REPORT

Colorado Basin Roundtable
Watershed Flow Evaluation Tool Study

Prepared for:

Northwest Colorado Council of Governments

Funded by:

Colorado Water Conservation Board Water Supply Reserve Account Grant

Prepared by:

John Sanderson, Ph.D.
The Nature Conservancy

Brian Bledsoe, Ph.D., P.E.
N. LeRoy Puff, Ph.D.
Thomas Wilding
Colorado State University

William Miller, Ph.D.
Miller Ecological Consultants, Inc.

Nathan Fey
American Whitewater

March 2012

CDM Smith

Appendix E

Geomorphic Subclassification

This page intentionally left blank.

A Geomorphic Valley Classification for Fluvial Riparian Areas

Brian P. Bledsoe, Ph.D., P.E. and Erick A. Carlson

Colorado State University

Department of Civil and Environmental Engineering and Graduate Degree Program in Ecology

Executive Summary

The upper Colorado River basin contains a diverse mosaic of geomorphic settings and fluvial riparian ecosystems. From the steep, v-shaped and glacial valleys of the high country to the gentle gradients and expansive floodplains of lowland alluvial valleys, geomorphic setting mediates the relationship between hydrology and riparian ecosystems. CSU has collaborated with the US Forest Service over the last 4 years in the development of a geomorphic valley classification (GVC) for describing the key geomorphic factors that influence riparian systems across large regions. The classification is geographic information systems (GIS) based and delineates different geomorphic valley settings using energy, hillslope coupling, and lateral confinement as the primary diagnostic characteristics. The GVC derives its class descriptions from geomorphic thresholds corresponding to significant transitions in the physical processes and boundary conditions that give rise to distinct floodplain and channel forms, disturbance regimes, and ecological attributes (Table ES1).

Table ES1: Valley classification names and attributes of the GVC.

Valley Class Name	Energy / Valley Gradient	Valley Bottom Width / Coupling / Confinement	Hillslope Gradient	Energy Potential
Headwaters	> 4%	$< (2\ L_D + W_{BF})$	Both > 30%	High
High-energy Coupled	> 4%	$< (2\ L_D + W_{BF})$ or $< (L_D + W_{BF})$	Both or at least one > 30%	High
High-energy Open	> 4%	$> (2\ L_D + W_{BF})$	Both or at least one > 30%	High
Moderate-energy Confined	0.1-4%	$< 7\ W_{BF}$	Variable	Moderate

Moderate-energy Unconfined	0.1-4%	> 7 W_{BF}	Variable	Moderate
Canyon	Variable	> 3 W_{BF}	> 70%	Moderate to High
Gorge	Variable	< 3 W_{BF}	> 70%	Moderate to High
Glacial Trough**	< 4%	> (2 L_D + W_{BF})	~ 10-% initially steepening to > 30%	Moderate to Low
Low-energy Floodplain	< 0.1%	> 7 W_{BF}	Generally < 30%	Low

L_D – length of debris runout W_{BF} - width of channel at bankfull stage

** Defined as valleys with the given characteristics, lying above the elevation of the most recent glacial activity

In the GVC, energy refers to the hydraulic power available to scour and shape valley bottoms and the channels they contain. Energy is characterized using unit stream power or valley slope as its surrogate. The slope thresholds selected for distinguishing between valley energy types correspond to widely recognized shifts in hydro-geomorphic processes. For example, valleys steeper than 3-4% slope tend to contain confined step-pool and cascade channels with varying degrees of hillslope coupling. As valley slopes become less than 3-4%, the channel types gradually shift to broader floodplains containing plane bed, pool-riffle, and sandy streams.

Coupling refers to the proximity of the hillslopes to the channel and the likelihood that landslides and debris flows on those slopes may move directly across the valley bottom into the stream channel at the slope base. In coupled settings, the channels and the riparian communities occurring along them may be more influenced by materials transported directly from hillslopes (colluvium) than by materials transported from upstream by water (alluvium). In uncoupled settings, sediment recruitment and transport largely become consequences of erosion of the streambed and banks.

Finally, confinement refers constraints on the planform (e.g. meandering, braiding) and lateral adjustability of stream channels. It is quantified by comparing the width of the valley bottom available for channel meandering and migration versus the size of the channel. A sinuous channel typically requires a minimum valley bottom width of approximately seven channel widths to freely meander. By distinguishing between coupling and confinement, the GVC provides a tool for mapping locations where hillslope processes may largely control riparian attributes versus those locations where fluvial processes dominate, as well as a method for distinguishing the degree to which valley bottom widths constrain channel patterns and floodplain processes.

A Geomorphic Valley Classification for Fluvial Riparian Areas

Brian P. Bledsoe, Ph.D., P.E. and Erick A. Carlson

Colorado State University

Department of Civil and Environmental Engineering and Graduate Degree Program in Ecology

Background

Riparian zones border flowing and permanent water bodies and are of great ecological and economic importance. These biologically-rich and geomorphically-dynamic areas perform numerous ecological functions that critically influence species distributions, water quality, hydrologic processes, and biogeochemical cycling. The upper Colorado River basin contains a diverse mosaic of geomorphic settings and fluvial riparian ecosystems. From the steep, v-shaped and glacial valleys of the high country to the gentle gradients and expansive floodplains of lowland alluvial valleys, geomorphic setting mediates the relationship between hydrology and riparian ecosystems.

For over a decade, riparian scientists and managers have identified a need for a robust, broadly-applicable fluvial classification for stratifying riparia across large regions (NRC 2002). In 2006, US Forest Service and Colorado State University began a project that aims to synthesize the large body of information on fluvial and riparian systems into a novel, process-based classification fluvial riparian zones in the western US. The specific five goals of this project were to: 1) examine existing fluvial classifications to identify gaps, opportunities for integration, and potential improvements to aid management of fluvial riparian systems; 2) synthesize previous knowledge in developing an *a priori* classification that is process based, hierarchical, and geographic information systems (GIS) based; 3) develop three suites of procedures focused on quantifying system energy, hillslope coupling, and lateral confinement; and 4) test the functionality and accuracy of the classification in several USFS units.

This document summarizes the resulting Geomorphic Valley Classification (GVC) that focuses on energy, hillslope coupling, and lateral confinement as primary diagnostic characteristics. The GVC framework provides a widely-transferable framework for stratifying fluvial systems in the context of management, planning, and monitoring. For example, the GVC can aid in identifying hydro-geomorphically similar reference locations for monitoring, mapping of critical resources for future inventorying activities, and identifying resources at risk from human influences.

In this study, three sets of GIS procedures were developed for stratifying fluvial riparian settings in the upper Colorado River Basin. These procedures measure the key geomorphic descriptors in the GVC using widely-available 10-m digital elevation models (DEMs). The GVC derives its class descriptions from process thresholds that identify significant adjustments to the flow of energy and matter in systems that result in unique landforms, disturbance regimes, and ecological attributes. The open framework of the GVC prompts the user to adjust specific values for hillslope stability, colluvial debris run-out, and fluvial network density. Field testing of the GVC was completed at 42 sites in five ecoregions across the western United States to assess the correspondence between classifications completed using GIS and field data as described below.

Conceptual and Theoretical Framework

The GVC identifies thresholds that describe distinctions between dominant fluvial processes and groups variability into functionally unique classes. The defining attributes of each class are related to the geomorphic processes most influential at a site with a particular set of physical characteristics. The characteristics are related to processes that directly result in the forms observed, disturbances likely to occur, and other physical constraints on the biota inhabiting the site. A connection between the geomorphic processes creating and maintaining fluvial landforms and the ecological community is supported by ecological theory (Gregory et al. 1991, Montgomery 1999, Goebel et al. 2006).

The conceptual framework developed for the GVC was developed by integrating several elements used in the large body of previous work on fluvial classifications of valleys, floodplains, channels, and hillslopes. A suite of fluvial processes including erosion, sedimentation, lateral migration, incision, and transport behave similarly across regions. This consistency provides a physical basis for developing a classification that can span geomorphically-distinct regions (Montgomery and Buffington, 1997; Brardioni and Hassan, 2006). A partial list of regionalized schemes, landform-specific classifications, and scale-specific studies that address the classification of valleys, streams, and riparian areas that were considered in developing the GVC are listed in Table 1.

For this investigation fluvial processes are grouped into three main spheres, which collectively describe the geomorphic setting of the valley: 1) system energy, 2) hillslope coupling, and 3) lateral confinement. Specific processes such as erosion, sedimentation, lateral migration, vertical incision, and sediment transport can be placed within one of the three spheres as described below.

Table 1: Listing of previous classification efforts and their approaches, applicability and attributes.

Group	Date	Approach	Hierarchical	Scale	Region	Advantages	Constraints
Kellerhals et al.	1976	Observational	NO	Channel	Western Canada	Extensive definitions, connects channel to valley	Relies on several qualitative variables when discussing valley attributes
Schumm	1977	Sediment, stability	NO	Channel	Great Plains	Relates sediment and power to channel form	Relies on qualitative measures
Collotzi	1976	Observational	YES	Multi	Pacific Northwest (Oregon)	Four-level hierarchy, strong definitions, incorporates channel and valley bottom	Regionally specific, ecologically redundant
U.S Department of Agriculture (USDA)	1977, 1978	Observational	YES	Multi	Pacific Northwest	Directly applied to management objectives	Regional specific, does not describe all valley geometries
Frissel et al.	1986	Process	YES	Multi	Pacific Northwest (Washington)	Links several scales, addresses temporal aspect	Not explicit with valley typology
Cupp	1989	Observational	YES	Valley Segment (300 m)	Pacific Northwest (Oregon)	Uses several variables to relate channel to valley	Regional specific, large number of types (19)
Nanson and Croke	1992	Stream Power, Sediment	YES	Channel-valley	US	Connects channel morphology to sediment and floodplain	Restricted to floodplain morphology
Knighton and Nanson	1993	Stream Power	NO	Channel	Australia	Relates energy to geomorphic conditions	Vacillates on the equilibrium nature of multiple channels
Whiting and Bradley	1993	Process	NO	Channel	Pacific Northwest	Explicitly uses process to predict form	Very limited morphological applicability, only Headwaters
Rosgen	1994	Observational	YES	Multi	US-Wide	Very detailed in definition and description	Gives no basis for thresholds
Montgomery and Buffington	1997	Process	NO	Channel	Pacific Northwest	Detailed channel morphology, forced and intermediate forms	Regional specific, not useful in lower gradient rivers
Montgomery	1999	Process	YES	Multi	Pacific Northwest	Connects process to ecological significance	Conceptual, limited quantitative measures
Brierley and Fryirs	2005	Process	YES	Multi	Australia	Addresses several major geomorphic processes	Subjective in its variables
Snelder and Biggs, Snelder et al.	2002, 2005	Process	YES	Multi	New Zealand	Uses a hierarchy of controlling factors	Relies on factors that may not be important in all areas
Church	2002, 2005	Process	NO	Channel	US	Quantifies sediment and channel morphology	Requires fine-scale data to be applied
Flores et al.	2006	Stream Power, GIS	NO	Channel	Western US	Introduced and tested drainage area as means of applying scale	Error introduced when using estimated stream power from drainage area
Jain et al.	2008	Process, Stream Power	NO	Catchment	Australia	Strong connections to sediment and stream power	Regionally-specific results, identifies single threshold

System Energy: Large-scale processes of channel pattern, landform development and orientation, and selection of resilient riparian species, have also been noted in connection with system energy (Hupp and Osterkamp, 1985, 1996; Bendix and Hupp, 2000; Twidale, 2004; Naiman *et al*., 2005; Parsons and Thomas, 2007). In the GVC, energy refers to the hydraulic power available to scour and shape valley bottoms and the channels they contain. Energy is characterized using unit stream power or valley slope as its surrogate. The equation for unit stream power (Bagnold, 1966) is

$$\boldsymbol{\omega = \frac{\gamma Q S}{w}}$$

where γ is the specific weight of water (9,810 N/m^3), Q is discharge (m^3/s), and S is the energy slope (m/m) approximated by valley gradient, and w is channel width (m) estimated from appropriate regional hydraulic geometry relationships. The divisions between the energy classes used in the GVC are directly related to the three dominant sediment domains of the fluvial system: 1) source areas of erosion and entrainment, 2) transport reaches, and 3) extensive depositional floodplains (Nanson and Croke, 1992; Montgomery, 1999; Brierley and Fryirs, 2005). The type of material and the method of transport are related to system energy (NRC, 2002).

Slope is often used as an effective surrogate for unit stream power in predicting stream types in mountain drainage basins (Grant et al., 1990; Montgomery and Buffington, 1998; Flores et al., 2006). For this study, valley slopes generated from DEMs were used for distinguishing between valley energy types correspond to widely recognized shifts in hydro-geomorphic processes. For example, valleys steeper than 3-4% slope tend to contain confined step-pool and cascade channels with varying degrees of hillslope coupling. As valley slopes become less than

3-4%, the channel types gradually shift to broader floodplains containing plane bed, pool-riffle, and sandy streams.

In low energy systems with unit stream power values less than approximately 10 W/ m^2, channels does not possess sufficient energy to effectively erode the channel banks or floodplain deposits (Nanson and Croke, 1992; Knighton, 1999), and lateral migration is minimal or very slow. Based on the definition of unit stream power for a channel with a typical discharge per unit width on the order of 1m^2/s, it follows that a slope on the order of 0.001 m/m (0.1%) corresponds to a specific stream power of ~10 W/ m^2 which has been previously identified as a threshold of stream power that separates floodplain types and behavior (Nanson and Croke 1992).

For high-energy fluvial systems, there is little consensus regarding a significant stream power value but general agreement regarding a channel gradient threshold. Many researchers agree that the shift from plane-bed / pool-riffle type channel morphologies to step-pool / cascades suggests a major shift in fluvial dynamics. This shift often occurs near 300 to 400 W/ m^2 or 3 to 4% channel gradient (Collotzi, 1976; USDA, 1992; Rosgen, 1994; Van den Berg, 1995; Montgomery and Buffington, 1997; Church, 2002; Flores *et al*., 2006; Brardioni and Hassan, 2006; Pyne *et al*., 2007; Wohl *et al*., 2007; Thompson *et al*., 2008). If a unit discharge on the order of 1 m^2/s is assumed as above, a slope of 0.03 to 0.04 m/m would yield a specific stream power of 300 to 400 W/ m^2, which corresponds to the Nanson and Croke (1992) threshold between high and moderate energy floodplains.

Hillslope Coupling: Sediment that is eroded, transported, and deposited as a result of fluvial processes is ultimately derived from the adjacent uplands, albeit potentially from distant upstream areas (Sear *et al*., 2003). Shallow landslides and debris flows are often smaller, occur more frequently, and occur on more varied terrain than deep-seated or fault-driven landslides. The contribution of material to the valley bottom or channel can have significant affects on local erosion and deposition, mechanically damage vegetation and adding to the heterogeneity of surfaces in the immediate area and considerable lengths downstream. For this reason, the GVC addresses the potential for colluvial debris to deposit on the fluvial valley bottom.

Coupling refers to the proximity of the hillslopes to the channel and the likelihood that landslides and debris flows on those slopes may move directly across the valley bottom into the stream channel at the slope base. In coupled settings, the channels and the riparian communities occurring along them may be more influenced by materials transported directly from hillslopes (colluvium) than by materials transported from upstream by water (alluvium). In uncoupled settings, sediment recruitment and transport largely become consequences of erosion of the streambed and banks.

The capacity for a hillslope to exert influence on the riparian system is correlated with both gradient and proximity to the fluvial valley bottom. The stability of a slope helps characterize its capacity to transfer material to the valley bottom and/or channel by methods other than simple surface erosion (USDA, 1992; Williams *et al*., 2000; Benda *et al*., 2007). The valley width is a key control on the probability that the colluvial material will encounter the channel and affect flow. Together these two geomorphic variables can be used to approximate the likelihood of colluvial debris being generated on the hillslope and depositing on the fluvial valley bottom (Whiting and Bradley, 1993).

A simple measure of the capability for adjacent hillslopes to generate colluvial material is the composition of slope gradients. Three hillslope gradient classes are designated in the GVC by two user defined thresholds: one describing the lower limit of unstable slopes and the other gradient above which shallow landslides and debris flows are common (Whiting and Bradley, 1993; Montgomery, 1999; Clarke and Burnett, 2003). Default values of hillslope angles used in the GVC were selected based on a review of several previous studies and recognized classifications. Previous work supports a lower threshold of 30% (Collotzi, 1976; Cupp, 1989; USDA, 1992). An upper threshold of ~70% is more uncertain, in part, because regional values of hillslope stability are so widely varied.

The colluvial potential of a valley is simplified into a single value termed the "coupling statistic" (Coup_stat), following Whiting and Bradley (1993). The equation below shows how the length of potential colluvial input deposits (Dr) is related to the "un-channelized valley width" (width of the *total* valley bottom – width of the bankfull channel). The "# *of 'steep' sides*" is used to treat the valley as having two, independent hillslopes, each with influence.

$$Coup\_stat = \frac{(\text{\# of 'steep' sides}) * (\text{Dr})}{\text{Wv - Wbf}}$$

Lateral Confinement: In most situations, the channel occupies only a portion of the valley bottom at bankfull stage. The un-channelized valley bottom is subject to becoming incorporated as active channel if lateral migration occurs. Lateral confinement can affect the development of extensive floodplains (Dodov and Foufoula-Georgiou, 2005) and the dynamics of floods, which are important considerations for riparian extent, biological composition, and ecological function (Hupp and Osterkamp, 1985, 1996; Bendix and Hupp, 2000; Quinn *et al*., 2000). The concept of lateral confinement has the advantage of scaling to the size of the system.

A common approach to examining confinement is to apply thresholds related to meander geometry advanced by Leopold and Wolman (1960), Leopold and Langbein (1966), Ferguson (1973, 1979), and others. Much of the work on meander geometry originates with the sine-generated wave introduced by Langbein (1966). This graphical approach mirrors concepts behind the adjustments in channel form as meanders and the sine-generated wave minimize the changes in direction and work performed by the system. Several mathematical relationships have been identified that describe the geometric shape of meandering channels and their cross sectional profiles (see Leopold and Wolman, 1957, 1960; Langbein, 1966; Leopold and Langbein, 1966; Williams, 1986; Hagerman and Williams, 2000; Soar and Thorne, 2001).

Two distinctive geometric characteristics of meanders of any origin are: 1) amplitude and 2) wavelength. Williams (1986) examined dozens of ways these and other attributes of channel meanders can be related to each other. Here we use the relationship between meander amplitude and wavelength, herein referenced as A and λ, respectively, to identify the threshold at which free-lateral adjustment becomes impeded. This relationship assumes a sine-generated curve (Leopold and Langbein, 1966). Hagerman and Williams (2000) developed a third-order polynomial to calculate the meander amplitude using λ as the independent variable:

$$A = \lambda(6.0625\varphi^3 - 5.1279\varphi^2 + 2.509\varphi + 0.0005)\,.$$

The term φ is $(P - 1)/P$, where P is the sinuosity. Wavelength cannot always be directly measured; however, but Soar and Thorne (2001) proposed a relationship between bankfull channel width Wc and λ based on a large meta-analysis of meandering rivers around the world: $\lambda = 12Wc$. The polynomial relationship for A above can be rearranged to calculate meander belt width (B) by substituting $12Wc$ for λ and adding a channel width:

$$B = (12(6.0625\varphi^3 - 5.1279\varphi^2 + 2.509\varphi + 0.0005) + 1)W_c$$

The additional channel width accounts for meander amplitude being measured between two points located in the center of the channel. For confinement, interest is in the outer edges of the channel.

To arrive at a threshold for the minimum unconfined valley width, the conventional definition of a meandering channel as maintaining a minimum *P* of 1.5 is used (Leopold and Wolman, 1957, 1960; Van den Berg, 1995). It follows from the relationship for *B* that the threshold for the minimum valley bottom width that can contain the belt width of a meandering channel with a *P* of 1.5 is approximately $7Wc$. To the extent that sine generated wave meander geometry is a reasonable approximation, this value is scale independent and transfers between regional physiographic boundaries.

A second threshold is identified for riparian settings in highly-confined situations. Lateral migration of the channel is not an option for these narrow valleys, but confinement is nonetheless still important. A shift in channel morphology from single thread to braided has been shown to be related to channel slope, sediment load, and variable discharge (Leopold and Wolman, 1957; Schumm and Khan, 1972; Fredsoe, 1978). This results in a dramatic change in the width- to-depth (W/D) ratio from ~25:1 for single-thread channel while braided channels are often twice that, at 50:1 (Fredsoe, 1978). A valley width index (VWI) (the ratio of valley width to bankfull channel width) of 2 has been highlighted as a threshold separating systems where there is no ability to maintain long-term depositional features. Transient floodplain features are critical in these habitats, but a characteristic alluvial floodplain does not develop. This value is supported by several established regional valley classifications (Collotzi, 1976; Cupp, 1989; Rosgen, 1996; O'Connor and Watson, 1998).

Hierarchical Organization

The three spheres of processes create a strong foundation for the development of a fluvial classification as they describe the significant forces which shape the valley, floodplain, and channel. The balance between explanatory power and complexity is a common struggle in scientific investigations. Each process can be quantified with a simple surrogate from readily available GIS-data layers with relatively simple, well-known procedures. Even within the GVC, a hierarchy exists for the geomorphic variables (see Figure 1) and is critical in the determination of the final valley classes (Table 2). The interplay between the three processes highlights the interconnectedness of the fluvial and hillslope components (Brierley and Fryirs, 2005; Wohl *et al*., 2007).

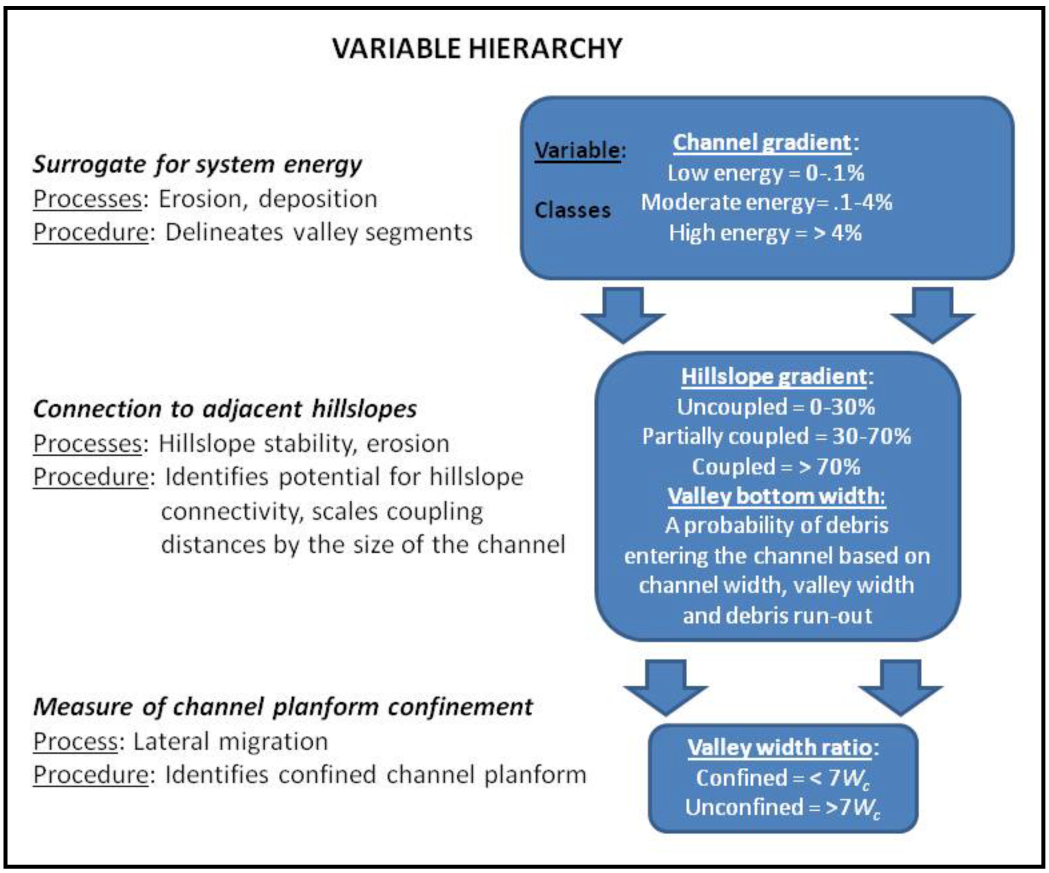

Figure 1: The variable hierarchy used to constrain processes and landforms at successively finer scales.

A direct comparison between the approach to valley classification presented by Rosgen (1994, 1996) and classes of the GVC defined in Tables 2 is warranted as Rosgen's approach has been widely used for the last fifteen years in public and private land management (Table 3).

Table 2: Valley classification names and attributes of the GVC.

Valley Class Name	Energy / Valley Gradient	Valley Bottom Width / Coupling / Confinement	Hillslope Gradient	Energy Potential
Headwaters	> 4%	< (2 L_D + W_{BF})	Both > 30%	High
High-energy Coupled	> 4%	< (2 L_D + W_{BF}) or < (L_D + W_{BF})	Both or at least one > 30%	High
High-energy Open	> 4%	> (2 L_D + W_{BF})	Both or at least one > 30%	High
Moderate-energy Confined	0.1-4%	< 7 W_{BF}	Variable	Moderate
Moderate-energy Unconfined	0.1-4%	> 7 W_{BF}	Variable	Moderate
Canyon	Variable	> 3 W_{BF}	> 70%	Moderate to High
Gorge	Variable	< 3 W_{BF}	> 70%	Moderate to High
Glacial Trough**	< 4%	> (2 L_D + W_{BF})	~ 10-% initially steepening to > 30%	Moderate to Low
Low-energy Floodplain	< 0.1%	> 7 W_{BF}	Generally < 30%	Low

L_D – length of debris runout W_{BF} - width of channel at bankfull stage

** Defined as valleys with the given characteristics, lying above the elevation of the most recent glacial activity

Table 3: A comparison between GVC valley classes and Rosgen (1994) valley types.

GVC				Rosgen (1994)			
Valley Class	Channel Gradient	Confinement	Hillslope Gradient	Valley Type	Channel Gradient	Confinement	Hillslope Gradient
Headwater	> 4%	Confined	Steep	1	> 2%	Confined	Steep
High-energy Coupled	> 4%	Confined	Steep	1	> 2%	Confined	Steep
High-energy Open	> 4%	Unconfined	Steep	2, 3, 6, 7	> 2%	Moderately confined	Moderate-Steep
Moderate-energy Confined	0.1 - 4%	Confined	Low-Steep	2, 3, 6, 7	< 4%	Confined-Moderately confined	Moderate-Steep
Moderate-energy Unconfined	0.1 - 4%	Unconfined	Low-Steep	6, 9	< 2%	Moderately confined	Moderate
Canyon	Variable	Confined	Steep	4	< 2%	Confined	Steep
Gorge	Variable	Confined	Steep	4	< 2%	Confined	Steep
Glacial Trough	< 4%	Unconfined	Moderate-Steep	5	< 4%	Unconfined	Moderate

Low-energy Floodplain	< 0.1%	Unconfined	Low-Moderate	8, 9, 10, 11	Low	Unconfined	Low

GIS Application of the Geomorphic Valley Classification

A suite of spatial techniques for analyzing river networks was developed parallel to the GVC in a robust computerized mapping environment. The code, scripts and spatial tools from ESRI ArcGIS v. 9.3 were manipulated in a protocol that yields the information about a given valley necessary to classify it using the GVC approach. Unique and novel portions of the coding are described below.

Data inputs: The single data input into the GVC Mapping Protocol is a 10-m resolution digital elevation model (DEM). Regional parameters are defined by the user as prompted, including hillslope stability analysis, elevation of glacial influence, and regression equation coefficients for estimating bankfull channel width (see Faustini et al. 2009). Defaults are provided within the Protocol, but are based on regional mean values.

Three spatial analysis modules: The spatial analysis of a given river network in the GVC can be broken down into three fundamental spatial analysis modules. The first module identifies the initial valley segments using a series of steps to create and smooth channel gradient into a measure of valley gradient. The raster cells are then reclassified into one of three gradient classes (High, Moderate and Low-as defined in Table 2) and grouped together. Groups of cells less than a user defined minimum are eliminated and the adjacent groups "extend" or "grow" into the empty network spaces. This gives a minimum length for valley segments. We recommend nothing smaller than 200m, as channel scale processes become more dominant below that distance and are more difficult to predict in GIS with current data limitations. The resulting segments are used throughout the remaining analysis as the defined valley segment network.

The second module examines the topographic and hydrologic attributes of each valley segment individually. A Q100 discharge (100-yr peak flow) is estimated for every valley segment using the equations from the USGS National Stream flow Statistics Program (http://water.usgs.gov/osw/programs/ nss/summary.html). This module employs Manning's equation to the DEM in order to extract the flood elevation that corresponds to the volume of water predicted by the Q100 estimation. The flood elevation is used to create the 'hydrologic' valley bottom. It is also used to limit the extent to which the landscape is analyzed to identify breaks-in-slope.

Following the NRP riparian definition, the Q100 is the default riparian boundary, but we wanted to incorporate the unique topography into a more descriptive valley extent. The horizontal area within a vertical distance above the channel (related to Q100) is used to define the area over which to examine breaks-in-slope. This extent is mirrored by a lower extent, defined as a factor of bankfull channel width, essentially creating an annulus (Figure 2) where the analysis of the break-in-slope occurs.

The *lowest* values of the curvature are the *most* concave cells (darker red). The 20% most concave cells (lowest values) within the area of analysis are extracted and their elevation above the channel is averaged and used to create a second valley bottom layer is created. These two layers are combined by reporting only the areas where they overlap, the *hydro-geomorphic* valley bottom (Figure 3). This is the ultimate representation of the valley extent used in the final classification.

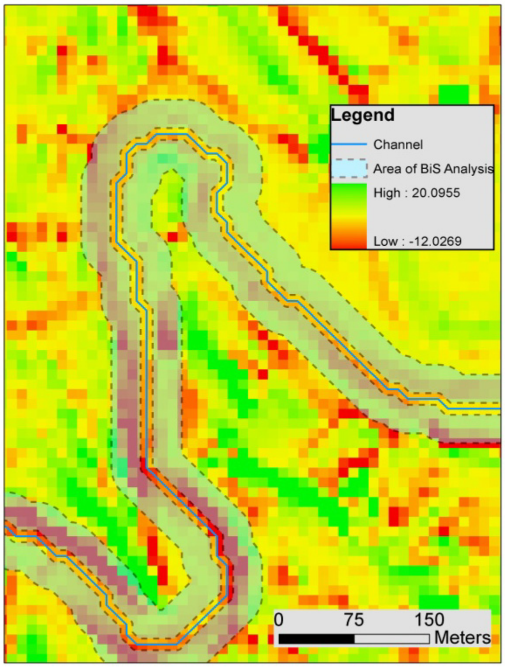

Figure 2-The area used to analyze the topography for breaks in slope

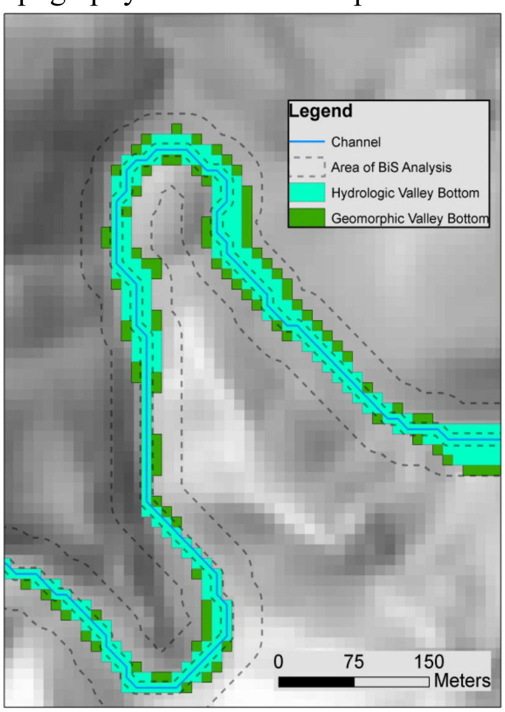

Figure 3-Overlay of hydrologic and geomorphic valley bottoms

The final module examines the adjacent landscape for its potential influence on the valley bottom through confinement and colluvial inputs. The adjacent slopes are categorized by gradient into three classes (Steep, Moderate, Low). All three affect confinement of the channel, while only Steep and Moderate have the potential to contribute colluvial material and are employed as the "'steep'sides" variable from Equation 4. It would be very difficult to examine hillslopes using cross-sections oriented transverse to the channel to obtain the slopes necessary for categorizing gradient. Instead we use a composition of the slopes, as a percentage of the slope in each of the three gradient classes. The proportions then give a slope its final category.

The second and third modules described above are completed automatically following the proper designation of files and parameter inputs. It is important to note that the valley bottoms are created and hillslopes analyzed on *a segment by segment* basis which makes this a more robust methodology.

Final Classification

The final classification is performed when all spatial layers have been created. Two additional calculations are completed to give values such as the ratio of valley width the channel width (used to determine confinement) and the coupling statistic. The entire protocol is set up in a series of three main steps: 1) create the initial valley segments, 2) manually edit inconsistencies in the valley segments and 3) create the valley bottom, analyze the hillslopes and classify the valley. Step 1 is a tool built in ArcGIS 9.3 and Step 3 is a Python script run within ArcMap as tool. Step 2 is a necessary manual step that allows the user to become familiar with the outputs to identify and address any errors.

Field Testing

Three study regions in three western states were chosen to test the GVC; two were located on USFS land and one was located on a combination of Bureau of Land Management (BLM), State of Wyoming, and private land. Forty-two field sites were visited: 17 in Arizona, 14 in Colorado, and 11 in Wyoming. Five ecoregions were encountered, each characterized by different climates, geology, and supporting unique species pools. Sizes of the watersheds examined were varied to capture differences inherent with gross size of the system (Table 7.2). Vegetation was dramatically different between the three study regions, ranging from desert to deep coniferous forests. Flow regimes also varied dramatically; for example, Cherry Creek in Tonto NF records its highest average monthly discharge in February and lowest in June, while the Fraser River in the Arapahoe NF records the exact opposite trend (USGS, 2009).

Table 4: Study area basin parameters showing the major stream name, USFS unit, drainage area, eco-region, vegetation, and landscape character.

Stream Name	Forest	Drainage Area	Eco-region	Upland Vegetation	Landscape
Green River	N/A	~19400 km^2	Temperate Desert	Sagebrush	Rolling
Black's Fork	N/A	~9500 km^2	Temperate Desert	Sagebrush	Rolling
Pinal Creek	Tonto	515 km^2	Tropical / Subtropical Steppe	Spruce/Pine forest, Semi-arid shrubs	Mountain headwaters, rolling
Pinto Creek	Tonto	482 km^2	Tropical / Subtropical Steppe	Arid - Semi-arid shrubs	Rolling
Cherry Creek	Tonto	720 km^2	Tropical / Subtropical Steppe; Tropical / Subtropical Regime Mountains	Spruce/Pine Forest, Semi-arid shrubs	Mountain headwaters, rolling
Williams Fork	Arapaho	370 km^2	Temperate Steppe Regime Mountains	Spruce/Pine/Fir forest	Mountain
St. Louis Creek	Arapaho (Fraser Experimental Forest)	96 km^2	Temperate Steppe Regime Mountains	Spruce/Pine/Fir forest	Mountain
Fraser River	Arapaho	78 km^2	Temperate Steppe Regime Mountains	Spruce/Pine/Fir forest	Mountain

N/A – not applicable

The under-estimation of slope values in GIS has been well-documented (Brardioni and Hassan, 2006). This investigation proved no different, as field values were higher than GIS values by 160, 83, and 48% for the Wyoming, Arizona, and Colorado study regions, respectively. Of the 42 field sites, 17 had channel gradients misclassified in GIS that led to the designation of a different energy regime. The under-estimation of gradient in GIS was common throughout all study regions and prompted the lowering of the GIS threshold between High- and Moderate-energy from 4% to 3%.

For the valley bottom width variable, the discrepancies between field and GIS values were the lowest of any variable. Differences were 27, 58, and only 8% for Wyoming, Colorado, and Arizona study regions, respectively. This was not expected and suggests that the measure of confinement is the most robust geomorphic variable for this data set. HEC-GeoRAS comparison to GIS data showed vast differences in the fluvial valley bottom extent identified by the modeled 100-yr flood extent and the GIS method used in the GVC. As predicted, the GVC method for identifying valley extent preformed better at the 1-m scale compared to the 10-m scale when using the Q100 extent from HEC-GeoRAS as the “true” extent.

Brardioni and Hassan (2006) also found that hillslope angles measured in GIS were routinely under-estimated in steep areas, and over-estimated in low gradient, depositional environments. As expected, the least amount of difference occurred in the Colorado study region. Here slopes were generally steep, which means that the contour lines from which the DEM was digitized and subsequently interpolated between are closer together. This equates to more data points within a given area and thus a more accurate value. The values in the Arapaho NF in Colorado had the differences of 20 to 50% between GIS and field-observed values. Hillslopes in Wyoming were the most poorly represented with disparities between field-observed values and GIS of values of 150 to 250%.

The poor identification of vertical hillslopes was most apparent in Arizona, where several Canyons were misidentified because they lacked the excessively steep hillslopes characteristic of

Canyons. Vertical and nearly vertical hillslopes are the key delineative criteria for Canyons and Gorges, along with a narrow valley bottom width. Lacking accurate hillslope classification likely led to the misclassification of Canyons as Moderate-energy Confined and High-energy Coupled valley classes.

In general, the testing, results, and subsequent analysis of the GVC classification and the GIS procedures illuminated some interesting successes and shortcomings. Qualitative field observations of the GVC generally succeed in identify logical breaks in geomorphic and ecological function at the valley scale; however, the quantification for the classification and the GIS procedures was not statistically robust, owing to the limited number of "sites" (42) in the field spread between 3 study regions, and 22 cross sections in HEC-GeoRAS. Despite these limitations, general patterns and shifts in valley setting could still be detected using the GIS-based approach.

Summary

The Geomorphic Valley Classification is a framework for stratifying fluvial riparian systems that aids in regional and landscape scale management decisions. The process-informed classification is simple, requires minimal data inputs, and is executed using a common GIS platform. The thresholds separating process groups are supported by detailed hydrologic, geomorphic and hydraulic research. In particular, the GVC builds upon work by Montgomery and Buffington (1993), Nanson and Croke (1992), Whiting and Bradley (1993) to create a widely applicable, process-based hierarchy to classify river networks. The GIS procedure has been developed as a semi-automated protocol for creating the necessary data layers to accurately assess the geomorphic structure of river networks. The open framework prompts users to specify local or regionally-calibrated values for thresholds such as the lower limit for unstable hillslope angle, debris run-out length, and a contributing area for valley initiation. Additional details on the GVC methodology are presented in Carlson (2009).

The GIS procedure was developed as a mix of accepted approaches, modified existing methods, and novel means of extracting geomorphic information from readily available DEM data. A novel approach to delineating fluvial valley bottoms was introduced at the center of the GIS procedures. The method for quantifying valley bottom width identifies changes in gradient of the land adjacent to the channel. This method extends a similar approach to evaluating relative surface slope and elevation as a method to characterize landforms (the TPI from Jenness (2006)) by adding components of hydrology to constrain the measurements around the channel.

Errors begin to accumulate immediately in GIS when using remotely-sensed data because the input layers are approximations of true values. Errors are further introduced by GIS procedures and smoothing algorithms. An analysis of error propagation was not performed in the study but it is understood that significant differences between remotely-sensed values and field values exist in some instances. For example, results indicate that the present GIS procedures do not perform satisfactorily when identifying channel gradients less than 0.1%.

With a limited number of test sites (42 field and 22 HEC-GeoRAS), the relatively large number of valley classes (9), and the amount of climate, geologic, and vegetation variability among the six ecoregions does not allow accurate estimates of misclassification rates. A larger data set of verified valleys would permit the examination classification strengths and perhaps illuminate problems with threshold values or measurement techniques.

The regions of the western US where the GVC is hypothesized to be the most accurate are in areas with high relief and wider valley bottoms. High-relief areas will provide a more accurate measure of channel and hillslope gradients, and wider valley bottoms limit the effect of horizontal data resolution on smaller valleys. In general, the technique performed relatively well in Colorado in the estimation of slope and hillslope angles as compared to other regions.

Regions of expected poor performance include extremely flat systems, with gradients less than 0.1%. The current measurement techniques cannot examine slopes below this value. Land highly dissected with canyons or arroyos are also expected to have higher misclassification rates because the valley morphology is often too narrow for the horizontal resolution of the 10-m DEMs. Highly-dissected regions also have the issue that the hillslopes may not be 150-m long, and land that drains to a different channel or the inclusion of a nearby valley bottom could skew the hillslope categorization. LiDAR or field reconnaissance would be necessary to identify canyons or arroyos with widths less than 10 m.

References

Adamus, P. 2004. Classification, assessment, monitoring and evaluation of riverine and palustrian wetland ecosystems. Pages 277-296 *in* M.C. McKinstry, W.A. Hubert, and S.H. Anderson (Eds.), Wetland and Riparian Areas of the Intermountain West: Ecology and Management, Chapter 12, Austin, TX: University of Texas Press.

Andrle, R. 1996. Measuring channel planform of meandering rivers. *Physical Geography* 17:270-281.

Bagnold, R.A. 1960. Some aspects of the shape of river meanders. *U.S. Geological Survey Professional Paper 282D*, pp. 135-144.

Bagnold, R.A. 1966. An approach to the sediment transport problem from general physics. *U.S. Geological Survey Professional Paper 422-I*.

Bailey, R.G. 1983. Delineation of ecosystem regions. *Environmental Management* 7:365-373.

Bailey, R.G. 1987. Suggested hierarchy of criteria for multi-scale ecosystem mapping. *Landscape and Urban Planning* 14:313-319.

Bailey, R.G. 1995. Descriptions of the Ecoregions of the United States (2nd Edition). *Miscellaneous Publication No. 1391*, Map scale 1:7,500,000, U.S. Department of Agriculture, Forest Service, 108 pp.

Bathurst, J.C., Burton, A., and Ward, T.J. 1997. Debris flow run-out and landslide sediment delivery model tests. ASCE, *Journal of Hydraulic Engineering* 123:410-419.

Beechie, T.J., Liermann, M., Pollock, M.M., Baker, S., and Davies, J. 2006. Channel pattern and river-floodplain dynamics in forested mountain river systems. *Geomorphology* 78:124-131.

Benda, L.E., Hassan, M.A., Church, M., and May, C.L. 2005. Geomorphology of steepland headwaters: the transition from hillslopes to channels. *Journal of the American Water Resources Association* 41:835-851.

Benda, L.E., Miller, D., Andras, K., Bigelow, P., Reeves, G., and Michael, D. 2007. NetMap: a new tool in support of watershed science and resource management. *Forest Science* 53:206-219.
Bendix, J. and Hupp, C.R. 2000. Hydrological and geomorphological impacts on riparian plant communities. *Hydrological Processes* 14:2977-2990.
Bracken, L.J. and Croke, J. 2007. The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. *Hydrological Processes* 21:1749-1763.
Brardioni, F. and Hassan, M.A. 2006. Glacial erosion, evolution of river long profiles, and the organization of process domains in mountain drainage basins of coastal British Columbia. *Journal of Geophysical Research* 111:1-12.
Brierley, G.J. and Fryirs, K.A. 2000. River styles, a geomorphic approach to catchment characterization: implications for river rehabilitation in Bega Catchment, New South Wales, Australia. *Environmental Management* 25:661-679.
Brierley, G.J. and Fryirs, K.A. 2005. Geomorphology and River Management. Blackwell Publishing, 398 p.
Brinson, M.M. 1993. A hydrogeomorphic classification for wetlands. *Technical Report WRP-DE-4*, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.
Brookes, A. 1985. The impact of river channelization, III: downstream morphological consequences of river channelization in England and Wales. *Geographical Journal* 151:57-62.
Bull, W.B. 1997. Discontinuous ephemeral streams. *Geomorphology* 19:227-276.
Campreale, C., Perona, P., Porporato, A., and Ridolfi, L. 2005. On the long-term behavior of meandering rivers. *Water Resources Research* 41:1-13.
Carlson, E.A. 2009. Fluvial riparian classification for national forests in the western United States. M.S. Thesis. Colorado State University.
Castro, J.M. and Jackson, P.L. 2001. Bankfull discharge recurrence intervals and regional hydraulic geometry relationships: patterns in the Pacific Northwest, USA. *Journal of the American Water Resources Association* 37:1249-1262.
Chapin, D.M., Beschta, R.L., and Shen, H.W. 2000. Flood frequencies required to sustain riparian plant communities in the Upper Klamath Basin, Oregon. Pages 17-22 *in* Riparian Ecology and Management in Multi-land Use Watersheds, Middleburg, VA: American Water Resources Association, 616 p.
Church M. 1992. Channel morphology and typology. Pages 126-143 *in* P. Calow and G.E. Petts (Eds.), The Rivers Handbook, Vol. 1, Oxford: Blackwell Science, 526 p.
Church, M. 2002. Geomorphic thresholds in riverine landscapes. *Freshwater Biology*, 47:541-557.
Church, M. 2006. Bed material transport and the morphology of alluvial channels. *Annual Review of Earth Plant Science* 34:325-354.
Clarke, S.E. and Burnett, K.M. 2003. Comparison of digital elevation models for aquatic data development. *Photogrammetric Engineering and Remote Sensing* 69:1367-1365.
Clarke, S.E., Burnett, K.M., and Miller, D.J. 2008. Modeling streams and hydrogeomorphic attributes in Oregon from digital and field data. *Journal of the American Water Resources Association* 44:459-477.
Collotzi, A.W. 1976. A systematic approach to the stratification of the valley bottom and the relationship to land use planning. Technical draft report, Jackson, WY.
Colorado State Forest Service. 2005. Report on the health of Colorado's forests. Colorado Department of Natural Resources Division of Forestry, Denver, CO, 32 p.
Cuhaciyan, C.O. 2006. Hydrogeomorphic characterization and classification of Pacific Northwest mountain streams for biomonitoring. Unpublished doctoral dissertation, Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, CO.
Cupp, E.C. 1989. Valley segment type classification for forested lands in Washington. Timber, Fish and Wildlife Ambient Monitoring Program, Washington Forest Protection Association.
Dalla Fontana, G. and Marchi, L. 2003. Slope-area relationships and sediment dynamics in two alpine streams. *Hydrologic Processes* 17:73-87.

Dodov, B. and Foufoula-Georgiou, E. 2005. Fluvial processes and streamflow variability: interplay in the scale-frequency continuum and implications for scaling. *Water Resources Research* 41:1-18.

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

Dury, G.H. 1960. Misfit streams: problems in interpretation, discharge, and distribution. *Geographical Review* 50:219-242.

Eaton, B.C. and Church, M. 2007. Predicting downstream hydraulic geometry: a test of rational regime theory. *Journal of Geophysical Research Earth Surface* 114:1-18.

Fannin, R.J. and Wise, M.P. 2001. An empirical-statistical model for debris flow travel distance. *Canadian Geotechnical Journal* 38:982-994.

Faustini, J.M., Kaufmann, P.R., and Herlihy, A.T. 2009. Downstream variation in bankfull width of wadeable streams across the Conterminous United States.

Ferguson, R.I. 1973. Channel pattern and sediment type. *Area* 5:38-41.

Ferguson, R.I. 1979. River meanders: regular or random? Pages 229-241 *in* N. Wrigley (Ed.), Statistical Applications in the Spatial Sciences, London: Pion.

Ferguson, R.I. 1993. Understanding braiding processes in gravel-bed rivers: progress and unsolved problems. Pages 73-88 *in* J.L. Best and C.S. Bristow (Eds.), Braided Rivers, Geological Society of London, Oxford, UK: Oxford Press.

Fisher, S.G., Heffernan, J.B., Sponseller, R.A., and Welter, J.R. 2007. Functional ecomorphology: feedbacks between form and function in fluvial landscape ecosystems. *Geomorphology* 89:84-96.

Flores, A.N., Bledsoe, B.P., Cuhaciyan, C.O., and Wohl, E.E. 2006. Channel-reach morphology dependence on energy, scale, and hydroclimatic processes with implications for prediction using geospatial data. *Water Resources Research* 42:1-15.

Fredsoe, J. 1978. Meandering and braiding of rivers. *Journal of Fluid Mechanics* 84:609-624.

Frissell, C.A., Liss, W.J., Warren, C.E., and Hurley, M.D. 1986. A hierarchical framework for stream habitat classification: viewing streams in a watershed context. *Environmental Management* 10:199-214.

Gangodagamage, C., Barnes, E., and Foufoula-Georgiou, E. 2007. Scaling in river corridor widths depicts organization in valley morphology. *Geomorphology* 91:198-215.

Goebel, P.C., Pregitzer, K.S., and Palik, B.J. 2006. Landscape hierarchies influence ground-flora communities in Wisconsin, USA. *Forest Ecology and Management* 230:43-54.

Golden, L.A. and Springer, G.S. 2006. Channel geometry, median grain size and stream power in small mountain streams. *Geomorphology* 78:64-76.

Goodwin, C. 1999. Fluvial classification: Neanderthal necessity or needless normalcy. *Wildland Hydrology* 229-236.

Graf, W.L. 1983. Downstream changes in stream power in the Henry Mountains, Utah. *Annals of the Association of American Geographers* 73:373-387.

Grant, G. E., F. J. Swanson, and M.G. Wolman. 1990. Pattern and origin of stepped bed morphology in high-gradient streams, Western Cascades, Oregon. *Geol. Soc. Am. Bull*. 102: 340-352.

Gregory, K.J. and Walling, D.E. 1973. Drainage Basin Form and Process. A Geomorphological Approach. London: Edward Arnold, 458 p.

Gregory, S.V., Swanson, F.J., McKee, W.A., and Cummins, K.W. 1991. An ecosystem perspective of riparian zones. *BioScience* 41:540-551.

Hagerman, J.R. and Williams, J.D. 2000. Meander shape and the design of stable meanders. *Riparian Ecology and Management in Multi-land Use Watersheds* August: 563-568.

Hancock, G.R. and Evans, K.G. 2006. Channel head location and characteristics using digital elevation models. *Earth Surface Processes and Landforms* 31:809-824.

Hansen, W.F. 2001. Identifying stream types and management implications. *Forest Ecology and Management* 143:39-46.

Harvey, A.M. 2001. Coupling between hillslopes and channels in upland fluvial systems: implications for landscape sensitivity, illustrated from the Howgill Fells, northwest England. *Catena* 42:225-250.

Harvey, A.M. 2007. Differential recovery from the effects of a 100-year storm: significance of longterm hillslope-channel coupling; Howgill Fells, northwest England. *Geomorphology* 84:192-208.

Hemstrom, M.A, Smith T., Evans D., Clifton, C., Crowe, E., and Aitkin, M. 2002. Midscale analysis of streamside characteristics in the Upper Grande Ronde Subbasin, Northeastern Oregon. U.S. Department of Agriculture, Forest Service Pacific Northwest Research Station, 20 p.

Hey, R.D. 2006. Fluvial geomorphological methodology for natural stable channel design. *Journal of the American Water Resources Association* 42:357-374.

Hupp, C.R. and Osterkamp, W.R. 1985. Bottomland vegetation distribution along Passage Creek, Virginia, in relation to fluvial landforms. *Ecology* 66:680-691.

Hupp, C.R. and Osterkamp, W.R. 1996. Riparian vegetation and fluvial geomorphic processes. *Geomorphology* 14:277-295.

Hurley, M. and Jensen, M.E. 2001. Geomorphic patterns, processes, and perspectives in aquatic assessment. Pages 367-389 *in* M.E. Jensen and P.S. Bourgeron (Eds.), A Guidebook for Integrated Ecological Assessments, New York, NY: Springer.

Hynes, H.B.N. 1975. The stream and its valley. *Verh. Int. Ver. Theor. Angew. Limnol*. 19:1-15.

Innis, S.A., Naiman, R.J., and Elliot, S.R. 2000. Indicators and assessment methods for measuring the ecological integrity of semi-aquatic terrestrial environments. *Hydrobiologia* 422/423:111-131.

Ikeya, H. 1981. A method of designation for area in danger of debris flow. Pages 576-588 *in* Erosion and Sediment Transport in the Pacific Rim Steeplands, IAHS Publication, 132 p.

Jain, V., Fryirs, K., and Brierley, G. 2008. Where do floodplains begin? The role of total stream power and longitudinal profile form on floodplain initiation processes. *GSA Bulletin* 120:127-141.

Jenness, J. 2006. Topographic Position Index (tpi_jen.avx) extension for ArcView 3.x, v. 1.3a. Jenness Enterprises. Available: http://www.jennessent.com/arcview/ tpi.htm.

Jensen, M.E., Goodman, I.A., Frissell, C.A., Brewer, C.K., and Bourgeron, P.S. 2001. Ecological classification and mapping of aquatic systems. Pages 352-366 *in* M.E. Jensen and P.S. Bourgeron (Eds.), A Guidebook for Integrated Ecological Assessments. New York, NY: Springer.

Johnson, A.C., Swanston, D.N., and McGee, K.E. 2000. Landslide initiation, runout and deposition within clearcuts and old-growth forests in Alaska. *Journal of the American Water Resources Association* 36:17-30.

Kellerhals, R., Church, M., and Bray, D.I. 1976. Classification of river processes. ASCE, *Journal of the Hydraulics Division* 102:813-829.

Knighton, D.A. 1998. Fluvial Forms and Processes: A New Perspective. New York, NY: Oxford University Press, 383 p.

Knighton, D.A. 1999. Downstream variation in stream power. *Geomorphology* 29:293-306.

Knighton, D.A. and Nanson, G.C. 1993. Anastamosis and the continuum of channel pattern. *Earth Surface Processes and Landforms* 18:613-615.

Knopf, F.L. and Samson, F.B. 1994. Scale perspectives on avian diversity in western riparian ecosystems. *Conservation Biology* 8:669-676.

Langbein, W.B. 1966. River meanders: theory of minimum variance. *U.S. Geological Survey Professional Paper 422L*.

Lecce, S.A. 1997. Spatial patterns of historical overbank sedimentation and floodplain evolution, Blue River, Wisconsin. *Geomorphology* 18:265-277.

Leopold, L.B. and Langbein, W.B. 1966. River Meanders. *Scientific American* June:60-70.

Leopold, L.B. and Wolman, M.G. 1957. River channel patterns: braided, meandering and straight. *U.S. Geological Survey Professional Paper 282-B*, 51 p.

Leopold, L.B. and Wolman, M.G. 1960. River meanders. *Geological Society of America Bulletin* 71:769-794.

Lorente, A., Begueria, S., Bathurst, J.C., and Garcia-Ruiz, J.M. 2003. Debris flow characteristics and relationships in the Central Spanish Pyrenees. *Natural Hazards and Earth System Sciences* 3:683-692.

Lunetta, R.S., Consentino, B.L., Montgomery, D.R., Beamer, E.M., and Beechie, T.J. 1997. GIS-Based evaluation of Salmon habitat in the Pacific Northwest. *Photogrammetric Engineering & Remote Sensing* 63:1219-1229.

Mac Nally, R., Molyneux, G., Thomson, J.R., Lake, P.S., and Read, J. 2008. Variation in widths of riparian-zone vegetation of higher-elevation streams and implications for conservation management. *Plant Ecology* 198:89-100.

Magilligan, F.J. 1992. Thresholds and the spatial variability in stream power during extreme floods. *Geomorphology* 5:373-390.

McNamara, J.P., Ziegler, A.D., Wood, S.H., and Vogler, J.B. 2006. Channel head locations with respect to geomorphologic thresholds derived from a digital elevation model: a case study in northern Thailand. *Forest Ecology and Management* 224:147-156.

Michaelides, K. and Wainwright, J. 2002. Modeling the effects of hillslope-channel coupling on catchment hydrological response. *Earth Surfaces Processes and Landforms* 27:1441-1457.

Montgomery, D.R. 1999. Process domains and the river continuum. *Journal of the American Water Resources Association* 35:397-410.

Montgomery, D. and Foufoula-Georgiou, E. 1993. Channel network source representation for digital elevation models. *Water Resources Research* 29:3925-3934.

Montgomery, D.R and Buffington, J.M. 1997. Channel-reach morphology in mountain drainage basins. *GSA Bulletin* 109:596-611.

Montgomery, D.R. and Buffington, J.M. 1998. Channel processes, classification and response. *In* R. Naiman and R. Bilby (Eds.), River Ecology and Management.

Moore, K., Jones, K.K., and Dambacher, J. 2002. Methods for Stream Habitat Surveys Aquatic Inventories Project. Natural Production Program, Oregon Department of Fish and Wildlife, Corvallis, OR, Available: http://oregonstate.edu/Dept/ODFW/ freshwater/inventory/pdffiles/habmethod.pdf, accessed July 2008.

Nakamura, F., Yajima, T., and Kikuchi, S. 1997. Structure and composition of riparian forests with special reference to geomorphic site conditions along the Tokachi River, northern Japan. *Plant Ecology* 133:209-219.

Naiman, R.J., Lonzarich, D.G., Beechie, T.J., and Ralph, S.C. 1992. General principles of classification and the assessment of conservation potential in rivers. Pages 92-123 *in* P.J. Boon, P. Calow, and G.E. Betts (Eds.), River Conservation and Management, New York, NY: John Wiley and Sons.

Naiman, R.J. and Decamps, H. 1997. The ecology of interfaces: riparian zones. *Annual Review of Ecology Systems* 28:621-658.

Naiman, R.J., Decamps, H., and McClain, M.E. 2005. Riparia: Ecology, Conservation and Management of Streamside Communities. London, UK: Elsevier Academic Press.

Nanson, G.C. and Croke, J.C. 1992. Genetic classification of floodplains. *Geomorphology* 4:459-486.

Nardi, F., Vivoni, E.R., and Grimaldi, S. 2006. Investigating a floodplain scaling relation using a hydrogeomorphic delineation method. *Water Resources Research* 42:1-15 (W09409).

National Research Council. 2002. Riparian Areas, Functions and Strategies for Management. Washington, DC: National Academy Press, 428 p.

Newson, M.D., Clark, M.J., Sear, D.A., and Brookes, A. 1998. The geomorphological basis for classifying rivers. *Aquatic Conservation: Marine and Freshwater Ecosystems* 8:415-430.

O'Callaghan, J.F. and Mark, D.M. 1984. The extraction of drainage networks from digital elevation models. *Computer Vision, Graphics and Image Processing* 28:323-344.

O'Connor, M. and Watson, G. 1998. Geomorphology of channel migration zones and implications for riparian forest management. Available: http://www.oei.com/ Reports/Geomorph_of_CMZ.htm.

Omernik, J.M. 1987. Ecoregions of the conterminous United States. *Annals of the Association of American Geographers* 77:118-125.

Orr, H.G., Large, A.R.G, Newson, M.D., and Walsh, C.L. 2008. A predictive typology for characterizing hydromorphology. *Geomorphology* 100:32-40.

Parsons, M. and Thomas, M.C. 2007. Patterns of physical-biological associations in river ecosystems. *Geomorphology* 89:127-146.

Petit, F., Gob, F., Houbrechts, G., and Assani, A. A. 2005. Critical specific stream power in gravel-bed rivers. *Geomorphology* 69:92-101.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., and Stromberg, J.C. 1997. The natural flow regime: a paradigm for river conservation and restoration. *BioScience* 47:769-784.

Poff, N.L., Bledsoe, B.P., and Cuhaciyan, C.O. 2006. Hydrologic variation with land use across the contiguous United States: Geomorphic and ecological consequences for stream ecosystems. *Geomorphology*, 79:264-285.

Polvi, L.E. 2009. Characterization of riparian zones in mountain of valleys of the Colorado front range. Unpublished master dissertation, Colorado State University, Fort Collins, CO.

Poole, G.C. 2002. Fluvial landscape ecology: addressing uniqueness within the river discontinuum. *Freshwater Biology* 47:641-660.

Pyne, M.I., Rader, R.B., and Christensen, W.F. 2007. Predicting local biological characteristics in streams: a comparison of landscape classifications. *Freshwater Biology*, 52:1302-1321.

Quinn, J., Taylor, A., Boyce, W., and Fenton, T. 2000. Riparian zone classification improves management of stream water quality and aquatic ecosystems. Pages 451-456 *In* Riparian Ecology and Management in Multi-land Use Watersheds. Middleburg, VA: American Water Resources Association, 616 p.

Rheinhardt, R.D., Brinson, M.M., Christian, R.R., Miller, K.H., and Meyer, G.F. 2007. A reference-based framework for evaluating the ecological condition of stream networks in small watersheds. *Wetlands* 27:524-542.

Rosgen, D.L. 1994. A classification of natural rivers. *Catena* 22:169-199.

Rosgen, D.R. 1996. Applied River Morphology. Pagosa Springs, CO: Wildland Hydrology.

Sarr, D.A. and Hibbs, D.E. 2007. Woody riparian plant distributions in western Oregon, USA: comparing landscape and local scale factors. *Plant Ecology* 190:291-311.

Schumm, S.A. 1977. *The Fluvial System*. New York, NY: Wiley-Interscience, 338 p.

Schumm, S.A. and Khan, H.R. 1972. An experimental of channel patterns. *Bulletin of the Geological Society of America* 83:1755-1770.

Schumm, S.A., Harvey, M.D. and Watson, C.C. 1984. Incised Channels: Morphology Dynamics and Control. Littleton, CO: Water Resources Publications, 200 p.

Schuster, R.L. and Highland, L.M. 2007. Overview of the effects of mass wasting on the natural environment. *Environmental & Engineering Geoscience* 13:25-44.

Scott, M.L. and Reynolds, E.W. 2007. Field-based evaluations of sampling techniques to support long-term monitoring of riparian ecosystems along wadeable streams on the Colorado Plateau. *U.S. Geological Survey Open File Report 2007-1266*.

Sear, D.A., Newson, M.D., and Thorne, C.R. 2003. Guidebook of applied fluvial geomorphology. *R&D Technical Report FD1914*, Defra, Flood Management Division, London, UK.

Shih, H. and Yang, C.T. 2009. Estimating overland flow erosion capacity using unit stream power. *International Journal of Sediment Research* 24:46-62.

Sidle, R.C. and Ochiai, H. 2006. Landslides – processes, prediction and land use. *Water Resources Monograph 18*, American Geophysical Union, Washington, DC, 312 p.

Simon, A. 1989. A model of channel response in disturbed alluvial channels. *Earth Surface Processes and Landforms* 14:11-26.

Simon, A. and Darby, S.E. 1999. The Nature and Significance of Incised River Channels. Pages 3-18 *in* S.E. Darby and A. Simon (Eds.), Incised River Channels, Chichester, UK: John Wiley and Sons Ltd.

Sinha, R. and Friend, P.F. 1993. River systems and their sediment flux, Indo-Gangetic Plains, Northern Bihar, India. *Sedimentology* 41:825-845.

Snelder, T.H. and Biggs, B.J.F. 2002. Multi-scale river environment classification for water resources management. *Journal of the American Water Resources Association* 38:1225-1240.

Snelder, T.H., Weatherhead, M., and Biggs, B.J.F. 2004. Nutrient concentration criteria and characterization of patterns in trophic state for rivers in heterogeneous landscapes. *Journal of the American Water Resources Association*, 40:1-13.

Snelder, T.H., Biggs, B.J.F., and Woods, R.A. 2005. Improved eco-hydrological classification of rivers. *River Research and Applications* 21:609-628.

Soar, P.J. and Thorne, C.R. 2001. Channel restoration design for meandering rivers. U.S. Army Corps of Engineers, Engineer Research and Development Center, Washington, DC.

Stock, J.D. and Dietrich, W.E. 2006. Erosion of steepland valleys by debris flows. *GSA Bulletin* 118:1125-1148.

Swanston, D.N. 1991. Natural processes. Pages 1399-1417 *In* W.R. Meehan (Ed.), Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats, American Fisheries Society Special Publication 19.

Thompson, C., Croke, J., and Takken, I. 2008. A catchment-scale model of mountain stream channel morphologies in southeast Australia. *Geomorphology* 95:119-144.

Twidale, C.R. 2004. River patterns and their meaning. *Earth Science Reviews* 67:159-219.

USDA. 1977. Valley bottomland classification: an interdisciplinary approach to consider the valley resource in land management. Technical review draft, U.S. Forest Service, Ogden, UT.

USDA. 1978. Valley bottomland inventories with management implications. Technical draft, U.S. Forest Service, Ogden, UT.

USDA. 1992. Integrated riparian evaluation guide: Intermontane Region, March 1992. Ogden, UT.

USDA. 2005. Developing an image-based riparian inventory using a multistage sample: Phase I report. U.S. Forest Service, Remote Sensing Applications Center, Salt Lake City, UT.

USGS. 1994. Nationwide summary of U.S. Geological Survey regional regression equations for estimating magnitude and frequency of floods for ungaged sites, 1993. Federal Highway Administration, Reston, VA.

USGS, 1998. National Mapping Program Technical Instructions: standards for digital elevation models. U.S. Geological Survey, National Mapping Division, Available: http://rockyweb.cr.usgs.gov/public/nmpstds/demstds.html, accessed May 2006.

USGS. 2009. USGS real-time water data for USA. Available: http://waterdata.usgs. gov/nwis/rt?, accessed July 2009.

Van den Berg, J.H. 1995. Prediction of alluvial channel pattern of perennial rivers. *Geomorphology* 12:259-279.

Whiting, P.J., and J.B. Bradley. 1993. A process-based stream classification system: *Earth Surface Processes and Landforms* 18:603-612.