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Do we know enough about controlling sediment to mitigate damage to stream ecosystems?

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ABSTRACT

Stream and river ecosystems have suffered extensive degradation, and billions are expended annually on restoration efforts. However, few of these projects are monitored, and restoration effectiveness is often unknown. Consequently, there is a poor scientific foundation for restoration designs. Since many stream restoration efforts are at least partially targeted at controlling erosion of channel banks and beds, the effects of a large-scale, long-term stream erosion control effort in six Mississippi watersheds was assessed using 10–16 years of suspended sediment and water discharge records. Flow-adjusted suspended sediment concentrations showed no trends in five of the watersheds and a slight downward trend in one watershed, which was treated with small reservoirs as well as bed and bank erosion protection. Results indicate the inability of orthodox stream management structures (weirs and bank protection) to reduce watershed sediment yield and the need for a stronger scientific basis for stream restoration.

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1. Introduction

The quality of U.S. rivers is in decline, and the attendant loss of ecological services is significant. Various types of development activities impact streams and adjacent riparian ecosystems, and in some states, regulations have required parties responsible for these damaging impacts to compensate by restoring damaged stream reaches off-site. Recently, compensatory stream mitigation policy was extended to all states at the federal level (Stokstad, 2008). Annual expenditures for compensatory stream mitigation have been estimated to range from \$179 million to \$955 million (Environmental Law Institute, 2007). Such compensatory mitigation is a subset of the larger class of projects collectively referred to as stream restoration. Not including a few extremely large-scale projects, about \$1 billion is spent annually on all types of stream restoration in the United States, and the number of restoration projects is increasing exponentially (Palmer et al., 2007). However, few restoration projects are monitored, and fewer are still evaluated for effectiveness. Some regional analyses have suggested that mitigation projects may fall short of their goals (Booth et al., 2002; Thompson, 2002; Lave et al., 2008), while a recent, more comprehensive review found that conclusive information is lacking to evaluate most techniques (Roni et al., 2008). Target conditions are often based on "reference" sites that may or may not be appropriate (Lester et al., 2006). In other cases, monitored projects exhibit short-term success, but long-term failure (Pezeshki et al., 2007; Shields et al., 2008) or produce equivocal findings (Price and Birge, 2005). Restoration of features responsible for hyporheic exchange and other physical elements that are coupled with chemical and physical processes is poorly understood at present (Murdock et al., 2004; Parkyn et al., 2005; Kasahara and Hill, 2008, Hester and Doyle, 2008). Do stream restoration projects result in a change in ecological conditions—either in terms of measurable habitat variables, biological populations, or ecological processes? In about 90% of the cases, no one knows (Palmer et al., 2007).

A previous federal research and demonstration program, the Demonstration Erosion Control Project (DEC), has yielded data that may be helpful in filling this gap. The DEC was intended to reduce sediment yield from 16 watersheds in northern Mississippi plagued with elevated levels of erosion and downstream sediment deposition since the onset of European settlement in the 1830s. Prior to the DEC, efforts to cultivate hillslopes led to accelerated valley sedimentation (up to 2 m), plugging channels (i.e., almost completely filling some reaches) and prompting subsequent efforts to clear and channelize entire stream networks. Channelization, coupled with large, federal flood-control reservoirs

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that reduced flood stages, triggered headward-progressing channel incision. Channel widths and depths often increased by a factor of five. Such accelerated channel erosion is often the source of most of the sediment emanating from disturbed watersheds (Simon and Rinaldi, 2006). The associated elevated stream sediment concentrations are harmful to aquatic biota (Rabeni and Smale, 1995; Newcombe and Jensen, 1996; Sutherland et al., 2002; Norris et al., 2007) and are often the very conditions targeted by stream restoration projects. Funding and work for the DEC commenced in 1985 in six Mississippi watersheds that ranged in size from 84 to 1234 km^2. Between 1985 and 1989, an additional nine watersheds were added to the DEC and a tenth was added in 1996. As of 2003, federal expenditures for the DEC totaled $309 million. Project activities consisted primarily of construction of riser pipe grade control structures, low- and high-drop grade control structures, small reservoirs and bank stabilization measures (Fig. 1). Land-treatment measures (i.e., parallel terraces, grassed waterways, diversions, water and sediment control basins) were also included in the DEC, but at a far smaller scale than in-channel structures. As of June 1996, nine high-drop grade control structures, 149 low-drop grade control structures, 766 riser pipes, 144 km of bank protection, 29.4 km of channelization (removal of sediment and debris plugs from channels impacted by upstream erosion), and nine small dams had been constructed. Although these measures

Fig. 1. Typical erosion control measures employed under the Demonstration Erosion Control Project. (a) Reservoir, (b) high-drop grade control structure, (c) low-drop grade control structure, (d) stone toe bank protection, and (e) riser pipe grade control structure. Note that only the inlet to pipe is shown. Underground portion of pipe passes through earthen embankment in left side of photo and discharges into a stream channel below.

Table 1
Suspended sediment records for selected DEC watersheds.

Watershed	USGS station	Suspended sediment record (length, year)	Watershed size (km^2)	DEC structures completed as of 1989/1996		
				Grade control structures (no.)	Bank protection (km)	Riser pipes (no.)
Hotopha Creek	07273100	1986–1997 (11.2)	90	2/15	4.3/9.8	26/46
Peters Creek	07275530	1986–1996 (9.8)	205	10/15	11/20	45/56
Hickahala Creek	07277700	1987–2003 (16.7)	313	5/34	4.3/10	87/119
Otoucalofa Creek	07274252	1986–1997 (11.3)	251	0/3	23/12	31/48
Batupan Bogue	07285400	1985–1996 (10.9)	622	8/32	16/27	7/76
Harland Creek[a]	07287404	1986–2000 (13.7)	161	0/3	14/45	28/95
Abiaca Creek	07287160	1991–2003 (11.9)	202	0/3	0	9

[a] Construction data are for the Black Creek watershed. Sediment records are for station 07287404, Harland Creek, a subwatershed comprising about 13% of Black Creek watershed.

were not intended to restore or rehabilitate stream habitats, they are essentially similar to the erosion control components of many stream restoration projects. Clearly, controlling accelerated channel erosion is a necessary but not sufficient condition for stream restoration (Lave et al., 2008). The results of the DEC should indicate whether or not generous application of stream erosion control is effective in addressing one of the key factors in stream ecosystem degradation.

2. Methods

In addition to design and construction, the DEC featured a monitoring effort that included high-frequency measurements of water and suspended sediment discharge at strategic locations. The entire record (1986–2003) of water discharge and suspended sediment concentration collected from the DEC watersheds by the U.S. Geological Survey (USGS) was obtained and examined for evidence of effects of the DEC project on watershed suspended sediment yield. Suspended sediment records were available for sites located near the outlets of five of the original six watersheds for the period commencing shortly after initiation of the DEC (i.e., 1986–1987) and ending at least 10 years later (1996–1997) (Table 1). The sixth watershed, Black Creek, was monitored by a gage located on Harland Creek, a key tributary. Much of the DEC construction in these six watersheds was also completed during this period (Table 1). In addition, longer periods of record were available for two of the six gages, Hickahala Creek and Harland Creek. An extensive data set was also available for a seventh watershed, Abiaca Creek, but these measurements covered a later period, 1991–2003 (Table 1). Sediment control work in Abiaca Creek watershed was also performed later than for the other six watersheds and involved a much different structural approach (using levee setbacks to create a natural floodway and sediment sink). Gaging sites for all seven watersheds are within reaches with sand ($D_{50} \sim 0.3$ mm) or sand and gravel beds (gravel $D_{50} \sim 20$ mm) downstream from incising channel networks.

Instantaneous measured values of water discharge, cross-sectional mean suspended sediment concentration, and sediment load were subjected to trend detection analysis. Trends in flow-adjusted sediment concentration were examined. Only measurements of sediment concentration and load based on either the equal-discharge or equal-width increment sampling methods (Edwards and Glysson, 1999) were used in the analysis. In addition, analysis was limited to sediment concentrations and loads for which simultaneously measured discharges were available.

Seasonal Kendall tests (Hirsch et al., 1982) were used to test for the presence of trends in the discharges, sediment concentrations, sediment loads and flow-adjusted sediment concentrations (Smith et al., 1982; Schertz et al., 1991) using software implemented as described by Slack et al. (2003) and Helsel et al. (2005).

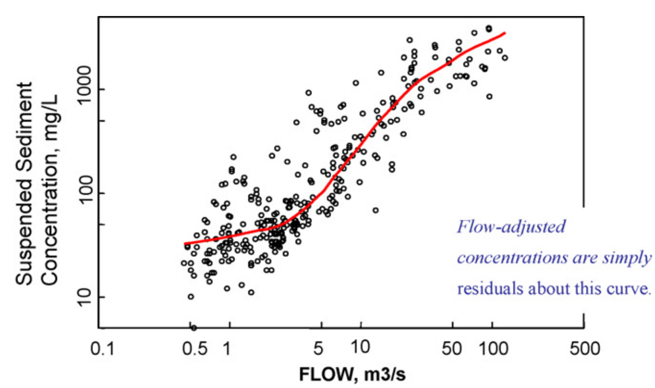

Fig. 2. Typical LOESS fit of observed instantaneous suspended sediment concentration and instantaneous discharge, Hotopha Creek, 1986–1997.

Table 2
Results of seasonal Kendall tests for presence of monotonic trend over approximately 11-year period. Test results include Kendall's τ (rank correlation coefficient) and the p-value for significance of τ, adjusted for serial correlations. Cases for which $p < 0.10$ are shown in bold font.

Watershed	Period used for this analysis	No. of observations[a]	Water discharge		Suspended sediment concentration		Flow-adjusted suspended sediment concentration		Suspended sediment load	
			τ	p	τ	p	τ	p	τ	p
Hotopha Creek	1986–1997	293/102	0.03	0.89	0.05	0.76	0.11	0.23	0.05	0.54
Peters Creek	1986–1997	248/114	**0.13**	**0.07**	−0.02	0.87	−0.04	0.69	0.02	0.89
Hickahala Creek	1987–1998	343/108	0.20	0.19	0.13	0.13	0.03	0.68	0.15	0.20
Otoucalofa Creek	1986–1997	312/82	**0.26**	**0.05**	0.06	0.57	**−0.13**	**0.08**	0.13	0.28
Batupan Bogue	1985–1986	259/109	0.004	0.98	0.04	0.72	0.08	0.31	0.06	0.55
Harland Creek	1986–1997	368/127	0.03	0.64	**0.18**	**0.04**	0.07	0.57	**0.11**	**0.05**

[a] The first number in each cell represents the total number of instantaneous discharge and suspended sediment measurements in the data set. Only one value from each month in the record was selected and used to construct an annual series for each month. When multiple values were available for a given month and year, the most central value with respect to time (the measurement collected on the date closest to the middle of the month) was used. The second number in each cell represents the number of values in the 12 constructed annual series.

Flow-adjusted concentrations were simply residuals of a LOESS regression of concentration against flow using $f = 0.5$ (Schertz et al., 1991). A typical LOESS fit to the observed data is shown in Fig. 2. The seasonal Kendall test minimizes effects of seasonal variability on trend detection by comparing only values from the same season for different years. Twelve seasons corresponding to the 12 calendar months were used for the seasonal Kendall tests. The 12 seasonal Kendall test results were combined algebraically and used to compute a nonparametric regression coefficient, τ (Table 2). A maximum p-value of 0.10 for τ was selected for rejection of the hypothesis that the data were free from a significant trend (Smith et al., 1982). Initial trend detection tests were run using only data from the first six gages listed in Table 1 and for the period 1986 through 1998. A second set of tests were run using all available data for the longer-term records (Hickahala and Harland Creeks) and data for the seventh site, Abiaca Creek. Finally, time-series plots of flow-adjusted suspended sediment concentration were visually examined to confirm statistical results.

3. Results

Initial screening of the available data using scatter plots showed that the instantaneous measurements were collected across the full range of flows and were more or less evenly distributed in time (Fig. 3). Flow-adjusted instantaneous suspended sediment concentration in the monitored watersheds exhibited a significant downward trend in only one of six watersheds (Otoucalofa Creek, Table 2 and Fig. 4), and no positive trends were detected. Seasonal Kendall tests of instantaneous water discharges indicated that two of the six gages experienced a trend of increasing water discharge over the 11-year record (Table 2). Only one watershed (Harland Creek) exhibited a significant trend in suspended sediment concentration. That positive trend also produced an upward trend in sediment load, but no trend was detected in flow-adjusted concentration at this gage. When longer, more recent periods were analyzed for three watersheds, only a slight increasing trend in suspended sediment concentration and load at one was noted

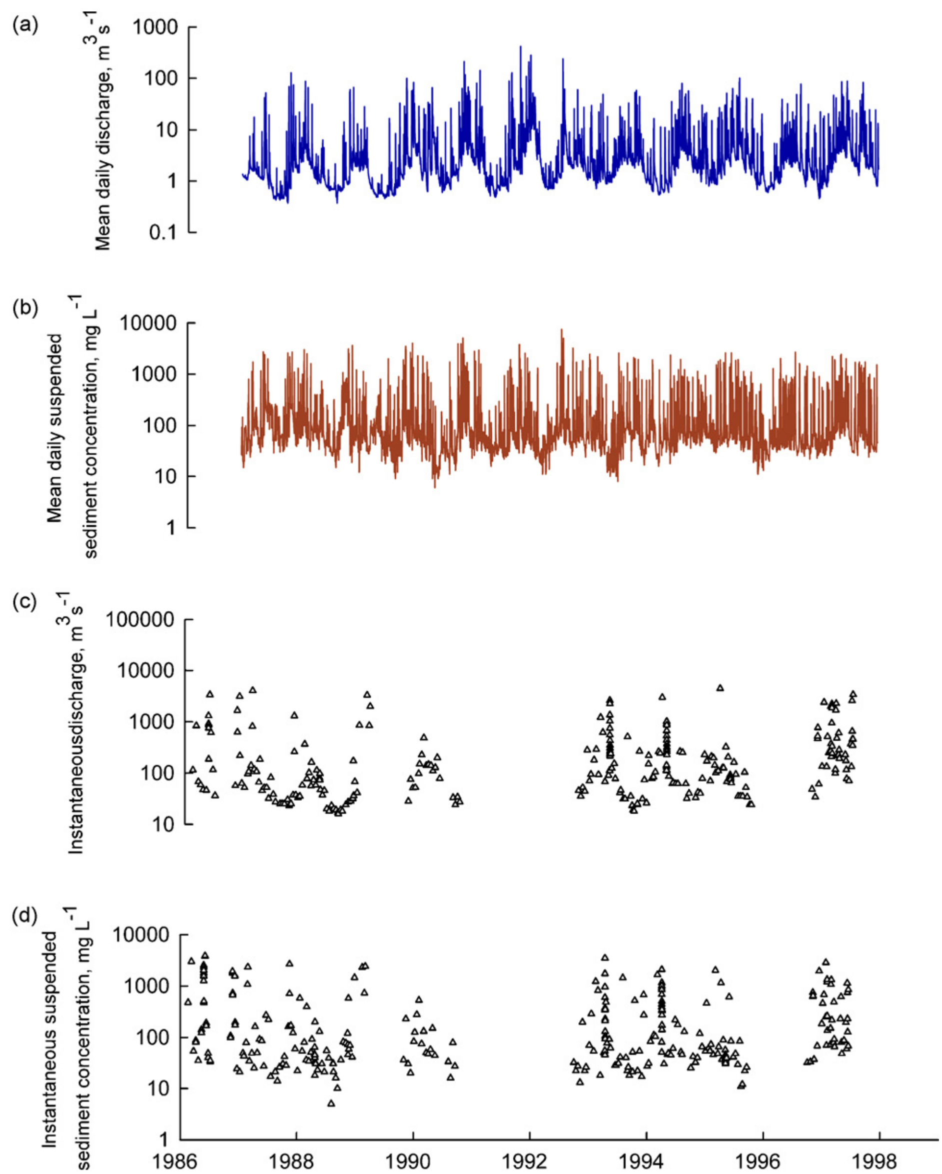

Fig. 3. Typical data set used in these analyses. (a) Mean daily discharge of water, (b) mean daily suspended sediment concentration, (c) instantaneous measured water discharge and (d) instantaneous suspended sediment concentration for a USGS gage located near the outlet of Otoucalofa Creek Canal near Water Valley, MS, station 07274252.

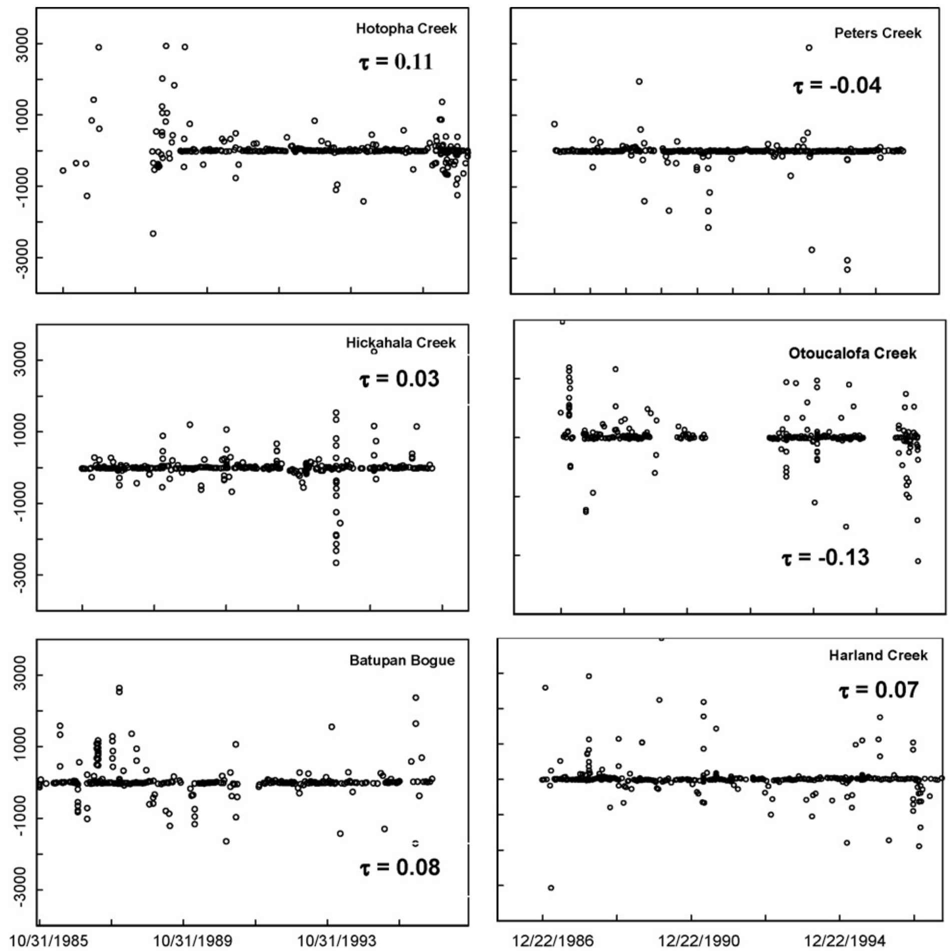

Fig. 4. Residuals of LOESS regression of suspended sediment concentration on discharge (in mg/L) plotted against date for the water years 1986–1997 for six northern Mississippi watersheds treated for erosion under the Demonstration Erosion Control Project.

(Harland Creek, Table 3). No trend was detected in flow adjusted sediment concentration over the longer term.

4. Discussion

Anthropogenically driven elevation of suspended sediment concentrations is responsible for degradation of many stream ecosystems. Expenditure of more than $404 ha^{-1} ($164 acre^{-1}) of federal funds and more in state and local funds for controlling erosion and reducing sediment yield from 16 watersheds in northwestern Mississippi was evaluated by monitoring water and suspended sediment discharge for 11 years at six watershed outlets and for periods ranging from 12 to 17 years at three watershed outlets. When sediment concentrations were adjusted for variations in streamflow, data from only one site exhibited a significant downward trend. In contrast to projects built in the other watersheds, which relied heavily on in-channel erosion control structures, eight reservoirs were built in this watershed, which attenuated high flows and reduced sediment concentrations at their outlets (Cullum and Cooper, 2001). The cohesive materials that occur frequently in the streambeds in this watershed likely resisted renewed channel incision in reaches further downstream. Accordingly, suspended sediment concentrations at the watershed outlet trended downward. However, the statistical analysis for this trend may not be valid, because water discharge in this watershed exhibited a significant upward trend ($p = 0.05$) (Table 2). The Seasonal Kendall

Table 3
Results of seasonal Kendall tests for presence of monotonic trend over periods ranging in length from 12 to 17 years. Test results include Kendall's τ (rank correlation coefficient) and the p-value for significance of τ, adjusted for serial correlations. Cases for which $p < 0.10$ are shown in bold font.

Watershed	Period used for this analysis	No. of observations[a]	Water discharge		Suspended sediment concentration		Flow-adjusted suspended sediment concentration		Suspended sediment load	
			τ	p	τ	p	τ	p	τ	p
Hickahala Creek	1987–2003	559/166	0.11	0.33	0.01	0.85	−0.08	0.18	0.04	0.69
Harland Creek	1986–2000	439/161	0.05	0.44	**0.13**	**0.09**	0.09	0.37	**0.11**	**0.06**
Abiaca Creek	1991–2003	468/139	−0.15	0.14	0.08	0.44	0.11	0.37	0.00	1.00

[a] The first number in each cell represents the total number of instantaneous discharge and suspended sediment measurements in the data set. Only one value from each month in the record was selected and used to construct an annual series for each month. When multiple values were available for a given month and year, the most central value with respect to time (the measurement collected on the date closest to the middle of the month) was used. The second number in each cell represents the number of values in the 12 constructed annual series.

analysis of trend in flow-adjusted concentrations is based on the assumption that the time series of flows is stationary (i.e., has undergone no change with time such as that produced by reservoir closure, Schertz et al., 1991).

We would expect that generally lower suspended sediment levels would be beneficial to aquatic organisms, including fish. A 10-year study of fish communities of selected stream reaches in the Hotopha and Long Creek watersheds showed that fish populations in reaches treated with standard types of erosion control did not improve despite the improved water quality (Shields et al., 2007). However, fish communities in reaches treated with habitat rehabilitation measures (instream stone structures, riparian plantings) generally responded positively, becoming more similar to those found in a lightly degraded, nonincised reference stream. Certainly, detailed, reach-scale models of habitat and water quality (e.g., Parkyn et al., 2005; Bockelmann et al., 2004; Kasahara and Hill, 2008) would have been great assets in designing DEC projects, but these were not generally available during the period of major design activity (1985–2000).

Studies by others using indirect approaches and focused on individual watersheds have indicated that sediment yields should have declined over the period of observation. Based on analysis of one watershed, Hotopha Creek, Simon and Darby (2002) argued that grade control structures trapped so much sand that they exacerbated erosion downstream even as they prevented additional upstream incision. It is possible that the absence of a detectable trend in the measured data reflects this type of complex response to the grade controls. Kuhnle et al. (1996) used a combination of measured data and watershed modeling to document a ∼60% reduction in sediment concentration and an attendant halving of fine sediment yield in Goodwin Creek, a Peters Creek tributary, over the period 1982–1991. They attributed most of the yield reduction to a 50% reduction in the area of cultivated land.

The lack of statistically significant trends in the DEC data may be due to temporal lags in watershed response (Trimble, 1974). Channel systems store sediments, and plugs of sediment may continue to move through channel networks even after source yields are reduced. However, the aforementioned indirect methods focus on the channel and indicate that yields should have been falling during the period corresponding to the data records analyzed above. Furthermore, analysis of a 17-year-long record produced the same results as analysis of an 11-year record for the same site. The strong random component in the time series of suspended sediment concentration may have obscured trends. Clearly, the large variance present in real sediment transport data tends to obscure effects of control measures. Such effects must be large to produce statistically significant differences.

On the other hand, it may be possible that the DEC did not significantly reduce sediment yields. Lane's relation states that the product of bed-material sediment discharge, Q_s, and sediment size, D_s, is proportional to the product of water discharge, Q, and energy slope, S:

$$Q_s D_s \sim QS$$

It follows that a reduction in bed-material sediment discharge, Q_s, requires that sediment size increase or flow or slope decrease. DEC treatments had limited direct effects on bed-material size, peak flow, and energy slope. DEC measures had only very local effects on boundary sediment size (bank protection measures with riprap). Natural temporal variations in bed-material size were quite dynamic, but tended to fall within a relatively narrow range due to the unavailability of coarser materials (Doyle and Shields, 2000). With the possible exception of Otoucalofa Creek, land treatment and reservoir construction were not employed widely enough to measurably affect peak flows.

DEC work included more than 29.4 km (18.3 miles) of channelization, which increased channel energy slope. Effects of other treatments on energy slope were limited to reaches immediately upstream from grade control structures. Furthermore, grade controls were sized and located to reduce energy slopes to stable values, but stable values were determined based on empirical relationships between slope and contributing drainage area using reaches visually characterized as stable for references (Shields et al., 1995). Even these apparently stable reaches may still convey elevated loads of sediment from upstream reaches, gullies, rills, and sheet erosion.

5. Conclusion

Fluvial systems may respond in complex ways to widespread application of channel erosion controls. Even very large expenditures may not be adequate to reduce watershed sediment yield if peak discharges and channel energy slopes are not reduced. Real reductions in sediment concentrations may be hard to achieve with the orthodox types of channel erosion controls applied in these watersheds, especially if channel energy slopes are either increased or not reduced. The science of predicting the response of unstable channel networks to erosion controls and practices applied at the watershed scale and the attendant impact on watershed sediment yield is currently inadequate for quantitative analysis. Since ecological responses cascade from underlying physical phenomena, uncertainty regarding the outcome of proposed ecological restoration of streams is very high. We echo the calls of others for a stronger scientific basis for stream restoration (Wohl et al., 2005; Palmer and Allan, 2006). Without such a basis, justification for funding future stream restoration projects will become increasingly difficult.

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References

Bockelmann, B.N., Fenrich, E.K., Lin, B., Falconer, R.A., 2004. Development of an ecohydraulics model for stream and river restoration. Ecol. Eng. 22, 227–235.

Booth, D.B., Hartley, D., Jackson, R., 2002. Forest cover, impervious-surface area, and the mitigation of stormwater impacts. J. Am. Water Resour. AS. 38 (3), 835–845.

Cullum, R.F., Cooper, C.M., 2001. Water quality from floodwater retarding structures. In: Proceedings of the Federal Interagency Sedimentation Conferences, 1947 to 2001, CD-ROM. Proceedings of the 7th Federal Interagency Sedimentation Conference, U.S. Subcommittee on Sedimentation, Reno, NV, March 25–29, 2001.

Doyle, M.W., Shields Jr., F.D., 2000. Incorporation of bed texture into a channel evolution model. Geomorphology 34, 291–309.

Edwards, T.K., Glysson, G.D., 1999. Field Methods for Measurement of Fluvial Sediment. Techniques of Water-Resources Investigations of the U.S. Geological Survey. Book 3, Applications of Hydraulics. U.S. Geological Survey, Reston, VA.

Environmental Law Institute, 2007. Mitigation of Impacts to Fish and Wildlife Habitat: Estimating Costs and Identifying Opportunities. Environmental Law Institute, Washington, DC.

Helsel, D.R., Mueller, D.K., Slack, J.R., 2005. Computer program for the Kendall family of trend tests. Scientific Investigations Report 2005-5275. U.S. Department of the Interior, U.S. Geological Survey, Washington, DC.

Hester, E.T., Doyle, M.W., 2008. In-stream geomorphic structures as drivers of hyporheic exchange. Water Resour. Res. 44, doi:10.1029/2006WR005810, W03417.

Hirsch, R.M., Slack, J.R., Smith, R.A., 1982. Techniques of trend analysis for monthly water quality data. Water Resour. Res. 18, 107–121.

Kasahara, T., Hill, A.R., 2008. Modeling the effects of lowland stream restoration projects on stream-subsurface water exchange. Ecol. Eng. 32, 310–319.

Kuhnle, R.A., Bingner, R.L., Foster, G.R., Grissinger, E.H., 1996. Effect of land use changes on sediment transport in Goodwin Creek. Water Resour. Res. 32, 3189–3196.

Lave, R., Robertson, M.M., Doyle, M.W., 2008. Why you should pay attention to stream mitigation banking. Ecol. Restor. 26 (4), 287–289.

Lester, R., Wright, W., Jones-Lennon, M., 2006. Determining target loads of large and small wood for stream rehabilitation in high-rainfall agricultural regions of Victoria, Australia. Ecol. Eng. 28, 71–78.

Murdock, J., Roelke, D., Gelwick, F., 2004. Interactions between flow, periphyton, and nutrients in a heavily impacted urban stream: implications for stream restoration effectiveness. Ecol. Eng. 22, 197–207.

Newcombe, C.P., Jensen, J.O.T., 1996. Channel suspended sediment and fisheries: a synthesis for quantitative assessment of risk and impact. North Am. J. Fisher. Manage. 16, 693–727.

Norris, R.H., Linke, S., Prosser, I., Young, W.J., Liston, P., Bauer, N., et al., 2007. Very-broad-scale assessment of human impacts on river condition. Freshwater Biol. 52 (5), 959–976.

Palmer, M., Allan, J.D., Meyer, J., Bernhardt, E.S., 2007. River restoration in the twenty-first century: data and experiential knowledge to inform future efforts. Restor. Ecol. 15, 472–481.

Palmer, M.A., Allan, J.D., 2006. Restoring rivers. Issues Sci. Technol., Nat. Acad. Sci. (Winter), 40–48.

Parkyn, S.M., Davies-Colley, R.J., Cooper, A.B., Stroud, M.J., 2005. Predictions of stream nutrient and sediment yield changes following restoration of forested riparian buffers. Ecol. Eng. 24, 551–558.

Pezeshki, S.R., Li, S., Shields Jr., F.D., Martin, L.T., 2007. Factors governing survival of black willow (Salix nigra) cuttings in a streambank restoration project. Ecol. Eng. 29, 56–65.

Price, D.J., Birge, W.J., 2005. Effectiveness of stream restoration following highway reconstruction projects on two freshwater streams in Kentucky. Ecol. Eng. 25, 73–84.

Rabeni, C.F., Smale, M.A., 1995. Effects of siltation on stream fishes and the potential mitigating role of the buffering riparian zone. Hydrobiologia 303, 211–219.

Roni, P., Hanson, K., Beechie, T., 2008. Global review of the physical and biological effectiveness of stream habitat rehabilitation techniques. North Am. J. Fisher. Manage. 28, 856–890.

Schertz, T.L., Alexander, R.B., Ohe, D.J., 1991. The computer program Estimate Trend (ESTREND), a system for the detection of trends in water-quality data. Water-Resources Investigation Report 91-4040. U.S. Geological Survey, Washington, DC.

Shields Jr., F.D., Knight, S.S., Cooper, C.M., 1995. Rehabilitation of watersheds with incising channels. Water Resour. Bull. 31, 971–982.

Shields Jr., F.D., Knight, S.S., Cooper, C.M., 2007. Can warmwater streams be rehabilitated using watershed-scale standard erosion control measures alone? Environ. Manage. 40, 62–79.

Shields Jr., F.D., Pezeshki, S.R., Wilson, G.V., Wu, W., Dabney, S.M., 2008. Rehabilitation of an incised stream with plant materials: the dominance of geomorphic processes. Ecol. Soc. 13 (2), 54, http://www.ecologyandsociety.org/vol13/iss2/art54/ (online).

Simon, A., Darby, S.E.S.E., 2002. Effectiveness of grade-control structures in reducing erosion along incised river channels: the case of Hotophia Creek, Mississippi. Geomorphology 42, 229–254.

Simon, A., Rinaldi, M., 2006. Disturbance, stream incision, and channel evolution: the roles of excess transport capacity and boundary materials in controlling channel response. Geomorphology 79, 361–383.

Slack, J.R., Lorenz, D.L., et al., 2003. USGS Library for S-PLUS for Windows—Release 2.1. U.S. Geological Survey Open-File Report 03-357. U.S. Department of the Interior, U.S. Geological Survey, Washington, DC.

Smith, R.A., Hirsch, R.M., Slack, J.R., 1982. A study of trends in total phosphorus measurements at NASQAN stations. Water-Supply Paper No. 2190. U.S. Geological Survey, Washington, DC.

Stokstad, E., 2008. New rules on saving wetlands push the limits of science. Science 320, 162–163.

Sutherland, A.B., Meyer, J.L., Gardiner, E.P., 2002. Effects of land cover on sediment regime and fish assemblage structure in four southern Appalachian streams. Freshwater Biol. 47, 1791–1805.

Thompson, D.M., 2002. Long-term effect of instream habitat-improvement structures on channel morphology along the Blackledge and Salmon Rivers, Connecticut. Environ. Manage. 29, 250–265.

Trimble, S., 1974. Man induced erosion on the southern piedmont: 1700–1970. Soil Conservation Society of America, Ankeny, IA.

Wohl, E., Angermeier, P.A., Bledsoe, B., Kondolf, G.M., MacDonnell, L., Merritt, D.M., Poff, N.L., Palmer, M.A., Tarboton, D., 2005. River restoration. Water Resour. Res. 41, 1–12, W10301.