The Application of Stream Classification Using the Fluvial Geomorphology Approach for Natural Channel Design: The Rest of the Story

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Abstract

The geomorphic approach for Natural Channel Design (NCD) using stream classification has been applied in river restoration projects by the author for nearly four decades. Lessons learned during this period have led to significant modifications and improvements in the method. The current procedure has evolved as scientific principles have been applied in field practice. These methods have been successfully implemented and monitored for large-scale restoration projects.

This method, however, has drawn criticism from individuals in the scientific community. This paper addresses specific issues raised in an attempt to clarify the proper use of the methodology.

The following topics related to natural channel design are reviewed: 1) Proper determination of bankfull discharge; 2) Process-based versus form-based approaches to stream restoration; 3) Field data collection and its relation to temporal and spatial variability; 4) The applicability of particle size analysis; and 5) Stream classification and population variance.

Introduction

River restoration using a "Natural Channel Design" (NCD) methodology has been developed, tested, implemented and monitored by the author for nearly four decades. The method has evolved as the result of lessons learned from detailed project monitoring. A component of the restoration methodology involves the application of a stream classification system. Current application "tools" used for NCD include the Rosgen Stream Classification (RSC) (Rosgen, 1994, 1996). The procedures developed for NCD in river restoration, including the RSC, have been taught in a series of training courses involving over 520 hours of formal instruction, homework and field application. The first course in Applied Fluvial Geomorphology taught by the author at the University of Nevada in 1986 was initially one week long, but due to the nature, extent and complexity of the subject, the courses were expanded to seven weeks.

Criticism of the use of the RSC for river restoration has been offered by several authors. It has consistently been called a "simple cookbook method" (Kondolf, 1995; Miller and Ritter, 1996; Kondolf and Downs, 1996; Hilderbrand et al., 2005). Juracek and Fitzpatrick (2003) and Simon et al. (2005) have stated that stream classification should not be used for stream restoration or engineering design. However, as none of the afore-mentioned authors have attended the formal training courses offered or contacted the author, their lack of familiarity with the method may result in misinformed conclusions. In science, one must test a hypothesis based on a robust program of data collection and analysis. In reviewing criticisms of the NCD procedure utilizing RSC, it is clear that there is a poor understanding of what is involved. The author therefore recognizes the need to present the developed and field-tested methods for river restoration taught in the Fluvial Geomorphology courses to the scientific community. The objective of this manuscript is to address some specific criticisms by providing information on the proper use and/or abuse of the RSC in NCD for river restoration.

As with any tool, it is important to understand appropriate application and limitations. The RSC is used in stream restoration to generate dimensionless ratios representing channel dimension, pattern and profile relations for rivers being restored of the same valley and morphological stream type. The morphological data provided represents a stable "reference reach" (Rosgen, 1998; Hey, 2004). *Prior to developing reference reach data for NCD, many other initial steps must be performed*. Contrary to statements by Juracek and Fitzpatrick (2003) and Simon et al. (2005), stream classification ***does not attempt*** to predict the stability of the stream. That is accomplished by detailed procedures including time-trend aerial photography, detailed measurements and analysis of field evidence. A two-week course is required to teach professionals (including individuals who have graduated from college with advanced degrees in engineering, geology, hydrology, fisheries, etc.) how to conduct a watershed and stream channel stability analysis. A stream classification does not substitute for a stability assessment. The stability assessment procedure has been in use for over twenty years and is documented in Rosgen (1999, 2001a, 2001b, 2001c) and in the EPA web document *Watershed Assessment and River Stability and Sediment Supply* (*WARSSS*) (Rosgen, 2006a). The Level III assessment procedure, or river state/condition, is also summarized in Rosgen, Chapter 6 (1996). It is mandatory to perform this assessment to determine both spatial and temporal variability in channel and watershed conditions leading to the cause, extent and consequence of disequilibrium. Watershed assessment is a key step in the NCD procedure. Classification is used in this step as a stratification of morphological types that exist within the watershed, and for reference reach characterization to conduct departure analysis. Departure analysis involves a stability analysis comparing the study stream to a stable reference condition. Sediment competence and transport capacity are also predicted at the stream channel stability assessment level.

Stream restoration outline using NCD

The NCD procedure developed by the author is outlined in the *National Engineer's Handbook* (Chapter 11) (USDA, NRCS, 2005) and Rosgen (2006a, 2006b). There are eight sequential phases documented in the method developed by the author using the geomorphic approach to NCD. These phases are:

1. Obtain specific restoration objectives associated with the physical, biological and/or chemical processes;
2. Develop regional and localized specific information of hydrological, hydraulic, geomorphological, sedimentological and biological data;
3. Conduct a watershed/river assessment to determine river potential, current state, and the nature, magnitude, direction, duration and consequence of change. Isolate the primary causes of instability and/or loss of physical and biological function. Field data collection/analysis is conducted including reference reach data to define sedimentological, hydraulic and morphological parameters. Biological data (limiting factor analysis) is obtained concurrent and on a parallel tract with the physical data;
4. Consider initial passive restoration recommendations based on land use change in lieu of mechanical restoration. If passive methods are reasonable to meet objectives, skip next phases except monitoring. If passive efforts and/or recovery potential do not meet stated objectives, then proceed with the following phases;
5. Initiate natural channel design (NCD) with subsequent analytical testing for hydraulic and sediment transport (competence and capacity) relations. Reference reach dimensionless relations are applied at this phase. The NCD procedure includes a combination of analog, empirical and analytical methods;
6. Select and design stabilization/enhancement /vegetation establishment measures and materials to maintain dimension, pattern and profile to meet stated objectives;
7. Implement the proposed design and stabilization measures involving layout, water quality control, and construction staging; and
8. Design a plan for effectiveness, validation and implementation monitoring to ensure stated objectives are met, prediction methods are appropriate and the construction is implemented as designed. A maintenance plan is also prepared at this phase.

It is beyond the scope of this paper to describe each phase of the NCD procedure in detail; however, this list gives the reader a general sense of the approach. Some of these phases are subsequently discussed with regard to specific issues.

Issues raised

Bankfull discharge. Determination of the bankfull discharge is a key to classification and river restoration. Many authors, including Juracek and Fitzpatrick (2003), have correctly stated that if one cannot identify bankfull stage in the field on an unstable (actively incising) channel, one could misclassify the reach. This is precisely why USGS gages must be used to develop regional curves for bankfull discharge versus drainage area for given hydro-physiographic provinces (See Phase 2, above). The streams in Wisconsin evaluated using the RSC were incised, making it difficult to observe bankfull (Juracek and Fitzpatrick, 2003). The authors classified the streams as B types, though B stream types are not incised. Since the authors did not properly apply the continuum of morphological variables to adjust the delineative criteria (Rosgen, 1996), the streams were misclassified. The adjustment of entrenchment ratio by +/- 0.2, and/or width/depth ratio by +/- 2.0 would have meant classification as either a G or F stream type, instead of the B type. The extensive bank erosion they observed would have been very consistent with the G or F stream types. If bankfull discharge is not selected correctly, the entrenchment and width/depth ratios will also be incorrect. The authors were, however, correct in their statement that if field observers are not properly trained, misclassification can occur. The use of the Level III assessment would have been more appropriate to answer their stability questions than the RSC, Level II.

Process versus form. Statements that stream restoration should avoid using form-based methods instead of process-based approaches (Wohl et al., 2005; Simon et al., 2005) may confuse the issue. Form and process are not mutually exclusive. They are critically linked and must be used interchangeably. NCD utilizes *analog, empirical* and *analytical* methods to accomplish river restoration. Hey (2004) determined that streambank stabilization was a required component of the “rational approach” to channel design. Different resistance and bed material transport equations produced very different results because they contained empirical calibration coefficients. None of these equations account for the effect of meandering on these processes (Hey, 2004). Empirical regime equations became a logical alternative to rational approaches (Hey and Thorne, 1986). These equations were developed in self-formed, gravel-bed, alluvial rivers from data collected from streamgage stations. All the necessary boundary condition variables were used in their derivation in order to maximize their range of application. Applying these equations to predict the three dimensional morphology of stable natural channels indicates that major errors could occur, particularly in the slope and plan form (Hey et al., 1990).

If regime equations, for example, are used to establish channel dimensions for restoration design, what regime equation is representative and selected? If regime equations (empirically derived) are stratified by stream type, then some of the variance is explained, such as width versus discharge. A morphological stratification using width/depth ratio effectively explained variability in width versus discharge in Kansas streams (Osterkamp et al., 1983). Thus, integrating a form variable such as width/depth ratio into stream classification would help reduce the variance in the width/discharge relation often used to obtain channel width for design purposes.

River morphology reflects boundary conditions and flow processes. Rivers having similar boundary and flow processes will have similar morphology, whereas variation in either boundary condition or flow process will alter channel morphology. Morphology (form) variables for stream classification involve width/depth ratio, slope, entrenchment ratio (vertical containment), sinuosity and channel materials. If boundary conditions change due to an event (such as willow spraying) that reduces the frictional resistance of streambanks, then channel adjustments occur, as shown in **Table 1**.

The relations in **Table 1** are just a few of many different examples of the interaction between stream classification (form) and processes relations. *To accomplish the NCD* *methodology, one must use* ***both*** *form and process-based approaches.* For example, to the author's best knowledge, no available analytical or process-based models predict the depth and slope of runs and glides, transverse bar features, point bar slope, and other features of riffle/pool stream types such as a C4. To design and construct such features, dimensionless ratios and morphological relations of these bed features of similar stream types are used. This is a *form-based* calculation using analog methods from reference reach data by stream type; however, the final design is checked for hydraulic and sedimentological response using analytical approaches. Using such a form-based calculation is appropriate, as the author is not aware of any analytical model or other option for design and construction of such features. Unfortunately, critics due not offer alternate design stategies that would improve the current state of the science of river restoration implementation. The reader must be reminded to revisit the eight phases of restoration, knowing the importance of each phase including stability assessment, flow regimes, reference reach requirements and the detailed field inventory and analysis required to accomplish the NCD methodology.

Table 1. Relation of form and process variables and consequence of adjustment to imposed change in stream type (morphology).

Stream Type Change Due to Disturbance	**Morphological (Form) Variable Change**	**Process Relations**	**Consequence of Adjustment And Channel Change**
1. C4 to D4 from willow spraying (boundary condition change)	• Width/Depth Ratio (*increased*) • Sinuosity (*decreased*) • Slope (*increased*) • Particle sizes of channel (*decreased*)	• Streambank erosion/lateral accretion *(accelerated)* • Relative roughness (*increased*) • Stream power *(decreased)* • Sediment competence (entrainment) (*decreased)* • Sediment transport capacity (*decreased*) • Aggradation • Channel Enlargement	• Land loss (*increased)* • Mean velocity *(decreased)* • Dissolved Oxygen (*decrease*) • Flood risk (increase) • Aquatic habitat (*decrease)* • Stream stability *(decrease*)
2. C4 to G4 due to advancing headcut	• Width/Depth Ratio (*decreased*) • Sinuosity (*decreased*) • Slope (in*creased*) • Entrenchment ratio (vertical containment) (*decreased*) • Particle sizes of channel (increased) • Bank height ratio (incision ratio) (*increased*)	• Streambed and streambank erosion rate (*increased*) • Incision/degradation (*increased/ accelerated*) • Relative roughness (*decreased)* • Shear stress *(increased*) • Stream power (*increased)* • Sediment competence – critical depth computation (*increased/ exceeded)* • Sediment transport capacity (*increased in excess)*	• Land loss (*increased*) • Mean velocity *(increased*) • Lowering local baselevel/ abandoning floodplain • Land productivity • *(decreased*) • Aquatic habitat loss *(increased*) • Riparian vegetation (*decreased*)

A failed restoration project using "NCD" in the conversion from a D4 to C4 on Uvas Creek, California (Kondolf et al., 2001; Simon et al., 2005) was used to exemplify the failure of a form-based restoration based on the RSC system. The "rest of the story" that has been formally documented, but not reported, is that the river restoration designer was a landscape architect with no training or experience, and who chose to disregard the advice of trained peer reviewers. The channel constructed had a width/depth ratio twice the value of the stable form of a C4 stream type, a flat gradient point bar and a uniform grade (no differential between riffles/pools). No sediment competence or transport capacity was calculated. This design violated the fundamental tenets of the NCD procedure, yet its failure was blamed on stream classification. Critics correctly note that inexperienced or untrained individuals have failed to properly design and implement stream restoration projects. When projects fail to meet stated objectives, the author encourages reviewers to obtain and present all the facts in order to make in-depth technical suggestions for improvement rather than *incorrectly assessing blame to a procedure that was not followed*.

The Deep Run rehabilitation project in Maryland, as reported by Smith and Prestegaard (2005), also proved unstable. Generic classification values were used for the design morphology instead of values from stable reference reach data in the Piedmont/Coastal Plain transition province. This valuable and thorough review points out the importance of using the correct reference reach data and checking the design based on hydraulic resistance for various flow levels. It also illustrates the importance of retaining floodplain vegetation for added flow resistance during flood events.

According to Simon et al. (2005), "[It is]…not clear that classification systems are needed, or are misleading, as typical geomorphic analysis is sufficient to provide necessary information for quantifying geomorphic processes." The authors support their point by showing a relation between channel width and stream power from New Zealand streams for single and braided channels. For widths greater than approximately 300 meters and a corresponding stream power of 11,000 W/m, the streams become braided, which is titled "the continuum of channel width with stream power."(see Figure 1, in Simon et al., 2005). Their discussion states that…"a classification approach suggests that the variation in width is the result of a change in stream type." This statement is an incorrect interpretation of the proper use of the RSC. The classification system *does not use width*, but rather uses width/depth ratio. The authors further state that…"Classification approaches may even suggest that the D channel be converted to a C type channel." Certainly, not every braided (D) channel should be converted to a C type stream. In many cases, the D type is the stable form in Valley Types III (alluvial fans), IX (glacial outwash) and XI (Deltas) (Rosgen, 1994, 1996). One very common landscape setting where this distinction is critical to recognize is where steep gradient tributary channels drop their coarse bedload as they enter a lower gradient valley floor. In these systems, an A3a stream type exists upstream of the fan in a Type I valley, and the D channel immediately downstream in a type III valley induces deposition of the large boulders on a debris fan or cone. The deposition in this transition region between the steep-gradient tributary and the lower-gradient trunk stream (i.e., Valley Type II, colluvial; Type IIV, terraced/alluvial; or Type X, lacustrine), is necessary to maintain stability of the drainage networks. It is often practical to construct a D channel to match the stable form within a certain valley type to induce deposition of naturally occurring flood debris or excess sediment supply upstream from channels that would be negatively impacted or de-stabilized by frequent addition of excess coarse bedload material and debris.

To address the "continuum of channel width versus stream power" relation presented in Simon et al. (2005), the author selected 45 river reaches spanning widths from 3m to 603m and slopes from 0.0001 to 0.25l located in New Zealand, Canada and the United States. These data were plotted first using only width and corresponding stream power at high flows. A second relation was developed with the same data set by stratifying the streams into broad groupings (Level I) of A, B, C and D stream types. Contrary to the inference presented by Simon et al. (2005), width was *not* the determinate relationship for stream power, as no relationships appeared (**Figure 1**). Stratifying the streams into their respective morphological types, however, helped explain the scatter in the data set (**Figure 2**). Thus, stream type can further explain variability within a large population. The A stream types that are steep with low width/depth ratios have the highest stream power for comparable widths of the other types. The B, C and D stream types have subsequently lower values of stream power for similar widths. In the example used by Simon et al. (2005), stream power increased with width up to a threshold, then the morphology was braided at the greatest of both width and stream power values. This result might exist in a unique situation, but would not necessarily be a reasonable general relation, as indicated in the contrast between **Figure 1** and **Figure 2**. Without stratification by stream type, there is no relation between width and stream power in this data set.

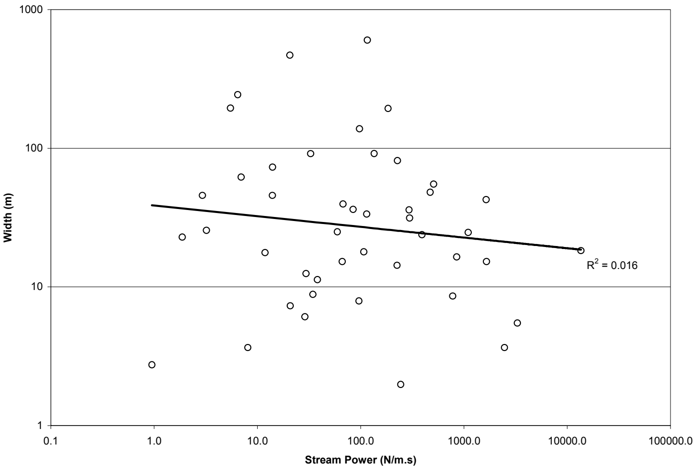

Figure 1. The relationship of width versus stream power for a variety of river sizes at high flows. Data from Barnes, 1967; Hicks and Mason, 1991; Annable, 1994; and Williams and Rosgen, 1989.

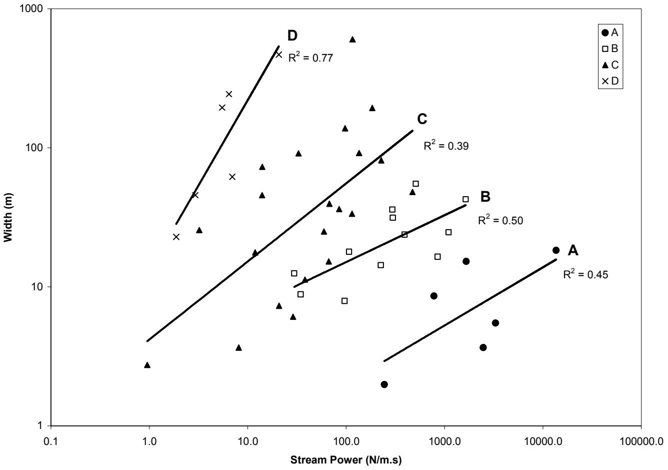

Figure 2. A stratification of the data in Figure 1 by major stream type, showing relationship of width to stream power.

When willow spraying occurred on Weminuche Creek in Colorado, the stream widened due to increased streambank erosion (**Figure 3**). The stream width *increased* three-fold. The width/depth ratio increased from 22 to 233 and the stream type changed from a single-thread channel, C4, to a multiple-thread, braided D4 stream type. The stream power, however, *decreased* from 491 N/m to 348 N/m with unit power changing (power per unit width) 40.6 N/m/s to 5.5 N/m/s (**Table 2**). The *decrease* in stream power due to the *increase* in width at this reach caused the stream to aggrade. Following aggradation, the stream avulsed by cutting off 640 m of its length, causing major incision. This change caused the stream to *decrease* width from 63.1 m to 5.5 m with a corresponding decrease in width/depth ratio of 233 to 5. The stream power *increased* with the corresponding width *decrease* from 348 N/m (5.5 N/m/s) to 1,651 N/m (300.2 N/m/s). This resulted in a stream type change from a D4 (braided channel) to G4 stream type (incised gulley). The stratification and eventual change in stream type helps explain the relation between width and stream power as well as other hydraulic, sedimentological and morphological variables (**Table 2**).

Figure 3. Stream channel adjustment from C4 to D4 stream type showing aggradation, lateral accretion, enlargement and potential avulsion, Weminuche Creek, Colorado, 1986 (photo by D. Rosgen).

Temporal and spatial variability. Simon et al. (2005) make a statement, echoed by others, that "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 stream systems." The author notes that the sequences of stream conversion depicted in **Figure 4** are based upon observations of the temporal and spatial evolution of streams. Because these sequences of stream change have been seen repeatedly in the field, they represent an empirical basis for predicting the probable future states of a stream. However, the prediction of future stream class and condition cannot be made without

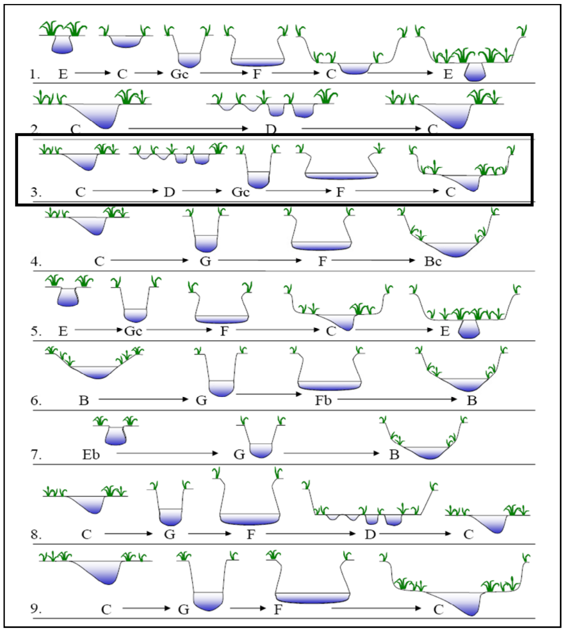

Figure 4. Example of various successional stage scenarios, indicating #3 for example from Weminuche Creek, Colorado (Rosgen, 2001a, 2003, 2006a).

investigating and understanding the landscape context of the stream in question.

The Weminuche Creek example is indicative of channel change over a 12-year period and changes in major stream types at specific locations. A wide range of stream type succession scenarios, noting the Weminuche example (scenario #3) is shown in **Figure 4** (Rosgen, 2001a, 2003, 2006a). These changes in stream type following disturbance represent the proper use of stream classification, knowing that channels have changed over time, as the data collected by stream type reflects the dynamic adjustment of the morphological, hydraulic and sedimentological data (**Table 1** and **Table 2**). A snapshot, indeed, only references the condition at that location in time. That is why a stability examination is completed as part of the NCD processes. Using time-space substitution (Schumm et al., 1984) the data collected both upstream and downstream allows for an understanding of channel adjustment as stream types change over time and space. In other words, the C4 to D4 conversion (**Figure 5**) created aggradation in the downstream direction, whereas the avulsion 600 m downstream created an incising gulley (G4 stream type) advancing headward. Over time, the G4 stream type widened to create an F4 stream type (entrenched, high width/depth ratio channel) (**Figure 6**). Further downstream, and over several years, the channel is rebuilding a new C4 stream type and floodplain at a lower elevation than the pre-disturbance floodplain (now a terrace) (**Figure 7**).

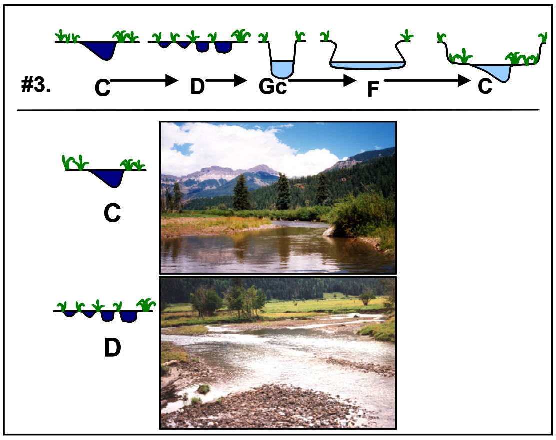

Figure 5. Successional stage change of a C4 to D4 stream type, Weminuche Creek, Colorado (Rosgen, 2003, 2006a).

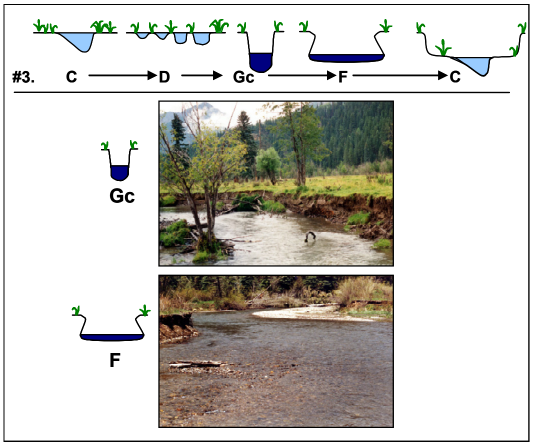

Figure 6. Successional stage change from G4c to F4 stream type, Weminuche Creek, Colorado (Rosgen, 2003, 2006a).

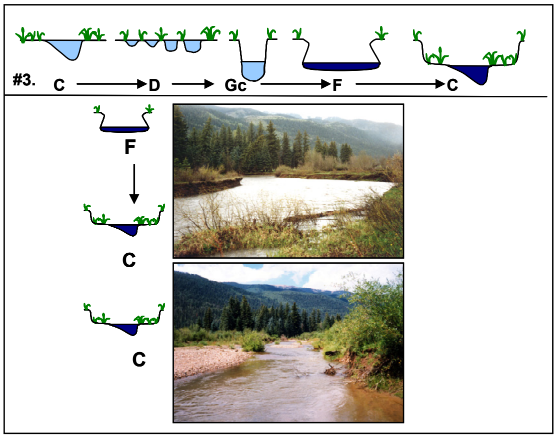

Figure 7. Successional stage change from F4 to C4 stream type, Weminuche Creek, Colorado (Rosgen, 2003, 2006a).

The interpretations of channel response based on morphological character (form) are appropriate, as actual channel response is used to forecast changes spatially (upstream and downstream) and over time (based on similar time-trend rates). The change in form is predicted due to the anticipation of similar processes responsible for the change. The morphological, sedimentological and hydraulic data reflecting these changes are shown in **Table 2**. Biological interpretations based on stream type change are shown in **Table 3** (Rosgen, 2003). This data was collected for a NCD proposal on the Weminuche Valley Ranch near Pagosa Springs, Colorado.

Also in their 2005 work, Simon et al. state that "the data required for stability evaluation, for example, does not provide all the information required to perform analyses of channel response and behavior but rather to make a qualitative evaluation of relative stability." In addition to the information provided in **Table 2**, a Level III stability examination was conducted (Rosgen, 1994, 1996, 2006a) for each reach using the stability variables shown in the standard form (**Table 4**). This review of the Weminuche NCD effort poses the question, "What else is needed as part of Phase 2 Assessment for a natural channel design?" These techniques have been developed over 20 years and the author is continually adding to prediction techniques as improvements become available. The Level IV data verifies predictions by actual measurements of velocity, shear stress, stream power, bank erosion rates, bed stability, suspended and bedload sediment and entrainment (using scour chains), etc. This not only improves the prediction methodologies, but also clarifies some of the complexity associated with disturbed river systems.

Particle size estimates. Criticisms of the field methods for particle size analysis used for classification and NCD argue that these methods have "questionable utility" (Kondolf et al., 2003). The use of dominant particle size distribution using combined bed and bank material provides inconsistencies (Kuhnle and Simon, 2000), and combining bank and bed material causes misclassification such that "numerous extensive particle data sets collected by State and Federal agencies cannot be used for analysis of entrainment and sediment transport because of the problem in sampling technique" (Simon et al., 2005). Again, however, misunderstanding can lead to misinformation. The frequency distribution pebble count is proportionately stratified by bed types and systematically sampled at even increments of observation to represent channel materials. The data are stratified further by separating riffles from pools; thus, particle size distribution can be distinguished between these bed features for sedimentological, hydraulic and biological purposes. Streambanks generally make up five percent or less of the channel boundary; thus, on a transect with ten observations, only one bank sample is obtained every other transect to provide the proper distribution. This would avoid the problem presented by Simon et al. (2005) of classifying a gravel-bed stream as a sand-bed stream by over-sampling bank material. The pebble count is often referred to as a "bed material sample," since generally 95 percent of the channel material sample is taken from the bed. For a Level III stability analysis, however, pebble counts are obtained on the active bed and only on riffles (in conjunction with a cross-section at the same location providing hydraulic radius). These data are used for resistance relations and sediment transport information. Bar samples are also obtained at this level to determine bankfull dimensionless shear stress. Field inventory has to be specific to the objective of the question; thus, the data collection from assessment levels I through IV vary considerably.

These techniques have been established and tested over many years and are taught in the field methods practicum of the short courses presented by the author.

Table 2. Morphological, hydraulic and sedimentological data for various stream types, Weminuche Creek, Colorado (Rosgen, 2003, 2006a).

Stream Type	C4 (stable)	C4 (unstable)	G4 (unstable)	F4 (unstable)	D4 (unstable)
Bankfull discharge	11.3 m^3s^{-1}	11.3 m^3s^{-1}	11.3 m^3s^{-1}	11.3 m^3s^{-1}	11.3 m^3s^{-1}
Bankfull width	12.1 m	16.7 m	5.5 m	28.3 m	63.1 m
Bankfull mean depth	0.54 m	0.55 m	1.1 m	0.35 m	0.27 m
Width/depth ratio	22.4	30.4	5	81	233
Bankfull XS area	6.5 m^2	9.3 m^2	6.1 m^2	9.9 m^2	17.0 m^2
Bankfull max depth	0.88 m	0.82 m	1.8 m	0.73 m	0.70 m
Width flood-prone area	152 m	152 m	8.2 m	31.4 m	152 m
Entrenchment ratio	12.6	9.1	1.5	1.1	2.4
D15	10.6mm	9.4mm	20.0mm	0.1mm	0.1mm
D35	19.7mm	15.0mm	40.0mm	6.0mm	0.1mm
D50	26.9mm	19.8mm	52.0mm	15.8mm	6.9mm
D84	52.5mm	48.2mm	70.0mm	38.2mm	28.8mm
D95	68.8mm	61.3mm	95.0mm	59.7mm	50.0mm
Water surface slope	.0045	.0050	.0150	.0051	.0032
Bankfull mean velocity	1.7 m/s	1.2 m/s	1.86m/s	1.2 m/s	0.64 m/s
Shear stress	23.9 N/m^2	26.8 N/m^2	161.4 N/m^2	14.4 N/m^2	8.6 N/m^2
Unit Stream Power	40.6 N/m/s	32.2 N/m/s	300.2 N/m/s	17.3 N/m/s	5.51 N/m/s
D50 bar	20 mm	12 mm	n/a	7 mm	7 mm
Largest particle on bar	75 mm	75 mm	100 mm	16 mm	10 mm
Relative roughness (d/D84)	10.4	11.4	15.7	9.2	9.4
Friction factor (u/u*)	11.04	7.3	4.6	9.1	6.9
Roughness coefficient (n)	0.027	0.039	0.067	0.031	0.037
Sediment competence (largest size)	75 mm	24 mm	400 mm	18 mm	12 mm
Bedload transport rate (bankfull)	1.5 kg/s	1.3 kg/s	4.2 kg/s	3.0 kg/s	0.25 kg/s
Bedload yield (bankfull)	129.6 tonnes/day	112.3 tonnes/day	363 tonnes/day	259 tonnes/day	21.6 tonnes/day
Suspended sediment concentration (bankfull)	400 mg/l	500 mg/l	750 mg/l	720 mg/l	520 mg/l
Suspended sediment yield (bankfull)	476 tonnes/day	595 tonnes/day	893 tonnes/day	869 tonnes/day	619 tonnes/day
Total sediment yield (bankfull)	605 tonnes/day	707 tonnes/day	1256 tonnes/day	1128 tonnes/day	641 tonnes/day
Stream bank erosion rate	0.03 tonnes/m/yr	0.04 tonnes/m/yr	3.5 tonnes/m/yr	1.8 tonnes/m/yr	0.9 tonnes/m/yr
Vertical stability process	**Stable**	**Slight Aggradation**	**Degradation**	**Aggradation**	**Aggradation**

Table 3. Aquatic habitat response for various stream type scenarios, Weminuche Creek, Colorado.

Variable	C→G	G →F	F →C	C →D
Instream Cover	↓	↓	↑	↓
Overhead Cover	↓	↓	↑	↓
Substrate Composition	↑	↓	↑	↓
Pool Quality	↓	↓	↑	↓
Holding Cover Velocity	↓	↓	↑	↓
Temperature	→	↑	↓	↑
Oxygen	→	↓	↑	↓
Macro Invertebrates	↓	↓	↑	↓
Spawning Habitat	↓	↓	↑	↓
Diversity	↓	↓	↑	↓
Rearing	↓	↑	↑	↑
IBI Score	↓	↓	↑	↓

Table 4. River stability summary sheet (Level III analysis).

Stream: **Location:** **Date:** **Observers:**

Level III Variables	Stream Type:	Flow Regime:	Stream Size:	Stream Order:	Meander Pattern:	Depositional Pattern:	Debris/Channel Blockage:	
	Riparian Vegetation	Current Composition/Density:	Potential Composition/Density:	Altered Channel State (Dimension, Pattern, Profile, Materials):				
Channel Dimension	Mean Bankfull Depth (ft):	Mean Bankfull Width (ft):	Cross Section Area (ft^2):	Remarks:				
Channel Dimension Relationships	Width/Depth Ratio (W/D):	Reference Condition Width/Depth Ratio (W/D$_{ref}$):	(W/D)/ (W/D$_{ref}$):	Circle:	Stable	Moderately Unstable	Unstable	Highly Unstable
Channel Pattern	Mean (Range)	MWR:	Lm/W$_{bkf}$:	Rc/W$_{bkf}$:	Sinuosity:			
River Profile and Bed Features	Circle:	Riffle/Pool	Step/Pool	Plane Bed	Convergence/Divergence	Dunes/antidunes/smooth bed		
	Max Bankfull Depth (ft):	Riffle	Pool	Depth Ratio (Max/Mean):	Riffle	Pool	Pool to Pool Spacing:	Slope Valley: Average Bankfull:
Channel Stability Rating	Pfankuch Rating:	Pfankuch Adjusted by Stream Type (use potential/reference reach):						
Bank Erosion Summary	Length of Reach Studied (ft):	Annual Streambank Erosion Rate: (tons/yr) tons/yr/ft	Curve Used:	Remarks:				
Degree of Confinement	Reference MWR:		MWR/ Reference MWR:		Unconfined (1.0 - 0.80)	Moderately Confined (0.79 - 0.30)	Confined (0.29 - 0.1)	Severely Confined (<0.01)
Lateral Stability	Circle:	Stable	Moderately Unstable	Unstable	Highly Unstable (accelerated lateral erosion)			
Sediment Capacity	Sufficent Capacity	Insufficient Capacity						
Stream Channel Scour/Deposition	Largest Particle - Bar Sample (mm):	τ_{ci}:	Existing Depth$_{BKF}$:	Required Depth$_{BKF}$:	Existing Slope$_{BKF}$:	Required Slope$_{BKF}$:		
Degree of Incision	Bank Height Ratio:	Stable (no incision)	Slightly Incised	Moderately Incised	Deeply Incised	Width of Flood Prone Area (ft):	Entrenchment Ratio:	
Channel Enlargement	Circle:	Stable	Slight	Moderate	Extensive			
Stream Successional Stage	→ → → → →	Existing Stream State (type):	Potential Stream State (type):					
Vertical Stability	Circle:	Stable	Aggradation	Degradation				
Sediment Supply (Channel Source)	Circle:	Very High	High	Moderate	Low	Score:	Remarks/Causes:	

Use of stream classification to minimize population variance. The relations between width and stream power as shown previously (**Figure 1**) are improved by a stream type stratification (**Figure 2**). Sediment relations of bedload for Colorado rivers are further improved by a stratification of the same data set by individual stream type, greatly reducing the variance of the populations (**Figure 8**, Rosgen, 1994, 1996). The data for Weminuche Creek indicates quite clearly how measured sediment supply changes (both bedload and suspended load) due to changes in stream type. The supply function is due to both accelerated streambank and streambed erosion rates due to channel adjustment from disturbance. Change thresholds are reflected in major morphological stream type changes (**Figures 5-7**, and **Tables 1-3**). Interpretations of channel behavior have been and continue to be made by such observations, contrary to the statements of Simon et al. (2005). There are many more scenarios of channel adjustment and stream type change beyond those presented here.

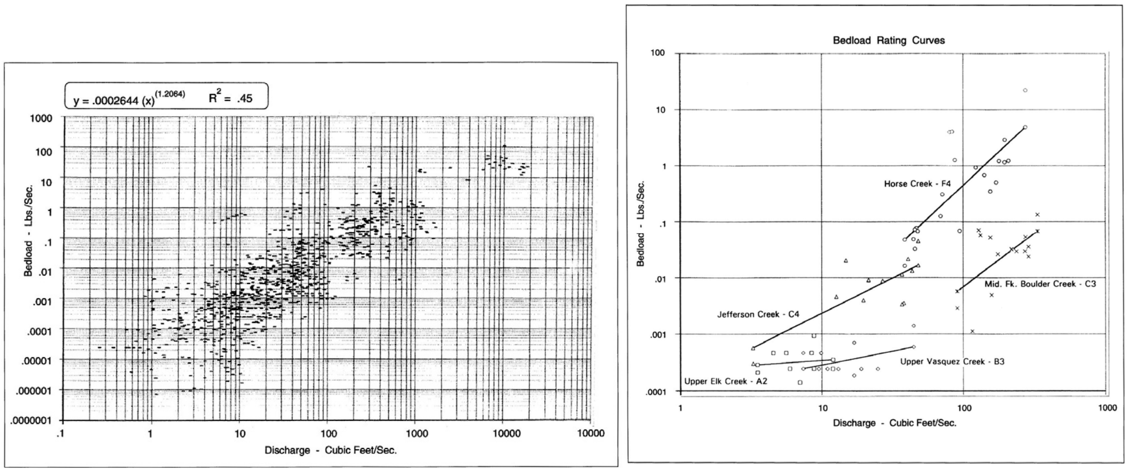

Figure 8. Comparison of bedload data of five different streams from the same population of 55 Colorado rivers showing a stratification by stream type, explaining much of the variability of the sediment relations (Rosgen, 1996).

Summary

A quote from Kellerhals et al. (1976) is particularly appropriate: "Consistent river channel classification with emphasis on those aspects of river behavior that are most important in practical river engineering problems, is a pre-requisite to the study of river processes…. Any analysis of river behavior or publication of river data should be qualified by river type."

The Rosgen stream classification was developed from morphological measurements of hundreds of river reaches from 1969 through 1994, indicating a trend of variables and their ranges that were then grouped into discrete channel types. They were not "force-fit" into arbitrary units, as claimed by Kondolf et al. (2003), Miller and Ritter, (1996) and Simon et al. (2005). Rather, these stream types were derived through the integration of the boundary conditions and flow processes from which they were formed.

The author recognizes and appreciates the crucial role of peer review and academic discussion in the improvement of river science. A focus on the true limitations of any method, generated with continued scientific rigor, may lead to improvements in design and application. A good example is Smith and Prestegaard's 2005 review of the Deep Run rehabilitation project. Their study used reliable data and careful analysis to reveal the limits of general classification values for design morphology. Critical review and discussion can only improve the methods and eventually help us meet our ultimate objective, to restore our rivers in terms of their physical stability and sustained ecological function.

Ackwnowledgements

The author appreciates the technical review by Dr. Douglas Smith and the editorial and manuscript preparation assistance of Darcie Frantila and Bridget Julian.

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