JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Vol. 43, No. 5 AMERICAN WATER RESOURCES ASSOCIATION October 2007

CRITICAL EVALUATION OF HOW THE ROSGEN CLASSIFICATION AND ASSOCIATED “NATURAL CHANNEL DESIGN” METHODS FAIL TO INTEGRATE AND QUANTIFY FLUVIAL PROCESSES AND CHANNEL RESPONSE[1]

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ABSTRACT: Over the past 10 years the Rosgen classification system and its associated methods of “natural channel design” have become synonymous to some with the term “stream restoration” and the science of fluvial geomorphology. Since the mid 1990s, this classification approach has become widely adopted by governmental agencies, particularly those funding restoration projects. The purposes of this article are to present a critical review, highlight inconsistencies and identify technical problems of Rosgen’s “natural channel design” approach to stream restoration. This paper’s primary thesis is that alluvial streams are open systems that adjust to altered inputs of energy and materials, and that a form-based system largely ignores this critical component. Problems with the use of the classification are encountered with identifying bankfull dimensions, particularly in incising channels and with the mixing of bed and bank sediment into a single population. Its use for engineering design and restoration may be flawed by ignoring some processes governed by force and resistance, and the imbalance between sediment supply and transporting power in unstable systems. An example of how C5 channels composed of different bank sediments adjust differently and to different equilibrium morphologies in response to an identical disturbance is shown. This contradicts the fundamental underpinning of “natural channel design” and the “reference-reach approach.” The Rosgen classification is probably best applied as a communication tool to describe channel form but, in combination with “natural channel design” techniques, are not diagnostic of how to mitigate channel instability or predict equilibrium morphologies. For this, physically based, mechanistic approaches that rely on quantifying the driving and resisting forces that control active processes and ultimate channel morphology are better suited as the physics of erosion, transport, and deposition are the same regardless of the hydro-physiographic province or stream type because of the uniformity of physical laws.

(KEY TERMS: geomorphology; fluvial processes; rivers/streams; restoration; sediment; Rosgen classification.)

Simon, A., M. Doyle, M. Kondolf, F.D. Shields Jr., B. Rhoads, and M. McPhillips, 2007. Critical Evaluation of How the Rosgen Classification and Associated “Natural Channel Design” Methods Fail to Integrate and Quantify Fluvial Processes and Channel Response. *Journal of the American Water Resources Association* (JAWRA) 43(5):1-15. DOI: 10.1111/j.1752-1688.2007.00091.x

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[1] Paper No. J05210 of the *Journal of the American Water Resources Association* (JAWRA). Received December 13, 2005; accepted January 9, 2007. © 2007 American Water Resources Association. No claim to original U.S. government works. **Discussions are open until April 1, 2008**.

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INTRODUCTION

Over the past 10 years, the Rosgen classification system (Rosgen, 1994) and its associated methods of "natural channel design" (Rosgen, 1996) have become synonymous to some with the term "stream restoration" and the science of fluvial geomorphology. The term "natural channel design" has been adopted by Rosgen (1996) and others advocating and using the Rosgen system (Hey, 2006) will be used here as such. Since the mid 1990s, this classification approach has become widely, and perhaps dominantly adopted by governmental agencies, particularly those funding restoration projects (Malakoff, 2004). For example, in a request for proposals for the restoration of Trout Creek in Montana, the Natural Resources Conservation Service *required* "experience in the use and application of a stream classification system and its implementation" (MDFWP, 1998). Similarly, classification systems have been used in evaluation guides for riparian areas and U.S. Forest Service management plans. Most notably, many highly trained geomorphologists and hydraulic engineers are often held suspect, or even thought incorrect, if their approach does not include reference to or application of a classification system (Malakoff, 2004). This, combined with training provided by some involved in "natural channel design" empower individuals and groups that may have limited backgrounds in stream and watershed sciences to engineer modifications of streams whose scientific underpinning is based on 50-year-old technology never intended for engineering design.

The purposes of this article are to present a critical review, highlight inconsistencies, and identify technical problems of Rosgen (1996, 2001) "natural channel design" approach to stream restoration. The paper's primary thesis is that alluvial streams are open systems that adjust to altered inputs of energy and materials and that a form-based system largely ignores this critical component. This is particularly important when restoration of a stream reach is implemented within an unstable system that is undergoing adjustments that are temporally and spatially variable. Modifications imposed on an alluvial stream channel, be they called "stream restoration" or "channel improvement" (as in the 1960s and 1970s) represents a disturbance. The paper aims to accomplish the stated objectives using (1) inconsistencies in the Rosgen classification, (2) basic principles of geomorphology, (3) scientific data on channel response, and (4) case studies. A large part of the "natural channel design" approach is the heavy reliance of artificial structures within the newly designed channel. This aspect of the approach is not addressed in this article.

At Level I, the Rosgen classification system consists of eight major types of streams (Rosgen, 1996:5-6), based on hydraulic-geometry relations and four other measures of channel shape to distinguish the dimensions of alluvial stream channels as a function of the bankfull stage (A, B, C, D, DA, E, F, and G). Six classes of particle size of bed and bank material are used to further subdivide each of the major categories, resulting in 48 stream types. Additional subtypes have also been identified (i.e., Aa+, Gc, Cb, Bc, etc.) representing intermediate cases between the eight major stream types and making for as many as 94 possible types. Aside from the difficulty in identifying bankfull stage (Williams, 1978; Johnson and Teil, 1996) particularly in incising channels, and the issue of sampling from two distinct populations (beds and banks) to classify the boundary materials, the classification provides a means for practitioners to describe channel morphology, although difficulties have been encountered in lower-gradient stream systems. The authors of this article recognize the utility of the scheme to communicate between users; however, this article will show that its use for engineering design or for predicting river behavior cannot be justified and that its use for designing mitigation projects in unstable fluvial systems seems beyond its technical scope.

FUNDAMENTAL ISSUES WITH APPLYING THE ROSGEN CLASSIFICATION

Application of the Rosgen methodology associated with classification can lead to inconsistencies in classification. Problems can be encountered with: 1. definition of the bankfull level (Williams, 1978; Johnson and Teil, 1996; Juracek and Fitzpatrick, 2003) and 2. classification of the dominant type of channel materials (Kuhnle and Simon, 2000).

The simple definition of "bankfull" by Leopold *et al.* (1964), as the "flow that just spills out onto the floodplain" has produced confusion (Williams, 1978). One of the primary reasons for the confusion in identifying bankfull stage is that, as originally defined, bankfull discharge and the dimensions represented by hydraulic geometry relations refer to *stable* channels. This is a critical issue in that "natural channel design" aims to restore highly modified and/or disturbed channels. The term "natural" does not mean "stable" because the latter implies a balance between transport capacity and load. The bankfull level in unstable streams can be exceedingly difficult to identify particularly in erosional channels (such as F and G types) because of a lack of depositional features and because channel dimensions, including water-surface elevations (of specific discharges), are changing with time.

Regarding Point 2 above, Rosgen stipulates that to characterize the boundary sediments for classification purposes, particle counts should be conducted from the bankfull level, down the bank, across the channel bed, and up the opposite bank to the bankfull level (Rosgen, 1996:5-25). This idea may date to work by Schumm (1960) in his report describing the shape of alluvial channels (mostly in the Midwestern United States), in relation to the percentage of silt and clay in the channel boundary. This approach, however, represents the mixing of two distinct populations of alluvial materials, potentially deposited at different times, under different conditions, and requiring different forces and processes to mobilize. Such a particle-size distribution, like a mixture of apples and oranges, is of questionable utility in geomorphic analysis (Kondolf *et al.*, 2003) and not useful for analysis of hydraulic erosion of bed or bank material. In fact, it is the authors' experience that numerous, extensive particle-size datasets collected by state and federal agencies cannot be used for analysis of entrainment and sediment transport because of this problem in sampling technique. A more appropriate method would be to sample these two populations separately, thereby permitting the use of the bed data for sediment-entrainment analysis.

Related to this problem of sampling mixed populations is the issue of the potential for inconsistent classification. For example, two "C" channels, one with gravel bed and silt-clay banks, the other with sand bed and sandbanks, might both have median diameters in the sand range, resulting in classification as stream type C5. Clearly, these two channels would have completely different sediment-transport regimes. Similarly, C channels having bedrock banks will, once disturbed, behave very differently than those having bedrock outcrops on the bed yet both would be classified as C1. Finally, some of the confusion may be related to the different definitions of the type of boundary materials needed for classification at Level II. Rosgen (1996) indicates that *bed material* be used as a "delineative criteria" (Figure 5-2; p. 5-5) but shows that *channel material* should be used in the "classification key" (Figure 5-3; p. 5-6) and discussion of sampling methods (p. 5-25).

CHANNEL FORM: USE, MISUSE, AND HISTORICAL CONTEXT

Channel form has long been recognized as a diagnostic tool in evaluating fluvial landforms. Since Davis (1899) conceptualized the temporal aspect of channel and drainage basin evolution in the form-based "cycle of erosion," geographers, geologists, and geomorphologists have used channel form as a parameter in classification, analysis, and prediction of fluvial response. Davis' descriptive view of fluvial landscapes was simplistic and can be contrasted with Grove Karl Gilbert's (1914) mechanistic-process approach to the understanding of rivers. The perspectives of these two legendary geomorphologists represent complementary extremes that have influenced subsequent approaches to the study of alluvial streams. Davis' work represents large-scale, qualitative assessments of channel form by which inferences about smaller-scale processes were advanced. Conversely, Gilbert's work represents the use of quantitative measurements by which inferences about larger-scale processes were advanced. Links between channel form and process have been the foundation of our understanding of fluvial geomorphology and as such, have been the topic of many textbooks and reports (e.g., Leopold *et al.*, 1964; Morisawa, 1968; Gregory and Walling, 1973; Schumm, 1977; Richards, 1982; Simon, 1994; Knighton, 1998).

Although Gilbert and Davis were both respected geomorphologists, it was Davis' historic view of geomorphology that dominated geomorphic investigation for the first half of the 20th century. Sack (1992) offers three possible reasons for why Davisian geomorphology became widely accepted during this time:

1. The application of a life-cycle analogy from biology to other fields was fashionable at the time;
2. The nonquantitative nature of the geographical cycle made it understandable to a large sector of the population; and
3. Davis, being a professor at Harvard, taught his model to numerous students, many of whom subsequently taught their students.

Rosgens' assumption that one can predict the future behavior of a river from its form is strikingly reminiscent of Davis' cycle of erosion. The rationale for the popularity of the Davisian approach also sounds remarkably similar to the current popularity of the Rosgen approach. However, Davis' ideas about landscape evolution have largely become obsolete as progress in earth science over the last century has revealed a much more complex system. Gilbert's findings and methodological approach are still in use today. There are, however, crucial differences between Davis' view of geomorphology in the early 20th century and the classification approach to river restoration today. Although Davis' approach was widely accepted as valid for almost 50 years (there were early detractors; i.e., Tarr, 1898), the classification approach to restoration design has been criticized since its first introduction to the scientific community and remains without support in much of the peer-reviewed scientific literature (Kondolf, 1995; Miller and Ritter, 1996; Doyle and Harbor, 2000; Kuhnle and Simon, 2000; Juracek and Fitzpatrick, 2003).

Form-based classification schemes are valuable communication and education tools (Miller and Ritter, 1996). However, it is not entirely clear that classification systems are needed, or are not misleading, as typical geomorphic analysis is sufficient to provide necessary information for quantifying geomorphic processes (Ashmore, 1999). For example, data from braided and single-channel rivers in New Zealand (Church and Rood, 1983) would fall into Rosgen class D and C channels, respectively (Figure 1). When analyzing channel width as a function of discharge, a classification approach suggests that the variation in width is the result of a change in stream type. Classification approaches may even suggest that the D type channel "should" be "restored" to a C type channel. However, if the data are treated continuously using stream power as a metric, the two channel types appear as part of a single population characterized by a continuous response to increasing stream power.

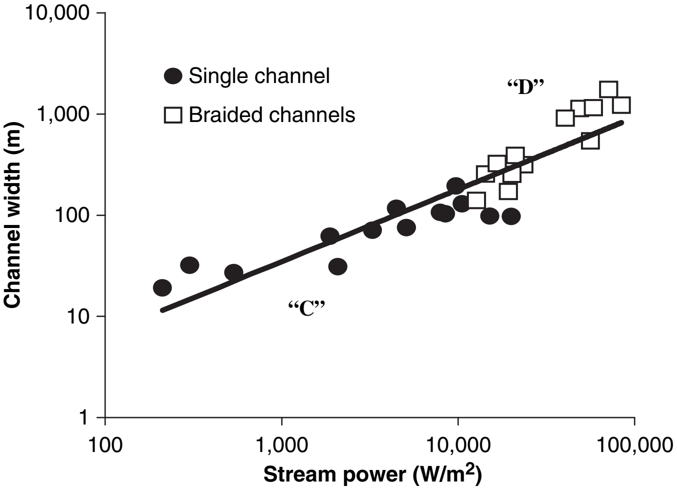


FIGURE 1. Continuum of Channel Width With Stream Power.

Channel form, which includes measurements and descriptions of the shape of channel profiles, cross-sections, and planforms can be used in combination with other diagnostic characteristics of a stream system, such as riparian vegetation, character of the boundary sediments, and bank instability to infer dominant trends in channel processes and response (Schumm *et al.*, 1984; Simon and Hupp, 1986; Montgomery and Buffington, 1997; Elliott *et al.*, 1999). However, using channel form to quantitatively predict channel adjustments (Rosgen, 2001), system disturbances, or rates of sediment transport, without rigorous analysis of channel processes is flawed (Miller and Ritter, 1996). The ramifications of this can be dramatic as shown in Figure 2, a project using "natural channel design" of a C4 stream type on Uvas Creek, California (Kondolf *et al.*, 2001). Smith and Prestegard (2005) describe a similar project on Deep Run, Maryland where reliance on "…classification systems to describe the channel form, empirical relations to predict channel dimensions, and a single design discharge to evaluate the hydraulic conditions…" created unstable morphologic conditions. Another example of how using a "reference reach" in a "natural channel design" approach would be untenable is shown in Figure 3.

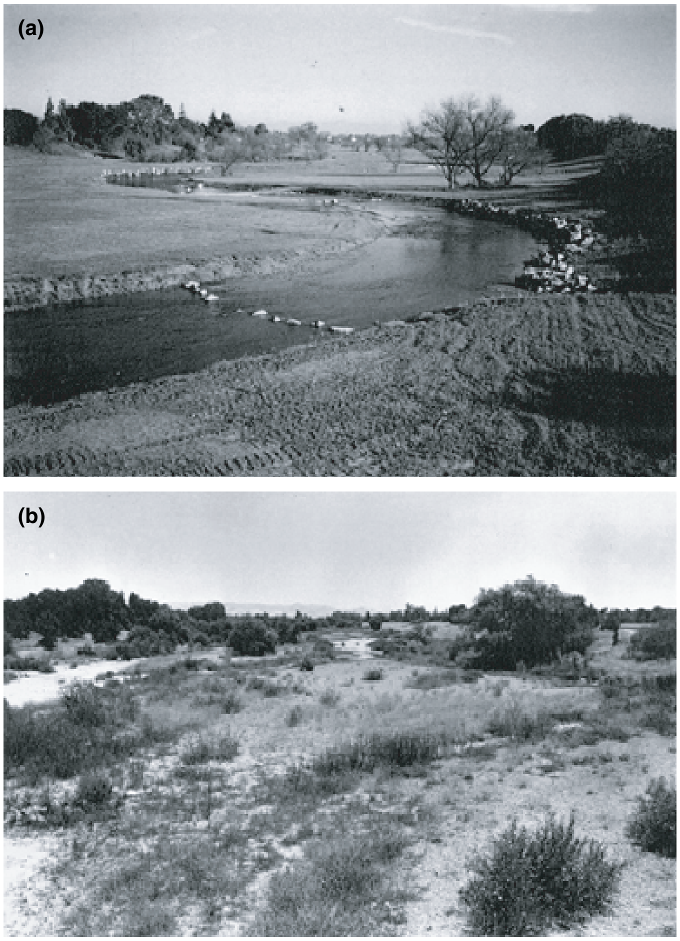


FIGURE 2. "Natural Channel Design" of Uvas Creek, California, 1996 (a), and Following a 6-year Flood in 1997 (b). From Kondolf *et al.* (2001; used with permission of Elsevier Publishers).

The key to using channel form in the analysis of fluvial landforms must be based on either (1) measurements of parameters that aid in quantifying channel processes such as flow hydraulics, sediment transport, and bank stability or (2) observations of diagnostic characteristics that provide information on active channel processes. Measurements should either directly or indirectly lead to analysis of those forces acting on the channel boundary and those forces resisting entrainment.

FIGURE 3. Example of a "Reference Reach" (a) Within an Unstable Channel System (b). Sites from Goodwin Creek, Mississippi. Sites are about 100 m apart, separated by a supercritical flume.

AN ALTERNATIVE CLASSIFICATION APPROACH BASED ON PROCESS

As an alternative to form-based classification, there are several *process-based* classifications available that allow assessing likely future geomorphic conditions based on current forms, although these are based on specific geomorphic processes and in some cases, conditions for particular regions (e.g., Schumm *et al.*, 1984; Simon and Hupp, 1986; Simon, 1989; Montgomery and Buffington, 1997; Elliott *et al.*, 1999).

Understanding alluvial channel behavior, channel response to disturbances, and stable channel forms can be accomplished by concentrating on those factors that directly control the balance or imbalance between applied forces and boundary resistance. This approach involves correctly identifying active processes. If force and resistance are generally in balance over a period of years, a channel reach will experience no net erosion or deposition and transport the bed-material sediment load delivered from upstream reaches. This balance indicates a stability of channel dimensions and is mathematically expressed as the familiar stream power proportionality (Lane, 1955),

$$QS_\mathrm{b} \propto Q_\mathrm{s} d_{50}, \tag{1}$$

where Q = discharge; S_b = bed slope; Q_s = bed-material discharge; and d_{50} = median grain size of bed material, indicating that 50% of the bed material is finer.

Relation 1 indicates that if available stream power were augmented by an increase in the discharge or the slope of the stream, there would be an excess amount of stream power relative to the discharge of bed-material sediment the resistance of which is measured by particle diameter. A similar response would be expected from a decrease in the erosional resistance of the channel boundary, a decrease in the size of bed-material sediment (assuming the bed is not cohesive), or a reduction in upstream sediment supply. In contrast, a decrease in available stream power or an increase in the size or discharge of bed-material sediment might lead to aggradation on the channel bed.

Response to disturbances imposed by natural or anthropogenic causes, emanating from upstream or downstream sources that cause excess stream power or flow energy relative to sediment supply typically result in channel adjustments that can be characterized by asymptotic, nonlinear reductions in flow energy and the rate of energy dissipation (Simon, 1992, 1999; Simon and Thorne, 1996; Simon and Darby, 1997). These studies clearly demonstrate how similar trends of energy adjustment can be the result of different and often opposite adjustment processes. An example from the North Fork Toutle River, Washington (Figure 4), shows two adjusting reaches following the eruption of Mount St. Helens, one dominated by aggradation and widening the other by degradation and widening. Still, the net result of these adjustment processes is a minimization of the rate of energy dissipation (Figure 4a) and the river's ability to transport bed-material sediment (Figure 4b; expressed as average boundary shear stress).

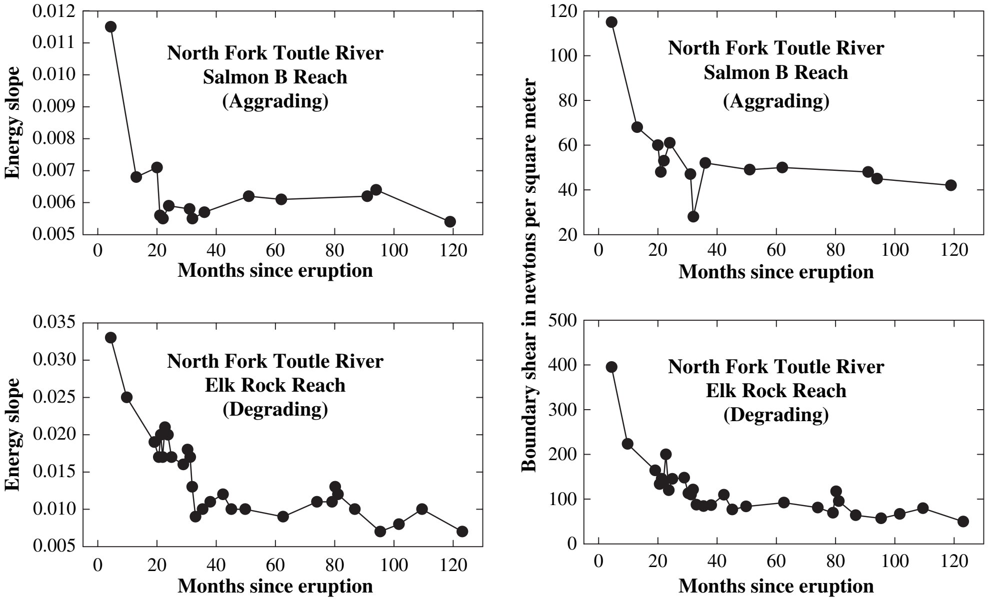


FIGURE 4. Nonlinear Reductions in the Rate of Energy Dissipation (expressed as energy slope; a) and Average Boundary Shear Stress (b) for a Constant Discharge Between 1980 and 1990 for Two Reaches Along the North Fork Toutle River, Washington, Following the 1980 Eruptions of Mount St Helens. (Modified from Simon, 1992, 1999).

The conceptual and semi-quantitative relation (Equation 1) provided by Lane (1955), and the example shown in Figure 4 still provide only limited insight into the type and hierarchy of adjustment processes. Excess stream power may erode additional sediment from the channel boundary (depending on the resistance of the boundary); however, Relation 1 does not indicate where the erosion will occur and, therefore, how channel form might change. Determining the current size, shape, and stream type of the channel will not address this question. Identifying instream sediment sources and dominant processes of adjustment and morphologic change in this case becomes a matter of determining the relative resistance of the bed and bank material to the applied forces imposed by the flow and/or by gravity. For a sand-bedded stream with cohesive banks, an initial adjustment might involve streambed incision because of low critical shear stresses, higher applied shear stresses on the bed than on the bank-toe, and more frequent exposure to hydraulic shear than adjacent streambanks. Conversely, if we assume that the streambed is highly resistant, composed of cohesive clays, bedrock, or large clasts such as cobbles or boulders and that the bank-toe is composed of significantly weaker materials, we could expect bank erosion to be the initial adjustment as a means of minimizing the imbalance between stream power and sediment transport.

Channel evolution models (CEMs) of Schumm *et al.* (1984) and Simon and Hupp (1986) rely on assessments of channel form, but use these assessments to distinguish "stream types" as stages of channel evolution connected to process dynamics. These systems provide insights into active, dominant channel *processes* and can be used to interpret channel-adjustment trends over time and space. The schemes incorporate the concept of balancing stream power (or flow energy) and sediment supply and have been found to be applicable in many diverse regions. The schemes have widespread applicability because they are based on the shifting balance or imbalance between driving and resisting forces (*processes*) and are not tied to specific ranges of channel shape. Use of CEMs further permits the user to determine whether channel instabilities are local or represent the adjustment of an entire fluvial system. Still, CEMs represent just another conceptual/empirical model and are not intended for engineering design or for quantifying channel response.

The sequence of stages does not imply that every reach will undergo each stage in order and stresses the point that any classification scheme, even if it is process based, must be applied cautiously. Reaches downstream from direct modifications typically undergo aggradation as a result of excess sediment supply from upstream relative to available shear stress or stream power (Schumm *et al.*, 1984; Simon, 1994; Landwehr and Rhoads, 2003). In these cases, widening of the channel bed during channelization results in a decrease in stream power per unit area during transport-effective flows, which in turn leads to deposition until the inset channel formed by this deposition has enough stream power to transport the supplied sediment. This example, or a similar one in downstream reaches of the Toutle River System (Simon, 1999) are not in contradiction to the CEMs and in fact provide further support for the concept that these schemes can be used to infer process from form by forcing the user to consider the potential imbalance between sediment supply and transport capacity. They provide the user with a reconnaissance tool and knowledge of what processes are currently active and, therefore, what measurements and analyses are required to make quantitative predictions of channel response.

If not applied correctly, however, classification schemes promote the perspective that the full range of stream dynamics is captured by the scheme, without exceptions. Thus, channels are often forced to fit into *some* category of the scheme whether it is appropriate or not. This is the case with attempting to use a time independent, form-based classification system (such as Rosgen, 1994, 1996) to try to explain the dynamics of alluvial streams that operate as open systems.

Rosgen (2001:II-9) provides at least eight examples of channel evolution that can be "*described and quantified*" by sequences of stream types (i.e., C to G to F to Bc or C to G to F to D). The stream-type approach in fact does not quantify channel response and does not explain how and why these sequences of forms occur or how two C channels, once disturbed, can result in at least three different stable forms (a Bc, a C, or a D; Rosgen, 2001). Similarly, Rosgen (1996) shows different evolutionary sequences for a disturbed E4 channel (p. 6-8 to 6-9).

All but one of the eight evolutionary scenarios shown in Rosgen (2001) mirrors the CEMs sequences of stages: incision, then widening, followed by filling. It seems more appropriate to acknowledge that once fluvial networks are disturbed such that they contain excess energy relative to the imposed upstream sediment load, that a systematic series of processes controlled by the imbalance between driving forces and the resistance of the boundary sediments takes place, and it is this imbalance that controls rates and magnitudes of adjustment and ultimately stable geometries. Neither the Rosgen classification nor the CEMs can determine within a reasonable degree of certainty the resulting sediment loads, stable-channel geometries, or period of adjustment. To accomplish these tasks, numerical, process-based modeling tools are much better suited (Langendoen, 2000; Shields *et al.*, 2003).

In the past, process-based modeling may have been limited by the availability of either computational resources or numerical models. However, with the proliferation of personal computers and the increased availability of free or low-cost numerical models, there is great potential to quantify river processes via numerical modeling (i.e., Simon *et al.*, 1999; Langendoen, 2000). Channel models such as CONCEPTS (Langendoen, 2000) have been linked to a watershed model that provides flow and sediment-boundary conditions and, therefore, can incorporate the effects of changes or disturbances to the watershed on sediment loadings, channel processes, and forms (i.e., Simon *et al.*, 2004a). Considerable work is still required, however to develop and link robust flow schemes (to account for secondary flows) with multidimensional sediment transport required to simulate planform adjustment with confidence and of equal importance, to make these models user-friendly for the engineering community.

These examples Rosgen (2001:II-9) are the crux of our criticism that using channel form to interpret channel response at the expense of understanding processes can lead to significant errors in prediction. The examples further illustrate the inherent contradiction in using a form-based "reference" approach to assume knowledge of future equilibrium morphologies. Using the examples provided by Rosgen (2001), if a practitioner had selected, designed, and constructed a "reference" C-type channel in these cases, two of the three designs would have been unstable because the systems were evolving to other morphologies. Thus, using Rosgen stream types and "natural channel design," how would a practitioner determine the "correct" channel dimensions to design a restoration project? If we assume that these eight examples are from a single morpho-climatic setting (perhaps the montane west?), we can assume that differences in the evolutionary sequences are probably the result of differences in boundary resistance to applied hydraulic and geotechnical forces. If these examples are from diverse regions then we can assume that the variations in sequences are the result of differences in both boundary resistance and applied forces. Without a quantifiable knowledge of specific hydraulic, sediment-transport and geotechnical forces, the various evolutionary sequences of stream types represent little more than a prediction that the shape of the channels will change with time.

Adjustment of a C5 Channel

That the "natural channel design" approach bestows knowledge to the practitioner of how a given stream type will respond to a disturbance, and what equilibrium morphology will result from the ensuing adjustment is implicit, yet flawed. For example, how would a stable C5 channel adjust to a disturbance? In the previous section, we saw that a C-type channel once disturbed can evolve to a number of different stream types Rosgen (2001). The form-based approach could not provide *a priori* knowledge of which evolutionary sequence would occur or the morphology of equilibrium channel forms. A similar example is also provided from Simon and Darby (1997) showing how and *why* sand-bedded alluvial channels (Rosgen C5) composed of different bank sediments but subjected to an identical disturbance, attained different equilibrium morphologies by different adjustment processes. In this case, a numerical model of bed deformation and channel widening was used to simulate channel response to a reduction of upstream sediment supply (50% of transport capacity) for a sand-, silt-, and clay-bank channel with an initial slope of 0.005 m/m. Characteristics of the boundary sediments are shown in Table 1, with the cohesion value for the clay-bank channel set such that the banks would remain stable throughout the simulations.

TABLE 1. Boundary Characteristics Used for Numerical Simulations of a Sand Channel With Initial Slope of 0.005 m/m and Width/Depth Ratio of 13.5.

Bank Material	Bed d_{50} (mm)	Bank Cohesion (kPa)	Friction Angle (°)	Sand Content (%)
Sand	1.0	4.0	32.5	100
Silt	1.0	7.5	32.5	20
Clay	1.0	40.0	32.5	10

Modified from Simon and Darby, 1997.

Because disturbances to the three channels represent an equal, but excessive amount of flow energy relative to upstream sediment supply, adjustments were manifest by almost identical nonlinear, asymptotic reductions in the rate of energy dissipation (to 0.80 of initial, and expressed as head loss; H_f) as the channels adjusted to new equilibrium morphologies. What is particularly germane to the discussion here is that these adjustments occurred by different processes operating at different rates and magnitudes, and resulted in different, stable channel morphologies (Table 2). For the 0.005 m/m cases, the clay-bank channel having essentially fixed banks experienced 3.5 m of incision, compared with 2.7 m for the silt-bank channel and 0.4 m for the sand-bank channel. In contrast, channel widening by mass failure did not occur in the clay-bank channel yet was 11.3 m and 13.1 m for the silt- and sand-bank channels, respectively. This divergence of processes, rates, and magnitudes occurred because although each of the channels was initially a stable C5, differences in bank resistance and composition resulted in different adjustment scenarios and stable morphologies (Table 2). Limited incision occurred in the sandbank channel because bank instability (widening) at the start of the simulation provided reductions in hydraulic depth and plentiful sand to the channel. In fact, aggradation was the dominant bed process for the sand-bank channel having an initial slope of 0.0005 m/m (Table 2). Finally, after adjustment from an initial slope of 0.005 m/m, equilibrium width/depth ratios ranged from 5.6 to 16.4, a considerable difference (about 200%), particularly if one considers the magnitude of uncertainty required for engineering design.

TABLE 2. Summary of Simulation Results Following Disturbance of Stable, "Reference" C5 Channels With Different Bank Materials.

Initial Channel Slope	0.005 m/m	0.001 m/m	0.0005 m/m
Clay-Bank Channel			
Degradation (m)	3.5	2.6	1.3
Widening (m)	0.0	0.0	0.0
W_f/D_f	5.6	6.7	9.0
Silt-Bank Channel			
Degradation (m)	2.7	1.8	1.1
Widening (m)	11.3	7.2	3.3
W_f/D_f	8.6	9.3	10.5
Sand-Bank Channel			
Degradation (m)	0.4	0.3	−0.2
Widening (m)	13.1	7.8	5.4
W_f/D_f	16.4	15.0	16.6

W_f/D_f = final, equilibrated width/depth ratio.

The control provided by different bank resistances on adjustment processes and channel form shown above is clear but runs counter to the "natural channel design" approach where bank-material properties are (1) not explicitly considered but are lumped with bed materials, and where for C-type channels (2) "…bank material had no effect on width/depth ratios despite the considerable range in their tensile strengths" (Hey, 2006:361). Hey (2006) does not provide the range of tensile strengths encountered and mistakenly attributes resistance to mass failure as a function of tensile strength (which is very small for soil materials) when in fact shear strength (defined by cohesive and frictional forces) provides the force resisting gravity. Further, in apparent contradiction to (2) above, Hey (2006:365) states that an anomalously low width/depth ratio for the South Fork Little Snake River (Colorado, USA) is due to the occurrence of lacustrine (clay) bank sediments. The control of bank vegetation (Thorne, 1990) on channel form acknowledged by Hey (2006), however, is because of the additional cohesion (shear strength) provided to the bank materials through root reinforcement (Abernethy and Rutherford, 2001; Simon and Collison, 2002; Pollen and Simon, 2005). Rosgen (1996) recognizes this to some extent through the semi-quantitative bank-erosion hazard index (BEHI), but this metric is used only to qualitatively evaluate bank stability and does not enter into the design approach. Whether this strength is provided by vegetation, by the soil skeleton, or both, the control on channel form is the same and is a matter of the magnitude of that shear strength.

WHY NOT COLLECT DATA THAT CAN BE USED TO ANALYZE CHANNEL PROCESSES?

"Natural channel design" methodology encourages the collection of field data, much of it centered on describing channel form at the bankfull stage. The debate over the meaning and value of "bankfull" discharge and "bankfull" channel dimensions has intensified in recent years with the popularity of the Rosgen classification and the renewed focus on stream restoration and channel design. The bankfull discharge has been ascribed various meanings and levels of importance over the past 50 years since Leopold and Maddock (1953) published their research on hydraulic geometry. Although Dunne and Leopold (1978) described the discharge at the bankfull stage as the most "effective" at forming and maintaining average channel dimensions, the variation in the recurrence interval of the bankfull discharge (Williams, 1978) can be extremely large. Others suggest that a more meaningful measure of channel-forming flows would be one based on sediment transport (Miller and Ritter, 1996; Juracek and Fitzpatrick, 2003; Simon *et al.*, 2004b) termed the effective discharge or the flow that transports the most sediment over the long term. Nevertheless, because of the recent popularity in the Rosgen classification and associated "natural channel design," considerable resources are being expended by state and federal agencies to determine bankfull channel dimensions and regional curves (based on channel and basin characteristics) to predict bankfull dimensions and discharge (e.g., Harman *et al.*, 1999; Odem *et al.*, 1999; Castro and Jackson, 2001).

Although data-collection efforts are applauded, the overriding emphasis on determining bankfull dimensions and Rosgen stream type may come at the expense of other important data-collection programs. It is estimated that between $28 million and $40 million (US$) has been spent for tuition and travel expenses for the roughly 14,000 students that have attended Rosgen "natural channel design" courses. The 1990s in fact represent the first decadal period since inception that saw a decline in the number of gages in the U.S. Geological Survey (USGS) streamgaging program (Figure 9 in Wahl *et al.*, 1995). Although a direct causal relation cannot be substantiated, a recent survey of active stream gages operated by the USGS from 1989 to present, also shows this disturbing trend (Figure 5).

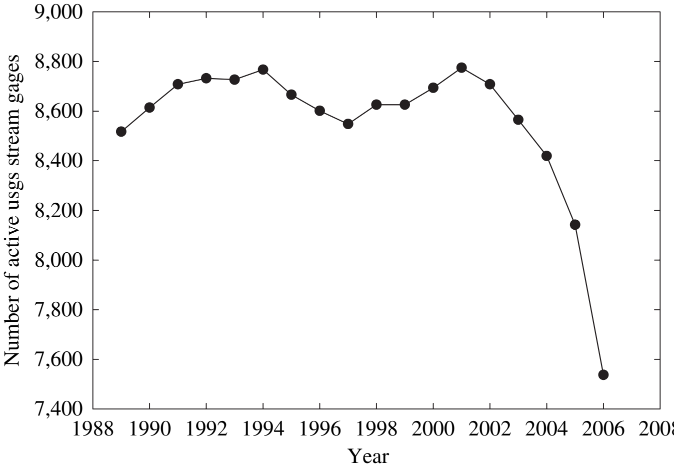


FIGURE 5. Number of Active Stream Gages Operated by the U.S. Geological Survey. Data obtained from National Water Information System, Web Interface (http://nwis/waterdata.usgs.gov).

The criticism of data-collection activities associated with the "natural channel design" methodology (aside from those previously discussed regarding sampling of channel materials) is not that the technique does not encourage data collection, but that the data required for evaluation of channel processes and stability does not provide all the information required to perform analyses of channel response and behavior. Instead, the data is used to make only a qualitative evaluation of relative stability. If resources are available to collect field data along a given reach or stream, it seems preferable to collect data that would permit mechanistic analysis of bed and bank processes (Simon, 1995). For example, instead of or in addition to determining the BEHI (Rosgen, 1996:6-41) to determine relative bank stability, collection of geotechnical data (cohesion, friction angle, and bulk unit weight) required to determine the critical conditions (dimensions) for stability (e.g., Osman and Thorne, 1988; Bank-Stability and Toe-Erosion Model, Simon *et al.*, 1999) would be possible. Using such mechanistic approaches, a practitioner is more likely to design a successful stabilization or restoration project.

Finally, data collection must be conducted above and below the reach in question to place the reach in the proper spatial context. Field data collected under the "natural channel design" methodology represents a single snapshot in time and utilizes a plethora of dimensionless ratios to describe relative channel stability with insufficient consideration for the spatial and temporal distribution of processes that control channel response in disturbed watersheds.

To put this in context, Figure 6 is provided showing a 1953 sinuous channel in northern Mississippi destabilized by the lowering of base level of the trunk stream. Incision, widening and meander migration

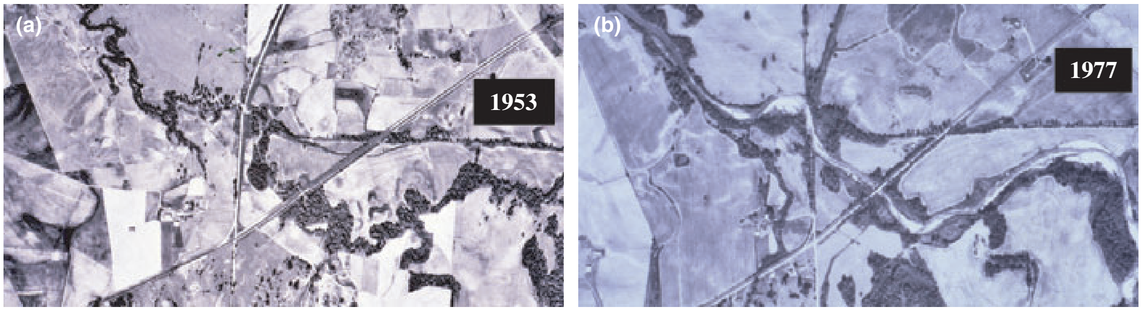


FIGURE 6. Aerial Photographs of Hotophia Creek, Mississippi, Showing a Destabilized Channel System. A "reference" reach, "natural channel design" approach would probably not be successful here.

dominates in 1977. How would data collection in a single unstable reach and selecting a "reference" reach for channel design mitigate channel instability in this case? Designing a bank-stabilization scheme in an actively degrading reach will similarly, have little chance of success. These examples point to the critical importance of temporal and spatial scales in channel adjustment and fluvial geomorphology.

TEMPORAL AND SPATIAL SCALES

Because streams are open systems, an alluvial channel adjusts to altered environmental conditions. Scour and/or fill may occur over the duration of a storm hydrograph but these processes do not necessarily indicate instability because the short time period of the event is not indicative of progressive change over a period of years. In fact, the important distinctions between the processes of scour and degradation, and fill and aggradation are issues of scale. Temporal aspects of channel behavior are masked in form-based approaches because they are based on a snapshot in time, provide no means of determining the magnitude, frequency, or duration of processes and neglect the history of the landscape system.

The previous example (Figure 6) highlights the importance of time scales in interpretation and analysis of channel form. In a classic paper, Schumm and Lichty (1965) demonstrate how even the dependency of variables can change as a function of the time scale considered. Variables describing channel form are indeterminate over geologic time, dependent over medium time scales, and independent over short time scales. Anthropogenic disturbances can cause channel adjustments of the type and scale represented by geologic time, but compressed to time periods of 50-100 years. This temporal scale becomes the timeframe of investigation that is most critical to practitioners involved in stream restoration and channel design. It is also the scale that is most difficult to define by form-based criteria because channel forms are changing with time. Nonlinear, asymptotic adjustment of variables such as width, depth, gradient, shear stress, stream power, and roughness can occur rapidly in these cases (Bull, 1979; Hey, 1979; Williams and Wolman, 1984; Simon, 1992, 1994; Simon and Thorne, 1996). Because of this, it is critical for the practitioner to appreciate that the form (and possibly stream type) that they measure today may not be the same that they measure tomorrow or next year. The reason the forms are different (evolve) is because the reach is continually adjusting to the changing sediment supply from upstream and the imbalance between force and resistance which leads to a shift in dominant adjustment processes (i.e., Table 2; Simon and Darby, 1997).

Constructing a channel designed to resemble a "reference" reach adjacent to unstable reaches will probably be unsuccessful unless dynamic adjustments operating over time and space are adequately considered. This dynamic nature of channels was recognized long ago by Heraclitus (quoted by Kitto, 1951:182): "You cannot step in the same river twice for the second time it is not the same river." The dynamic nature of river channels implies that any meaningful evaluation of river behavior for the purpose of management should consider *rates and directions of change over time* (i.e., Simon, 1995) relative to rates of change produced by natural processes in stable, yet dynamic, fluvial systems (Rhoads *et al.*, in press).

In contrast to the discussion above, restoration of an unstable reach within an otherwise stable system using "natural channel design" would have a much better chance of success, provided that the channel was constructed using boundary materials of similar hydraulic and geotechnical resistance. In this case, where the problem is localized such as a bridge constriction, a local structure, livestock impacts, or deflected flow among others, the practitioner has more options, including a "reference reach" approach.

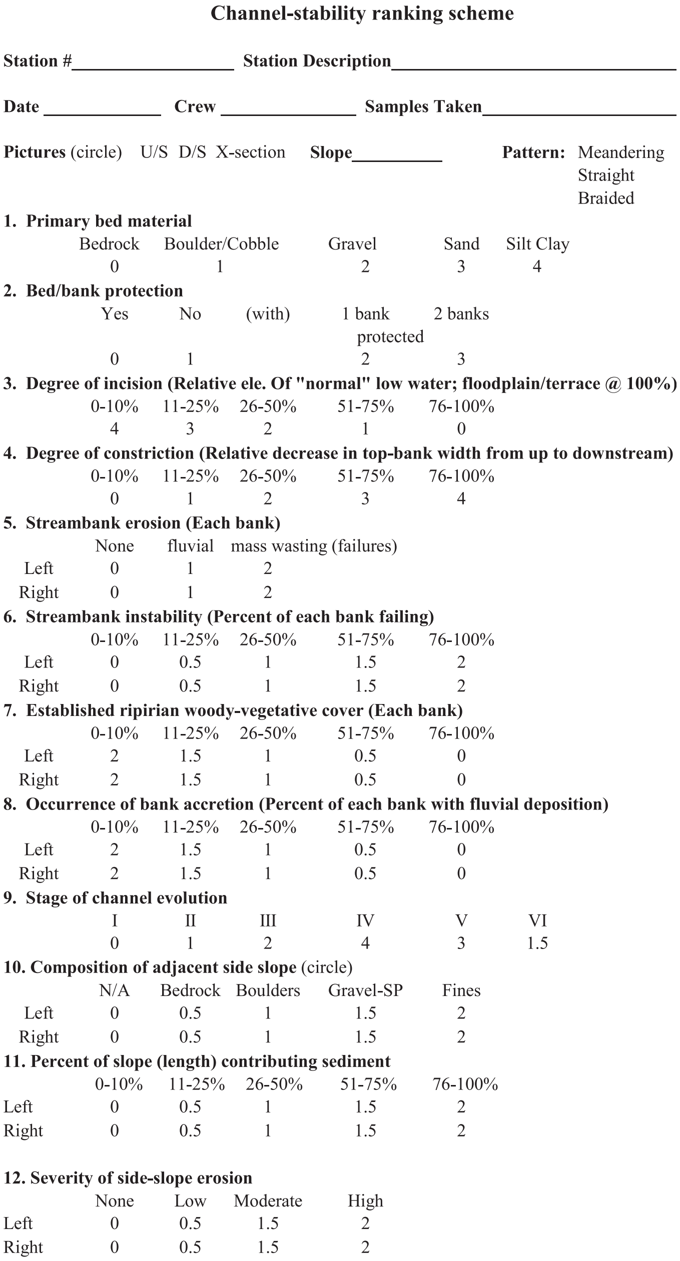
Still, with similar resources, one could use a deterministic approach that implicitly analyzes bed and bank processes. To determine, however, whether the disturbance is localized or system-wide and, therefore, whether a "reference reach approach" may be appropriate, requires an evaluation that extends well beyond the reach in question.

A TIERED APPROACH TO RESTORATION

As discussed throughout this article, approaches to stream restoration may be broadly classified as empirical (such as "natural channel design") or deterministic, where driving and resisting forces are quantified and linked to the upstream delivery of flow and sediment. Thus, a large "toolbox" of techniques and analyses are available to the practitioner. Selection of appropriate approaches should be based on the objective and spatial scale of the project and may not be mutually exclusive. Because of the importance of determining the spatial and temporal scales of disturbance in understanding and quantifying channel adjustment and response, a two-tiered approach termed reconnaissance and analytic levels is presented as one possible solution.

The reconnaissance level is aimed at (1) identifying the nature and scale of the instability for the reach that has been designated for restoration and (2) determining whether the instability is localized or system-wide. To accomplish this, rapid geomorphic assessments (RGAs) that use diagnostic characteristics of channel form and the riparian corridor to identify active processes and relative stability can be conducted (Figure 7). RGAs, including calculation of an objective stability index may take an hour to complete for a reach designated by 6-20 channel widths, several meander beds or several pool-riffle sequences. Stability-index values of 10 or less are generally indicative of stability. Values of 20 or greater are indicative of severe instability. These, in combination with CEMs are particularly well suited for this purpose because results can be mapped to identify the extent of processes and conditions, thus aiding in determining if the instability is localized or system wide (i.e., Hadish, 1994; Simon, 1995).

Other schemes such as the BEHI (Rosgen, 1996) may also be useful to rapidly assess and map bank-stability issues over long reaches. The Pfankuch (1975) system of channel-stability evaluation that is included in Rosgen (1996) is of questionable utility because its numerical scheme is more subjective (different parameter weighting), limited to coarse-grained systems, and contains some questionable ranking schemes (i.e., more stable values for deep, narrow channels). In addition, analysis of historical or time-series aerial photographs, gaging station records (i.e., Blench, 1973; Simon and Hupp, 1992; Jacobson, 1995; Rus *et al.*, 2003), historical surveys (i.e., Daniels, 1960; Parker and Andres, 1976; Rinaldi and Simon, 1998; Simon and Rinaldi, 2000)) and dendro-chronologic evidence of recent bank-failure frequency and deposition rates (i.e., Simon and Hupp, 1992) may aid in identifying the scale of the problem and not just the local symptom.



Channel-stability ranking scheme

Station #________________ **Station Description**____________________________

Date ____________ **Crew** ______________ **Samples Taken**____________________

Pictures (circle) U/S D/S X-section **Slope**_________ **Pattern:** Meandering
Straight
Braided

1. Primary bed material

Bedrock	Boulder/Cobble	Gravel	Sand	Silt Clay
0	1	2	3	4

2. Bed/bank protection

Yes	No	(with)	1 bank protected	2 banks
0	1		2	3

3. Degree of incision (Relative ele. Of "normal" low water; floodplain/terrace @ 100%)

0-10%	11-25%	26-50%	51-75%	76-100%
4	3	2	1	0

4. Degree of constriction (Relative decrease in top-bank width from up to downstream)

0-10%	11-25%	26-50%	51-75%	76-100%
0	1	2	3	4

5. Streambank erosion (Each bank)

	None	fluvial	mass wasting (failures)
Left	0	1	2
Right	0	1	2

6. Streambank instability (Percent of each bank failing)

	0-10%	11-25%	26-50%	51-75%	76-100%
Left	0	0.5	1	1.5	2
Right	0	0.5	1	1.5	2

7. Established ripirian woody-vegetative cover (Each bank)

	0-10%	11-25%	26-50%	51-75%	76-100%
Left	2	1.5	1	0.5	0
Right	2	1.5	1	0.5	0

8. Occurrence of bank accretion (Percent of each bank with fluvial deposition)

	0-10%	11-25%	26-50%	51-75%	76-100%
Left	2	1.5	1	0.5	0
Right	2	1.5	1	0.5	0

9. Stage of channel evolution

I	II	III	IV	V	VI
0	1	2	4	3	1.5

10. Composition of adjacent side slope (circle)

	N/A	Bedrock	Boulders	Gravel-SP	Fines
Left	0	0.5	1	1.5	2
Right	0	0.5	1	1.5	2

11. Percent of slope (length) contributing sediment

	0-10%	11-25%	26-50%	51-75%	76-100%
Left	0	0.5	1	1.5	2
Right	0	0.5	1	1.5	2

12. Severity of side-slope erosion

	None	Low	Moderate	High
Left	0	0.5	1.5	2
Right	0	0.5	1.5	2

FIGURE 7. Channel-Stability Ranking Scheme Used to Conduct Rapid Geomorphic Assessments (RGAs).

Once the scale of the instability has been determined, the second, or analytic level of investigation is conducted. For a localized disturbance and instability, data needs to be collected to define the hydraulic and geotechnical variables that control channel processes and morphology. This includes not only accounting for tractive stress issues on the bed, but stability (geotechnical) analysis of streambanks, including quantitative evaluation of bank steepening at the toe by hydraulic forces (i.e., Simon *et al.*, 2006). Critical conditions for bank stability and the effect of restoration strategies can be quantitatively evaluated using a spreadsheet bank-stability model (Simon *et al.*, 1999). Although many "natural channel design" practitioners conduct tractive stress analyses, they tend to use only a single discharge (bankfull), which has been shown in some cases to be insufficient for sustainable design (i.e., Kondolf *et al.*, 2001; Smith and Prestegard, 2005). The field and analytic resources required for these deterministic analyses are not particularly restrictive and certainly are no more time consuming than the Rosgen "natural channel design" approach.

If, however, the disturbance and instability are determined to be system-wide (or in an urban setting), the practitioner needs a complete quantitative understanding of hydrology, sediment transport, magnitudes and trends of adjustment processes, as well as the absolute and relative resistance of the boundary materials to erosion by hydraulic and geotechnical forces. Because the scale of the problem is much broader, an approach to successful restoration design requires considerably more resources because one must account for the delivery of energy and materials from the watershed to the channel. In fact, system-wide channel instability may be due to changes or disturbances imposed on the watershed itself such as deforestation, urbanization or other land-use changes that effect flow magnitude and frequency, and the delivery of sediment to the channel.

Upland flow and sediment-delivery models can be used to provide flow and sediment loadings as an upstream boundary condition to a deterministic channel-process model that then routes flow and sediment and simulates channel adjustment. Several 1-D and quasi 2-D channel models are available for this purpose and are listed in order of increasing applicability for streams with deformable banks: HEC-6 (HEC, 1992) assumes the banks are fixed, FLUVIAL-12 (Chang, 1982, 1998) adjusts the banks according to the theory of the minimum rate of energy dissipation, and CONCEPTS (Langendoen, 2000) deterministically models mass-wasting processes and channel widening. Several upland models that route flow and sediment are also available: AnnAGNPS (Bosch *et al.*, 1998; Cronshey and Theurer, 1998), CASC2D-SED (Johnson *et al.*, 2000), and SWAT (Arnold *et al.*, 1995). The models cited above are not meant to be an exhaustive list but merely some of the more popular numerical tools used by practitioners and researchers.

For example, this coupled numerical-modeling approach has been used successfully over a range of physiographic and geomorphic settings (i.e., Simon *et al.*, 2002, 2003, 2004a) by linking the upland model AnnAGNPS (Bosch *et al.*, 1998; Cronshey and Theurer, 1998) to the channel-evolution model CONCEPTS (Langendoen, 2000). Populating the upland model is largely from raster-based GIS data sources. Input data for the CONCEPTS channel model to simulate channel processes and resulting morphology is, for the most part, identical to the field data required for analysis of a single reach (geometry and bed- and bank-material properties) but extended over the length of the simulated stream. In addition, CONCEPTS requires a flow hydrograph and sediment-rating relation. These can be provided by the upland model.

DISCUSSION AND SUMMARY

Empirical approaches such as those inherent in "natural channel design" or CEMs do not provide cause and effect solutions or means of predicting stable channel dimensions within unstable systems and represent only one possible alternative to evaluating stream channels. CEMs are best applied at the reconnaissance level because they can provide a system-wide evaluation of the distribution of channel processes and inherently acknowledge that fluvial networks are open systems. The Rosgen classification is probably best applied as a communication tool to describe channel form. It is critical to understand though that a given channel form can be the result of many combinations of processes (equifinality) and, therefore, is not diagnostic of how or why a system is unstable or how to make it stable (Schumm, 1991). This is counter to the assertion made by Hey in defense of "natural channel design" (Hey, 2006:372) who states that "…identical channels must have the same boundary conditions."

Physically based, mechanistic approaches on the other hand rely on quantifying the driving and resisting forces that control active processes and ultimate channel morphology, be they hydraulic, hydrologic, or geotechnical. The physics of erosion, transport, and deposition are the same regardless of what hydro-physiographic province one is in or what the stream type may be, because of the uniformity of physical laws. Channel adjustment is driven by the imbalance between driving and resisting forces, sediment supply and sediment-transporting capacity. Determining rates and magnitudes of adjustment, sediment-transport rates and ultimate channel forms are a matter of defining those spatially and temporally varying forces and variables.

Physically based approaches that concentrate on processes do not require extraordinary data collection or analytic efforts. Our experience is that the field data required to analyze channel stability including resistance of bed and bank material to erosion, can be collected by a crew of four at a site in 1 day. The resources required to collect appropriate data to simulate channel stability and adjustment over extended lengths of a stream is a function then of the number of sites (length of reach or river). For all the emphasis placed on collection of field data and the effort and resources associated with data collection, it is surprising that the "natural channel design" methodology does not aim to quantify the specific variables and processes that control channel processes and morphology. Practitioners should make use of the best available science and analytic approach that are appropriate to the scale and resources of the project.

While there are several reasons for limiting the use of classifications in restoration design, there are equally important reasons for maximizing the use of physically based analyses in restoration design. The foremost advantage of the process-based approach is that it is well established in the scientific and engineering literature. For decades, geomorphologists and hydraulic engineers have been quantifying river processes and developing models that have been tested and refined over time. Developing a design based on such analysis and models and using this rich literature leverages off of a substantial scientific background, and thus provides a critical foundation from which to defend the design approach. Such a scientifically based background and foundation is lacking in the "natural channel design" approach to engineering channel design. As stated by Einstein (1916) "Concepts that have proven useful in ordering things easily achieve such authority over us that we forget their earthly origins and accept them as unalterable givens…The path of scientific progress is often made impassable for a long time by such errors."

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