INVITED COMMENTARY

HP TODAY

HYDROLOGICAL PROCESSES
Hydrol. Process. **21**, 2539–2545 (2007)
Published online 17 July 2007 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/hyp.6840

Evaluating 'natural channel design' stream projects

Greg Nagle*

Cornell University, Department of Natural Resources, Fernow Hall, Ithaca NY 14853, USA

*Correspondence to:
Greg Nagle, Cornell University, Department of Natural Resources, Fernow Hall, Ithaca NY 14853, USA.
E-mail: gnagle2000@yahoo.com

Received 5 June 2007
Accepted 6 June 2007

We need a coherent, deliberate process to learn from failures and successes in stream rehabilitation projects. Insightful evaluations comparing projects in varied regions have been limited by the diversity of approaches and some scientific uncertainty as to how to best accomplish longer-term monitoring (Bernhardt *et al.*, 2005; Giller, 2005; Palmer *et al.*, 2005; Palmer and Bernhardt, 2005; Reid, 2001, Reid and Furniss, 2002). Addressing just the critical issue of biological assessments would take an entire paper but with hundreds of natural channel design (NCD) projects completed across the country, simply evaluating their performance and impacts on bank erosion would be a step forward. Too often critiques of NCD projects have returned continually to the same few locations, and have yet to grapple with many other projects with different designs, disturbance histories, and environments. I hope this brief review will encourage better dialogue between scientists and stream rehabilitation practitioners.

NCD most often seeks to restore the dimension, pattern, and profile of a disturbed river system to emulate the natural stable river (Rosgen, 2006). A stable channel is defined as a dynamic, alluvial channel whose characteristic dimensions or features do not change over engineering time scales (Niezgoda and Johnson, 2005). Stream bank erosion is a natural process, but when accelerated by human impacts creates a disequilibrium condition, although in some cases a braided river and/or anastomozing river type is the stable form (Rosgen, 2006; Jaquette *et al.*, 2005).

With a surge in funding for stream restoration in the United States, prompted by the decline of Pacific coast salmon runs and water quality problems across the country, public and private groups have spent more than $14 billion on 37 000 stream restoration projects since 1990 (Bernhardt *et al.*, 2005). The Chesapeake Bay watershed alone had 747 projects to reconfigure channels and reduce bank erosion (Hassett *et al.*, 2005), most completed since 1995. In North Carolina there have been over 400 NCD projects (Miller *et al.*, 2006).

Some of the most successful stream restoration in the western United States has been the simplest and least expensive, including riparian planting and controlling livestock use of riparian areas, thus allowing bank vegetation to recover which alone can sometimes much improve channel conditions (Nagle and Clifton, 2003). Other projects using NCD are quite controversial (Malakoff, 2004), with costs from $165/m in small rangeland streams to $2300/m in urban areas. Although NCD is expensive, the more common approaches of armoring banks with rock rip-rap can cost $325/m or more in medium-sized streams while berming and channelization can cost $7400/m (Lovegreen and Petlock, 2006), with both resulting in major problems with largely negative impacts on aquatic habitat.

Dave Rosgen, a former regional hydrologist for the US Forest Service Rocky Mountain Region, devised the NCD approach and is its most influential proponent. Drawing on research by Luna Leopold and many others, Rosgen distilled decades of his own field observations into

a system for classification of natural rivers (Rosgen, 1994, 1996) that is now widely used to build channel shapes with the goal of establishing stable rivers ableto carry floods and sediment without significantly altering their channels. Stable reference-reach geometry and dimensionless ratios are used to recreate similar geometry for restored reaches in an effort to re-establish natural ecologic, hydrologic, and sediment transport processes. He has personally reconstructed nearly 160 km of small and medium-sized rivers across the United States. (Malakoff, 2004). Rosgen concedes that classification may be problematic on some kinds of rivers, particularly urban ones where massive disturbance makes it nearly impossible to make key measurements, but in his judgement he has had only one failure out of his 50 projects (Malakoff, 2004). He has yet to publish clear critiques of other projects although he reportedly openly discusses failures in his courses. More than 12 000 professionals have taken NCD training and despite continuing robust (if not furious) criticism of the method, there have been only a few peer-reviewed evaluations of older projects (Kondolf *et al.*, 2001; Kondolf, 2006; Smith and Prestegaard, 2005) and none examining more recent projects in different geomorphic settings.

Some scientists are adamant that NCD is often ill-advised due to uncertainty about sediment transport and channel stability in highly disturbed watersheds, especially in gravel bed streams (Wilcock and Parker, 2006). Especially vexing to them are people with relatively little field experience and a few weeks training in NCD calling themselves fluvial geomorphologists and designing projects.

Criticisms include:

- The Rosgen classifications are a useful tool for describing channels but using them for prescribing channel reconstruction is unwise. The aura of certainty around NCD is sometimes too appealing to people looking to do anything to 'fix' a stream when the problem is too often development near shifting channels.
- A weakness in the design of these projects is that the sediment load is assumed to be unchanging or that the stablilized channel is resilient to change (Niezgoda and Johnson, 2005).
- Instead of using channel form assessments as Rosgen does, critics stress the need for process-based geomorphic evaluations of likely future conditions in assessing the viability of restoration approaches (Kondolf *et al.*, 2001; Simon *et al.*, 2005). Assessments must begin with an understanding of the dominant processes that are operating in the channel, on the floodplain and throughout the watershed with a diagnostic approach explaining causes of channel degradation, not just describing the symptoms (Montgomery and Macdonald, 2002).
- Catastrophic failure of restoration projects can be usually attributed to poor or missing estimates of water or sediment supply and adequate forecast of sediment supply can only be done in a watershed context (Wilcock and Parker, 2006).
- Historical records can reveal that some channels tend to be naturally braided due to flow and sediment supply. Attempting to construct meandering, stable forms ignores this. The 'scruffy' environments of unstable shifting channels can be some of the most biologically productive and locking a channel in place may meet social goals but not ecological ones (Kondolf, 2006).

These are important criticisms, so I asked Gordon Grant, a fluvial geomorphologist with the US Forest Service (USFS) Pacific NW Research Station, for his views on Rosgen and NCD:

Dave had done a credible and conscientious job of cross-walking fundamental concepts of geomorphology and sediment transport to a much wider audience of river practitioners and managers. We have not yet come up with rigorous standards of what 'success' looks like in the restoration field, i.e. over what timescales, over what space scales, and cost to benefit ratios., so it is hard to know how to judge the outcomes of NCD or any other schemes. But I do think that Dave has had a major hand in helping people understand more about tuning river interventions to specific landscapes. I do believe that classification is not destiny—prior history, including geological history, and trajectory have a lot to do with where a system goes. But I also do not see many academics making the same effort to communicate that Dave does although Peter Wilcock of Johns Hopkins and other colleagues with the stream restoration group at the National Center for Earth Surface Dynamics offer alternative perspectives (Grant 2007, Personal Communication. US Forest Service, Pacific Northwest Research Station, Corvallis, OR.).

With few evaluations published in scientific journals, most information on the varied performance of NCD projects over the last 10 years is anecdotal, grey literature, or conference presentations too often lacking rigor in evaluating outcomes and likely future conditions. Although largely anecdotal, they are all we have to work with until more intensive monitoring studies are published, a process which may take years.

Over the last 30 years, I have seen several hundred stream and fisheries restoration projects across the United States. Most of these were livestock exclusion or gully control projects (Nagle, 1993) but my examinations included 36 NCD project sites in five states, averaging 3 years old and including three which had washed out completely. Some examinations were one-time visits while other sites were visited repeatedly over 5 years. My judgment is that 64% of the NCD projects performed adequately or even well for maintaining channel stability and sometimes in restoring floodplains, although often not as planned. Also, it

Hydrol. Process. **21**, 2539–2545 (2007)
DOI: 10.1002/hyp

is not clear how well they will function over longer periods even after surviving floods with 5–10 year recurrence intervals.

Some colleagues who are the strongest opponents of NCD advocate the least complicated passive approach of halting damaging agriculture, grazing or logging to allow recovery and re-vegetation of riparian areas rather than aggressive repair of channels (Beschta *et al.*, 1991, 1994). Although results of such passive restoration may be excellent, especially in streams protected from heavy grazing pressure, other channels have been so degraded that recovery can take decades or longer, especially where accelerated erosion of high banks is severe. Recovery of too many gullied rangeland channels has been marginal even after livestock were excluded for years and incised channels may continue to migrate upstream to destroy intact riparian areas without aggressive intervention. With many streams deeply channelized in agricultural areas or severely degraded in rangelands, re-establishment of floodplain dynamics and associated vegetation complexes is sometimes difficult without structures for bank protection or the use of NCD in re-configuring channels.

Reconstructions of channelized streams seem most effective when they are moved back into their original alignments, although this is rarely possible. New channels dug to replace entrenched or channelized streams often do not work as well as planned due to problems with bankfull flow estimates, meaning they can be too deep to spread out across their floodplains or too shallow, resulting in meander cutoffs.

In two projects for fisheries restoration in deeply entrenched rangeland streams, entirely new meandering channels dug to re-establish wet riparian meadows through enhanced groundwater storage have not worked well since those valley bottoms had much less near surface water holding capacity than assumed. These constructed channels have been stable over 5 years but habitat value appears minimal.

Catskill Natural Channel Design Projects

Some poorly conceived projects have pacified at enormous public expense a few vocal landowners complaining about their eroding banks. But far more pressing concerns about sediment from widespread bank erosion in some Catskill water supply tributaries (Nagle *et al.*, 2007) could force New York City (NYC) to spend $8 billion on a filtration plant. As an alternative watershed management approach, the NCD method has been used extensively and relatively successfully in these tributaries since 1999, with 13 large projects completed in conjunction with watershed wide programs to reduce agricultural runoff, conduct streamside planting, and protect 28 000 ha from development. Serious pressure from the US Environmental Protection Agency (EPA) to reduce sediment compelled an experienced staff to develop better designs with extensive maintenance required to correct emerging problems. Construction costs have climbed recently to $964/m since much more rock is used in channel structures and 30% of total costs are needed for dewatering channels.

Practitioners such as NYC do not have much choice about aggressive efforts to reduce bank and channel erosion since these processes are a serious problem in the Schoharie Reservoir, accounting for about 50% of the sediment delivered from its major tributaries (Nagle *et al.*, 2007). Faced with the need to implement immediate solutions to sediment problems, they moved forward with NCD projects. Much of this channel erosion is from impacts to streams from land clearing and intensive agriculture more than 150 years ago, although there is now little agriculture in most of the watersheds and more than 75% is now forested. Across much of the United States there are many channels recovering from such impacts, and sediment loads from bank erosion can still be high even with widespread adoption of soil conservation measures on the uplands (Trimble, 1983; Nagle and Ritchie, 2004).

In the Catskills, erosion of glacial deposits and other stream bank material likely increased greatly after settlement, with high levels of bank erosion persisting in response to changes in stream channel morphology. Historically, dense riparian vegetation probably protected many stream banks and spread flood flows, stabilizing alluvial sediment. Post-settlement impacts on stream channels included the elimination of beavers, increased peak flows from forest clearing and agriculture, trampling by livestock, and impacts on banks from agricultural development and logging.

Although we do not have specific data for the Catskills, based on the examination of the bankfull dimensions of abandoned stream channels in similar glaciated terrain in the upper Midwest, Fitzpatrick *et al.* (1999) estimated that volumes of bankfull flows in North Fish Creek, Wisconsin increased three-fold after agricultural clearing in the late 19th century. Knox (1977) estimated a similar three- to five-fold increase in bankfull flows in other Wisconsin streams, causing some headwater channels to widen greatly. Transportation and deposition of bedload sediment accompanied by bank erosion was a principal cause of channel widening (Knox, 1977), which also appears to be the case in some Catskill tributaries.

Some critics of NCD do not seem to grasp the need to deal immediately with pressing problems in severely degraded streams. At a total cost of less than $25 million for all the Catskill projects to date, if a filtration plant can be avoided it seems well worth the effort. On all Catskill NCD projects, channel adjustment is monitored to inform maintenance and an extensive study to improve bankfull flow estimates for streams across the Catskill region has been completed (Miller and Davis, 2003), which is important for the design of NCD projects. With long-term funding assured, the Catskills projects also have one of the most comprehensive channel and long-term biological monitoring programs in the country, using before-after-controlled-impact (BACI) to examine fisheries response in NCD projects in three streams over time by comparing them to untreated control sites and intact reference reaches, tracking channel adjustments, habitat and fisheries population changes. Significant increases in species richness and biomass equitability were found in NCD treated reaches (Baldigo *et al.*, 2007) in spite of the fact that dense riparian vegetation has yet to establish in many areas. The Catskills projects also have some of the best riparian planting I have ever seen in this country, and ecological conditions will continue to improve as project sites revegetate.

Mark Vian, one of the NYC Department of Environmental Protection managers in the Catskills, states:

'We would like to see what specific projects would be designed by those scientists advocating using the geomorphological process approach to assessing watersheds. The appeal of the form approach to channel design, as advocated by Rosgen, is that it assumes stable morphology drawn from reference reaches with the same hydrophysiographic conditions will integrate all of the dynamics and variables, the process approach tries to quantify although some cannt be quantified yet very satisfactorily, such as form roughness or the role of vegetation in bank strength. More importantly, there is a difference between evaluating a NCD project, and evaluating NCD. To evaluate a project, you only have to compare objectives and performance. To evaluate NCD, you first have to determine that the design process was followed rigorously, that the data were good, and the project was built to specifications'.

In a study of one of the earliest projects a year after completion, channel stability was much improved with greatly reduced bank erosion compared to untreated areas although a storm hit, a week after project completion. (Chen *et al.*, 2005). A more intensive evaluation of three projects after a major flood in 2005 described problems that emerged over a longer period (Buck Engineering, 2006). On two projects, water cut behind some flow deflection bank vanes, nonetheless overall project designs appeared effective and average bank erosion on these two reaches was reduced considerably. Despite their widespread use, such bank vanes are not central to NCD in the Catskills, but are a temporary risk reduction measure meant to maintain stable morphology until bank vegetation re-establishes. One advantage of vanes is to avoid rip-rapping long lengths of the stream, leaving more of the bank vegetated.

The third and largest project site (1570 m) exhibited problems perhaps more typically found in steeper valleys with higher rates of bedload movement. Streams with higher sediment loads have been the subject of the most intense criticism of NCD, although sediment loads in three failed projects in the California Coast Range were extreme compared to the Catskills. During the 2005 flood, the channel cut across three of 19 meanders, necessitating extensive repair work, and it is unclear how the project as designed will perform in the future. The upper project reach with its steep riffles and pools characteristic of a step/cascade-pool sequence functioned well but the lower reaches constructed with a meandering riffle-pool sequence to dissipate energy showed continued adjustment in channel dimension. A problem may have been a design that was not well suited to the site by trying to squeeze the project into too narrow a corridor to avoid encroaching development on the valley bottom.

The design called for a meander width ratio of 3·6, just above Rosgen's recommended minimum value of 3·5 for meandering streams. The three channel avulsions across the meanders occurred just downstream of reaches with meander width ratios less than 3·5, at the breakpoints where the channel transitioned from a step pool to a meandering plane form. 'With dissipation of energy too limited horizontally, the steam may have been dissipating energy vertically, seeking stability through a step pool configuration' (Buck Engineering, 2006). However, the people who worked on the project contend that the critical weakness was not the meandering channel design, but the lack of vegetation protecting the meander bends from flood scour (Greene County Soil and Water Conservation District, 2006).

The role of bedload movement in channel avulsions was unclear. Deposition of bedload just downstream of the meander avulsions might have contributed to the channel shifting. Problems with bedload deposition were also found on channel reconfiguration sites in Connecticut (Thompson, 2003) and Maryland (Smith, 1997). Although the estimation of rates and distances of bedload movement is notoriously difficult, my guess is that much of this bedload material probably came from within the project reach. It seems likely that as shrubs and trees cover the banks and floodplains, future scour and erosion of coarse material will be much reduced.

Prior to the project, this was one of the largest single sediment producing sites in the Catskills, with bank erosion along 55% of the stream reach including fine glacial deposits 17 m high and numerous exposures of lacustrine clay deposits in the channel bottom. It was estimated that there was about 1 m^3 eroded annually from every meter of bank. (Greene County Soil and Water Conservation District, 2006) Despite important lessons from design limitations, bank erosion has been reduced considerably and the channel is much more stable, even after the damage in the large flood. Other than NCD, I cannot see any other viable approach which would have worked on this site to accomplish sediment reduction.

DOI: 10.1002/hyp

Project Experiences in Other Locations

Although their construction is much simpler than NCD projects, research on the durability of 4100 simple fisheries habitat structures, including large logs, weirs, boulders or gabions, in 109 Northwest streams with varying hydrologic regimes and disturbance histories provide insights about the potential suitability of NCD projects in different environments. Watershed driven aspects are a more important influence on structure success than the construction or materials. Structures were less durable where sediment transport and peak runoff were extreme, such as in the rain-on-snow zone and in valley segments prone to natural instability aggravated by logging of riparian vegetation (Frissel and Nawa, 1992). Structures often function better in watersheds less disturbed by logging related landslides and in smaller or lower energy streams such as those dominated by snow melt runoff (Roper *et al.*, 1998).

Specific examples of NCD project evaluations include the following:

- A recent NCD project completed in 2003 at a cost of $154/m to reduce bank erosion with along 770 m of channel in a 2660 ha Pennsylvania agricultural watershed has survived a hurricane and four floods completely intact. In conjunction with channel livestock exclusion on 1500 m, the project helped greatly reduce total suspended sediment loads downstream. Bedload movement in this stream was minimal.
- Projects most often appear to fail where sediment transport and peak runoff are more extreme, such as in the Mediterranean climate of the California Coast Range with its extremely erosive Franciscan geology (Hansen, 2003; Kondolf *et al.*, 2001; Zuckerman, 1997). This was the location of a failed project Rosgen designed in a heavily logged watershed (Kondolf, 2006).
- Early projects in a Pennsylvania stream with extremely high levels of bedload movement were rebuilt unsuccessfully several times at a cost of $2 million. Problems were poor bankfull flow estimates and serious design and construction problems when the project was pushed through quickly as a demonstration project.
- The key section of a 900 m project completed less than 2 years ago in central NY at a cost of over $1 million to halt bank erosion is already severely compromised by accumulation of bedload above a bridge constricting the channel at its lower end, with much of this material likely eroded from the project site itself during a 10-year flood. Inability to extend the bank protection vanes far enough back into the floodplain was a problem, with some vanes completely covered with gravel and the channel now cutting behind them in two of the most critical locations. Low meander belt width and channel sinuosity may also be contributing to channel instability.
- Conflicting reports come from North Carolina which has over 400 completed NCD projects. In surveys of 40 projects completed since 1998, 70% of structures in 30% of the projects no longer functioned after 'significant damage', and sometimes were destroyed in the first significant flood (Miller *et al.*, 2006). However, monitoring of the 500 2 year-old channel structures in 13 other projects across three geographic regions reported that 74% showed high stability (Mondry *et al.*, 2006)

Some Simple Lessons

- Some projects proposed by landowners with eroding banks should be viewed with skepticism since reputed water quality benefits are sometimes exaggerated. There is often strong local support for such efforts since costs are usually covered by an outside agency, not the local governments.
- Projects function better in streams that have stabilized from past incisions or channelization and where future increases in peak flows are not anticipated from urbanization. Poor construction and design have been problems, which may be relatively easy to remedy with more experience and project evaluations.
- Lack of funding for major maintenance can be a serious problem.
- Bankfull flow estimates may need much improvement in places since NCD hinges on this critical parameter.
- Although it is evident that some channels will usually have unstable, shifting channels (Jaquette *et al.*, 2005), it is not always clear where. Some rivers can shift back and forth between braided and meandering channel types with changes in floods and sediment pulses with riparian vegetation sometimes playing a key role in maintaining meandering channels (Jaquette *et al.*, 2005). We do have clear documentation in some areas that channels that were previously meandering have been recently degraded due to destruction of riparian vegetation and present braided forms resulted primarily from human impacts (Rosgen, 1996). One of the earliest projects by Rosgen on the East Fork of the Blanco River was one such location where recent elimination of the streamside willows resulted in extreme degradation of the channel.
- Assessments of the role of bedload movement appear to be a key weakness in project design. It is questionable whether channels passing relatively large amounts of bedload can be held in place over years with grade control structures. The ability of some projects to survive major floods may have less to do with their capacity to withstand flows than with the smaller amount of bedload moving through them. I have been told by a NCD designer that grade control structures hold the thalweg in place even during

Hydrol. Process. **21**, 2539–2545 (2007)
DOI: 10.1002/hyp

floods and can be designed to pass bedload, although this seems questionable in places.

- Long-term viability of projects will often depend on riparian vegetation protecting banks and floodplains from scouring during high flows. Re-vegetation of bare gravel floodplains is quite difficult and too often existing vegetation is destroyed during construction. Projects with bare ground are sometimes prone to rapid invasion of exotics such as Japanese knotweed in the Catskills, which provides little protection for banks and impedes the recovery of the native woody riparian species necessary for long-term ecological recovery.

The varied outcomes described in this commentary indicate that NCD can work at least over the medium term, although exactly why and where needs much further explanation. Adaptive management requires a constant analysis and re-evaluation of project experiences. Although there are scant institutional rewards for professionals who did the work to explicitly discuss project mistakes, we need detailed reports back from many more projects so that rigorous evaluations can be made on a range of sites.

Acknowledgements

Funding for this work was provided by the Agricultural Ecology Program at Cornell University. I appreciate the ready assistance extended to me by the staff of the New York City Department of Environmental Protection and Rene VanSchaack from the Greene County Soil and Water Conservation District.

References

Baldigo BP, Warren DR, Gallagher-Ernst AS, Miller SJ, Davis WD, Keller W, Baudanza TP, DeKoskie D, Buchanan JB. 2007. Restoring geomorphic stability and biodiversity in streams of the Catskill Mountains, New York, USA. *Proceedings of the Fourth World Fisheries Congress: Reconciling Fisheries With Conservation*. American Fisheries Society: Washington.

Bernhardt PMA, Alexander AJD, Barnas GK, Brooks S, Carr J, Clayton S, Dahm C, Follstad-Shah J, Galat D, Gloss S, Goodwin P, Hart D, Hassett B, Jenkinson R, Katz S, Kondolf GM, Lake PS, Lave R, Meyer JL, O'Donnell TK, Pagano L, Powell B, Sudduth E. 2005. Synthesizing U.S. river restoration efforts. *Science* 308: 636–637.

Beschta RL, Platts WS, Kauffman JB. 1991. *Field Review of Fish Habitat Improvement Projects in the Grande Ronde and John Day River Basins of Eastern Oregon*. U.S. Dept of Energy, Bonneville Power Administration, Division of Fish and Wildlife: Portland, Oregon, DOE/BP-21493-1.

Beschta RL, Platts WS, Kauffman JB. 1994. Artificial stream restoration-money well spent or expensive failure? In *Universities Council on Water Resources Annual Conference*, Big Sky.

Buck Engineering. 2006. *Batavia kill watershed stream design and monitoring evaluation: Green county, New York*. Prepared for GCSWCD and NYCDEP, Clary, North Carolina.

Chen Y, Bhatia SK, Buchanan J, DeKoskie D. 2005. Evaluation of the effectiveness of stream restoration in batavia kill watershed. In *Managing Watersheds for Human and Natural Impacts: Engineering, Ecological, and Economic Challenges. Proceedings of the 2005 Watershed Management Conference*, July 19–22, 2005, Sponsored by Environmental and Water Resources Institute of the American Society of Civil Engineers: Williamsburg.

Fitzpatrick FA, Knox JC, Whitman HE. 1999. *Effects of historical land-cover changes on flooding and sedimentation*, North Fish Creek, Wisconsin, USGS Water Investigations Report 99–4083.

Frissel CA, Nawa RK. 1992. Incidence and causes of physical failure of artificial fish habitat structures in streams of western Oregon and Washington. *North American Journal of Fisheries Management* 12: 182–297.

Giller PS. 2005. River restoration: seeking ecological standards: Editor's introduction. *Journal of Applied Ecology* 42: 201–207.

Greene County Soil and Water Conservation District. 2006. *Implementation and monitoring report big hollow restoration project*. Cairo, New York.

Hansen A. 2003. Post-project appraisal of a channel reconstruction on Cuneo Creek, California. University of California Berkeley. Available online at: http://repositories.cdlib.org/wrca/restoration/ [accessed 2006].

Hassett B, Palmer M, Bernhardt E, Smith S, Carr J, Hart D. 2005. Restoring watersheds project by project: trends in Chesapeake Bay tributary restoration. *Frontiers in Ecology and the Environment* 3: 259–267.

Jaquette C, Wohl E, Cooper D. 2005. Establishing a context for river rehabilitation, North Fork Gunnison River, Colorado. *Environmental Management* 35: 593–606.

Knox JC. 1977. Human impacts on Wisconsin stream channels. *Annals of the Association of American Geographers* 67: 323–342.

Kondolf GM. 2006. River restoration and meanders. Ecology and Society 11. http://www.ecologyandsociety.org/vol11/iss2/art42/.

Kondolf GM, Smeltzer MW, Railsbeck SF. 2001. Design and performance of a channel reconstruction project in a coastal California gravel bed stream. *Environmental Management* 28: 761–766.

Lovegreen M, Petlock J. 2006. Bentley Creek Case Study: Presentation to Cornell Department of Natural Resources Stream Restoration Seminar, September 2006.

Malakoff D. 2004. The river doctor. *Science* 305: 937–939.

Miller SJ, Davis D. 2003. *Identifying and Optimizing Regional Relationships for Bankfull Discharge and Hydraulic Geometry at USGS Stream Gages in the Catskill Mountains*. City Department of Environmental Protection: New York.

Miller J, Kochel RC, Lord M, Martin TT. 2006. Limitations of the use of in-steam structures in stream restoration projects in North Carolina. *Geological Society of America Abstracts with Programs* 39: 43.

Mondry Z, Melia G, Haupt M. 2006. *Stability of engineered stream structures in north carolina stream restoration projects*. North Carolina Ecosystem Enhancement Program, Raleigh. http://www.bae.ncsu.edu/programs/extension/wqg/sri/2006conference/presentations.html [accessed 2007].

Montgomery DR, Macdonald LH. 2002. Diagnostic approach to stream channel assessment and monitoring. *Journal of American Water Resources Association* 38: 1–16.

Nagle GN 1993. *The rehabilitation of degraded riparian areas in the Northern Great Basin*. MS Thesis. Cornell University, Department of Natural Resources, Ithaca.

Nagle GN, Clifton C. 2003. Channel changes over 13 years on grazed and ungrazed stream reaches in eastern Oregon. *Physical Geography* 24: 77–95.

Nagle GN, Ritchie J. 2004. Wheat field erosion rates and channel bottom sediment sources in an intensively cropped northeastern Oregon drainage basin. *Land Degradation and Development* 14: 1–12.

Nagle GN, Fahey TJ, Ritchie J, Woodbury PB. 2007. Variations in sediment sources and yields in the finger lakes and catskills regions of New York. 2007. *Hydrological Processes* 21: 828–838.

Niezgoda SL, Johnson PA. 2005. Improving the urban stream restoration effort: identifying critical form and processes relationships. *Environmental Management* 35: 579–592.

DOI: 10.1002/hyp

Palmer MA, Bernhardt ES. 2005. Hydroecology and river restoration: ripe for research and synthesis. *Water Resources Research* 42. DOI: 10.1029/2005WR004354.

Palmer MA, Bernhardt ES, Allan JD, Lake PS, Alexander G, Brooks S, Carr J, Clayton S, Dahm CN, Follstad Shah JD, Galat L, Loss SG, Goodwin P, Hart DD, Hassett B, Jenkinson R, Kondolf GM, Lave R, Meyer JL, O'Donnell TK, Pagano E, Sudduth E. 2005. Standards for ecologically successful river restoration. *Journal of Applied Ecology* 42: 208–217.

Reid LM. 2001. The epidemiology of monitoring. *Journal of the American Water Resources Association* 37: 815–820.

Reid LM, Furniss MJ. 2002. *The Use of Regional Channel Based Indicators for Monitoring*. US Forest Service, Redwood Sciences Laboratory: Arcata.

Roper BB, Konnoff D, Heller D, Wieman K. 1998. Durability of pacific northwest instream structures following floods. *North American Journal of Fisheries Management* 18: 686–693.

Rosgen D. 1994. A classification of natural rivers. *Catena* 22: 169–199.

Rosgen D. 1996. *Applied River Morphology*. Wildland Hydrology, Lakewood: Colorado.

Rosgen DL. 2006. River restoration using a geomorphic approach for natural channel design. In *Proceedings of the Eighth Federal Interagency Sedimentation Conference*, April 2–6, 2006, Reno.

Simon A, Doyle M, Kondolf GM, Shields FD, Rhoads BL, Grant GE, Fitzpatrick FA, Juracek KE, McPhillips M, MacBroom JG. 2005. How well do the Rosgen classification and associated "natural channel design" methods integrate and quantify fluvial processes and channel response? In *Proceedings of: Environmental and Water Resources Institute World Congress*. ASCE: Anchorage.

Smith S. 1997. *Changes in the hydraulic and morphological characteristics of a relocated stream channel*. MS thesis. Department of Geology, University of Maryland, College Park.

Smith SM, Prestegaard KL. 2005. Hydraulic performance of a morphology-based stream channel design. *Water Resources Research* 41. DOI: 10·1029/2004WR003926.3926.

Thompson DM. 2003. A geomorphic explanation for meander cutoff following channel relocation of a coarse-bedded river. *Environmental Management* 31: 385–400.

Trimble SW. 1983. A sediment budget for Coon Creek Basin in the Driftless Area, Wisconsin, 1853–1977. *American Journal of Science* 283: 545–574.

Wilcock P, Parker G. 2006. Research, coordination and open-source models to improve stream restoration practice. In *Proceedings of the Eighth Federal Interagency Sedimentation Conference April 2–6*, Reno.

Zuckerman S. 1997. Thinking like a watershed. In *Watershed Restoration: Principles and Practices*, Williams JE, Wood CA, Dombeck MP (eds). American Fisheries Society: Bethesda, Maryland; 216–234.

Hydrol. Process. **21**, 2539–2545 (2007)
DOI: 10.1002/hyp