MODELING STREAM CHANNEL ADJUSTMENT TO WOODY VEGETATION

Sean J. Bennett, Associate Professor, Department of Geography, University at Buffalo, Buffalo, NY, seanb@buffalo.edu; Weiming Wu, Research Assistant Professor, National Center for Computational Hydroscience and Engineering, University of Mississippi, University, MS, wuwm@ncche.olemiss.edu; Carlos V. Alonso, Supervisory Research Hydraulic Engineer, USDA-ARS National Sedimentation Laboratory, PO Box 1157, Oxford, MS, calonso@msa-oxford.ars.usda.gov; Sam S. Y. Wang, F.A.P. Barnard Distinguished Professor and Director, National Center for Computational Hydroscience and Engineering, University of Mississippi, University, MS, wang@ncche.olemiss.edu

Abstract River restoration and bank stabilization programs often use vegetation for improving stream corridor habitat, aesthetic, and function. Yet no study has examined the use of managed vegetation plantings to transform a straight, degraded stream corridor into a more functional, aesthetically-pleasing meandering channel. Experimental data using a distorted Froude-scaled flume analysis shows that channel expansion and widening, thalweg meandering, and riffle and pool devlopement is possible using discrete plantings of rigid, emergent vegetation. These results were verified and validated using a recently developed numerical model. A hybrid method of meander design is proposed herein where managed vegetation plantings are used to trigger the desired morphologic response, transforming a straight, degraded reach into a more functional meandering corridor.

INTRODUCTION

Within the loess region of the south-central U.S., channelization has disrupted many stream systems, causing widespread bed incision, bank destabilization, and channel widening (Schumm et al., 1984; Simon and Rinaldi, 2000; Simon and Thomas, 2002). Degraded streams in northern Mississippi are characterized by flashy hydrographs, banks that are steep and prone to failure, excessive sediment loads, channels that are straight and wide, beds composed of sand, sand and gravel, or cohesive clay, corridors lacking woody debris, and baseflows that are shallow in depth (Shields et al., 1995a, b). Moreover, many of the riparian zones are denuded due to agricultural practices, or the channel is so wide that any vegetation present provides little canopy. These streams would be considered impaired using the water quality criteria of the US-EPA (2000), and stream restoration and bank stabilization programs employing vegetation might be used to remedy these deficiencies (FISRWG, 1998; Shields et al., 2003; Wohl et al., 2005).

Transforming a straight, degraded stream into a meandering channel through the use of vegetation should enhance greatly the functionality and recreational opportunities of the corridor, and this approach was first proposed by Bennett et al. (2002). Using an experimental channel, Bennett et al. (2002) showed that a straight, degraded stream channel could adopt a meandering thalweg by introducing rigid, emergent vegetation like willow posts (e.g., Watson et al., 1997) at the prescribed spacing of equilibrium meander beds, but the results were limited because the bed and banks of the flume were fixed. While many studies have discussed the effects of riparian vegetation on flow and sediment transport in rivers (see review in Bennett and Simon, 2004), none has utilized vegetation for the purpose of inducing a straight stream to meander. The objectives of the present study were to systematically vegetate a straight, degraded experimental channel with freely adjustable banks and bed and to document the effects of vegetation density on alluvial response and morphology. This study employed a distorted Froude-scaled flume analysis to quantify the effects of vegetation on channel morphology and the results were compared to a recently developed numerical model capable of simulating flow, sediment transport, and bed morphology in meandering streams with riparian and in-stream vegetation.

METHODS

Physical Scale Model The prototype reach selected for flume analysis was Abiaca Creek, located in northern Mississippi. This water course was extensively studied by Wallerstein and Thorne (2004) primarily because of the large woody debris accumulations, and such corridors would be selected for stream restoration and bank stabilization programs. Channel dimensions for the two-year return flow or channel forming discharge Q_B are presented in Table 1.

Table 1 Summary of field conditions for Abiaca Creek, MS (prototype) and the distorted Froude-scaled flume model of Wallerstein et al. (2001) and the present study.

Parameter	Prototype Abiaca Creek, MS	Wallerstein et al. (2001) model	This study
w_T (m)	17.9	0.3	0.312
w_B (m)		0.1	0.1
L (m)	65.0	1.0	5.0
Q_B (m^3 s^{-1})	48.1	0.0033	0.0033
d (m)	1.9	0.07	0.069
u (m)	1.4	0.24	0.232
S	0.011	0.0022	0.0019
D (mm)	0.25	0.8	0.8
u_* (m s^{-1})	0.13	0.029	0.030
θ	4.17	0.065	0.070
Fr	0.32	0.29	0.28
D_E (m)	1.1	0.019	0.005

$u_* = \sqrt{gRS}$, $\theta = \rho u_*^2 / (\sigma - \rho) gD$ where u_* is shear velocity, S is bed slope, R is hydraulic radius, θ is dimensionless shear stress, ρ is fluid density, and σ is sediment density

The physical model used here had the following requirements: (1) scaling was based on Froude number $Fr = u / \sqrt{gd}$ where u is mean flow velocity, d is mean flow depth, and g is gravitational acceleration; (2) both bed and banks were movable (freely adjustable boundary); and (3) the channel bed was just below the threshold of motion for the sediment used. This last requirement ensured that the channel was stable prior to the vegetation plantings and all subsequent alluvial adjustment was the direct result of the vegetation. Wallerstein et al. (2001) presented a detailed discussion of the Froude-scale model used here, including all justifications and necessary distortions. The experimental model parameters used by Wallerstein et al. (2001) and this study are given in Table 1.

The experiments were conducted in a tilting, recirculating flume 0.63 m wide, 0.61 m deep, and 10 m long. The channel was filled with 0.8 mm-diameter sediment D to a depth of 0.5 m. After pre-wetting the sand, a trapezoidal channel with a top width w_T of 0.312 m, a bottom width w_B of 0.1 m, and a reach length L of 5 m was cut into the sediment using a aluminum plate mounted to a movable carriage above the flume. Flow depth d was controlled within the trapezoidal channel by an adjustable weir at its downstream end, and flow discharge Q was measured with a V-notch weir installed below the flume's overfall. Steady, uniform flow conditions for this trapezoidal channel, which were just below the threshold of sediment motion, are summarized in Table 1.

Areas along this trapezoidal channel were populated with emergent, rigid vegetation. Wooden dowels with a diameter D_e of 5 mm were systematically planted into the channel bed at prescribed locations, overall shapes, and packing densities. Using the model Q_B and a riffle-to-riffle spacing of 5 to 7w (e.g., Ackers and Charlton, 1970), an equilibrium meander wavelength λ of 3 m was imposed on the channel and three vegetation zones were designated: two on the left-side of the channel spaced 3 m apart and one of the right-side of the channel spaced 1.5 m from the other two zones. Three vegetation shapes were used, each extending to the mid-channel region (0.245 m): (1) a full rectangle 0.5 m long; (2) a half rectangle 0.25 m long; and (3) a hemisphere 0.5 m long. These shapes were populated with emergent wooden dowels placed in a staggered arrangement at relatively low, medium, and high vegetation densities *VD* (m^{-1}) defined as the ratio of the frontal areas of the vegetation elements divided by the volume of water occupied over one meander wavelength, $VD = 2nD_e d / d\lambda w$ where n is the number of dowels.

The trapezoidal channel was reformed after each experiment, in-flow conditions were invariant between runs, and the bed was digitized before and after each experiment with a laser microrelief system using a 2-mm by 5-mm grid with an effective resolution equal to the bed material size. The time length for each vegetation density was held constant, limited by the magnitude of bank erosion (stream channel expansion).

Numerical Model Wu et al. (2005) developed a depth-averaged, two-dimensional numerical model to simulate flow, sediment transport, and bed topography in river channels with vegetation of various types. The essential components of the model, which builds upon the work of Wu and Wang (2004a), are as follows: (1) the governing hydrodynamic equations are the depth-integrated and spatially-averaged Navier-Stokes equations for continuity of flow and fluid momentum using the Boussinesq closure scheme; (2) the density, placement, and associated drag of the vegetation within the channel were addressed explicitly; and (3) the dispersion terms in the depth-averaged fluid momentum equations attributed to helical flow in curved channels were determined using the algebraic equations given in Wu and Wang (2004b). Issues pertaining to boundary conditions and numerical techniques are discussed further in Wu et al. (2005). For the simulations presented here, the computational mesh was finer around the vegetation zones than elsewhere, Manning's roughness coefficient was adjusted to 0.028, which yielded a uniform flow in the absence of vegetation, the drag coefficient C_d was 2.0, and the computational time step was 5 seconds. Additional coefficients used in the model simulations were chosen based on the work of Wu and Wang (2004b) and Wu (2004).

RESULTS

Channel Adjustment to Vegetation Response of the stable, trapezoidal channel to the introduction of emergent, rigid vegetation depended upon the shape and density of the vegetation zone. In all cases, the added vegetation caused flow deceleration upstream of the vegetation zone, acceleration of flow near the vegetation zone and scour hole development, channel expansion opposite of the vegetation zone through bank erosion, and sediment deposition within the mid-channel regions upstream and downstream of the vegetation zones.

These effects can be seen from the topographic maps of the full vegetation zone (Figure 1). Marked channel expansion occurred downstream and opposite of the vegetation zone and an aggradational front can be observed in the mid-channel region upstream of the vegetation zone (Figure 1c). As vegetation density increased, the magnitude of these effects increased as well as channel sinuosity *Sn* (Table 2), defined herein as the curvilinear distance of the minimum channel elevation per linear distance downstream.

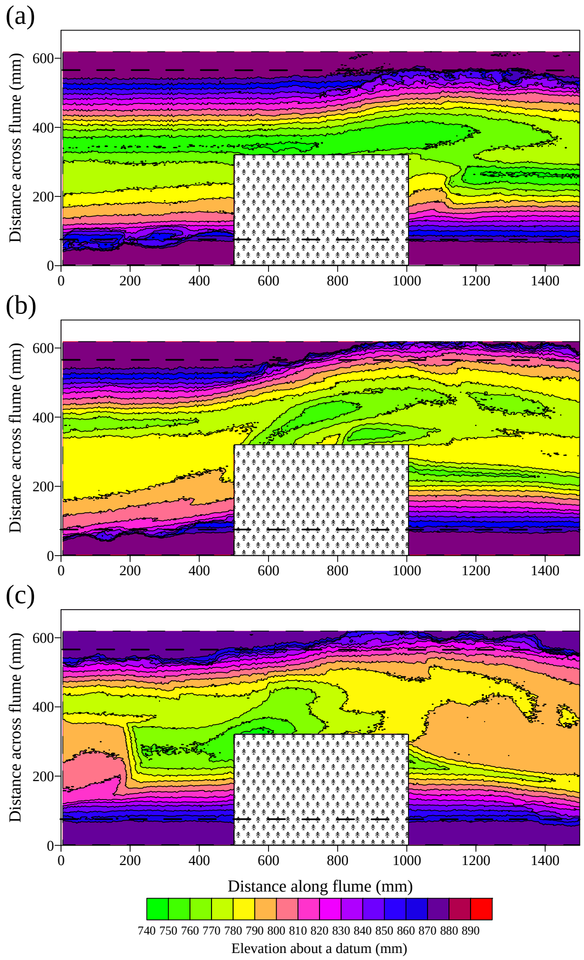

Figure 1 Contour maps of the bed surface using the full vegetation zone with densities of (a) 0.77, (b) 2.94, and (c) 11.53 m^{-1}. Flow is left to right.

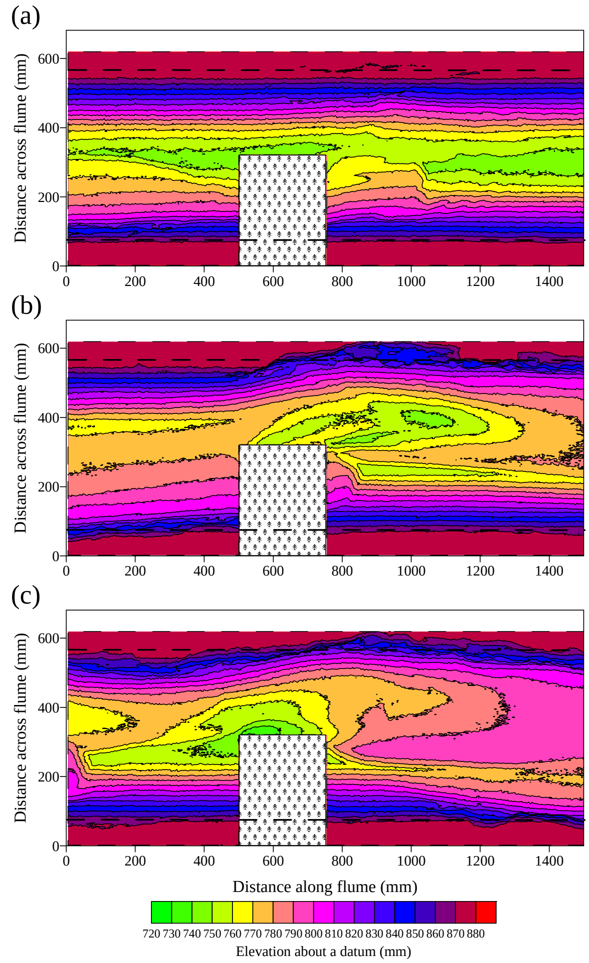

Figure 2 Contour maps of the bed surface using the half vegetation zone with densities of (a) 0.38, (b) 1.47, and (c) 5.76 m^{-1}. Flow is left to right.

Similar results were observed for the half (Figure 2) and the hemispherical vegetation zones (Figure 3). For these cases, two cross-sections were defined for comparison. Cross-section A is located just upstream of the vegetation zone at a downstream distance of 250 mm, whilst cross-section B is located at or near the vegetation apex at a downstream distance of 750 mm. The upstream cross-sections show increases in channel width (up to 19%), decreases in channel depth (up to −22%), and increases in channel velocity (up to 19%) in response to the added vegetation (see Figures 2 and 3, Table 2). Cross-section B shows an increase in channel width (up to 28%), an increase in channel depth (up to 18%), and a decrease in channel velocity (up to −30%) as compared to the unvegetated, uniform flow channel (see Figures 2 and 3, Table 2). In both cases, channel sinuosity *Sn* and the magnitude of these morphologic changes increased as vegetation density increased (Table 2).

Table 2 Summary of bulk hydraulic conditions at test section locations 250 and 750 mm at the conclusion of the experiment. Time refers to length of experiment, and NA means data are not available. All other parameters are defined in the text.

				250 mm			750 mm		
Vegetation	VD (m^{-1})	Time (s)	Sn	w (m)	d (m)	u ($m\ s^{-1}$)	w (m)	d (m)	u ($m\ s^{-1}$)
None	0	--	1.00	0.330	0.050	0.200	0.330	0.050	0.200
Full	0.77	14400	1.00	0.360	0.051	0.180	0.336	0.052	0.189
	2.94	6600	1.03	NA	NA	NA	NA	NA	NA
	11.53	900	1.04	NA	NA	NA	NA	NA	NA
Half	0.38	14400	1.01	0.340	0.042	0.231	0.356	0.054	0.172
	1.47	6600	1.02	0.380	0.039	0.223	0.411	0.053	0.151
	5.76	900	1.03	0.358	0.046	0.200	0.424	0.052	0.150
Hemisphere	0.61	14400	1.00	0.346	0.040	0.238	0.327	0.053	0.190
	2.40	6600	1.02	0.390	0.042	0.201	0.378	0.051	0.171
	9.35	900	1.02	0.350	0.045	0.210	0.401	0.059	0.139

The added vegetation caused the expansion of the channel width and increased channel sinuosity through bank erosion and thalweg meandering. This failed bank material, coupled with the sediment liberated from the near-vegetation scour hole, created a downstream migrating aggradational front, as clearly shown in Figure 1c at 200 mm. This sediment flux could not exit the flume due to the imposed experimental conditions, i.e., the original bed was near threshold conditions. A similar effect of channel scour and downstream deposition was observed by Wallerstein et al. (2001) in response to large woody debris. In natural streams composed of relatively finer-grained bank material, as is the case for Abiaca Creek, these eroded materials presumably would be transported downstream rather than deposited near its source. As the channel expanded and its thalweg meandered, in-channel deposition occurred upstream and downstream of the vegetation zones, creating a riffle or cross-over region, and in-channel erosion created a pool or scour hole opposite and just downstream the vegetation zone.

Comparison to the Numerical Model Figure 4 shows the comparison of the measured and predicted changes in bed and bank topography near the central vegetation zone in an elapsed time of 110 minutes (Figures 4a and 4b correspond to the contour maps shown in Figures 1b and 3b, respectively). Here, the contour maps show the difference in elevation before and after the experiment, where positive values indicate net deposition and negative values indicate net erosion. As discussed above, net deposition occurred upstream and downstream of the vegetation zone, whereas net erosion occurred in the area away from the vegetation zones, resulting in a meandering channel planform. For the case of full vegetation zone (Figure 4a), approximately 50% and 75% of the simulated elevation data are within ±10 and ±20 mm of observed elevation data (within 15% and 29% of the flow depth), respectively. For the case of hemispherical vegetation zone (Figure 4b), approximately 60% and 80% of the simulated elevation data are within ±10 and ±20 mm of observed elevation data, respectively. In summary, the overall adjustment of the stream channel to the added vegetation can be accurately simulated using the numerical model of Wu et al. (2005). The magnitude of channel erosion is predicted reasonably well, whilst the magnitude of deposition is somewhat over-predicted.

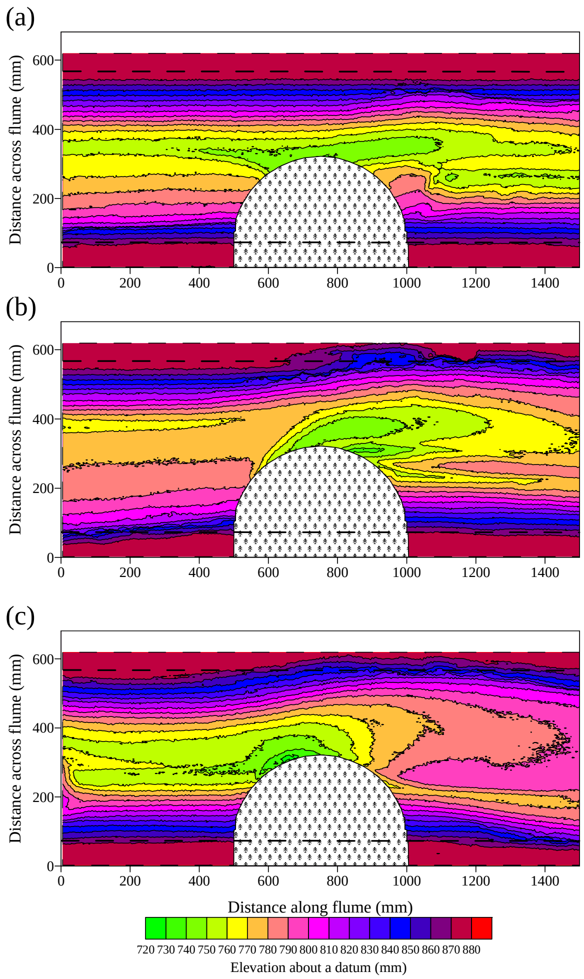

Figure 3 Contour maps of the bed surface using the hemisphere vegetation zone with densities of (a) 0.61, (b) 2.40, and (c) 9.35 m^{-1}. Flow is left to right.

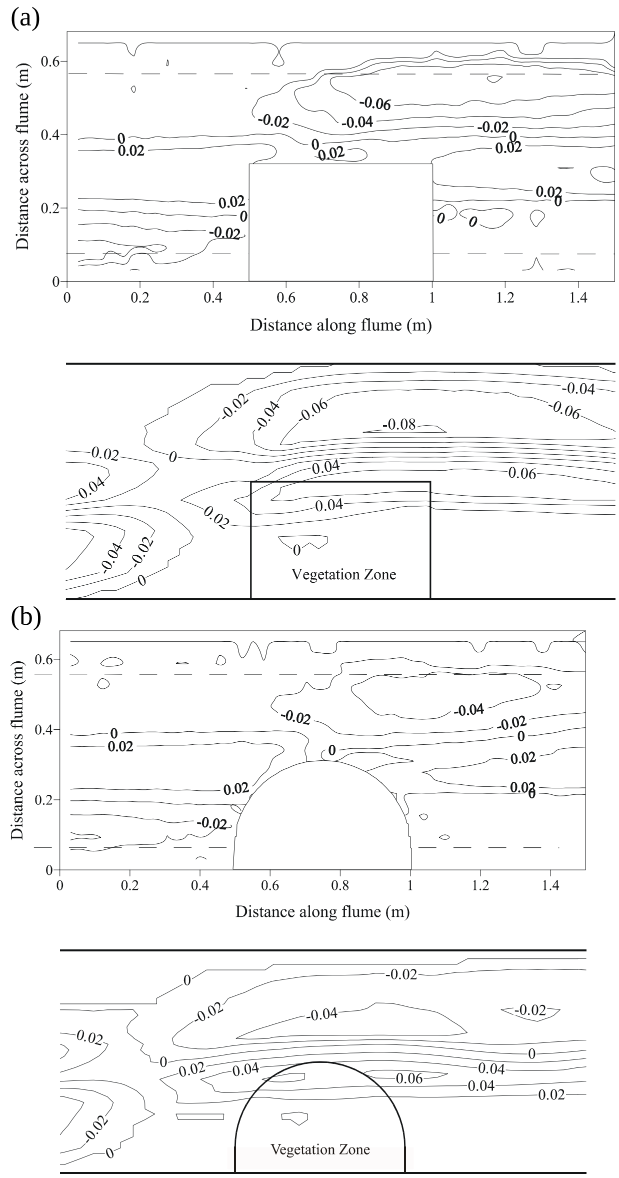

Figure 4 Measured (upper) and predicted (lower) changes in bed topography due to (a) full and (b) hemisphere vegetation zones. Contour interval is 0.02 m, and flow is left to right.

DISCUSSION AND CONCLUSIONS

The motivation for the present work was to experimentally verify the transformation of a straight, degraded stream channel to a meandering, ecologically-functional river corridor through the use of managed plantings of emergent, rigid vegetation. Whilst Bennett et al. (2002) showed that such thalweg meandering could be achieved in a fixed-bed flume using vegetation placed at equilibrium meander bend locations, the data presented herein show that planform meandering could be achieved using a distorted Froude-scaled model in response to similar vegetation plantings. The magnitude of this channel response—bank erosion, pool and riffle development, and increased channel sinuosity—depended upon the shape of the vegetation zone and the density of the vegetal elements, and these observations were verified with a recently developed two-dimensional numerical model.

Based on these results and those presented in Bennett et al. (2002), a hybrid method is suggested for the design of a meandering stream corridor using vegetation (see Shields, 1996, for a review of these methods). For a design flow (bankfull), an equilibrium meander wavelength is derived using empirical methods, and dormant willow posts (or similar vegetation) are planted in a hemispherical shape with a radius up to one-half the channel width. The vegetation should be planted in staggered arrangement at a vegetation density greater than 1.0 m^{-1} as averaged over one meander wavelength. Once planted and established, these vegetation stands will cause the development of scour pools and riffles and bank erosion at prescribed locations, resulting in thalweg meandering.

This hybrid technique should cost less than conventional construction designs, and work with and not against natural flow processes. While the final channel planform may look markedly different compared to the original design, the stream corridor would be both stable and appropriate for the drainage system since it can freely adjust to the imposed temporal and spatial variations in boundary conditions and hydrology. Moreover, the numerical model developed by Wu et al. (2005), which has been successfully verified and validated with data here and elsewhere, could be employed as the primary tool for stream channel design and rehabilitation. Practitioners could use this model to explore the utility of vegetation, whether as willow plantings or large woody debris jams, in a variety of stream rehabilitation designs. This would ensure that the morphologic responses of the stream channel are in concert with the goals of the restoration program.

ACKNOWLEDGEMENTS

We thank Glenn Gray and Chris Francher for technical assistance during the mobile-bed experiments, and Mathias Römkens for use of the laser microrelief system. This research was financially supported by a grant from the USDA-CSREES NRI program and a USDA-ARS Specific Research Agreement No.58-6408-2-0062.

REFERENCES

Ackers, P., and Charlton, F.G. (1970). The slope and resistance of small meandering channels, Proceedings, The Institution of Civil Engineers, Supplement 15 Paper 7362 S, London, pp. 349-370.

Bennett, S.J., Pirim, T., and Barkdoll, B.D. (2002). Using simulated emergent vegetation to alter stream flow direction within a straight experimental channel, Geomorphology, 44, 115-126.

Bennett, S.J., and Simon, A., editors (2004). Riparian Vegetation and Fluvial Geomorphology. American Geophysical Union, Water Science and Application Series Volume 8, Washington, D.C., 282 pp.

Federal Interagency Stream Restoration Working Group, (1998). Stream Corridor Restoration: Principles, Processes and Practices. National Technical Information Service, U. S. Department of Commerce, Springfield, VA.

Schumm, S.A., Harvey, M.D., and Watson, C.C. (1984). Incised Channels: Morphology, Dynamics and Control. Water Resources Publ., Littleton, 200 pp.

Shields, F.D., Jr. (1996). Hydraulic and hydrologic stability, in River Channel Restoration, edited by A. Brookes and F.D. Shields, Jr., pp. 23-74, John Wiley and Sons, Chichester.

Shields, F.D., Jr., Copeland, R.R., Klingeman, P.C., Doyle, M.W., and Simon, A. (2003). Design for stream restoration, Journal of Hydraulic Engineering, 129, 575-584.

Shields, F.D., Jr., Knight, S.S., and Cooper, C.M. (1995a). Use of the index of biotic integrity to assess physical habitat degradation in warmwater streams, Hydrobiologia, 312, 191-208.

Shields, F.D., Jr., Knight, S.S., and Cooper, C.M. (1995b). Rehabilitation of watersheds with incising channels, Water Resources Bulletin, 31, 971-982.

Simon, A., and Rinaldi, M. (2000). Channel instability in the loess area of the Midwestern United States, Journal of the American Water Resources Association, 36, 133-150.

Simon, A., and Thomas, R.E. (2002). Processes and forms of an unstable alluvial system with resistant, cohesive streambeds, Earth Surface Processes and Landforms, 27, 699-718.

U.S. Environmental Protection Agency, (2000). The Quality of Our Nation’s Waters, A Summary of the National Water Quality Inventory: 1998 Report to Congress, Report EPA841-S-00-001, Washington, D.C.

Wallerstein, N.P., Alonso, C.V., Bennett, S.J., and Thorne, C.R. (2001). Distorted Froude-scaled flume analysis of large woody debris, Earth Surface Processes and Landforms, 26, 1265-1283.

Wallerstein, N.P., and Thorne, C.R. (2004). Influence of large woody debris on morphological evolution of incised, sand-bed channels, Geomorphology, 57, 53-73.

Watson, C.C., Abt, S.R., and Derrick, D. (1997). Willow posts bank stabilization, Journal of the American Water Resources Association, 33, 293-300.

Wohl., E., Angermeier, Bledsoe, B., Kondolf, G.M., MacDonnell, L., Merritt, D.M., Palmer, M.A., Poff, N.L., and Tarboton, D., (2005). River restoration, Water Resources Research, 41, W10301, doi:10.1029/2005WR003985.

Wu, W. (2004). Depth-averaged 2-D numerical modeling of unsteady flow and nonuniform sediment transport in open channels, Journal of Hydraulic Engineering, 130(10).

Wu, W., Shields, F.D., Jr., Bennett, S.J., and Wang, S.S.Y. (2005). A depth-averaged 2-D model for flow, sediment transport and bed topography in curved channels with riparian vegetation, Water Resources Research, 41, W03015, doi:10.1029/2004WR003730.

Wu, W., and Wang S.S.Y. (2004a). Depth-averaged numerical modeling of flow and sediment transport in open channels with vegetation, in Riparian Vegetation and Fluvial Geomorphology, edited by S.J. Bennett and A. Simon, pp. 253-265, American Geophysical Union, Water Science and Application Series Volume 8, Washington, D.C.

Wu, W., and Wang, S.S.Y. (2004b). Depth-averaged 2-D calculation of flow and sediment transport in curved channels, International Journal of Sediment Research, 19, 241-257.