RESEARCH, COORDINATION, AND OPEN-SOURCE MODELS TO IMPROVE STREAM RESTORATION PRACTICE

Peter Wilcock, Department of Geography and Environmental Engineering, Johns Hopkins University, Baltimore MD 21218, wilcock@jhu.edu; Gary Parker, Department of Civil and Environmental Engineering and Department of Geology University of Illinois, Urbana IL 61801, parkerg@uiuc.edu; through the National Center for Earth-surface Dynamics

Abstract: Most agree that there is room for improvement in the science and engineering basis for stream restoration. There is also a bewildering array of methods and models, the application of which requires a diverse range of expertise and effort with little clear indication of need, reliability, efficacy, and effort. There is a need for not only research and improved methods supporting stream restoration practice, but also for improved organization, distribution, and coordination of existing and emerging methods and training. The National Center for Earth-surface Dynamics (NCED), a Science and Technology Center funded by the National Science Foundation, has formed a Stream Restoration Group to organize and focus research relevant to stream restoration, to collaborate with agencies and practitioners in identifying knowledge gaps and developing improved tools for restoration practice, and to disseminate this knowledge to practitioners. Our goal is to move restoration practice to an analytical, process-based approach that will ultimately lead to better prediction and hence better design. Predictive understanding is needed in a number of key areas, including sediment routing at the reach to network scale, channel and floodplain response to watershed changes, and linkages between physical channel conditions and nutrient cycling, stream metabolism, primary production, and population dynamics. The broadest challenge facing restoration is placing projects in a watershed context. A central part of the Restoration Group's efforts involves support and interaction with a partners group consisting of agency and industry professionals. This group helps to define research needs, to identify and contribute useful models for restoration design, to evaluate restoration practice, and to coordinate training in restoration practice.

This paper outlines some efforts of the NCED Stream Restoration Group to support improved stream restoration practice, including our research priorities and examples of knowledge transfer. Research efforts focus on laboratory and field experiments on sediment transport and stream channel change. With its partners, NCED is conducting short courses and developing training materials and a web-based "toolbox" that provides numerical models and supporting information to improve evaluation of stream channels, design of restoration projects, and linkages between geomorphic design and ecological outcomes. The toolbox is intended to address the need for useful models of tested reliability and documented limitations that more immediately link research to practice. Toolbox programs are open source and address a wide range of practical problems, such as hydraulic geometry, transport and sorting in coarse-bedded streams, bed evolution below dams, and the delineation between threshold and alluvial channels. Although it is widely acknowledged that most predictions and design choices associated with stream restoration have large uncertainty, estimates of uncertainty are rarely incorporated into restoration design. We propose approaches by which uncertainty can be incorporated into stream restoration design and decision-making. Example toolbox applications are discussed in this paper.

RESTORATION PRACTICE

To be effective, research, models, and training must be developed in the context of current practice and understanding. Current stream restoration practice is based on analogy – a template is sought in a nearby channel, stream type, or hydraulic geometry relation that the designer judges to be suitable. The template channel is then scaled to the design site, typically using estimates of bankfull discharge (FISRWG, 1998). When scaling is accomplished via an estimated bankfull discharge, an implicit assumption of equilibrium is introduced: it is assumed that the disturbed channel is adjusting toward some 'stable' state and that evidence of this future condition can be found. But if a disturbed stream is adjusting to changes in essential controlling factors, particularly water and sediment supply, its future steady-state condition may not yet be evident. An appropriate template is unlikely to exist and would, in any case, be difficult to reliably demonstrate. The experience of designing stream channels when no suitable reference reach or identifiable bankfull discharge are available appears to be common (e.g. Sortman, 2004). Beyond its deficiencies in supporting channel design, an analogy approach does not efficiently support learning and cannot lead to true prediction because it provides no basis for linking cause and effect in a logically complete and testable framework.

An analogy approach may have some practical use in particular cases for which the channel disturbance is not driven by essential changes in forcing, but by changes internal to the channel and reversible. The primary examples are exclusion of livestock from the riparian corridor and restoring a natural geometry to artificially straightened stream channels. If no substantial changes in water and sediment supply are anticipated, a basis exists for transplanting the geometry of a similar stable channel.

What is the alternative to an analogy approach to stream restoration design? It must begin with specification of the materials and configuration of the stream valley and the water and sediment supply, including the variability and uncertainty in these quantities. In the essential next step, the specified conditions must be connected via predictive relations sufficient to link cause and effect. The predictive relations must satisfy general physical principles of mass, momentum, and energy conservation and will include empirical relations of demonstrated generality.

As all seem to acknowledge, streams adjust to the water and sediment supplied to them. To this must be added essential feedbacks between the physical channel and the chemistry and biology of its waters, flora, and fauna which can influence details of transport processes and broad expression of channel geometry. A predictive, science-based approach to stream restoration must be built on these essential inputs. An ability to predict water and sediment supply is needed, as is an ability to predict the patterns of erosion and deposition within a design reach. Although existing methods invoke sediment transport in their designs, even calculate transport at some stages of the design process, only recently has a logically complete structure for predicting inputs and outcomes in stream channels emerged (Shields et al., 2003).

There is good reason that an analogy approach dominates stream restoration practice: in most practical cases, current approaches do not permit predictions of sediment transport of sufficient accuracy to support channel design. This is particularly the case in gravel-bed streams, for which neither empirical nor theoretical approaches can provide suitable accuracy on a routine basis (Wilcock, 2001). A predictive approach requires that the future supply of sediment can be adequately forecast. With current technology, this is possible only for threshold channels. In this case, a precise estimate of sediment supply is not needed, it is only necessary to determine that the supply will be smaller than a critical threshold amount. One NCED Stream Restoration tool provides a basis for estimating this threshold.

The primary challenges facing development of a predictive stream restoration science are:

1. Forecasting water and sediment supply. Stream channel change is driven by changes in water and sediment supply. Catastrophic failure of restoration projects can usually be attributed to a poor (or missing) estimate of the water and sediment supply. A reliable estimate of sediment supply is the essential threshold between analog and predictive design.

2. Variability and uncertainty. There is enormous uncertainty in virtually every aspect of channel design: historical trends, future forcing, and calculated water and sediment fluxes. Estimates of uncertainty in water and sediment supply are rarely made and incorporation of uncertainty in channel design is virtually absent. Ignoring uncertainty does not make its consequences disappear.

3. Watershed context. An adequate forecast of future water and sediment supply can only be done in a watershed context.

NCED RESTORATION ACTIVITIES

Research: NCED research addresses a wide range of erosion and sediment transport topics supporting improved restoration science and practice.

Routing and supply of sediment: Channels develop in response to their water and sediment supply. An inability to predict sediment supply (mean and variability) is the primary technical barrier to predicting future channel configuration and composition. Development of predictive sediment supply relations will require a means of determining sediment storage throughout the stream network and a reliable treatment of sediment storage in reach-scale transport models. We are currently developing models for routing sand and fine gravel through coarse immobile beds (Dietrich, et al., 2005; Grams, et al., 2005). Our goals are to develop reach-averaged transport models incorporating storage dynamics and to test these models at the watershed scale in different transport environments.

Transport, sorting, and morphodynamics of mixed-size sediment: The transport of streambed material drives channel change and the composition and configuration of the bed, which determines the essential, organism-scale template for the stream ecosystem. We now have in place surface-based transport models (Wilcock and Crowe, 2003) and a general framework for bed scour and aggradation (Parker, et al., 2000). Current NCED work (Blom and Parker, 2004; Dietrich, et al., 2005;Wilcock and DeTemple, 2004; Wong and Parker, 2005) focuses on rates of lateral and vertical sorting to provide the detail needed to complete a predictive mixed-size morphodynamic model.. With this model, our focus will shift to verification and application of the model in different settings and scaling up to the reach and channel network and integration of the model into predictive relations for streambed ecology.

Size, shape, and planform of resilient, dynamically stable channels: The size, shape, composition and planform of the stream channel define the physical framework of a stream restoration project, but we still cannot predict channel geometry reliably. Current NCED activity focuses on channel geometry and channel change as it varies through a watershed, on morphodynamic models, and on the interaction between vegetation and channel dynamics. As improved predictions of sediment supply and its variability become available, we will develop methods that effectively incorporate variability and risk in channel design. Our goal is to develop predictive relations between valley slope, water discharge, sediment supply rate and caliber, riparian vegetation, and channel geometry.

Rates, mechanisms, and location of floodplain deposition: Floodplain "reconnection" is a common restoration objective in order to provide habitat, support riparian vegetation, sequester nutrients and contaminants, and protect delta shorelines. Current NCED work focuses on channel-floodplain exchange of sediment through overbank flow and via tie channels.

From grains to the reach and network scale – placing restoration projects in their watershed context: The most obvious and persistent cause of physical failure is ignoring, or predicting erroneously, the supply of water and sediment from the watershed. Current best practice includes a narrative watershed history identifying the timing and location of major watershed disturbances. A predictive restoration science will require transforming this history to a form suitable for providing quantitative predictions, including uncertainty.

NCED Stream Restoration Toolbox: A primary vehicle for our knowledge transfer is the online NCED Stream Restoration toolbox, a set of tools supporting channel assessment and design. Our goal is to make the latest research results readily available in a useable form. Both tools and documentation are open source. Not only is free use encouraged, but the code can be modified as needed by the user. Tools are developed to address particular topics and tasks and it is up to the user to determine the appropriate tools for the job. The principal overhead of this approach is that use of the tools requires an ability to understand their context, purpose, and function. The alternative would be complex 'black box' models that perform many interconnected calculations without requiring complete understanding of the supporting principles. We argue that the first approach is needed for informed application, but also to support development of a predictive restoration science. This latter approach works against informed application of the underlying principles and inhibits dissemination – and evaluation – and improvement – of methods. Complex black-box models with insufficient exposition of the underlying principles also limit discussion of assumptions, methods, and results and thereby reduce the opportunity for learning and improvement.

A range of tools have been developed and posted on the NCED web site (www.nced.umn.edu; Table 1) and the list will be updated during the FISC conference. We are eager to learn of information needs that could be addressed with the development of new tools. Contact either author regarding suggested tools and the availability of other useful, open source models.

Table 1 Partial List of NCED Stream Restoration Tools

Tool Name	Description
Bankfull Estimator	A 2-in-1 tool using dimensionless criteria to estimate channel geometry from a specified bankfull discharge and to estimate bankfull discharge from specified channel geometry. Currently implemented for gravel-bed streams; a general version for both sand-bed and gravel-bed streams available soon.
Spawning Gravel Refresher	Calculates changes in gravel bed composition, including fines content in the subsurface, in response to specified discharge and sediment supply, to support design of controlled dam releases and gravel augmentation to restore the integrity of spawning gravels.
The Dam Remover	This tool predicts the morphodynamic development of a dam deposit after the sudden or gradual removal of a dam. It implements a 1-D model flow and transport model that predicts the evolution of channel width and stream gradient as a channel incises into the reservoir deposit.
Monte Carlo Transport	Provides estimate of uncertainty in critical discharge for incipient motion and calculated transport rates based on specified uncertainty in the input variables. Gives guidance for incorporating this uncertainty in restoration design.
Monte Carlo Channel	A 2-in-1 tool. One tool provides an estimate of channel aggradation/degradation in response to changes in discharge, sediment supply rate and grain size, including uncertainty in the calculated result, to support historical analysis of channel change. The other tool estimates combinations of channel slope and width, and their uncertainty, that produce equilibrium transport of a specified water and sediment supply.
Threshold Channel Calculator	Provides a quantitative estimate of the boundary between threshold and alluvial channels, supporting a determination of whether a detailed analysis of sediment transport is necessary.
iSURF	Applies a surface-based transport model to predict equilibrium bed surface grain size for specified sediment transport rate and grain size, to support estimates of stream bed grain size changes.
Willow post velocity analyzer	Predicts depth-averaged velocity distributions in straight trapezoidal channels with newly constructed willow post systems, to support planting design for channel stabilization.
Bank Stabilization Diagnostic	This tool presents a methodology for evaluating the reduction in sediment yield possible from bank stabilization, to support analysis of one of the more expensive elements of a stream restoration project.
Channel Planform Statistics Tool	A GIS tool that develops a centerline and computes width and radius of curvature from specified banks locations and local channel shift from specified centerlines.

Tool Format: The tools are presented as Visual Basic modules embedded in Microsoft Excel documents in order to promote the broadest possible accessibility. The programs are accompanied by a Microsoft Powerpoint documents that explain the background and application of the module.

An example tool is the Bankfull Estimator, a 2-in-1 tool that uses dimensionless criteria to estimate channel geometry from a specified bankfull discharge and to estimate bankfull discharge from specified channel geometry. The tool is currently implemented for gravel-bed streams and a general version for both sand-bed and gravel-bed streams is forthcoming. The Powerpoint document includes background information, guidelines for measuring the bankfull channel, caveats about appropriate application, explanation of the underlying analysis, the data and their sources (Figure 1). The Excel workbooks that calculate bankfull properties are embedded in the Powerpoint document, allowing the user to go directly to the desired calculations (Figure 2).

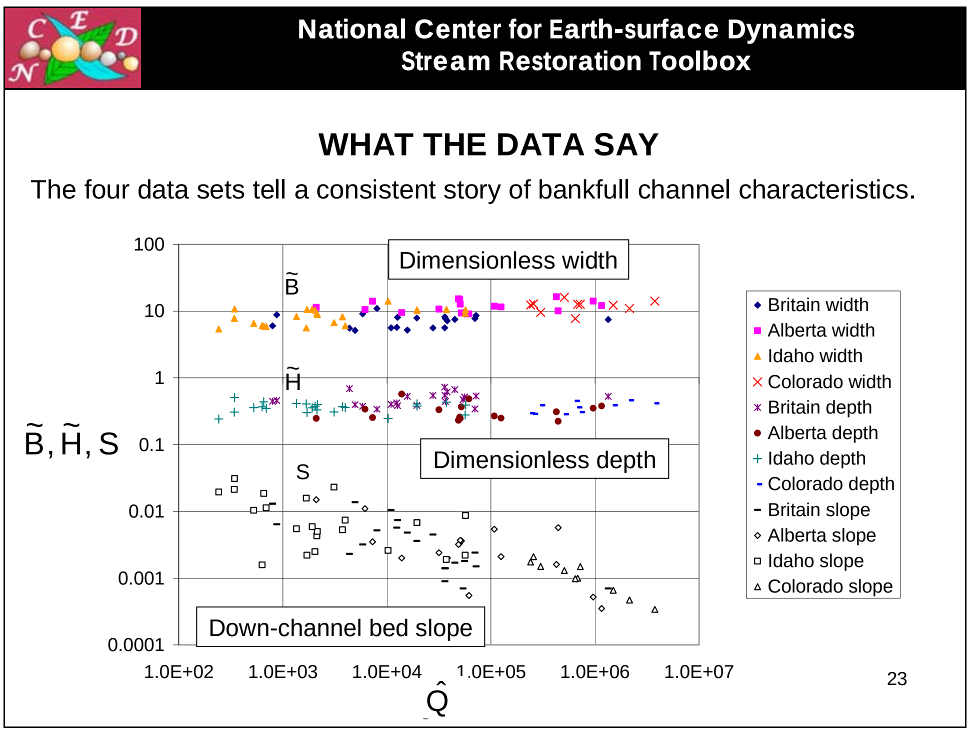

Figure 1 Example page from the Bankfull Estimator tool, showing the data used to develop the hydraulic geometry relations.

National Center for Earth-surface Dynamics
Stream Restoration Toolbox

TOOL IMPLEMENTATION: BANKFULL GEOMETRY PREDICTED FROM THE REGRESSION RELATIONS

Stop the slide show and double-click to activate the Excel spreadsheet.
The spreadsheet is then live: you can change input as you please.

Input		SI		English	
Bankfull discharge	Q_{bf}	200.0	m^3/s	7060.0	ft^3/s
Surface median size	D_{s50}	66.0	mm	66.0	mm
Calculated					
	D_{s50}	0.066	m	0.217	ft
Dimensionless discharge	Qhat	5.71E+04		5.70E+04	
Output					
Bankfull depth	H_{bf}	1.996	m	6.547	ft
Bankfull width	B_{bf}	51.1	m	167.6	ft
Estimated channel slope	S	0.0023		0.0023	

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Caution: use the relations subject to the caveats of Slides 5, 6, 7, 8 and 14!

Figure 2 Example page from the Bankfull Estimator tool, showing embedded Excel workbook.

CONCLUDING REMARKS

Consider a project involving realignment of a stream and construction of a new highway bridge. The transportation industry has developed standards that require (correctly, we think) that those building bridges have specific and thorough training not only in the principles of structural statics and dynamics and the specifics of bridge design, but in the supporting science, mathematical, and engineering disciplines. Uncertainties are accounted for using safety factors associated with methods that have been developed in an organized and open approach allowing for testing, learning, and improvement. Despite the uncertainty in materials, traffic, and future flows, the design is predictive in the sense that the final product is developed via a sequence of decisions and calculations based on clear, logically complete and general principles within a tested application. Compare this with the design of the stream that flows beneath the bridge. What are the principles that the design is based on? Have the controlling factors been defined and incorporated in a thoroughly evaluated and truly predictive model? Has the uncertainty associated with future water and sediment supply and undetected variability in bed and bank materials been accounted for? We place our trust in the reliability of the design methods every time we drive over a bridge. Should the design of the stream and its ecosystem beneath the bridge be any different?

REFERENCES

Blom, A., and G. Parker (2004), "Vertical sorting and the morphodynamics of bedform-dominated rivers: a modeling framework," Journal of Geophysical Research Earth Surface, 109.

Dietrich, W. E., et al. (2005), "Sediment patches, sediment supply and channel morphology," paper in River, Coastal, and Estuarine Morphodynamics: RCEM 2005, edited by G. Parker and M. Garcia, pp. 131-139, Taylor and Francis Group, London.

Federal Interagency Stream Restoration Working Group (FISRWG) (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.

Grams, P., P. Wilcock, and S.M. Wiele (2005), "Entrainment and nonuniform transport of fine sediment in coarse-bedded rivers," in River, Coastal, and Estuarine Morphodynamics: RCEM 2005, edited by G. Parker and M. Garcia, pp. 1074-1081, Taylor and Francis Group, London.

Parker, G., C. Paola, and S. LeClair (2000), "Probabilistic form of Exner equation of sediment continuity for mixtures with no active layer," Journal of Hydraulic Engineering, 126, 818-826.

Shields, F.D. Jr., R. R. Copeland, P. C. Klingeman, M. W. Doyle, and A. Simon (2003). "Design for Stream Restoration," J. Hydraulic Engineering, 129(8), 575-584.

Sortman, V.L. (2004). "Complications With Urban Stream Restorations, Mine Bank Run: A Case Study," in Clar, M., D. Carpenter, J. Gracie, and L. Slate (eds.), Protection and Restoration of Streams 2003, ASCE, pp. 431-436.

Wilcock, P.R., 1997. "Friction Between Science and Practice: The Case of River Restoration," Eos, Transactions, Am. Geophysical Union 78(41): 454

Wilcock, P.R., 2001. "Toward a practical method for estimating sediment transport rates in gravel-bed rivers," Earth Surface Processes and Landforms 26, 1395–1408.

Wilcock, P.R., 2004. "Sediment Transport in the Restoration of Gravel-bed Rivers," Proceedings, ASCE Environmental and Water Resources Institute Annual Congress, Salt Lake City.

Wilcock, P., and J. C. Crowe (2003), "A surface-based transport model for sand and gravel," Journal of Hydraulic Engineering, 129, 120-128.

Wilcock, P., and B. T. DeTemple (2005), "Persistence of armor layers in gravel-bed streams," Geophysical Research Letters.

Wong, M., and G. Parker (2005), "Flume experiments with tracer stones under bedload transport," in *River*, Coastal, and Estuarine Morphodynamics: RCEM 2005, edited by G. Parker and M. Garcia, pp. 131-139, Taylor and Francis Group, London.