THESIS

FLUVIAL RIPARIAN CLASSIFICATION FOR NATIONAL FORESTS IN THE WESTERN UNITED STATES

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY ERICK A. CARLSON ENTITLED FLUVIAL RIPARIAN CLASSIFICATION FOR NATIONAL FORESTS IN THE WESTERN UNITED STATES BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

FLUVIAL RIPARIAN CLASSIFICATION FOR NATIONAL FORESTS IN THE WESTERN UNITED STATES

Riparian zones border flowing and permanent water bodies and are of great ecological and economic importance. These biologically-rich and geomorphically-dynamic areas function as ecological systems, which critically influence water quality, hydrologic processes, bio-geochemical cycling, and species distributions. A need for a robust, broadly-applicable fluvial classification for stratifying riparia across large regions was identified by the U.S. Forest Service (USFS) and led to this project, which aims to synthesize the large body of information on fluvial and riparian systems into a novel, process-based classification.

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 on USFS land; 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; 4) test the functionality and accuracy of the classification in several USFS units; and 5) create preliminary maps for several areas.

The resulting Fluvial Riparian Classification (FRC) spans multiple spatial scales from the ecoregion level to the channel reach, and emphasizes the connection between the two focal scales: 1) valley and 2) channel. The classification focuses on energy, hillslope coupling, and lateral confinement as primary diagnostic characteristics. Three sets of GIS procedures were developed to measure the key geomorphic variables used by the FRC using widely-available 10-m digital elevation models (DEMs). The FRC 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 FRC prompts the user to adjust specific values for hillslope stability, colluvial debris run-out, and fluvial network density.

Field testing was completed at 42 sites in five ecoregions across the western United States to assess the level of correspondence between classifications completed using GIS and field data. Results from field observations indicated a poor correlation between classifications using GIS and field data. This was associated with limitations of GIS procedures and the resolution of the digital data. Hydrologic modeling was performed with HEC-GeoRAS (a set of procedures, tools, and utilities for processing geospatial data in ArcGIS using a graphical user interface in Hydrologic Engineering Centers - River Analysis System (HEC-RAS)) and light detection and ranging (LiDAR) data to examine correspondence between GIS estimates of valley bottom width and floodplain widths associated with $Q2$ to $Q100$ flood discharges. Valley widths estimated in GIS are extremely sensitive to DEM resolution and tend to be over-estimated when calculated using 10-m DEMs when compared to $Q100$ floodplain widths and field data.

Finally, the Topographic Position Index was explored to examine a landscape classification and the effect of scale on a moving window approach to topographic analysis. The FRC framework provides a widely-transferable framework for stratifying fluvial systems in the context of management, planning, and monitoring. For example, the FRC 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 disturbances.

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My committee provided unique insight and three different perspectives on the project that has led to an accessible, flexible, straightforward product. They provided encouragement to develop new approaches for measuring, organizing, and analyzing the data. Brian and Ellen have complete familiarity with river morphology; their insight and experiences helped to develop the foundation in geomorphic processes. Dave Merritt was the project liaison with the U.S. Forest Service and helped shape the project from its inception, pushing for more work in one area or another. His insight into land-management agencies will improve this project's utility.

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LIST OF SYMBOLS, UNITS OF MEASURE, AND ABBREVIATIONS

Symbols

a	parameter
A	drainage area
A_m	meander amplitude
b	parameter
B	meander belt width
C	coupling probability
D	scale-independent percent difference
D_{50}	median grain size
DR	debris flow run-out
E	expected values
G_c	channel gradient
G_h	hillslope gradient
h	depth of a given stream grid cell
L	depositional zone of the hillslopes
L_d	debris run-out length
n	Manning's roughness
O	observed values
q	unit discharge
Q	discharge (m^3/s)

$Q2$	2-yr recurrence interval discharge
$Q100$	100-yr recurrence interval discharge
s	energy slope (m/m)
W/D	width-to-depth
W_c	bankfull channel width
W_u	un-channelized width of the valley bottom
W_v	total valley width
x	horizontal distance
y	vertical distance
α	constant
β	constant
γ	specific weight of water (9,810 N/m^3)
λ	wavelength
τ	mean boundary shear stress
τ_{cr}	critical shear stress
φ	$(P - 1)/P$, where P is the sinuosity

Units

km	kilometer(s)
km^2	square kilometer(s)
hr	hour(s)
m	meter(s)
m/m	meter(s) per meter

m/m^2	meter(s) per square meter
m^2/s	square meter(s) per second
m^3/s	cubic meter(s) per second
N/m^3	Newton(s) per cubic meter
%	percent
W/m^2	Watt(s) per square meter
yr	year(s)

Abbreviations

Arapaho NF	Arapaho National Forest
BiS	breaks-in-slope
BLM	Bureau of Land Management
CEM	channel evolution model
DEM	digital elevation model
ESRI	Environmental Systems Research Institute
FEMA	Federal Emergency Management Agency
FRC	Fluvial Riparian Classification
GIS	geographic information systems
GPS	global positioning system
HEC-GeoRAS	a set of procedures, tools, and utilities for processing geospatial data in ArcGIS using a graphical user interface in Hydrologic Engineering Centers - River Analysis System (HEC-RAS)
ID	identification

LiDAR	light detection and ranging
LWD	large woody debris
N/A	not applicable
NRC	National Research Council
PDC	Process Domain Concept
®	registered
TIN	triangulated irregular network
Tonto NF	Tonto National Forest
TPI	Topographic Position Index
US	United States
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
VWI	valley width index

CHAPTER 1

INTRODUCTION

1.1 NEED

Arguably the most important and coveted resource in the West is water. Understanding the origins, paths, and destinations of the precipitation that traverses the western landscape is pivotal to its management. Flowing water and associated riparian communities provide a disproportionate amount of ecosystem resources compared to the area they occupy (Knopf and Samson, 1994; Naiman and Decamps, 1997). These "ribbons of green" are easily identified visually yet have a complex mosaic of physical attributes at several spatial scales (valley, channel, and habitat), which poses challenges to consistent observation and measurement.

As a resource, riparia have received much attention in recent decades as recognition of their economic, aesthetic, and ecological values has increased (National Research Council (NRC), 2002). There is an ongoing need to better understand the nature of the various landforms and habitats that border flowing water. The protection and management of riparian resources are directly linked to the identification of potential riparian areas (Hansen, 2001; NRC, 2002). Information about the extent of riparia, their geomorphic and ecological dynamics, and biotic community structure are necessary to successfully manage this valuable resource (Gregory *et al*., 1991). For example, restoration efforts require detailed knowledge of the geomorphic and ecological setting of

a degraded habitat. Reference sites can provide a benchmark for understanding natural disturbance regimes, plant assemblages, and geomorphic processes. In some situations, natural disturbance processes can restore systems just as quickly and with much fewer resources invested; the ability to identify these circumstances could prove very beneficial (NRC, 2002).

Classification schemes have been developed to describe fluvial landscapes on many scales, for many specific landforms, using scores of variables (e.g., Leopold and Wolman (1957), Collotzi (1976), Schumm (1977), Frissell *et al*. (1986), Rosgen (1994), and Montgomery and Buffington (1997)). Regional protocols developed for the Northwest, Southwest, Great Plains, etc. have been used over the past few decades with limited congruence between regions. Perpetuating these regional divergences are classifications that primarily describe a regional suite of landforms. For example, Goebel *et al*. (2006) focused their classifications on headwater streams and hillslopes in the upper Midwestern United States (US), Dodov and Foufoula-Georgiou (2005) focused primarily on floodplains, and Knighton and Nanson (1993) emphasized multi-channel complexes at the distal ends of river courses.

Landscape, valley, and channel typologies have existed for several decades (e.g., Kellerhals *et al*. (1976), Frissell *et al*. (1986), Whiting and Bradley (1993), Rosgen (1994), Montgomery and Buffington (1997), and Church (2002, 2006)). Support for these efforts has been derived from detailed field data, theoretical examinations of geomorphic processes, and remotely-sensed spatial analysis. In recent decades, automated procedures for measuring geomorphic characteristics of valleys and channels for classification using remotely-sensed data (digital elevation models (DEMs), light detection and ranging

(LiDAR), and aerial photographs) have been developed and become frequently utilized tools.

Present science and management lack a well-accepted and broadly-applicable approach to classifying fluvial networks and their surrounding landscapes. Bailey (1987) noticed a lack of consistency in general ecosystem identification that led to the development of his widely-accepted regional-scale ecoregions. Regional methodologies developed for the Northwest, Southwest, Great Plains, etc. have been used over the past few decades with limited continuity between regions.

1.2 TERMINOLOGY

Consistency with terminology is imperative to the usefulness of any classification that strives to synthesize and build from previous work (Beechie *et al*., 2006). A set of clear definitions will aid in the understanding of the thoughts and direction this document will take. The NRC defines riparian areas as follows:

> *"Riparian areas are transitional between terrestrial and aquatic ecosystems and are distinguishable by gradients in biophysical conditions, ecological processes and biota. They are areas through which surface and subsurface hydrology connect water bodies with their adjacent uplands. They include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems (i.e., a zone of influence). Riparian areas are adjacent to perennial, intermittent, and ephemeral streams, lakes and estuarine-marine shorelines."* (NRC, 2002, page 29).

The definition addresses both the biotic and abiotic components of these unique landscapes; it also underscores water (surface and/or subsurface) as the main driver of these systems, as well as the connectedness of upland landscapes and aquatic systems. I wish to further this definition in some ways and constrain it in others. For the purposes of

this study, only riparian areas along lotic (flowing water) water bodies will be considered. This includes intermittent and ephemeral surface streams, as they often have ecologically-significant riparian zones, but are naturally spatially and temporally discontinuous. For these dynamic systems, a more appropriate definition of riparian needs to include the idea of "potential" in terms of presence of water and riparian biota (Hemstrom *et al*., 2002). Discontinuity in space and time of surface flow often misrepresents terrestrial/aquatic interactions and attributes of riparian systems including, but not limited to, seasonality, flow flashiness, seed banks, and high-water tables in these settings.

Riparian communities can exist beyond the extent of fluvial influence of the contemporary flow regime. High-water tables have been shown to allow riparian vegetation to exist outside the zone of fluvial influence both vertically and horizontally in the Upper Klamath Basin in Oregon (Chapin *et al*., 2000). An attempt was made to exclude these areas from their study focused on vegetation/discharge relationships. This study will not examine water tables, but will attempt to identify only those areas directly connected to the channel by floods; therefore, the following definition is proposed for the purposes of this project:

> *"A* ***fluvial riparian area*** *is one adjacent to a channel with intermittent, interrupted, or perennial flow that exhibits regionally-distinctive streamside vegetation (or has the* ***potential*** *to) and signs of fluvial processes and/or fluvial features created under the current climatic regime. If other criteria do not apply or cannot be determined, the default riparian boundary is the area within the 100-yr flood stage."* (Pers. Comm., D. Merritt, USFS Riparian Ecologist, 2007)

1.3 SUMMARY

There is a pressing need for a rapid and science-based methodology for identifying and classifying riparian areas and a strongly-scientific approach to classification is required that can support the variety of management goals on public lands (NRC, 2002). Interdisciplinary questions and interagency cooperation necessitate a transparent approach to classification of riparian settings (Fisher *et al*., 2007).

A recent NRC (2002) report has identified the need for a classification approach that can relate the interconnected geomorphic and ecological attributes of fluvial settings and riparian communities. The ability to compare these ecosystems among varying climates, geophysical settings, and species assemblages is an important decision-making tool that has yet to be developed for the USFS (NRC, 2002; Poole, 2002). Efforts to revise land classifications, sampling protocols, and maps became a top priority of the USFS in 1993 (NRC, 2002) and would benefit greatly from a consistent and robust multi-scale classification of fluvial systems that facilitates cross-region comparisons (Bailey, 1987; Montgomery, 1999).

Presented here are the components of this study which are reported in detail in the following chapters. The objectives are outlined in Chapter 2 and identify specific goals of creating a fluvial classification and utilization it with geographic information systems (GIS) procedures. A review of relevant literature is presented in Chapter 3. Chapter 4 examines the geomorphic processes and thresholds significant in fluvial systems. Chapter 5 introduces the proposed classification, examining its structure, conceptual basis, and attributes as a synthesis of knowledge of fluvial systems. The methods used to develop the classification, descriptions of key GIS procedures and courses of action used to assess

the classification and GIS methods are outlined in Chapter 6. The results from field observations, HEC-GeoRAS modeling and the Topographic Position Index are presented in Chapter 7. The discussion in Chapter 8 analyzes the results from the previous chapter and presents insights about the outcomes of the classification and GIS tests. Chapter 9 summarizes the findings from the project, highlights possible applications, and suggests a direction for future work.

CHAPTER 2

OBJECTIVES

The five specific 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 on USFS land; 2) synthesize previous knowledge in developing an *a priori* classification that is process-based, hierarchical, and GIS-based; 3) utilize the classification with GIS procedures, which quantify system energy, hillslope coupling, and lateral confinement; 4) test the functionality and accuracy of the classification in several USFS units; and 5) create preliminary maps for several areas.

The first three objectives create novel approaches to stratifying the fluvial network and quantifying that approach using GIS. Scientific studies focused on river landscape classifications, channel typologies, and fluvial processes compose a large body of knowledge which describes innovative methods and unique descriptive approaches from which to begin future studies. The attributes of a classification to fill the gap in fluvial riparian science include being: based on geomorphic processes, hierarchical, based on GIS, and a synthesis of previous concepts. Geomorphic processes, specifically those operating within the channel and on the floodplain and adjacent slopes, are the foundation of a robust fluvial classification. The quantification of geomorphic processes in GIS necessitated unique arrangements of spatial tools. Objectives 4) and 5) are used to

develop methods to test the accuracy of the classification in the field, or the precision of geomorphic variables measured in the GIS when compared to field values.

CHAPTER 3

BACKGROUND LITERATURE REVIEW

The scope of this study has been narrowed to examine only lotic riparian landscapes, as these are the most abundant and dynamic of the habitats that border water (NRC, 2002). The form and function of lacustrian, bog, and marsh riparian areas are less influenced by processes such as disturbance and system kinetic energy. *A Hydrogeomorphic Classification for Wetlands* (Brinson, 1993) is a widely-accepted classification of these systems, some of which are fluvial in origin. The following sections review previous investigations examining rivers, streams, and valleys to provide a synthesis from which to build a novel fluvial classification.

3.1 EXISTING CLASSIFICATIONS

A collection of regionalized schemes, landform-specific classifications, and scale-specific studies has been developed to address the classification of valleys, streams, and riparian areas (see Table 3.1). Some of these works span regional boundaries and encompass many landforms and scales. Work on classifying rivers, specifically channel types, has been performed by scientists, land managers, industry professionals, and others with diverse results during the past several decades (see Naiman *et al*. (1992) for a comprehensive review). The proposed classification is intended to synthesize the geomorphic processes and thresholds identified in previous classification schemes.

Table 3.1: A summary of previous influential works on fluvial network classification.

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	Regionally specific, does not describe all valley geometries
Frissell *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	Regionally 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	Regionally 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, 2006	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

Early process-based classifications often lacked extensive data to support postulates and were susceptible to harsh debates (Gregory and Walling, 1973). However, Frissell *et al*. (1986) advanced river classification by beginning to use fluvial processes as the foundation for description. By addressing the spatial and temporal variability of river systems at several scales, they introduced the idea of scaling the variables to the investigation. Nanson and Croke (1992) continued to develop process-based fluvial classification by organizing their system for identifying floodplains within the system energy and lateral migration spheres, using stream power and bank or floodplain cohesiveness. These two variables can be viewed as surrogates for erosion potential, sediment transport/deposition, and the potential for lateral migration. Whiting and Bradley (1993) focused on classifying headwater and steep mountain channels that incorporated investigating the hillslope coupling sphere with the connection of the hillslope to the valley bottom. Montgomery and Buffington (1997) also addressed the processes related to sediment entrainment, transport, and deposition in their classification of channels into alluvial, colluvial, and bedrock classes. Church (2002) explored geomorphic thresholds of channel slope and sediment dynamics as a first step in river classification. Specifically, he examined a threshold in the system energy sphere, the shift from sediment evacuating to sediment accumulating and a threshold in the hillslope coupling sphere, the de-coupling of channels from the hillslopes.

The Process Domain Concept (PDC) developed by Montgomery (1999) explored the idea that major geomorphic processes can predictably constrain form at successively finer spatial and temporal scales, down to vegetation composition. These “domains” have common locations in the fluvial network and describe dominant processes (e.g.,

landslide, debris flows, and alluvial deposition). The PDC, along with work by Frissell *et al*. (1986), Nanson and Croke (1992), Whiting and Bradley (1993), and Montgomery and Buffington (1997), strongly influenced later work that utilized innovative methods in GIS and significant advancements in data resolution and coverage.

Work by Lee Benda and his colleagues in the Pacific Northwest followed the Whiting and Bradley (1993) and Montgomery and Buffington (1997) focus on the connection of hillslopes to valley bottoms and channels. This culminated in the development of NetMap, a collection of tools for interpreting watershed characteristics (Benda *et al*., 2007). Other studies including Williams *et al*. (2000), Flores *et al*. (2006), Nardi *et al*. (2006), Wohl *et al*. (2007), Clarke *et al*. (2008), and Jain *et al*. (2008) further advanced the science by developing and testing methods for river, floodplain, and valley classification using remotely-sensed data and GIS.

3.2 REGIONAL SPECIFICITY AND SCALE

The two major dissimilarities between existing classifications are the regional specificity and the scale of application. Classifications created for describing a specific region (Pacific Northwest, Arid Southwest, and Appalachian Mountains) or landscape scale (basin, valley, and channel) are generally precise, detailed, and spatially bound. This specificity, however, can often limit the extent to which they can be applied to other locations. Many existing classifications address stream and/or valley types within a hydrologically distinct region (intermountain West, Pacific Northwest, Great Plains, etc.). These classifications are exceptionally representative of their respective regions, for example, Jensen *et al*. (2001) and Montgomery and Buffington (1997) for the Pacific

Northwest, but most lack the capability of multi-regional application. Whiting and Bradley (1993) suggested some classifications are useable in regions with similar climate and topography to the areas in which they were originally developed. The concepts central to these classification systems, the breaks defined, thresholds identified, and underlying processes described assisted in developing a more broadly applicable valley and channel classification.

Systematic analysis of the Fluvial Riparian Classification (FRC) is grounded in landscape level and local fluvial processes, strengthening the connection between the two focal scales: valley and channel (Goodwin, 1999). Appropriate scaling of variables and conclusions is pivotal to the success of projects and the progression of science and management. For example, some projects require coarse, broadly-collected data to infer basic trends that would become lost in statistical noise of variables measured at finer spatial scales (Naiman *et al*., 2005). Conversely, local studies may require the finest spatial data available to address relevant questions. Secondly, the nesting of finer scale levels within a coarser class helps to manage overall variability, complexity, and redundancy within the classification. Constraints are placed on the range of physical conditions at each successively finer level (Brierley and Fryirs, 2000; Snelder *et al*., 2004; Poff *et al*., 2006; Parsons and Thomas, 2007; Wohl *et al*., 2007). The variables that need to be measured and the range they can be expected to take will be more focused, therefore simplifying categorization at finer scales and aiding in identifying anomalies.

Similar climate and geomorphic conditions may allow for comparison between regions, but significant error can be introduced if there is inconsistent variability within focal variables (Whiting and Bradley, 1993) or additional factors. For example, work on

the relationship between drainage area and floodplain geometry by Dodov and Foufoula-Georgiou (2005) was focused on the Central Plains and the Appalachian regions. Significant differences in the geomorphic controls of rivers exist in other locations and until the same investigations are conducted in the West, Gulf Coast, or New England, one should be cautious in extrapolating their findings.

Classifications that examine a single scale (valley or channel) often ignore other scales. Hynes (1975) reminds us that "*In every aspect the valley rules the stream*," thus the appropriateness of a scale above channel reach is acknowledged, yet it would be an error to omit the channel from analysis as it reorganizes fluvial landforms on the valley bottom. The resulting classification uniquely synthesizes previous information and techniques regarding fluvial network stratification.

The geomorphic processes that influence landforms change with the scale of observations. For example, examining a small portion of a hillslope adjacent to a valley may suggest stability and a very low probability of generating colluvial material. Perhaps 10 m away, a weak rock layer may be exposed, which consistently contributes material down slope. Locally the two areas are different, but when the observation scale incorporates both areas, the effect on the valley bottom changes. The effect of hillslope coupling has been observed upstream and downstream of the initial area of colluvial deposition (Swanston, 1991; Sear *et al*., 2003; Schuster and Highland, 2007). It is important to correlate the observation scale to the process scale to best understand the history and development of current landforms and possible future adjustments in form.

The scale at which previous classifications measured the landscape varied with the types of landforms of interest, the regional importance of variables, and whether the

classification was field or GIS based. Channel gradient, bed substrate, stream power, and valley width were common variables used by the classifications in Table 3.1. The FRC borrows many of the approaches to variable measurement and evaluation from the methods of existing classifications.

Classifications focused on channel form relied heavily on field-measured variables as most were developed at a time and in areas where fine-scale GIS elevation data were not available. Empirical relationships were created from data sets but theoretical components were not always explicitly described. Automated measurement of gradient and valley width has become more prevalent in the previous decades and classifications that aim to tackle larger areas without intensive field campaigns have developed novel techniques to measure variables and identify process surrogates from digital elevation data. These studies were most useful in developing the novel methods presented here and understanding the limitations of specific procedures.

3.3 COMMON CONCEPTS AND THEMES

Most successful fluvial classifications address processes that operate in the longitudinal or lateral dimension. Trends in downstream channel and valley characteristics including: planform, bedform, floodplain development, and sediment-transport capacity have been examined using the energy of the system (Graf, 1983; Brookes, 1985; Magilligan, 1992; Nanson and Croke, 1992; Lecce, 1997; Knighton, 1999; Brierley and Fryirs, 2005; Thompson *et al*., 2008). The proposed classification characterizes the longitudinal dimension by system energy, using channel gradient as a surrogate measure for energy. Reach-scale examinations of channel morphology

associated with channel gradient (Wohl *et al*., 1993) and floodplain development processes (Nanson and Croke, 1992; Beechie *et al*., 2006) are examples of studies directly or indirectly examining the connection of form to system energy.

The lateral dimension has been examined in the literature as a combination of constraint or confinement of valley width (Leopold and Wolman, 1957; Williams, 1986; Van den Berg, 1995; Soar and Thorne, 2001) and coupling (Bull, 1997; Harvey, 2001, 2007; Michaelides and Wainwright, 2002; Benda *et al*., 2005). Studies of fluvial networks often examine the influence of hillslopes on sediment budgets and the development of channel planform (Frissell *et al*., 1986; Nanson and Croke, 1992; Whiting and Bradley, 1993; Rosgen, 1994; Benda *et al*., 2005, 2007). The proposed classification addresses lateral confinement and hillslope coupling as two distinct spheres of geomorphic processes affecting the fluvial network.

Studies addressing one or more of these were of the greatest utility. The spheres were derived from conceptual understanding of the controls on fluvial form. These concepts and the discussion about important geomorphic thresholds are explored in later sections. Classifications of fluvial networks aim to describe the dynamics of flow and sediment.

3.4 SPHERES OF GEOMORPHIC PROCESSES OPERATING AT THE VALLEY SCALE

The immense variability of geomorphic and climatic conditions, land use, and vegetation communities necessitates the simplification of the heterogeneity existing in riparia of the western US. A hierarchical approach was applied to measuring geomorphic

variables on different scales that are intrinsic to the processes that shape the valleys and channels. These processes determine how valleys are formed and the type and degree of disturbances that maintain the physical setting for vegetation. Two scales at which fluvial systems are commonly stratified are valley segment and channel reach. Each of these is influenced by a suite of geomorphic processes operating at a spatial scale, which are observed to control morphology. Figures 3.1 and 3.2 show the conceptual grouping of valley and channel classes along gradients of energy, confinement, and coupling; and Tables 3.2 and 3.3 give primary geomorphic descriptions of the valley and channel hierarchical levels. Below, I will discuss the geomorphic processes, which strongly influence the character of fluvial settings at the valley scale.

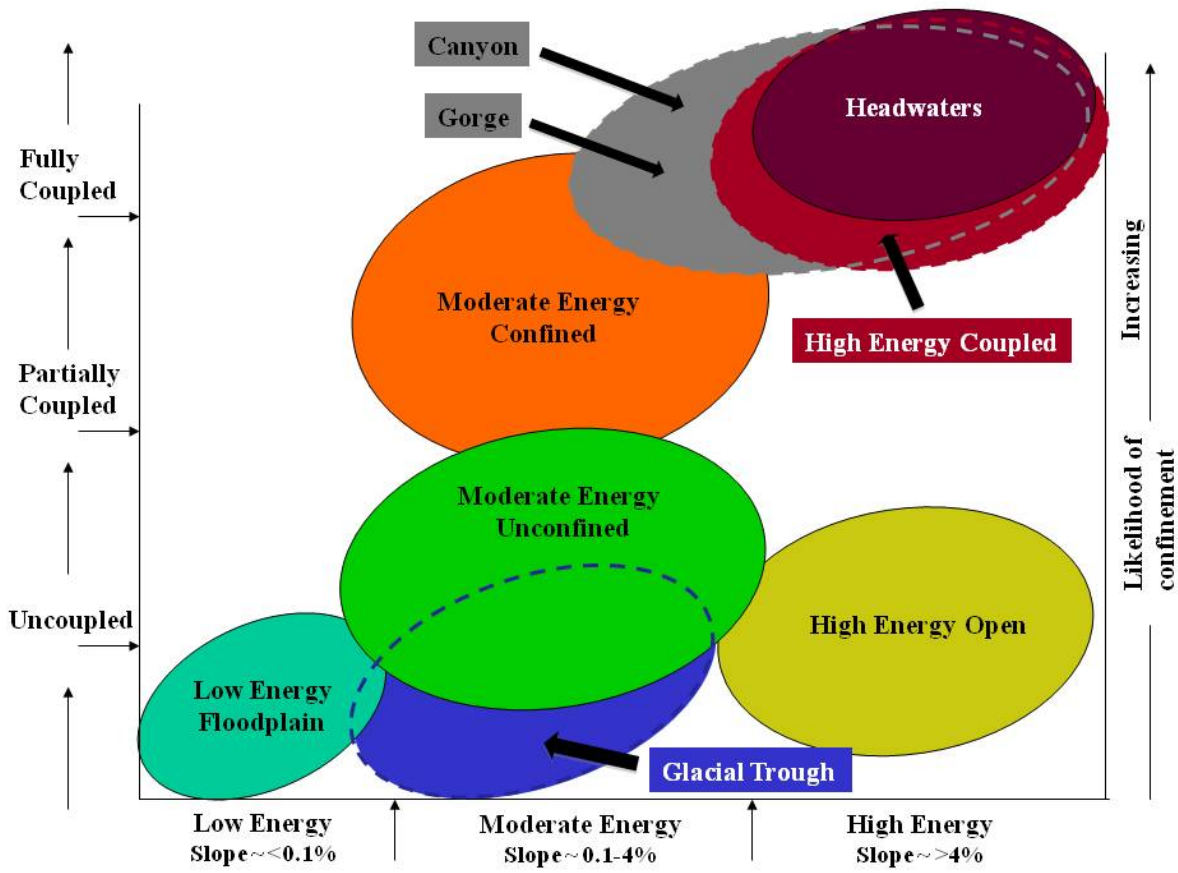


Figure 3.1: Conceptual diagram showing the energy level, degree of confinement, and coupling for each valley class. The overlap between classes and across geomorphic thresholds illuminates the variability present within each class.

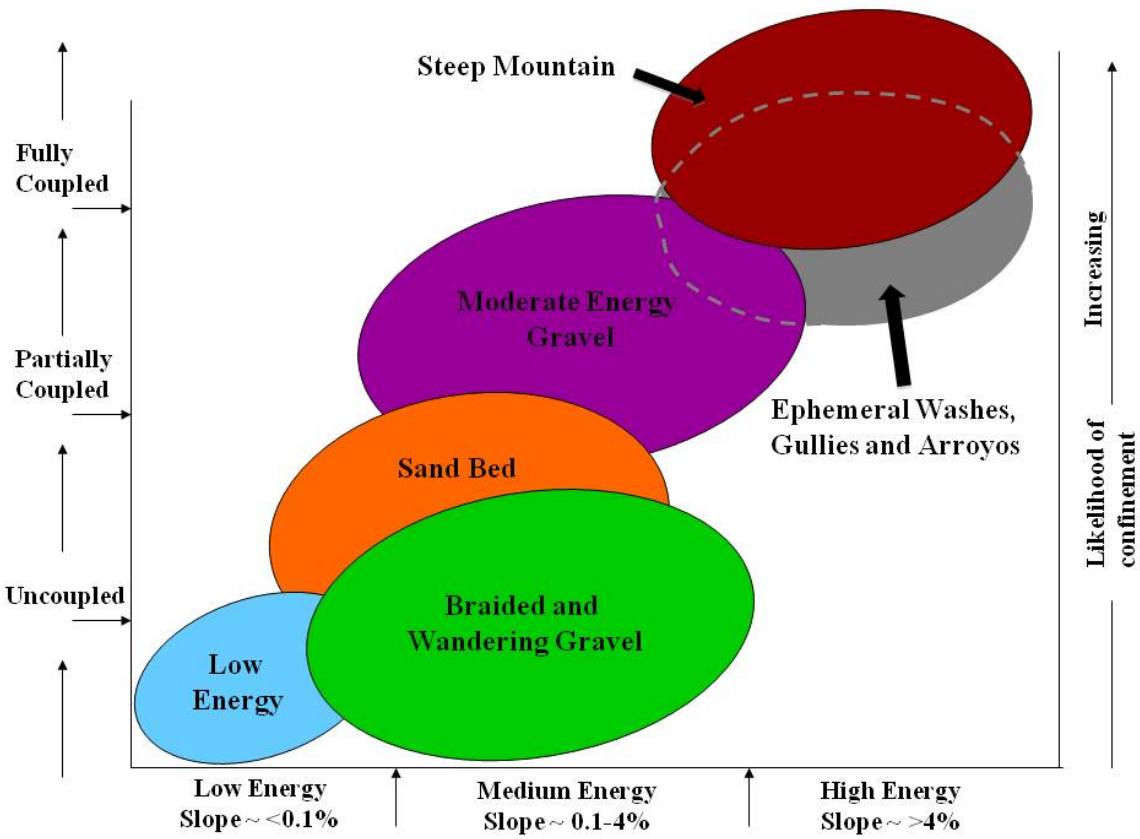


Figure 3.2: Conceptual diagram showing the energy level, degree of confinement, and coupling for each channel type. The overlap between classes and across geomorphic thresholds illuminates the variability present within each class.

Table 3.2: Table of names and characteristics of the FRC valley classes.

	Energy/ Valley Gradient	Valley Bottom Width/Coupling/ Confinement*	Hillslope Gradient	Energy Potential	Rosgen Valley Type
Headwaters	>4%	< (2 L_d + W_c)	Both >30%	High	1
High-energy Coupled	>4%	< (2 L_d + W_c) OR < (L_d + W_c	Both >30% OR At least one >30%	High	1
High-energy Open	>4%	> (2 L_d + W_c)	Variable	High	2, 3, 6, 7
Gorge	Variable	> 2W_c	>70%	Medium - High	4
Canyon	Variable	< 2W_c	>70%	Medium - High	4
Moderate-energy Confined	<4%	< 7W_c	Variable	Medium	2, 3, 6, 7
Moderate-energy Unconfined	<4% Generally <2%	> 7W_c	Variable	Medium	6, 9
Glacial Trough**	<4%	> (2 L_d + W_c)	~10% initially then >30%	Low - Medium	5
Low-energy Floodplain	<.1%	> 7W_c	Generally <30%	Low	8, 9, 10, 11

* W_c = bankfull channel width and L_d = debris run-out length
**Defined as valleys existing above the elevation of furthest extent of glaciations in regional mountain ranges.

Table 3.3: Table of names and characteristics of the Fluvial Riparian Classification channel types

General Type	Energy / Channel Gradient	Channel Type / Bedform	Dominant Substrate	Planform	Rosgen Types	Hillslope Influence
Steep Mountain Rivers	High >4%	NA	Colluvial	Single thread – straight	N/A	High
	High >4%	NA	Bedrock	Single thread – straight	A1	Variable
	High >4%	Cascade	Alluvial – boulder/cobble	Single thread – straight	A2-3, B2-3	High
	High >3 - 4%	Step Pool	Alluvial – boulder/cobble	Single thread – straight	A2-3, B2-3, C2-3	High to Mod
Mountain Ephemeral, Washes, Gullies, Arroyos, Gulches	High to Moderate	Limited Structural Development	Alluvial, bedrock, hardpan	Single thread – straight to meandering	A1-6, G1-6	Variable
Moderate-energy Gravel Rivers	Moderate	Transitional / Plane Bed	Alluvial – cobble / gravel	Single thread – straight	B2-4, C2-4	Mod to Low
	Moderate	Pool Riffle	Alluvial – cobble / gravel / sand	Single thread – straight to meandering	B3-4, C3-4 + modifiers for E3-4, F3-4	Low
Braided / Wandering	Moderate	Braided / Wandering / Anabranched	Alluvial – sand to cobble	Multiple thread	D3-5, DA3-5	Low
Sand Rivers / Dune Ripple	Moderate to Low	Dune Ripple – may have alternating bars as in Pool-Riffle	Alluvial – sand dominated	Single thread - straight to meandering	B5, C5 + modifiers for E5, F5, G5	Low to High
Low-energy Anastamosed, Single-thread Cohesive	Low <0.1%	Anastamosed or single-thread equi-width	Alluvial – cohesive, organic	Multiple thread or straight to meandering Single-thread equi-width	DA 5-6, C5-6, E5-6	Low

N/A – not applicable

A suite of fluvial processes including erosion, sedimentation, lateral migration, incision, and transport behave similarly across regions. This consistency provides a common ground to develop a classification that can span geomorphically-distinct regions. Understanding process prepares the researcher to infer previous conditions, understand the current state, and predict future morphological change (Montgomery and Buffington, 1997; Brardioni and Hassan, 2006). Forecasting future adjustments to fluvial systems as climate shifts cause changes in precipitation patterns and intensity will likely be one of the major uses of the FRC.

Fluvial processes can be grouped into three main spheres, which collectively describe the geomorphic setting of the valley, channel, and riparian area: 1) 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. A classification built upon fluvial process establishes that hydrologic forces driving morphological and ecological form behave similarly across diverse regions (Montgomery, 1999). Observational investigations (e.g., Rosgen (1994)) rely on physical landforms that are transient and extremely variable even within geomorphically-similar regions (Church, 2002).

3.4.1 System Energy

System energy can best be visualized by the dynamics of flooding. Poff *et al*. (1997) described in detail the five spatial and temporal components of flooding in rivers; the geomorphic and ecological importance of 1) timing, 2) duration, 3) magnitude, 4) frequency, and 5) rate of change in flows is well accepted. Floods impact the riparian

area by causing mechanical disturbance, bank erosion, sediment deposition, and periods of inundation. System energy is a conceptual characteristic of fluvial systems stemming from stream power and the disturbance regime. The divisions between the energy classes 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).

Moving water is a force that can transport material by the ton. The type of material and the method of transport are related to system energy (NRC, 2002). The transportation of large woody debris (LWD) and variable caliber sediment can temporarily or permanently adjust the bed, bank, and floodplain morphology. Erosion can cause slope failures, remove tons of sediment from floodplains, and shift the position of channels by hundreds of meters. Channels have a limited amount of energy to do work. Energy is expended as work is performed overcoming boundary resistance and internal shear stress (Knighton, 1998). The remaining energy can then be used to erode or move sediment. In supply-limited systems, where little suspended, dissolved, or bedload sediment is available for movement, most of the energy of the stream is focused on the channel margins and bed doing geomorphic work. In these conditions, incision and degradation occur. In low-energy systems much of the energy is employed transporting sediment, thus allowing the banks to be relatively stable, shored up with cohesive material (Nanson and Croke, 1992; Knighton, 1998, 1999).

As the water overtops the banks and begins to flow over the floodplain, the water is impeded by vegetation, relict channels and bars, and hillslope debris that reduce

velocity and lower stream power and contribute to the deposition of sediment on floodplain surfaces. The entrainment of material and reorganization of floodplain sediment are two small-scale fluvial processes primarily controlled by system energy (Knighton, 1999; Brierley and Fryirs, 2005; Golden and Springer, 2006; Thompson *et al*., 2008). Large-scale processes of channel pattern, landform development and orientation, and selection of resilient riparian species, have also been noted (Hupp and Osterkamp, 1985, 1996; Bendix and Hupp, 2000; Twidale, 2004; Naiman *et al*., 2005; Parsons and Thomas, 2007).

Deposition is a critical process that builds and maintains fluvial landforms within the channel and on the floodplain. Low-energy systems are defined as a dominantly-depositional environment (Nanson and Croke, 1992; Knighton, 1998, 1999). Equations representing the mean boundary shear stress (τ) and critical shear stress (τ_{cr}) can be manipulated to calculate the amount of energy required to entrain, transport, and deposit sediment of different sizes and in different flow situations (Knighton, 1998, 1999). Specific thresholds for entrainment and deposition of particular grains are derived at a scale below channel reach (Church, 2006), but it is important to connect these fine-scale, in-channel processes to overall system energy in a conceptual sense.

3.4.2 Hillslope Coupling

The sediment that is eroded, transported, and deposited in response to system energy is ultimately derived from the adjacent uplands, albeit potentially from distant upstream areas (Sear *et al*., 2003). The connection of the valley bottom to the adjacent hillslopes is also of critical importance (Michaelides and Wainwright, 2002; Brardioni

and Hassan, 2006; Benda *et al*., 2007). Montgomery (1999) noted that two of the four ways physical processes affect in-stream biota are related to hillslope connectivity to the valley bottom and channel. Coupling is of special interest in regions with high-sediment yields, dissected landscapes, limited vegetation cover, and flashy precipitation patterns (Michaelides and Wainwright, 2002).

The riparian community includes components of the upland system (Rheinhardt *et al*., 2007) and the degree of connection varies along the network (Harvey, 2007). Shallow landslides and debris flows are often smaller (see Figure 3.3), 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 add to the heterogeneity of surfaces in the immediate area and considerable lengths downstream. Colluvial debris on the fluvial valley bottom can have several major affects on riparian structure in the local vicinity and downstream. The impingement of lateral migration can influence riparian function in fluvial settings where colluvial debris narrows the valley beyond the threshold of free-lateral migration, concentrating flow during flood events and limiting the spatial extent of riparian surfaces. For this reason, the FRC addresses the potential for colluvial debris to deposit on the fluvial valley bottom. Large amounts of debris can dam the channel, increasing downstream scour, deposition, avulsions, and total blowouts, should the landslide dam fail, as well as lacustrian-type deposits upstream (Swanston, 1991; Schuster and Highland, 2007).

Figure 3.3: A shallow landslide along the outside of a meander bend on the William's Fork River, Arapaho National Forest, Colorado.

The capacity for a hillslope to exert influence on the riparian system is correlated with both gradient and proximity to the fluvial valley bottom. Gradient, lithology, land cover, and precipitation control the stability of hillslopes and determine the probability that colluvial material could be generated (Whiting and Bradley, 1993; Brardioni and Hassan, 2006; Benda *et al*., 2007). The valley width determines the probability that the colluvial material will encounter the channel. It is understood that during flood events, flowing water can reach far beyond the banks of the channel and encounter colluvial material at the toe of adjacent hillslopes. However, flow energy on the floodplains is often too low to move significant amounts of material or sizeable clasts.

The stability of a slope characterizes 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). Channelized debris flows, mass wasting, shallow landslides (Figure 3.3), and avalanches (Figure 3.4) have the ability to contribute significant amounts of material down slope, onto the valley bottom and possibly directly into the channel. The magnitude and frequency of the addition of this non-fluvial sediment to the valley bottom can have significant impacts on the fluvial and ecological processes operating within the riparian area.

Hillslope stability can change in response to fire, land-use change, and adjacent slope stability over short time scales. The temporal and spatial variability in hillslope stability related to accumulated affects of time and changes in land cover characterize local stability thresholds. Present conditions should be used to estimate stability thresholds as probabilities over short time and spatial scales. If a major factor such as land use or cover type changes, the hillslope stability will likely change.

Figure 3.4: Avalanche chute showing the connectivity of source areas on high slopes to the valley bottom (Arapaho National Forest, Colorado).

The local-scale slope gradient is important for identifying stability. At the valley scale, however, a more coarse grain is appropriate for evaluating the potential for landslides and debris flows over the length of a valley section. The coarsening is completed by using a proportional analysis of slope stability classes on the hillslopes. A smoothing algorithm is not used on the gradient because areas of high instability are often small or narrow and would likely be lost in this approach. Instead the small areas of high instability are included in the total proportion and weighted such that their influence is properly accounted for.

3.4.3 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 into the channel if lateral migration occurs. The restriction of channel position on the valley bottom by hillslopes can change the dynamics of both hillslope coupling and energy distribution during floods. 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 relative size of the system, therefore providing a consistent approach to describe headwaters and large floodplains.

The quantification of river meandering has interested researchers from the turn of the twentieth century through significant advances in meander geometry with Leopold

and Wolman (1960), Leopold and Langbein (1966), Ferguson (1973, 1979), and others. Much of the work on meander geometry comes back to 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. The FRC accepts the sine-generated wave as a theoretical approach to examining meander characteristics.

The potential for a channel to move across a valley bottom can describe unique morphological scenarios and enhance or inhibit the development of specific landforms (Nanson and Croke, 1992; Montgomery and Buffington, 1997). The expenditure of system energy on banks can lead to localized erosion and the slow or rapid adjustment of channel position on the valley bottom (Twidale, 2004). The non-equilibrium nature of extensively meandering rivers describes a dynamic physical setting, which can have significant influence on the species able to survive and the ecological function of interacting biotic and abiotic components of the riparian community (Hupp and Osterkamp, 1985, 1996; Campreale *et al*., 2005).

Channel position and sinuosity cannot be reliably generated with the 10-m horizontal resolution GIS layers used by the FRC (Andrle, 1996); therefore, a ratio of bankfull channel width to fluvial valley width is used as a surrogate to compare with confinement thresholds described in the next section. The estimation of bankfull channel width in GIS introduces error, which is propagated through subsequent steps examining confinement, making confinement the weakest of the three process spheres.

3.5 CONTRADICTORY FINDINGS

The vast majority of research supports the idea that riparian vegetation is intimately reliant upon and involved in the fluvial processes associated with flowing water. There are some studies, however, which found little or no correlation between the biotic assemblages and abiotic landscape components. Mac Nally *et al*. (2008) measured the riparian extent using vegetation analysis in the Central Highlands of Victoria, Australia. They did not find evidence linking the observed riparian width to local physical conditions or drainage area. A study in the Pacific Northwest was careful to note that with so many variables involved (geology, climate, biogeography, and soils), riparian species composition may not even be primarily related to fluvial processes (Sarr and Hibbs, 2007). Investigations in Oregon suggested that not all woody vegetation is controlled by fluvial processes and would, therefore, be a poor indicator of process dominance (Sarr and Hibbs, 2007). The scale of both of these studies is most similar to the channel-reach scale of the FRC hierarchy. The attention to more detailed variables and fine-scale variability is likely to have resulted in these conclusions. This reinforces the need to examine systems at the scale appropriate for the question and supports the use of a hierarchical classification to constrain variability and help to relate similar systems in different regions.

Vegetation patterns can be ordered by disturbance related to fluvial or hillslope processes and may have false boundaries between riparian and upland communities, not related to valley morphology and slope breaks (Mac Nally *et al*., 2008). The scales at which geomorphic variables and vegetation patterns are measured and observed do not always align, posing challenges for association.

3.6 CONCLUSIONS REGARDING EXISTING CLASSIFICATIONS

Poole (2002) noted that streams are strongly hierarchical systems, and describes them as patchy dis-continuums from headwaters to lower gradient sections. The separation of these systems into discrete units is possible and human nature at multiple spatial scales (Whiting and Bradley, 1993; Hey, 2006). The continuous nature of river networks cannot be ignored, but many researchers subscribe to the tenet that thresholds can be defined which appropriately separate distinct geomorphic units in the network (Schumm, 1977; Church, 2002).

Classifications exist that have foundations in fluvial processes (see Frissell *et al*. (1986), Montgomery (1999), and Jain *et al*. (2008)), as do classifications that have been widely applied (see Rosgen (1994)), but few classifications exhibit both qualities. In the previous two decades, significant advances have been made in the resolution and availability of digital data and satellite imagery. Techniques have been developed to measure characteristics of these new data sources. In a strained financial climate, cost efficiency is a top priority for most public and private groups and management decisions are increasingly based on remotely-sensed data. Previous stream and valley classifications may have one or two of these attributes, but none can be described as process-based, GIS-based, broadly applicable, and utilizing remotely-sensed data.

All the conceptual, field-based, and remote-sensing based river classifications discussed above address at least one of the main geomorphic process spheres: system energy, hillslope coupling, or lateral confinement. In this study, I built on previous work by explicitly addressing all three of these major processes in the riverine landscape.

CHAPTER 4

SPECIFIC GEOMORPHIC PROCESS THRESHOLDS

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 FRC, a hierarchy exists for the geomorphic variables (see Figure 4.1) and is critical in the determination of a final valley class. The interplay between the three processes highlights the interconnectedness of the fluvial and hillslope components (Brierley and Fryirs, 2005; Wohl *et al*., 2007).

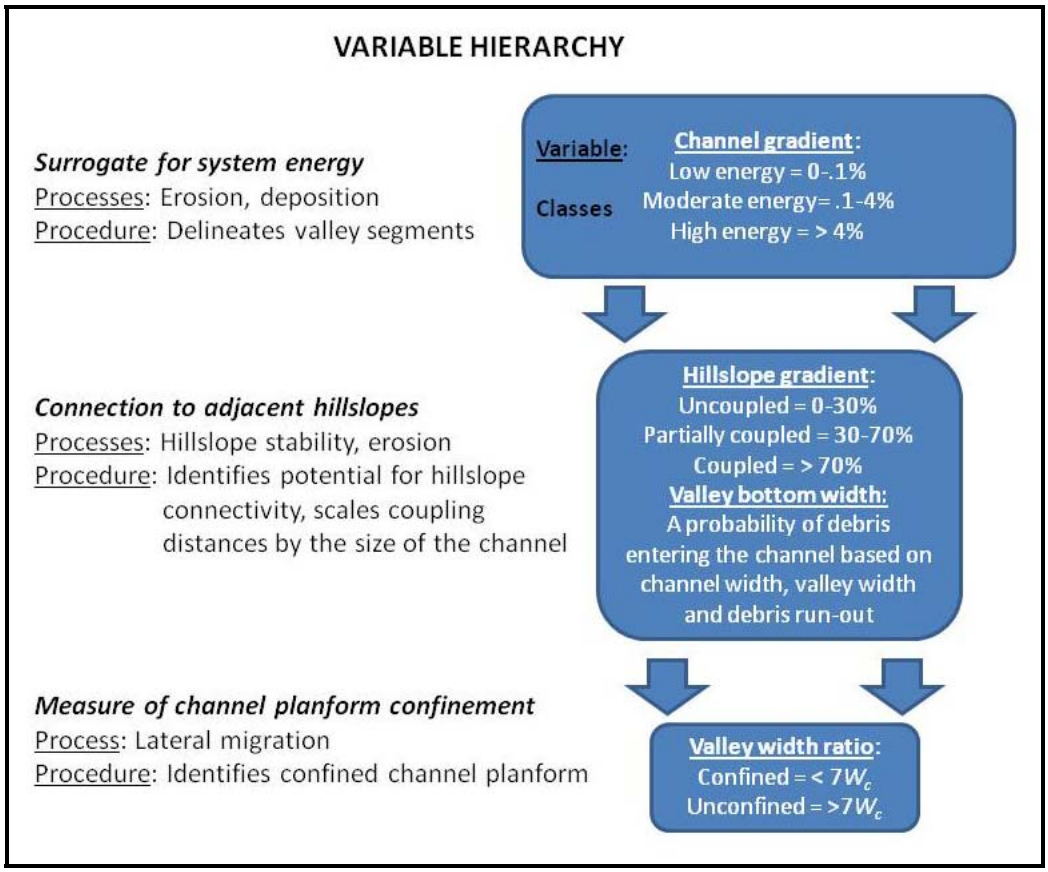


Figure 4.1: The variable hierarchy used to constrain processes and landforms at successively finer scales.

A conceptual basis for class distinctions was made, followed by the identification of surrogate measures for important variables and thresholds, which describe significant changes in process dominance and influence. Below, the process components of the fluvial system which are examined by the FRC are described in terms of their surrogate variables and significant geomorphic thresholds. The thresholds separating process groups are supported by detailed hydrologic, geomorphic, and hydraulic research. The FRC 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.

4.1 SYSTEM ENERGY

System energy is a concept most directly related to the geomorphic and hydrologic variables of slope and discharge. Fluvial energy is correlated to the ability of the system to entrain, transport, sort, and deposit sediment (Bagnold, 1960, 1966; Graf, 1983; Brookes, 1985; Nanson and Croke, 1992; Lecce, 1997; Knighton, 1998, 1999; Petit *et al*., 2005; Shih and Yang, 2009). To mathematically derive threshold-separating unique fluvial processes, a simplified hypothetical channel is described. I assume a unit discharge (q) on the order of 1.0 m^2/s, as this is a fairly representative value of many channels types at bankfull conditions. The equation for specific stream power is:

$$\omega = \frac{\gamma Q s}{w} \qquad \textbf{Equation (4.1)}$$

(this is equivalent to *unit stream power* defined by Bagnold (1966)) 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 channel gradient (Knighton, 1999). The understanding that unit discharge (q) can be represented by Equation (4.2):

$$q = \frac{Q}{w} \qquad \textbf{Equation (4.2)}$$

allows the simplification of Equation (4.1) into:

$$\omega = \gamma q s \qquad \textbf{Equation (4.3)}$$

It follows that a slope on the order of 0.001 m/m corresponds to a specific stream power of ~10 W/m^2.

Below 10 W/m^2, the channel does not possess sufficient energy to effectively erode the channel banks and floodplain deposits (Nanson and Croke, 1992; Knighton, 1999), thus lateral migration is minimal. Coarser material is deposited closer to the channel during floods, thereby creating natural levees that further reinforce the channel banks and support stable channels (Van den Berg, 1995).

For high-energy fluvial systems, there is less agreement about a significant stream power value but more agreement about a channel gradient threshold. Here 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 (q) on the order of 1.0 m^2/s is assumed as above, a slope of 0.03 to 0.04 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.

These thresholds identify the boundaries between three distinct fluvial systems. I apply the concept that slope has a significant role in determining specific stream power as the basis for estimating system energy. The parameters needed to actually measure stream power are not readily available for all areas and estimations of discharge introduce significant error in certain regions. Channel gradient can be more accurately estimated from fine-scale GIS data (>10-m scale) than discharge and is commonly measured in both the field and GIS, creating a strong geomorphic descriptor of fluvial setting. The

slope thresholds of 0.1 and 4% are tentatively set as boundaries between energy classes and provide the cornerstones of the proposed classification outlined in Chapter 5. A large range of gradient values are included in the moderate energy class. Between 0.1 and 4% channel gradient a range of shifting bedform morphologies can occur and are transient in space and time. The adjustments to sediment type, pool spacing, and bedforms occur at the reach level scale and cannot be accurately identified with the 10-m DEM data.

4.2 HILLSLOPE COUPLING

The gradient of the hillslope and the width of the valley bottom are key variables useful in categorizing hillslope coupling. 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). Local soil characteristics, stabilizing vegetation, and saturation dynamics influence the area, depth, and volume of shallow landslides (Whiting and Bradley, 1993; Benda *et al*., 2005).

The local-scale slope gradient is important for identifying stability. At the valley scale, however, a more coarse grain is appropriate for evaluating the potential for landslides and debris flows over the length of a valley section. The coarsening is completed by using a proportional analysis of slope stability classes on the hillslopes. A smoothing algorithm is not used on the gradient because areas of high instability are often small or narrow and would likely be lost in this approach. Instead the small areas of high instability are included in the total proportion and weighted such that their influence is properly accounted for.

Hillslope gradient is the logical focus of an assessment of hillslope coupling, as the other factors influencing hillslope stability do not have consistent coverage or resolution as GIS-data layers for the western US. A simple measure of the capability for adjacent hillslopes to generate colluvial material is the composition of slope gradients. Gradient is a commonly-measured, easily-visualized characteristic of hillslopes that influence their stability. Three hillslope gradient classes are defined by two thresholds: one describing the lower bound 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).

The initiation of hillslope failures occurs at a wide range of gradients, between 25 and 170% (Bathurst *et al*., 1997; Lorente *et al*., 2003; Sidle and Ochiai, 2006). Mean hillslope gradients of ~67% are common for many studies examining landslide events (Lorente *et al*., 2003). The inputs into the failure equations of soils, saturation levels, and friction planes are complicated and require detailed knowledge at a scale much finer than what the FRC can logistically address. While each location has a critical gradient that can be attributed to slope failure, a threshold cannot be confidently applied across the heterogeneous landforms, soils, and land covers in the West. The thresholds are critically connected to local soil-forming properties, land cover, land use, and regional precipitation patterns.

Several studies and recognized classifications support a lower threshold of 30% (Collotzi, 1976; Cupp, 1989; USDA, 1992). An upper threshold of 70% holds less support because regional values of hillslope stability are so widely varied. These are

default values of the FRC, but the classification user is strongly urged to apply values that are representative of the region of interest.

The relationship between slide volume and run-out was investigated by Ikeya (1981) in Japan with Equation (4.4):

$$L = 8.6\ V(\tan \Phi)^{0.42} \qquad \textbf{Equation (4.4)}$$

This and other methods attempt to relate run-out length to the physical dimensions of the slide and the energy implicit in the action of the slide (Bathurst *et al*., 1997). Run-out lengths or deposition lengths have been calculated from the head scarp (Stock and Dietrich, 2006) and as the length of substantial deposition at the toe of the slide (Bathurst *et al*., 1997; Fannin and Wise, 2001; Lorente *et al*., 2003). This second definition aligns well with the approach Whiting and Bradley (1993) take to characterizing coupled and decoupled valleys. Whiting and Bradley (1993) used the equations from Ikeya (1981) to approximate run-out lengths for valleys in Washington; they estimated a run-out length of ~25 m from the toe of the slide where significant deposition begins. Independently in the Pyrenees of Spain and France, Lorente *et al*. (2003) examined run-out lengths from small debris flows and shallow landslides and found a mean deposit length of 22.1 m.

The width of the valley bottom, the amount occupied by the channel and the estimated run-out lengths of landslides and debris flows are necessary to identify the potential for unstable slopes to influence fluvial landforms. A run-out length is needed to characterize a valley bottom as coupled or uncoupled. The hillslope coupling measure follows the logic of Whiting and Bradley (1993) and relies on probabilities of colluvial debris entering the channel to categorize valleys.

It is important to realize the additional width of the channel when assessing the probability of colluvial debris contacting the channel. Equation (4.5) calculates the "un-channelized" width of the valley bottom:

$$W_u = W_v - W_c \qquad \textbf{Equation (4.5)}$$

where W_v is the total valley width, W_c is the bankfull channel width, and W_u is the un-channelized width of the valley bottom. This is the area potentially available for colluvial deposition and channel occupation:

$$C = 1 / (W_u / L) \qquad \textbf{Equation (4.6)}$$

Equation (4.6) describes the probability of the channel occupying an area within the depositional zone of the hillslopes (L). The coupling probability (C) needs to be adjusted if only one hillslope is categorized as unstable; C would then be divided by 2 to account for asymmetrical valleys. A somewhat arbitrary value of 0.25 is used by this study to describe a valley bottom as coupled based on its probability of coupling. This suggests that the channel on a valley bottom with a C of 0.25 has a 25% chance of colluvial debris directly entering the channel from the hillslopes.

4.3 LATERAL CONFINEMENT

Several mathematical relationships have been identified that describe the geometric shape of meandering channels and cross sections (Leopold and Wolman, 1957, 1960; Langbein, 1966; Leopold and Langbein, 1966; Williams, 1986; Hagerman and Williams, 2000; Soar and Thorne, 2001). Channels adjust planform and bedform to minimize the amount of work performed by flowing water (Leopold and Langbein,

1966). Confinement constrains the ability of the channel to adjust and develop equilibrium with its bed and banks. Two thresholds of confinement can be identified for fluvial systems. The potential for braided channel development in gorges and not canyons reflects the severe constraint on planform evident in these fluvial settings. A second threshold is more applicable to wider, alluvial systems. The width at which the channel has the potential to adjust its planform without contacting either adjacent hillslope defines the lower limit of an unconfined fluvial setting in the FRC.

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.

I use the relationship between meander amplitude and wavelength, herein referenced as A_m 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 (Equation (4.7)):

$$A = \lambda(6.0625\varphi^3 - 5.1279\varphi^2 + 2.509\varphi + 0.0005) \qquad \textbf{Equation (4.7)}$$

to calculate the meander amplitude using λ as the independent variable. The term φ is $(P - 1)/P$, where P is the sinuosity. Wavelength cannot always be directly measured. Soar and Thorne (2001) proposed a relationship between bankfull channel width W_c and λ based on a large meta-analysis of meandering rivers around the world: $\lambda = 12W_c$. Equation (4.6) can be rearranged to calculate meander belt width (B) by substituting

$12W_c$ for λ and adding a channel width. The additional channel width accounts for amplitude being measured between two points located in the center of the channel. For confinement, interest is in the outer edges of the channel:

$$B = (12(6.0625\varphi^3 - 5.1279\varphi^2 + 2.509\varphi + 0.0005) + 1)W_c \quad \textbf{Equation (4.8)}$$

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 Equation (4.4) 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 $7W_c$. 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. First, a simple discussion on the 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. An average single-thread channel has a *W/D* ratio of ~25:1, while *W/D* ratios of 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). The development of braided systems suggests room for lateral adjustment of channel form and position.

CHAPTER 5

THE FLUVIAL RIPARIAN CLASSIFICATION

The ultimate goal of the FRC is to provide a consistent, process-based classification of fluvial riparian areas at valley and reach scales on USFS lands in the western US. The focus of this study is the intermediate level of the FRC hierarchy, the valley scale. O'Connor and Watson (1998) found catchment-scale variables more predictive of in-stream biotic integrity, and Hurley and Jensen (2001) proposed that valleys are the essential scale at which to examine the connection between aquatic and terrestrial systems.

5.1 ATTRIBUTES

The FRC is intended to provide a process-based foundation for stratifying regional variability in fluvial systems at multiple scales for the western US. A broadly-applicable, process-informed classification based on variables derived from widely-available GIS data could be a powerful predictive landscape stratification tool but has yet to be developed. The desired attributes of the FRC were developed as the gap in riparian classifications was identified.

5.1.1 Broad Applicability

Though the proportional influence of fluvial processes is often inconsistent across physiographically-distinct regions, analogous landforms can be produced. This understanding allows for the development of a classification of fluvial valleys that is applicable across vast, physically-heterogeneous regions. The majority of land managed by the USFS exists west of the 100th meridian, thus providing a convenient break that allows for concentration of studies.

Variable climate, geology, landscape evolution, and regional species assemblages exist in the western US. The FRC aims for consistency across the region and identifies the heterogeneity of the West and creates valley classes to capture it. The range of fluvial forms and riparian settings present in the West suggests that the FRC could be applicable in other areas as well. Large areas of USFS land have seen limited manipulation from humans, providing reference conditions for geomorphic and ecological attributes. The information gained from these areas on natural channel and valley processes and forms will aid in planning sustainable mitigation, restoration projects, and management plans.

5.1.2 Process-based

The FRC identifies thresholds that describe fluvial processes and groups variability into functionally unique classes. The physical shape of the valleys within a class will naturally resemble each other, but the defining attributes are directly related to process and indirectly result in form. A connection between the geomorphic processes creating and maintaining fluvial landforms and the ecological community exists in theory (Gregory *et al*., 1991; Montgomery, 1999; Goebel *et al*., 2006). These processes are

grouped into three spheres: 1) system energy, 2) hillslope coupling, and 3) lateral confinement. The FRC will provide a crucial link between geomorphic and ecological classifications, solidifying the theory in an applied framework.

5.1.3 Group Geomorphically/Ecologically Similar Areas

The dynamics of erosion, sedimentation, debris flows, migrating channels, and flooding in part constrain the development of the riparian ecological community by controlling some of the primary abiotic stressors (Gregory *et al*., 1991; Montgomery, 1999). The physical setting of riparian areas is formed and manipulated by flowing water and the species able to survive from the regional species pool are those suited to the particular soil, inundation periods, and disturbances related to flooding (Poff *et al*., 1997). The FRC quantifies geomorphic variables to describe the regions affected by specific fluvial processes, grouping areas into classes which have similar ecological settings and function. Here, ecological function is treated as a qualitative attribute of the fluvial system and a product of fluvial process that can feed back into landform maintenance.

5.2 HIERARCHY

It is understood that a single methodology for sampling rivers and riparian landscapes may not be as precise as local models when applied to an area as diverse as the West. Classifications struggle to balance complexity, precision, and applicability as competing qualities (USDA, 2005). A method to achieve this goal is to develop levels at which regional and local variability are addressed independently yet are connected through constraints based on processes operating at each level. Feedback between levels

and strong connections between landforms at each level highlight the strengths of a top-down hierarchical approach (Snelder and Biggs, 2002; Naiman *et al*., 2005). The two levels developed for the FRC were shown in Tables 3.2 and 3.3, which name and describe the valley classes and channel types, respectively. These are nested within ecoregions described by Bailey (1983, 1987, 1995). This creates a three-level hierarchy for stratifying fluvial networks.

A hierarchical approach provides several benefits to the final valley classification. The primary advantage is realized as spatially explicit levels allow projects and studies to be completed at appropriate scales (Bailey, 1987). Jensen *et al.* (2001) suggested that a hierarchal design promotes systematic analysis of fluvial networks which can aid in assessments and interpolation.

5.3 REGIONAL THRESHOLD CALIBRATION

For the open framework of the FRC to be most effective, the user is strongly encouraged to provide regional thresholds to replace the preliminary defaults. The thresholds describe major shifts in process dominance and critical stability values, and should address variables intrinsically important to the geo-climatic and ecological environment. Regionalized values strengthen the ability to extrapolate into un-sampled areas (Wolock *et al*., 2004), which is a major objective of the FRC.

The user is encouraged to identify and input regional values for the two hillslope thresholds when prompted by the GIS procedure. These include valley density, hillslope gradient thresholds, debris flow run-out lengths, and an estimation of channel width. Preliminary defaults are provided, but some could be very unrepresentative of specific

regions. The equations derived by Faustini *et al*. (2009) have good results in some regions and poor results in others. Local knowledge, regional regression equations, or extrapolated values from field measurements are all suitable substitutions.

The open framework, supported with user-defined regional values, is an alternative to numerous individual regionalized approaches, which can be counterproductive (Montgomery and Buffington, 1997). A single classification with opportunities to adjust critical process thresholds maintains consistency and power. The user is prompted to provide values for the geomorphic variables that represent key shifts in physical processes as discussed below. The subjectivity introduced with adjusting the thresholds is negated by the accuracy gained from fine-tuning the classification. A national-level oversight should be implemented to guide the designation of regional thresholds for the various inputs. A range of values appropriate for different regions (e.g., ecoregions and USFS regions) would aid in continuity and the appropriate use of the classification.

5.3.1 Bankfull Channel Width

This channel-scale measurement is critically linked to the processes controlling the features and functions of valley bottoms. It cannot be measured with the base layer 10-m DEMs due to limitations on horizontal resolution. Regional regression equations for discharge at different recurrence intervals are generated from empirical data from stream flow gages (U.S. Geological Survey (USGS), 1994; Faustini *et al*., 2009). The areas in which the equations are most accurate are commonly small and a single state may have a dozen or more equations to address hydro-geomorphic heterogeneity. An additional step

going from discharge to bankfull width is an additional equation very specific to the region. The user should choose the equation or set of equations that best aligns with previous studies and suits the available data.

5.3.2 Hillslope Gradient

The gradient at which hillslopes begin to contribute material to the valley bottom is a significant geomorphic threshold that is regionally and locally controlled primarily by geology, precipitation, and land cover (Whiting and Bradley, 1993; Sidle and Ochiai, 2006). The default value of 30% slope has been used by several studies in the past (USDA, 1977, 1978, 1992), but cannot be confidently applied throughout the western US.

Field investigations suggest that more frequent, smaller amounts of debris can be generated on less steep slopes in arid regions because of lack of vegetation and intense precipitation events, while moist areas appeared more stable, but evidence of larger debris flows on steep slopes was also evident. The user should identify thresholds of slope stability dependent on land cover, disturbance, climate, and geology. Two thresholds are required for this regionalization step: 1) the gradient at which debris begins to be generated or the slope begins to fail and 2) the gradient at which slope failure is consistently occurring in large or small events. The gradient defaults in the FRC are 30% and 70% for the two thresholds, respectively, supported by work in the Pacific Northwest by the USDA (1977, 1978, 1992) and Lunetta *et al*. (1997). Local thresholds may need to consider the influence of region-specific litho-topography and human activities that could shift the stability threshold up or down.

5.3.3 Valley Initiation

This base metric is similar to drainage density but is scaled up to valley-level processes. The shift from diffusive hillslope processes to incisive alluvial processes marks the initiation of a channel (Hancock and Evans, 2006; Montgomery and Foufoula-Georgiou, 1993) and that idea is scaled up to valleys. The value is a threshold of drainage area that is identified as first producing a valley, where flow is sufficient to produce continuous fluvial landforms in and/or along a defined channel. Sufficient flow convergence from headwater channels is necessary to begin a *consistent* transition from hillslope processes to alluvial processes. Extensive work has been conducted on identifying channel-head locations (see O'Callaghan and Mark (1984), Montgomery and Foufoula-Georgiou (1993), Hancock and Evans (2006), and McNamara *et al*. (2006)), and Jain *et al*. (2008) investigated floodplain initiation points, but valley initiation has not been directly investigated. The area of interest lies between the points of channel initiation and floodplain initiation. Aerial photographs and satellite imagery are very useful in identifying this threshold; field excursions are also suggested. Geo-climatic and antecedent conditions can greatly affect this value; additionally, changes to land cover or land use have typically led to gullying and upslope migration of channels and small valleys. The FRC identifies a 3-km^2 drainage area default for mapping valleys. The subjectivity in identifying the beginning of a valley does not change the classification decisions but will change the proportion of the network in each valley class and the total stream length that is classified. The unmapped *headwater valley* class was designed to extend beyond the final mapped valley segments to include small first- and zero-order channels.

5.4 RATIONALE FOR CLUSTERING

Each valley class is created to group valley settings that have similar combinations of fluvial and hillslope processes. A detailed description of each valley class is found in Appendix A and channel-type descriptions are in Appendix B. Appendix C describes some additional morphological modifiers for valleys and channels. A range of values are expected for each of the geomorphic variables, with thresholds at upper and lower limits of stream power, hillslope stability, and free-lateral movement. Some of the thresholds are regionally specific, while others are universal across fluvial systems in the western US (see Section 3.4 for more detail). Valley types are not limited to political or even ecoregion boundaries. The fluvial surfaces and riparian setting of a canyon in the tropical/subtropical desert are very similar to one in the temperate steppe.

The physical settings of the channel, floodplain, valley bottom, and hillslopes create the abiotic habitat for regional biota. Stressors including prolonged inundation, mechanical stress, drought, and burial eliminate plants not suitable for the dynamic fluctuations of water in riparian areas. Valleys with similar fluvial processes controlling the formation and maintenance of landforms are proposed to have similar physical habitats, similar biotic composition, and therefore similar ecological function.

5.5 COMPARISON TO EXISTING CLASSIFICATIONS

The FRC is designed to support the existing use of the Rosgen (1994) classification. Many federal agencies utilize this method to delineate channels on public land. The FRC strives to be transparent in its identifications of process thresholds. The thresholds identify significant adjustments to the flow of energy and matter in systems

that result in unique landforms, disturbance regimes, and ecological attributes which are not explicitly addressed by Rosgen (1994). The thresholds for channel gradient, lateral confinement, and hillslope stability are supported by numerous field and theoretical studies. Table 5.1 shows the type-by-type comparison between Rosgen's (1994) system and the FRC.

Table 5.1: A comparative analysis between FRC valley classes and Rosgen's valley types.

FRC				Rosgen (1994)			
Valley Class	**Channel Gradient**	**Confine-ment***	**Hillslope Gradient****	**Valley Type**	**Channel Gradient**	**Confine-ment**	**Hillslope Gradient**
Headwater	>4%	Confined	Steep	I	>2%	Confined	Steep
High-energy Coupled	>4%	Confined	Steep	I	>2%	Confined	Steep
High-energy Open	>4%	Unconfined	Steep	III	>2%	Moderately Confined	Steep - Moderate
Moderate-energy Confined	0.1 - 4%	Confined	Low - Steep	II, III	<4%	Confined - Moderately Confined	Steep - Moderate
Moderate-energy Open	0.1 - 4%	Unconfined	Low - Steep	VII	<2%	Moderately Confined	Moderate
Canyon	Variable	Confined	Steep	IV	<2%	Confined	Steep
Gorge	Variable	Confined	Steep	IV	<2%	Confined	Steep
Glacial	Variable	Unconfined	Moderate - Steep	V, IX	<4%	Unconfined	Moderate
Low-energy Floodplain	<0.1%	Unconfined	Low - Moderate	VIII, X	Low	Unconfined	Low

*Confined valleys have widths <7W_c
Very Unstable hillslopes are >70%; **Moderate Unstable** hillslopes are 30 to 70%; and **Stable** hillslopes are <30%.
These values are averages from data sets collected around the world (Sidle and Ochiai, 2006).

The advantage to a fluvial classification grounded in process is the ability to identify similar geomorphic conditions in very different landscape and climatic settings. Observation alone does not support the understanding of past conditions or the prediction of future morphological change. A sound management tool needs to be effective in describing system alterations through time and interpolating past observational data. The FRC builds upon work by Rosgen (1994), Montgomery and Buffington (1997), Nanson

and Croke (1992), and others to create a widely-applicable, process-based hierarchy to classify fluvial networks across the western US.

CHAPTER 6

METHODS

6.1 DEVELOPMENT OF THE FRC

Concepts and methods from successful classifications, for example, Frissell *et al*. (1986), Nanson and Croke (1992), Knighton and Nanson (1993), Whiting and Bradley (1993), Rosgen (1994), Montgomery and Buffington (1997), and Montgomery (1999) were examined for their ability to be incorporated into hierarchical, GIS-based classification of fluvial setting. A classification focused on identifying shifts in fluvial processes was an early objective of the project that dictated much of the subsequent structure. Shifts in fluvial processes were thresholds determined from theoretical and empirical investigations. GIS methods for identifying these thresholds were then developed.

6.2 GEOGRAPHIC INFORMATION SYSTEM PROCEDURES

All procedures are developed using existing tools in the Environmental Systems Research Institute (ESRI) ArcGIS 9.2 software package. To develop the layers for analysis, spatial tools are linked together in automated sets and run directly in the Arc operating system. Cuhaciyan (2006) has completed similar work at the channel scale and the content would be of the greatest utility if the GIS environment remained in the Arc format. ESRI ArcGIS products have become the industry standard and by working within

the 9.2 operating system, most users should have the ability to perform the procedures with the basic ArcGIS Info software package. The resulting procedure with steps are combined into a toolbox organized and ready for user-defined inputs. Information on the location of major process shifts, the extent of the valley, the coupling to hillslopes, and the relative size of the valley and channel are the major goals of the semi-automated GIS procedures.

The theoretical approaches to fluvial landform classification are explicit at the valley and channel scale, yet procedures for a GIS-based classification are only developed for the valley scale. Further considerations need to be made to assess the effects of coarse-grain data on the classification of finer scale landforms before a semi-automated procedure is developed for the channel scale.

The order in which GIS procedures are completed is important; the data layers representing the four major variables: 1) channel gradient, 2) channel width, 3) valley bottom width, and 4) hillslope gradient are created through a series of steps aimed at controlling variability, limiting bias, and emphasizing scale. A toolbox is created in ArcGIS that prompts the user to input calibrated regional values and designate the names of the layers. An accompanying document describes the process and identifies steps where manual delineation or editing is necessary. Each of the spatial layers could be further manipulated to support data requirements for other research questions at different (generally at coarser) scales. Maps are generated identifying spatial extents of the valley classes using GIS-identity algorithms that follow the decision tree in Figure 6.1. The GIS work is then verified by field visitation to several physiographically unique basins.

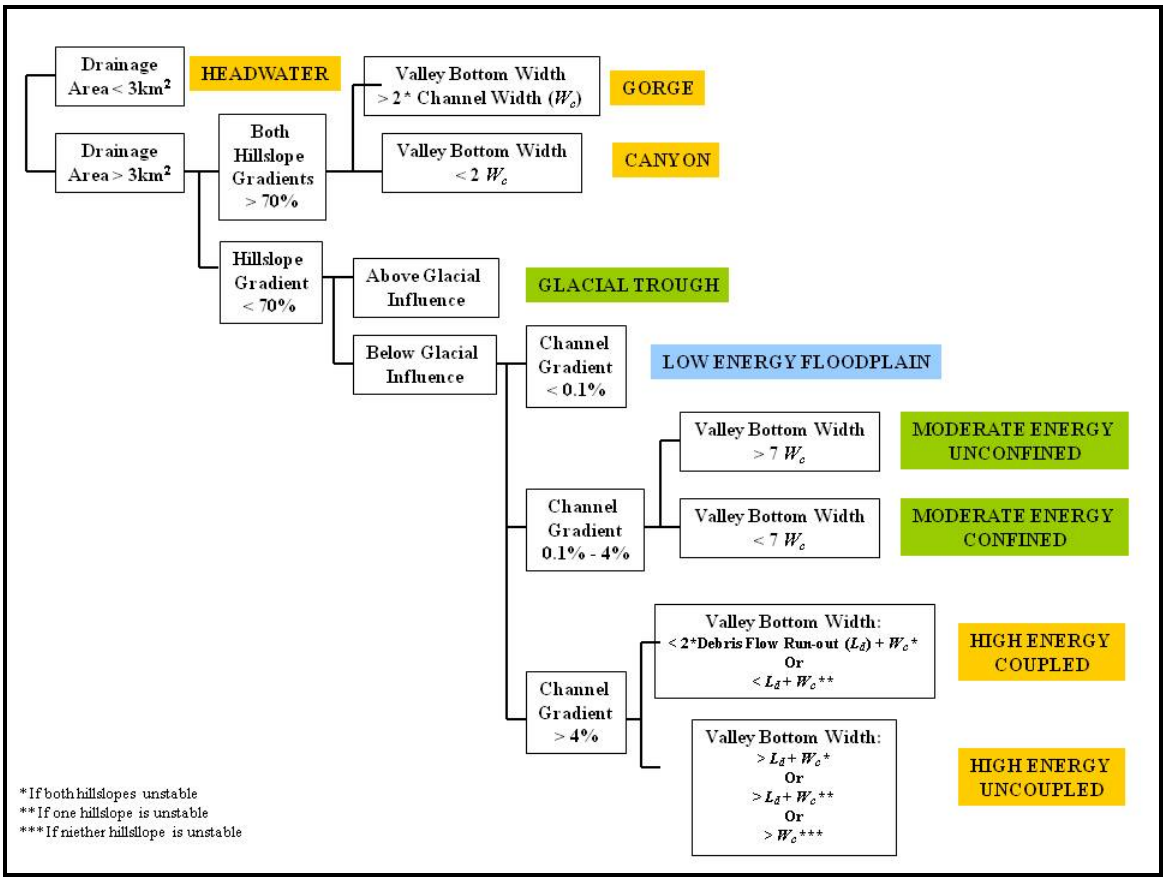


Figure 6.1: Valley class decision tree.

The three process spheres (system energy, hillslope coupling, and lateral confinement) are quantified with a set of novel procedures in GIS. The sets of procedures utilize many standard measurement techniques, organized in a unique manner to most directly capture the influence of each process sphere. The method for delineating the fluvial valley bottom was the most innovative of the three sets of procedures. All three approaches are outlined below with further discussion available in Appendix A.

6.2.1 Channel Gradient

The elevation values along the synthetic stream network are used in the analysis. A moving 3x3 window of 10-m raster cells is used to average the change in elevation

along the channel. At the channel-reach scale this value may be an appropriate scale, but for valley segments the stream slopes are grouped. A smoothing algorithm that increases the moving window to a circle with a 50-m radius is used to calculate the mean slope for each cell on which the window is centered. A recent report from the USFS (USDA, 2005) used focal analysis to smooth channel gradient for spatial analysis. At the valley scale, slope is more meaningful over longer distances as the morphological features of valleys (floodplains, oxbows, and terraces) are larger than those of channels (pools, riffles, and steps). This "elevated" view of the gradient is used in place of a direct measure of valley bottom gradient because it is simpler and does not require the identification of a mean valley direction.

6.2.2 Break in Valley Class

A minimum value was needed to stratify the fluvial network at the valley scale. A somewhat arbitrary value of 200 m was applied to the GIS mapping performed for this study. This is within the bounds of other studies that examined the valley scale (Frissell *et al*., 1986; Cupp, 1989; Rosgen, 1994; Naiman *et al*., 2005). This value is applied to the system energy process sphere to create the initial valley segments. Persistent change in the channel gradient must be observed for 200 m for a segment to be created. Segments of persistent gradient that are <200 m are incorporated into adjacent segments. The channel lengths that have not been identified as a valley segment are split, with half the length being designated as the gradient of each of the adjacent valley sections. This "growth" restores the continuous linear characteristic of fluvial networks. There is no upper limit to the length of a valley segment. Some preliminary GIS work suggests this

valley could be as high as several kilometers or more. The valley segments created at the beginning of the GIS procedures are used as the individual units for the calculation of all remaining variables.

6.2.3 Valley Bottom Delineation

The method for identifying the valley bottom is a crucial component of the FRC as it is used to classify hillslope coupling and lateral confinement. The rationale behind its operation and how it has developed from previous methods is helpful to understand. In developing the measurement tools to identify the fluvial valley bottom, I explored two methods to identify the portion of the landscape influenced by fluvial processes: one based on hydrology and one on geomorphology. The hydrologic method combines several techniques from Williams *et al*. (2000) and Nardi *et al*. (2006) to relate floodplain width to the magnitude of the system, but neither method was a satisfactory measure of valley width within the FRC. Both methods utilize GIS as the main tool for delineation. However, inconsistent inputs and intensive calculations prohibit the utility of these methods at the scale the FRC addresses.

Williams *et al*. (2000) applied a constant "depth of inundation" for each stream cell. The extent of the area "inundated" is considered the valley bottom and its width is measured by transects perpendicular to the channel position (Williams *et al*., 2000). Two major problems occur with this method: 1) over- or under-estimation of valley area is probably related to the constant flood depth in smaller headwater channels and larger floodplain areas, and 2) the orientation of perpendicular width measurements are complicated along meandering channels and tributary junctions (Nardi *et al*., 2006).

However, the simplicity of applying a constant inundation depth and its limited data requirements are notable advantages of this method.

The hydrogeomorphic delineation method proposed by Nardi *et al*. (2006) requires discharge data or field-verified flood depths to be accurately applied. Equation (6.1):

$$h = a\,A^{b} \qquad \textbf{Equation (6.1)}$$

is used to determine the depth (h) of a given stream grid cell as it is related to drainage area (A). Known pairings of h and A or an outlet discharge are necessary to generate the parameters a and b. This component is central to the method yet is difficult to achieve in remote areas where flood and discharge data are extremely limited. The incorporation of network analysis is an important advantage to note.

Another influential work that was strongly considered was Dodov and Foufoula-Georgiou (2005), which explored fluvial processes and a threshold for drainage area at which floodplain development became extensive. The study examined the Central Plains and Appalachian Mountains. These systems more closely follow the idealized river profile of steep headwater source regions flowing towards the flatter, open floodplains at the distal ends of river courses. The varied topography of the West often punctuates the river profile with erratic sections of geomorphically-forced morphology departing from the ideal ordered progression of river form.

Topographic breaks-in-slope (BiS) have been used to identify riparian areas with fluvial influence (Polvi, 2009). Attempting to measure these breaks with GIS is often limited by the grain of the data, as appears to be the case with the BiS method used here. This was developed considering that the majority of landforms on the valley bottom and

the relationship to the adjacent hillslopes are influenced by contemporary fluvial processes. Examples where this concept is not supported include glacial valleys over-widened by the action of erosion by ice, and recently incised channels with insufficient flow to reconnect to the former floodplain, even at extreme flow events.

The BiS accumulates changes in gradient until a user-defined threshold is passed. The areas with an accumulation below the threshold are defined as fluvial valley bottom. The accumulation begins at the channel and moves outward. The network is stratified by Strahler stream order and sample cross sections are used to estimate the threshold for accumulation by stream order. Cross sections are used to identify the significant breaks in slope or elevations above the channel at which fluvial processes are hypothesized to be of limited influence. A mean threshold value (in m/m^2) is calculated for each order and applied to all sections of the same stream order in the study area.

To the author's knowledge, a method of valley bottom delineation that examines the BiS, identified by accumulated changes in gradient, has not yet been fully explored. The geomorphic method is a simple innovation similar to the Topographic Position Index (TPI) (Jenness, 2006) in that it uses relative comparisons. The TPI uses a comparison of elevation and slope, while the BiS method utilizes the second derivative of the elevation shown using Leibniz's equation below to identify topographic BiS, where y is the vertical distance and x is the horizontal distance:

$$d^2y / dx^2 \qquad \textbf{Equation (6.2)}$$

An accumulation of gradient changes are measured radiating outward from the channel. The threshold was varied by stream order to incorporate the increasing size of the valley bottom and increased heterogeneity of floodplain features likely to occur in the

downstream direction. All areas within an accumulated change less than the user-defined threshold are considered part of the valley bottom.

To measure the valley width, a series of random points are populated along the channel and the closest distance to the edge of the valley is measured. The technique does not involve defining general valley direction or perpendicular angles. Figure 6.2 shows the orientation of the measurements for a sample valley. A mean valley width is generated for each valley section. This approach, however, has several limitations including manually-intense edits and a consistent under-estimation of valley width.

The approach that was adopted for the GIS procedure measured a Euclidean distance from the channel to the valley edge. A mean width was calculated for each valley section. This value was doubled as the Euclidean distance represents only one of the un-channelized portions of the valley. This method does not require a manual-editing session, which would be a significant advantage for large study areas.

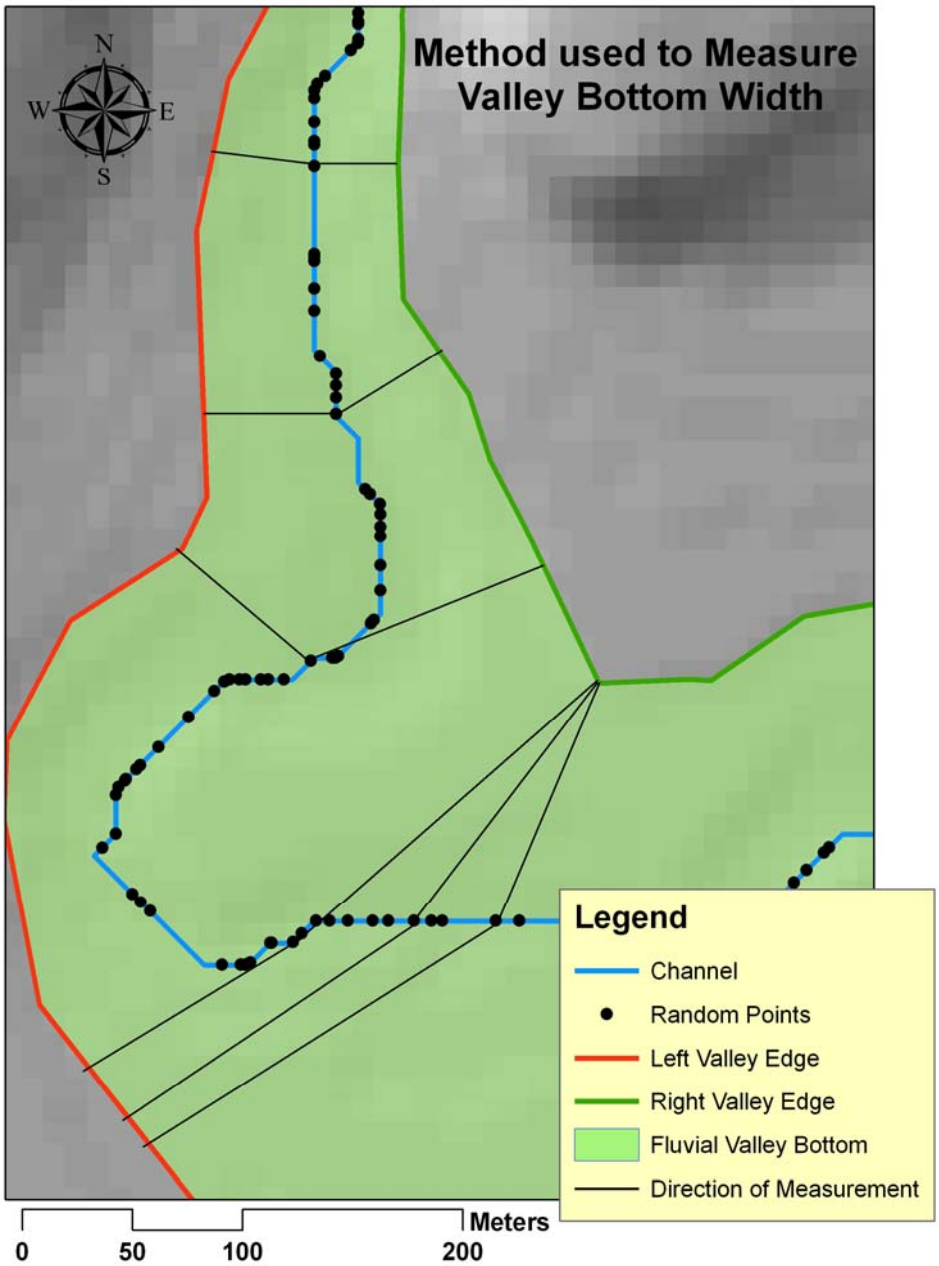


Figure 6.2: A map showing the approximate direction of the measurement of valley bottom width using random points along the channel.

6.2.4 Hillslope Categorization

Hillslopes are categorized by using the gradient composition of slopes immediately adjacent to the valley bottom. To obtain the proportion of the area in each of

the hillslope gradient classes, the "hillslope area" must be defined. A band 150 horizontal meters upslope from the valley edge is bounded at the upstream and downstream ends of each valley section. By way of these bands, hillslopes for each valley section are evaluated independently of the surrounding landscape. The band width is designed to balance capturing important source zones for landslides and debris flows, while limiting the inclusion of slopes that lie across local drainage divides. Preliminary GIS sampling and field reconnaissance were conducted to determine this width as an appropriate distance to examine hillslope character.

6.3 FIELD MEASUREMENTS

Field-derived values of geomorphic variables are considered to be the true value. The GIS values are then estimations, reliant on the resolution and precision of base data layers. Similarly, the FRC uses values for geomorphic parameters generated using GIS and thus the difference between GIS and field values is critical to understand. Hillslope gradient may not be accurately recorded using remotely-sensed data and geospatial techniques (Cupp, 1989); therefore field verification is necessary. Comparisons between field and GIS values can suggest adjustments to the measurement tools in GIS or the identification of a direction bias that can be written into the classification decisions.

The valley classes of the FRC are ultimately designed to describe areas with unique ecological function related to the geomorphic shape and fluvial processes operating in an area. Measured values for the geomorphic parameters of channel gradient, hillslope gradient, valley width, and bankfull channel width describe the physical setting of valleys. Additional qualitative variables such as vegetation composition, channel

planform, substrate characteristics, and bank stability may not feed into the FRC decision tree directly, but they are useful in depicting ecological function.

6.3.1 Channel Gradient

In GIS, the channel gradient is calculated over ~30 m of stream length, and then averaged over 100 m. In the field, measurements are taken over 100-m transects to match this smoothing distance. Total channel gradient is calculated over the 100 m and in instances of limited line of sight, more detailed gradient measurements were recorded and a mean calculated. A clinometer is used to measure gradient, allowing for quick measurements in difficult terrain. Gradient was measured at the current water surface at all points along each channel.

6.3.2 Bankfull Channel Width

Bankfull width is estimated in the field using physical indicators such as flat depositional surfaces, tops of point bars, shelves, and flood debris. This critical value can be difficult to identify in the field, especially if the system is significantly influenced by bedrock, is severely confined, the channel is entrenched, or the banks are highly erodible (Williams, 1978; Rosgen, 1996; Knighton, 1999). Field indicators of bankfull can be matched with different return-period floods in different physiographic regions or even within the same basin (Williams, 1978; Knighton, 1999). Mean width was also estimated if the width at the site was atypical due to debris jams, bridges, or other major restrictions not common along the section. Channels were either waded across, or crossed on logs and bridges to permit the placement of the measuring tape for accurate width

measurements. In extremely wide areas, or areas where brush was thick, global positioning system (GPS) points were placed at the bankfull channel edge and the width was later measured in GIS. Bankfull width includes the entire active channel complex, multiple channels, and low bars and islands (Figure 6.3).

Figure 6.3: Low sandy bar as part of the bankfull channel width of the Big Sandy River, a tributary of the Green River (southwestern Wyoming). Note low-flow channel is much narrower than the bankfull extent. Flow is from left to right.

6.3.3 Valley Width

Topography, vegetation, soil development, flood debris, and fluvial landforms were used to identify the boundaries of the fluvial valley bottom (Hupp and Osterkamp, 1985, 1996; Polvi, 2009). In some situations, a fluvial valley bottom was observed to be

contained within a larger, geomorphic valley bottom set between two prominent hillslopes. Information on both widths was considered useful for evaluating the strength of the BiS method for delineating fluvial valley bottoms in GIS.

6.3.4 Hillslope Gradient

Gradient is measured for 150 m, perpendicular from the valley edge. If the slope varies, measurements are taken at points of inflection. A clinometer is used to aid in quick measurements in difficult terrain. The capacity for a slope to exert influence on the riparian system is considered by measuring the composition of hillslope gradient. The 150-m distance balances the need to consider longer hillslopes with concave profiles and shorter hillslopes in areas of high drainage density where divides are low. The composition is considered over the length of the valley segments defined by channel gradient, matching the parallel hillslopes to valley sections. This is a means of averaging the connectivity to the hillslope over the entirety of the segment.

6.3.5 Qualitative Variables

Several characteristics of the channels and valleys were noted in a qualitative way to assist in understanding the geomorphic processes and ecological function of the valley, channel, and riparian complex. These include presence of hillslope debris; channel planform and bedform; bed substrate; bank substrate and stability; and vegetation on the hillslopes, valley flat, and streamside areas. Ecological function considered the frequency and magnitude of disturbance; the link to hillslope material during floods; the dynamics

of channel movement; and the stability of channel banks, valley walls, and the floodplain surface.

6.4 HEC-GeoRAS

The objectives of this test included using HEC-GeoRAS (a set of procedures, tools, and utilities for processing geospatial data in ArcGIS using a graphical user interface in Hydrologic Engineering Centers - River Analysis System (HEC-RAS)) to: 1) plot the horizontal extent of the water surface at several flood-recurrence intervals, and 2) compare the 100-yr flood top widths with topographically-defined valley bottoms at 1- and 10-m scales for the H.J. Andrews Experimental Forest in Oregon. Flood top width is the horizontal distance across the channel and floodplain as measured between the locations where the water intersects the land surface. Hydrologic parameters (estimated discharge, channel slope, and boundary conditions) were used to model floods of several recurrence intervals. Discharge was calculated from USGS (1994) regional flood regression equations. Channel slope was measured in HEC-GeoRAS from the 1-m LiDAR data and boundary conditions were estimated for the system using general knowledge of hydrologic and hydraulic patterns. I modeled extents of the 2-, 5-, 10-, 25-, 50-, and 100-yr flows, but only analyzed the 2- and 100-yr extents. Many scientists regard the 2-yr flow as closely representing an estimate of bankfull discharge (Church, 1992) and the 100-yr flow is a fundamental component of the *fluvial riparian area* definition from the USFS.

The main data inputs into the HEC-GeoRAS program include: elevation grid, discharge values, or equations. The input elevation grid was a 1-m horizontal resolution

triangulated irregular network (TIN) that was created from a 1-m DEM generated using LiDAR. The discharge values for each flood-recurrence interval of interest were computed using USGS flood regression equations. The regression equations used drainage area and maximum 24-hr rainfall rates at the 2-yr recurrence interval as inputs in the equation. Error rates for the discharge were reported as 34 to 60% (USGS, 1994). The discharge is sensitive to the rainfall rates, with a 100% increase in discharge when increasing the rainfall rate from 3.7 to 4.25. Boundary conditions influencing in-channel hydraulic processes and flood dynamics were estimated and some defaults within HEC-GeoRAS were accepted. The model is sensitive to channel and floodplain roughness (Manning's *n*). The area is known to have LWD influence and is in a mountainous setting, so the roughness was estimated on the higher end of the normal range.

Once the model was built with its hydrologic parameters and boundary conditions defined, 22 cross sections were taken from the LiDAR and flows were generated for these locations. The locations where cross sections would be extracted from the LiDAR data were identified *a priori* to balance time constraints with adequate representation of the network of valleys in the study area. No interpolation was made between these cross sections and flood top width was only estimated at the 22 cross sections.

Bankfull channel width is a required value used to calculate valley confinement. Sources of error in the identification of field indicators and the large residuals for some of the regional parameters from Faustini *et al*. (2009) could lead to very large differences between bankfull estimations and true bankfull stage. The *Q*2 approach in the H.J. Andrews Experimental Forest used flood discharge equations from the USGS and a very fine-scale DEM to estimate bankfull stage following the calculation of hydraulic

geometry for the channel. This method also proved to have substantial error from the regional flood discharge equations and the 1-m scale DEM still not accurately representing the channel morphology. Channel morphology was especially critical because the top width of $Q2$ was directly related to the precision at which hydraulic area could be measured. A preliminary comparison between the two methods did not yield any useful conclusions of accuracy owing to the substantial error involved in these two approaches and their different sources of error.

However, an estimation of bankfull channel width was required to quantify confinement for the valleys. The equations from Faustini *et al*. (2009) were used for the field study sites located in Arizona, Colorado, and Wyoming, while the USGS discharge equations and 1-m LiDAR DEM data were used to calculate $Q2$ and flood top width, respectively, in Oregon. These methods were chosen for the different locations based on data availability. I hypothesized that estimates of bankfull channel width would be more accurate using the $Q2$ and 1-m LiDAR approach. Bankfull channel widths for the H.J. Andrews Experimental Forest, Oregon, were estimated using the $Q2$ and 1-m LiDAR approach, as the data were available. The equations from Faustini *et al*. (2009) were applied to other regions where 1-m LiDAR data were not available. USGS flood regression equations are available for all the study regions, but without very fine-scale DEM data, hydraulic geometry could not be calculated.

6.5 TOPOGRAPHIC POSITION INDEX

The TPI was developed to classify the entire landscape (Jenness, 2006). The tool extension is run in ArcView V.3 (an earlier product platform of ESRI ArcGIS); therefore,

layers are of the same file type and moving between programs is generally easy. The concept uses slope and elevation in relative comparisons within a user-defined window. The scale of the study defines the approximate scale of the window and can have significant influence on the resulting landform classes identified and their spatial extent.

The TPI identifies landscape elements such as valleys, ridges, plains, and hillslopes. The descriptions and extent of TPI-specific valley landforms (incised canyons, shallow valleys, U-shaped valleys, or headwaters) can be compared to the FRC. Their extent is based on slope and elevation without considering drainage area (a common surrogate for discharge and general stream size). This method does not provide detailed, hydrologically-connected examinations of valley extent, channel slope, or hillslope connectivity. However, the qualitative classification of the entire landscape is a useful endeavor in many aspects of land use and resource planning, but fluvial networks need a more detailed methodology for identifying the unique collection of processes that maintains areas of distinct geomorphic and ecological function. The FRC uniquely fills this role in landscape classification. It is applicable at wide scales while using fine-grain data and fine-scale measurement methods to identify and classify fluvial features within watersheds.

6.6 SUMMARY

Four independent efforts were completed to test the FRC: 1) the GIS procedure was performed for several locations with varied physiographic, climatic, and biological environments; 2) field surveys were conducted at the regions mapped with the FRC to test the validity of assumptions and accuracy of GIS-measurement approaches; 3) a

detailed investigation of flooding with very fine-scale (1-m LiDAR) data was completed using HEC-GeoRAS; 4) the landscape classification (TPI) was implemented to examine its effectiveness and compare valley types with the FRC. Each effort tested the FRC from a different approach to determine its weaknesses and suggest bounds for it application. Methods were evaluated to examine the accuracy of the input variables using GIS, the validity of the approach was examined and the overall performance of the FRC GIS-based classification was tested against the classification performed in the field.

CHAPTER 7

RESULTS

The FRC is designed to be operated with widely-available, remotely-sensed data in an office setting, yet will support modifications in the form of threshold regionalization. A user with knowledge of local climate patterns, geology, soils, and vegetation can complete the classification process and generate maps from a desk. Improving objectivity and creating a GIS-based procedure were top priorities when developing the FRC. Below, I will present the results from the application of the FRC in three study regions, the development of a fine-scale hydrologic flooding model, and a landscape classification.

7.1 GIS PROCEDURES

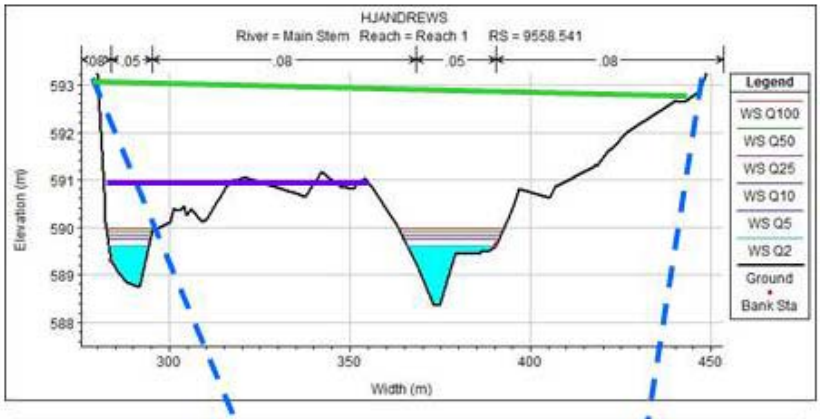
7.1.1 Channel Gradient / System Energy / Valley Segments

Intermediate steps were observed during the implementation of the set of GIS procedures for measuring channel gradient and creating valley sections. The detailed procedure worked very well with only a few minor errors that required manual attention. These occur at tributary junctions. Large sections of the fluvial network were noted to consist of sections of an energy class (High, Moderate, or Low) that were shorter than the 200 m minimum for a valley segment. With several of these adjacent to one another it was not uncommon to have sections of the fluvial network nearly 1 km in length that

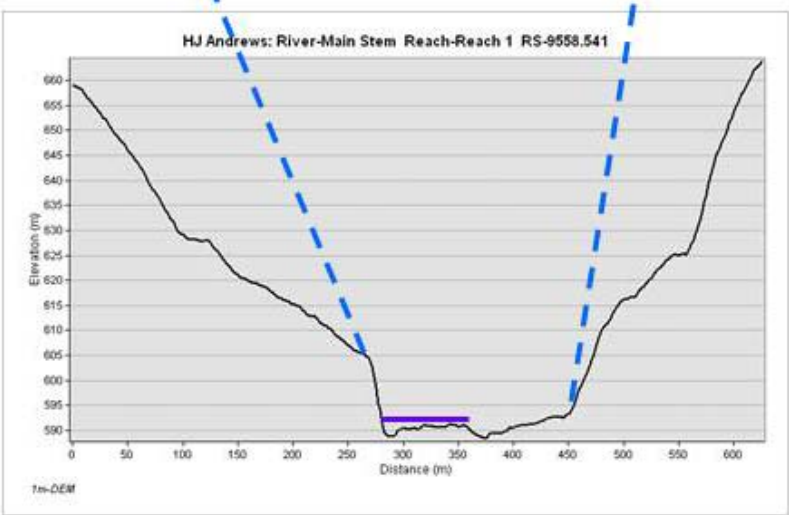
were not categorized initially. The procedures split these areas and apply half of each uncategorized area to the adjacent valley sections.

7.1.2 Valley Bottom Width / Lateral Confinement

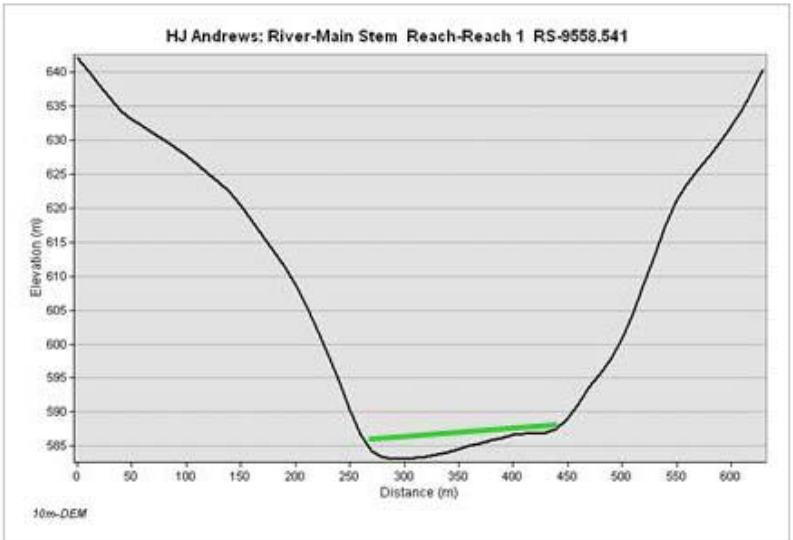
Cross-section profiles, flood top width, and water-surface elevation from the 100-yr discharge in HEC-GeoRAS were examined and compared to the extent of the fluvial valley bottom generated using the BiS method at 1- and 10-m scales (see Figures 7.1 through 7.5). Flood modeling and the BiS were completed on a synthetic fluvial network initiating at 1 km^2.



(a) HEC-GeoRAS flood extents

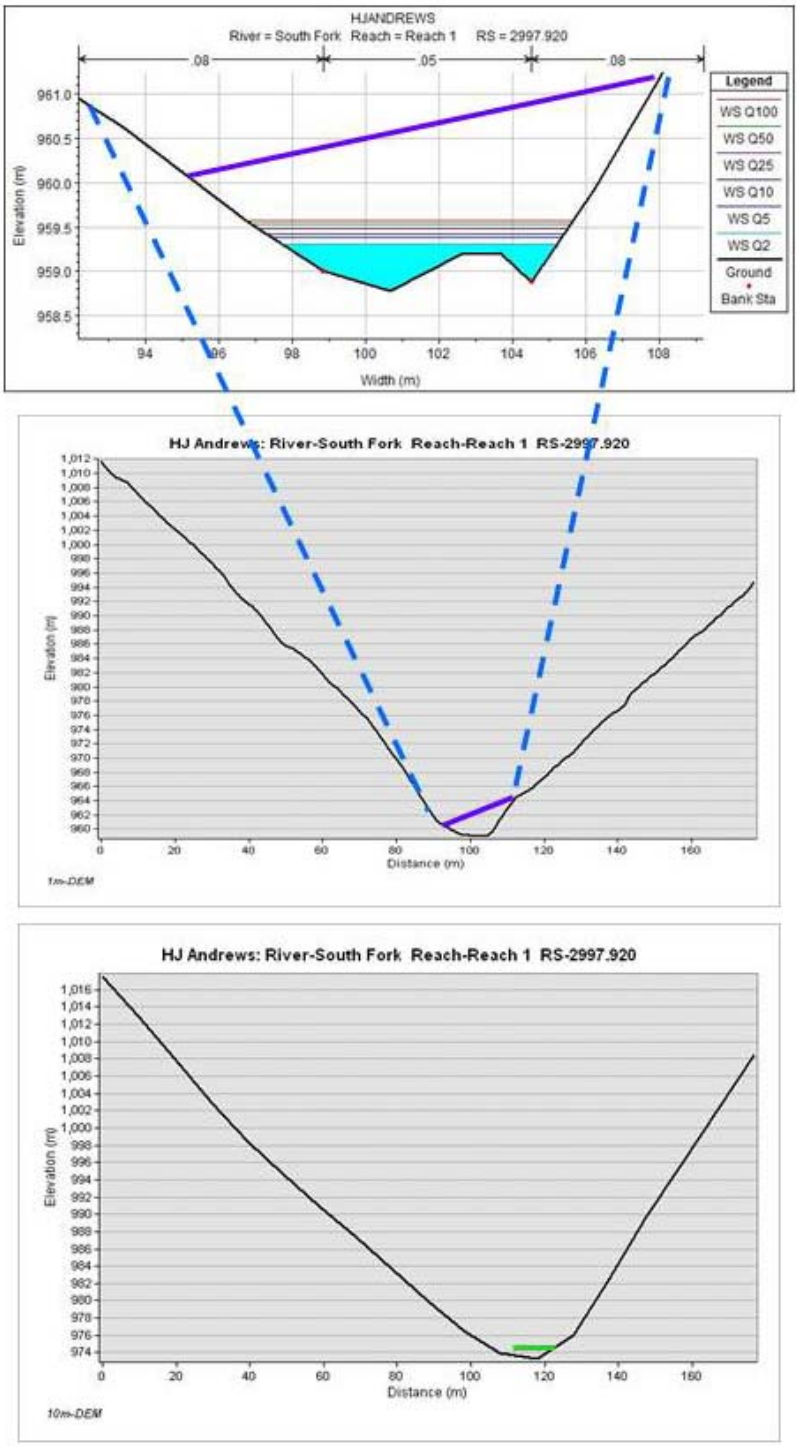


(b) 1-m valley extent (BiS method)



(c) 10-m valley extent (BiS method)

Figure 7.1: Cross sections of valley (H.J. Andrews Experimental Forest, Willamette National Forest, Oregon). Note the overlay of all three scales/methods in (a).

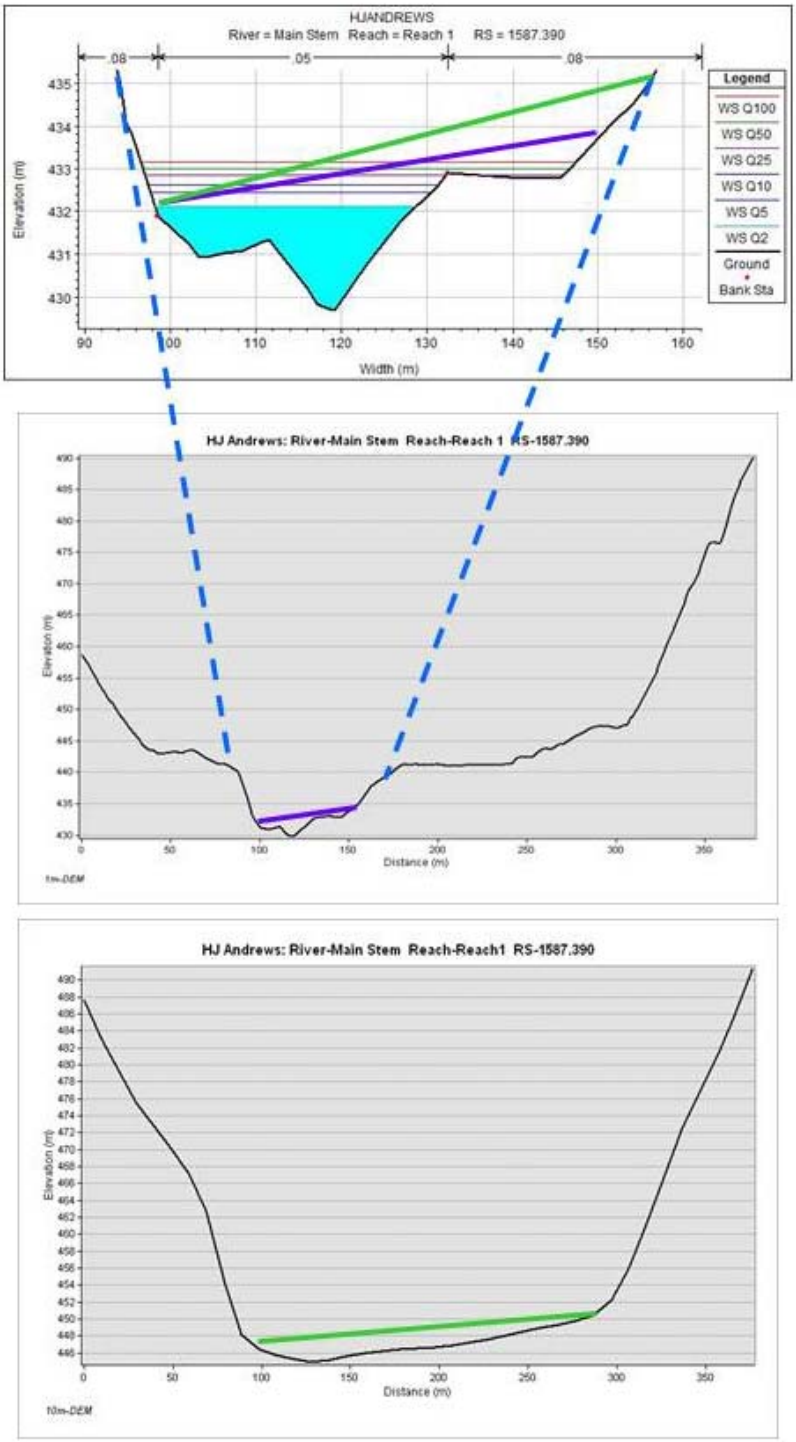


(a) HEC-GeoRAS flood extents

(b) 1-m valley extent (BiS method)

(c) 10-m valley extent (BiS method)

Figure 7.2: Cross sections (South Fork) of valley (H.J. Andrews Experimental Forest, Willamette National Forest, Oregon). Note the lack of overlay of all three scales/methods in (a).

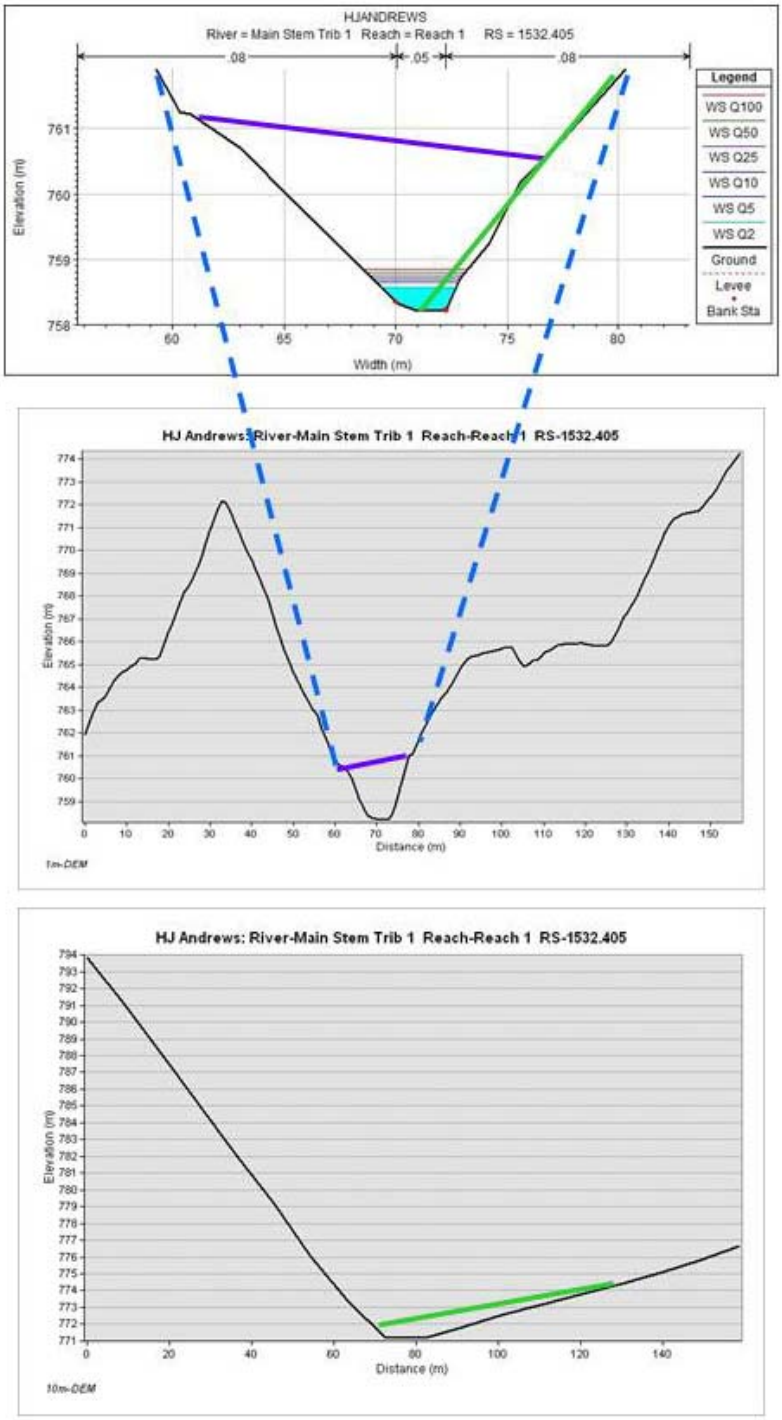


(a) HEC-GeoRAS flood extents

(b) 1-m valley extent (BiS method)

(c) 10-m valley extent (BiS method)

Figure 7.3: Cross sections of valley (H.J. Andrews Experimental Forest, Willamette National Forest, Oregon). Note the overlay of all three scales/methods in (a). Also note the gross simplification of surface topography between (a) and (c) as one moves from 1-m to 10-m scale.

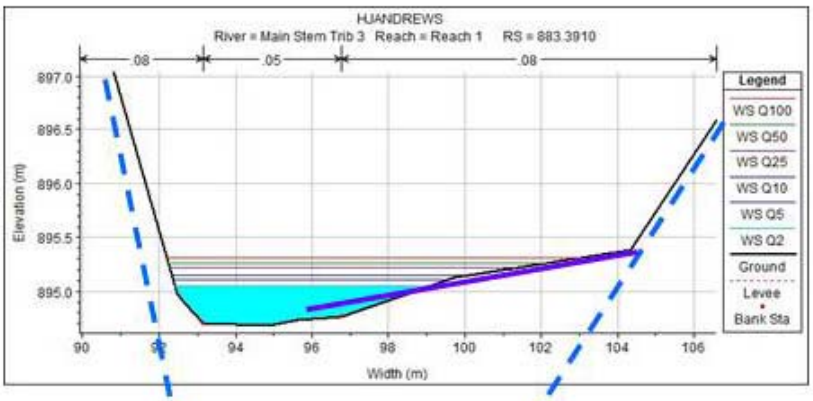


(a) HEC-GeoRAS flood extents

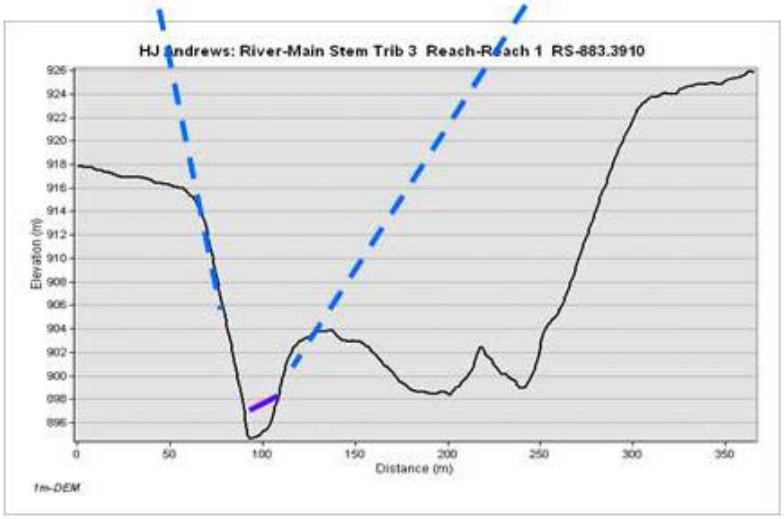
(b) 1-m valley extent (BiS method)

(c) 10-m valley extent (BiS method)

Figure 7.4: Cross sections of valley (H.J. Andrews Experimental Forest, Willamette National Forest, Oregon). Note the overlay of all three scales/methods in (a). Also note the simplification of topography of the right slope in (b) and (c).



(a) HEC-GeoRAS flood extents



(b) 1-m valley extent (BiS method)

(c) 10-m valley extent (BiS method)

Figure 7.5: Cross sections of valley (H.J. Andrews Experimental Forest, Willamette National Forest, Oregon). Note the overlay of all three scales/methods in (a).

Numerical analysis plotting flood top width against drainage area, and other plots of calculated stream power versus discharge, flood top width, and drainage area were all completed in Microsoft Excel®. The three-paneled illustrations (Figures 7.1 through 7.5) show the valley bottom area delineated using (a) hydrologic flood modeling at the 1-m scale; (b) employing the BiS method at the 1-m scale; and (c) the BiS method at the 10-m scale. Panel (a) also shows the overlap of the three results. All three valley bottom extents did not always correlate. Figure 7.2(a) shows the 10-m valley bottom does not match with the other two results, not overlapping at all. Figure 7.3(b) shows the 10-m valley bottom as significantly larger than valley bottom extents from the other methods. An examination of the coarsening of the land surface that occurs when moving from the 1-m scale to the 10-m scale is very apparent through the series of cross-section profiles in Figures 7.1 through 7.5.

The largest overestimations of valley width, at both the 1-m and 10-m scales, came on the upper-most headwater reaches of the network. A strong bias towards overestimation, suggests valleys are wider than the 100-yr flood top width. This pattern was shown in 43 of the 44 comparisons (see Table 8.1 in *Discussion*). Figure 7.6 compares the $Q100$ flood calculated at the 1-m scale to the BiS valley extent calculated at the 1-m and 10-m scale.

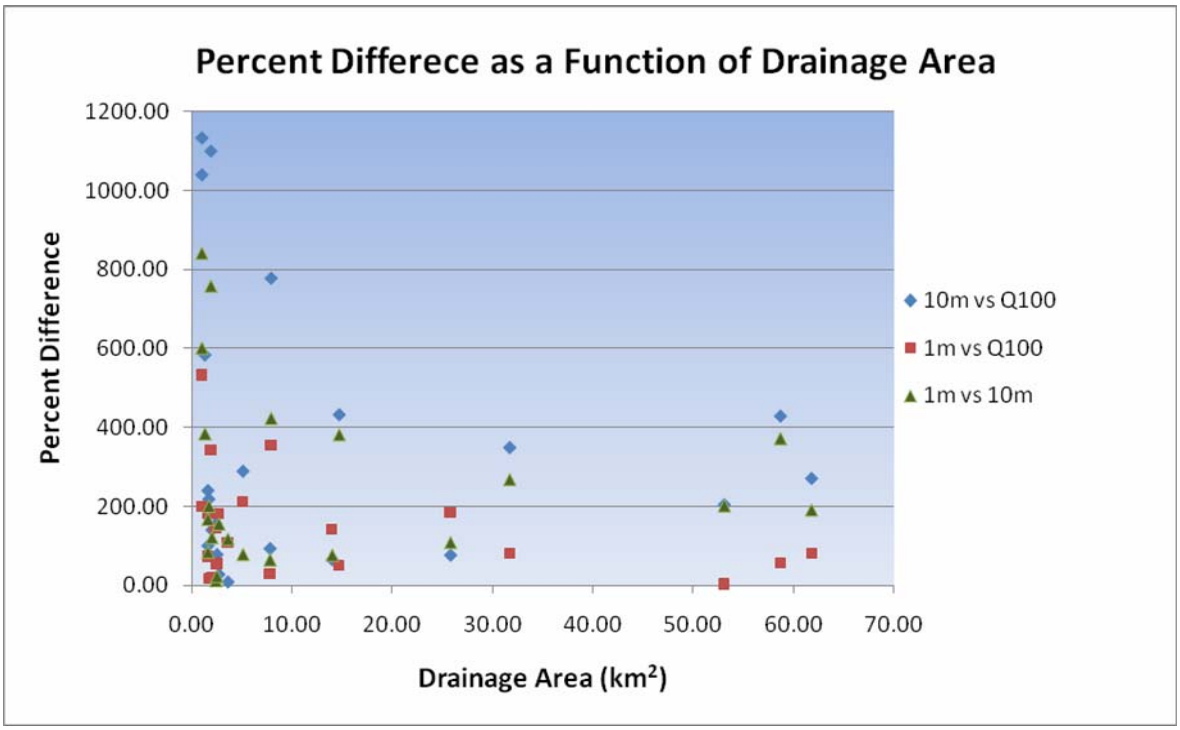


Figure 7.6: The percent difference between the BiS method computed at 1 m and 10 m, and the *Q*100 flood extent from HEC-GeoRAS.

When the results are stratified by drainage area, the BiS method appears to perform better as contributing area increases (see Figure 7.6). The difference between the 100-yr flood extent and the 1-m BiS fluvial valley bottom decreased from 178% at cross sections for valleys at 1 to 3 km^2 to 118% for cross sections at 25 to 65 km^2 valleys. A large reduction in difference (438 to 266%) also occurred between the same drainage area groups when comparing the 100-yr flood extent to the 10-m BiS fluvial valley bottom (see Table 7.1). This pattern of improved performance for systems with larger drainage areas could be a result of more abrupt BiS, more of the slope-change accumulation occurring on the generally broader valley bottoms characteristic of lower network positions, or some other factor.

Table 7.1: Percent difference in fluvial valley width measurements. Comparisons between two approaches (BiS and hydrologic modeling at *Q*100) and at two scales (1 m and 10 m).

Drainage Area (km^2)	1-m BiS vs. *Q*100	10-m BiS vs. *Q*100	1-m BiS vs. 10-m BiS
1 - 3	177.53	437.77	303.49
3 - 25	149.39	277.47	189.68
25 - 65	81.25	265.69	227.60

7.1.3 Hillslope Gradient Categorization / Hillslope Coupling

The hillslope areas associate with each valley segment were categorized based on the gradient composition. The procedure is simple and the output is an overall categorization of stable, moderately unstable, and very unstable. Hillslopes categorized as moderately and very unstable can potentially be coupled to the channel as they have the potential to generate colluvial material. It should be noted that no hillslopes were categorized as very unstable. A very unstable hillslope is characteristic of Canyon and Gorge valley classes of the FRC.

7.1.4 Mapping

The GIS procedure was followed to create maps for three watersheds in each of the study regions on USFS land. Without expert local knowledge, most defaults were accepted for the FRC, including the hillslope stability thresholds (30 and 70%), debris run-out length (25 m), and the valley initiation threshold (3 km^2). The channel scale of the FRC hierarchy was not mapped.

Maps created for the Tonto National Forest (Tonto NF) and Arapaho National Forest (Arapaho NF) in Arizona and Colorado, respectively, were created prior to field

reconnaissance. For the sites in Wyoming along the Green and Black's Fork Rivers, maps were generated after the field visits. In Tonto NF and Arapaho NF, complete watersheds were mapped and sampled. The rivers in Wyoming were much larger and mapping the complete watershed of the Green River would have exceeded the time constraints of this project. The GIS procedure can be adjusted to work with data that do provide complete watershed coverage. This is useful when examining especially large systems or when river corridors are the spatial unit of interest. The methods used to generate the valley sections showed promise during the procedure and on final maps. The techniques used to: smooth channel gradient, group it into sufficiently long sections (>200 m), and identify tributary junctions appeared effective.

7.1.4.1 Advantages

All of the decisions in which human subjectivity could affect the assignment of a valley class have been made objective by utilizing the tools in ESRI ArcGIS 9.2. The assignment of gradient classes, the identification of valley sections of suitable length and the measurement of channel width, valley width, and hillslope gradient are all semi-automated. Semi-automated refers to a procedure where some steps require minor clerical work in labeling features, but the critical decisions are written into the procedure and are not to be altered. The attention required between groups of analysis invites the user to scrutinize intermediate data layers, further adjust user-defined thresholds, or repeat with slightly different values.

Additional research questions may prompt further analysis on some of the intermediate data layers. The GIS procedures allow for the quick use of the methods with

prompts for manual efforts and prompts for regionalized variables clearly identified. The procedure is transparent, allowing the user to replace groups of steps creating a specific data layer, if one has already been created. For instance, if channel width has been mapped at the reach scale, it can replace the estimations using regional regression equations for a more realistic analysis of the fluvial setting.

7.1.4.2 Disadvantages

Any manual component adds time and human errors. While biases are not involved in the decisions, misspellings and typing errors can lead to confusing or inaccurate attribute correlation. With several manual steps required by the FRC procedure, error can build upon itself and can be difficult to detect. Some of the variable measurements were limited in their methodology by implicit restrictions in ArcGIS and, therefore, do not match well with field procedures. Weaknesses of specific geomorphic variables, identification of critical process thresholds and methods are further discussed in Chapters 4 and 6.

The final product of the GIS procedures is a map showing the fluvial network stratified by valley class. Valleys could either be displayed as linear features, using the lines that represent features of flow accumulation that exceed the valley initiation threshold, or as valley areas. Regardless, the attributes for each valley segment include information on channel gradient, hillslope stability and coupling, mean bankfull width, mean valley width, and the VWI. Maxima, minima, variance, and median values could also be calculated for these attributes.

Maps can be created for entire watersheds of various sizes or for single valley sections of interest. Constraints of time, money, and data may force users into the latter approach. If feasible, there is great benefit in watershed analysis by understanding the location of valley types within a watershed, the proportion of valleys of a particular class, and the total valley bottom area. Overlaying the valley classes with land-cover data, proposed transportation routes, development expansion, etc. will aid management agencies and planning firms in making economic and environmentally sound decisions. Total area in each valley class, the length of channel in each valley class, and the number of valleys in each class can be easily calculated for a given study region.

Wyoming had the most consistent valley types even as drainage area and channel size varied. The FRC maps showed that of the eleven sites, seven are classified as low energy, and four were moderate energy. Of the moderate-energy valleys, three were described as unconfined and one as confined. The *Site-specific Procedure* was used to classify the main stem of the large rivers and some of the tributary valleys. The boundary of classification had no hydrologic significance.

The watersheds examined in Arapaho NF and Tonto NF were more diverse. Each study region was found to have four different valley types. The Arapaho NF had no High-energy systems, one Low-energy Floodplain, and three Glacial valleys. Tonto NF was predominantly moderate energy with three low-energy and two high-energy systems. The classifications were completed without expert knowledge of the regions.

Below is an example of a completed map section (Figure 7.7) from Tonto NF, Arizona. The FRC procedure was applied to each area and colored lines follow the general pattern of the channels and contain the attributes of valley characteristics.

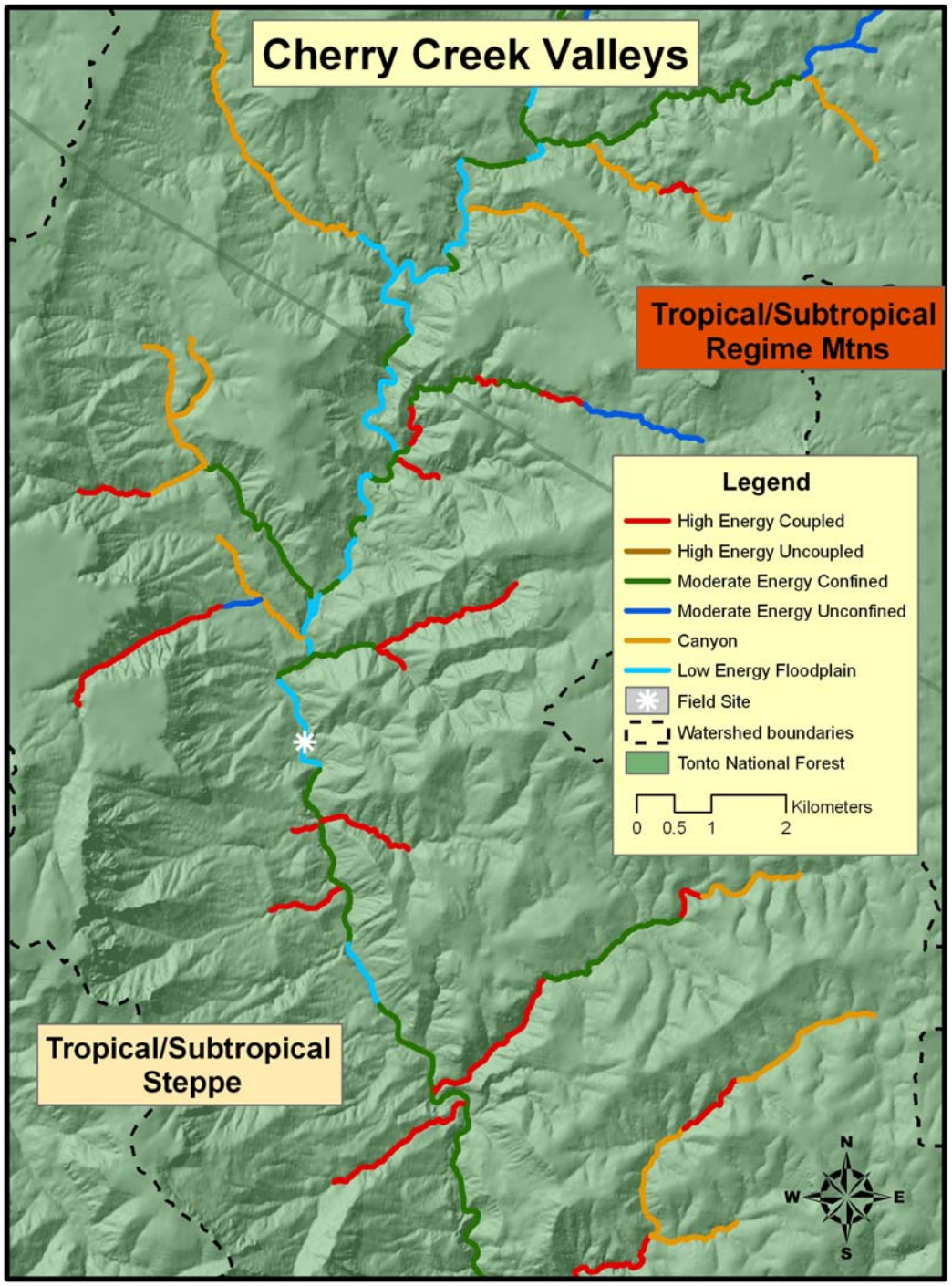


Figure 7.7: An example of the valley maps that can be created using the FRC. This map shows the extent of the fluvial valley bottom, the classified valley sections, and a colored and shaded background relief. This area is in the central portion of the Cherry Creek watershed in Arizona.

7.2 FIELD OBSERVATIONS

While the FRC is designed to be implemented in an office setting, on-the-ground testing was used to assess the accuracy of the geomorphic variables used, truthfulness of the final valley class and the correspondence of valley classes to ecological function. Field methods were developed that would measure the main geomorphic variables central to the FRC (channel gradient, hillslope gradient, channel width, and valley bottom width) in a similar way to the tools in ArcGIS 9.2. The values recorded in the field were used in the decision tree to determine a "field valley class" that was then compared to the "GIS valley class."

The four main geomorphic variables used in the objective valley-scale classification, including: 1) channel gradient; 2) hillslope gradient; 3) bankfull channel width, and 4) valley bottom width, were measured in the field. The methods of their measurement followed as closely with those used in the GIS procedures as possible. For example: the distance over which channel gradient is calculated in GIS spans ten 10-m cells or about 100 m. One hundred meters along the channel was used as the distance over which the field gradient is calculated.

The speed and single-person use of the clinometer was advantageous throughout field investigations but its limitations at very low gradients (<0.5%) were apparent. Interestingly, the GIS-slope calculations also had a difficult time describing very low gradients. Eaton and Church (2007) noted problems with calculating gradient in the field for anastamosing channels in British Columbia over even longer distances of 250 m. The GPS was critical in determining the location of pre-identified sites. It was also useful in measuring the valley width when greater than 200 m, or where dense vegetation

prohibited the use of a 100-m tape. In box canyons or deep forests, however, sufficient satellites were not available to accurately fix the location, so paper maps were used in combination with the GPS to verify some site locations.

Qualitative measures of bank stability, bed substrate, vegetation communities, and general ecological function were made in the field as well to augment the quantitative variables. While these had no direct comparison with office-predicted values, they aided in the most accurate classifying of valleys in the field.

7.2.1 Locations

Three study regions in three western states were chosen to test the FRC; 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 7.2: 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

7.2.2 Site Selection

Sites were chosen in the office after reviewing final FRC valley class maps, satellite imagery, and road maps for the areas. Locations that idealized a particular valley type and locations between two valley types were prioritized. Proximity to roads was a consideration for access, but sites were positioned as far from the influence of roads or other major human influences as feasible. Several of the sites along the Green and Black's Fork Rivers in Wyoming were located near bridges to facilitate the safe crossing of the larger 30- to 100-m wide channels. LWD jams made ideal crossings of the fast-moving mountain channels in Colorado. Several small footprint bridges were utilized in the Fraser Experimental Forest to cross the swift mountain channels. Sites located exactly on tributary junctions were avoided but proximity to junctions was not a restriction.

7.2.3 Study Region Details

7.2.3.1 Arapaho National Forest and Fraser Experimental Forest, Colorado

In the Temperate Steppe Regime Mountains ecoregion (Bailey, 1983, 1987, 1995), the Arapaho NF and Fraser Experimental Forest were chosen as ideal locations for observing valley types in a high, glacially influenced mountain setting. Several other projects are in progress in the experimental forest, with a multitude of data available. The possibility for interdisciplinary cooperation and multi-agency use is high here. The flow regime of the high mountain system is dominated by snowmelt, predictable seasonal peak flows, and low-flow variability. Glacial influence is likely to have major influence in overall valley shape and gradient, as mountain glaciers carved and widened valleys. The watersheds examined in the experimental forest include the headwaters of the Fraser River, St. Louis Creek, and William's Fork River, shown in Figure 7.8.

Figure 7.8: Map showing the boundary of watersheds, streams, overlain on shaded relief to highlight the mountainous terrain for the Arapaho NF study region in Colorado.

The mountain pine beetle epidemic in the region has many public and private parties interested in forest health and concerned about changes in forest composition, fire hazards, erosion, and subsequent effects on sediment flux and water quality (Colorado State Forest Service, 2005). The presence of beaver, a natural modifier of channel form, was expected and observed (presented later in Figure 7.12). Valley types expected in this study region include High-energy Coupled/Open, Moderate-energy Confined/Open, Glacial and Low-energy Floodplains.

7.2.3.2 Tonto National Forest, Arizona

The arid southwestern US is known for its hot summers, cold winters, unpredictable precipitation, and extreme vertical stratification of vegetation in mountainous regions. A substantial amount of work has been completed on Cherry Creek in northern Arizona, with detailed surveys of the channel, valley bottom, and vegetation for an ongoing investigation involving private parties, the U.S. Environmental Protection Agency (USEPA) and the USFS. The information gathered from previous studies could be used to test the accuracy of coarse-scale predictors on fine-scale variability in the channel and riparian zone. The watersheds classified in the Tonto NF of central Arizona include Cherry Creek, Pinal Creek, and Pinto Creek and are shown in Figure 7.9.

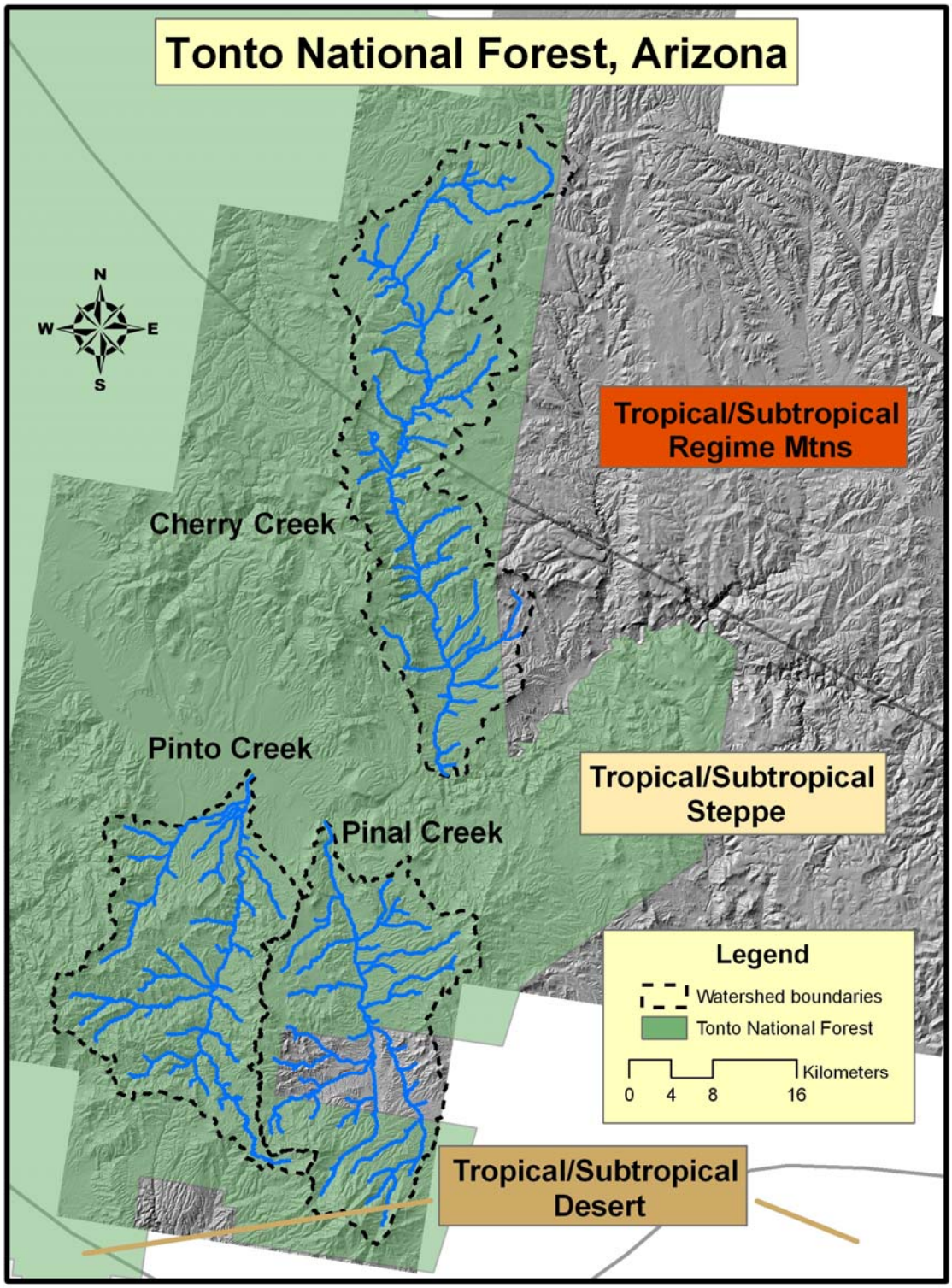


Figure 7.9: Map showing the boundaries of watersheds, streams, and eco-regions for the Tonto NF study region in Arizona.

Upper Cherry Creek borders the Mogollon Rim and receives substantially more precipitation than the Pinto and Pinal Creek watersheds. Periodic intense rainfall, coupled with bands of easily erodible bedrock and sparse vegetation, indicates a strong sediment component to the fluvial system. Infrequent flows of great magnitude can shift the location of channels by hundreds of meters and change the width of the channel by an order of magnitude. Much of the vegetation in the Southwest relies on pulses of growth following infrequent moist periods several years apart. The "*potential*" phrasing in the definition of riparian area used for this project was directed at this region. Seed banks and dormancy are critical for naturally sustaining populations of many species of desert annuals.

7.2.3.3 Green and Black's Fork Rivers, Wyoming

Larger rivers in the West have unique and diverse floodplains that can extend for more than 1 km from the channel banks. The Green River area in southwest Wyoming was chosen to examine how well the GIS procedures identified wide valleys in lower relief areas. The climate here is semi-arid, common to other areas of the West, including eastern Washington, eastern Colorado, parts of Idaho, and Montana. The Green River originates high in the Wind River Mountains and historically had a hydrograph dominated by a snowmelt peak in early summer; however, diversions and dams have altered the flow regime in the last century. In this area, riparian areas can be greatly affected by the widespread grazing of livestock, construction or roads, and the reduced and more stable annual hydrograph.

Figure 7.10 shows the location of the Green and Black's Fork Rivers in southwestern Wyoming. This study region is significantly larger than the other two but still maintains homogeneity of riparian and terrestrial vegetation communities, dominant geology, and general landscape shape.

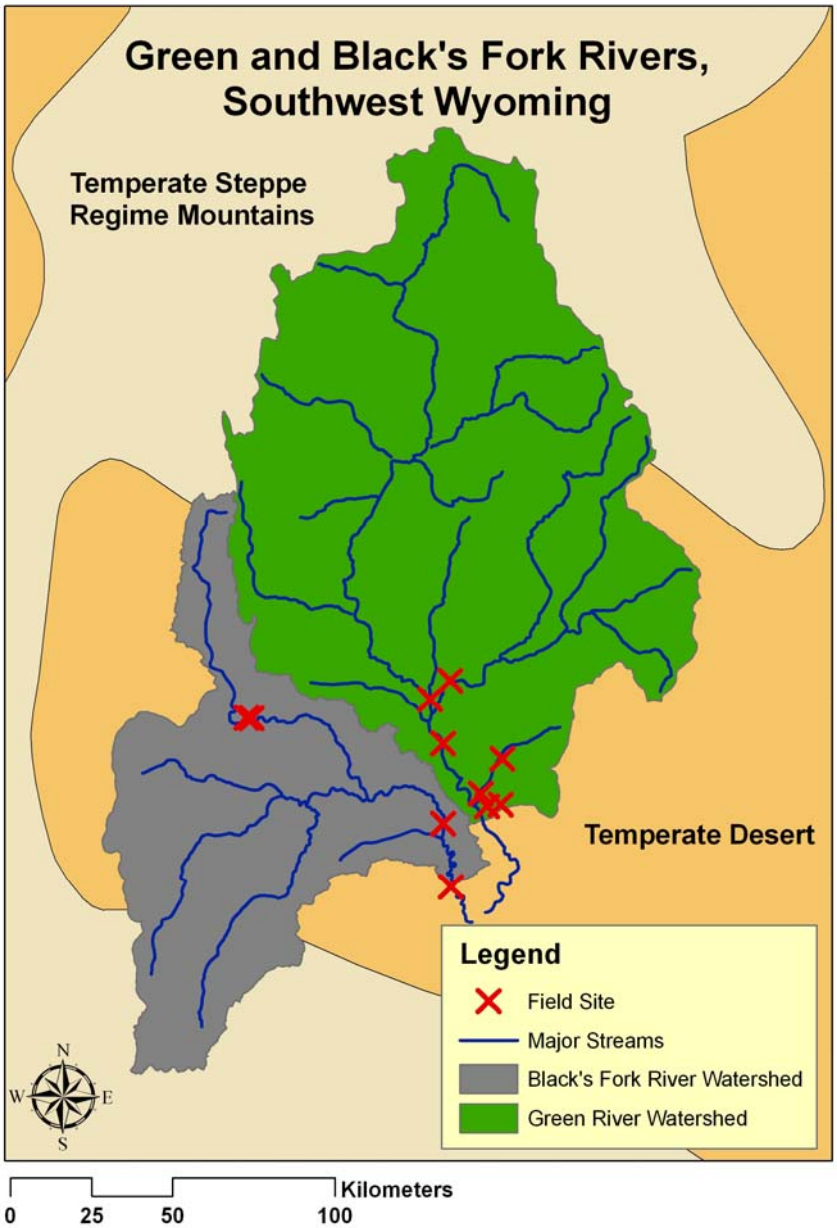


Figure 7.10: Map showing the boundaries of watersheds, streams, and eco-regions for the Green and Black's Fork Rivers in Wyoming.

7.2.4 Geomorphic Variables

Two of the four variables consider the gradient of the landscape: 1) channel gradient and 2) hillslope gradient. Brardioni and Hassan (2006) computed slope in GIS and measured it in the field. They used the field-measured slope to be the true slope and error rates were computed using the field data as the baseline. Deviations from the observed field value were measured as a percentage of the predicted GIS value using Equation (4.1). The difference between the observed field value and the expected GIS-generated value is considered the error rate of the variable. The values for the geomorphic parameters most accurately reflect the true shape of landforms and the GIS values are compared to them as either under- or over-estimating the true geomorphic character. The variance and direction of differences between the two values can suggest extreme heterogeneity in landforms or a shortcoming of the GIS-measurement tool.

7.2.4.1 Channel Gradient

Channel gradient is used to define the valley sections providing the basic spatial unit of the FRC. All other variables are averaged within each valley section to give a mean value. Channel gradient can vary tremendously within short distances. The FRC is interested in valley-scale patterns in channel gradient as it is used as a surrogate for valley gradient. Channel gradient is closely related to the potential energy of the fluvial system within a valley section, which is why it resides at the top of the variable hierarchy (Figure 4.1).

Where possible, a single measurement of channel gradient using the clinometer was made over 100 m. This was only practical on larger rivers or in open areas. In

meandering and forested streams, several measurements would be made along a 100-m length of stream. In these instances (which were the majority in the Tonto NF and Arapaho NF), the details of the channel gradient were recorded and showed the variability in gradient values. Within a single 100-m reach, gradient could vary from 0% in a pool to 13% in a cascade and 3% in a riffle, for a mean reach value of 4.5%, depending on the length of each section.

Figure 7.11 shows the values from each field site compared to the values for each site extracted from GIS. Tonto NF had the most diverse gradient values, ranging from 0.75 to 15%, while the larger channels in Wyoming were more consistent, ranging from 3 to 0.5%. Region-wide under-estimation of slope in the GIS led to mean error rates of close to 200% in each study region. The difference error was calculated before smoothing, which could bias the results even further. Under-estimation of slope in GIS is a widely-observed phenomenon (Brardioni and Hassan, 2006) and is in part related to the horizontal and vertical resolution of the base-elevation data.

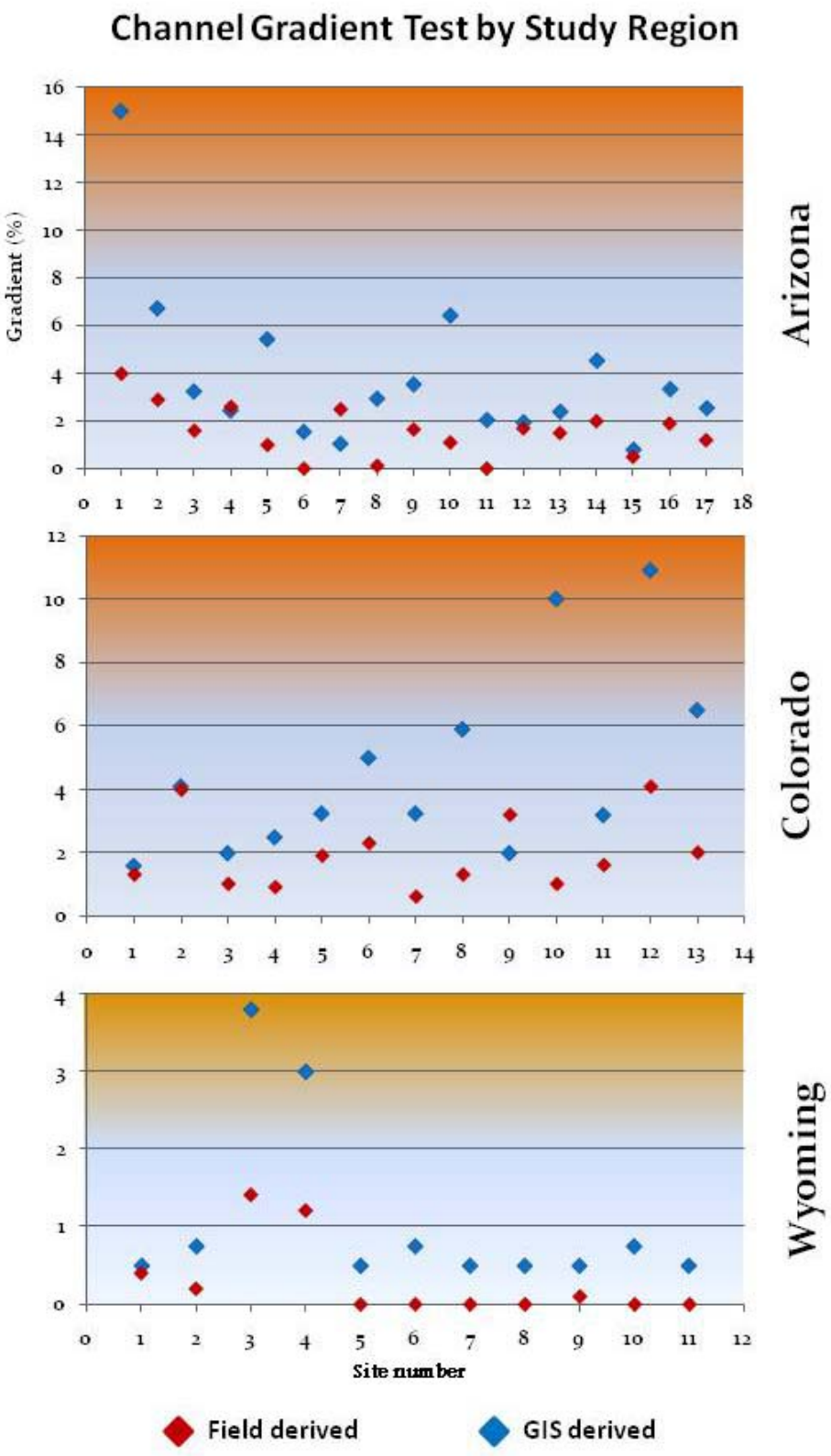


Figure 7.11: Comparison between channel gradient derived in GIS and at study regions.

7.2.4.2 Bankfull Channel Width

Bankfull stage was often difficult to determine in the field. In ephemeral channels, litter and vegetation re-growth following infrequent flows made identification of bankfull stage challenging. Bankfull width (meters) can change dramatically within a short channel reach as LWD jams tend to increase local width by causing upstream pooling of water, and colluvial debris and bedrock walls can constrict width. Beaver dams could also dramatically effect the field bankfull stage as in Figure 7.12. Watermarks and the presence of aquatic vegetation (algae, rushes, and cattails) were used to help identify the boundary.

Figure 7.12: Wetland created by a series of beaver dams located in upper left corner of the photograph (Arapaho NF, Colorado). Flow is from right to left.

While single-thread channels were the dominant channel form, multi-thread, braided, and anastamosed channels were also encountered. Bare and vegetated bars and islands were included in the bankfull width if they lay below the water-surface elevation identified at bankfull stage on the outer-most channel banks.

The values calculated in ArcGIS 9.2 were below the observed field values at 23 of the 31 sites. Error rates averaged 35% for Arapaho NF and 61% for Tonto NF. Bankfull width was not calculated in GIS for Wyoming because a sufficiently strong equation was not readily available or reliable in the varying conditions of southwestern Wyoming. The bankfull width of the site was treated as the true value and applied to the entire reach.

7.2.4.3 Valley Width

The correct extent of the valley bottom is notoriously difficult to extract. When applicable, two definitions were used and two widths were recorded for valley width. The fluvial valley bottom is defined as that which would likely be inundated during a 100-yr flood or the area that could be occupied by a channel that is actively migrating laterally. Evidence of this boundary included vegetation, soils, debris, relict channels and bars, and terraces. The geomorphic valley bottom was identified primarily by points of inflection between the valley bottom and the hillslope, where a shift in process dominance was perceived. Often the fluvial and geomorphic valley bottom boundaries coincided, but not always. At some sites the difference between the two could be as much as 200%. The shift from narrow to wide valleys could also be abrupt (Figure 7.13), caused by resistant bedrock, beaver activity, or dams and diversions.

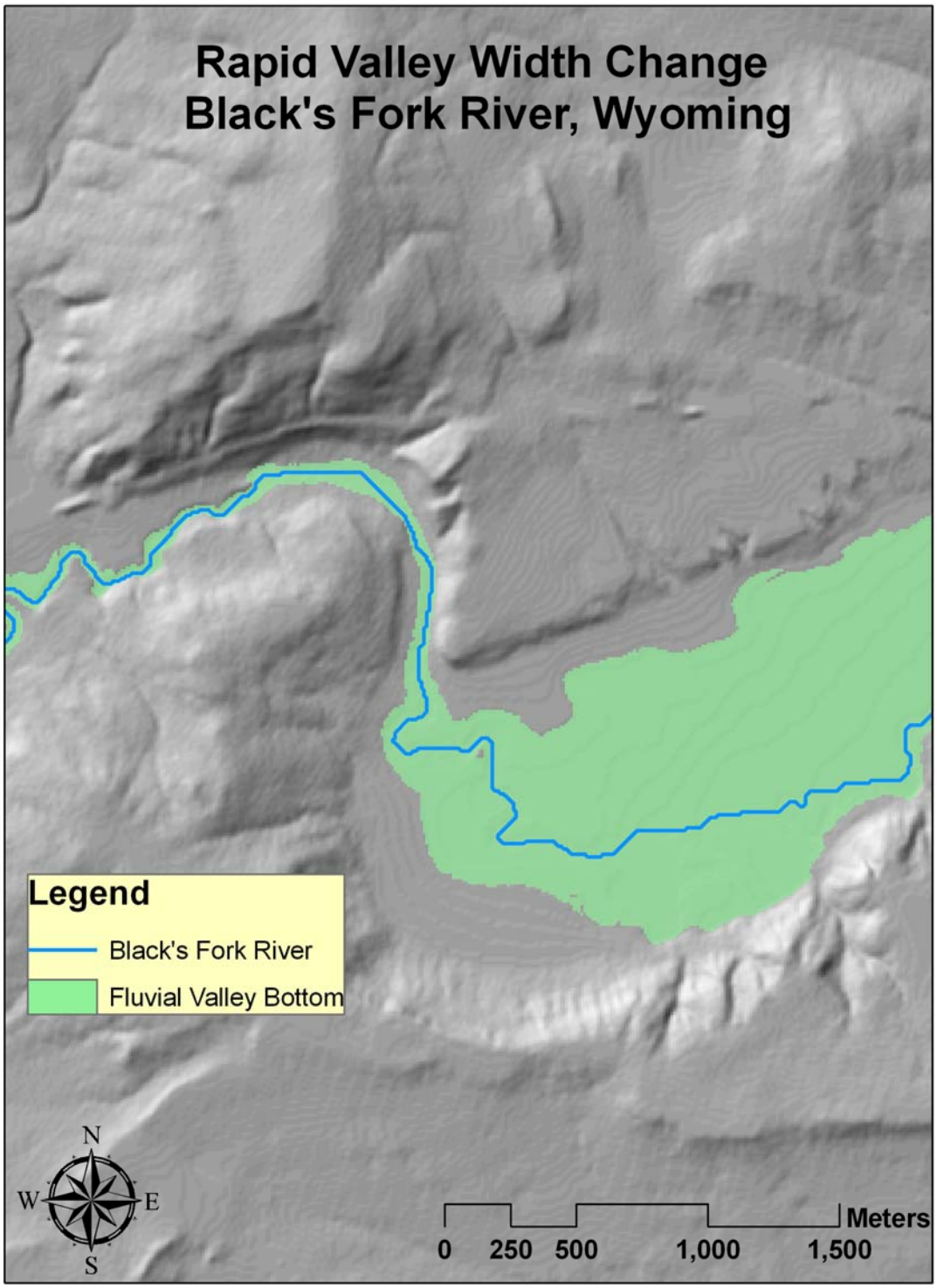


Figure 7.13: A rapid change in fluvial valley width along the Black's Fork River in Wyoming.

Canyon valleys in Tonto NF, Arizona, have bankfull widths the same as the fluvial and geomorphic valley widths; this is the most extreme example of confinement shown in Figure 7.14. The opposite was observed on the Green River, Wyoming, where the fluvial valley width was large at ~250 m, but the geomorphic valley width was over 1,000 m (Figure 7.15). In the higher mountain valleys of the Arapaho NF in Colorado, glacial scour has widened valleys to a width much beyond that which the current stream could have produced, usually ~250 m. In glacial settings, the high ground water content and moist climate extends riparian vegetation beyond the zone of fluvial influence and, therefore becomes a less powerful factor. Figure 7.16 shows a series of graphs comparing field and GIS-derived values for each of the study regions.

Figure 7.14: A canyon along Pinto Creek, Tonto NF, Arizona.

Figure 7.15: A wide valley along the Black's Fork River, just upstream of Flaming Gorge Reservoir in Wyoming where the fluvial valley bottom and geomorphic valley bottom are different. The geomorphic valley edge is at the base of the rise in the foreground.

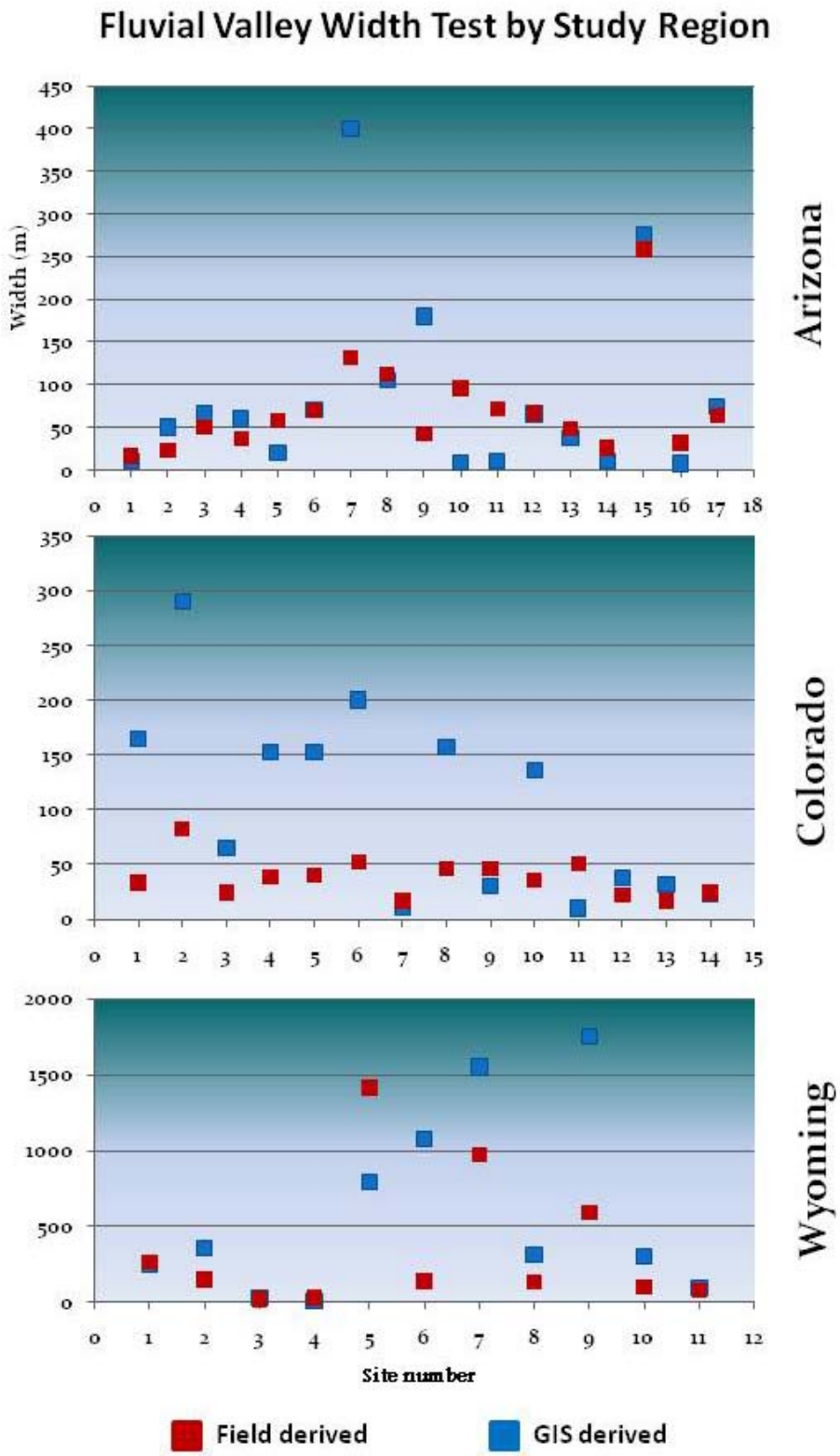


Figure 7.16: Comparison between fluvial valley widths derived in GIS using the BiS method and at study regions using geomorphic indicators.

In the FRC GIS procedure, the valley width is directly connected to the magnitude of the channel (bankfull width), the climate patterns of the region (Ecoregion), and the accuracy of equations which yield discharge estimations for flood-return intervals. In the absence of the discharge values, estimations of flood depth were made and used to "inundate" the valley bottom in GIS. Distance from the channel is then measured to each of the valley edges and summed.

7.2.4.4 Hillslope Gradient

Each hillslope was measured independent of its twin across the valley. A single steep hillslope can change the sediment and debris dynamics of a valley, particularly in narrow ones. Gradient values in GIS are most often an under-representation of the true gradient. Vertical walls were particularly problematical for the GIS, and were not well represented in the hillslope gradient layer. These areas are of critical importance for identifying Canyon and Gorge valley classes. Hillslope gradient was measured only along hillslopes that "drained" towards the site in the valley of interest. If there was a drainage divide, hillslope gradient was measured only to the top of the divide. It was rare that a divide was less than 150 m from the valley edge and it occurred only once in Colorado and once in Arizona. In low relief, highly-dissected landscapes, this number might increase and an adjustment to the length over which hillslope gradient is calculated in the field and with GIS might have to be adjusted.

7.2.4.5 Confinement Ratio

As expected, confined valley bottoms (valley width $<7W_c$) had channels that came into contact with the hillslope more often. This connection led to more direct hillslope inputs, significant slope failures, and unstable banks (Figure 7.17). Channels in unconfined valleys were observed to contact the hillslope, but much less frequently. Floodplain sediment was more variable as it appeared that channel position changed rapidly through time. Forced morphologies from hillslope debris and LWD were more common in these valleys as the channel did not have as much room to adjust to changes in local base level.

Figure 7.17: Channel undercutting rotten bedrock hillslope (southwestern Wyoming). Flow is from viewer to bedrock.

7.2.4.6 Valley Class

All eleven Wyoming field sites were moderate-energy systems. The sites identified in GIS as low energy were classified in the field as moderate energy, open systems. The gradients were very low, ~0.5%. The Arapaho NF had five different valley types including seven high-energy valleys. Four glacial valleys were also visited. Tonto NF had five valley types, including gorges and canyons, not seen in the other two study regions.

7.2.4.7 Qualitative Variables

The stark differences in vegetation between study regions were expected. The more interesting differences and lack of differences came within study regions and with comparisons between valleys designated the same class. In some instances, several valley classes would have very similar riparian vegetation and transitions. In other instances, two of the same valley class would have a very different vegetation composition. Sediment was more homogenous within study regions exhibiting the idealized fining of bed substrate down the network. Local differences were observed where the bedrock changed or a rapid shift in valley width or gradient would support major sediment deposition. Bank stability was locally variable and could be related to recent flood and human disturbances. Figure 7.18 shows a failing channel bank, recently eroded by a naturally high flow, while Figure 7.19 shows unstable banks related to a dam breach nearly 15 yrs prior.

Figure 7.18: Eroding bank along lower Pinto Creek, Tonto NF, Arizona. Roots in the sediment cannot resist the energy of the channel during high flows.

Figure 7.19: An unstable channel bank along upper Pinto Creek (Tonto NF, Arizona) that resulted from a flash flood/debris flow that occurred 15 yrs prior to the photograph.

7.2.4.8 Summary

The selection of sites to maximize variability and quick and safe access was tempered with avoiding human influence. This aim met with mixed results. For instance, logistical considerations regarding access and personal safety forced the adjustment of several proposed sites in watersheds in the Tonto NF. Several sites in the Pinal Creek watershed had to be abandoned because of seasonal wildfires. The accessible lower sections were heavily influenced by urban manipulations including channelization, dams, diversions, and recreational use. Private land and infrastructure influenced the location of sites in Wyoming.

Forty-two field sites were visited: 17 in Arizona, 14 in Colorado, and 11 in Wyoming. At each site, four measurements were made with a combination of a 100-m tape, GPS unit, and clinometer. Observations about the vegetation community, sediment, and channel morphology and planform were noted to provide additional information about the geomorphic setting and ecological function of the site. A fixed distance of 100 m was used to measure channel gradient to match the smoothing procedure in ArcGIS, while hillslope gradient was measured over a variety of lengths. Low divides, unsafe conditions, and physical barriers impaired the measurement of hillslope gradient over 150 m for all slopes.

Human activities that could affect the decisive physical variables were avoided when possible but some larger rivers had roads, bridges, or rail lines present within or on the edges of the valley bottom, thereby making accurate valley width and hillslope gradient measures difficult. This only occurred, however, at three sites in Colorado and two sites in Wyoming. Alteration of the landscape due to timber harvest or agriculture was difficult to identify because secondary growth was well established. Grazing was a widespread land use at most field sites but appeared to have little effect on the gross geomorphic setting of the valley and channel.

Quantitative field measurements of channel gradient, hillslope gradient, valley width, and channel width were performed in a rapid but precise manner. Site locations were chosen to vary the size of the channel and valleys to capture heterogeneity of fluvial systems. Bankfull width varied from 1 to 98 m and fluvial valley width ranged from 7.5 to 805 m. Hillslope gradient was just as diverse between sites with observed gradients of nearly flat 5% slopes to vertical walls. Channel gradient was measured over 100-m

channel reaches to match with the smoothing procedure in ArcGIS; values ranged from <0.5 to 15%.

Vegetation was expected to vary, as regions were located in three different ecoregion divisions according to Bailey (1983, 1987, 1995). Arid system vegetation including yucca, cactus, and acacia scrubland were present at the outlet and contrasted with pine and spruce forests of the headwaters within the Cherry Creek watershed. Bed and bank substrate and channel planform and bedform also showed remarkable variability. Stable bedrock canyons (Figure 7.20) would be followed with unconsolidated, actively eroding banks and hillslopes (Figure 7.21). Low-gradient pools would transition to boulder strewn, moderate energy, forced step-pool sequences (Figure 7.22).

Figure 7.20: A box canyon with stable, bedrock walls (Pinto Creek, Tonto NF, Arizona).

Figure 7.21: An actively eroding hillslope on a tributary of the William's Fork River, Arapaho NF, Colorado.

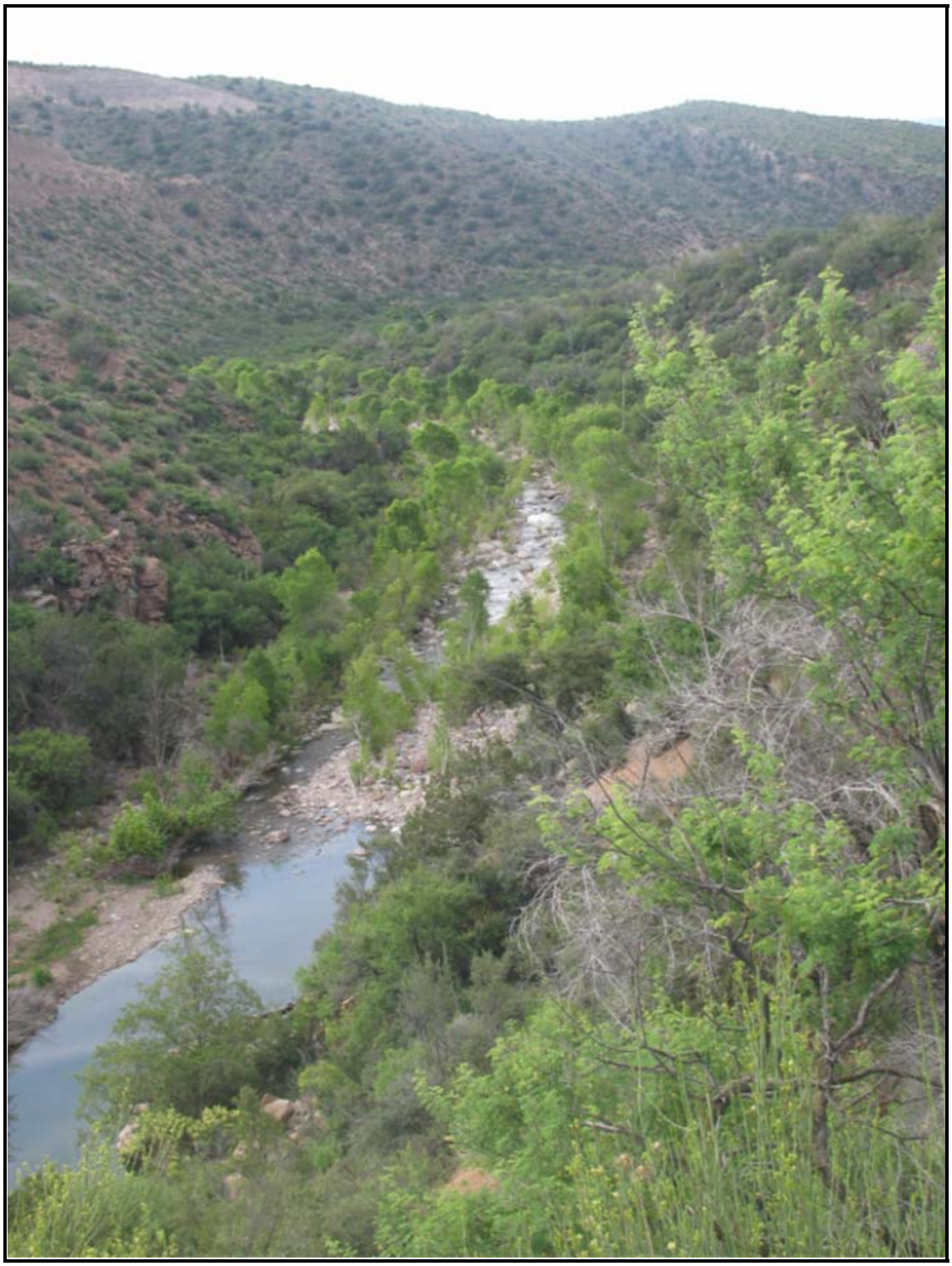


Figure 7.22: Transition from low-gradient section (lower left) to moderate energy (center) (Cherry Creek, Tonto NF, Arizona). Flow is from the bottom of the photograph to the top.

Ecological function was viewed as a combination of all of the variables described above combined with climate, regional species pool, and disturbance regime (Snelder *et al*., 2004). The diversity of plant species, vertical complexity, and horizontal stratification away from the channel lead to a qualitative understanding of compositional stability, temporal, and spatial dynamics (Nakamura *et al*., 1997; Bendix and Hupp, 2000). The interaction between vegetation, fluvial landforms, and flood frequency make this a strong relationship that is more useful as a comparative variable than an absolute value (Goebel *et al*., 2006).

7.3 TOPOGRAPHIC POSITION INDEX

The TPI does not consider the fluvial network in its analysis of the landscape. The identification of landforms is based solely on relative slope and elevation. Obvious valleys can be identified as a disconnected mosaic of valley landforms, slopes, ridges, etc. (see Figure 7.23), most notably valleys. Part of this misclassification can be remedied by adjusting the scale at which the TPI compares the relativity of features, at the expense of precision in identifying other landform types.

Using an average window size and accepting the defaults, a landform classification map was created for the H.J. Andrews Experimental Forest in Oregon. With both maps created using the 10-m DEM, there was poor correlation between the TPI and FRC in valley identification.

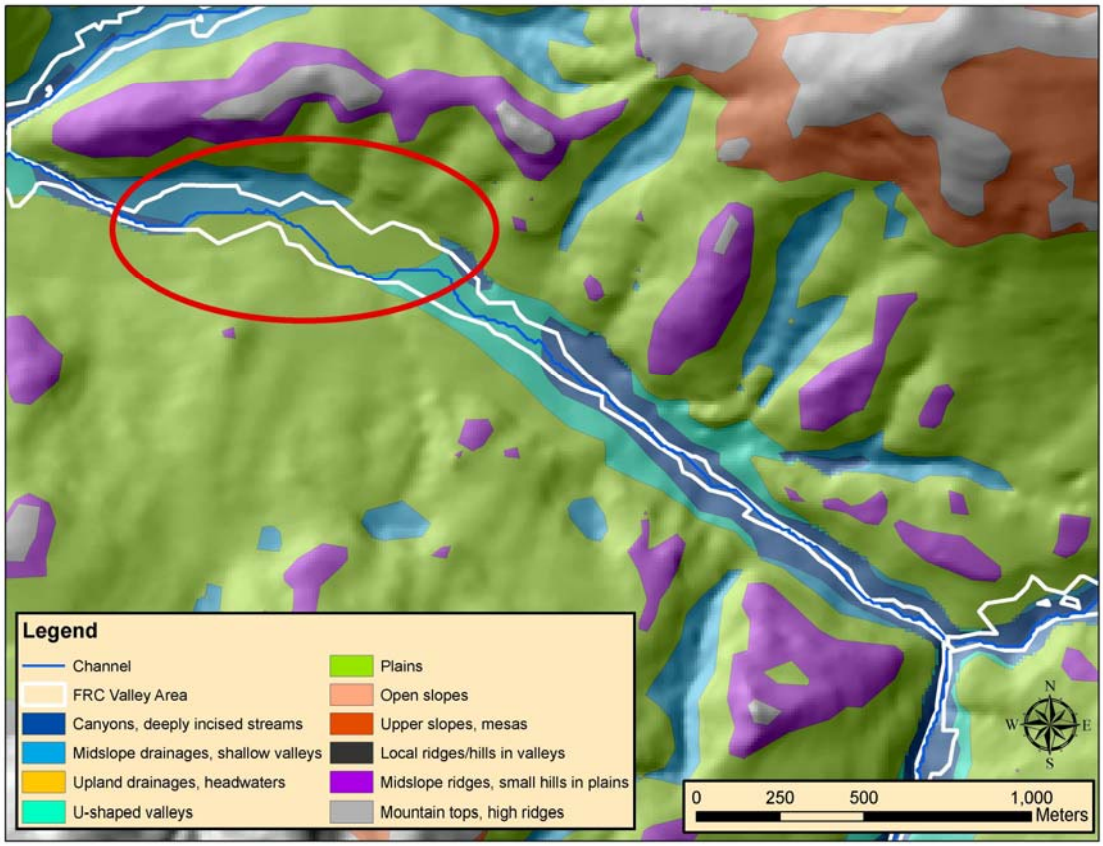


Figure 7.23: The TPI method does not incorporate hydrologic network information and, therefore, can have disconnected valleys. The area inside the red oval is a fine example of this in the H.J. Andrews Experimental Forest in Oregon. This map also shows the poor correlation of valley area defined by the BiS method of the FRC and the TPI.

CHAPTER 8

DISCUSSION

The development of a landform classification involves the cultivation of a novel approach, the creation of methods, and rigorous tests of utility and accuracy. Below, I will discuss the results of testing components of the FRC against fine-scale flood models, a landscape classification, and field observations. The relatively low number of field observations (42) and cross sections used in the HEC-GeoRAS modeling prohibits quantifying comparisons using standard statistical analysis and hypothesis testing. Instead a semi-quantitative method was used to directly compare the differences in width. Equation (8.1):

$$D = 100 \times \frac{(O - E)}{E} \qquad \textbf{Equation (8.1)}$$

is used to establish a scale-independent percent difference (D) between observed (O) and expected (E) values. Field observed and HEC-GeoRAS values were considered the expected values for any given comparison. The observed values were those generated with the novel GIS methods.

8.1 HEC-GeoRAS

The objectives of using HEC-GeoRAS as a method of testing the FRC were to determine the lateral extent of several flood-recurrence intervals and compare the 100-yr top width to the valley extent derived in GIS using the BiS method. The comparison of the flood top width defined valley bottoms to those identified by the BiS method for 1- and 10-m DEMs examined the connection of the BiS method to the fluvial setting. This analysis was only completed for the small watershed of the H.J. Andrews Experimental Forest in Oregon because the LiDAR 1-m DEMs are costly to develop and not widely available.

Discrepancies were expected, as going from a 10- to 1-m raster grid, the resolution increases by 100. The very fine-scale elevation data with 1-m horizontal resolution revealed great detail when valleys were observed in cross section (see Figures 7.1 through 7.5). It was helpful to qualitatively examine cross sections at the 1-m and 10-m horizontal scale for the same location and observe how the coarsening of the grain affected representation of the topographic surface. The additional information from a detailed field survey could provide some interesting comparisons between flood modeling at the 1-m scale and the BiS delineated valley bottoms at the 1- and 10-m scales. Table 8.1 shows results and comparisons between fluvial valley bottom widths using different methods and at different scales. Bankfull channel widths were estimated by the *Q*2 flow in HEC-GeoRAS and by regression equations from Faustini *et al*. (2009). It is recognized that the top width of the *Q*2 flow in HEC-GeoRAS is a poor representation of the actual bankfull width that is not used in estimating any of the valley metrics. Therefore, it does not provide an accuracy assessment of the confinement

Table 8.1: A comparison of valley width using the HEC-GeoRAS hydrologic modeling, 1-m and 10-m DEMs. Widths are in meters and differences are percents.

Cross-section ID	GIS	BiS method		HEC-GeoRAS		Faustini *et al.* (2009)	Comparisons		
	Drainage Area (km^2)	1-m Valley Width	10-m Valley Width	Width at *Q*2	Width at *Q*100	Channel Width	Width % Difference (1 m vs. *Q*100)	Width % Difference (10 m vs. *Q*100)	Width % Difference (10 m vs. 1 m)
1532	1	15	57	3.3	5	3.05	200	1040	840
1693	1	38	74	5	6	3.05	533.33	1133.33	600
899	1.3	18	41	4	6	3.35	200	583.33	383.33
1164	1.6	17	12	4	6	3.61	183.33	100	-83.33
1322	1.6	26	51	10	15	3.61	73.33	240	166.67
883	1.7	13	35	7	11	3.69	18.18	218.18	200
361	1.9	31	84	6	7	3.84	342.86	1100	757.14
592	2	6	12	4	5	3.91	20	140	120
7551	2.4	22	23	7	9	4.18	144.44	155.56	11.11
2997	2.5	14	16	7	9	4.24	55.56	77.78	22.22
378	2.7	31	14	7	11	4.36	181.82	27.27	-154.55
18350	3.6	25	11	9	12	4.84	108.33	-8.33	-116.67
1656	5.1	28	35	6	9	5.48	211.11	288.89	77.78
4422	7.8	18	27	11	14	6.39	28.57	92.86	64.29
354	7.9	41	79	7	9	6.42	355.56	777.78	422.22
14226	14	41	28	11	17	7.89	141.18	64.71	-76.47
1425	14.7	47	165	22	31	8.03	51.61	432.26	380.65
11878	25.8	108	67	29	38	9.83	184.21	76.32	-107.89
9558	31.7	78	193	36	43	10.58	81.4	348.84	267.44
6796	53.1	100	295	68	97	12.74	3.09	204.12	201.03
3556	58.7	33	111	18	21	13.21	57.14	428.57	371.43
1587	61.8	92	189	31	51	13.46	80.39	270.59	190.2
Mean							147.98	354.18	206.21

metric. The error of the confinement metric depends on the difference between the Faustini *et al*. (2009) estimate of bankfull width and the actual field bankfull width.

While flood-recurrence intervals that correspond to bankfull stages vary widely (Williams, 1978), regional studies have been conducted in an effort to narrow the range. For the H.J. Andrews Experimental Forest in Oregon, we assume that findings for the Pacific Northwest can be applied with sufficient accuracy. Castro and Jackson (2001) found a recurrence interval for watersheds in the Pacific Northwest of 1.4, which they note is well within the approximation of 1 to 2 yrs commonly used for bankfull conditions. Interestingly, their regional approach found the most significant spatial factors related to bankfull-recurrence interval were incorporated into the level III ecoregions from Omernik (1987), which are very similar in spatial extent and hydrogeomorphic factors to Bailey's (1983) level III ecoregion divisions.

8.2 TOPOGRAPHIC POSITION INDEX

The scale used in the calculations of the TPI procedures can be adjusted and results can vary dramatically between two different scales (Figures 8.1 and 8.2). There is, however, no suggestion on how to identify proper scales. This presents a problem as the user essentially chooses arbitrary numbers to create the basis for a landform classification. The method of comparison using slope and elevation without an input for hydrologic pathways appears to hold the TPI back from being an effective valley classification methodology. The discontinuity of valleys using the TPI method shown in Figure 7.19 could be related to the scale at which elevation and slope were examined relative to the surrounding area. It could also be related to the finer resolution elevation

data (10 m instead of 30 m). However, notice in Figures 8.1 and 8.2 that a change in the "viewing window" does not fix the discontinuity problem. This is a major hindrance in identifying and classifying valley forms for use as predictors of riparian function.

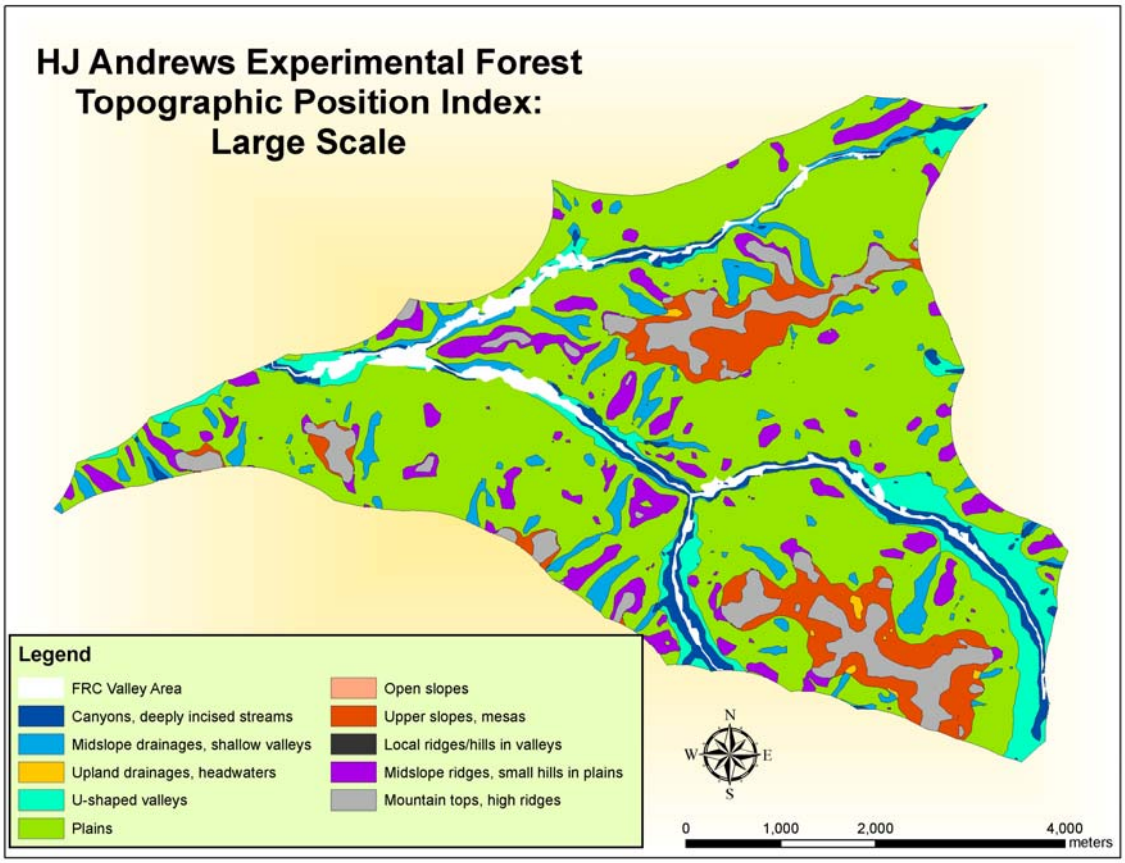


Figure 8.1: A map of the H.J. Andrews Experimental Forest, Oregon, using the TPI approach from Jenness (2006) using large-scale windows of analysis, 250 and 200 m.

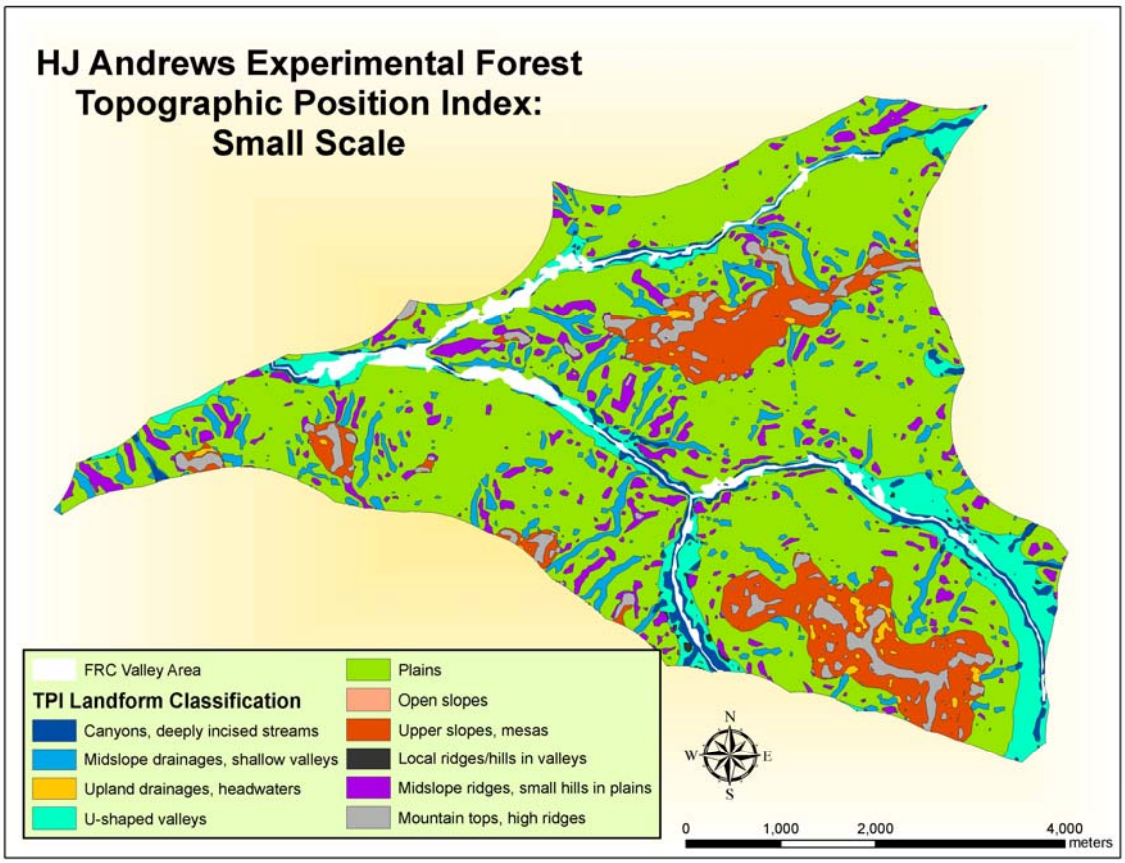


Figure 8.2: A map of the H.J. Andrews Experimental Forest, Oregon, using the TPI approach from Jenness (2006) using small-scale windows of analysis, 150 and 700 m.

In general, it can be seen from Figure 8.1 that the TPI significantly overestimates valley area; the larger scale (Figure 8.2) has an even poorer correlation. Although the TPI is not a classification designed specifically for valleys, it was productive to qualitatively test its ability to identify the extent and types of valleys. The method of comparing surrounding hillslope gradient and elevation follows a similar inspiration as the BiS. The closer approximation of fluvial valley width suggests an appropriate direction to take the BiS and link it more closely to the hydrology. This gives support for the FRC and GIS procedures as filling a niche within remote-sensing land classifications for identifying valley bottoms.

8.3 COMPARISON OF FIELD OBSERVATIONS, HEC-GEORAS, AND GIS MEASUREMENTS

Site locations were chosen prior to departure but inaccessibility, recent human influence, and land ownership required that some sites be moved or completely abandoned. The terrain, vegetation, and equipment provided some challenges as well. Impenetrable thickets of acacia and poison ivy required estimations of hillslope gradient using an adjacent more open slope. Steep, loose rock, and cliffs also prohibited access and obstructed views. Swift currents, wide, deep channels, and frigid water temperatures prevent the crossing of some of the larger mountain rivers in Colorado and Wyoming. Estimations of valley width and hillslope gradient were thoughtfully made using binoculars at only one site in Colorado.

8.3.1 Channel Gradient

The USGS (1998) recognizes that slope calculations from the DEMs they produce are sometimes more important than the actual elevation values; this is the situation with the FRC. 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. It is hypothesized that the large size of rivers at the study sites in Wyoming may have led to slopes being under-estimated and even reported at 0 for significant lengths. The vertical precision of the DEM data is critical to the accurate calculation of low gradients. In valley bottoms where

elevation from the valley edge to the channel is only 1 to 2 m over 1000 m, the slope algorithm has a difficult time finding changes in elevation with which to calculate slope. In the valleys where channel gradient was predicted to be 0, the field-observed gradient was at least 0.5% with a strong flow, gravel/cobble bed material, not indicative of a Low-energy Floodplain, which is characteristically dominated by fine sands, silt, and clay.

8.3.2 Bankfull Channel Width

Bankfull channel width is used in the critical measure of confinement. It was not the intent of this study to examine the accuracy of bankfull width estimations from Faustini *et al*. (2009), but there was a need to estimate bankfull channel width, as it is critical to the quantifying of confinement and coupling. The controversy over discharges, return periods, and field indicators of bankfull clouds this measure with bias in the field, and errors in GIS and modeled widths (Faustini *et al*., 2009). The width of the channel is used to evaluate its free-lateral movement within the valley bottom. A ratio is calculated, which identifies the number of bankfull width channels that could exist, side by side, on the valley bottom. If the number is less than seven, then lateral migration is likely restricted; greater than seven and it has the potential for its form to be unimpeded by the valley edges. Correct measurement of bankfull channel width in the field and its accurate prediction in GIS is critical for quantifying the confinement characteristic of valleys. These values must also be averaged over the valley sections as anomalies in bankfull width can occur and lead to unrepresentative ratios.

Local constrictions from bedrock hillslopes and colluvial debris are not of particular interest to fluvial systems at the valley scale. Representative locations within a

valley section were chosen for field measurements. The method of using a power equation to develop a channel width for each stream cell in a raster grid based on its drainage area leads to a gradual increase in width in the downstream direction. The bankfull width values were derived from the equation $y = \alpha A^{\beta}$ taken from Faustini *et al*. (2009), where A is drainage area in square kilometers and the parameters α and β are regionalized. The values for Tonto NF were $\alpha = 2.12$ and $\beta = 0.27$. The Arapaho NF used the same equation with parameters $\alpha = 2.34$ and $\beta = 0.32$. The lack of an equation with reasonable predictive power for the semi-arid southwestern Wyoming sagebrush lands prohibited the prediction of bankfull width in GIS.

Bankfull channel width was estimated using an equation and parameters identified by Faustini *et al*. (2009), but any method of width estimation could be used. Bankfull channel width is used to determine the VWI (fluvial valley width divided by channel width) and categorize a valley as Confined or Unconfined. The estimated widths had one of the better correlations between field and GIS data, with a percent difference of 50.

8.3.3 Valley Bottom Width

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. There was consistent over-estimation of valley bottom width using the BiS method at the 10-m scale, compared to the 100-yr floods modeled at 1-m resolution in HEC-GeoRAS. A possible suggestion for the poor result is that the accumulation value used was too large. The cross sections used to identify the change in slope accumulation threshold may not have been representative of the fluvial setting. The

stratification by stream order may not be appropriate for dissecting the fluvial network. This result, however, accentuates the need for some approach for scaling the accumulation threshold. A larger study of correlation between 100-yr flood extent or field observations with more robust statistical analysis could detect a pattern that could be used for regional or ecoregion specification.

The detailed examination of the BiS method and hydrologic characteristics was only conducted in the small watershed of the H.J. Andrews Experimental Forest in Oregon. This single study area was chosen because it had very fine-scale elevation data at the 1-m scale. LiDAR with 1-m resolution is costly and large coverages are not yet widely available. Fine-scale DEMs are becoming more readily available as more areas are scanned and processed and the technology becomes cheaper. The stronger performance of the BiS method at the 1-m scale was predicted and holds promise for continued threshold development as we will optimistically see an increased availability of very fine-scale DEMs.

The comparison of modeled flood extents using HEC-GeoRAS at a scale of 1 m showed poor correlation to the fluvial valley bottom identified by the BiS method at scales of 1 and 10 m. This suggests the BiS method has a weak connection to system hydrology. The concept that valley bottom topography reflects processes is well accepted (Bendix and Hupp, 2000). This bottom-up control of valley features by channel processes, however, is complicated by the strong influence of large-scale physiography of the basin, geology, faulting, and glaciers (Gregory and Walling, 1973; Nanson and Croke, 1992; Nakamura *et al*., 1997; Brierley and Fryirs, 2005; Goebel *et al*., 2006; Poff *et al*., 2006).

The adjustment of the accumulation threshold by stream order was not sufficient to address the downstream variability in hydrologic patterns. A different method used to stratify the fluvial network and apply accumulation thresholds could aid in a better correlation of the BiS method to system hydrology in the fluvial network. An approach that varies the threshold by some measure of drainage area could enhance the ability to vary the threshold and capture changes in slope variability along the fluvial network. Another method similar to the slope and drainage-area relationship examined by Dalla Fontana and Marchi (2003) in alpine basins of northern Italy could also be used to identify the fluvial network and a more representative accumulation threshold. Studies like this could be used to define the base fluvial network at the valley scale or to identify a "sliding scale" for the BiS thresholds. This approach was not implemented for the FRC, however, because it was completed for alpine basins and time constraints did not allow for the development of similar relationships for other landscape types. The FRC and its GIS procedures were designed to run on fluvial networks of various drainage densities. A synthetic fluvial network more representative of the true network could only enhance the utility of this approach.

8.3.4 Hillslope Gradient

Brardioni and Hassan (2006) found that slopes 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%. Over the three regions, hillslope gradient was under-estimated in GIS by nearly 100% on average.

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.

8.3.5 Confinement Ratio

At the majority of sites in all the three study regions, the confinement ratio was over-estimated in GIS. This means that an area that is actually confined would be classified as unconfined. This was most likely due to the under-estimation of bankfull channel width and valley bottom width in GIS compared to values from field data. Over the Arizona and Colorado study regions, bankfull channel width was under-estimated by 50%, while valley width was under-estimated only 29%, therefore skewing the relationship towards the unconfined class.

More than half of all the sites were moderate-energy systems where lateral confinement is the critical valley characteristic that describes the dynamics, disturbance, and local-scale landforms. Confinement ratio on average was the least variable

geomorphic characteristic within each study region and overall. This is a positive result because with the majority of field sites observed in the moderate-energy gradient class, the confinement ratio is the second selective criterion.

8.3.6 Valley Class Comparisons

The importance of accurate geomorphic variable measurements in both GIS and the field is highlighted by the poor agreement between valleys defined by GIS and those in the field. The two variables whose misrepresentation was the most influential were channel gradient and hillslope gradient. Both were under-estimated in GIS and limited the identification of Canyons, Gorges, and High-energy valleys.

Field channel gradients were 200% steeper than GIS-measured channel gradients for all three field regions. The under-estimation of slope in Wyoming suggested that seven valleys were low energy with smoothed and unsmoothed channel gradients of 0%, while field investigations showed channel gradients 0.5 to 0.75%. The difference was seven Low-energy Floodplains on the GIS maps compared to the six Moderate-energy Open and one Moderate-energy Confined field-derived valleys.

Hillslope gradient is the major delineative criteria for identifying a Canyon or Gorge valley. Extremely steep hillslopes are easily identified in the field as vertical or nearly vertical walls, but the elevation base grid in GIS is inherently an average over the horizontal area the grid cell occupies. Four Canyon valleys from the field were identified as being Moderate-energy Confined or High-energy Coupled in the GIS. The Gorge in the field was misidentified as Moderate-energy Open.

8.3.7 Vegetation, Substrate, and Stability

Dominant vegetation types were to be used as an auxiliary variable to assist in qualifying ecological function, biological complexity, and human impact. The FRC is based on fluvial and geomorphic processes, not biological attributes of riparian areas. Vegetation and biological composition of riparia is viewed as a product of the physical processes, although interaction between the biotic and abiotic domains was observed and should not be ignored. Vegetation and soil-forming processes did aid in identifying fluvial valley edges and bankfull boundaries at several sites in each of the study regions. These were used because their presence is linked to the fluvial processes the geomorphic variable was attempting to quantify.

Bed and bank substrate followed closely with system energy; high- and moderate-energy systems had more coarse beds, while low-energy systems had sand beds. Bank stability varied. The presence and type of vegetation present on the bank appeared to be the best correlated with stability. The material and soil development unsurprisingly seemed to co-vary with vegetation. While vegetation was useful in identifying fluvial valley edges and was actively used in the field methods, substrate and stability did not aid in identifying geomorphic variables or defining field valley classes.

8.3.8 Ecological Function

The interactions of geomorphic and ecological processes are cumulative and the present condition is sometimes difficult to attribute to antecedent conditions or the present situation (Gregory and Walling, 1973; Nanson and Croke, 1992; Naiman *et al*., 2005; Brardioni and Hassan, 2006). Relict riparian forests may exist on terraces no longer

in contact with a degraded channel (Scott and Reynolds, 2007); channels flowing through glacial valleys are underfit and do not match the size of the valley (Dury, 1960). Sediment, bank stability, vegetation stratification, channel bed and planform, and flood debris helped depict the fluvial systems as more than its geomorphic signature. Large-scale spatio-temporal stability of the system was better understood with the addition of qualitative assessment of riparian attributes to the field investigations.

8.4 SUMMARY

The testing, results, and subsequent analysis of the FRC classification and the GIS procedures illuminated some interesting successes and shortfalls. Qualitative field observations of the FRC seem to identify logical breaks in geomorphic and ecological function at the valley scale. 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. General trends could still be detected by analyzing these data.

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%. Differences in hillslope gradient were less consistent in their direction of difference but had a lower total difference by about half. Estimated bankfull channel width and measured valley bottom width showed the lowest difference between field and GIS values. 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 BiS method. As predicted, the BiS method for identifying valley extent preformed better at the 1-m scale compared to the 10-m scale when using the *Q*100 extent from HEC-GeoRAS as the "true" extent. The results supported several predictions including the smoothing effect as the base-elevation layer was coarsened. This resulted in larger valley extents, even as BiS thresholds were adjusted between base-elevation resolutions. Some unexpected patterns were also observed that could receive further attention in the future in larger, more diverse systems such as the apparent improvement of width comparisons for larger drainage areas. The results were derived from work in a small watershed (<70 km^2) with limited morphological heterogeneity. Data were not collected to test the patterns in different ecoregions, larger watersheds, and valley densities.

CHAPTER 9

CONCLUSIONS

The FRC is designed to aid in regional and landscape-scale management decisions by stratifying fluvial landscapes by the processes shaping them. The classification is robust in the sense that it has a transparent foundation based on fluvial processes. The thresholds separating process groups are supported by detailed hydrologic and hydraulic research. The GIS foundation has been developed as a semi-automated procedure for creating the necessary data layers to coarsely stratify the geomorphic structure of fluvial 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.

The FRC was developed using an *a priori* approach and with the objective of basing the framework and classes on fundamental geomorphic process thresholds. Theoretical, experimental, and observational studies identified significant shifts in geomorphic processes related to sediment, planform, and flooding that were used to identify the classes. The classification and GIS methods were trained *a posteriori* to improve functionality and accuracy. This order also parallels how the classification is proposed to be utilized: stratify and map the fluvial network "*a priori*" in GIS and examine selected sites in the field "*a posteriori*" to assess accuracy.

However, with the 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 between the six ecoregions does not make accurate estimates of misclassification possible. A larger data set of verified valleys would permit the examination classification strengths and perhaps illuminate problems with threshold values or measurement techniques.

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 BiS method 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)), adding a component of hydrology by orienting the measurements around the channel. However, using channel position to orient measurement and stream order to stratify the fluvial network was not sufficient to provide strong correlations with modeled flood extent.

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.

Results show the present GIS procedures do not perform satisfactorily when identifying channel gradients less than 0.1%. A method to measure gradient that could be

explored to overcome this limitation is the constant drop approach. This uses the contour interval from which the DEM was created and measures the horizontal distance between contour intervals. This method requires knowledge of the contour interval from which the DEM was created and a method of identifying points at which the contours cross and the length of the channels between the two points. This could be developed as an alternative to gradient extraction in future revisions of the GIS procedures.

The regions of the western US where the FRC 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. Regions with extensive data sets examining bankfull channel width, and landslide activity and characteristics could more precisely inform the regional thresholds.

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.

9.1 APPLICATIONS

The FRC is designed such that users from various agencies (public and private) could utilize the GIS procedure and describe the fluvial landscape with its classes. Collaboration with professionals from the USFS and the USGS has helped to direct the structure of the FRC to be practical for government land and resource-management agencies, including the Bureau of Land Management, U.S. Environmental Protection Agency, and U.S. Army Corps of Engineers (USACE). A basic goal of this work was to develop a consistent terminology that would provide continuity between government agencies, private groups, and the public.

As a hierarchical classification, the FRC can be used to answer questions at several scales. The established boundaries of the ecoregion divisions, identified by Bailey (1983), are the first level of describing the heterogeneity of landscape patterns. The ecoregion in some cases will limit the type of valleys that one would expect to find. For instance, Glacial valleys are not likely to be present in Temperate Deserts. Valleys further constrain the types of natural channels that could exist. The hierarchy allows for investigations to occur at scales appropriate to the question and help manage heterogeneity at successively finer spatial scales.

Many critical functions of riparian areas; including nutrient cycling, sediment storage, debris storage, and biological diversity, are not directly addressed. It is suggested that these ecological attributes of riparian areas are correlated, if not controlled by, the physical setting. The process-based approach of the FRC constrains the variables related to scales at which fluvial and hillslope processes operate and connects the variable values to the local ecological attributes of riparian areas. The detailed information gained from

the geomorphic classification of fluvial networks provides researchers a more focused scope with which to select field sites, analyze regional patterns, and conduct future research.

The USFS is working towards a reorganization of its sampling protocols for riparian areas. The ability to stratify the fluvial network according to the dominant geomorphic processes shaping the landforms and influencing the biotic community would be very advantageous to this effort. The further ability of simple quantification and inventorying of riverine resources will also be aided by this classification.

Some components of the fluvial network are examined at the valley scale because of their relative stability in the local-time scale (geology and fluvial valley width). Others can significantly adjust their influence in the network between years (channel gradient and hillslope stability). The combination of these two allow for some limited analysis of change in basin environmental parameters over time (Benda *et al*., 2007). While overall valley gradient is less likely to change over short-time scales, channel gradient can shift dramatically as knickpoints migrate upstream or planform changes. Hillslope stability is perhaps the physical variable that could change the most rapidly and affect the valley class designation. A change in the measure of coupling could be detected in GIS but is strongly informed by local knowledge. Channel-scale adjustments to planform could change the valley class by shifting the energy state of the valley section. Morphological adjustments to bankfull channel width could affect the measure of confinement, as the threshold is based on the number of bankfull channel widths contained within the valley. The scenarios describing changes in hillslope coupling and lateral confinement would

require local knowledge and field verification in order to detect changes at the valley scale.

9.2 USERS

The methodology is presented such that a variety of government and private groups could utilize the FRC and develop a common physical stratification of fluvial riparian resources. Standardization of methods and terminology facilitates repeatability, objectivity, and the dissemination of knowledge (Adamus, 2004). Close work with professionals from the USFS and USGS has influenced the structure of the FRC to be practical for government land and resource-management agencies including the BLM, USEPA, and USACE.

9.3 FUTURE WORK

The continued advancement of DEMs in their precision, coverage, and resolution will prompt adjustments to the FRC in the future. The process shifts that identify the location for process thresholds will not change, as they are not a function of resolution, scale, or any other artifact of remotely-sensed data. Regional values for hillslope gradient, debris run-out, valley initiation, and other variables will still be critical to the accuracy of the methods. If different resolution DEMs were used to stratify fluvial networks using the GIS procedures created for the FRC, specific measurements would need to be adjusted in order to measure the geomorphic variables at the scale appropriate for valley analysis. As already determined with the results from the field reconnaissance, the geomorphic thresholds, for example the 4% break between high and moderate energy,

might have a different value in the GIS procedure because of the limitations of base-layer resolution. With finer scale DEMs, adjustment may be different or not needed at all. Some of the problems with hillslopes and narrow valleys could also be resolved with a finer resolution base-elevation layer.

For the BiS method to be more effective in identifying fluvial valley bottom areas, the method needs to have a stronger connection to the hydrology. One avenue that could be explored is a constantly varying BiS threshold related to drainage area, rather than stratified and sampled by stream order. A significant amount of field data would be needed to test for a relationship. Another approach might be to create a "sandwich" between estimated flood depths and the BiS method. A minimum flood-return interval would provide the base valley extent and the BiS would potentially identify the outer boundary. The BiS method, which appears to have problems with constant slope and low-relief areas, would then be capped by an upper limit defined by another flood-recurrence interval. The large errors associated with modeling low-frequency floods will need to be addressed.

A logical next step would be to provide a range of acceptable values for hillslope stability gradient, valley initiation, and debris run-out length at an ecoregion or USFS region level. These could be matched to USGS discharge equations to further develop a strong data set of geomorphic parameters for hydrological and landscape analysis in the US. A document suggesting a range of values would be a positive addition to this classification and greatly promote continuity among users.

Increased field observations to test the accuracy of variables and the final valley classes in a greater number of ecoregions and landscape settings will increase the

accuracy of the FRC. Comparison of FRC data layers (valley width, channel gradient, and valley class) to other data including land cover, Federal Emergency Management Agency (FEMA) flood maps, and geology could help develop a more holistic picture of riparia in specific valleys, watersheds, and regions. With fluvial processes as the foundation of the FRC, further work within the classification or applying the classification to other types of research will be scientifically defensible.

Development of additional modifiers specific to regions, landforms, reach-scale processes, land use, or existing nomenclature of management documents (an example in Appendix E) would continue to support the integration of the FRC as a management tool. Synthesizing decades of valley, floodplain, and river classifications requires attention to detail in the wording of descriptions, as features have been termed several different ways for different approaches (Beechie *et al*., 2006).

The inclusion of geology in the FRC was not explored because of, in part, the coarseness and inconsistency of geology coverages for the western US. The development of a larger mapped valley data set of field-referenced locations could allow for correlation of valley type to dominant lithology. It can be speculated that resistant rock types would lead to more confined valley settings, while more easily erodible strata could develop a variety of forms including wide gorges or very narrow slot canyons.

CHAPTER 10

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APPENDIX A

GIS PARAMETER DESCRIPTION

A.1 CHANNEL SLOPE

This geomorphic variable is calculated at a scale that is appropriate for valley classification. A moving 3x3 window of raster cells is used to average the change in elevation along the synthetic stream network. The elevation values along the stream cells are used in the analysis. In a straight channel, three cells are evaluated; along a curve the number can grow to five. Values range from 0 in very flat reaches to greater than 50% in extremely steep mountain headwaters, knickpoints, and waterfalls. At the channel reach-scale, individual 10-m grid cell values may be an appropriate scale, but for valley segments the stream slopes are grouped. A smoothing algorithm that increases the moving window to a circle with a radius of 50 m is used to calculate the mean slope for each cell on which the window is centered. At the valley scale, slope is more meaningful over longer distances as the morphological features of valleys (floodplains, oxbows, and terraces) are larger than those of channels (pools, riffles, and steps). This "elevated" view of the gradient is used in place of a direct measure of valley bottom gradient for two reasons: 1) computationally it is simpler and 2) a direct link is created to channel-scale parameters. The original stream slope layer or other intermediate layers can be used if the channel reach scale is of interest, thus connecting the channel scale to the valley scale with one procedure.

The slope thresholds between classes are constant values in the FRC, which do not change between unique hydroclimatic regions. They are the cornerstones of the FRC. Slope values are classified into one of three categories describing the potential stream energy: 1 – low, 2 – moderate, 3 – high. In the field, low-energy channels have very low slopes < 0.1%, moderate-energy channels have a wider range of 0.1 to 4%, and high-

energy channels exist above the 4% mark. Field work showed a consistent bias towards under-estimating slope in GIS. For instance, a slope of 5.1 in the field might be measured as 3.8 before any smoothing occurs. This places the same area in two different energy classes, which affects the final valley classification. Therefore, channels with slopes exceeding 3% are considered to be high energy. This correction is an estimate based on only a few dozen data points, so some error is still introduced.

A segment length of 200 m is used as the minimum grain for the valley scale. Therefore, groups of channel slope cells are required to be at least twenty 10-m cells. Groups of cells smaller than twenty are dissolved and each of the adjacent groups of acceptable length "grow" into the vacant stream cells. The empty space is split between the two adjacent groups. Because of the importance of channel gradient for stream energy and potential system energy, these final cell groupings are the units with which all other parameters will be spatially associated.

A.2 VALLEY BOTTOM WIDTH

The linear and often narrow nature of riparian areas naturally leads to width as one of the more descriptive attributes. Several methods exist for determining the extent of the valley bottom. Constant inundation depth methods "flood" all cells within a fixed elevation threshold above the stream cell elevation and become classified as valley bottom. This method, however, lacks a hydrogeomorphic foundation and often over-predicts valley bottom width in the upper reaches of watersheds (Nardi *et al*., 2006) where smaller channels do not have the ability to flood as high as larger channels

downstream. The hydrogeomorphic delineation method developed by Nardi *et al*. (2006) uses a scaling relation to predict floodplain width at several return periods.

The terms "floodplain" and "valley bottom" are often used interchangeably. The goal is to identify the "natural floodplain" (Dodov and Foufoula-Georgiou, 2005). To increase confusion, FEMA defines floodplains based on 100-yr return intervals, while Moore *et al*. (2002) describe the "floodprone width" as a 50-yr flow and others at 1 to 3 years (Rosgen, 1994; Hupp and Osterkamp, 1996). A major drawback to the hydrogeomorphic approach of Nardi *et al*. (2006) is the loss of predictive power as the return interval increases. This arises from limited data representing flows of extremely high magnitude and inherent increase in error from the resulting estimations.

The FRC introduces a new technique for identifying valley bottoms. The slope of a valley, its landforms, and topographic signatures reflect the geomorphic and ecological function of the riparian area. The connection between fluvial processes and valley morphology has been well-documented (Frissell *et al*., 1986; Montgomery and Buffington, 1997; Goebel *et al*., 2006; Clarke *et al*., 2008). A sudden change in the gradient of the land surface or a BiS can have significant meaning in riparian systems. Channel banks, floodplain terraces, and hillslopes can often be identified by significant BiS. The BiS method used to identify valley bottom area uses a derivative of the topographic slope, essentially a measure of how fast the slope is changing. This change in slope is accumulated in a direction away from the channel. A user defined threshold is applied to the system and places a boundary when the slope changes significantly, thereby identifying the valley bottom. The network is stratified by Strahler stream order and sample cross sections are used to estimate the threshold for accumulation by stream

order. Cross sections are used to identify the significant breaks in slope or elevations above the channel at which fluvial processes are hypothesized to be of limited influence. A mean threshold value is then applied to all sections of the same stream order.

The threshold can be reached in two situations. First, the accumulation could suddenly increase as a significant BiS is encountered, exceeding the threshold very quickly. Second, a consistent slope could modestly undulate and the accumulated change in slope could increase slowly until the threshold is exceeded. This second situation can lead to erroneously large valley extents on planar surfaces.

The width of the defined valley bottom area is measured using a series of random points populated along the channel that were created at a density of approximately one point per raster stream cell. The randomly-placed points may not sit on every stream cell or one cell may have several points. The distance from the point to each of the valley edges is measured as the closest distance. This method does not orient the measurement axis perpendicular to the channel. The true location and shape of the channel cannot be predicted with the 10-m base DEM. Therefore, under-estimation of valley bottom width is a known limitation of this method. The mean width value for each of the valley segments is recorded and used later in determining the degree of coupling and confinement.

In landscapes where the channels are often gaining reaches with springs and high-water tables, riparian flora can extend beyond the fluvial edge of the valley bottom.

A.3 HILLSLOPE GRADIENT

Hillslopes perform two critical functions with regard to rivers: 1) hillslopes have the potential to add substantial material to the channel or valley bottom and 2) hillslopes constrain the lateral movement of channels over time. Hillslope position, aspect, gradient, vegetation cover, and geologic composition influence fluvial processes involving runoff, erosion, sedimentation, and lateral migration. Relative position, gradient, and aspect are the only hillslope characteristics that can be measured solely from a DEM, with the first two being used exclusively to describe the hillslope features. Aspect can have opposite influences in different regions related to seasonal weather and precipitation patterns.

The area considered a hillslope extends upslope from the valley edge, excluding the flatter valley bottom. The FRC classifies hillslopes by the composition of the entire area bordering each valley segment. The proportions of the total area in each of the three slope classes are used to give the entire area a single slope class value. The slope classes describe the potential likelihood for a slope to contribute material to the valley bottom through debris flows and shallow landslides. The three classes low, steep, and very steep are separated by two thresholds of 30 and 70%. Both of these numbers could be defined regionally based on precipitation, lithology, and land cover. The upper threshold is especially important as that describes slopes that are very likely to contribute material and is critical for identifying the degree of hillslope influence.

The gradients of the hillslopes are easily measured with the built-in tools from ArcGIS 9.2. Slope values are calculated as the percent change in elevation in a 3x3 cell window. Each cell has a unique window. This creates a large and complicated data layer that needs to be simplified to be useful for valley classification. Orientation problems

with using a cross-sectional method are avoided by using the proportional composition method. Cells are then classified into one of three groups based on their percent slope. The three groups represent the potential for the area to contribute material to the valley floor: 1 – low, 2 – moderate, 3 – high chance (see Appendix B for details). The combination of hillslope gradient and valley bottom width forms the coupling measure. Hillslope gradient is viewed as one of the more important delineative criteria for valley morphology and needs to be accurately measured for the automated classification to accurately predict class membership.

The landslide potential, as defined by Whiting and Bradley (1993) and Sidle and Ochiai (2006), is related in part to hillslope length, soil type, gradient, precipitation, and vegetation. Information on soils, vegetation, and precipitation is not linked with the DEMs, nor are these variables usually available at similar resolutions (1 m to 1 km). Large areas of lower slope can result in an apparently skewed proportion. However, significant debris can contribute to the valley bottom from small areas of steep slopes. Small linear ridgelines and cliffs have the potential to contribute disproportionate amounts of material and need to be identified. The "roughness" of the terrain of an area and the complexity of minor and major drainage divides create difficulty in defining a value which to extend hillslope areas. This value could be scaled with drainage area, set with regional knowledge, or varied by hand during the mapping process. The default value for the FRC procedure is 150 m and was determined from field reconnaissance in Arizona, Colorado, and Wyoming. The hillslope buffer should be added to the suite of variables that should be regionalized for the most accurate use of the FRC.

A.4 BANKFULL CHANNEL WIDTH

Bankfull channel width can be considered a measure of river magnitude and is an important morphological component of valleys, but it cannot be directly measured from the base DEM data. The resolution limitation of 10-m DEMs requires that a surrogate be employed to derive this parameter. Bankfull width has been shown to correlate with drainage area by Faustini *et al*. (2009). Faustini *et al*. (2009) have developed and tested regional regression equations and linked different alphas and betas with Omernik's (1987) Level III eco-regions. The extensive *USEPA Wadeable Streams Assessment* data set was used to develop the equations. A return interval of 1.5 to 2 yrs is commonly referenced to create bankfull conditions (Rosgen, 1994; Moore *et al*., 2002) for the stream that could be used as a measure of active channel width. The equations calculate six return-interval floods, the 2-, 5-, 10-, 20-, 50-, and 100-yr, using parameters such as drainage area, basin slope, soil characteristics, precipitation, etc. The bankfull channel width used to test the FRC was calculated using the Faustini *et al*. (2009) regional equations. Channel width is required to estimate degree of coupling and confinement.

APPENDIX B

HILLSLOPE COUPLING AND VALLEY CONFINEMENT

B.1 INTRODUCTION

Two primary controls on valley morphology resulting in limited channel patterns are the degree of Hillslope Coupling and Valley Confinement. Below, I address the importance of each, their definitions and hierarchical setting in terms of process importance to fluvial system evolution. The terms "coupling," "confinement," and "constraint" have frequently been used interchangeably among geomorphologists to describe valley and channel settings. Precise definitions are necessary to give an accurate picture of what each of these valley morphology metrics relate to and the process inherent in their influence on river networks. I provide explicit definitions for how these hillslope characteristics and their function in the FRC are viewed. The top-down approach of the FRC is a reversal in the recent reductionist approach to fluvial systems. Qualitatively and quantitatively addressing hillslope-channel interactions reconnects the system as an interactively dynamic assemblage of processes (Michaelides and Wainwright, 2002).

Coupled systems are inherently confined. As hillslope gradient lessens or valley width increases dramatically, Confinement becomes the dominant hillslope influence on the valley bottom and channel.

B.2 HILLSLOPE COUPLING

This describes the connection between possible hillslope-generated colluvium and the active channel in the valley bottom. This connection is influential in systems across all spatial and temporal scales and among geomorphically-dissimilar regions (Michaelides and Wainwright, 2002). Bracken and Croke (2007) suggest the term *landscape* connectivity to describe the connection between landforms, i.e., hillslopes to

channels. The connection to uplands can have geomorphic influence and input biological material (soils, LWD, etc.) in large quantities to the fluvial network (Rheinhardt *et al*., 2007). Hillslopes with gradients exceeding a critical threshold are likely to contribute material to the valley bottom in the form of landslides and debris flows triggered by climatic and tectonic events. The critical gradient is a regionally-specific value related to soil type, bedrock planes, precipitation, and vegetation among other variables (Bracken and Croke, 2007; Gangodagamage *et al*., 2007). The value (30%) used in the valley classification is an average of work completed by Whiting and Bradley (1993), Johnson *et al*. (2000), and Sidle and Ochiai (2006). Thirty percent has been used in previous classification efforts by the USFS (Collotzi, 1976; USDA, 1977). Debris flow run-out (*DR* in the valley table) is where this measure of hillslope coupling is integrated into the valley classification.

Two geomorphic factors central to the idea of hillslope-channel coupling are run-out length and a regional hillslope stability threshold. Regional landslide models will predict with greater accuracy the volume of shallow landslides and common run-out lengths. The initial label of a "coupled" hillslope is connected to two simple measurements of valley form: 1) hillslope gradient and 2) valley bottom width. The gradient measure maintains that debris could be generated because the gradient is above a threshold of stability. The valley bottom width reflects how likely it is that debris will enter the channel. In general, as the valley bottom width increases, the probability of debris input into the channel decreases; this buffering effect has significant influence on the connectivity of the channel to the hillslope sediments and hydrology (Michaelides and Wainwright, 2002; Bracken and Croke, 2007). There are several limitations in the DEM

data that hinder accurate predictions of this relationship in GIS. First, the 10-m DEM does not support measurements related to channel width. This could have significant effects on small- to medium-sized valleys if the majority of the valley bottom is occupied by active channel. Also, for smaller systems, averaging elevation across 10 horizontal meters could grossly under-estimate the hillslope gradient, causing an unwanted smoothing effect.

The metric is applied to an entire valley segment with the understanding that there is averaging of the hillslope morphology occurring over the course of the segment. This measure is applied as a categorical variable to the hillslopes on each side of the channel. The variability in lithology, soils, precipitation, and vegetation across the West is acknowledged and suggests that regionally calculating the run-out length for landslides of common magnitudes and hillslope stability thresholds will significantly improve the accuracy of this valley morphology metric.

The measurement of hillslope coupling also requires a measure of channel width. Valley bottom (not including the active channel) is considered a buffer between the hillslope and the channel. Understanding the ratio of total valley bottom width to channel width will be used to determine the probability of colluvial inputs entering the channel. Because of limitations in flow-path generation in GIS, channel position on the valley bottom with respect to the toe-slope is not considered. Channel position could also be influenced by previous colluvial inputs, which might confound the measure of position if used in this valley metric. A common equation for channel width using drainage area as a surrogate for discharge looks like:

From Faustini *et al*. (2009): $W_c = \alpha A^{\beta}$ **Equation (B.1)**

where bankfull channel width (W_c) equals the constant α (0.86 to 3.79) multiplied by the drainage area (A) raised to β (0.23 to 0.51). Numbers in parentheses are the range of values shown for the Western Mountain ecoregions. Field measurements would more accurately place the channel and valley bottom into the classes defined below, but limitations of accessibility make this predictive method extremely useful.

A hillslope has the potential to be coupled to the channel if it is moderately to very unstable. Stable hillslopes with gradients below the lower limit for instability (default 30%) do not support the connection of the hillslope to the channel insofar as debris flows and landslides are concerned.

B.2.1 Fully Coupled

If **BOTH** hillslopes are unstable, then **Valley Bottom Width** is **< (2 * *Debris Flow Run-out* + *Channel Width*)**	*OR*	If only **ONE** hillslope is unstable, then W_v is **< (DR + W_c)**

There exists a probability of at least 0.50 that colluvial inputs from adjacent hillslopes with gradients above 30% will enter the channel. As the channel increases in size, the valley bottom can also increase without changing the probability of debris entering the channel. Coupled systems of headwater channels to large canyons and gorges highlight the variability in size at which hillslope coupling can influence valley and channel morphology.

B.2.2 Partially Coupled

If **BOTH** hillslopes are unstable, then $\boldsymbol{W_v}$ is **> (2 * *DR* + $\boldsymbol{W_c}$)**	*OR*	if only **ONE** hillslope is unstable, then $\boldsymbol{W_v}$ is **> (*DR* + $\boldsymbol{W_c}$)**

The probability of hillslope colluvium entering the channel is reduced to 0.50 to ~.10.

B.2.3 Uncoupled

If **BOTH** hillslopes are unstable, then $\boldsymbol{W_v}$ is **> (8 * *DR* + $\boldsymbol{W_c}$)**	*OR*	If only **ONE** hillslope is unstable, then $\boldsymbol{W_v}$ is **> (4 * *DR* + $\boldsymbol{W_c}$)**	*OR*	**NEITHER** hillslope is unstable

Whiting and Bradley (1993) describe the potential for direct hillslope inputs of water, sediment, and organic debris as "rare." A probability of <.010 can be associated with this class. The width of the valley bottom functionally disconnects the hillslopes from the channel.

B.3 VALLEY CONFINEMENT

Valley confinement is the measure of the effect of the relative hillslope position in controling the planform/pattern of a channel. Confinement itself is not a process but a portion of hillslope processes that affect valley bottoms and channels throughout the fluvial network (Nanson and Croke, 1992). Universally-applied finite thresholds of width are not useful in defining valley confinement. The extent of free-channel movement across the valley bottom is related to channel width (W_c) and a measure of confinement should be scaled as such. There is a relationship between Valley Confinement and

Hillslope Coupling, but they are not equivalent and control different processes related to valley and channel form.

Width-to-depth (W/D) ratio studies conducted by Fredsoe (1978) show that braided channels commonly occur at ratios in excess of 50:1, whereas single-thread channels are commonly 25:1. Thus, if flow regime or sediment load or caliber were to change, shifting a single-thread channel into a braided channel, it would occupy an area approximately twice the width of the former single-thread channel. A threshold then of $2W_c$ at bankfull stage would suggest the limit to which the channel is likely to grow under a disturbance in the direction of channel braiding. I propose a threshold of $2W_c$ to classify the valley into confined and partially-confined segments. Valley segments with a VWI (fluvial valley width (W_v) divided by W_c) of < 2 would, therefore, confine both a braided channel pattern and free-channel meandering. This was also used by the Oregon Forestry Practices Board to describe valleys where channel pattern was likely to be "constrained" (Cupp, 1989).

It has been shown that fully unconfined valleys can contain channels that meander with amplitudes up to $7W_c$ (Williams, 1986; Hagerman and Williams, 2000; Faustini *et al*., 2009). With this in mind, a threshold was set that addressed this as a minimum valley bottom width that would allow a channel to be completely free of confinement from hillslopes. This should be viewed as the *potential* for a channel to freely meander ,not an assurance of complete lateral freedom.

B.3.1 Fully Confined: *VWI* < 2

These valley segments have hillslopes of various gradients which confine the extent to which the channel can free migrate laterally across the valley bottom. These narrow valleys could also limit the extent to which a single-thread channel could develop into a braided channel through disturbance.

B.3.2 Partially Confined: 2 < *VWI* < 7

The channel is free to develop into a braided system yet is likely to have the fullest extent of its meanders be truncated by the hillslopes. A fully unconfined setting would allow a channel to meander with a meander belt width of up to $7W_c$. These valley segments will limit the extent of the meandering of the most laterally active channels.

B.3.3 Unconfined: *VWI* > 7

Hillslopes provide no restrictions on the planform of the channel. These fully alluvial systems are free to migrate across the valley bottom with the potential to reach meander amplitudes of $7W_c$ or more. Channels may contact toe-slopes, but the dynamic nature of lateral migration suggests that adjustments could be made to shift the channel away from the hillslope with ample room to avoid future contact.

APPENDIX C

VALLEY CLASS DESCRIPTIONS

C.1 INTRODUCTION

Valleys are the largest identifiable segments of the fluvial network. In-channel fluvial processes combine with potentially strong influences from adjacent hillslopes to form unique geomorphic settings. Potential valley energy is defined as High, Moderate, and Low with thresholds set at 300 to 400 W/m^2 and 10 to 30 W/m^2 (Nanson and Croke, 1992). Energy itself is difficult to measure, so I have elected to use channel gradient (G_c) as a plainly measured surrogate with thresholds of 4% and 0.1%, respectively. Hillslope gradient (G_h) is paired with valley bottom width to examine the degree of hillslope coupling. The descriptions below attempt to illustrate the key characteristics of the valley classes as an interaction of processes that constrain the character of channels that can develop and the development of floodplain features. Only with clear definitions of classes can we hope to partition the variability in the longitudinal direction (Innis *et al*., 2000).

C.2 VALLEY CLASSES

C.2.1 Headwaters

Headwaters are V-shaped valleys strongly influenced by hillslope processes (Benda *et al*., 2005). Hillslope gradient and length is sufficient to contribute colluvial debris directly into the channel at a probability of >0.5. Valley bottom width is very narrow (<10 m) and the channel is steep (>4%). Headwaters are considered high-energy systems although flow may not be continuous during all seasons. Although the system energy potential is high, the substantial colluvial inputs (often large clasts >1 m) are not entrained or transported regularly. Channel types commonly existing on the valley bottom include steep mountain rivers. Cascade and step-pool bedforms are often forced

by boulder, bedrock, or LWD present on the valley bottom (Montgomery and Buffington, 1997). The limited valley bottom width does not support the development of a floodplain.

The resolution limitations of the DEM base layer in GIS force the identification of headwaters to be based on a measurable descriptive parameter, different than those used to identify other valley classes. Drainage area is viewed as an appropriate surrogate. Channel initiation points are defined on a regional basis, utilizing climate, soils, and vegetation data (Clarke *et al*., 2008) to appropriately identify the beginning of continuous fluvial features. Regional hydrologic equations developed and tested by Faustini *et al*. (2009) predict channel width using drainage area as a surrogate for discharge. I suggest a similar approach to define headwaters. Headwater valleys will exist within a bracket of drainage areas (e.g., 0.1 to 5 km^2). The position of headwaters in the fluvial system and their characteristic morphology permit the use of drainage area.

C.2.2 High-energy Coupled

The general valley morphology is similar to Headwater Valleys (see above). Steep hillslopes (>30%) and steep channel gradients (>4%) continue the strong influence of hillslope processes on fluvial form. These valleys can be identified in any position in the network, but are most often found immediately downstream of Headwaters, in the upper reaches of watersheds. These systems exist as fully coupled and fully confined (see definitions in Appendix A). The high-energy potential of the system limits lateral floodplain development, though discontinuous pockets of alluvium may be present in sheltered areas. Larger rivers can flow through High-energy Coupled Valleys if the VWI suggests that colluvial debris inputs have a probability of at least 0.5 of entering the

channel (Whiting and Bradley, 1993; Thompson *et al*., 2008). The VWI is a measure of the proportion of the valley bottom that is occupied by active channel, therefore leading to a measure of the buffering capacity of the non-channel valley bottom.

C.2.3 High-energy Uncoupled

The high-energy descriptor (G_c > 4%) is most likely to occur in high relief areas with hillslope gradients in excess of 30%. However, landscapes exist where these unstable slopes are separated from the channel enough to lower the probability of direct material transfer to below 0.1. Another landscape that could exist in this class is a steep valley bottom with relaxed hillslope gradients. In both settings, fluvial processes control form and function of landforms on the valley bottom.

With a steep channel gradient, the suite of channel types likely to develop are mostly Steep Mountain Rivers, though meandering channels could sufficiently lower the gradient of channels to permit Moderate-energy Gravel Rivers and Braided Rivers to develop. Valley bottom not occupied by the active channel is available for floodplain development, but the high energy potential creates an erratic deposition/erosion surface. Periods of mass deposition following swift flood attenuation are as influential as floodplain stripping for the current morphology and ecological functionality of the riparian area.

C.2.4 Canyon

The most distinctive attribute of a canyon is the containment of the channel by nearly vertical walls (G_h > 70%) and narrow valley bottoms (<2W_c), naturally limiting the ability to develop floodplains. These systems are fully coupled to, and confined by, the hillslopes. Alluvial sediment can accumulate in sheltered downstream locations associated with boulders, LWD, or structural bedrock irregularities, but subsequent high flows routinely flush the system of the deposited sediment (Bendix and Hupp, 2000). Canyons can exist along a gradient of energy conditions from High Energy to near Low Energy. The variability in potential system energy is expressed mostly in channel type diversity. Bedrock is often the dominant influence on channel planform and bedforms. Colluvial inputs and large sediment deposits from tributaries can also significantly alter valley bottom structure and channel form.

Ephemeral or intermittent systems are not uncommon in arid regions, or those driven by seasonal snowmelt or monsoonal climate patterns. Due to this variation in flow regime, wide sediment budget variation, and possible forcing of channel gradient, a number of channel types can exist in canyons. Steep Mountain Rivers with cascade and step-pool bedforms exist when Canyons have consistent G_c > 4%. Mountain Ephemeral Washes and Moderate-energy Gravel Rivers develop in the lower gradient reaches. Braided Rivers and Sand Rivers may even exist when gradients trend toward moderate energy and there is a high sediment load in the system.

C.2.5 Gorge

Gorges are similar to Canyon Valleys in general morphology (G_h > 70%), but have a wider W_c. These systems are still fully coupled to, and confined by, the hillslopes. I utilize Gregory *et al.*'s (1991) distinction that constrained rivers exist when the valley bottom is <2W_c at bankfull conditions. This threshold is used to define the point at which floodplain development along the channel has the potential to become consistent along the river and persistent through time. Colluvial and tributary influences are still significant for channel pattern. Moderate-energy potential is most common in Gorge Valleys, although a similar spread of energy conditions can exist as with Canyon Valleys. Channel types range from Steep Mountain Rivers to Braided and Sand Rivers along the energy gradient. Hydraulic, hydrologic, and ecologic functionality of Gorge Valleys are very different from Canyon Valleys despite their similar morphologies.

C.2.6 Moderate-energy Confined

In the middle reaches of the idealized river system, hillslope gradients are relaxed (usually below 30%) and colluvial inputs are no longer a major influence on valley bottom and channel morphology. Channel gradient is below 4% and usually lower than the channel slope as the channel moves laterally across an increasingly wider valley bottom. The influences of hillslope still exist but in these valleys it is the presence, not steepness, of the hillslopes that constrains the system. Free-lateral motion has been related to channel width during bankfull conditions, approximately 7W_c (Williams, 1986; Hagerman and Williams, 2000; Faustini *et al.*, 2009). Confined valleys have valley bottoms less than seven W_c, therefore restricting the lateral migration of the channel.

With the ability for a channel to meander within a valley gradient range of 0.1 to 4%, there are a number of channel forms likely to occur including: Mountain Ephemeral Washes, Moderate-energy Gravel Rivers, Sand, and Braided/Wandering Rivers. The various bedforms of pool-riffle, dune-ripple and plane-bed are related to channel slope and bed material; this is especially true for braided systems (Knighton, 1998).

C.2.7 Moderate-energy Unconfined

Moderate-energy valley bottoms (G_c < 4%) are not bounded by hillslopes restricting meander extent. Colluvium is not a significant morphological consideration for this valley class. Valley bottom width is >7W_c, allowing the channel to freely meander. Channel types include: Mountain Ephemeral Washes, Moderate-energy Gravel Rivers, Sand, and Braided/Wandering Rivers. These channels have the potential to develop extensive floodplains and high sinuosity in the wide valley bottoms. Floodplains can be complex as there are several distinct processes that could contribute sediment for long-term storage.

C.2.8 Glacial Trough

Many valleys were enhanced by ice during the Pleistocene glacial period. These areas can be identified by existing above an elevation threshold considered the maximum extent of glacial influence. These thresholds should be regionally specific because ice sheet expansion and mountain glacial formation are highly reliant on local climate conditions. The distinctive U-shaped valleys have uniquely large amounts of sediment derived from moraine, outwash plains, and lacustrian sources present on the valley

bottom. Fully-formed Glacial Trough Valleys are essentially disconnected from the steep slopes that form the walls of the "U" (Brardioni and Hassan, 2006).

Removing the elevation component of their classification, Glacial Trough Valleys are Moderate-energy Unconfined Valleys. The decision to separate these high elevation, glacially-influenced valleys from their lowland twin was based on the uniqueness of these systems. Flow regime, biotic communities, and abundant sediment are all driven by the morphological shape and landscape position of these valleys (Montgomery and Buffington, 1997).

C.2.9 Low-energy Floodplain

These valleys are completely manipulated by alluvial processes; although, where channels contact large bodies of water, tidal or lotic processes may influence these systems as well. Hillslopes are effectively disconnected from the channel as W_c exceeds $7W_c$. Hillslope gradient is usually below 30%, therefore eliminating hillslope coupling as a limiting geomorphic process, regardless of width. Channel patterns can range from single-thread, equi-width channels to a complex system of anastamosed channels with large, vegetated, stable islands. Generally low-energy potential of the system does not lead to dramatic shifts in floodplain morphology; however, avulsion can shift channel location very rapidly. Dominant sediment type is fine and cohesive sands, silts, and clays, leading to the development of stable banks. The common terminal position in the river network suggests that tidal or lentic processes may influence these systems as well.

APPENDIX D

CHANNEL AND FLOODPLAIN DESCRIPTIONS

D.1 INTRODUCTION

Climate, bedrock, and valley structure directly affect the conditions of current channels and floodplains forming a complex fluvial network across the landscape (Montgomery, 1999; Hurley and Jensen, 2001). Hillslope connectivity, slope, and valley bottom width are important factors at the valley and channel scale. Other factors including sediment caliber, sinuosity, and planform become more important at the channel scale. Ecological functionality, lateral extent, and connectivity of floodplains to the channel can change along the course of a river (Brierley and Fryirs, 2005).

Potential fluvial system energy is a conceptual variable that can be used to organize river networks into functionally similar groups. Energy has been shown to be a driver of form and function of channel planform and bedform, and floodplain morphology, dictating the erosion, transport, and deposition capabilities of specific river reaches. Channel slope and valley width are the primary controls on potential energy in the fluvial system in any location (Brierley and Fryirs, 2005). Please see Table 3.2 for an ordered representation of channel types and Figure 3.3 for a conceptual diagram of the three controlling variables associated with the valley the channel inhabits: 1) energy, 2) hillslope coupling, and 3) valley confinement. Below, I describe the networks on the scale of individual channel and floodplain types. Each description addresses the energy potential of the system, its dominant erosion/deposition regime, dominant landforms, and significant slope or width thresholds.

D.2 CHANNEL TYPES

D.2.1 Steep Mountain Rivers

These channels exist in high relief areas where the confined setting of the valleys constrains the extent of planform adjustment, lateral migration, and floodplain development (O'Connor and Watson, 1998). These streams are often directly 'coupled' (see Appendix A for definition) to adjacent hillslopes and sediment mobilized on those slopes may move directly into the stream channel by Hortonian overland flow or during catastrophic events, debris flows, and shallow landslides (Church, 2002). Fluvial sediment deposition by typical overbank processes is limited by the steepness of the channel profile and confinement by valley walls. Sediment of various diameters may exist along the margins and bed of the channel, but it is often related to hillslope processes. Slackwater deposits in canyons and gorges should not be considered functional floodplains because of their diminutive size, consistent longitudinal extent, and temporal transience.

Common bedforms include bedrock and boulder cascades, and step-pool formations. Bedrock, boulders, and large gravels dominate the bed material. Channels are generally straight with slopes ranging from 4 to 20+%. These are supply-limited systems with excess energy dispersed along rough beds and channel boundaries (Montgomery and Buffington, 1997, 1998).

D.2.2 Moderate-energy Gravel Rivers

As the valleys become less coupled to adjacent hillslopes and less confined by valley walls, more valley bottom is available for lateral channel adjustment, attenuation

of floodwaters, and the deposition of sediment. With increased valley bottom width and alluvial banks, these rivers have the ability to migrate across the valley bottom. In cross section, these meandering channels would have characteristic alternating symmetry and asymmetry along straights and bends, respectively, owing to the meandering of the thalweg within the channel.

The moderate energy of the system controls the average sediment size and limits the floodplain building processes. Vertical accretion is not a prominent method of floodplain building because of the size of the material. While the floodplain may be continuous, its micro topography may vary greatly depending on rates and stages of bar development and channel migration, and history of large events.

Common bedforms include plane-bed/transitional reaches and pool-riffle sequences. Channels can be straight to moderately sinuous with $G_c < 4\%$. All stages of incision are possible and could have dramatic effects on floodplain development and near-channel landforms. Sands can become the functionally dominant bed material even with gravels as the dominant size as measured using the D_{50} method. These channels have bedform characteristics more similar to Sand Rivers and should be classified as such.

D.2.3 Braided and Wandering Gravel Rivers

Braided rivers are bedload-dominated systems characterized by high-sediment loads with an unstable network of multiple channels (Knighton and Nanson, 1993). Moderate stream power (10 to 300 W/m^2), moderate slope (~3%) and high width-to-depth ratios are characteristic of this river type (Nanson and Croke, 1992; Ferguson, 1993). Shifts in channel position are caused by and lead to deposition of material in mid-

channel bars and islands, and as levees at channel banks. While lateral migration may be a strong driver of channel shifts, point-bar development characteristic of lateral accretion is not a prominent floodplain developmental process. Bars and islands are created between the channels but would not be considered part of the floodplain because of their extremely non-permanent nature. The topography of the floodplain is varied as it contains filled abandoned channels and partially built bars. The laterally dynamic nature of braided channels leads to more permanent floodplain deposits existing in sheltered locations, unlikely to be occupied by the migrating channel.

Wandering channels tend to be more stable than truly braided channels and often have a dominant main channel. Wandering rivers develop in an intermediate position between higher energy braided rivers and lower energy anastamosed rivers. Planform stability, sediment caliber, and energy of wandering rivers occupy the continuum between these two types (Knighton and Nanson, 1993; Knighton, 1998).

Several processes build floodplains of varying spatial extents and at different rates; these include vertical accretion, lateral accretion, island formation, and avulsions. It is the interaction of these processes that make this a unique river and floodplain type. The dominant sediments exist as a continuum from gravels to sands. These channel complexes are relatively straight as helical flow is limited by bar and island development, reducing the energy expended on lateral migration (Sinha and Friend, 1993).

D.2.4 Sand Rivers

These rivers have a characteristic live-bed composed of sand-sized bed material entrained during a range of flows (Brierley and Fryirs, 2005). Vegetation can have a

major impact on stabilization of the banks and towards reduction of flood power on the floodplain. Major adjustments in channel width, position, and planform may occur during single events. Bedforms include pool-riffle, dune-ripple, and anti-dune morphologies. The mobility of the bed material can cause heterogeneity in bedforms along a channel through space and time (Brierley and Fryirs, 2005). These channels are some of the most dynamic, responding dramatically to high flows and changes in sediment budget and flow regime. Sand-bed channels typically maintain high width-to-depth ratios (Brierley and Fryirs, 2005).

These floodplains can exhibit extended periods of inactivity or, conversely, nearly continuous construction and erosion along portions of the channel. Lateral accretion and vertical accretion are common floodplain building processes for these channels depending on sediment load type (bedload, suspended load, and dissolved load) and the erosion potential of the bank material. Oxbow lakes, chutes, and channel scars are possible floodplain landforms in highly sinuous systems. These channels exist in the moderate-energy class with channel slopes ~0.1% to ~4%.

D.2.5 Washes, Gullies, Arroyos, and Mountain Ephemeral Streams

Also called "*discontinuous ephemeral streams*" by Bull (1997) and "*discontinuous watercourses*" by Brierley and Fryirs (2005). These "channels" have uniquely transient and unstable morphologies related to a widely-variable flow regime. Erosion and aggradation often occur in alternating locations along a channel as the threshold can shift longitudinally along the channel. Significant periods of inactivity are punctuated by extreme morphological changes.

Bull's (1997) definition described the channels as continuously entrenched, while Brierley and Fryirs (2005) suggested that open, unconfined valley bottoms exhibit similar physical properties. Degrees of channel development (stable and vegetated, scoured, and accreted) suggest the recent flow history of the section. Schumm *et al*. (1984) defined four classes of entrenched streams, three of which would be included in this channel class: 1) Gully, 2) Entrenched Stream, and 3) Composite Incised Channel. The combination of these classes is based on the appreciation that similar processes and patterns occur at similar temporal and spatial scales.

Floodplains are limited in confined settings to pockets of alluvium in the shadow of bends or behind obstructions. In open-valley settings these channels can develop extensive floodplains, with extent related to sediment caliber, magnitude of flows, and existing floodplain roughness elements (vegetation, micro-topography, etc.). Reworking of deposits occurs during extreme events in which lateral channel migration can erode the channel margins.

These channels have very flashy flow regimes and can remain dry for several years. Bedforms are usually poorly defined and are transient and discontinuous in both time and space. Subsequent flows often obliterate previous bedforms. Channels can have a range of variability in channel gradient (~3% to well above 4%) and substrate type (gravels to sands with larger boulders and cobbles possibly present). Hillslopes commonly influence these channels through direct sediment input and confinement, though actual levels of influence vary across this class. All stages of incision (Schumm *et al*., 1984; Stages I through V) are possible and could have dramatic effects on floodplain development and near-channel landforms (see Appendix E)

D.2.6 Low-energy Rivers

Valley slopes are very low, ~0.1% but can be an order of magnitude lower. Multi-channel complexes can be straight to sinuous, with individual channels exhibiting a similar range of planforms. In cross section, many channels will have low width-to-depth ratios (Knighton and Nanson 1993; Rosgen 1994). The distinction made by Nanson and Croke (1992) of 10 W/m^2 defines the specific stream power for Low-energy Rivers. Knighton (1998) notes that the threshold of low-energy limit has been subject to adjustments, but he agrees with the value. Other studies agree with extremely low specific stream power values, all suggesting a threshold of 30 W/m^2 or less (Magilligan, 1992; Lecce, 1997; Newsom *et al*., 1998; Jain *et al*., 2008; Orr *et al*., 2008). The low power, suspended-sediment load and cohesive bank material create a dominantly depositional environment (Knighton and Nanson, 1993; Knighton, 1998). Common landscape positions include distal ends of rivers, delta, and tidal areas. Cohesive bank material is often reinforced with grasses and vegetative mats stabilizing channel banks.

Channel patterns range from small, equi-width, single-thread channels comparable to Rosgen's (1994) E channels to large anastamosing systems of channels (Brierley and Fryirs, 2005). Regardless of channel number and shape, floodplains exist as very low relief features with fine-grained sands, silts, clays, and organic matter. Vertical overbank accretion is the primary floodplain-building mechanism (Knighton, 1998). In anabranched and anastamosed systems, island building processes also increase floodplain area. The stability of the channel margins and the caliber of the sediment are the most distinctive characteristics of anastamosing channels (Knighton and Nanson 1993). Swampy depressions filled with organics are common in these floodplains. The cohesion

of the bank material and low specific stream power limit lateral erosion and migration. Brookes (1985) found that 35 W/m^2 is necessary for significant lateral migration to adjust the channel position, thus Low-energy Rivers have potential energies below this threshold. The water table is usually high and restricts vegetation types, selecting for hydrophilic species tolerant of prolonged inundation.

APPENDIX E

CLASS MODIFIERS (SCALE SPECIFIC)

E.1 GULLYING AS A VALLEY CLASS MODIFIER

In many arid and semi-arid regions, dynamic valleys can develop in essentially flat landscapes through episodic and catastrophic erosion and deposition events. These swale and gully-like landforms are unique in that they begin to straddle the accepted scales of valleys and channels. These features are often too small to be accurately captured in remotely-sensed data, especially with a horizontal resolution of 10-m. I suggest that as incision is used as a modifier for channel classes (see below), gullying should be used as a descriptor for valleys that commonly experience dramatic vertical and horizontal adjustments. Not surprisingly, channels that are likely to be characterized within our three incision classes are most often associated with a valley identified as gullied. Hillslope influence is extreme in gullied systems where steep, unstable surfaces can contribute significant amounts of sediment during periods of sporadic, intense precipitation characteristic of arid and semi-arid regions (Michaelides and Wainwright, 2002). Hillslopes are often short as minor drainage divides can be frequent in heavily dissected stream networks.

E.2 INCISION AS A CHANNEL CLASS MODIFIER

Channel incision into bedrock, alluvial valley bottom deposits, and other floodplain features can have a dramatic effect on which physical processes actively drive channel morphology. Examining the flow regime, bed material, bank material, gradient, and riparian vegetation along a reach can aid in prediction of incision rates and location. Identifying the stage of incision is important in understanding dominant channel-adjustment processes (Simon and Darby, 1999). The well-known channel evolution

model (CEM) with five stages of incision from Schumm *et al*. (1984) has been used to modify the general morphology of channels to describe their position along a continuum of conditions from unstable eroding to aggrading or stable. This added description becomes exceedingly important for the moderate to higher energy classes including Washes/Gullies, Steep Mountain Rivers, Meandering Gravel Rivers, Braided and Wandering Rivers, and Sand Rivers

Simon (1989) advanced this thinking, using six stages to describe the complete temporal progression of incision from a stable beginning point (Stage I) to a stable end point (Stage VI). Doyle and Shields (2000) advanced the thinking about channel evolution by relating upstream sediment supply, bed material and bank material to temporal and longitudinal shifts in grain-size dominance of channel beds. The importance of considering incision stage and the size of entrained sediment is focused in the downstream direction. Reaches currently aggrading are likely downstream of reaches which are currently incising. The spatial relation can be followed through time as these dynamic systems slowly change the immediate banks, channel slope, and composition of their bed sediment (Doyle and Shields, 2000).

As a simplification of the well-accepted CEM (Schumm *et al*., 1984), I have grouped Stages II and III as a single "actively incising" class and Stages IV and V as "actively aggrading." The incision modifiers "actively incising" and "actively aggrading" represent the intermediates between the two stable states shown by Simon's (1989) Stages I and VI, respectively.

The stage of channel incision is useful in identifying the stability of landforms and sediment in the channel, on the floodplain, and on the valley bottom as a whole.

Floodplain features can be obliterated, shifted, or added to during periods of degradation and aggradation or be vegetated during periods of stability. Controlling for incision is an important management objective for many management agencies and private landowners. Incision is a natural, typically cyclic process, but humans can amplify the intensity and increase the time a system operates at a single stage (Bull, 1997). The CEM proposed by Schumm *et al*. (1984) and supported by Simon (1989) provides the ability to approximate the future direction of change on the valley bottom (Doyle and Shields, 2000). This is a key component to understanding geomorphic structure that affects the function of riparia and the concepts that direct management.