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Evaluation of stability threshold analysis as a cursory method of screening potential streambank stabilization techniques

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Abstract

A water quality issue that is of particular concern in human-modified streams is sediment pollution. In-stream areas of sediment production have been targeted and managed using stream channelization and, more recently, biotechnical streambank stabilization. The objective of this study was to evaluate the use of stability threshold analysis as a cursory method to develop a range of potential streambank stabilization techniques for eroding stream reaches. Stability threshold analysis compares permissible velocity and shear stress thresholds to velocity and shear stress values in stream reaches where stabilization is required. Geomorphological data were collected in four reaches of Cazenovia Creek, NY, where bank erosion has been occurring. Lowflow and bankfull flow velocity and shear stress values for each reach were compared with permissible thresholds for several biotechnical bank stabilization methods. Results indicate that stability threshold analysis provides a simple first step towards determining the appropriate type of bank stabilization to use in eroding reaches and that velocity and shear stress values for this study's sites fall within permissible thresholds for biotechnical streambank stabilization methods.

Keywords: Streambank erosion; Stability threshold analysis; Biotechnical streambank stabilization; Sediment pollution; Watershed management

Introduction

Human modification of watersheds has produced profound changes in streams throughout the US. A growing emphasis on environmental quality has generated concern about the effects of humans on stream ecosystems. One water quality issue that is of particular concern in human-impacted streams is sediment pollution, as sediment is the largest pollutant in our waters by volume and mass. Sources of sediment in a stream may include bed and bank erosion, overland erosion, and discharges from anthropogenic activities (e.g., industrial and municipal discharges and combined sewer overflows). In-stream areas of sediment production have been targeted and managed using stream channelization (i.e., hard engineering) and, more recently, biotechnical streambank stabilization (i.e., soft engineering). Biotechnical bank stabilization uses vegetation to stabilize eroding streambanks instead of large amounts of rock or concrete. The use of

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vegetation to stabilize banks has increasingly become an attractive watershed management solution because natural vegetation is more aesthetically pleasing to local landowners and community members than concrete or rock riprap and it can enhance aquatic habitat in the stream (Li & Eddleman, 2002).

Biotechnical streambank stabilization is a relatively new soft engineering practice that addresses some of the shortcomings of traditional hard stream channelization, such as decreased spatial variability of channel morphology (Brookes, 1988; Dietrich, 1987; Frothingham & Rhoads, 2003; Rhoads & Urban, 1997; Rhoads & Welford, 1991) and the adverse impacts of channelization on aquatic communities (Brookes, 1988; Frothingham, Rhoads, & Herricks, 2001; Gelwick, 1990; Portt, Balon, & Noakes, 1986; Swales, 1988, 1982). Biotechnical streambank stabilization combines vegetation, for example, willow posts and root wads and rock (e.g., riprap) to stabilize unstable banks (Table 1) (Federal Interagency Stream Restoration Working Group (FISRWG), 1998; Fischenich, 2000; Li & Eddleman, 2002; Shields, Cooper, & Knight, 1995; Simon & Steinemann, 2000; Sotir & Nunnally, 1995). In biotechnical projects, vegetation is used to stabilize banks in two primary ways: (1) by reducing water velocity through vegetation near streambanks and (2) roots of the vegetation help support banks and reduce scour. Projects utilizing biotechnical bank stabilization techniques often use natural channel design, which considers the function and stability of streams and their floodplains (Akridge, Eigel, & Athanasakes, 1999; Fischenich, 2000). Natural channel design may include maintaining stream planform pattern, which is an improvement over traditional channelization because spatial variability of channel morphology and, therefore, habitat diversity is preserved. Vegetation also provides shading, cover, and organic material, all of which are beneficial to the biotic functioning of a stream. In addition, streamside vegetation provides habitat for birds and some land animals, as well as insects (Allen & Fischenich, 2000a; Sotir, 1998a). A downfall of biotechnical streambank stabilization is the lack of quantitative post-construction evaluation of the success or failure of projects. Some studies have monitored biotechnical projects after one growing season (Akridge et al., 1999; Shields et al., 1995; Simon & Steinemann, 2000) and success or failure has been noted qualitatively. However, for the most part, quantitative, long-term post-construction evaluation has not widely taken place (with the notable exception of quantitative measures provided by Shields et al., 1995).

The objective of this study was to evaluate the use of stability threshold analysis (Fischenich, 2001) as a cursory method to develop a range of potential streambank stabilization techniques for eroding stream reaches. In particular, the potential to use biotechnical streambank stabilization was investigated. Stability threshold analysis compares permissible velocity and shear stress thresholds to velocity and shear stress values in reaches where stabilization is required. Given that this type of data can be readily obtained, stability threshold analysis ostensibly provides an easy, relatively quick way of determining if biotechnical techniques can be used to stabilize a streambank to reduce sediment input to a stream. The results obtained from stability threshold analysis can be used to inform watershed management decisions. They can, for example, provide justification for further study in the targeted reaches to quantify factors such as dominant erosion processes and soil moisture conditions (FISRWG, 1998; Shields, Copeland, Klingeman, Doyle, & Simon, 2003; Thorne, 1982) and warrant performing the more data intensive and time consuming tractive stress analysis (Goon, 1978; Snover, 1981) that may be needed to develop design specifications. Using stability threshold analysis as a cursory step augmented with a more detailed analysis should increase the likelihood of a successful bank stabilization outcome.

Table 1
Explanation of various types of biotechnical bank stabilization methods

Boundary type	Description
Wattles	Straw (rice or wheat) rolled in natural geotextile fibers, placed in trenches and staked down; provides medium for seeds to sprout and develop root system
Coir roll	Coconut fiber rolls bound together to form cylindrical structures; wetland plants (rooted sprigs, cuttings) typically incorporated into coir roll where roots become interlocked in fibers
Live fascine	Long bundles of live cuttings tied together in linear cylindrical bundles
Live brush mattress	Combination of branch cuttings placed on the bank face, live stakes, and live fascines
Brush layering	Live cuttings installed into streambanks between layers of soil
Live willow stakes	Planting live, rootable willows directly into the soil
Rolled erosion control products (RECPs)	Blankets or mats of natural fibers and long-lasting nets that are rolled over the bank and anchored with staples/stakes

Study area

The Buffalo River, NY watershed (Fig. 1) has been severely impacted by human activity and sediment pollution has been a particular problem. Sediment from upstream bank erosion has been cited as a primary problem in the watershed (Versar, 1975). The International Joint Commission (IJC) has designated the Buffalo River as one of 43 Areas of Concern (AOC). The designation was based, in part, on factors like degradation of fish and wildlife habitat and contaminated bed sediment in the river (New York State Department of Environmental Conservation (NYS DEC), 1989). Early work in the Buffalo River watershed found that soil and bed and bank erosion from the upper watershed has been the primary contributor of sediment to the AOC (Versar, 1975). Versar (1975) estimated that sediment load to the Buffalo River AOC from upstream erosion was 460,000 tons/year; 66% and 40% greater than sediment loads from combined sewer overflows and direct industrial discharges, respectively.

Cazenovia Creek (Fig. 1) is 48 km long and has a drainage basin area of 350 km^2. The creek is one of three main tributaries to the Buffalo River. Cazenovia Creek has received a high prioritization for the identification of non-point pollution sources to improve water quality (Erie County Water Quality Coordinating Committee (ECWQCC), 2000) and silt-sized sediment from streambank erosion from upstream sources has been cited as the primary impairment in Cazenovia Creek (New York State DEC, 1996). Bank stabilization has been implemented in the creek in an effort to reduce sediment input from streambank erosion. Fourteen kilometers of Cazenovia Creek were part of a Natural Resources Conservation Service (NRCS) (formerly the Soil Conservation District) bank stabilization program that began in 1953 (Parsons, Apman, & Decker, 1963). Moreover, the creek has been the target of recent streambank stabilization projects to address the issue of in-stream sediment sources, and there has been considerable interest in using biotechnical bank stabilization to reduce sediment inputs in the watershed.

Methods

Field data

Geomorphological data were collected during summer lowflow conditions in four reaches of Cazenovia Creek where bank erosion had been observed (Frothingham, 2005). Field work for this study included surveying the reach using a total station and taking water velocity measurements.

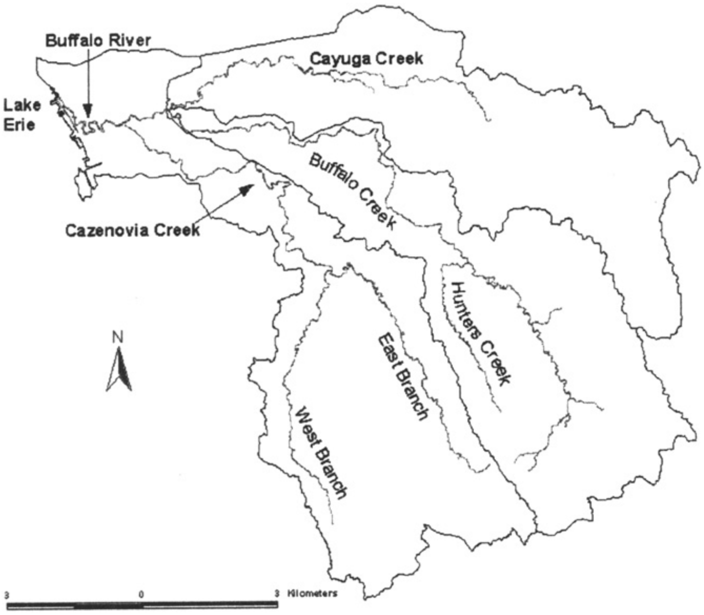

Fig. 1. Cazenovia Creek and the Buffalo river watershed.

Survey data were collected using a Sokkia® total station. A baseline was established at each site and easting, northing, and elevation data were obtained along cross sections. Between 5 and 10 cross sections were surveyed in each reach depending on the length of the reach, and the number of points surveyed in each cross section ranged from 7 to 11 depending on the geomorphological complexity of the cross sections. At each cross section, points on the banks, gravel bars, and edges of water (EOW) were surveyed.

Survey data were used to compute reach-averaged lowflow and bankfull channel widths and depths. Reach-averaged lowflow channel width was calculated as

$$W_{\mathrm{lf}} = (w_1 + w_2 + \ldots w_n)/n, \tag{1}$$

where w is cross section width and n is the total number of cross sections surveyed. The following equation was used to calculate reach-averaged lowflow channel depth:

$$D_{\mathrm{lf}} = ((wse_1 - be_1) + (wse_2 - be_2) + \ldots (wse_n - be_n))/n, \tag{2}$$

where wse is the water surface elevation, be is the bed elevation, and n is the total number of point depths surveyed. The same procedure was used to calculate reach-averaged bankfull channel width and depth (W_{bf} and D_{bf}) for each reach. Survey data were also used to calculate channel slope:

$$S = (be_{\mathrm{u}} - be_{\mathrm{d}})/L, \tag{3}$$

where be_{u} is the upstream thalweg (i.e., deepest part of the channel) bed elevation, be_{d} is the downstream thalweg bed elevation, and L is the length of the reach.

Velocity measurements were taken near the left and right banks, as well as near the middle of the channel in the thalweg, using a Global Waters® velocity meter. A reach-averaged lowflow velocity value was calculated for each reach by averaging all the measured velocities.

Stability threshold analysis

Stability threshold analysis compares field data with permissible velocity and shear stress values for different types of bank stabilization materials (Table 2). Reach-averaged lowflow velocity values were calculated from measured velocity values. Bankfull velocity values were calculated using Manning's equation:

$$V = (1/n)(D^{2/3}S^{1/2}), \tag{4}$$

where n is Manning's roughness coefficient, D is the reach-averaged bankfull channel depth, and S is slope. Shear stress was calculated for lowflow and bankfull conditions as follows:

$$\tau o = \gamma DS, \tag{5}$$

where γ is the specific weight of water, D is the reach-averaged channel depth, and S is slope. These data were compared with the permissible velocity and shear stress thresholds (Table 2).

Table 2
Permissible shear stress and velocity for selected lining materials (adapted from Fischenich, 2001)

Boundary category	Boundary type	Permissible shear stress (N/m^2)	Permissible velocity (m/s)
Soil bioengineering	Wattles	9.6–47.9	0.91
	Coir roll	143.6–239.4	2.44
	Live brush mattress (initial)	19.2–196.3	1.22
	Live brush mattress (grown)	186.7–392.6	3.66
	Brush layering (initial/grown)	19.2–299.3	3.66
	Live fascine	59.9–148.4	1.83–2.44
	Live willow stakes	100.5–148.4	0.91–3.05
RECPs	Unvegetated	143.6	1.52–2.13
	Partially established	191.5–287.3	2.29–4.57
	Fully vegetated	383.0	2.44–6.40

Results

Results indicate that stability threshold analysis provides a simple first step toward determining the appropriate types of streambank stabilization to use in eroding reaches. In addition, velocity and shear stress values for this study's sites fall within permissible thresholds for biotechnical streambank stabilization methods.

Reach descriptions

The study reaches are located on the West Branch of Cazenovia Creek (see Fig. 1) and are similar in terms of physical characteristics, particularly under lowflow conditions (Table 3). Reach lengths range between 68.7 and 140.8 m and average lowflow depth is approximately 0.25 m in all four reaches (Table 3). Bankfull depths and widths are also similar in Reaches 1, 2, and 4; however, Reach 3 is more narrow (16.32 m) and deeper (2.22 m) than the other reaches. The dominant erosion process in each reach appears to be fluvial entrainment, whereby, the toe of the outer bank is being eroded, which has led to failure of the overhanging cohesive material (i.e., cantilever) created by the loss of material at the bank toe (Thorne, 1982).

Reach 1 (Fig. 2) is the furthest downstream and consists of a large gravel bar on the left inner bank located between cross-sections 2 and 10. The right outer bank is vertical and steepest between cross-sections 4–8, where it ranges between 0.61 and 3 m high.

Reach 2 is located immediately downstream (i.e., north) of Reach 3 (Fig. 3). The left outer bank in Reach 2 is vertical and approximately 1.5 m high. There is a gravel/cobble bar along the inner right bank between cross-sections 3–8. Reach 3 contains a bar consisting of primarily large cobbles and spring/summer vegetation growth on the left side of the stream. The right outer bank is steep (~3 m high) with exposed sediment.

Reach 4 (Fig. 4) has a gravel bar deposit on the left side of the stream that extends the length of the reach. Vegetation on the bar is well established (e.g., shrubs and grasses). The right bank is steep (~3 m) with exposed roots and some small fallen trees. Vegetation at the top right bank is thick at the upstream end of the reach and decreases in the downstream direction.

Stability threshold results

Results of the stability threshold analysis indicate that lowflow velocity and shear stress values for the four reaches are well within the acceptable threshold limits for all types of biotechnical streambank stabilization construction (Tables 2 and 4).

Bankfull shear stress values for all the reaches are also within the threshold limits for most biotechnical methods. However, some methods are excluded for all the reaches because velocity values are above threshold limits (Tables 2 and 4). Reaches 1 and 2 have relatively low velocity values and any biotechnical stabilization method could be used except wattles and initial live brush mattress. High (>2 m/s) velocity values in Reaches 3 and 4 limit biotechnical bank stabilization options in these reaches. Based on the stability threshold analysis results, only fully established RECPs can be used in Reach 3, while a grown live brush mattress and brush layering, and partially and fully established RECPs can be used in Reach 4.

Table 3
Reach characteristics

Site	Reach length (m)	Reach-averaged lowflow depth (m)	Reach-averaged lowflow width (m)	Reach-averaged bankfull depth (m)	Reach-averaged bankfull width (m)
Reach 1	140.8	0.23	9.71	1.37	42.13
Reach 2	136.3	0.27	11.29	1.36	23.91
Reach 3	99.1	0.31	9.70	2.22	16.32
Reach 4	68.7	0.30	8.88	1.30	20.34

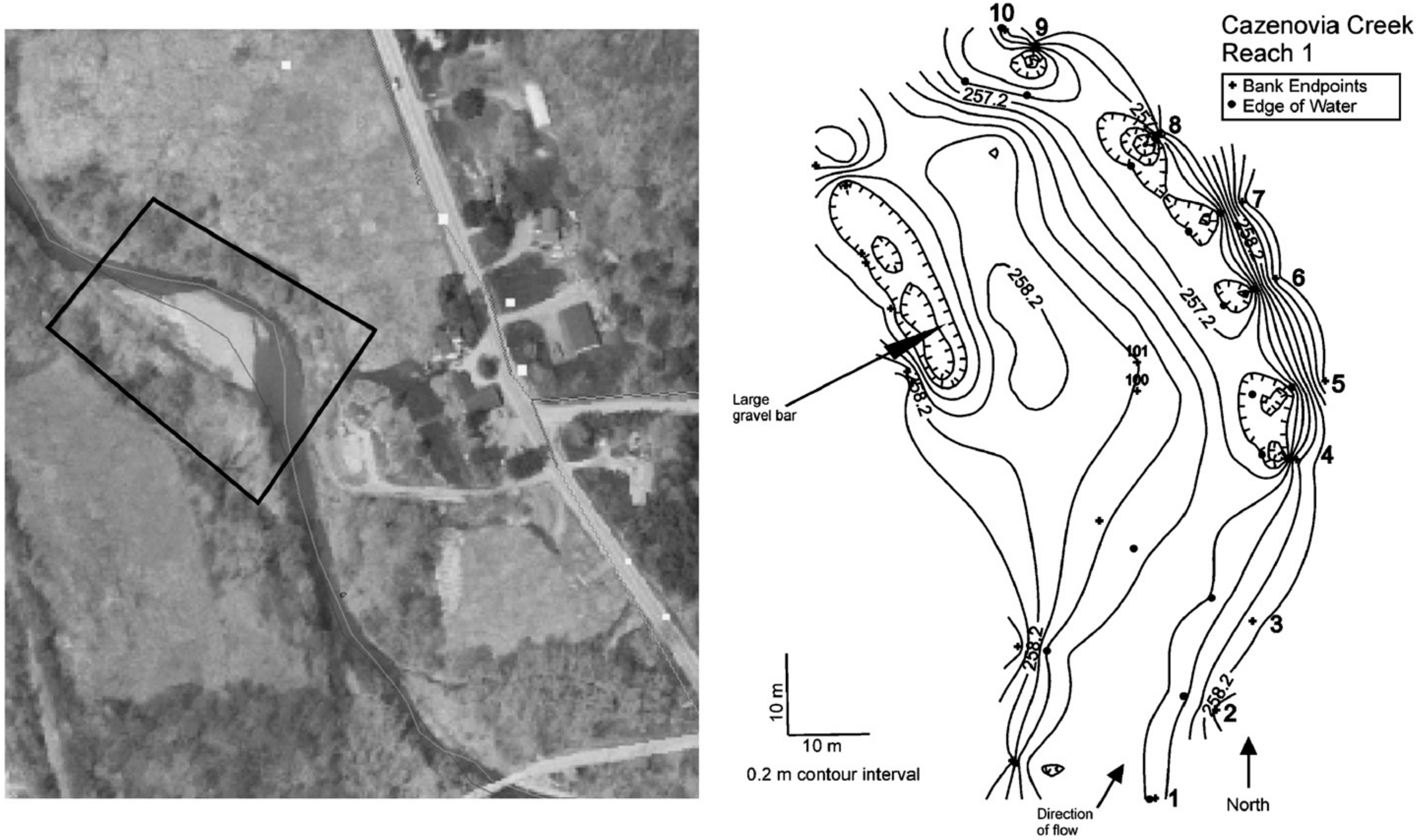

Fig. 2. Reach 1 channel morphology.

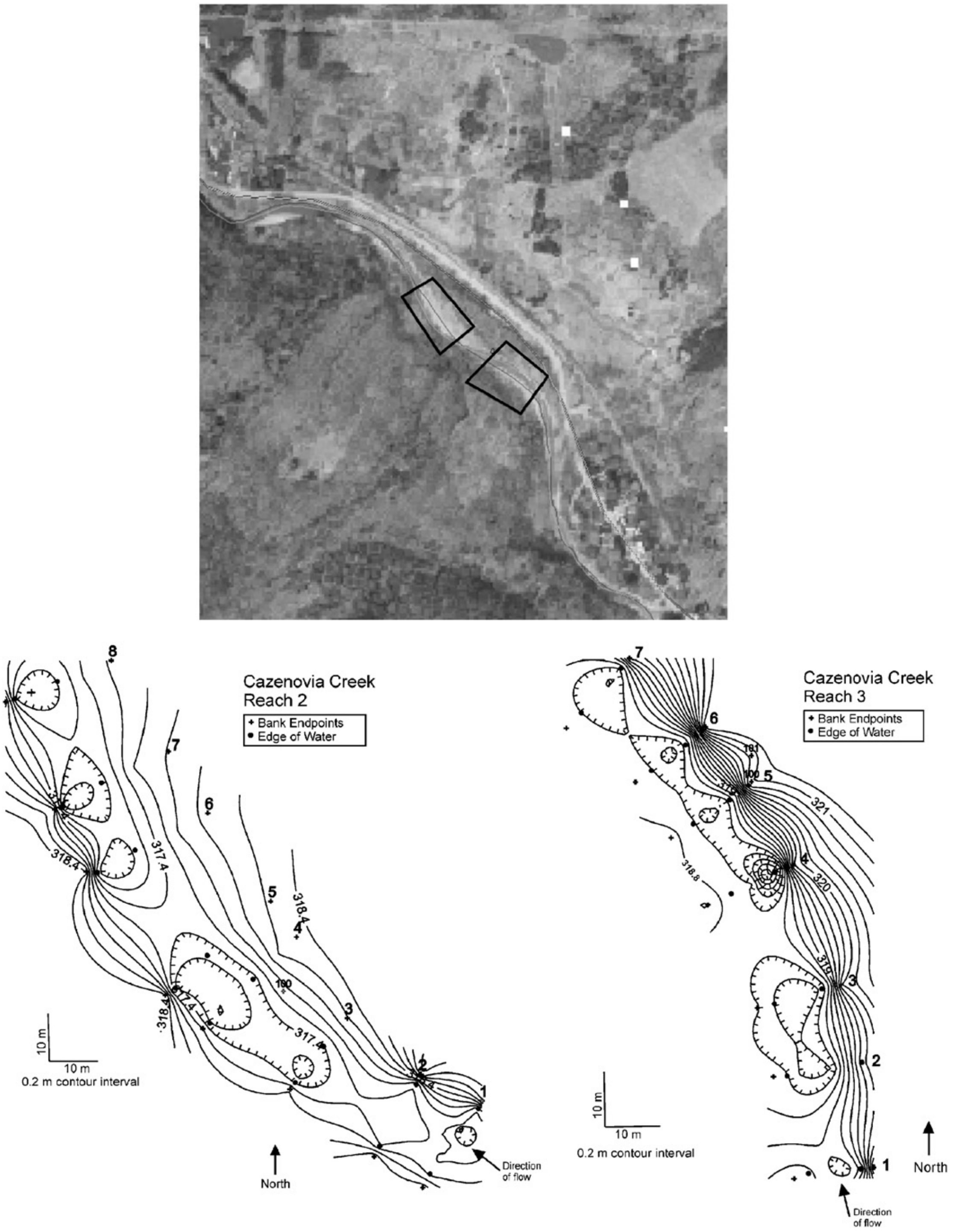

Fig. 3. Reaches 2 and 3 channel morphology.

Discussion

Lowflow velocity and shear stress values for all four study reaches are within permissible threshold limits for biotechnical bank stabilization methods; however, bankfull velocity values limit the appropriate biotechnical options. In order for bank stabilization to be successful, both lowflow and bankfull shear stress and velocity values need to be considered. Lowflow conditions, with the corresponding low shear stress and velocity values, persist through much of the year; however, the more infrequent bankfull conditions are typically the channel changing events that stabilization methods have to withstand (Wolman & Miller, 1960).

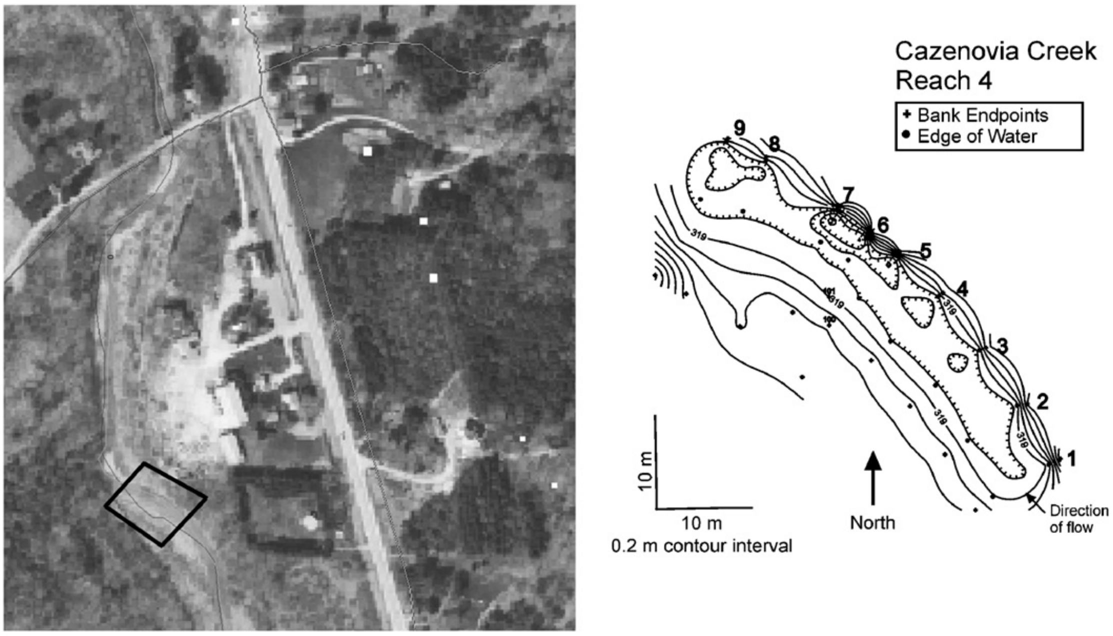

Fig. 4. Reach 4 channel morphology.

Table 4
Stability threshold analysis results

Site	Lowflow		Bankfull flow		Recommended biotechnical bank stabilization
	Shear stress (N/m^2)	Velocity (m/s)	Shear stress (N/m^2)	Velocity (m/s)	
Reach 1	4.79	0.20	26.81	2.22	Any except wattles and live brush mattress (initial)
Reach 2	5.27	0.43	26.81	2.21	Any except wattles and live brush mattress (initial)
Reach 3	15.32	0.39	108.69	4.86	Only fully established RECPs
Reach 4	14.84	0.28	63.68	3.39	Only live brush mattress (grown), brush layering (grown), and partially or fully established RECPs

High (>2 m/s) bankfull velocity values make using wattles, coir rolls, and live fascines inadvisable in all four reaches. Wattles and coir rolls (Table 1) increase roughness, thereby, decreasing water velocity and they provide a good medium for both seeded and natural vegetation to take root to provide additional bank support (Allen & Fischenich, 2000b; Li & Eddleman, 2002). Live fascines (Table 1) also increase roughness and decrease water velocity and, once established, the root systems stabilize streambanks (FISRWG, 1998). Stability threshold analysis provides velocity and shear stress thresholds for each of these biotechnical methods; however, in practice, these methods typically are not used alone to stabilize a streambank. Wattles, coir rolls, and fascines can be used with a brush mattress and RECPs, for example, to provide a higher level of bank protection than using those methods alone (Allen & Fischenich, 2000a; Li & Eddleman, 2002).

Higher bankfull velocities require the level of protection that brush mattresses, brush layering, and RECPs offer (Fischenich, 2001). A brush mattress (Table 1) is a commonly used biotechnical streambank stabilization technique (e.g., Cunningham, 2001; Derrick, 1997; Sotir, 1998a, 1998b)because it provides immediate low-strength bank protection and vegetation typically establishes quickly, restoring riparian vegetation and streamside habitat (Li & Eddleman, 2002). Native vegetation is used to construct the brush mattress and usually includes woody species with fibrous root systems (e.g., willow and dogwood species) (Allen & Fischenich, 2000a; Sotir, 1998a). A brush mattress can be used on moderate bank slopes (2:1) where fluvial entrainment is the dominant erosion process (Allen & Fischenich, 2000a; FISRWG, 1998). Brush layering (Table 1) also uses native vegetation and it can be used on steeper slopes than a brush mattress (FISRWG, 1998; Li & Eddleman, 2002). Brush layering is effective in stabilizing a bank where soil seepage is causing mass movement of bank material (FISRWG, 1998; Li & Eddleman, 2002). High-velocity threshold values for fully established RECPs (Table 1) are greater than the purely biotechnical stabilization methods because they control erosion by combining the strength of the fiber (e.g., coconut and/or plastic netting) blanket and vegetation. Brush mattresses, brush layering, and RECPs can be used in conjunction with traditional bank stabilization techniques (e.g., a rock toe) to attain higher levels of streambank stabilization. A rock toe will have high permissible velocity and shear stress thresholds (Fischenich, 2001), and it will provide immediate bank protection while vegetation becomes established (Li & Eddleman, 2002).

Conclusion

Biotechnical streambank stabilization is used to curb bank erosion and soil loss, as well as to provide habitat enhancements for in-stream and riparian organisms, such as birds, mammals, and insects. The results of this study indicate that stability threshold analysis was useful for easily developing a range of potential biotechnical streambank stabilization techniques for eroding stream reaches. Based on the results from the stability threshold analysis, a brush mattress installed with a rock toe would likely be the best streambank stabilization options for the four study reaches. The calculated velocity and shear stress values for the reaches fall within or near the threshold values for a brush mattress, and the addition of a rock toe should increase permissible flow velocities and shear stresses to levels that would adequately protect the streambanks in the study reaches. As with any biotechnical stabilization project, timing of construction is important because initial brush mattress velocity thresholds are slightly low, so the vegetation will require time to become established before the onset of winter and any highflow conditions.

This information will be used to provide justification for more detailed analyses in the four reaches, which is critical to the successful implementation of any streambank stabilization technique. The dominant erosion process in the reaches appears to be lateral migration by fluvial entrainment, but this needs to be investigated further (FISRWG, 1998; Shields et al., 2003). A quantitative assessment of bank stability should include evaluating soil characteristics such as soil moisture conditions and texture to ensure that (1) bank loss is not occurring as a result of mass movement and (2) the soil will be good plant habitat. In addition, the impact of stream channel curvature on bank erosion should also be investigated in a quantitative bank stability assessment, especially since the observed erosion in all four reaches was located along the outer banks of meander bends. Detailed tractive stress analysis should be done to determine adequate design specifications for the rock toe (Goon, 1978; Snover, 1981). Lastly, after stabilization construction is completed, detailed post-project monitoring should take place (FISRWG, 1998; Li & Eddleman, 2002) and stability threshold analysis can be a part of the monitoring process. Monitoring could include periodically surveying channel morphology and calculating the stability threshold analysis parameters using the new channel depth, slope, and roughness values.

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References

Akridge, A., Eigel, J. D., & Athanasakes, J. G. (1999). Stream restoration and soil bioengineering. *Public Works*, *130*, 48–51.

Allen, H. H., & Fischenich, C. (2000a). *Brushmattress for streambank erosion control*. Technical notes collection TN EMRRP SR-23, Vicksburg, MS: USACE ERDC, Environmental Laboratory.

Allen, H. H., & Fischenich, C. (2000b). *Coir geotextile roll and wetland plants for streambank erosion control*. Technical notes collection TN EMRRP SR-04, Vicksburg, MS: USACE ERDC, Environmental Laboratory

Brookes, A. (1988). *Channelized rivers*. Chichester: Wiley.

Cunningham, W. J. (2001). Bioengineered channel design: protects urban streamway. *Public Works Magazine*, 1–3.

Derrick, D. L. (1997). Harland Creek bank stabilization demonstration project. *Land and Water Magazine*, 1–6.

Dietrich, W. E. (1987). Mechanics of flow and sediment transport in river bends. In K. Richards (Ed.), *River channels and environment and process* (pp. 179–224). Oxford: Basil Blackwell.

Erie County Water Quality Coordinating Committee. (2000). Erie County Water Quality Strategy, 42pp.

Federal Interagency Stream Restoration Working Group. (1998). *Stream corridor restoration: Principles, processes, and practices*. GPO Item no. 0120-A; SuDocs no. A 57.6/2:EN 3/PT.653. ISBN-0-934213-59-3.

Fischenich, C. (2000). *Resistance due to vegetation.* Technical report EMRRP SR-07, Vicksburg, MS: USACE ERDC, Environmental Laboratory.

Fischenich, C. (2001). *Stability thresholds for stream restoration materials*. Technical report EMRRP SR-29, Vicksburg, MS: USACE ERDC, Environmental Laboratory.

Frothingham, K. M. (2005). *Stream channel change in Cazenovia Creek*. Final report, Great Lakes Basin Program for Soil Erosion and Sediment Control, Ann Arbor, MI.

Frothingham, K. M., & Rhoads, B. L. (2003). Three-dimensional flow structure and channel change in an asymmetrical compound meander loop, Embarras River, Illinois. *Earth Surface Processes and Landforms*, *28*, 625–644.

Frothingham, K. M., Rhoads, B. L., & Herricks, E. E. (2001). Stream geomorphology and fisheries in channelized and meandering reaches of an agricultural stream. In J. Dorava, D. Montgomery, B. Palscak, & F. Fitzpatrick (Eds.), *Geomorphic processes and riverine habitat,* (pp. 105–118). Washington, DC: American Geophysical Union.

Gelwick, F. P. (1990). Longitudinal and temporal comparisons of riffle and pool fish assemblages in a northeastern Oklahoma Ozark stream. *Copeia*, *4*, 1072–1082.

Goon, H. J. (1978). *Water surface profiles and tractive stresses for riprap gradient control structures*. Technical report Engineering no. 59 Supplement 2, Hyattsville, MD: USDA.

Li, M., & Eddleman, K. E. (2002). Biotechnical engineering as an alternative to traditional engineering methods: A biotechnical streambank stabilization design approach. *Landscape and Urban Planning*, *60*, 225–242.

New York State DEC. (1989). *Buffalo river remedial action plan*, Report to the International Joint Commission.

New York State DEC. (1996). *The 1996 priority waterbodies list for The Niagara river–Lake Erie basin.*

Parsons, D. A., Apman, R. P., & Decker, G. H. (1963). *The determination of sediment yields from flood sampling. land erosion, precipitations, hydrometry,sSoil moisture*, IASH Publication No. 65, pp. 7–15.

Portt, C. B., Balon, E. K., & Noakes, D. L. G. (1986). Biomass and production of fishes in natural and channelized streams. *Canadian Journal of Fisheries and Aquatic Science*, *43*, 1926–1934.

Rhoads, B. L., & Urban, M. A. (1997). Human-induced geomorphic changes in low-energy agricultural streams: An example from east-central Illinois. In S. S. Y. Wang, E. J. Langendoen, & F. D. Shields Jr. (Eds.), *Management of landscapes disturbed by channel incision* (pp. 968–973). Oxford: The Center for Computational Hydroscience and Engineering, The University of Mississippi.

Rhoads, B. L., & Welford, M. R. (1991). Initiation of river meandering. *Progress in Physical Geography*, *15*, 127–156.

Shields, F. D., Jr., Cooper, C. M., & Knight, S. S. (1995). Experiment in stream restoration. *Journal of Hydraulic Engineering*, *121*, 494–502.

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

Simon, K., & Steinemann, A. (2000). Soil bioengineering: Challenges for planning and engineering. *Journal of Urban Planning and Development*, *1262*, 89–102.

Snover, S. D. (1981). *Open channel curves-stability and design of riprap protection using tractive stress*. Technical report Engineering no. 29, Broomall, PA: USDA, NETSC.

Sotir, R. B. (1998a). Brushing up on erosion control. *American City and Country Magazine*, 1–11.

Sotir, R. B. (1998b). Brushing off erosion: Soil bioengineering techniques offer a natural way to repair streambank erosion while benefiting the environment. *Civil Engineering News*, 1–14.

Sotir, R. B., & Nunnally, N. R. (1995). Use of riprap in soil bioengineering streambank protection. *River, Coastal and Shoreline Protection*, 1–11.

Swales, S. (1982). A 'before and after' study of the effects of land drainage works on fish stocks in the upper reaches of a lowland river. *Fisheries Management*, *13*, 105–114.

Swales, S. (1988). Fish populations of a small lowland channelized river in England subject to long-term river maintenance and management works. *Regulated Rivers: Research and Management*, *2*, 493–506.

Thorne, C. R. (1982). Processes and mechanisms of river bank erosion. In R. Hey, J. Bathurst, & C. R. Thorne (Eds.), *Gravel-bed rivers* (pp. 227–272). New York, NY: John Wiley & Sons.

Versar, I. (1975). *Water pollution investigation: Buffalo river*. EPA-905/9-74-010, US EPA Report, 144pp.

Wolman, M. G., & Miller, J. P. (1960). Magnitude and frequencies of forces in geomorphic processes. *Journal of Geology*, *68*, 54–74.