

Arcement, Jr., G.J. and Schneider, V.R. 1989. Guide for selecting Manning's roughness coefficients for natural channels and flood plains. *United States Geological Survey Water-Supply Paper 2339*, United States Government Printing Office, Denver, Colorado.

Boss International, Inc. and Brigham Young University. 1997. SMS: Surfacewater Modeling System. Boss International, Madison, WI.

Darby, S.E. In Press. Effects of riparian vegetation on flow resistance, discharge capacity, and flood potential. Manuscript submitted to the *Journal of Hydraulic Engineering.*

Dennis, N. B., Ellis, D., Arnold, J. R. and Renshaw, D. L. 1984. Riparian Surrogates in the Sacramento/San Joaquin Delta and Their Habitat Values. In: Richard, E. W. and Hendrix, K. M. (eds.), *California Riparian Systems.* University of California Press, Berkeley, Calif., pp. 566-576.

Dwyer, J. P., Wallace, D. and Larsen, D. R. 1997. Value of woody corridors in levee protection along the Missouri River in 1993. *Journal of the American Water Resources Association* 33(2), 481-489.

Edminster, F.C., Atkinson, W.S. and McIntyre, A.C. 1949. Streambank Erosion Control on the Winooski River, Vermont. *USDA Soil Conservation Service* publication no. 837.

Fairbanks, J. D. and Diplas, P. 1998. Sediment movement in riparian wetlands. *Proceedings of Wetlands Engineering & River Restoration Conference, 1998.* American Society of Civil Engineers, New York.

Fukuoka, S. and Watanabe A. 1997. Horizontal Structure of Flood Flow with Dense Vegetation Clusters along Main Channel Banks, *Environmental and Coastal Hydraulics: Protecting the Aquatic Habitat.* Holly, F. M., Jr. and Alsaffar, A. eds., American Society of Civil Engineers, New York, pp. 1408-1413.

Garcia, M. H. 1996. Role of vegetation in hydraulics of channel restoration. *Proceedings of the North American Water and Environment Congress*, American Society of Civil Engineers, New York.

Gippel, C.J., O'Neill, I.C., Finlayson, B.L. and Schnatz, I. 1996. Hydraulic guidelines for the re-introduction and management of large woody debris in lowland rivers. *Regulated Rivers: Research and Management*, Vol.12, pp. 223-236.

Hickin, E. J. 1984. Vegetation and river channel dynamics. *Canadian Geographer* 28:2 111-126.

Hodges, C., Diplas, P. and Younos, T.1997. Resistance to Flow Through Riparian Wetlands, *Environmental and Coastal Hydraulics: Protecting the Aquatic Habitat.* Holly, F. M., Jr. and Alsaffar, A. eds., American Society of Civil Engineers, New York, pp. 913-918.

Kouwen, N.1988. Field estimation of the biomechanical properties of grass. *Journal of Hydraulic Research* 26(5), 559-568.

Lopez, F. and Garcia, M. 1997. Open-channel flow through simulated vegetation: turbulence modeling and sediment transport, Wetlands Research Program Technical Report WRP-CP-10, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

McKenney, R., Jacobson, R.B. and Wertheimer, R.C. 1995. Woody vegetation and morphogenesis in low-gradient, gravel-bed streams in the Ozark Platearus, Missouri and Arkansas. *Geomorphology*, Vol. 13, pp. 175-198.

Nunnally, N.R. and Sotir R.B.1997. Criteria for Selection and Placement of Woody Vegetation in Streambank Protection. In *Management of Landscapes Disturbed by Channel Incision,* Wang, S.S. Y. Langendoen, E. J.,and Shields, F. D., Jr. eds., The University of Mississippi, pp. 816-821.

Petryk, S., and Bosmajian, G. III. 1975. Analysis of flow through vegetation. *Jour. Hydr. Div.* ASCE, Vol. 99(5), pp. 793-814.

Pezeshki, S.R., Anderson, P.H. and Shields, F. D., Jr. 1998. Effects of soil moisture regimes on growth and survival of black willow (*Salix nigra*) posts (cuttings). *Wetlands* 18:3 460-470.

Schumm, S. A., Harvey, M. D., and Watson, C. C. 1984. *Incised channels: morphology, dynamics, and control.* Water Resources Publications, Littleton, Colorado, 200pp.

Sellin, R.H.J. and Keast, J. 1997. Seasonal Variation in River Channel Hydraulic Roughness, *Environmental and Coastal Hydraulics: Protecting the Aquatic Habitat.* Holly, F. M., Jr. and Alsaffar, A. eds., American Society of Civil Engineers, New York, pp.1390-1395.

Shields, F. D., Jr. 1991. Woody vegetation and riprap stability along the Sacramento River mile 84.5-119. *Water Resources Bulletin,* Vol. 27(3), pp.527-36.

Shields, F. D., Jr., Bowie, A.J. and Cooper, C.M. 1995. Control of Streambank Erosion Due to Bed Degradation with Vegetation and Structure. *Water Resources Bulletin,* Vol. 31(3), pp.475-489.

Shields, F. D., Jr. and Gippel, C.J. 1995. Prediction of effects of woody debris removal on flow resistance. *Journal of Hydraulic Engineering.* Vol. 121(4), pp. 341-354.

Shields, F. D., Jr., and Gray, D.H. 1992. Effects of woody vegetation on sandy levee integrity. *Water Resources Bulletin,* Vol. 28(5), pp. 917-931.

Shields, F. D., Jr. and Cooper, C. M. 1998. Principles for Woody Vegetation in River Restoration: Problems and Opportunities. Proceedings of the International Symposium on River Restoration, Technology Research Center for Riverfront Development, Tokyo, Japan, pp. 43-52.

Shields, F. D., Jr., Pezeshki, S.R. and Anderson, P.H. 1998. Probable Causes for Elevated Willow Post Mortality. *Proceedings of the Wetlands Engineering and River Restoration Conference 1998,* American Society of Civil Engineers, New York.

Simon, A.1989. A Model of Channel Response in Disturbed Alluvial Channels. *Earth Surface Processes and Landforms,* Vol. 14(1), pp.11-26.

Snider, J. A. 1996. Biotechnical erosion control. Jamie L. Whitten Plant Materials Center Technical Note 12:2 1-8, United States Department of Agriculture, Natural Resources Conservation Service, Coffeeville, MS.

Swenson, E.A. and Mullins, C.L.1985. Revegetating Riparian Trees in Southwestern Floodplains. *Proceedings, North American Riparian Conference, Tuscon, AZ; April 16-18, 1985,* pp. 135-138.

Tsujimoto, T. and Kitamura T. 1997. Morphological Change and Change of River Vegetation Cover in Fluvial-Fan River. *Management of Landscapes Disturbed by Channel Incision,* Wang, S. S. Y. Langendoen, E. J., and Shields, F. D., Jr. eds., The University of Mississippi, pp. 157-162.

Volny, S.1984. The Riparian Stand as a Stabilizing Factor in Torrent Control and River Channel Reconstruction. *Forest Amelioration.* Riedl, O. and Zachar, D. eds., Amsterdam: Elsevier Science Publishing Company, pp. 429-434.

Watson, C.C., Abt S.R., Derrick, D. 1997. Willow Posts Bank Stabilization. *Journal of the American Water Resources Association,* Vol. 33(2), pp. 293-300.

Wu, T.H. 1994. Slope Stabilization Using Vegetation. *Geotechnical Engineering: Emerging Trends in Design and Practice.* editor K. R. Saxena, Chapter 15. New Delhi: Oxford and IBH Publishing Co. Pvt. Ltd.

York, J.C. 1985. Dormant Stub Planting Techniques, *Riparian Ecosystems and Their Management: Reconciling Conflicting Uses (USDA-Forest Serv. Gen. Tech. Rep. RM-120),* Rocky Mountain Forest and Range Exp. Sta., Fort Collins, Colorado, pp. 513-514.

Yuuki, T. and Okabe, T. 1997. Influence of Vegetation on Hydrogeomorphic Process of Alternating Bars. , *Environmental and Coastal Hydraulics: Protecting the Aquatic Habitat.* Holly, F. M., Jr. and Alsaffar, A.eds., American Society of Civil Engineers, New York, pp. 1402-1407.