STREAM GEOMORPHOLOGY AND CLASSIFICATION IN GLACIAL-FLUVIAL VALLEYS OF THE NORTH CASCADE MOUNTAIN RANGE IN WASHINGTON STATE

By

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To the Faculty of Washington State University:

The members of the Committee appointed to examine the dissertation of WILLIAM BARRY SOUTHERLAND find it satisfactory and recommend that it be accepted.

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IN WASHINGTON STATE

Abstract

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In the Pacific Northwest, *A Classification of Natural Rivers* developed by Dave Rosgen (1994) has been the focus of much debate concerning the question of bankfull relevance to channel shaping flow, classification and stream restoration. This study is important because hydrologists and restoration technicians alike need to know whether Rosgen's bankfull indicator-based classification system can systematically and consistently apply to both east and west slope streams of the North Cascade Mountain Range. If so, do bankfull indicators provide consistent relationships to drainage area and other stream dimensions? Can geomorphic stream classification be implemented with consistency and accuracy on both east and west side slopes within glacial-fluvial valleys? Because Rosgen's system depends on dimensions based on stable, reference reaches, it is critical that measurable attributes for assessment of stability be identified. To meet reference site conditions, these attributes must be reproducible and show consistent relationships to bankfull indicators. The research present here demonstrates that bankfull indicators and geomorphic stream dimensions can be applied with consistency for stream classification in glacial-fluvial valleys on both east and west slopes on the North Cascade Mountain Range. A tool for stream stability based on reference reach dimensions was developed and described.

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DEDICATION

I want to express my loving regard for my wife, Denise, and for our sons, Daniel and Shane. They have been a constant inspiration and motivation throughout this rigorous doctorate program. Without their love and support this level of accomplishment would have been considerably more difficult.

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CHAPTER ONE

STREAM GEOMORPHOLOGY AND CLASSIFICATION IN GLACIAL FLUVIAL TROUGHS OF THE NORTH CASCADE MOUNTAIN RANGE IN WASHINGTON STATE

INTRODUCTION

As anthropogenic uses along stream corridors increase, so do channel disturbances. Cumulatively, disturbances may alter channel physics, impacting biological structure and diversity and inducing instability. Traditional approaches to correct stream problems such as bank stability, sedimentation, and fish habitat have focused on spot treatments and riparian buffers. Unfortunately, spot treatments may alter stream dynamics, transferring problems downstream and/or upstream. Riparian management also has proven ineffective in many cases, as unstable stream channels can migrate laterally and obliterate buffers (Riley, 1998). The negative effects of human-induced practices have created a need for understanding, assessing, and restoring streams to a natural, stable state.

Recently, natural channel restoration has emerged as a more holistic approach to stream planning and design (Commerce, 1998). Natural channel restoration is premised on restoring stream dimensions based on geomorphic templates taken from stable, relatively undisturbed reference reaches. A geomorphic reference reach is the natural stable reach within the similar hydro-physiographic area. A hydrophysiographic area is a drainage basin where the combination of the mean annual precipitation, lithology, and landuses produces similar discharge for a given drainage basin (Rosgen, 2003). Reference reaches for a specific stream classification and valley type can serve as a template for planning and/or designing naturally stable systems. The reference reach is a valuable source of information for an estimate of the current state of departure the unstable reach of interest may manifest and also for the physical design template should natural channel restoration be implemented.

The reference reach concept is based on the idea that there is a most probable form of a stream (Leopold, 1994). A reference reach should reflect a minimum expenditure of energy moving towards an equal distribution of stream power. A major assumption of natural channel restoration is that streams in similar geologic settings evolve similar geomorphic dimensions within predictable ranges. Geomorphic dimensions resembling those described by Leopold (1994) and Rosgen (1998) can then be used to stratify stream reaches into a classification system so that appropriate reference dimensions can be applied.

To date, the most widely accepted classification system used for natural channel restoration is Rosgen's (1994) Stream Classification System. In an evaluation of the use of Rosgen's stream classification in the Chequamegon-Nicolet National Forest in Wisconsin, researchers were able to correctly classify 94.7 % of lower relief terrain streams (Savery, T., Belt, G., and Dale A Higgens, 2001). Annable (1995) evaluated Rosgen's 1994 stream classification in Southeastern Ontario and consistently found specific morphological and hydraulic characteristics on 47 study sites when stratified by geomorphic stream type. Castro (2000) successfully used Rosgen's system to classify streams on both the east and west slopes of the Cascades. Epstein (2002) agrees that the Rosgen system is applicable to varied climates and is a useful tool for assessing the origin, channel evolution, and development of streams.

Though it is elaborately devised, comprehensive and utilized extensively, Rosgen's hierarchal classification system has its detractors. Some practitioners have suggested that the Rosgen system, which was strongly influenced from observations in the arid southwestern United States, is not appropriate for streams in more humid climates with abundant large woody debris such as the west slopes of the Cascade Range in the Pacific Northwest (Miller and Skidmore, 2001). Others believe that to use Rosgen's stream classification system beyond the purpose of describing and communicating a particular stream type is inappropriate and that misapplications may result as a system has not yet been developed to assess stream stability, channel evolution, and potential response (Juracek, 2003).

Some practitioners have anecdotally suggested that Rosgen's stream classification system does not correspond with a bankfull discharge of a 1.5Q event on the west side of the Cascade Mountain Range (Liquori, 2002). The 1.5 year Q event for bankfull is an overall average discharge rate worldwide (Williams, 1978). Williams also concludes that variability in the 1.5 Q return interval is common. Regional conditions can cause a significant difference from the worldwide 1.5 Q return interval. Castro (2001) found common bankfull return intervals of 1.1 to 1.2 on the west side of the North Cascades and 1.4 Q common on the east side of the Cascades. The differences between these bankfull return intervals may appear to be small, but the discharge differences are significant.

Certainly, a key test of geomorphic stream classification, and thus natural channel restoration, is the applicability of the system to various climactic and geologic settings, and the appropriateness of associated geomorphic bankfull dimensions. Unfortunately, few tests are available involving a comprehensive statistical experimental design of the Rosgen System that analyzes and compares both humid and dry settings such as the west and east slopes of the Cascade Mountain Range.

Goals of this Study

This study tests the applicability of the Rosgen Stream Classification System in glacial-fluvial valleys on both the east and west slopes of the North Cascade region of Washington State. The gentler, depositional slopes of the glacial-fluvial valley areas of the North Cascades are often both developed and important habitat for threatened and endangered anadromous salmonids. The classification system was tested on relatively undisturbed streams on both the drier east slopes and on the more humid west slopes.

Rosgen's stream classification system is based on geomorphic measurements and indicators taken at bankfull discharge. The term bankfull discharge is sometimes used interchangeably with the term effective discharge and/or the term channel-forming flow; yet, their meanings are distinct and should be explained as such because under specific circumstances such as channel incision, bankfull discharge and effective discharge may vary significantly.

Wolman (1954) characterizes the bankfull discharge as the dominant discharge that forms the channel. Bankfull discharge is described as the point of incipient flooding, at which flow overtops the natural channel and spreads across the floodplain, also termed as bankfull stage. It is believed that the discharge or flow at the bankfull is most effective to carry sediments overtime (Leopold, 1994). Though the formation process of a natural channel is complex, there are quantifiable and consistent patterns for the process, especially at the bankfull stage (Leopold et al., 1964).

The effective discharge is a quantifiable term. It is used to describe the discharge that is most effective in transporting the most bedload over time. The effective discharge is a calculation of sediment curves and frequency of flow return intervals that determine the greatest amount of bedload movement over time.

Channel forming flow is a term used to express a discharge that completes the amount of energy required to maintain a river's general conveyance size and form such as width and depth associated with shaping flow.

Andrews (1980) showed that bankfull discharge coincides closely with effective discharge. Dunne (1978) argued that the bankfull stage corresponds to the discharge at which channel maintenance is most effective. Wolman and Miller (1960) concluded that bankfull discharge is the most effective and is the dominant channel forming flow. The dominate discharge is the flow which determines channel patterns such as cross-section channel capacity, widths, and bar to bar formation (Wolman and Leopold, 1957) with a strong correlation to meander wavelength (Ackers and Charlton, 1970).

Bankfull, effective, and channel-forming are all commensurate with the discharge that dominates the shape and pattern of a stream and occur at nearly the same flow return interval in most streams where the floodplains are developed. The terms bankfull discharge, effective discharge, and channel-forming flow (also known as dominate flow) vary in how they are defined, but are all nearly the same in a natural morphological relatively stable stream. However, in highly perturbated or incised conditions there may be significant discharge differences between effective and bankfull flows (Doyle et al, 1999). Kemp (2002) argued that regional relationships relative to bankfull discharges need to be developed to estimate bankfull discharges for ungaged streams. In alluvial channels downstream, hydraulic geometry concerns spatial changes in channels with increasing discharge along a river or within a region.

Because Rosgen's stream classification system is based on geomorphic measurements and indicators taken at bankfull discharge, it is essential that bankfull indicators are identified and measured accurately. To implement natural channel restoration based on bankfull dimensions several central questions need to be addressed.

First, can bankfull related indicators be consistently identified and used for regional curves and do bankfull measures of width, depth, cross-section, and discharge correlate with drainage area? Can bankfull discharge variables and geomorphic stream dimensions, which are used to geomorphically classify streams in glacial-fluvial troughs, be quantified, described, compared, and statistically correlated? Do the test streams on both the east and west slopes in the North Cascade Mountain Range of Washington State have bankfull indicators that correlate with their respective drainage areas. If so, what are the return intervals associated with bankfull indicators?

Secondly, do bankfull indicators correlate with channel forming flow return intervals? Both gaged and ungaged streams were tested for bankfull dimensions with the purpose of generating regional runoff curves and identifying return intervals at channel forming flow. Can the overall worldwide average return interval for bankfull of 1.5 Q (Williams, 1978) be used to determine bankfull discharge on both the east and west slopes of the North Cascade Mountain Range?

Third, Does Rosgen's classification system adequately predict a range of dimensions found in natural stable reference conditions? If so, what impact does the abundance and size of woody debris have on stream dimensions such as width, slope, width to depth ratio and do these dimensions fit within the Rosgen Classification system/key (See Appendix A, Figure 2)?

And lastly, since the concept of natural stability is essential to Rosgen's system, can a practical and beneficial tool be developed to establish a measure of stability and percent of departure from the naturally stable (reference) morphology? If physical field measurements for bankfull discharge are consistent and reproducible in the field, can a simple stability index and a measure of a departure from reference reach conditions within similar valley types and watersheds be used by the landowner or field technician when restoring streams to natural stability?

Study Area

The overall study area encompasses 6,358 square miles of the North Cascades in Washington State. (Figure 1). The streams selected for study were characteristically pool/riffle morphologies within valleys where glacial-fluvial processes have been the dominant natural formative factor.

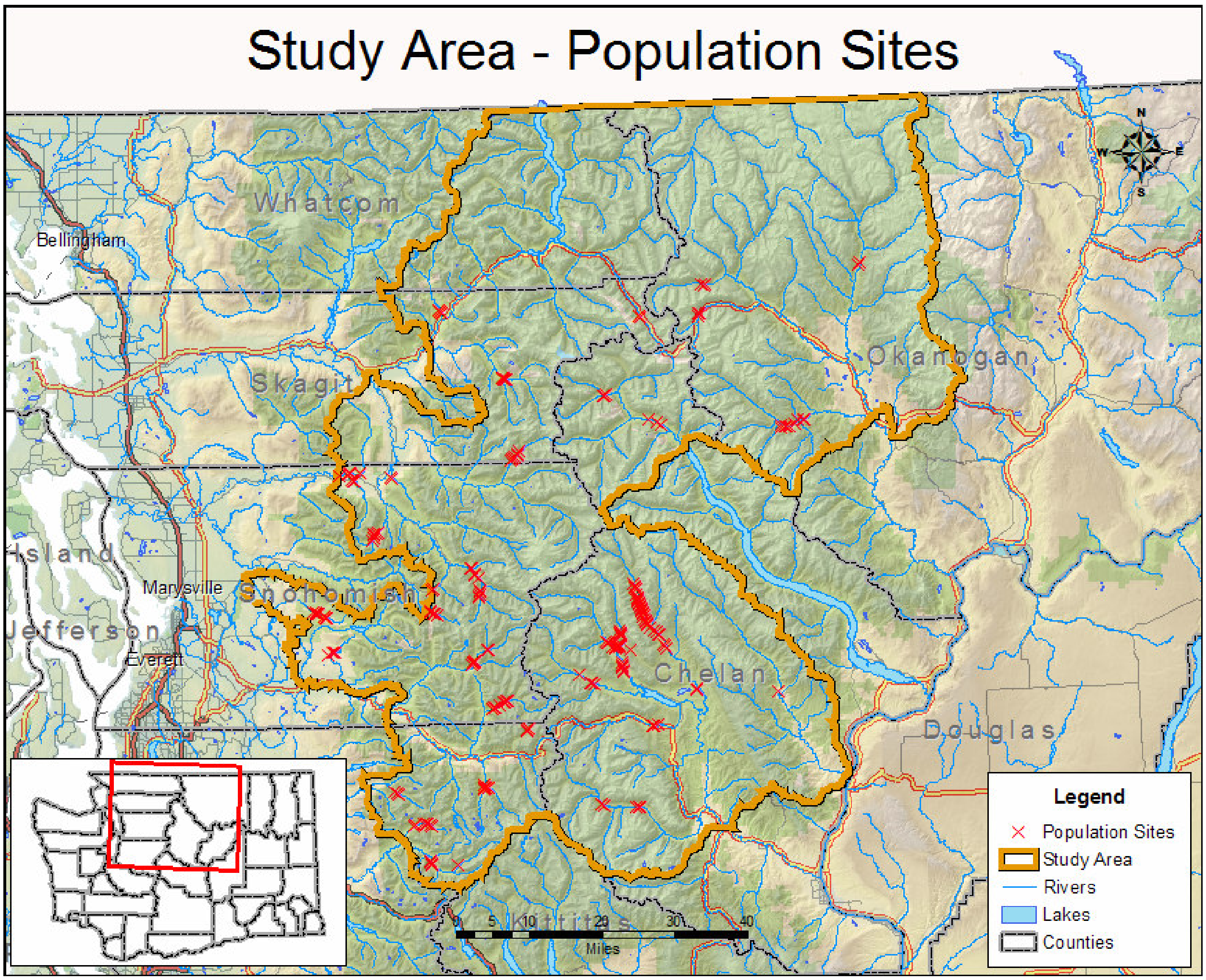

Figure 1. Study area with sampled sites in the North Cascades Mountains of Washington State

Rosgen (1996) describes glacial-fluvial valley types as the product of glacial scouring where the resultant trough is now a wide, "U" shaped valley with the valley floors generally less than 4% slope. The trough-like valley shape does not have the wider alluvium developed floodplains of the considerably more mature valleys found at lower elevations where fluvial processes have dominated over time. Soils in the glacial-fluvial troughs are derived from materials deposited as moraines or more recent alluvium from the Holocene period to the present. Landforms locally include lateral and terminal moraines, alluvial terraces, and floodplains (see Figures 3 and 4, Appendix C). The streams within the valley type V are predominately pool/riffle morphologies vs. the steeper rapids, cascades, or step/pool morphologies found in the steeper-narrower, more youthful valleys located at higher elevations. Glacial-fluvial troughs of the North Cascades can vary significantly due to variations in geologic, climatic, vegetative, and anthropogenic induced conditions.

The studies discussed in the following chapters where chosen to test bankfull dimensions, stream classification, and the variability of stream morphologies within the same valley type. Chapter one includes a general introduction and a discussion of relevant literature and research, natural stability, and stream classification with a brief description of methods and research design. Chapter two examines bankfull discharge dimensions within glacial-fluvial troughs on both the east and west sides of the North Cascade Mountain Range in Washington State. Chapter three compares geomorphic attributes for single or dual thread stream channels within eastern and western slope glacial-fluvial valleys. Chapter four describes and illustrates a practical method for land operators, stakeholders, and field technicians to use for stream stability determination based on reference reach data.

Background and Relevant Research

Rivers and streams are among the most complex natural systems on the planet. They are major contributors to the health and happiness of society. Though they have been the subject of writing by rulers, scholars, and scientists for thousands of years, it was not until the eighteenth and nineteenth centuries that scientists and engineers turned their attention to understanding the physics and morphologies of rivers and streams (Schumm, 1973).

One of the first well-known authors to talk about physical attributes of a riverine system was W. M. Davis in the Geographical Cycle (1899). Davis argued that changes in valleys are relative to age, which he generally described as youthful, mature, and old. These were stages of adjustment generally described from a higher to a lower elevation. Davis wrote about how streams seek base level and the process of grade change and valley incision continues until they reach sea level, which is the ultimate base level. For nearly a century, Davis's cyclical explanation of geomorphic landscape evolution was widely accepted because he was the first to relate stream form as having some dependence upon a valley type. Though Davis's critics pointed out that it has been difficult to identify examples of broad flat plains of the old age topography described as peneplains, it is accepted that Davis's lack of knowledge of plate tectonics and uplifting was the void in explaining why all stream valleys are not flat like the peneplain he describes in the Geographical Cycle of 1899.

Global eustatic cycles (rising and falling of sea level relative to geologic cooling and warming cycles) were another worldwide characteristic poorly understood in Davis's time. Variations in eustatic cycles would have significantly affected base grade levels along coastlines and lower elevations, complicating the concept of the peneplain formation. Though much of our current knowledge was yet undiscovered in 1899, Davis's concept is still useful as a foundation for understanding geomorphic stream evolution.

Another leading contributor to the study of valley and stream geomorphologies was Gilbert (1909). Gilbert made significant contributions to the concept of slope profiles within a valley and its tributaries. His basic premise of a convex slope formation on a longitudinal profile was innovative. He proposed the idea that hill slope forms are dependent upon discharge, stream slopes, and sediment transport. His work was highly applicable because hillside tributaries are an integral geomorphic feature which contribute to the overall valley form. Both Davis and Gilbert identified morphological features and processes on the geomorphic landscape that provide an excellent analysis of glacial-fluvial processes in many valleys located in the Cascades of the Pacific Northwest and throughout mountain ranges elsewhere.

First to introduce the concept of stream orders as a way to classify streams relative to size and location within a drainage area was Horton (1932). In 1945, Horton modified his system to bring together the attributes of stream order, length, and slope. Horton's development of stream morphology relationships contributed to a widely accepted form of stream classification based on order number. Strahler (1957) modified Horton's stream order classification based on an order number that begins at the highest most youthful streams at the tip of the network and increases in order as tributaries. Shreve (1967) proposed a similar classification system where the order of a stream is the sum of the order of the upstream tributaries. Shreve's stream order classification system was designed to synthesize both stream order and size.

Leopold, Wolman, and Miller (1964) completed the first comprehensive quantitative textbooks in the emerging field of fluvial geomorphological processes. Channel processes and form were quantified in both morphological and morphometric terms. The relevance of bankfull discharge and the most probable form of a river became the central basis for numerous studies that followed.

By the mid-1970s and into the 80s, the importance of stream geomorphology with its underlying physics was being recognized as an important component of healthy riparian and benthic communities (Platts, 1974, and Binns, 1982). Currently there continues to be considerable scientific literature regarding streams and rivers and their interrelationships with their adjacent riparian communities.

Contemporary scientists of fluvial geomorphology recognize the importance of stream geomorphology with its underlying physics as an important component of healthy riparian and benthic communities (Platts, 1980). Achieving the benefit of greater biodiversity in both stream and riparian areas is dependent upon a quantifiable geomorphic stream classification system as a tool to guide technicians in restoring a channel to its natural, stable state.

Natural Channel Stability

For over a century, it has been recognized that streams reach a kind of equilibrium in their natural setting (Dutton, 1882), (Davis, 1909), (Gilbert, 1877, 1914 and 1917), and (Lane, 1955). These authors recognized that streams take on a natural morphological state where equilibrium between channel forming discharge, sediment load, and slope could be achieved.

The process of equilibrium relative to bed load and size is explained in an article by Lane (1955). Lane introduces a proportionality equation (Appendix A, Figure 1) which illustrates the relationship that bedload and size have with slope and discharge. Lane described the necessity of being able to observe a set of conditions and predict morphological changes and the rate at which they will occur in order to restore a stream to equilibrium. These attributes, often referred to as geomorphic attributes, represent an energy balance on the landscape, most specifically within the floodplain.

Anthropogenic uses along stream corridors can negatively impact the energy balance as described by Lane. For example, when homes and roads are built in floodplains, stream corridors may be changed and meanders can be cut off, resulting in lower sinuosity. Reduction in sinuosity comes with two significant tradeoffs. First, in relation to the reduction in sinuosity, the loss of stream length results in fewer habitats for fish, macroinvertebrates, and other aquatic organisms. Secondly, the loss of sinuosity or a reduction in its length or width results in steeper slopes, a loss of surface roughness during flood stage events causing higher velocities, and a greater stream power. Cumulatively, the changes in these physical attributes cause greater damage to streambanks and properties during floodstages. There are considerable anthropogenic benefits to maintaining a natural stable stream.

Hack (1960) defined equilibrium (sometimes referred to as dynamic equilibrium) as a balance between process and form where small-scale adjustments are made in order to achieve an approximate state. The physical attributes of a stream such as sediment load, sediment size, slope, discharge, sinuosity, roughness, and width to depth ratios are critical variables affecting the equilibrium of natural channels in such a way that a change in one of these variables sets up mutual adjustments in some or all of the others (Leopold, 1964).

Natural stable streams include both relic (anthropogenically undisturbed) and present stable conditions. Rosgen (1996) argued that natural stream channel stability is achieved by allowing the river to develop a stable dimension, pattern, and profile so that over time, channel features are maintained and the stream neither aggrades or degrades. He notes that for a stream to be stable it must consistently transport its sediment load, both in size and type, associated with the local deposition and scour. Streams that cannot transport their bedload and washload in a stable manner, are often highly embedded, leaving little space in between the larger particle interstices causing instability for the valuable niches needed for aquatic organisms. Greater departures from the geomorphic stable reference condition lead to negative impacts on aquatic and riparian communities. Over time, morphological stable reaches have a tendency to produce a set of characteristic forms (Knighton, 1998).

The positive benefits of a natural stable stream needed to support riparian and benthic communities along with their associated functions and values are an integral part of the aquatic landscape (Commerce, 1998). Because natural stability is inherent to many riverine landscapes, restoration of watersheds and stream sites is often seen as a worthy goal that can benefit society.

Stream Classification

Streams are classified to organize and convey knowledge of stream morphology and behavior, but even amongst working professionals, technical descriptions of streams can be perplexing and uninformative. There must be consistency and reproducibility in stream classification in order for it to be effective. The stream classification must have a high enough resolution on the landscape that various stages of channel evolution can be measured and identified.

The list (not all inclusive) of classification systems, developed by significant contributors previous to the early 1990s for both stream and valley types, is not small. Scientists such as Davis (1899), Melton (1936), Horton (1945), Matthes (1956), Leopold and Wolman (1957), Lane (1957), Schumm (1963), Culbertson (1967), Thornbury (1969), Khan (1971), Kellerhals (1972), Galays et al. (1973), Mollard (1973), Schumm (1977), Brice and Blodgett (1978), Howard (1980), Paustian et al. (1983); (1992), Frissell and Liss (1986), Cupp (1989), Bradley and Whiting (1991), and Montgomery (1993), are among those who have developed classification systems. Though they vary, the systems cover applications based on regions, as well as worldwide use. Many of the classification systems provide general descriptions, while others are based on specifics such as bedload or channel evolutionary processes. Although most of these classification systems remain in use, few of these systems are suitable for the characterizations based on the essential morphometric and morphologic variables needed to restore streams.

A good example of a regionally based classification system used on the west slopes of the Cascade Mountains in the Pacific Northwest is that of Montgomery and Buffington (1993). This system focuses on channel form and process. Stream networks are divided into channel reach types, based on bed morphology, sediment transport processes, sediment supply, and discharge.

Montgomery and Buffington's system uses bed morphology or slope as an indicator of channel reach type. Less emphasis is placed on the variables that contribute to constructing the bed morphology (James, 1995). The end products are an array of general descriptions of streams based on attributes such as debris flow to drainage area, large woody debris, transport-limited versus supply-limited, bed profile forms, and typical slope ranges.

Another relevant application of fluvial geomorphology is the use of classification systems that reflect the physics of the channel. Stream channel evolution is common on the landscape. A good example of a channel evolution model that illustrates various phases of channel adjustments is the Channel Evolution Model (Simon, 1989). In Simon's model, the various adjustment processes are measured in terms of cross-section, longitudinal profile, and bank heights to determine the stage of evolution. The Simon's Channel Evolution Model provides a very useful tool for the practitioner to analyze the degree of channel incision and the natural processes that are likely to occur.

One of the most recent as well as broadly accepted classification systems is that of Dave Rosgen (1994). This system is designed to predict a river's behavior from its appearance; develop specific hydraulic and sediment relations for a given morphological channel type and state; provide a mechanism to extrapolate site-specific data collected on a given stream reach to those of similar character; and provide a consistent and reproducible frame of reference of communication.

The measurements in Rosgen's system are based on bankfull discharge dimensions and the system places various physical, measurable geomorphic attributes into a hierarchal order. The classification hierarchy is: 1) Single or multiple threaded channels (three or more channels at bankfull); 2) Entrenchment ratio (defined as the floodprone width divided by the bankfull width); 3) Width to depth ratio; 4) Sinuosity; 5) Slope ranges; and 6) Channel material. Figure 2 in Appendix A is Rosgen's key to classification of natural streams.

Rosgen (1996) describes stream classification as part of a four level hierarchal system of river inventory. Level I is a geomorphic characterization which describes the integration of land forms, valley morphology and basin relief. Level II is a more detailed description of stream types extrapolated from field measured reference reaches. At level II, specific stream types are keyed using channel entrenchment, dimensions, patterns, profile slope, and the boundary materials (d_{50} particle size). Level III is the existing morphological state of the river on a reach basis. At this level, additional physical features that influence the stream state are evaluated. Some of the physical features include sediment supply, woody debris, flow regime, depositional features, channel stability ratings, and channel disturbances. Level IV inventory is a validation of level III involving quantitative measurements to verify process relationships. Degrees of departure from the reference site, empirical relationships used in prediction like Mannings "n" derived from velocity, and utilization of gage data to extrapolate hydraulic geometry relationships are level IV type inventories.

Rosgen's classification system uses variables that are directly related to channel forms, processes, and bedload transport characteristics. Rosgen uses a woody debris inventory included in the level III analysis of stream morphology. Rosgen’s I to IV hierarchal river inventory levels provide a comprehensive geomorphic characterization of drainage network, morphological description, stream condition (relative to stability and channel adjustments) and validation to verify data and to develop empirical relationships for a specific stream segment. Rosgen’s recent approach to natural channel restoration offers a contemporary alternative based on natural channel variables and the dimensionless ratios that characterize a desired reference reach condition.

Stream classification is a necessary planning tool to natural channel restoration. Because streams types vary in their bedload transport capability, morphology, and their physical relationship with the floodplain, it is necessary to plan accordingly for that potential. Understanding the stream site potential should be a cornerstone to early phases in channel designs suited to natural stream restoration. Since a natural channel stream typing system is needed for planning and designing desirable features such as channel classification, valley typing, stratification and quantification, a comprehensive geomorphic stream classification system was chosen and used as an integrative part of this study.

Traditional versus Contemporary approaches to channel restoration and characterization

Traditional approaches developed to address stream bank stability and/or complete corridor restoration often lack vital geomorphic attributes such as sinuosity, width-to-depth ratios, meander belt widths, attachment to floodplains, and various natural profile components such as pools, riffles, glides, and runs relative to the channel evolutionary adjustment processes.

Without these attributes, restoration designing to achieve a state of equilibrium (natural stable form) will be ineffective.

In restoration designs, some stream geometries are still being calculated through regime equations. Regime equations are developed by establishing exponents and coefficients for hydraulic geometry formulas determined from data for the same stream. The broad application of regime equations often takes place without the benefit of knowing the geomorphic stream types. The kinds of problems associated with this approach are significant. Regime equations do not account for variations in stream and valley geomorphology. Most regime equations do not account for meander containment, bedload sizes associated with specific conditions of a watershed, and the natural dimensions of a floodplain relative to a specific valley type. The presence of woody debris, by natural recruitment or otherwise, adds another complicated dimension not accounted for in regime equations. If a technician applies a regime equation to a stream not similar to the geomorphic stream site where the equations were developed, the risk of failure is great.

There are some noticeable differences between the traditional fluvial geomorphologic study methods and the research completed in the following chapters. Numerous fluvial geomorphological studies were and still are the more typical morphology-based approaches. Because the term "morphology," as it applies to classification, is often debated, a distinguishable definition is provided. Morphology is described as "*the scientific study of form and structure.*" The Oxford English University Press dictionary, 2003 defines morphology as "shape, form, external structure or arrangement, esp. as an object of study or classification." Examples of morphology-based studies are more descriptive of form and structure. Stream and floodplain characteristics such as cascade form, pool/riffle form, step-pool form, plane-bed form, dune-ripple form, valley form, and stream threaded-ness are all examples of morphological characteristics.

This study involves both morphology and morphometry based data and field surveys, with an emphasis on morphometry. Morphometry is described as the physical dimensions of a (fluvial) object through measurements (Bunte and Abt, 2001). The 2003 Oxford University Press Dictionary defines morphometry as “the art or process of measuring the external form of objects, esp. in *Geomorphology.*” In *A Study of Landforms,* quantification is applied to landscape forms, giving rise to a branch of modern geomorphology know as ‘morphometry’ (Small, 1970). Examples of stream and floodplain morphometry would include field measurements of width to depth ratios, floodprone widths, entrenchment ratios, stream gradients, woody debris, and velocities based on field-sampled roughness characteristics. These physical dimensions must be directly measured on-site. They are valuable ecosystem attributes that support the need to use a stream classification system that expresses the natural morphological variables such as particle size, slope, width to depth ratios, and floodplain attachment.

Distinct quantitative morphological variables of a natural system listed in hierarchal order as well as accurate physical measurements are essential to understanding the relationships between physical and biological components such as benthics, fish, riparian complexity, and plant life. These geomorphic data essential to stream classification are both consistent and reproducible in the field. Geomorphic stream classification provides a valuable link to understanding the relationships of the physical stream parameters and optimal biological conditions.

Greater understanding and knowledge about stream geomorphic types and their various adjustments to watershed or channel disturbances allows restoration practitioners to effectively assess, analyze, inventory and monitor stream courses and make more informed decisions. The descriptions and measured stages of the various departures from natural channel stable potential provided by channel evolution models and geomorphic stream classification compared to reference reach dimensionless ratios, can guide restoration towards worthy goals that benefit society. This study, as detailed in the following chapters, contributes to a greater understanding of geomorphic approaches to natural channel restoration in the North Cascades. Chapters two, three, and four are intended to stand-alone in their content.

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CHAPTER TWO

BANKFULL DISCHARGE IN GLACIAL FLUVIAL STREAMS OF THE NORTH CASCADE MOUNTAINS IN WASHINGTON STATE

Abstract

Because bankfull discharge (long term channel forming flow) is site-specific and restoration and/or stream classification practitioners are highly dependent on bankfull associated dimensions, a more in-depth study was completed in order to assess the practicality of bankfull discharge use on both the east and west slopes of the North Cascade Mountain Range. In the Pacific Northwest, *A Classification of Natural Rivers* developed by Dave Rosgen (1994) has been the focus of much debate concerning the question of bankfull relevance to channel shaping flow and stream restoration. This study is important because hydrologists and restoration technicians alike need to know whether bankfull indicators can systematically and consistently apply to streams on both east and west sides of the North Cascade Mountain Range. Twenty-five stable morphological sites (reference reaches) were randomly located representing 26 percent of the total population on both east and west slope drainages. Sampled streams sites were all located within a distinct valley type referred to as a glacial-fluvial trough. The hydrophysiographic areas within these areas represent 462 square miles on the east slope and 314 square miles on the west slope. The discharge measurements at the 25 reference sites, which include both east and west slopes of the North Cascade, were robust enough to define stream flow ratings and localized regional curves for bankfull discharges. The data indicated that an analysis with the intent of generating regional bankfull curves on smaller hydrophysiographic units in the North Cascades of Washington State is needed in order to acquire a more robust analysis of bankfull dimensions for classification and restoration purposes. Return intervals for bankfull discharge ranged from 1.1Q to 1.4Q.

CHAPTER TWO

INTRODUCTION

Because bankfull discharge (long term channel forming flow) is site-specific and restoration practitioners are highly dependent on the associated dimensions, a more in-depth study is needed to assess the practicality of the use of bankfull discharge on both the east and west sides of the Cascade Mountain Range. Few documented and published studies have been conducted in the Pacific Northwest to validate bankfull discharge. In one such study, Castro (2001) determined that the overall average for bankfull discharges for the entire Pacific Northwest had a return interval of 1.4 years instead of the worldwide average of 1.5 years. The flow associated with a specific return interval of the bankfull discharge within a hydrophysiographic region is an essential factor in stream classification.

In the Pacific Northwest, *A Classification of Natural Rivers* developed by Dave Rosgen (1994) has been the focus of much debate concerning the question of bankfull relevance to channel shaping flow and stream restoration. Bankfull discharge measurements have been successfully used to classify and/or restore streams (Beechie and Silbey, 1990, and Dyrland 2002), while others claim bankfull is inappropriate for a wood dominated and wet hydrophysiographic region common to the west slopes of Oregon and Washington (Miller and Skidmore, 2001). The theme of a number of anecdotal comments from field technicians is that return interval of 1.5 years was used to determine bankfull in Rosgen's system without success and that woody debris makes it inappropriate to use Rosgen's classification on the west side. These same technicians have reported that subsequent classification in Rosgen's system based on measurements at 1.5 bankfull return interval do not accurately fit the streams. Some have speculated that higher amounts of woody debris on west side streams alter stream geometries, negating the underlying assumptions.

Hydrologists and restoration technicians need to know whether bankfull indicators can systematically and consistently apply to both east and west sides of the North Cascade Mountain Range for classification and design. Relevant to classification and design, bankfull discharge is often used interchangeably with two other identified flows or discharges, effective and/or channel-forming. However, their meanings are distinct and should be explained as such because under specific circumstances such as channel incision, bankfull and effective discharge may vary significantly.

Bankfull discharge, as characterized by Wolman (1954), is the dominant discharge that forms the channel. Bankfull stage is described as the point of incipient flooding, at which flow overtops the natural channel and spreads across the floodplain. It is believed that the flow at the bankfull is most effective to carry sediments overtime (Leopold, 1994). Though the formation process of a natural channel is complex, there are quantifiable and consistent patterns for the process, especially at the bankfull stage (Leopold, 1964).

The effective discharge is a quantifiable term. It is used to describe the discharge that is most effective in transporting the bedload over time. The effective discharge is a calculation of sediment curves and frequency of flow return intervals that determine the greatest amount of bedload movement over time.

Channel forming flow is a term used to express a discharge that completes the amount of energy required to maintain a river's general conveyance size and form such as width and depth associated with shaping flow. Bankfull, effective, and channel-forming are all commensurate with the discharge that dominates the shape and pattern of a stream and occur at nearly the same flow return interval in most streams where the floodplains are developed.

Leopold (1994) pointed out an important observation on the Little Snake River near Dixon, Wyoming relevant to bankfull discharge. The study showed that bankfull discharge was nearly the same flow as the effective discharge. Leopold (1994) describes the bankfull discharge stage as the last point of channel capacity before a river reaches the incipient floodstage, thus any discharge greater than bankfull would be defined as a flood event. The amount of sediment carried by the maximum probable flood or a cluster of flood conditions would be small relative to bankfull or effective discharge over time. Andrews (1980) described the effective discharge as the flow that carries the largest amount of sediment over a long period of time. Bankfull stage coincides closely with the effective discharge (Andrews, 1980). In practicality, effective discharge, channel-forming flow, and bankfull discharge coincide at approximately the same return interval and flow. The exception to this would be in incised river systems.

If a river reaches bankfull stage at a constant statistical frequency (recurrence interval), it follows that the floodplain is flooded at a less common frequency. The floodplain is by definition the valley level corresponding to the bankfull stage (Dunne, 1978). Dunne (1978) argued that the bankfull stage corresponds to the discharge at which channel maintenance is most effective; the discharge being that of moving sediment, forming of or removing bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of channels. If a specific interval or a significant cluster of floodstage intervals is to be characterized as channel shaping flow, then why is the current channel so much smaller than some larger flow or the maximum probable flood? To the other extreme, low-flow conditions have little effect on significant bedload displacement, bank features, or floodplain development (Dunne, 1978).

Wolman and Miller (1960) argued that the very large events were too infrequent to govern channel characteristics, though when they did occur, their effectiveness for channel change would be great. Testing the idea by computing the flow size that transports the largest total amount of sediment over the years, Wolman and Miller concluded that the bankfull stage is the most effective or is the dominant channel-forming flow. The most effective channel shaping flow has an average recurrence interval of 1.5 years in a large variety of rivers. The important inference here is Wolman's reference to average, noting that there is variability based on geographic location and hydrophysiography. Because the flow associated with a specific return interval of the bankfull discharge within a hydrophysiographic region is an essential factor in stream classification, it is crucial to understand that bankfull discharge, effective discharge, and channel forming flows are nearly one in the same and the most probable state of a river is directly dependent on its return interval.

In order to appropriately classify, the geomorphic stream classification system developed by David L. Rosgen (1994) is completely bankfull dimension dependent. The classification system groups variables by bankfull morphological similarity to reduce statistical variance.

Reference reach data basing, using characteristics of stable channel morphology for a similar stream and valley type, can provide an integrative approach resulting in a reconstruction of a stream with the stable dimension, pattern, and profile. These design templates (quantitative morphological dimensions) referred to as reference reach database, are based on bankfull discharge dimensions (Rosgen, 1998).

The process of bankfull validation involves tying stream site indicators and channel dimensions to USGS (United States Geological Survey) gages to establish a return interval and hydraulic geometries of width, depth, discharge and cross-sectional area relative to the respective drainage size. Bankfull discharge closely correlates to drainage size (Dunne, 1978). A drainage area delineated to a bankfull determination site is a geographical feature that is easily attainable. Bankfull discharge dimensions from gaged stations can be extrapolated to ungaged reaches by the use of a regional curve providing both sites are within a similar hydrophysiographic province.

On the west slope of the Cascade Mountains, the lack of bankfull validation process and the presence of significant amounts of woody debris may contribute to difficulties in identifying stream types within the Rosgen's hierarchal classification key. This is problematic, as bankfull elevations form the basis for cross-sectional areas and size relationships.

Goals of the Study

The Goals of this study are to quantify, describe, and compare bankfull dimensional flows relative to width, depth, discharge, and cross-sectional area that are used to geomorphically classify streams in glacial-fluvial troughs on both the east and west slopes in the North Cascade

Mountain Range of Washington; to validate return intervals of bankfull discharge in three specific hydrophysiographic drainages in the North Cascade Mountains; and to test and compare bankfull dimensions within specific drainage basins relative to the east and west slopes of the North Cascades relative to drainage area.

Hypothesis

East and west slope drainages have similar, predictable bankfull dimensions relative to drainage areas based on reference conditions.

METHODS AND RESEARCH DESIGN

Study Area

The research area population and sampled sites were located on both east and west slopes of the North Cascade Mountain Range in Washington State (Figures 2 and 3). The Sauk River Drainage is located on the west slope and both the White and Chiwawa Rivers are located on the east slopes. All sites and their relative drainage basins are located between North 47^{o} 51’ to 48^{o}16’ and West 120^{o}38’ to 121^{o}39’. The hydrophysiographic areas within these coordinates represent 462 square miles on the east slope and 314 square miles on the west slope. Elevations on the west slope range from 340 to 10,528 feet above sea level. Elevations on the east slope range from 340 to 8270 feet above sea level. The White and Chiwawa River Basins of the east slope are conjoined along the North Cascade Divide.

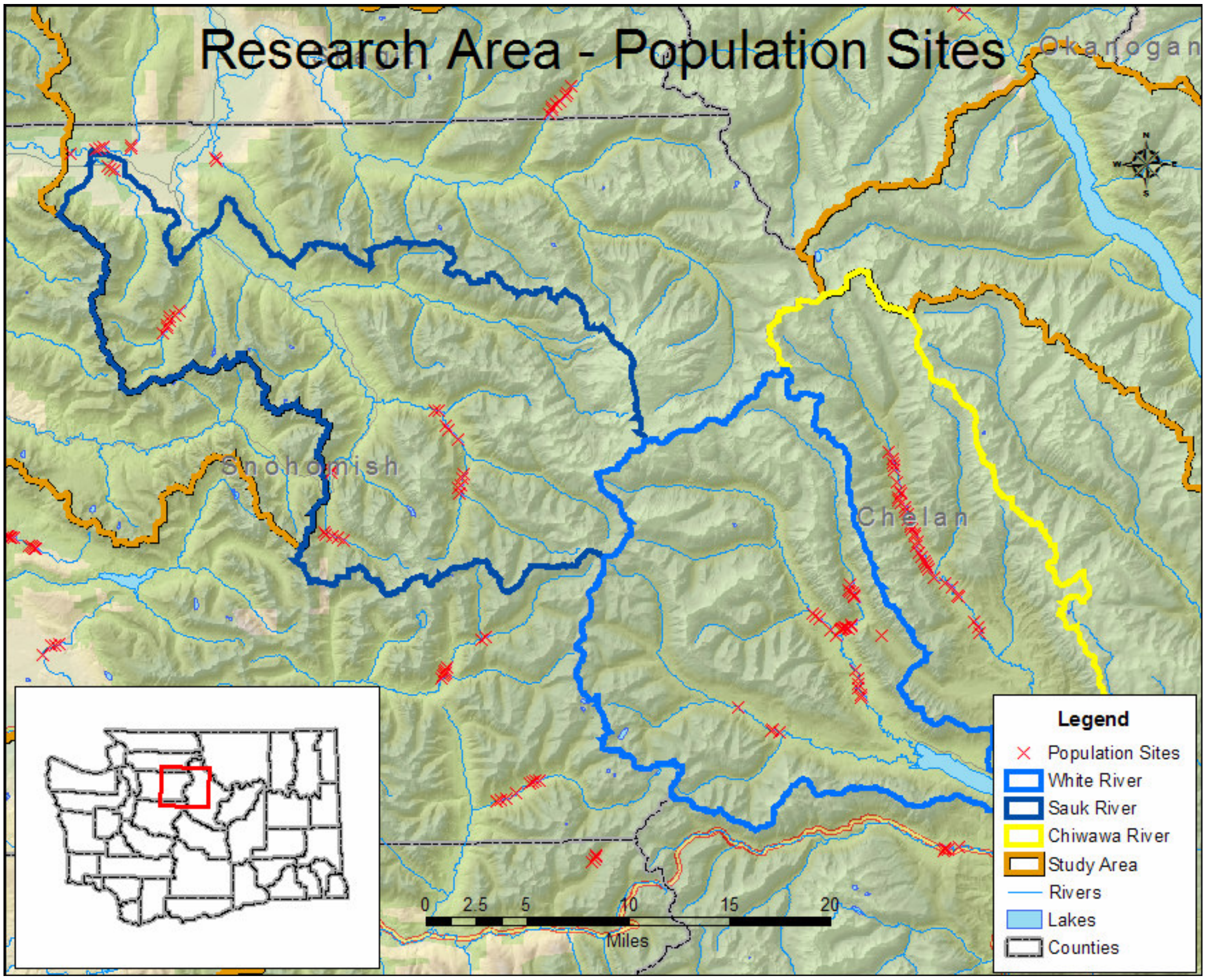

Figure 2. Research area with population sites

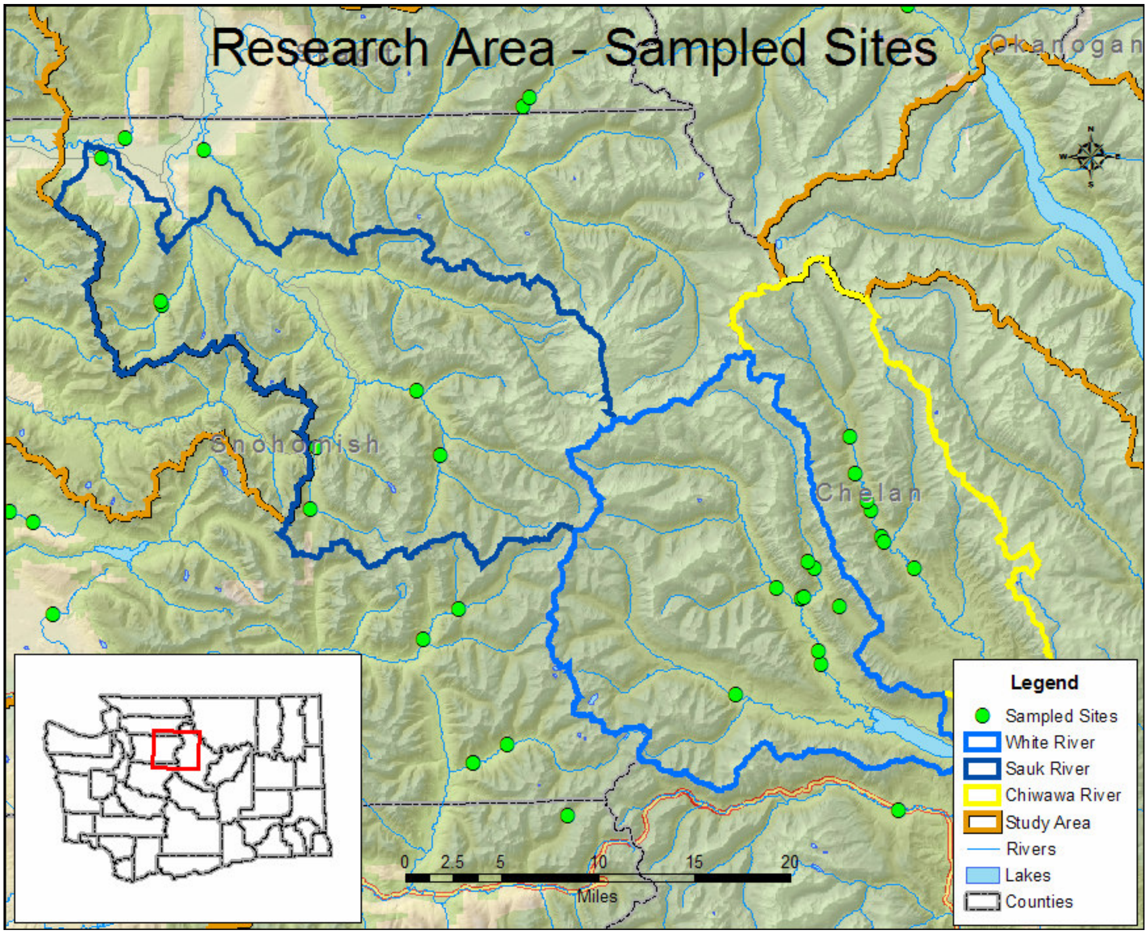

Figure 3. Research area, sampled sites

Climate

The hydrophysiographic areas were typical of North Cascade azimuth, elevation, precipitation, lithology, and valley geomorphology. Annual precipitation in the study areas typically ranges from 12 to 120 inches (304.8 to 3048 mm) on the east slope and 84 to 160 inches (1008 to 4064mm) on the west slope, depending on elevation. Mean minimum and maximum annual temperatures range from 17 to 77 ^{o}F (9.4 to 42.7 ^{o}C) on the west slope and 7 to 87 ^{o}F (3.8 to 48 ^{o}C) on the east slope (Rocky Mountain Clime, 2003.02.19 PRISM Database). The east slope mountain drainages receive a higher portion of the runoff from snowmelt. The west slope is typically more humid with less variation in mean minimum and maximum temperatures than the east slope.

Koppen-Geiger (1930) classification provides a general verbal description used throughout the globe of climatic-hydrophysiographic characteristics such as temperature, precipitation, seasonality, and vegetation. Koppen-Geiger characterizes both east and west slopes of the Cascade Mountains on a broader regional basis. The Sauk River Basin lies within a mesothermal climate characterized as dry summer subtropical marine influence (warm summer). Summer and fall of 2002, the climate of the Sauk River Basin was characteristically, humid and cool but unusually dry in October. The White and Chiwawa Rivers both lie within mountainous ranges on the east slope where microthermal, summer-dry continental and humid continental climates may exist (Jackson, 1992). The Little Wenatchee and White Rivers are two of the eight main tributaries to the Wenatchee River. Both are dominated by a snowfall precipitation regime and as a unit receives 101 inches of mean annual precipitation (310 inches mean annual snowfall) (Prism, 2003.02.19 database).

Washington State's Cascade Mountain Range is largely the product of plate convergence near the spreading ridges of Gorda and San Juan de Fuca. Converging plates and tectonic uplifting produced a steep, narrow continental shelf and rising coastal mountains. From Alaska to northern Washington, the area consists of extensively glaciated ice expansions containing primary coasts punctuated by major westward-draining fjords and U-shaped valleys (Chernicoff, 1999).

Site Selection

Streams were located in glacial-fluvial trough valleys on the east and west sides of the North Cascade Mountain Range in Washington State. Glacial-fluvial troughs were classified as Valley Type V, in Applied River Morphology (1996) (Figure 3 and 4, Appendix C.) Bankfull discharge elevations were attached to floodplain (bank height ratio of 1.2 or less) with two or less channels flowing at bankfull discharge. All sites were located in segments that did not have reservoirs or diversions upstream. All stream sites were morphologically stable and able to consistently transport sediment load, associated with the local deposition and scour and able to develop a stable dimension, pattern and profile so that channel features were maintained and the stream system neither aggraded or degraded (Rosgen, 1996). Streams were wadeable, generally less than 200 feet wide at channel forming discharge and less than three feet on the riffle portion at low flow conditions. All 96 population sites were accessible both by permission and within physical limitations.

Sample sites from the Sauk, White, and Chiwawa Rivers were chosen for three reasons. First, the Sauk, White, and Chiwawa are adjacent drainages located on both the east and west slopes of Cascade Mountain Ridge at the same latitude. Secondly, the delineated study sites of the Sauk, White, and Chiwawa River Basin represent similar kinds of glacial-fluvial trough formations with distinct reliefs that are representative of the east and west slopes of North Cascades in Washington State. And third, the Sauk, White, and Chiwawa drainages had numerous glacial-fluvial trough population sites along with stream segments of stable reference site conditions. Sampled sites were drawn for a 25% proportion of the entire population. The east slope had twice as many reference sites identified and located in its population as did a similar size west slope study drainage area.

Twenty-two ungaged stable morphological reference sites with identifiable bankfull indicators were randomly selected upstream from the four USGS gage sites (Figure 3). Three of the twenty-five sites were selected within three river basin areas where USGS gage sites existed for the purpose of analyzing bankfull return intervals.

Initial investigation of potential sites began in June of 2002 with aerial photography, USGS topological maps, orthophoto quads, shaded relief maps, U.S. Forest Service high altitude photos, FSA-NAPP photos where available, USGS gage data, site visitation and consultation with U.S Forest Service Hydrologists, Geologists, and Fish Biologists. June and July of 2002, Valley Type "V's" were located on aerial photos and orthophotoquads, then reattributed on U.S. Forest Service Topological District maps at a scale of 1 inch = 5280 feet. During initial populations site visitation a Global Positioning System, Garman Map 76, was used to locate and geo-reference all potential research areas. The sampling season lasted six months, from June through December.

Population Size and Selection

Within the Valley Type "V"s, ninety-six population sites where generated and visited in the field to verify whether each site could meet selection criteria. Potential sites were initially identified and labeled by using the name of the stream or river and an alphabetical letter (i.e., White River B). A limited sample size was used due to the limited reference site populations within the three study areas.

The random generation was implemented by using a common six-sided die where the six sides were assigned a corresponding alphabetical letter. After sites were generated from the die; they would be assigned their name and a sequential number (i.e., White River 012). The sequential number followed chronological order of the research season. For example, Little Wenatchee River 005 was the first site to be completed and Sloan Creek 038 was the last site to be completed. Site numbers were not contiguous.

In the random sampling of stream study sites within the valley type “V”, every different sample size “n” from the population had an equal probability of being selected. The goal of the sampling size was to complete 25% of the total site populations of reference reaches within the Sauk, White and Chiwawa River Basins. Twenty-six percent of the total population was sampled (Figure 3).

Site Procedure

Engineer flags and biodegradable paints were used to identify bankfull indicators for a minimum distance of twenty channel widths along the stream profile (Dunne and Leopold, 1978). After consistent indicators were found, bankfull discharge elevation was established at a cross-section. Surveys were performed with laser level equipment, fiberglass tapes, and steel pins. Bankfull discharge return intervals were determined by establishing bankfull indicators and cross-section at USGS gages within the Sauk, White and Chiwawa River Basins.

Particle sizes were measured at intermediate axis as described by C. Harrelson et al, 1994. The size classification was based on the categories developed by Wentworth, C. K., 1922, *A Scale of Grade and Class Terms for Clastic Sediments*. The particles were pulled at one-foot intervals from bankfull to bankfull. Measurements over the cross-section on the riffle were taken directly under a fiberglass tape at the one-foot interval with the use of a metal staff extending from the tape to the particle at a perpendicular angle. The particle sizes in the pools were measured in a heal-to-toe manner at 12-inch intervals at the same perpendicular angle to the streambanks. The pool to riffle ratio was also determined and additional pebble counts were completed relative to their proportions. (For example, 60% pools and 40% riffles may have a representative pebble count of 120 from pools and 80 from riffles.) No less than a hundred particles were measured at each site.

At the 25 randomly selected sites, an average of 29 bankfull widths were measured with a laser (Leica Disto Classic model). The accuracy of the laser Leica Disto distance tool was + or – 5 mm. Because the red laser beam was difficult to locate beyond 50 feet, a Leica 4-power BFT4 ocular attachment was used. Sixteen percent of the bankfull widths were measured with fiberglass tapes and metal pins. No less than 20 bankfull widths were measured at any site. Floodprone widths were measured at an elevation of twice the bankfull maximum depth with a string Chainman II – hip chain accurate to + or – 0.2%. Elevations on floodprone areas were measured by the use of a 5-power Sokkia hand level, and in the few instances that the foliage was not too dense to receive a beam a laser receiver was used.

At each width-transect measurement, woody debris categories of large, medium, or small were measured and recorded. Woody debris size classifications were based on the USFS *Stream Inventory Handbook* (2002). At the same bankfull width transect, the profile morphology consisting of pools, riffles, glides, or runs was recorded. Longitudinal profile glides and runs were combined into the pool portion to compute a pool to riffle ratio to establish proportionally correct pebble counts. A glide segment of the longitudinal bed profile is the reverse gradient leading out of the pool often referred to as the tailout. The run segment is the steepest gradient located immediately below the riffle segment of the longitudinal profile leading into the pool.

Cross-sectional areas, water surface slopes, and portions of the floodprone areas were measured by the use of a laser level (Laser Beacon Model 3900, Laser Alignment Incorporated). Water surface slope was measured through a complete meander wavelength from the same point of profile morphology (i.e. top of the riffle to the top of the riffle).

The thalweg and the straight down-valley lengths were measured over a distance of at least two meander wavelengths. To calculate the sinuosity, thalweg length was divided by the straight, down-valley length (Rosgen and Silvey, 1998).

Discharge measurements at ungaged sites were derived by the use of the relative roughness factor (d/d84), Manning's "n", and the continuity equation.

$$(d/d84) \qquad (1)$$

Where d = depth at bankfull over the riffle and d84 is the 84^{th} percentile sized particle on a log normal distribution.

The relative roughness factor was used to compute a dimensionless friction factor (u/u*) by the following equations:

$u/u^* = (2.83 + 5.7\log(d/d84)$ (2)

(Limerinos 1970 and Leopold , Wolman, Miller 1964).

Where u = velocity, u* = shear velocity, A = Cross-sectional area, R = hydraulic Radius, and S = Slope, V = Velocity

Then: $u = u^*(2.83 + 5.7\log(d/d84)$. u = Velocity (3)

($Q = V$ (or u)* A). Continuity Equation (4)

Where Q = Discharge, V= velocity, and A = Cross-sectional area

Also using a Manning's n value can be solved for an ungaged stream type:

"n" = $1.486/Q * (A) * (R^{2/3}) * (S^{1/2})$. (5)

Where R = Hydraulic Radius and S = Slope

The Manning's value was compared to derived measurement diagrams from (Barnes, 1967) and (Annable, 1997) which show the combined relation of friction factor u/u* to Manning's *n.*

Substrate Analysis

Two types of substrate analysis were completed. A Wolman Pebble count of bed surface size material and the largest mobile particle on the lower 1/3 of the pointbar were measured to a location half way between the thalweg and the bankfull indicator on the pointbar side. Wolman pebble counts, which provide data for characterization of the percent finer than vs. size class plotted on log-normal graphs, were completed at all sites. The proportion of pool to riffle ratios was measured through at least 20-bankfull discharge widths along the profile and samples were gathered relative to the ratio.

Size class percent, slope, and cross-sectional data were measured in the field and estimated by the use of software. Rivermorph (2002) software was used to calculate the field data of particle size distribution, bankfull discharge, and regional bankfull curves. An excel macro developed by Dan Mechlenberg (2001) was also used in the field to aide with on-site data entry from field notes.

For additional analysis and watershed delineation, all geo-referenced sites, both total potential sites and those randomly selected, were transferred from the Garmin Map 76 GPS into the Terrain Navigator Pro Land Mapping software developed by Map Tech Inc. Drainage areas for each of the 22 randomly selected sites were digitally delineated and calculated by the use of the Terrain Navigator 2.0 and Terrain Navigator Pro 6.0 GIS/CAD map export version. Both 2 and 3 dimensional analysis was used to visually validate delineation lines for all of the 25 watersheds. Valley profiles, also referred to as valley cross-sections, were also analyzed using

Terrain Navigator Pro. Terrain Navigator Pro Digital orthophotoquads have one meter resolution.

USGS 9-207 forms include hydraulic geometry measurements throughout a broad range of flows. Forms 9-207 were attained for east and west slope sites from Ray Smith, Hydrologist, at the Spokane USGS office and Darrin Miller, Hydrologist, at the Sedro Wooley USGS office. Peak flow data was downloaded from the USGS and analyzed by a Log-Pearson Type I distribution provided by Rivermorph Computer Software LCC.

The data in the three river basins were analyzed by 1st order simple linear regression models with one or two predictors:

$$Y_i = \beta_0 + \beta_1 X_1 + \varepsilon_I \qquad (5)$$

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \varepsilon_I \qquad (6)$$

Minitab Professional Version 13.31 was used to generate statistics and as an aide in plotting and analyzing data.

RESULTS

Bankfull dimensions are identifiable on both the east and west slopes of the North Cascades in Washington State. With the exception of a drainage area regressed on depth for the west slope of the upper Sauk River Basin, all bankfull dimension parameters have significant slope and correlation coefficient values.

The discharge measurements at the 25 reference sites, which include both west and east slopes of the North Cascades, were sufficient to define stream flow ratings and localized regional curves for bankfull discharges.

In the study area, the average CFSM (Cubic Feet Per Square Mile) of runoff at bankfull discharge on the west slope was 85.5, while the average CFSM of runoff on the east slope was 26.3 including both White and Chiwawa Drainages. Bankfull discharge recurrence intervals on the west slope gages in the study were 1.12Q and 1.15Q. Bankfull discharge recurrence intervals on the east slope gages were 1.15Q and 1.4Q.

First order simple regression models were used to analyze the data. The results summarized in Table 1 show 11 out of 12 p-values within 0.05 and 7 out of 12 correlation coefficient (r^2 values) higher than 0.86. Drainage area versus bankfull depth indicated that drainage area on the west slope is not a reliable predictor (nor field indicator) of bankfull depth. The regression slope is nearly 0.00. All other coefficient signs were positive which is consistent with field observation and conventional bankfull regression analysis.

Table 1. Slope estimates, R^2, sample sizes from simple linear regression using drainage as the predictor. See Appendix B for field data and statistical analyzes.

	Sauk River Drainage West Slope (314.4 m^2)			White River Drainage East Slope (273.4 m^2)			Chiwawa River Drainage East Slope (188.8 m^2)		
Response	Slope (P value)	R^2	n	Slope (P value)	R^2	n	Slope (P value)	R^2	n
X-Section	4.72 (.001)*	91%	7	4.58 (<0.001)	98%	10	2.70 (<0.001)	86%	8
Width	1.59 (0.003)	86%	7	0.72 (<0.001)	86%	10	0.27 (0.029)	58%	8
BFQ	46.49 (<0.001)	96%	7	25.09 (<0.001)	94%	10	14.25 (0.014)	66%	8
Depth	-0.0016 (0.910)	5.2%	7	0.020 (<0.01)	59%	10	0.035 (0.017)	55%	8

No transformations were performed on the data. Plotted regression lines and equations for the data are shown in (Appendix B, Drainage Analyses.)

Results indicate that high correlation coefficients are present for predicted versus actual values for cross-section, width, and bankfull discharge. With the exception of drainage area regressed on depth in the Sauk River drainage, p-values were less than 0.05. Drainage area regressed on depth for both the White and Chiwawa East slope streams had correlation coefficients of 59% and 55%, respectively.

Variations in Bankfull Discharge Return Intervals

Data show that a return interval difference from a 1.1 to a 1.5-year event can have as much as 68% more flow. For example, A Log Pierson type I distribution was generated by use of the Rivermorph Software and USGS peak flows data after acquiring laser grade morphometry on the following four sites:

- Squires Creek USGS Gage 12164500 with 19 years of data, located on the west slope of the Cascade Mountains had return intervals with discharges of 1.5Q = 2710 cfs and 1.1Q = 1600 cfs. The bankfull discharge, which flows at 1610 cfs, was calibrated by bankfull indicators at and near the gage to be a 1.12 return interval. This is a 68 percent flow difference between the 1.5 and 1.12 return intervals.
- Sauk River near Whitechuck USGS Gage 12186000 with 78 years of data located on the west slope of the Cascade Mountains had return intervals with discharges of 1.5Q = 7220 cfs and 1.1 Q = 4970 cfs. The bankfull discharge, which flows at 5140 cfs, was calibrated by bankfull indicators at and near the gage to be a 1.15 Q return interval,. This is a 40% difference in flow between the 1.5 and 1.15 return intervals.
- White River in Chelan County USGS Gage 12553600 with 29 years of data located on the east slope of the Cascade Mountains had return intervals with discharges of 1.5 Q = 4410 cfs and a 1.1 Q = 3440 cfs. The bankfull discharge, which flows at 3570 cfs, was calibrated by bankfull indicators at and near the gage to be a 1.15 Q return interval. This is a 25 % difference in flow between the 1.5 and 1.15 return interval.
- Chiwawa River in Chelan County USGS Gage 12556500 with 28 years of data located on the east slope of the Cascade Mountains had return intervals with discharges of 1.5 Q = 2740 cfs and a 1.1 Q = 1390 cfs. Bankfull discharge, which flows at 2540 cfs, was calibrated by bankfull indicators at and near the gage to be 1.4 Q. This is an 8% difference in flow between the 1.5 and 1.4Q return interval.

The Sauk River at the Whitechuck gage site 12816000 was selected for bankfull determination by indicators and was measured only for bankfull validation. Bankfull indicators and gage data could not be accessed without entering a hazardous portion of the stream course, as the stream was not wade-able in October, 2002.

DISCUSSION AND CONCLUSIONS

The presence of significant amounts of woody debris in both west and east slope streams may be the reason why some individuals find it difficult to accurately and consistently identify bankfull discharge indicators. Another potential problem that may cause misidentification of bankfull indicators is stream stability and its definition. A quantifiable, consistent, and reproducible approach to assessment is necessary for a determination of stream stability. Understanding the environment and natural recruitment and placement of woody debris relative to bankfull indicators is necessary in order to assess stability.

While observing ninety-six potential stable morphological stream types in glacial-fluvial troughs on both the east and west slopes of the North Cascades, it was found that bankfull indicators were more difficult to identify on the west slopes. For this purpose it was necessary to walk and flag nearly thirty bankfull discharge lengths in order to confidently and consistently find indicators. Leopold (1994) and Dunne (1978) recommended an analysis of at least 20 bankfull widths along the studied longitudinal profile.

All reference reach sites within this study were natural stable morphological stream segments within glacial-fluvial troughs. All study sites had bank height ratios of less than 1.1 and reference sites had a consistent presence of bankfull indicators. Yet there were significant measurable differences of bankfull return interval in glacial-fluvial troughs on the east side of the

North Cascades. The Lake Wenatchee drainage basin, which includes both White and Little Wenatchee River drainages, had a return interval of 1.15 for bankfull discharge while the Chiwawa River drainage had a return interval of 1.4 at bankfull discharge. The grouping of these two drainage areas to determine bankfull dimensions could likely result in unreliable bankfull dimensional analysis (different hydrophysiographics). However, the regression cross-section slopes for The Sauk and White River Basins are very similar, 4.72 and 4. 52 respectively, (Table 1). The hydrophysiographic grouping of these two drainages yields a slope of 4.92, a p-value of < 0.001 and an R^2 value of 82.2%. The combined R^2 value is lower than the separate drainage area R^2 values. The consistently higher correlations of the two drainages may indicate that hydrophysiographic units with similar or close bankfull return intervals may have similar slopes. Additional research to include more drainage areas in the Pacific Northwest will be needed to establish bankfull dimensions and return interval.

The data indicate that an analysis with the intent of generating regional bankfull curves on smaller hydrophysiographic units in the North Cascades of Washington State is needed in order to acquire a more robust analysis of bankfull dimensions for classification and restoration purposes. Some grouping of bankfull regional curves from both east and west side slopes will not provide reliable data for bankfull dimensional analysis. When all data from east and west slopes were combined, correlation coefficient values were consistently below 0.12 and p-values were typically above 0.3.

The data support the conclusion that east and west slope drainages in the North Cascades of Washington State should not be combined to develop bankfull regional discharge curves even though there is the temptation to use more sampled data points that may exist on a larger geographical basis. This finding is similar to Castro (2002). The data support the conclusion that when collecting bankfull discharge dimensions in glacial-fluvial troughs of the North Cascades of Washington State, the predictive values of drainage area when regressed on bankfull dimensions must come from a more localized river basin database in order to be robust.

The data also support the conclusion that west slope drainage areas regressed on bankfull depth will not produce a significant regression slope or a correlation coefficient in glacial-fluvial troughs. On the east slope of the North Cascade in Washington State, drainage area regressed on bankfull depths are significant; however correlation coefficients drop to 59% and 55% with p-values below 0.05.

Morphometric and morphologic consistent measures of bankfull discharge will continue to remain a topic of debate. The importance of bankfull dimensions as a measure to derive essential kinds of geomorphic characterizations to river restoration cannot be understated. Geomorphic stream classification, stream channel evolutionary stage of adjustment, and a template for design based on stable reference reach measures called dimensionless ratios are all three bankfull dependent. Field office GIS studies of stream morphology with minimal field validation by technicians are no substitute for laser level accuracy field studies of natural channel morphology.

The field collection and comparison of additional bankfull discharge data from stable reference sites to reliable USGS gages on a river basin should and must continue in order for data to be collectively more robust and for stream classification and river restoration to be successful.

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CHAPTER THREE

STREAM TYPES IN GLACIAL-FLUVIAL VALLEYS ON EAST AND WEST SLOPES OF THE NORTH CASCADE RANGE IN WASHINGTON STATE

Abstract

A study of stream morphology and morphometry on both east and west slopes of the Cascade Mountain Range was completed during the fall and summer of 2002. Fifty-eight glacial-fluvial valley streams were randomly selected from a population of 218 natural stable morphological sites. Twenty-four geomorphic attributes, measured and quantified, were classified using two popular classification systems. All sites fell within both Montgomery and Buffington's 1993 classification and Dave Rosgen's 1994 geomorphic classification. Within the glacial-fluvial troughs, there were significant differences in morphology. For example, woody debris was more plentiful on the west slopes. Geomorphic attributes such as width to depth ratios, sinuosities, depth and percent woody debris were significantly different. Even with the abundance of woody debris, the results showed that both east and west slope streams fell within distinct ranges of variability for geomorphic attributes tested. The overall conclusion is that with exception of bankfull velocities and widths, field measured pool-riffle and plane-bed morphological and morphometric attributes in glacial-fluvial troughs are considerably different on each side of the North Cascades, but the range of variability for each key parameter still rests within both classification systems. When field measurements were used, both classifications were robust.

CHAPTER THREE

INTRODUCTION

Stable morphological rivers within similar glacial-fluvial valley types of the North Cascade Mountain Range have observable patterns and physical attributes which exist within a range of natural variability. These natural variations of morphological features of a riverine system within similar valley types are of considerable interest to field technicians who study, classify, and attempt natural channel restoration. Glacial-fluvial troughs of the North Cascades can vary significantly due to variations in geologic, climatic, vegetative, and anthropogenic induced conditions.

Rosgen (1996) describes glacial-fluvial valley types as the product of glacial scouring where the resultant trough is now a wide, "U" shaped valley with the valley floors generally less than 4% slope. The trough-like valley shape does not have the wider alluvium developed floodplains of the considerably more mature valleys found at lower elevations where fluvial processes have dominated overtime. Soils in the glacial-fluvial troughs are derived from materials deposited as moraines or more recent alluvium from the Holocene period to the present. Landforms locally include lateral and terminal moraines, alluvial terraces, and floodplains (Figures 3 and 4, Appendix C). The streams within the valley type V are predominately pool/riffle morphologies vs. the steeper rapids, cascades, or step/pool morphologies found in the steeper-narrower, more youthful valleys located at higher elevations.

This study is important because more data and analyses about the differences and similarities of east and west slope streams are needed in order to assess stream stability and to appropriately implement natural channel restoration. A keener understanding of the morphological differences in ranges of variability for a similar stream type between east and west slope glacial-fluvial troughs can substantially improve our ability to properly classify streams.

Glacial-fluvial troughs are ubiquitous throughout the entire Pacific Northwest landscape and are often the subject of intense debate regarding management and endangered species. Glacial-fluvial troughs of the Cascades offer a combination of important attributes such as prime habitat for threatened and endangered salmonids species with plentiful woody debris, concentrated anthropogenic activities involving various land uses, and access to naturally stable stream study sites, both relic and disturbed.

Much of the existing literature in the Pacific Northwest discusses woody debris material within the context of generalized morphological patterns, associated biological benefits, and specific integrations as part of a natural channel design. However, data including specific field measured morphology and morphometry on numerous randomly selected glacial-fluvial troughs relative to bankfull discharge are sparse.

A study of the similarities and differences in stream morphology and morphometry on both east and west slopes of the North Cascade Mountains in Washington State was completed over a six-month period during the summer and fall of 2002. Two-sample T-tests were used to analyze the results of fifty-eight glacial-fluvial valley streams randomly sampled from a population of 218 natural stable morphological sites in the North Cascades of Washington State (Figure 4).

The study area is located in the North Cascade Mountain Range in Washington State and included 6,358 square miles. Potential study sites located closer to the Canadian border were restricted due to the 2002 Pasaytan Wilderness fire and limited national park access.

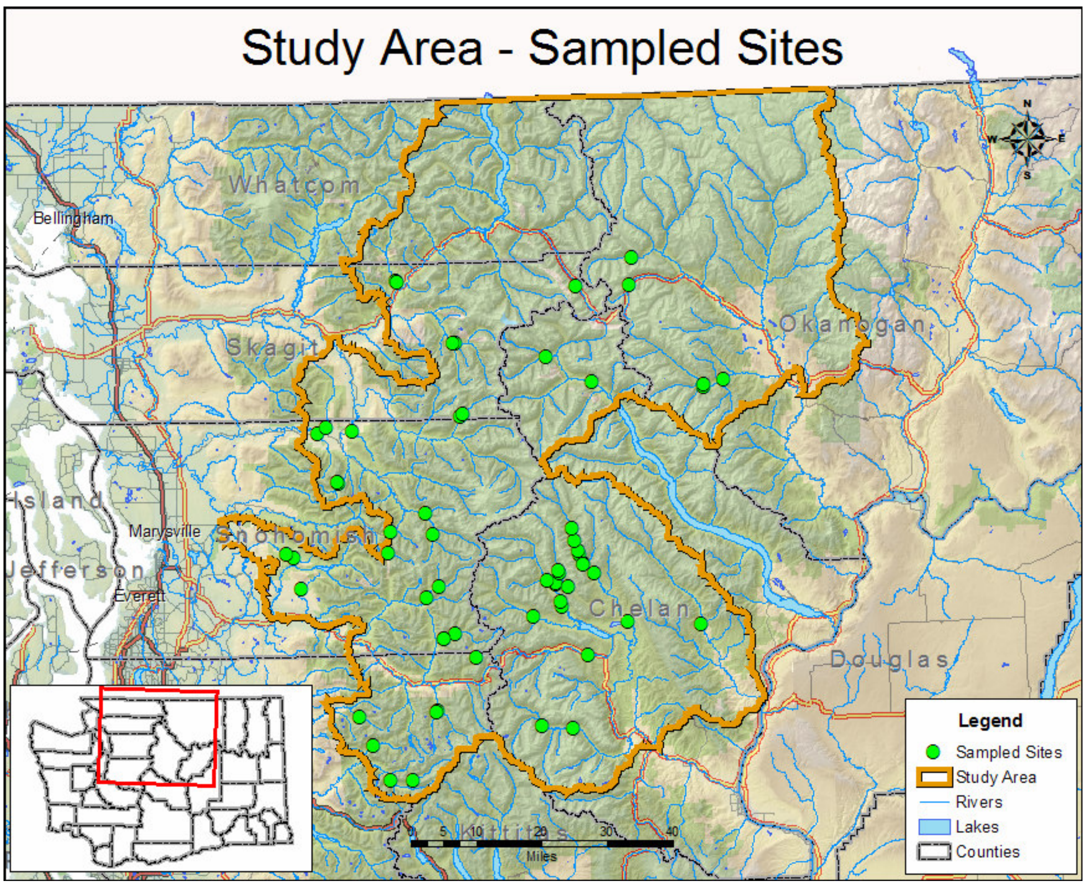

Figure 4. Study area, sampled sites

Glacial-fluvial troughs are some of the most common valley types found in the Cascade Range of the Pacific Northwest. The pool-riffle and plane-bed morphologies in these valley types bear both common resemblances and similar physical attributes such as meander geometry and floodplain development on both the east and west slopes. Plane-bed morphologies have similar slopes to pool-riffle morphologies but lack significant pool features. Glacial-fluvial valleys, or type V valleys, (Rosgen ,1996) with their associated waterways are some of the most important geomorphic features on the landscape and were chosen for several important reasons.

They are substantial reposits of woody debris, native seed source, spawning sized gravels and various detritus in the active channels and floodplains from the contributing watershed. They offer significant resting and hiding habitat for rare and endangered fish species such as spring chinook and bull trout. Steelhead, resident trout populations and other important native species are abundant too.

They are the first valley types from higher to lower elevations to appear as having both substantial and noticeable floodplains with considerably more sinuous stream channels, most often well-connected with their floodplains. It is common for them to be severely disturbed since early European-descent settlement times. The kinds of disturbances in glacial-fluvial valleys that have largely taken place in the last century are stream straightening for road and bridge building, over harvesting of timber in the uplands and riparian areas, clearing and snagging of woody debris for channel conveyance maintenance, and realigning stream channel for agricultural uses such as orchardland or hayland. However, restoration and or improved management of streams within the valley type V are common.

Glacial-fluvial valleys provide a larger study population and the highest amount of stable natural morphological reference sites with pool-riffle and plane-bed and other stream morphologies, despite perturbations. Other valley types at lower elevations had considerably more development and stream course alterations. As a result, the population of natural stable morphological sites were far too few in the more geomorphically mature valleys found at lower elevations.

Goals of the Study

The Goals of this study are to measure, quantify, and classify geomorphic stream types within glacial-fluvial troughs and compare values from both the east and west slopes of the North Cascade Mountain range of Washington State for the purpose of statistical comparison; to measure and compare the impacts of woody debris abundance for both east and west slope and analyze their impacts on stream classification and stable morphological reference stream sites; and, to compare and test east and west slope geomorphic parameters that are commonly used for hydraulic analysis and stream classification.

Relevant Research

One of the first well-known authors to talk about geologic and climatic attributes of a valley that could impact the form and extent of a riverine system was W. M. Davis (1899). Davis argued that changes of valleys are relative to ages, which he generally described as youthful, mature, and old age (Davis, 1902). These were stages of adjustment generally described from a higher to a lower elevation. Davis argued that the older valleys had considerably more developed floodplains. Davis wrote about how streams seek base level and the process of grade change and valley incision continues until they reach sea level, which is the ultimate base level. Davis recognized the important morphological characteristics of valley types and how the various valley types would manifest specific stream types with varying degrees of floodplain development.

Another leading contributor to the study of valleys and stream geomorphologies was Gilbert (1909). Gilbert made significant contributions to the concept of slope profiles within a valley and contributing tributaries. Gilbert's basic premise of a convex slope formation on a longitudinal profile was innovative. He proposed the idea that hillslope forms are dependent upon discharge and various slopes associated with sediment transport. Gilbert's work was highly applicable to small contributing hillside tributaries. These hillside tributaries are an integral geomorphic feature that contributes to the overall valley form. Both Davis's and Gilbert's theories are identifiable features on the geomorphic landscape that provide an excellent analysis of glacial-fluvial processes in many valleys located in the Cascades of the Pacific Northwest and throughout mountain ranges elsewhere.

Leopold (1964) observed that channels differ in shape depending not only on the size of a river, but also on climatic-geologic setting. This observation has been the focus of contemporary scientists interested in organizing streams into classification units, and is the focus of this study as well. From June of 2002 to December of 2002, streams on the west and east slopes of the North Cascades were studied and differences were measured, compiled, and analyzed for the purpose of applying geomorphic-based stream classification systems. The study herein is limited to a broad category of streams referred to as pool-riffle or plane-bed morphologies in glacial-fluvial troughs. The pool-riffle and plane-bed streams are sometimes referred to as depositional or response segments by D. Montgomery and J. Buffington (1993). In Rosgen's classification, pool/riffle and plane/bed morphologies are most closely associated with a well-developed floodplain and gentler slopes. Slopes typically range from 0.1% (0.001 ft/ft) to 2.0% (0.02 ft/ft).

Prior to anthropogenic uses by European settlers, the glacial-fluvial troughs of the North Cascades were in a relatively pristine, natural stable morphological state where most of the adjustments were caused by or relative to natural disturbances such as fire, plate tectonic movement, and/or *Castor canadensus*, commonly known as the Rocky Mountain Beaver. When natural barriers to anadromous fish were not present, mature streams within the glacial-fluvial troughs were highly productive habitats for salmonids such as spring chinook and steelhead of the Pacific Northwest Sedell (1997). Bull Trout, a char species, and numerous other native species were present in similar kinds of glacial-fluvial valley habitats. In 2003, all three of these species were found to still exist within stream courses located in glacial-fluvial troughs of the North Cascades of Washington (as recorded in this study).

Since 1994, there has been much debate over the application of geomorphic-based stream classification systems to the Cascade Mountain Range in the Pacific Northwest. Beechie and Silbey evaluated Dave Rosgen's 1985 classification system (GTRM –120 Rocky Mountain). Rosgen's 1985 classification was presented for the first time at the First North American Riparian Conference in Phoenix, Arizona. Beechie and Silvey concluded that the results of all three sampling techniques show that without considering other hierarchal classification levels, Rosgen's segment types stratify physical habitat with moderate success.

Rosgen's classification system, published in the Catena Journal in 1994, was considerably more refined than the 1985 classification. The 1994 geomorphic stream classification was a hierarchal geomorphic stream classification system including both morphologic and morphometric measures based on bankfull discharge. Streams were stratified into distinct categories based on entrenchment ratios, width to depth ratios, sinuosity, slope, and bed material sizes organized into six commonly recognized classes as described by Wentworth (1922).

METHODS AND RESEARCH DESIGN

Criteria for Site Selection:

Sites were located in glacial-fluvial trough valleys on the east and west sides of the North Cascade Mountain Range in Washington State. The glacial-fluvial troughs were classified as a Valley Type V, according to Applied River Morphology. Channel forming flow (bankfull discharge flow) and floodplains were connected, i.e. streams were not entrenched. Stream sites had two or less channels at bankfull discharge and were not located below reservoirs or upstream diversions.

All sites were morphologically stable, by definition, which means the stream must be able to consistently transport its sediment load, both in size and type, associated with the local deposition and scour and the stream must be able to develop a stable dimension, pattern and profile such that over time, channel features are maintained and the stream systems neither aggrades or degrades Rosgen (1996). Overall, streambank root cohesion and toe stability were required to be consistent with the Rosgen (1996) definition.

Sites had to be wade-able streams, generally, less than 200 feet wide at channel forming discharge and less than 2.5 feet on the riffle portion at low flow conditions. Sites needed to be accessible both physically and by permission of landowners.

Site Selection

Initial investigation of potential sites began with aerial photography, USGS topological maps, orthophoto quads, shaded relief maps, U.S. Forest Service high altitude photos, FSA-NAPP photos where available, USGS gage data, site visitation, and consultation with U.S Forest Service hydrologists, geologists, and fish biologists (Tom Robison, Rick Edwards, Matt Karr, and Phil Archibald) personal communication, June, 2002). June and July of 2002, Valley Type "V"s were located on aerial photos and orthophotoquads then reattributed on Forest Service Topological District maps at a scale of 1 inch = 5280 feet. A Global Positioning System, Garman Map 76 was used to locate and geo-reference research areas during initial visitation to sites.

Within valley type V's, 218 potential sites where generated and visited in the field to verify whether each site could meet selection criteria. Potential sites were initially identified and labeled by using the name of the stream or river and an alphabetical letter (i.e., White River B). The random generation was implemented by using a common six-sided die, where the six sides were assigned a corresponding alphabetical letter. After sites were generated from the die they would be assigned their name and a sequential number (i.e., White River 012). The sequential number followed chronological order of the research season. For example, Entiat River 001 was the first site to be completed and Lennox Creek 060 was the last site to be completed.

Population Size and Selection

Initially, thirty sites on each side of the North Cascade Range were chosen to approach a more normal distribution. With the assumption that the population is not heavily skewed and sample sizes (n) are 30 or more, populations tend to have a more normal distribution according to the central limit theorem. Studies have been conducted over the years and the results of these studies suggest that, in general, the Central Limit Theorem holds true for $n > 30$. (Ott and Longnecker, 2001). In the random sampling of stream study sites within the valley type V, every different sample size n from the population had an equal probability of being selected.

Sixty-one sites, 30 from the east side and 31 from the west side, were randomly generated and sampled from the 218 potential sites (Figure 4). Three sites from the east side were eliminated because after a more complete analysis of the randomly sampled sites, they did not meet the selection criteria outlined above. Because of work season limitations and forest fires, three additional sites on the east side and two from the west side were not generated. The final site selection included 27 from the east side and 31 from the west side. Of the 58 sites selected, 10 were on private land, 1 was on Chelan County Trust Land, 3 on Washington State owned land, 2 on National Park Service land and 40 on United States Forest Service land. Permission was granted from ownership entities prior to ingress and keys to locks were obtained.

Site Procedure

Geomorphic stream dimensions were measured to laser grade accuracy. Engineer flags were used to identify bankfull indicators for a minimum distance of twenty channel widths measured along the stream profile (Leopold, 1994). After consistent indicators were found within this longitudinal distance, bankfull elevation was established at a single thread riffle cross-section located near the midpoint of the reach study length. A single-thread channel on a riffle was necessary in order to use a consistent slope at the bankfull cross-section.

On each stream, particle sizes were measured directly under the fifty-eight riffle cross-sections at the intermediate axis (Harrelson, 1994). Cross-sections and water surface slopes were measured in the same manner as described in Harrelson (1994). The pool to riffle ratio was also measured and additional pebble counts were completed relative to their proportions, i.e. 60% pools and 40% riffles may have a representative pebble count of 120 from pools and 80 from riffles (Wolman, 1954) and (Harrelson, 1994). No less than a hundred particles were measured at each site. A total of 12,268 particles ranging from silt to boulders were measured at the 58 randomly selected sites. An additional 174 particles were measured on the lower one-third portion of the pointbar feature immediately below the measured riffle cross-section.

The size classification was based on the categories developed by C.K. Wentworth (1922.) The pebbles were pulled and measured at one-foot intervals from bankfull to bankfull at an angle perpendicular to the streambank. Measurements over the cross-section on the riffle were taken directly under a fiberglass tape at the one-foot interval. The particle sizes in the pools were measured in a heal-to-toe manner at one-foot intervals at the same perpendicular angle to the streambank. The particle size sampling technique used was a modified Wolman procedure (Wolman, 1954).

At the 58 randomly selected sites, an average of 29 bankfull widths (minimum 20 widths) along the longitudinal profile were measured with a laser Leica Disto measuring distance tool (Classic model). The accuracy of this instrument was + or – 5mm. For bankfull widths beyond 50 feet, a Leica 4-power BFT4 ocular was attached to the classic for improved accuracy. Sixteen percent of the bankfull widths were measured with fiberglass tapes and pins. Floodprone widths were determined by an elevation of twice the bankfull maximum depth with a string Chainman II – hip chain, accurate to + or – 0.2%. Elevations on floodprone areas were surveyed by the use of a 5 power Sokkia hand level. A laser-surveying receiver was used in the some instances when foliage was not too dense to receive a beam from the laser plane.

At each width- transect, woody debris categories of large, medium, or small were recorded. At the same bankfull width transect, the profile morphology consisting of pools, riffles, glides, or runs was recorded. A glide segment of the longitudinal bed profile is the reverse gradient leading out of the pool often referred to by fish biologists as the tailout. The run segment is the steepest gradient of the longitudinal profile leading into the pool. Glides and runs were combined into the pool portion to calculate a pool to riffle ratio to establish proportionally correct pebble counts.

Cross-sectional areas, water surface slopes, and portion of the flood prone areas were measured by the use of a laser level, Laser Beacon model 3900 built by Laser Alignment

Incorporated. Laser Beacon model 3900 was used to measure all but site 001, which was surveyed by a total station. Water surface slope was measured through a complete meander wavelength from the same point of profile morphology (i.e. top of the riffle to the top of the riffle).

Stream sinuosity was measured by two different procedures. In the first procedure, the actual or true stream sinuosity (K) relative to the valley length was measured from digital orthophoto-quads (1 meter resolution) using Terrain Navigator Pro Software, and U. S. Forest Service high altitude photos using a digital Scalex Plan Wheel. Most of the digital orthophoto quads were flown in 1998. The thalweg and the straight down-valley lengths were measured over a distance of at least two meander wavelengths. Thalweg length was divided by the straight down-valley length to calculate sinuosity, (Rosgen and Silvey, 1998).

A second procedure, which is referred to as the segment sinuosity procedure, was accomplished on-site by using chainman II measurements of both the thalweg and the straight down valley line between two channel pin points at a distance of at least two meander wavelengths passing midpoint through the laser- measured cross-section. The distance of the thalweg was divided by the straight-line distance between the two points. Distinct stream profile morphology points were used to begin and end the measurement through the wavelengths, i.e. from the top of the riffle to the top of the riffle.

Fish use of habitat within each study segment was assessed by visual observation of live fish, counts of dead carcasses of spawners, and counts of color-coded tagged redds. In most cases, fish inventory technicians from the Washington State department of Fish and Wildlife, and the USFS had counted and tagged redds in 2002 prior to site selection.

When large woody debris jams were present (especially on meander bend jams), fish counts as well as bedload particle size collections were achieved by using a drysuit and diving snorkel. When diving beneath the water, a bucket was used to collect particles along a set pebble count line transect.

Woody Debris Measurements

Woody debris measurements were based on size classes outlined in the U.S. Forest Service Stream Inventory Handbook (2002).

Woody debris size classes for Eastside Forests (East of the High Cascades) are as follows:

* Small = Diameter > 6 inches, at a length of 20 feet from the large end
* Medium = Diameter > 12 inches, at a length of 35 feet from the large end
* Large = Diameter > 20 inches, at a length of 35 feet from the large end

Woody debris size classes for Westside Forests (West of the High Cascades) are as follows:

* Small = Diameter > 12 inches, at a length of 35 feet from the large end
* Medium = Diameter > 24 inches, at a length of 50 feet from the large end
* Large = Diameter > 36 inches, at a length of 50 feet from the large end

A pace transect along the longitudinal profile with distances close to the average bankfull discharge width was used to sample woody debris. If woody debris did not exist at these points, the transect point was listed as No Woody Debris (NWD).

Substrate Analysis

Two types of substrate analysis were completed. A Wolman Pebble count of bed surface size material (Wolman, 1954) and the largest mobile particle on the lower 1/3 of the pointbar were measured at a location half way between the thalweg and the bankfull indicator on the pointbar side. A percent finer than vs. size-class plotted on lognormal graphs was completed at all sites. The proportion of pool to riffle ratios was measured through at least 20-bankfull discharge widths along the profile and samples were gathered relative to the ratio.

Bedload sized class percentages, slope, and cross-sectional data were estimated both in the field and by the use of software. Rivermorph, L.L.C. Software (2002) was used to provide calculations of field data such as particle size distribution and regional bankfull curves, Log Pierson I analysis of flood frequency, and hydraulic geometries. An Excel macro developed by Dan Mechlenberg was also used in the field to aide with data entry of the field notes (Mechlenberg, 1999).

Date Source, Hardware, and Software Uses

Watersheds were digitally delineated and calculated by the use of both Terrain Navigator 2.0 and Terrain Navigator Pro 6.0 GIS/CAD map, Terrain Navigator (2002 and 2003). Both two and three-dimensional analysis was used to visually validate delineation lines for each of the 58 watersheds. Valley profiles, also referred to as valley cross-sections, were also analyzed using Terrain Navigator Pro. All study sites, both total potential sites and those randomly selected, were transferred from a GPS unit into the Terrain Navigator Pro Land Mapping software for location and additional analysis.

RESULTS

Table 2 shows an overall summary of two-sample T test results of 24 specific attributes for both east and west slope comparisons. Table 3 provides specific definition for each measured and tested attribute.

Table 2. Summary of Two-Sample T Test Results and Classification of all 58 North Cascade Stream Sites.

Cascade Study	**Two Sample T-Test on East versus West Attributes**							
Geomorphic Attribute	**E vs W P-Value**	**East 95% C.I.**		**West 95% C.I.**		**Standard Error**		**Rosgen Range**
		Mean	**Lower Upper**	**Mean**	**Lower Upper**	**East**	**West**	**Glacial Fluvial**
W/D Ratio Average in Segment (ft/ft)	0.003	25.7	21.98 29.42	34.2	30.67 37.73	1.9	1.8	12-40 Glac. Fluv.*
Entrenchment Ratio (ft/ft)	0.018	5.56	4.40 6.76	3.85	3.11 4.59	0.59	0.38	2.2-31.6*
Floodprone Width (ft/ft)	0.027	566	385.7 746.3	340	281.2 398.8	92	30	**
Cross-Section Area at Bankfull Q (ft^2)	0.037	350.8	278.28 423.32	258.3	217.14 299.46	37	21	**
Average Bankfull Width (ft)	0.992	91.0	77.28 104.72	90.9	80.9 100.9	7.0	5.1	**
Average Bankfull Depth (ft)	0.001	3.69	3.26 4.12	2.75	2.52 2.99	0.22	0.12	**
Sinuosity (ft/ft)	0.000	1.62	1.47 1.77	1.26	1.22 1.30	0.078	0.021	1.2-2.8*
Slope (%)	0.061	0.61	0.38 0.84	0.89	0.72 1.06	0.12	0.088	0.1-2.0%*
(u) Velocity (FPS)	0.305	5.47	5.06 5.88	5.18	4.83 5.53	0.21	0.18	**
BFQ estimated by relative rough.	0.027	1914	1493 2335	1351	1088 1614	215	134	**
d/d84	.004	8.8	3.12 14.48	6.1	4.42 7.79	2.9	0.86	**
u/u*	.001	8.67	7.81 9.53	6.75	6.18 7.32	0.44	0.29	**
D84 Riffle (mm)	0.027	129	89.3 168.2	196	152.9 239.1	20	22	**
D50 Overall (mm)	0.098	46.3	32.38 60.20	64.5	48.62 80.38	7.1	8.1	>.062mm*
Largest Particle Transported on Lower 1/3 Bar (mm)	0.01	212	151.2 272.8	328	269.2 386.8	31	30	**
Drainage Area (m^2)	0.000	90.2	66.68 113.72	29.3	22.05 36.55	12	3.7	**
Woody Debris (%)	0.000	30	24.9 35.1	57	51.7 62.3	2.6	2.7	**
LWD (%)	0.350	3.8	1.06 6.54	5.5	3.15 7.85	1.4	1.2	**

Table 2. Continued

Geomorphic Attribute Continued	E vs W P-Value	East 95% C.I.		West 95% C.I.		Standard Error		Rosgen Range
		Mean	Lower Upper	Mean	Lower Upper	East	West	Glacial Fluvial
LWD & MWD (West) vs. LWD (East)	0.000	3.8	3.53 3.83	31	30.9 31.1	.014	.027	**
MWD (%)	0.000	11.6	8.46 14.73	25.2	21.48 28.92	1.6	1.9	**
SWD (%)	0.000	12.9	10.16 15.64	26.7	23.37 30.03	1.4	1.7	**
Ft^3 per Square Mile	0.000	24.6	20.88 28.32	59.0	47.83 70.17	1.9	5.7	**
Ft^2 of cross section per sq mile	0.000	4.51	3.942 5.078	11.55	9.394 13.706	0.29	1.1	**
Elevation	0.000	2324	2152 2496	1594	1318 1870	88	141	**
Rosgen Classification		**All 58 streams fit within classification key**						
Montgomery and Buffington Classification		**All 58 streams fit within classification key**						

- *Indicates 95% Confidence Interval within Rosgen Range
- ** Not Applicable
- Upper limits of classification key described in data base in Rosgen (1996).

Table 3. Geomorphic Attributes Tested and Definitions

Geomorphic Attributes Tested	Definition
W/D Ratio Average in Segment (ft/ft)	(BFW/mBFD) Bankfull width divided by the mean bankfull depth
Entrenchment Ratio (ft/ft)	(FPW/BFW) Floodprone width divided by bankfull discharge width
Floodprone Width (ft/ft)	Width of the commonly flooded area above the bankfull channel. A measure of the valley width at and elevation of 2 times the bankfull maximum depth.
Cross-Section Area at Bankfull Q (ft^2)	The Square feet measured at a cross-section relative to bankfull elevation
Average Bankfull Width (ft)	Average Bankfull Width (Average width throughout two meander wavelengths (20 channel widths or more)
Average Bankfull Depth (ft)	Average Bankfull Depth (Average depth throughout two meander wavelengths (20 channel widths or more)
Sinuosity (ft/ft)	(Thalweg distance/straight distance) thalweg length divided by the straight down-valley length.
Slope (%)	(Rise/Run) slope measured and computed through meander wavelength where cross-section was completed.
(u) Velocity (FPS)	Velocity in Feet-Per-Second determined at cross-section for bankfull flow using relative roughness and friction factor to derive a Manning's N value.
BFQ estimated by relative rough.	(Velocity x cross-section area -continuity equation) velocity times cross-section at bankfull discharge stage estimate by relative roughness
d/d84 (Relative roughness)	Bankfull depth/d84th percentile and a log normal distribution at the cross-section Relative roughness
u/u* (friction factor)	(Velocity/shear velocity) derived by relative roughness (List equation)
D84 Riffle (mm)	D84th percentile directly underneath bankfull cross-section on the upper 1/3 of the riffle
D50 Overall (mm)	D50 medium size particle on the entire reach relative to percent pool/riffle
Largest Particle Transported on Lower 1/3 Bar (mm)	The medium access (sieve passing) largest particle moving on the lower 1/3 end of the point bar below the measured bankfull cross-section
Drainage Area (m^2)	Square miles of watershed contributing runoff to the cross-section
Woody Debris (%) (0.00)	The percent counted of large, medium and small woody debris of at least two meander wavelengths at the study site.

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Table 3. Continued

LWD (%)	Percent of Large Woody Debris counted within each study segment (see methods for size class and procedure).
LWD & MWD (West) vs. LWD (East)	Percent of both large and medium woody counted on the west side study sites compared to large woody debris counted on the East side.
MWD (%)	Percent of medium woody debris counted within each study segment (see methods for size classes and procedure).
SWD (%)	Percent of small woody debris counted within each study segment (see methods for size classes).
(CFSM) Ft^3 per Square Mile at BFQ	(Ft3/drainage area) Bankfull discharge divided by watershed size contributing to measured bankfull cross-section
Ft^2 of cross section per sq mile at BFQ	(Ft^2/Drainage Area) Square feet of cross-section per square mile of contributing drainage
Elevation	Elevation at cross-section

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Within the glacial-fluvial troughs of the North Cascades in Washington there are significant differences relative to morphology. Woody debris was observed to be considerably more plentiful on the West slope with the exception of the two Stehekin River sites. The 58 sample sites were plotted for width to depth ratio vs. % woody debris and depth vs. % woody debris. Figures 5 and 6 illustrate the pattern of woody debris occurrence on west vs. east slope streams. There are significant trends in stream morphology when % woody debris is plotted against bankfull width to depth ratio, and depth. The width to depth ratios significantly increase relative to percent of woody debris.

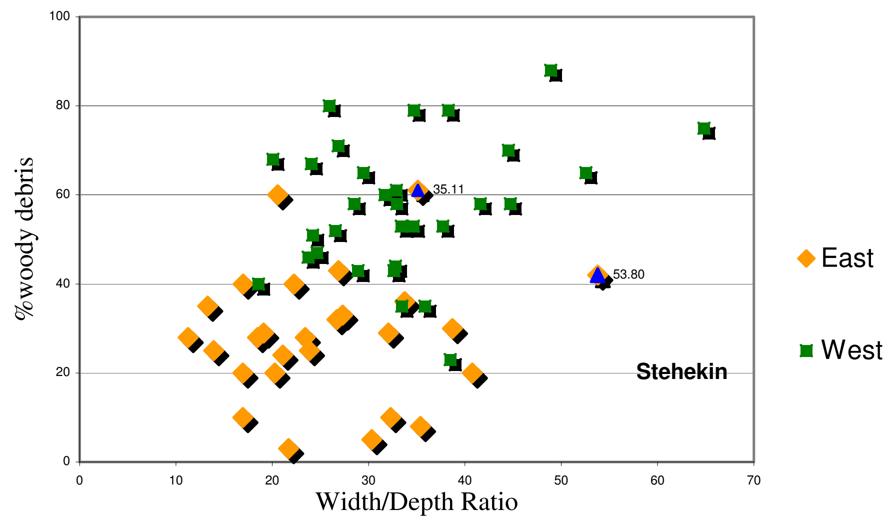

Figure 5. W/D Ratio vs Woody Debris

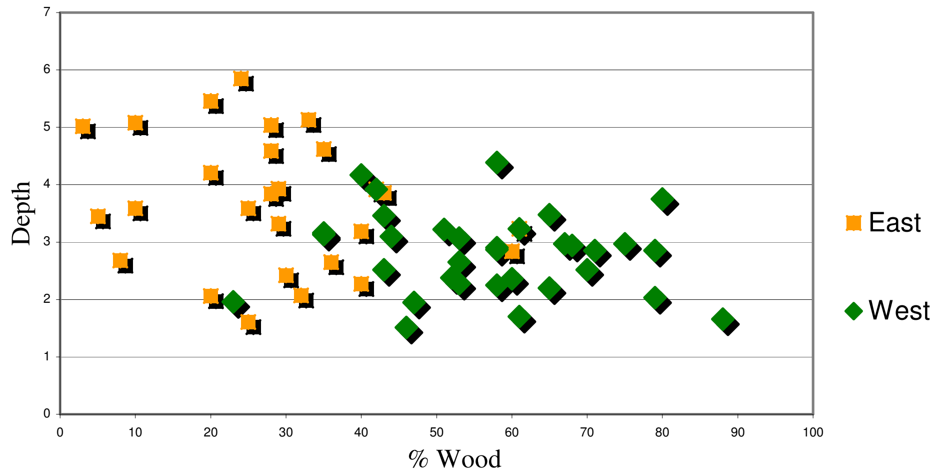

Figure 6. Depth vs Woody Debris

In Figure 6, there is an inverse relationship between depth and percent woody debris. The west slope streams have less depth with more woody debris. There is a direct correlation between percent woody debris and width/depth ratio with the west slope showing consistently higher values for both attributes. The west slope has higher percentages of woody debris yielding higher width to depth ratios. The two significant outliers on the east slope are both Stehekin River sites (as indicated in Figure 5 by the two east slope markers with triangles within and in Figure 6 with the two square markers to the far right).

Woody debris and depth at bankfull discharge have a consistent relationship that is illustrated with Figure 5 results. In Figure 6, with the exception of the two markers with the highest percentage of woody debris, the east slope streams are deeper with lower percentages of woody debris. The east slope outliers are both Stehekin River sites.

When tested, bankfull width and velocity on east and west slopes were not significantly different. Large Woody Debris (LWD) is not significantly different on east and west slopes by the Region 6 USFS definition USDA (2002). As stated in the methods, large woody debris has smaller size classification criteria on the east slope. Medium size woody debris classification on the west slope is larger than the east slope. When west slope categories of medium and large woody debris were combined there is a significant difference between the east and west slope LWD recruitment into streams. When both the large and medium woody debris were combined on the west slope, which was 24 inches and larger at fifty feet from the large end, and tested against the LWD only for the east slope, which was 20 inches and larger at thirty-five feet from the large end, the p value in the two-sample T test was 0.000. The mean for LWD and MWD combined on the west slope was 31% while the mean of LWD on the east slope was 3.8%. The standard deviations on the west and east slopes are 15% and 7.1% respectively. Bankfull velocities and widths are similar.

CONCLUSION AND DISCUSSION

The more humid, less variable temperature climatic conditions of the west slopes grow larger forest trees. Recruitment of larger trees into streams within each woody debris size classification criteria is higher on west slope streams. Stream habitat and physical features are profoundly affected by this material. The data indicates that both larger debris classification criteria and higher percentages of woody debris are consistent with higher width to depth ratios on the west slopes. Higher width to depth ratio streams with abundant woody debris would have a greater resistance to flow, thus a greater roughness factor.

The mean west side water surface slope is 0.0892 ft/ft (0.89%) compared to the mean east side water surface slope of .0618 ft/ft (0.62%). Despite the higher water surface slopes, mean friction factors (based on bedload) were lower on the west slope, resulting in higher Manning's roughness coefficients. Friction factor averaged 28% greater on the west slope. Mean Manning's roughness coefficient on the west slope was .039 compared to .030 on the east slope streams, a 30% difference.

The overall conclusion is that with the exception of bankfull velocities and widths, pool-riffle and plane-bed morphologic attributes in glacial-fluvial troughs are considerably different on each side of the North Cascades. However, the range of variability for each key parameter still rests within both classification systems. Therefore, fifty-eight out of fifty-eight stream sites found a distinct place within both Rosgen's and Montgomery's classification systems. Fifty-five out of fifty-eight streams were classified as major stream types within Rosgen's classification system. Only three stream sites had additional subscript letters due to flatter slopes on B morphologies. When field measurements were used, both classifications were robust.

Relevant to stream classification**,** woody debris is a major physical attribute impacting west side streams in several important ways. Width-to-depth ratios are higher on the west slope streams. Sinuosity values are lower on the west slope streams. The channel roughness characteristics are greater on the west slope streams, but the abundance of woody debris does significantly slow bankfull discharge velocities when compared to the east slope streams. The data also shows that the streams on the east slopes have greater variability among most of the 24 tested attributes.

Field data and personal observations are consistent with the conclusion that the two outlying Stehekin River sites, analyzed for many of the 24 attributes in Table 1, behave and appear much the same as a west side river despite the fact that the river is located on the east slope (Phil Archibald, USFS-Fish Biologist, Jennifer Molesworth USFS- Fish Biologist, Reed Glesne, North Cascade NPS Fish Biologist, and Jon Riedel North Cascade NPS Geologist, personal conversations, July, 2002). This statistical pattern may be due to the similar hydrophysiographic, climatic, woody debris growth and recruitment characteristics of the Stehekin drainage.

The paradigm of more woody debris impeding bedload transport resulting in smaller sized bedload movement may be shifting toward a larger overall sized bedload material despite the fact that backwater eddy induced by woody debris produces small sized bedload material in the immediate downstream vicinity. It is possible that the presence of substantial streambank root matrix and cohesion may be the reason that woody debris, in a reference site condition, actually stabilizes and facilitates the bedload transported at bankfull discharge. In glacial-fluvial valley type streams with unstable banks, a greater source of fine bedload is continuously being deposited at a high rate of delivery. Sedell and Froggatt (1984) argue that woody debris can narrow a stream and reduce the width to depth ratio. Large and Medium size woody debris can direct velocities towards streambanks and accelerate toe instability and erosion. Bedload entrainment appears to improve in the presences of natural stable alluvium boundaries.

Because of woody debris size and abundance on the west slope and Stehekin River drainage and its consistent impacts on geomorphic measures such as width to depth ratios, sinuosity, and entrenchment ratios, it is recommended that a small subscript following the appropriate geomorphic stream classification be introduced. The subscript would be wdom. for wood dominated systems, i.e. $C4_{wdom}$. This addition would contribute a better understanding of the more humid geomorphic conditions that exist in the North Cascade Mountain Range.

It is recommended that additional studies of various valley types ensue. Other parameters such as meander belt-width, bedload studies, and bankfull dimensions relative to woody debris, dimensionless ratio relationships along the profile and cross-sections would be beneficial to engineers and technicians who are interested in natural channel restoration and riparian and/or stream management. Naturally recruited woody debris is an important component of North Cascade stream geomorphology that needs additional studies due to its impact on natural stream morphologic variability.

More information based on field data about the natural channel morphology and morphometry, based on bankfull discharge sized measurements relative to different geologic-climatic settings is needed in order to appropriately manage or restore riverine systems. Studies based on geomorphic valley types and hydrophysiographic regions or watersheds will be beneficial for sake of proper geomorphic stream classification and restoration design, both structural and non-structural.

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Chapter Four

A PRACTICAL APPROACH TO ASSESSING STREAM STABILITY
USING GEOMORPHIC REFERENCE SITES

Abstract

Landowners and operators who live next to streams have a practical understanding of stream behavior and the problems associated with instability. Technical personnel have the expertise of stream dynamics and other related sciences, but often lack the personal witness and intimate knowledge of a particular stream's behavior. The combination of experience and expertise by both the landoperator and technician can lead to a superior solution to stream instability problems. In a recent study, an area referred to as the geomorphic "reference reach" was used as a study for managing riverine and riparian systems for stability and biological diversity. The reference reach, with its associated physics, is an excellent model of the natural stable morphological stream type and characterizes the potential a stream and its dependent riparian plant and animal community have to achieve equilibrium. Comparing the reference site condition with the reach of interest and quantifying the degree of departure accomplishes both the assessment of stream instability and buffer zone effectiveness. To meet reference site conditions, a stream must manifest certain physically measurable attributes that are reproducible and meet specific criteria. These measurable attributes are relative ratios that are identifiable features in the field. Answers to approaches of management and restoration of streams and riparian communities can be acquired with a better understanding of the geomorphic processes, natural channel stability and reference reach comparisons discussed in this study.

Key Terms: natural stream stability, reference site, bankfull discharge, bank height ratio, aggradation, degradation, longitudinal profile, dimensionless ratios, pool-riffle morphology, root matrix and density.

INTRODUCTION

Landowners and operators who own or lease property along stream riparian corridors are in a continual battle to balance their needs with those of natural stream stability, healthy riparian plant and animal communities, and the regulations of government agencies. Some of the current issues to be considered are habitat for threatened and endangered species, downstream impacts on neighbors, and current proposals by various agencies to maintain buffers between land uses and the active channel. In the battle to balance, stream stability problems need to be addressed in order to have successful restoration.

Lack of understanding of stream stability and miscommunication becomes a caveat for both the landowner and the administering agency. For example, when an administrating agency proposes arbitrary buffers without considering stable morphology, one may question the value of a 50 foot buffer along an active stream course if the channel has an accelerated bank erosion potential that would cut back 60 feet in a period of one to two years. If a stream is not stable and the active channel is moving around beyond natural adjustments, what good will buffers do?

To address these problems, a stream stability assessment tool is proposed to aid both landowners and technical field personnel in discussing, analyzing and planning for restoration measures. This tool is designed to assess stream stability conditions, to aide landowners with management decisions regarding their property and the related resources in both the stream and riparian corridors, to address rapid channel adjustment problems, and to justify solutions such as non-structural and/or structural practices needed for restoration.

When an informed landowner has determined from practical experience that a river is at risk, the combination of experience and expertise of both the landoperator and technician can lead to enlightened communication, teamwork, and superior solutions to stream instability problems. Landowners who live next to and observe streams for many years have the advantage of a common sense knowledge base about a stream's behavior. Their favorite fishing holes are often the reference reaches where natural stability exists. Landowners know these areas well because they have remained intact and stable while many of the other reaches of a stream are degraded due to flood events. Interviews with long-time landowners such as tribal elders can provide some of the answers for which managers are looking. The key is in knowing what to ask, assessing the information source, and putting the answers in a proper context.

The kinds of information a technician can seek from the landowner would include such facts as how often flooding occurs, the extent of damage caused by flooding, stream migration pattern and an identification of a segment of stream that has remained unchanged. Technicians and landowners can use aerial photos, past and present, to discuss stream migration behavior and past streambank protection practices. From this information, both the technician and landowner can begin to put together a picture of streambank stability problems.

The answers to future stable stream conditions and long term self-maintenance restoration exist on small stream segments called reference sites. Local landowners and operators know these sites well when described. Reference sites often turn out to be the shady swimming holes and fishing places with generous pools, glides, riffle, runs and salmonids (Figure 10).

At a reference site, one will immediately notice abundant lush riparian vegetation and the conspicuous presence of large woody debris (LWD). The dense overhanging vegetation, depending on the species, will often have a dense root matrix providing streambank cohesion and a generous microclimate that supports a healthy aquatic ecosystem. Streambank cohesion (ability for the streambank to stay together) is desirable and managers and landowners alike want to take advantage of what is referred to as natural stream stability. Natural stream stability means that a stream is able to consistently transport its sediment load, both in size and type, associated with the local deposition and scour and the stream is able to develop a stable dimension, pattern and profile (see Figure 1, Appendix D) such that over time, channel features are maintained and the stream system neither aggrades or degrades (Rosgen, 1996). Aggradation is the accelerated rise of the streambed relative to the floodplain, and degradation (sometimes referred to as incision) is the lowering of the streambed relative to the floodplain (Figure 6, Appendix D). Over time, a natural stable stream will adjust towards a state of natural equilibrium or most probable state.

A basic assessment of stability conditions is a necessary tool to manage stream courses and restore streams to natural equilibrium. In order to complete a basic assessment of stream stability, four terms need to be discussed. They are as follows.

1. Bankfull Discharge: Bankfull discharge is the channel shaping flow. It is the incipient point at which the channel is at full capacity and nearly at floodstage. Ranchers and farmers sometimes refer to this flow as ordinary high water. Overtime, the recurrence of the bankfull discharge has the greatest impact on

bedload transport, channel shape and channel size. The Bankfull discharge moves the most bedload over time. Bankfull discharge has distinct features associated with its elevation along streambanks. Depositional features such as gravel bars, changes in particle sizes and so forth are often found at the bankfull stage.

2. Bank Height Ratio (BHR): Bank height ratio is the height of the top of the bank (lower to the two banks) divided by the top of the bankfull discharge elevation (see Figure 2). The BHR provides a relative measure of floodplain attachment to the channel forming flow. When stream incision occurs in a system, the bank height ratio begins to increase above 1.1 (see Figure 6 stages, Appendix D).
3. Root density (RD): The root density is the percent bank cover from the toe to the top of the bank (Figure 4, Appendix D). When RD drops below 30% cover, the hazard of failure is high (Rosgen, 2001).
4. Root Matrix (RM): Root matrix is a relative measure of how high the streambank is relative to the depth of the rooting system (Figure 2, Appendix D). RM is defined as the root depth divided by the bank height (Rosgen, 1996). Roots provide streambank structure and resistance to the lateral shear stress coming from the water column. Some roots are shallow and fibrous such as grasses, while other roots like willow, cottonwood, and western red cedar are deeper and more highly integrated into the streambank strata (stream bank layers). Fibrous root systems such as grasses, depending on the streambank strata (layers of various soil textures), often yield marginal protection against lateral shear stress at higher flows. When bank height ratios increase substantially to values above 1.2, a fibrous root system may have little to no value in preventing both lateral shear

stress and toe slope failure. Good root matrix and densities will lower the potential for bank failure and toe collapse. Older woody debris firmly lodged into the banks can add strength to the root matrix. When the RM falls below 30 to 49%, the bank erosion potential moves from moderate to high.

The Reference Reach

In the Northeastern part of Washington State, in the spring of 2001, Washington State University staff funded by the Rural Technology Intuitive (RTI) began an area of study referred to as the geomorphic "reference reach." These studies involved methods and quantitative measurements of streams and floodplains. RTI's collection of data and field work provide a baseline to manage riverine and riparian systems for stability and biological diversity.

The reference reach, with its associated physics, is an excellent model of the natural stable morphological stream type from which landoperators and scientists can gain a well-rounded understanding of the potential for a stream and its dependent riparian plant and animal community.

The measurement and definition of a natural stable reference reach is neither precarious nor frivolous. To meet reference site conditions, a stream must manifest certain physically measurable attributes that are reproducible and meet specific criteria. These measurable attributes are dimensionless ratios that spatially describe the proportion, planview, profile, bedload, woody debris, and floodplain attachment of the stream system. Understanding the degree of departure a reach of interest has can aide the technician and landoperator in identifying the phase of channel adjustment within channel evolutionary changes. A comparison between a geomorphic reference reach and a reach of interest provides a measure of degree of departure (see Quilcene and Entiat Figures 7-11).

Two good examples of reference reaches that have been subjected to numerous perturbations on both the western and eastern sides of the Cascades are on the Big Quilcene River, located on the Olympic Peninsula and the Entiat River in Chelan County on the east side of the Cascades. It is an impressive natural state when reference reaches have remained stable despite numerous perturbations of upstream segments and hydrologically contributing watersheds.

The landscapes of both the Big Quilcene watershed and river corridor have been altered numerous times by timber harvesting, road building, and grazing. Both Figures 7 and 8 are located in the reference reach just above the town of Quilcene. Figure 8 shows the abundant chum salmon that were present on September 2, of 1998. Immediately upstream (Figure 9) is the right half (left bank with downstream orientation) of a severely braided river system. Some attempts at stabilizing the left bank were made to keep the stream from laterally migrating resulting in the increased loss of floodplain. Although these remedial measures will slow the loss of streambanks and floodplains, the high width to depth ratio braided river system will continue to be highly unstable and unpredictable.

Figure 7. Big Quilcene reference site with abundant chum and steelhead located 600 feet below figure 9

Figure 8. Chum salmon spawning in Figure 7 reference site

Figure 9. Big Quilcene, several hundred feet above Figure 7, no visible salmonids, very little natural LWD recruitment, higher temperatures all within the same valley type

Figure 10. Entiat reference reach river mile 20, excellent root cohesion and bedload transport

Figure 11. Entiat river mile 20 looking upstream from Figure 10, same site potential as reference reach below, multiple center bars and high width to depth ratios (wide and shallow).

The design template of the reference reach shown in Figure 7 could be emulated and applied to the severely braided conditions shown in Figure 9. The design template is a blueprint for structural restoration of a degraded stream system (Rosgen, 1998). The reference reach in Figure 7 has maintained itself despite the land uses upstream. The design templates, which consist of dimensionless ratios (surveyed measurements of the shape and attributes of the reference reach) on the reference site in Figure 10, formally known as the Frank Thomas Property, are the exact match needed to restore the degraded stream segment illustrated in Figure 11.

Longtime landowners often know that the stream segment of study once looked like the stream reach described as the reference. Both reaches may even be located adjacent to each other, such is the case with Figures 10 and 11 located on the east side of the Cascade divide and

Figures 7 and 9 located on the Olympic Peninsula. When both are measured and compared, a percent of departure can be quantified.

METHODS

The following methodology provides step-by-step instruction for landowners and technicians to use in assessing stream stability. Six simple pieces of equipment are used. They are: 1) 50 to 100 foot cloth tape, 2) simple measuring staff between four to six feet long, 3) eight foot collapsible carpenter's ruler, 4) material for flagging, 5) metal pins with spring clamps, and 6) camera.

1. Measure off a segment of interest for a distance of 20 channel widths (Leopold, 1994). Identify and flag meander apex and riffle portion of the profile (Figure 1, Appendix D). Use flagging to identify the dominate scour line associated with the deposition bar features which are at bankfull discharge height. Notice the common scour line features on both sides of the stream channel associated with discharge height. Sometimes woody plant species, such as willow or western red cedar are good indicators of a bankfull scour line; however, the depositional features are the best indicators. Use paint if necessary to connect the flagged elevations to a riffle and a meander bend cross-section.

2. Use a left bank and a right bank pin to mark the bankfull discharge elevations centrally located a riffle segment. Span the channel and connect the two pins with a cloth tape and

secure with clamps to show where bankfull discharge is relative to the floodplain (Figure 2).

3. With a measuring staff or tape, record the height of the top of the bank (lowest of the two bank tops) to the deepest part of the channel (Table 1, TOB, Appendix D), then measure and record the height to the bankfull elevation to the same depth (Table 1, MBF, Appendix D) for the BHR (see Figures 3 and 4, Appendix D).

4. With a measuring staff, measure the depth of the roots relative to the height of the bank and root matrix depth relative to channel depth (Figure 4, Appendix D), record on Table 1, Appendix D.

5. With a square grid held up against the bank as illustrated in Figure 5, estimate or measure the percent of bank cover provided by roots and lodged woody debris when present. A carpenter's ruler (eight feet long shaped into a four square foot shape) can be used or a grid with even sized squares for counting hits can be used. It may be necessary to use two bank pins to hold grid in place. Record on Table 1, Appendix A. A photograph of the four foot square grid in place on the bank is recommended. Digital cameras and slide films offer opportunities to further analyze root matrix if needed. Attach photographs to Table 1. Photograph cross-section and bank and attach for documentation.
6. Complete the process on both a riffle and the meander apex.
7. Put together a matrix similar to Table 4.

The above process is illustrated in Figures 2, 3, 4, 5, 6 and recorded on Appendix D, Table 1.

Table 4 is an example of a comparison of stability measurements for erosion potential and percent departure similar to the values shown in the Figures 2 through 6.

Table 4. Percent Departure from Reference Site Condition

Measured Feature (Apex of meander)	Reference Reach	Reach of Interest	Erosion Potential	Percent Departure
Bank Height Ratio	1.07	1.25	Moderate	17%
Root Density	70%	25%	High	64%
Root Matrix	.78	.30	Low	62%

The three measured features percent departures are computed by simple division, For example:

Reference reach BHR value minus reach of interested BHR value (use absolute value) divided by the reference reach BHR,

i.e. $(|1.07 - 1.25|)/ 1.07 \times 100\% = 17\%$

i.e. $(|70\% - 25\%|)/ 70\% = 64\%$

i.e. $(|.78 - .30|)/ .80\text{x } 100\% = 62\%$

For root density % value it is not necessary to multiply by 100%.

- In this example, the loss of natural stability is high. If any of the three categories are high, the reach of interest is at risk of rapid adjustments at higher flows. Lack of root density to cover exposed streambank soils, and the condition of early incision (BHR 1.25) cause the stream system to be susceptible to overall higher shear stresses. If the streambed has incised to a stable material such as bedrock, boulders, or cobbles, then the stream will migrate laterally causing accelerated bank erosion. When flood stages occur in an incised channel they are at higher elevations than bankfull discharge and the entire flow is still within the bounds of the previous natural bankfull elevations. This condition allows for higher velocities in deeper water which exerts more shear stress on the streambed. The reach of interest may continue to degrade (incise), while toe slope failure along banks continues. The cumulative effects of all three features having high erosion potential should be of concern to the landoperator or shareholder who desires natural stability or lower maintenance. A likely outcome of this process is the loss of riparian habitat negating positive effects of a prescribed buffer width.

With regard to functional buffers, if bank height ratio has increased to a value exceeding the rooting depth for native woody or fibrous root species, riparian growth cannot continue regardless of a prescribed buffer width. If riparian restoration is to be achieved, the watertable has to be restored to original level before buffers can produce predisturbed conditions of a functioning riparian plant and animal community. Some structural approaches to natural channel restoration are designed to accommodate the re-attachment of the bankfull channel to the riparian, thus re-establishing a watertable and riparian habitat. If a stream has accelerated lateral migration (accelerated erosion with over-extended meanders) buffers may be effective given re-establishment of root matrices, depth, and cohesion. It may be necessary to provide structure to reduce stress on the flow column closest to the concave bank with the highest velocities and deepest water known as the near bank 1/3. The velocities and thalweg (low flow channel) may be directed slightly away from the bank by the use of minor structural measures such as rock vanes or root wads. Accelerated lateral erosion will render buffers ineffective unless bank stability is restored.

DISCUSSION AND CONCLUSION

Understanding and gathering data about reference reaches within specific geomorphic stream types and comparing them with a reach of interest can provide valuable information such as:

1. Analysis of the effectiveness or appropriateness of a buffer zone.
2. Amount of a departure, in measurable quantitative terms, the stream segment of interest has from its potential natural stable condition.
3. Assessment of whether deferment, management, or structural measures are needed to bring the specific stream type back to a naturally self-sustaining stream system.
4. Benefit of not having to pay for expensive remedial measures to protect property which do not address the bedload transport capabilities of the stream segment of interest; thus, causing problems for the downstream neighbor.
5. Guidance for allowing the stream to co-exist in a state of dynamic equilibrium and answering questions such as: How much of a meander width is really needed for the specific geomorphic stream type and the associated riparian? Are we asking too much for the stream to be in geomorphic balance or have we not asked for enough? Does the present sinuosity (one kind of measure of the meandering of the stream) reflect sufficient channel energy dissipation of the stream system?
6. Consistent and predictable local deposition and scour which provide a stable and highly productive aquatic environment for salmonids. This consistent local deposition and scour can be measured from year to year and quantified as pools glides, riffles, and runs on the flatter pool/riffle morphology types were so much riparian and stream use is common.

If landoperators and shareholders desire a more in-depth and quantifiable analysis of stream bank stability, the bank erodibility hazard index (BEHI) developed by Dave Rosgen (1996) and the channel stability evaluation developed by Pfankuch (1975) provide a precise enough analysis to predict bank erosion rates. At such a time, it is recommended to contact a professional with the technical expertise to assist landowners. Other analyses regarding such features as bank material assessments, stream classification type (Rosgen, 1994) woody debris interactions, buffer width determination and an in-depth air photo analysis are always preferable, but will also require some additional technical expertise. It is appropriate that an initial stability assessment be made prior to buffer recommendations.

Approaches to natural channel stability and riparian condition have been and will continue to be the subject of intense debate. Regardless of debate, many of the answers to approaches of management and restoration of streams and riparian communities that private and public landoperators seek cannot be acquired without a better understanding of the geomorphic processes, natural channel stability and reference reach comparison. The combination of experience and expertise by both the landoperator and technician can lead to improved communication and superior solutions to stream instability problems.

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APPENDICES

Appendix A. Chapter 1

Figure 1

Lane's Proportionality Equation

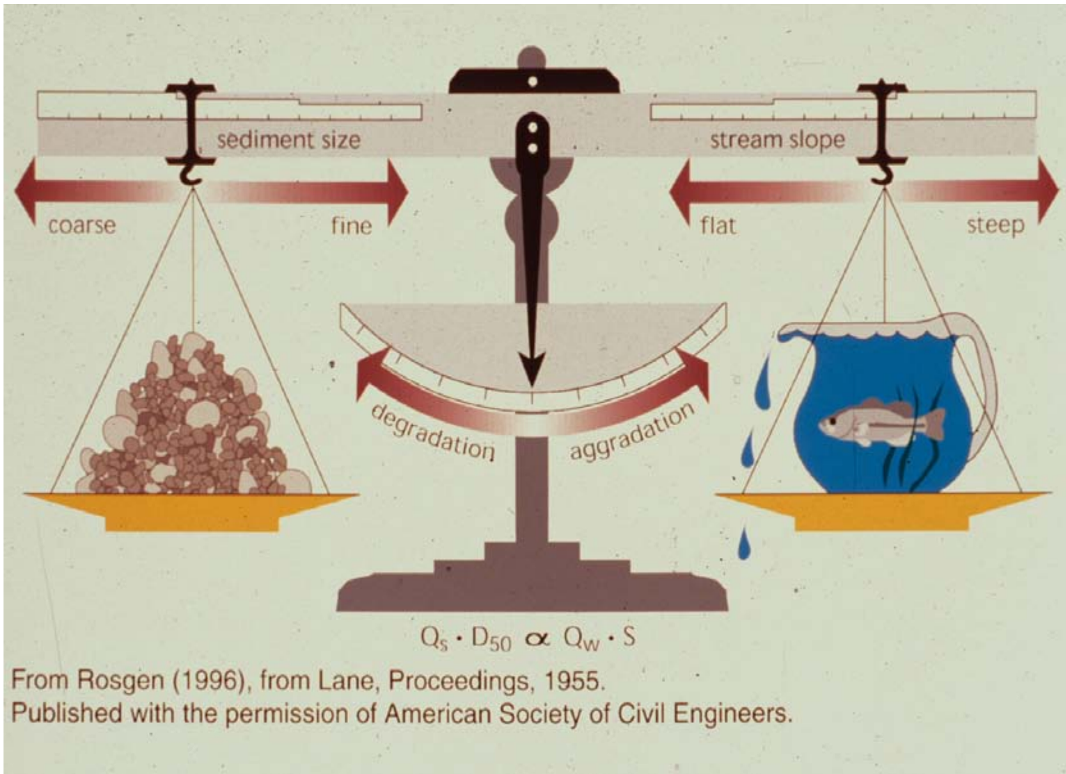

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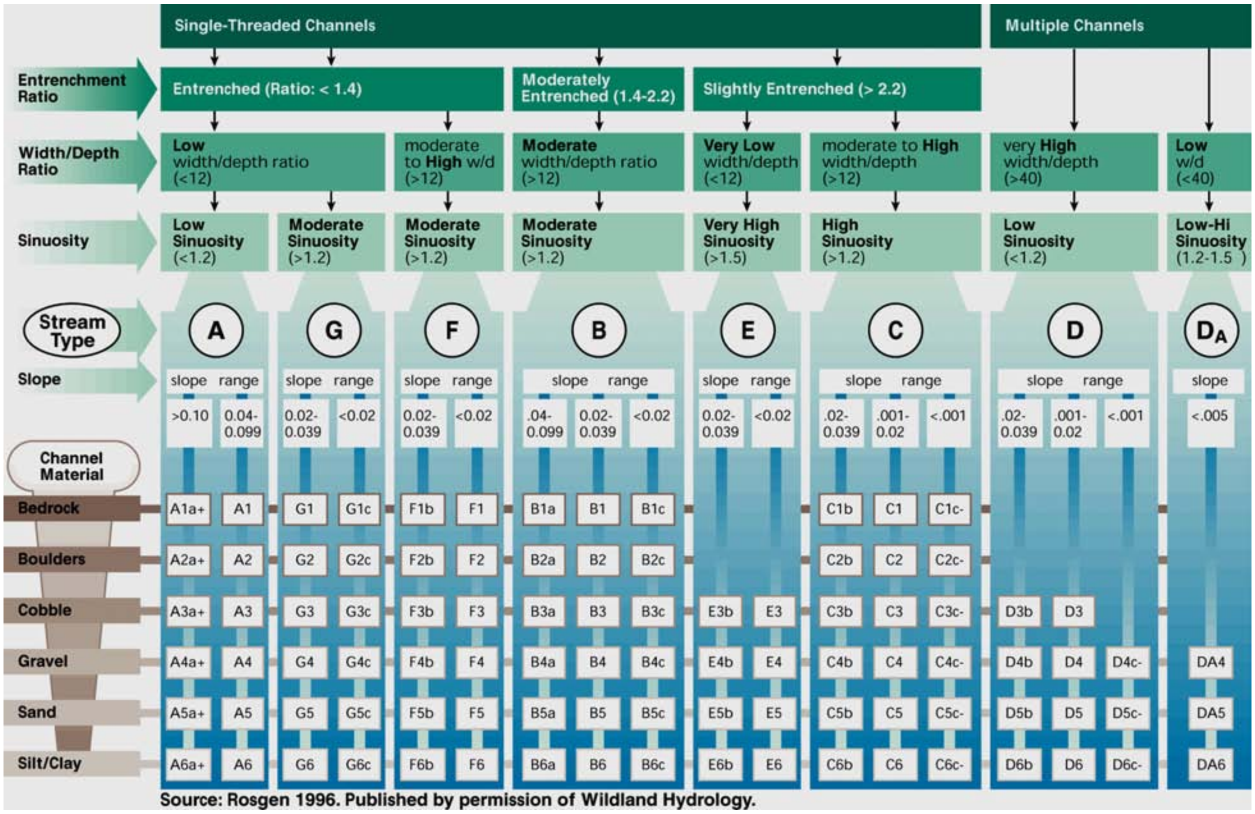
Figure 2

Rosgen's Level II Stream Classification Key



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Appendix B. Chapter 2
Table 2
Field Data: Random Selected Sites

Sauk River Drainage				
Drainage Area (m^2)	X-Section (ft^2)	Width (ft)	Bankfull Q (cfs)	Depth (ft)
13.5	254.3	115.6	1703.0	2.20
13.7	281.6	98.9	1181.0	2.85
13.9	323.2	77.5	1314.0	4.17
18.0	356.7	102.5	1370.0	3.48
27.9	364.2	97.2	2109.0	3.75
73.7	571.0	192.5	4138.5	2.97
18.2	271.2	94.5	1519.0	2.87

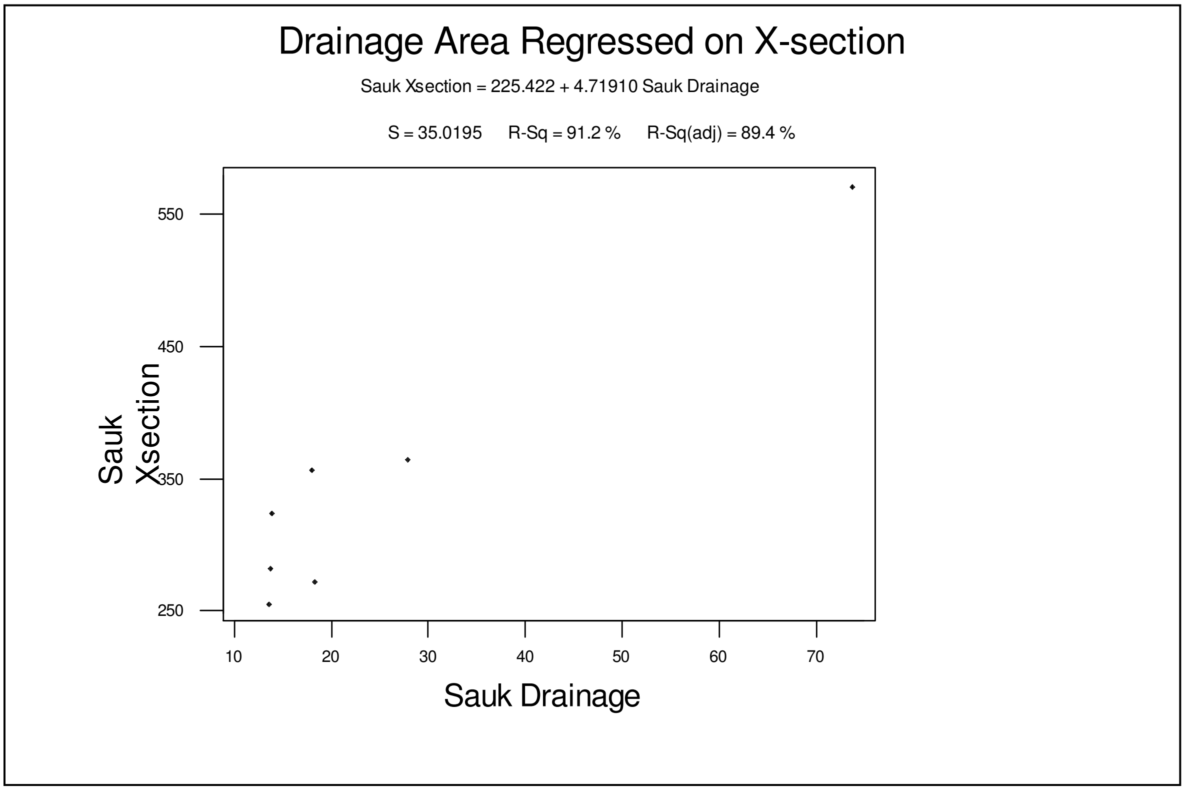
White River Drainage				
Drainage Area (m^2)	X-Section (ft^2)	Width (ft)	Bankfull Q (cfs)	Depth (ft)
28.7	165.7	58.20	763.8	2.84
35.3	172.9	54.20	877.5	3.19
45.0	285.9	56.70	1212.9	5.04
45.3	283.8	61.40	1659.2	4.62
89.6	416.6	115.95	2658.0	3.59
147.2	718.8	140.10	3822.1	5.13
149.5	722.0	123.50	4142.4	5.85
16.3	138.3	46.00	1310.0	3.00
61.0	361.0	108.10	2359.0	3.30
5.0	25.1	22.40	162.1	1.40

Chiwawa River Drainage				
Drainage Area (m^2)	X-Section (ft^2)	Width (ft)	Bankfull Q (cfs)	Depth (ft)
64.2	236.6	89.45	1729	2.65
65.4	307.2	85.60	1943	3.59
50.1	210.3	63.40	855	3.32
57.9	227.2	93.70	1036	2.42
70.6	345.7	90.00	1835	3.84
78.2	389.4	84.80	1570	4.59
104.2	400.3	103.80	2692	3.86
170.0	546.7	108.90	2739	5.02

Appendix B. Chapter 2
Figures 3 and 4
Sauk Drainage Analyses

Regression Analysis: Sauk X-section versus Sauk Drainage Area

```
The regression equation is
Sauk Xsection = 225 + 4.72 Sauk Drainage Area

Predictor        Coef     SE Coef          T        P
Constant       225.42       21.35      10.56    0.000
Sauk Dra       4.7191      0.6552       7.20    0.001

S = 35.02       R-Sq = 91.2%     R-Sq(adj) = 89.4%

Analysis of Variance

Source            DF          SS          MS         F        P
Regression         1       63610       63610     51.87    0.001
Residual Error     5        6132        1226
Total              6       69742

Unusual Observations
Obs   Sauk Dra   Sauk Xse        Fit      SE Fit    Residual    St Resid
  6       73.7      571.0      573.2        34.2        -2.2       -0.30 X

X denotes an observation whose X value gives it large influence.
```



Appendix B. Chapter 2
Figures 5 and 6
Sauk Drainage Analyses

Regression Analysis: Sauk BKF Width versus Sauk Drainage Area

The regression equation is
Sauk BkF Width = 70.5 + 1.59 Sauk Drainage Area

Predictor	Coef	SE Coef	T	P
Constant	70.482	9.448	7.46	0.001
Sauk Dra	1.5949	0.2900	5.50	0.003

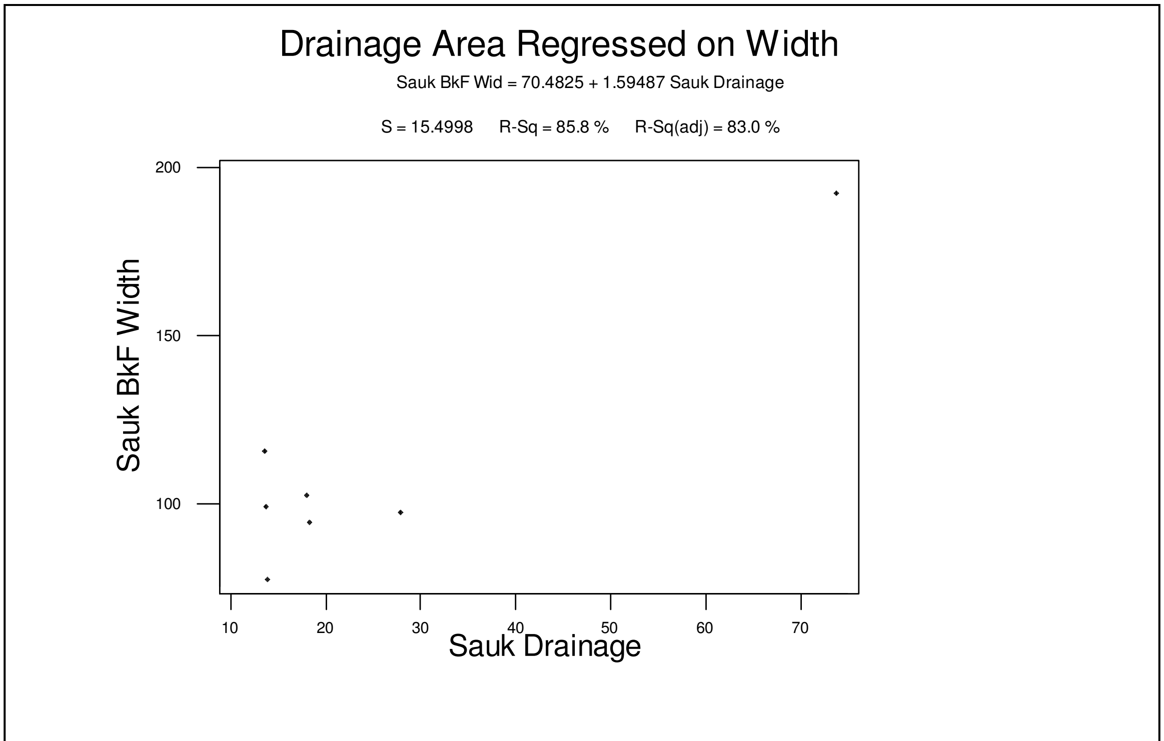
S = 15.50 R-Sq = 85.8% R-Sq(adj) = 83.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	7265.4	7265.4	30.24	0.003
Residual Error	5	1201.2	240.2		
Total	6	8466.6			

Unusual Observations

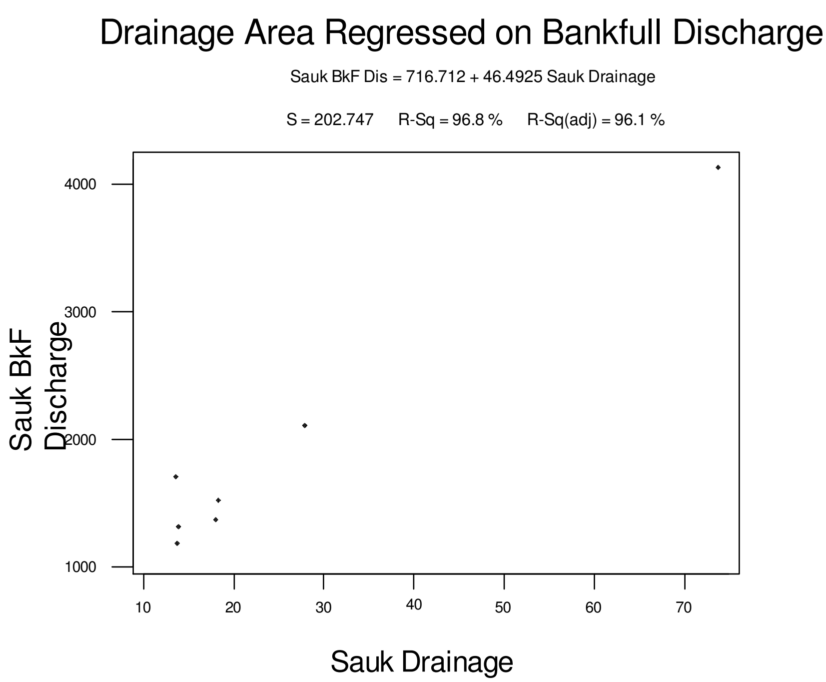
Obs	Sauk Dra	Sauk BkF	Fit	SE Fit	Residual	St Resid
6	73.7	192.50	188.02	15.14	4.48	1.35 X



Appendix B. Chapter 2
Figures 7 and 8
Sauk Drainage Analyses

Regression Analysis: Sauk BKF Discharge versus Sauk Drainage Area

```
The regression equation is
Sauk BkF Discharge = 717 + 46.5 Sauk Drainage Area

Predictor        Coef     SE Coef          T        P
Constant        716.7       123.6       5.80    0.002
Sauk Dra       46.493       3.794      12.26    0.000

S = 202.7       R-Sq = 96.8%     R-Sq(adj) = 96.1%

Analysis of Variance

Source            DF          SS          MS         F        P
Regression         1     6174089     6174089    150.20    0.000
Residual Error     5      205531       41106
Total              6     6379620

Unusual Observations
Obs   Sauk Dra   Sauk BkF         Fit      SE Fit    Residual    St Resid
  6       73.7     4138.5      4143.2       198.1        -4.7       -0.11 X

X denotes an observation whose X value gives it large influence.
```



Appendix B. Chapter 2
Figures 9 and 10
Sauk Drainage Analyses

Regression Analysis: Sauk BKF Depth versus Sauk Drainage Area

The regression equation is
Sauk BkF Depth = 3.23 - 0.0016 Sauk Drainage Area

Predictor	Coef	SE Coef	T	P
Constant	3.2252	0.4393	7.34	0.001
Sauk Dra	-0.00160	0.01349	-0.12	0.910

S = 0.7207   R-Sq = 0.3%   R-Sq(adj) = 0.0%

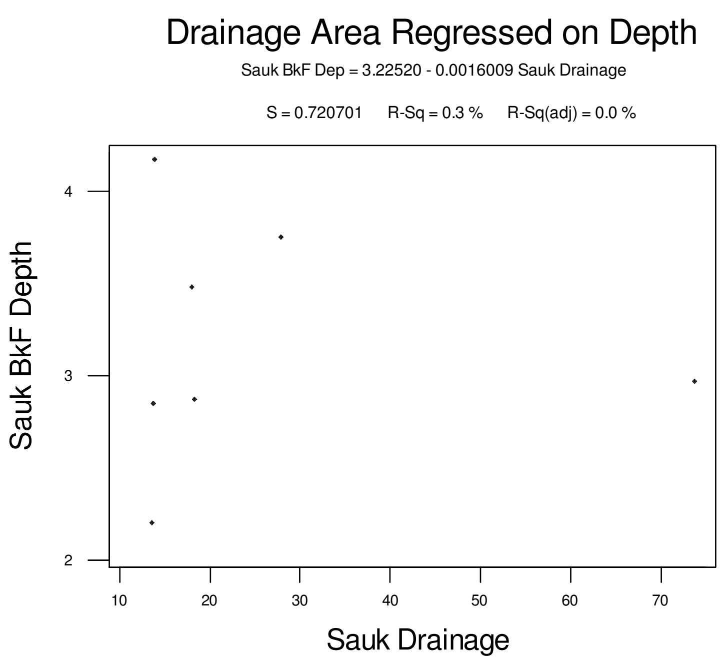
Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.0073	0.0073	0.01	0.910
Residual Error	5	2.5971	0.5194		
Total	6	2.6044			

Unusual Observations

Obs	Sauk Dra	Sauk BkF	Fit	SE Fit	Residual	St Resid
6	73.7	2.970	3.107	0.704	-0.137	-0.89 X

X denotes an observation whose X value gives it large influence.



Appendix B. Chapter 2
Figures 11 and 12
White River Drainage Analyses

Regression Analysis: White River section versus White River Drainage

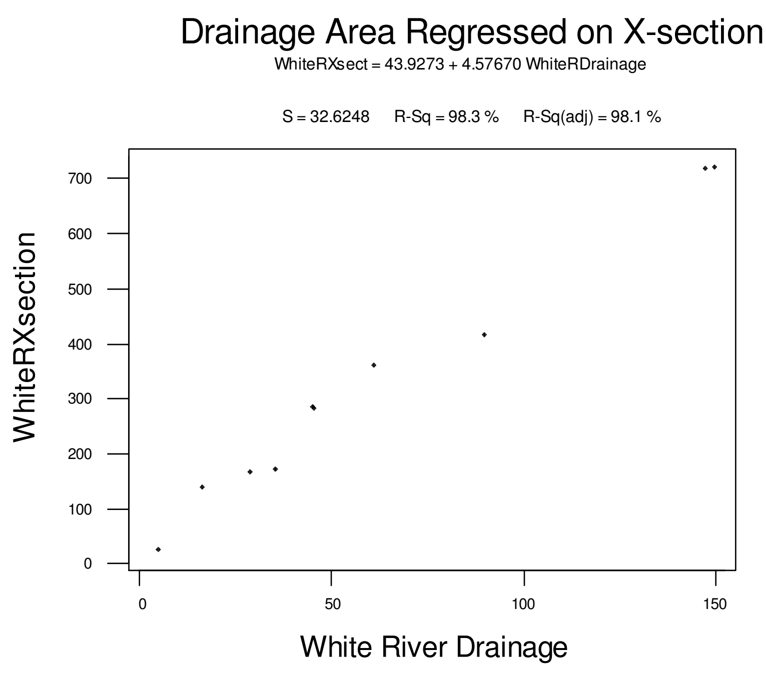
The regression equation is
WhiteRXsect = 43.9 + 4.58 White River Drainage

Predictor	Coef	SE Coef	T	P
Constant	43.93	16.82	2.61	0.031
WhiteRDr	4.5767	0.2133	21.46	0.000

S = 32.62 R-Sq = 98.3% R-Sq(adj) = 98.1%

Analysis of Variance

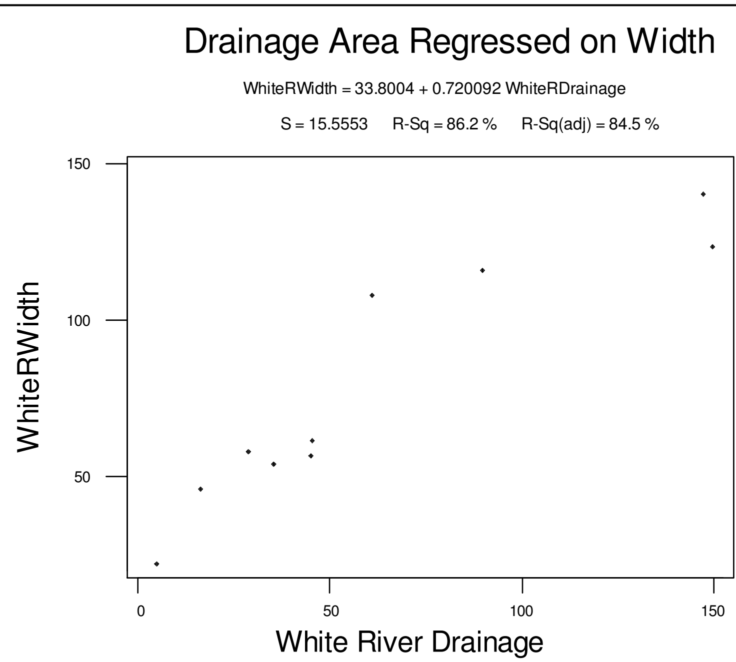
Source	DF	SS	MS	F	P
Regression	1	490232	490232	460.58	0.000
Residual Error	8	8515	1064		
Total	9	498747			



Appendix B. Chapter 2
Figures 13 and 14
White River Drainage Analyses

Regression Analysis: White River Width versus White River Drainage

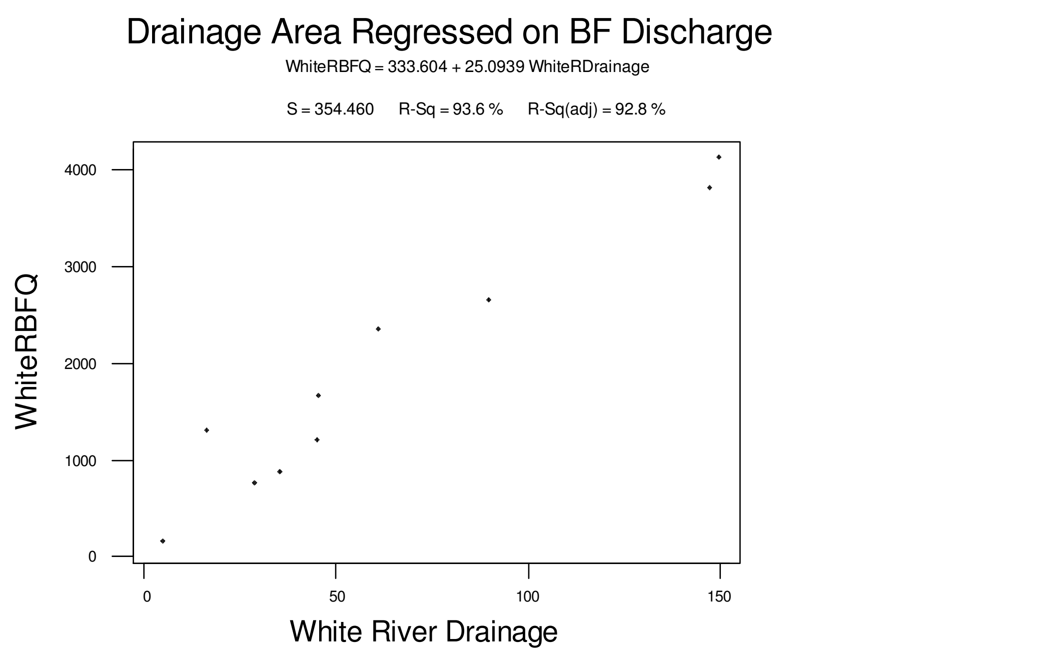
```
The regression equation is
WhiteRWidth = 33.8 + 0.720 WhiteRDrainage

Predictor        Coef     SE Coef          T        P
Constant       33.800       8.019       4.21    0.003
WhiteRDr       0.7201      0.1017       7.08    0.000

S = 15.56       R-Sq = 86.2%     R-Sq(adj) = 84.5%

Analysis of Variance

Source            DF          SS          MS         F        P
Regression         1       12136       12136     50.16    0.000
Residual Error     8        1936         242
Total              9       14072

Unusual Observations
Obs   WhiteRDr   WhiteRWi         Fit      SE Fit    Residual    St Resid
  9         61     108.10       77.73        4.92       30.37       2.06R

R denotes an observation with a large standardized residual
```



Appendix B. Chapter 2
Figures 15 and 16
White River Drainage Analyses

Regression Analysis: White River BFQ versus White River Drainage

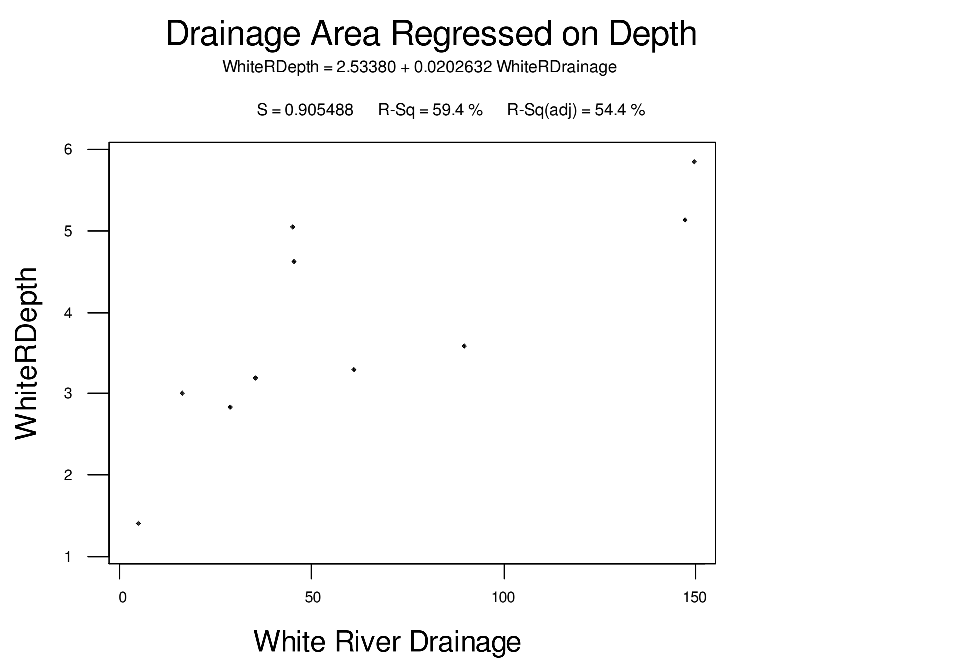
```
The regression equation is
WhiteRBFQ = 334 + 25.1 WhiteRDrainage

Predictor        Coef     SE Coef          T        P
Constant        333.6       182.7       1.83    0.105
WhiteRDr       25.094       2.317      10.83    0.000

S = 354.5       R-Sq = 93.6%     R-Sq(adj) = 92.8%

Analysis of Variance

Source            DF          SS          MS         F        P
Regression         1    14737769    14737769    117.30    0.000
Residual Error     8     1005138      125642
Total              9    15742906
```



Appendix B. Chapter 2
Figures 16 and 17
White River Drainage Analyses

Regression Analysis: White River Depth versus White River Drainage

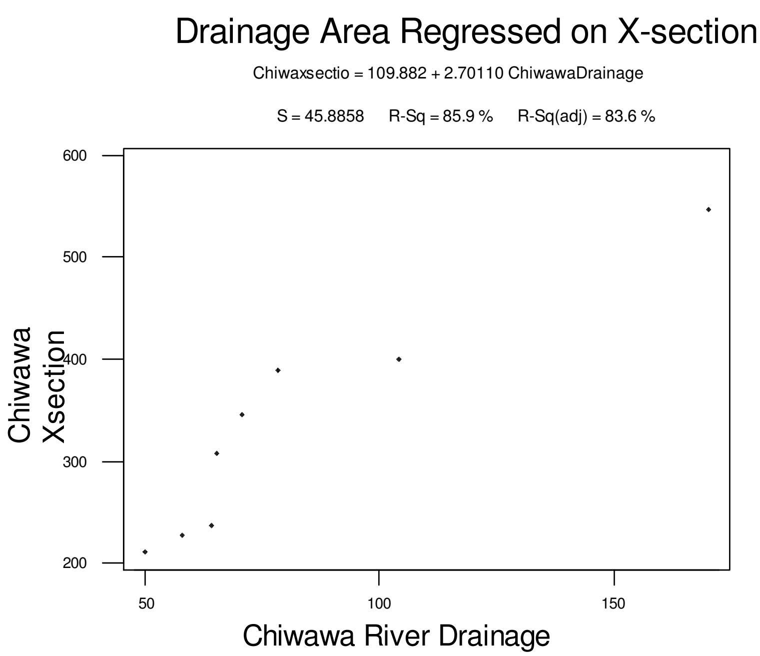
```
The regression equation is
WhiteRDepth = 2.53 + 0.0203 WhiteRDrainage

Predictor        Coef     SE Coef         T        P
Constant       2.5338      0.4668      5.43    0.001
WhiteRDr     0.020263    0.005919      3.42    0.009

S = 0.9055      R-Sq = 59.4%     R-Sq(adj) = 54.4%

Analysis of Variance

Source            DF          SS          MS         F        P
Regression         1      9.6098      9.6098     11.72    0.009
Residual Error     8      6.5593      0.8199
Total              9     16.1690
```



Appendix B. Chapter 2
Figures 18 and 19
Chiwawa River Drainage Analyses

Regression Analysis: Chiwawa X-section versus Chiwawa Drainage Area

```
The regression equation is
Chiwaxsection . = 110 + 2.70 ChiwawaDrainageArea

Predictor        Coef     SE Coef          T        P
Constant       109.88       40.27       2.73    0.034
ChiwawaD       2.7011      0.4463       6.05    0.001

S = 45.89       R-Sq = 85.9%     R-Sq(adj) = 83.6%

Analysis of Variance

Source            DF          SS          MS         F        P
Regression         1       77114       77114     36.62    0.001
Residual Error     6       12633        2106
Total              7       89747

Unusual Observations
Obs   ChiwawaD   Chiwaxse         Fit      SE Fit    Residual    St Resid
  8        170      546.7       569.1        42.3       -22.4       -1.25 X

X denotes an observation whose X value gives it large influence.
```



Appendix B. Chapter 2
Figures 20 and 21
Chiwawa River Drainage Analyses

Regression Analysis: Chiwawa Width versus Chiwawa Drainage Area

The regression equation is
ChiwawaWidth = 67.8 + 0.268 ChiwawaDrainageArea

Predictor	Coef	SE Coef	T	P
Constant	67.833	8.455	8.02	0.000
ChiwawaD	0.26792	0.09371	2.86	0.029

S = 9.634 R-Sq = 57.7% R-Sq(adj) = 50.6%

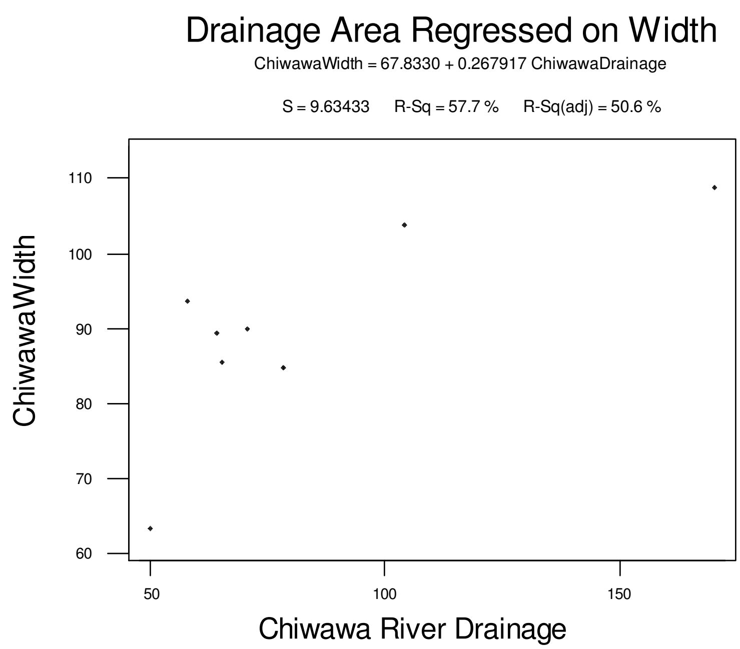
Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	758.67	758.67	8.17	0.029
Residual Error	6	556.92	92.82		
Total	7	1315.59			

Unusual Observations

Obs	ChiwawaD	ChiwaWid	Fit	SE Fit	Residual	St Resid
3	50	63.40	81.26	4.57	-17.86	-2.10R
8	170	108.90	113.38	8.87	-4.48	-1.19 X

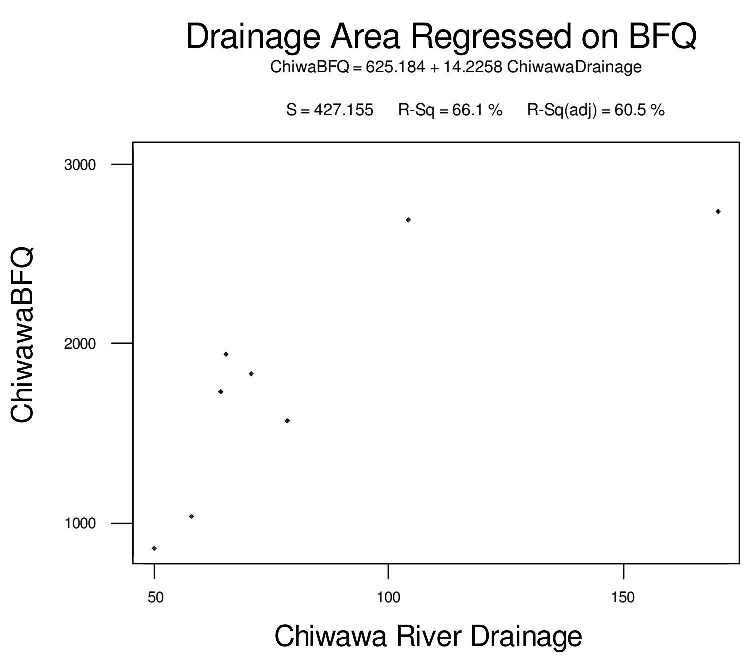
R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.



Appendix B. Chapter 2
Figures 22and 23
Chiwawa River Drainage Analyses

Regression Analysis: Chiwawa BFQ versus Chiwawa Drainage Area

```
The regression equation is
ChiwawaBFQ = 625 + 14.2 ChiwawaDrainageArea

Predictor        Coef     SE Coef          T        P
Constant        625.2       374.9       1.67    0.146
ChiwawaD       14.226       4.155       3.42    0.014

S = 427.2       R-Sq = 66.1%     R-Sq(adj) = 60.5%

Analysis of Variance

Source            DF          SS          MS         F        P
Regression         1     2138954     2138954     11.72    0.014
Residual Error     6     1094767      182461
Total              7     3233721

Unusual Observations
Obs   ChiwawaD   ChiwaBFQ         Fit       SE Fit    Residual     St Resid
  8        170       2739        3044          393        -305       -1.83 X

X denotes an observation whose X value gives it large influence.
```



Appendix B. Chapter 2
Figures 24 and 25
Chiwawa River Drainage Analyses

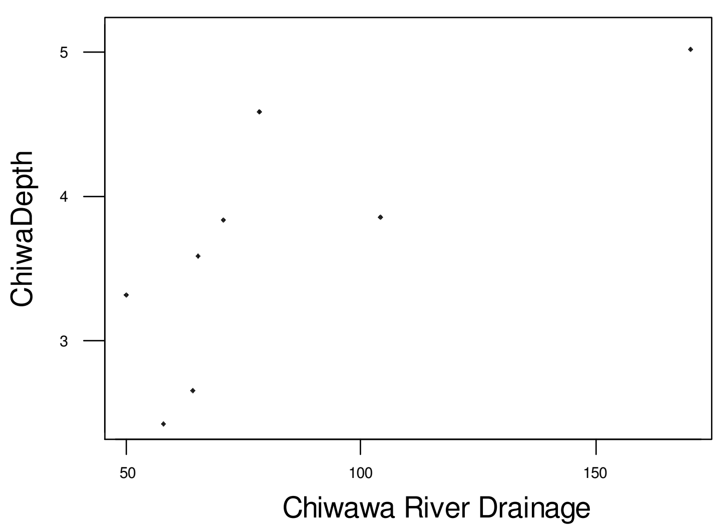
Regression Analysis: Chiwawa Depth versus Chiwawa Drainage Area

```
The regression equation is
ChiwaDepth = 2.27 + 0.0169 ChiwawaDrainageArea

Predictor        Coef     SE Coef          T        P
Constant       2.2675      0.5612       4.04    0.007
ChiwawaD     0.016879    0.006221       2.71    0.035

S = 0.6395      R-Sq = 55.1%     R-Sq(adj) = 47.6%

Analysis of Variance

Source            DF          SS          MS         F        P
Regression         1      3.0111      3.0111      7.36    0.035
Residual Error     6      2.4540      0.4090
Total              7      5.4651

Unusual Observations
Obs   ChiwawaD   ChiwaDep          Fit       SE Fit    Residual    St Resid
  8        170      5.020        5.137        0.589      -0.117       -0.47 X

X denotes an observation whose X value gives it large influence.
```

Drainage Area Regressed on Depth

ChiwaDepth = 2.26749 + 0.0168787 ChiwawaDrainage

S = 0.639525 R-Sq = 55.1 % R-Sq(adj) = 47.6 %



Appendix C. Chapter 3

Field Data

Drainage Basin	River or Stream	Valley Type	Ent. Ratio	W/D Ratio Average in Segment	Sinuosity (k)	Slope (%)	D50 Overall (mm)	Rosgen Classification
Entiat	001 Entiat	V	7.03	32.1	1.79	0.27	24.8	C4
Icicle	002 Icicle Ida	V	3.75	16.9	1.42	0.23	62.9	C4
Icicle	003 Icicle Alpine	V	2.73	17.5	1.71	0.14	34.2	C4
Icicle/Nason	004 Nason	V	4.80	20.4	2.1	0.33	26.5	C4
Lake Wenatchee	006 Little Wenatchee	V	6.48	30.3	1.5	0.7	69	C3
White River	007 White River	V	2.51	32.2	1.25	0.9	84.8	C3
White River	008 Napeequa Lower 1	V	3.42	13.2	1.58	0.33	23.1	C4
White River	009 Napeequa Lower 2	V	4.65	11.3	2.3	0.11	36.5	C4
White River	010 Twin Lakes Creek	V	8.13	14	1.4	0.46	0.7	C5
White River	011 White River @USGS	V	16.24	21.2	2.9	0.13	7.8	C4
White River	012 White River @ Gray's	V	12.57	27.2	1.65	0.14	28.9	C4
White River	013 Napeequa Historical	V	5.48	16.9	1.4	0.36	14.8	C4
White River	014 Napeequa Historical	V	2.87	20.5	1.26	0.71	53.2	C4
Chiwawa	015 Chiwawa	V	5.21	33.8	1.35	0.7	22.8	C4
Chiwawa	016 Chiwawa	V	5.78	23.8	1.72	0.32	22.5	C4
Chiwawa	017 Chiwawa	V	3.78	19.2	1.56	0.43	39.4	C4
Chiwawa	018 Chiwawa	V	5.32	38.5	1.62	0.36	32.2	C4
Chiwawa	019 Chiwawa	V	6.33	24.4	2	0.26	19.5	C4
Chiwawa	020 Chiwawa	V	7.85	18.3	2.28	0.15	33.9	C4
Chiwawa	021 Chiwawa	V	5.34	26.9	1.75	0.31	19.3	C4
Chiwawa	022 Chiwawa @ USGS	V	2.19	21.7	1.7	0.3	118.9	C3
Methow	023 Twisp	V	6.61	41.1	1.26	0.9	52.9	C4
Methow	024 Twisp	V	4.16	35.4	1.42	0.73	79.2	C3
Methow	026 Methow West Fork	V	4.96	22.2	1.15	2.07	84.3	C3
Methow	027 Early Winters	V	5.98	26.8	1.18	1.9	24.8	C4
Stehekin NPS	029 Stehekin Upper	V	3.49	35.2	1.13	2.4	65.8	C3
Stehekin NPS	030 Stehekin Lower	V	2.59	53.8	1.26	0.9	167.7	C3
Ross Lake NPS	028 Granite Creek	V	2.05	32.8	1.15	1.18	18.8	B4c
Sauk	031 Sauk NF	V	3.45	64.8	1.53	0.48	30.2	C4
Stilliqaumish	032 Squire Creek	V	2.76	32.9	1.23	0.55	32	C4
Sauk	033 Dan's Creek	V	2.52	20.1	1.21	2	81.9	C3
Stilliqaumish	034 Stillaguamish NF	V	2.15	33.4	1.16	0.84	23.5	B4c
Sauk	035 Clear Creek Upper	V	2.51	34.2	1.31	0.5	75.9	C3
Sauk	036 Clear Creek Lower	V	4.85	18.5	1.44	0.44	106.5	C3
Sauk	037 Sauk South Fork, Lower	V	4.36	29.5	1.49	0.24	33.8	C4
Sauk	038 Sloan Creek, Upper	V	5.07	25.9	1.39	0.28	11.5	C4
Suiattle	039 Downey Creek Lower	V	2.84	38.2	1.18	1	55	C4
Suiattle	040 Downey Creek Upper	V	4.02	48.9	1.22	1.24	31.4	C4
Sauk	041 Sauk South Fork Upper	V	4.82	52.5	1.24	1.3	71.5	C3
Cascade	042 Cascade River Upper	V	3.64	44.5	1.34	0.77	64.8	C3
Cascade	043 Cascade River Lower	V	3.96	28.5	1.26	0.71	70.1	C3
Skagit	044 Bacon Creek Upper	V	3.46	41.6	1.21	0.73	71	C3
Skagit	045 Bacon Creek Lower	V	2.05	35.8	1.28	0.69	98.7	B3c
Skykomish	046 Foss Creek Upper	V	11.96	24.6	1.17	2.1	55.4	C4
Skykomish	047 FossCreek Lower	V	9.21	24	1.28	0.23	11.6	C4
Skykomish	048 Rapid Creek Upper	V	2.02	33	1.12	1.47	163.7	C3
Skykomish	049 Rapid Creek Lower	V	3.42	44.9	1.24	0.5	50.5	C4
Skykomish	050 Skykomish NF Upper	V	5.05	26.8	1.35	0.76	64.6	C3
Skykomish	051 Skykomish NF Lower	V	2.55	28.9	1.13	1.35	109.5	C3
Skykomish	052 Martin Ck	V	5.20	23.7	1.21	1.1	35.9	C4
Pilchuck	053 Pilchuck Upper	V	2.46	26.6	1.42	0.58	32.9	C4
Pilchuck	054 Pilchuck Lower	V	2.48	24.2	1.41	0.74	72	C3
Pilchuck	055 Olney Creek	V	2.82	33.4	1.17	1	22.7	C4
Snoqualmie	056 Snoqualmie Middle F. Up.	V	4.54	38.5	1.07	1.8	220.4	C3
Snoqualmie	057 Snoqualmie Middle F. Low.	V	1.78	32.7	1.15	0.53	60.6	C4
Snoqualmie	058 Taylor Creek Upper	V	4.03	31.7	1.25	0.69	39.5	C4
Snoqualmie	059 Taylor Creek Lower	V	4.21	34.6	1.38	0.52	58.6	C4
Snoqualmie	060 Lennox Creek	V	2.99	37.7	1.17	1.32	124.1	C3

River or Stream	Bankfull Width at X-section	Overall Average Bankfull Width	Sinuosity (Segment)	Overall Bankfull Depth in segment
001 Entiat	150.7	126	1.7	3.93
002 Icicle Ida	99.1	92.6	1.1	5.46
003 Icicle Alpine	107	86	1.13	5.08
004 Nason	88	85.35	1.18	4.21
006 Little Wenatchee	108.1	104.7	1.21	3.45
007 White River	108.7	115.95	1.27	3.59
008 Napeequa Lower 1	71.9	61.4	1.4	4.62
009 Napeequa Lower 2	63.4	56.7	1.5	5.04
010 Twin Lakes Creek	25.1	22.4	1.43	1.61
011 White River @USGS	134.2	123.5	1.6	5.85
012 White River @ Gray's	158.6	140.1	1.54	5.13
013 Napeequa Historical	59.1	54.2	1.18	3.19
014 Napeequa Historical	76	58.4	1.14	2.84
015 Chiwawa	87.9	89.45	1.18	2.65
016 Chiwawa	89.6	85.6	1.14	3.59
017 Chiwawa	83.9	63.4	1.31	3.32
018 Chiwawa	99.3	93.7	1.48	2.42
019 Chiwawa	99.1	90	1.09	3.84
020 Chiwawa	92.6	84.8	1.3	4.59
021 Chiwawa	100.7	103.8	1.31	3.86
022 Chiwawa @ USGS	137.4	108.9	1.06	5.02
023 Twisp	84	84	1.21	2.06
024 Twisp	106.9	94.8	1.31	2.68
026 Methow West Fork	58.3	50.5	1.11	2.27
027 Early Winters	56.2	55.3	1.22	2.07
029 Stehekin Upper	146	113.4	1.16	3.23
030 Stehekin Lower	209.3	210.9	1.12	3.92
028 Granite Creek	45.4	55.9	1.08	1.70
031 Sauk NF	132.4	192.5	1.27	2.97
032 Squire Creek	80.7	94.5	1.17	2.87
033 Dan's Creek	79.5	59	1.09	2.94
034 Stillaguamish NF	114.3	105.7	1.07	3.16
035 Clear Creek Upper	99.9	98.9	1.08	2.85
036 Clear Creek Lower	94.6	77.5	1.1	4.17
037 Sauk South Fork, Lower	138	102.5	1.08	3.48
038 Sloan Creek, Upper	113.7	97.2	1.16	3.75
039 Downey Creek Lower	75	77.7	1.22	2.03
040 Downey Creek Upper	78.1	81.2	1.17	1.66
041 Sauk South Fork Upper	92.1	115.6	1.19	2.20
042 Cascade River Upper	95.6	112.2	1.22	2.52
043 Cascade River Lower	180	125.1	1.17	4.39
044 Bacon Creek Upper	136.6	120.6	1.29	2.90
045 Bacon Creek Lower	117.8	112.2	1.09	3.13
046 Foss Creek Upper	47.9	48.1	1.38	1.95
047 FossCreek Lower	81	71.4	1.4	2.97
048 Rapid Creek Upper	76.6	82.2	1.17	2.52
049 Rapid Creek Lower	88.4	100.6	1.16	2.25
050 Skykomish NF Upper	76.9	76.5	1.13	2.85
051 Skykomish NF Lower	119.3	100	1.15	3.46
052 Martin Ck	44	35.8	1.31	1.51
053 Pilchuck Upper	62.7	63.2	1.27	2.38
054 Pilchuck Lower	77.1	77.9	1.24	3.22
055 Olney Creek	96.3	88.5	1.09	2.65
056 Snoqualmie Middle F. Upper	58.8	75.4	1.05	1.96
057 Snoqualmie Middle F. Lower	127.3	101.7	1.11	3.10
058 Taylor Creek Upper	57.6	74.8	1.22	2.36
059 Taylor Creek Lower	101.3	106.42	1.15	3.07
060 Lennox Creek	76.6	86	1.24	2.28

River or Stream	Average Bankfull Depth at Cross-Section	Cross-section area	Floodprone Width	D84 Riffle (mm)
001 Entiat	3.28	495.2	1060	74
002 Icicle Ida	5.10	505.6	372	248
003 Icicle Alpine	4.08	437	292	96
004 Nason	4.08	359.4	422	55
006 Little Wenatchee	3.34	361	701	145
007 White River	3.83	416.6	273	310
008 Napeequa Lower 1	3.95	283.8	246	49
009 Napeequa Lower 2	4.51	285.9	295	54
010 Twin Lakes Creek	1.43	36	204	8
011 White River @USGS	5.38	722	2179	25
012 White River @ Gray's	4.53	718.8	1993	46
013 Napeequa Historical	2.93	172.9	324	67
014 Napeequa Historical	2.18	165.7	218	145
015 Chiwawa	2.69	236.6	458	55
016 Chiwawa	3.43	307.2	518	39
017 Chiwawa	2.51	210.3	317	153
018 Chiwawa	2.29	227.2	528	59
019 Chiwawa	3.49	345.7	627	58
020 Chiwawa	4.21	389.4	727	95
021 Chiwawa	3.98	400.3	538	44
022 Chiwawa @ USGS	3.98	546.7	301	325
023 Twisp	2.06	172.8	555	152
024 Twisp	2.37	253.8	445	206
026 Methow West Fork	1.96	114.5	289	214
027 Early Winters	2.03	114.3	336	116
029 Stehekin Upper	2.51	366.1	510	246
030 Stehekin Lower	3.95	826.5	543	394
028 Granite Creek	2.09	94.8	93	152
031 Sauk NF	4.31	571	457	105
032 Squire Creek	3.36	271.2	223	153
033 Dan's Creek	2.18	173.7	200	278
034 Stillaguamish NF	2.92	334.1	246	105
035 Clear Creek Upper	2.82	281.6	251	188
036 Clear Creek Lower	3.42	323.2	459	264
037 Sauk South Fork, Lower	2.58	356.7	602	75
038 Sloan Creek, Upper	3.20	364.2	577	39
039 Downey Creek Lower	2.10	157.7	213	200
040 Downey Creek Upper	1.73	135.1	314	120
041 Sauk South Fork Upper	2.76	254.3	444	198
042 Cascade River Upper	2.96	283.1	348	212
043 Cascade River Lower	3.05	549.2	713	295
044 Bacon Creek Upper	2.56	349.8	473	261
045 Bacon Creek Lower	2.99	351.7	242	235
046 Foss Creek Upper	1.95	93.6	573	161
047 FossCreek Lower	2.62	211.9	746	53
048 Rapid Creek Upper	2.71	207.4	155	463
049 Rapid Creek Lower	2.56	226.1	302	104
050 Skykomish NF Upper	2.83	218	388	179
051 Skykomish NF Lower	2.90	346.2	304	334
052 Martin Ck	1.23	54	229	105
053 Pilchuck Upper	2.40	150.6	154	77
054 Pilchuck Lower	3.25	250.6	191	238
055 Olney Creek	2.43	234.2	272	118
056 Snoqualmie Middle F. Upper	2.51	147.7	267	526
057 Snoqualmie Middle F. Lower	2.48	315.4	227	135
058 Taylor Creek Upper	3.07	176.9	232	103
059 Taylor Creek Lower	3.23	327.1	426	115
060 Lennox Creek	2.56	195.9	229	490

River or Stream	Lower 1/3 Bar Transport size	(u) Velocity (FPS) by use of d/d84	Montgomery and Buffington Classification
001 Entiat	148	5.3	Response- pool:riffle
002 Icicle Ida	190	4.5	Response pool:riffle
003 Icicle Alpine	145	3.9	Response pool:riffle
004 Nason	203	6.8	Response pool:riffle
006 Little Wenatchee	215	6.5	Response pool:riffle
007 White River	458	6.4	Response pool:riffle
008 Napeequa Lower 1	89	5.8	Response pool:riffle
009 Napeequa Lower 2	72	4.2	Response pool:riffle
010 Twin Lakes Creek	33	4.5	Response pool:riffle
011 White River @USGS	65	5.7	Response pool:riffle
012 White River @ Gray's	82	5	Response pool:riffle
013 Napeequa Historical	84	5.1	Response pool:riffle
014 Napeequa Historical	198	4.6	Response pool:riffle
015 Chiwawa	105	7.3	Response pool:riffle
016 Chiwawa	122	6.3	Response pool:riffle
017 Chiwawa	220	4.1	Response pool:riffle
018 Chiwawa	150	4.6	Response pool:riffle
019 Chiwawa	98	5.3	Response pool:riffle
020 Chiwawa	133	4	Response pool:riffle
021 Chiwawa	90	6.7	Response pool:riffle
022 Chiwawa @ USGS	355	5.2	Response pool:riffle
023 Twisp	180	4.8	Response pool:riffle
024 Twisp	335	4.4	Response pool:riffle
026 Methow West Fork	435	5.7	Response pool:riffle
027 Early Winters	242	7.5	Response pool:riffle
029 Stehekin Upper	650	7.5	Response pool:riffle
030 Stehekin Lower	620	5.9	Response pool:riffle
028 Granite Creek	178	5.2	Response pool:riffle
031 Sauk NF	265	7.2	Response pool:riffle
032 Squire Creek	285	5.6	Response pool:riffle
033 Dan's Creek	735	5.8	Response pool:riffle
034 Stillaguamish NF	205	7.1	Response pool:riffle
035 Clear Creek Upper	395	4.2	Response pool:riffle
036 Clear Creek Lower	405	4.1	Response pool:riffle
037 Sauk South Fork, Lower	170	3.8	Response pool:riffle
038 Sloan Creek, Upper	98	5.8	Response pool:riffle
039 Downey Creek Lower	345	4.5	Response pool:riffle
040 Downey Creek Upper	300	5.4	Response pool:riffle
041 Sauk South Fork Upper	404	6.7	Response pool:riffle
042 Cascade River Upper	398	5.4	Response pool:riffle
043 Cascade River Lower	460	4.7	Response pool:riffle
044 Bacon Creek Upper	370	4.2	Response pool:riffle
045 Bacon Creek Lower	385	4.9	Response pool:riffle
046 Foss Creek Upper	360	6.5	Response pool:riffle
047 FossCreek Lower	85	4.1	Response pool:riffle
048 Rapid Creek Upper	555	4.6	Response pool:riffle
049 Rapid Creek Lower	215	5	Response pool:riffle
050 Skykomish NF Upper	298	5.4	Response pool:riffle
051 Skykomish NF Lower	540	5.8	Response-plane:glide.
052 Martin Ck	185	3.9	Response pool:riffle
053 Pilchuck Upper	130	5.5	Response pool:riffle
054 Pilchuck Lower	275	5.4	Response pool:riffle
055 Olney Creek	230	6.3	Response pool:riffle
056 Snoqualmie Middle F. Upper	780	4.2	Response pool:riffle
057 Snoqualmie Middle F. Lower	220	4.6	Response pool:riffle
058 Taylor Creek Upper	158	6.5	Response pool:riffle
059 Taylor Creek Lower	238	4.3	Response pool:riffle
060 Lennox Creek	512	3.9	Response pool:riffle

River or Stream	Elevation	Drainage Area m2	Square Feet of cross section per sq mile	CFSM	(n) Woody Debris Counts	% Woody Debris
001 Entiat	1575	192.1	2.6	12.5	21	0.29
002 Icicle Ida	2510	126.6	4.0	17.8	20	0.2
003 Icicle Alpine	2763	73.7	5.9	23.2	20	0.1
004 Nason	2124	92.1	3.9	26.4	20	0.2
006 Little Wenatchee	2105	61.0	5.9	38.7	20	0.05
007 White River	1925	89.6	4.7	29.7	20	0.1
008 Napeequa Lower 1	1940	45.3	6.3	36.6	20	0.35
009 Napeequa Lower 2	1946	45.0	6.4	27.0	21	0.28
010 Twin Lakes Creek	2822	5.0	7.3	32.7	20	0.25
011 White River @USGS	1884	149.5	4.8	27.7	29	0.24
012 White River @ Gray's	1895	147.2	4.9	24.3	27	0.33
013 Napeequa Historical	2500	35.3	4.9	24.9	20	0.4
014 Napeequa Historical	2510	28.7	5.8	26.7	20	0.6
015 Chiwawa	2485	64.2	3.7	26.9	22	0.36
016 Chiwawa	2478	65.4	4.7	29.7	20	0.25
017 Chiwawa	2635	50.1	4.2	17.1	24	0.29
018 Chiwawa	2560	57.9	3.9	17.9	20	0.3
019 Chiwawa	2457	70.6	4.9	26.0	32	0.28
020 Chiwawa	2453	78.2	5.0	20.1	25	0.28
021 Chiwawa	2420	104.2	3.8	25.8	30	0.43
022 Chiwawa @ USGS	2120	170.0	3.2	16.1	30	0.3
023 Twisp	2390	119.0	1.5	7.0	31	0.2
024 Twisp	2210	177.0	1.4	6.3	47	0.08
026 Methow West Fork	3010	32.1	3.6	20.4	20	0.45
027 Early Winters	3570	22.2	5.1	38.6	35	0.32
029 Stehekin Upper	2188	58.6	6.2	47.1	21	0.61
030 Stehekin Lower	1285	266	3.1	18.3	28	0.42
028 Granite Creek	3680	26.4	3.6	18.8	31	0.61
031 Sauk NF	1850	73.7	7.7	56.2	24	0.78
032 Squire Creek	479	18.2	14.9	83.4	31	0.58
033 Dan's Creek	497	16.38	10.6	61.0	22	0.68
034 Stillaguamish NF	495	48.5	6.9	48.8	20	0.35
035 Clear Creek Upper	1590	13.7	20.6	86.2	28	0.79
036 Clear Creek Lower	1560	13.9	23.3	94.6	33	0.4
037 Sauk South Fork, Lower	1960	18	19.8	76.2	35	0.65
038 Sloan Creek, Upper	2270	27.9	13.1	75.6	25	0.8
039 Downey Creek Lower	2180	24.7	6.4	28.7	34	0.79
040 Downey Creek Upper	2237	22	6.1	33.0	25	0.88
041 Sauk South Fork Upper	2320	13.5	18.8	126.2	23	0.65
042 Cascade River Upper	1145	66.5	4.3	22.9	27	0.7
043 Cascade River Lower	1140	91.2	6.0	28.1	24	0.58
044 Bacon Creek Upper	414	50.2	7.0	29.5	31	0.58
045 Bacon Creek Lower	386	51.4	6.8	33.6	37	0.35
046 Foss Creek Upper	1540	25.2	3.7	24.1	30	0.47
047 FossCreek Lower	1530	46.2	4.6	18.9	30	0.67
048 Rapid Creek Upper	1789	31.2	6.6	30.4	37	0.43
049 Rapid Creek Lower	1542	39.4	5.7	28.5	46	0.58
050 Skykomish NF Upper	2478	19	11.5	62.2	28	0.71
051 Skykomish NF Lower	1735	34.1	10.2	58.7	30	0.43
052 Martin Ck	3264	2.79	19.4	76.0	30	0.46
053 Pilchuck Upper	1060	7.6	19.8	109.1	46	0.52
054 Pilchuck Lower	952	17.6	14.2	76.7	45	0.51
055 Olney Creek	830	10.8	21.7	136.3	30	0.53
056 Snoqualmie Middle F. Upper	1980	16.7	8.8	37.4	36	0.23
057 Snoqualmie Middle F. Lower	1435	38.8	8.1	37.0	46	0.44
058 Taylor Creek Upper	1620	12.5	14.2	91.7	35	0.59
059 Taylor Creek Lower	1515	18.5	17.7	75.2	38	0.53
060 Lennox Creek	1952	12.3	15.9	62.5	32	0.53

River or Stream	LWD	MWD	LWD&MWD West slope	SWD	NWD	Redds on Glide	Fish Sighted	Carcasses
001 Entiat	0	0.05		0.24	0.71	YSC	ASC	
002 Icicle Ida	0	0		0.2	0.8	N	ASH	
003 Icicle Alpine	0	0		0.1	0.9	Y-		
004 Nason	0	0.1		0.1	0.8	YSC		SC2
006 Little Wenatchee	0	0.05		0	0.95	YSOK	ASOK	
007 White River	0	0.05		0.05	0.9	YSC	ASC	SC
008 Napeequa Lower 1	0	0.1		0.25	0.65	YSOK	ASOK, ASC	
009 Napeequa Lower 2	0	0.14		0.14	0.72	YSOK	ASOK, ASC	
010 Twin Lakes Creek	0	0		0.25	0.75	N	RT	
011 White River @USGS	0	0.1		0.14	0.76	YSOK	ASOK	SOK
012 White River @ Gray's	0.03	0.15		0.15	0.67	YSOK	ASOK, 700+	SC3
013 Napeequa Historical	0.1	0.15		0.15	0.6	YBT	RT	
014 Napeequa Historical	0.15	0.25		0.2	0.4	YBT	RT	
015 Chiwawa	0.09	0.09		0.18	0.64	YSC		SC
016 Chiwawa	0	0.1		0.15	0.75	YSC		SC2
017 Chiwawa	0	0.13		0.16	0.71	YSC		N
018 Chiwawa	0	0.1		0.2	0.7	YSC		SC
019 Chiwawa	0	0.13		0.15	0.72	YSC		SC2
020 Chiwawa	0	0.08		0.2	0.72	YSC		SC2
021 Chiwawa	0.17	0.2		0.06	0.57	YSC		SC2
022 Chiwawa @ USGS	0	0.03		0	0.7	N		SC
023 Twisp	0	0.1		0.1	0.8	YSC		SC
024 Twisp	0	0.02		0.06	0.92	YSC		SC
026 Methow West Fork	0.05	0.25		0.1	0.55	YBT	RT	
027 Early Winters	0	0.23		0.09	0.68	N	RT	
029 Stehekin Upper	0.23	0.33		0.05	0.39	N	ASH	
030 Stehekin Lower	0.21	0.21		0	0.58	YKOK	ASH, AKOK	
028 Granite Creek	0	0.35	0.35	0.26	0.39	YBT		
031 Sauk NF	0.08	0.46	0.54	0.21	0.22	YBT		
032 Squire Creek	0.06	0.29	0.35	0.23	0.42	YSOK	ASOK	
033 Dan's Creek	0.04	0.23	0.27	0.41	0.32	YSOK	ASH	
034 Stillaguamish NF	0	0.1	0.1	0.25	0.65	Y-	ASH	
035 Clear Creek Upper	0.25	0.36	0.61	0.18	0.21	N	RT	
036 Clear Creek Lower	0.03	0.27	0.3	0.1	0.6	N	RT	
037 Sauk South Fork, Lower	0.14	0.31	0.45	0.2	0.35	YBT		
038 Sloan Creek, Upper	0.08	0.44	0.52	0.28	0.2	Y-		
039 Downey Creek Lower	0.21	0.32	0.53	0.26	0.21	YBT	RT	
040 Downey Creek Upper	0.2	0.36	0.56	0.32	0.12	YBT	RT	
041 Sauk South Fork Upper	0.09	0.43	0.52	0.13	0.35	YBT		
042 Cascade River Upper	0.03	0.3	0.33	0.37	0.3	YBT,SC	ASH	
043 Cascade River Lower	0.08	0.29	0.37	0.21	0.42	YBT		
044 Bacon Creek Upper	0.06	0.1	0.16	0.42	0.42	YBT, SC	ASH	
045 Bacon Creek Lower	0.03	0.19	0.22	0.13	0.65	YBT		SC
046 Foss Creek Upper	0	0.2	0.2	0.27	0.53	N	RT	
047 FossCreek Lower	0.03	0.24	0.27	0.4	0.33	N	RT	
048 Rapid Creek Upper	0.03	0.13	0.16	0.27	0.57	YBT		
049 Rapid Creek Lower	0.02	0.26	0.28	0.3	0.42	YBT,SC	ASH	SC
050 Skykomish NF Upper	0.07	0.35	0.42	0.29	0.29	YBT		
051 Skykomish NF Lower	0.1	0.2	0.3	0.13	0.57	YBT		
052 Martin Ck	0	0.23	0.23	0.23	0.54	N	RT	
053 Pilchuck Upper	0	0.13	0.13	0.39	0.48	Y	ASH	
054 Pilchuck Lower	0.02	0.18	0.2	0.31	0.49	Y	ASH	
055 Olney Creek	0	0.16	0.16	0.37	0.47	YSC		SC
056 Snoqualmie Middle F. Upper	0.03	0.14	0.17	0.06	0.77	N		
057 Snoqualmie Middle F. Lower	0	0.07	0.07	0.37	0.56	YBT		
058 Taylor Creek Upper	0.03	0.29	0.32	0.29	0.41	YBT	RT	
059 Taylor Creek Lower	0	0.18	0.18	0.35	0.47	YBT	RT	
060 Lennox Creek	0	0.25	0.25	0.28	0.47	N	RT	

SC = Spring Chinook
BT = Bull Trout
ASH = Adult Steelhead
RT = Resident Trout
SOK = Sockeye

A = Adult
Y = Yes - Fish
N = No - Fish

River or Stream	d/D84	u/u*	Bankfull Discharge estimated by relative roughness
001 Entiat	13.5	9.3	2400
002 Icicle Ida	6.3	7.4	2250
003 Icicle Alpine	13.0	9.1	1707
004 Nason	22.6	10.6	2431
006 Little Wenatchee	7.0	7.6	2359
007 White River	3.8	6.1	2658
008 Napeequa Lower 1	24.6	10.8	1659
009 Napeequa Lower 2	25.5	10.8	1213
010 Twin Lakes Creek	54.6	12.7	162
011 White River @USGS	65.6	13.2	4142
012 White River @ Gray's	30.0	11.3	3576
013 Napeequa Historical	13.3	9.2	877.5
014 Napeequa Historical	4.6	6.6	763.8
015 Chiwawa	14.9	9.5	1729
016 Chiwawa	26.8	11.0	1943
017 Chiwawa	5.0	6.8	855
018 Chiwawa	11.8	8.9	1036
019 Chiwawa	18.3	10.0	1835
020 Chiwawa	13.5	9.3	1570
021 Chiwawa	27.5	11.0	2692
022 Chiwawa @ USGS	3.7	6.1	2739
023 Twisp	4.1	6.3	837
024 Twisp	3.5	5.9	1107
026 Methow West Fork	2.8	5.4	655
027 Early Winters	5.3	7.0	856
029 Stehekin Upper	3.1	5.6	2758
030 Stehekin Lower	3.1	5.7	4870
028 Granite Creek	4.2	6.4	497
031 Sauk NF	12.5	9.1	4139
032 Squire Creek	6.7	7.5	1517
033 Dan's Creek	2.4	5.0	1000
034 Stillaguamish NF	8.5	8.1	2366
035 Clear Creek Upper	4.6	6.6	1181
036 Clear Creek Lower	3.9	6.2	1315
037 Sauk South Fork, Lower	10.5	8.7	1371
038 Sloan Creek, Upper	25.0	10.8	2109
039 Downey Creek Lower	3.2	5.7	710
040 Downey Creek Upper	4.4	6.5	726.4
041 Sauk South Fork Upper	4.2	6.4	1704
042 Cascade River Upper	4.3	6.4	1522
043 Cascade River Lower	3.2	5.7	2560
044 Bacon Creek Upper	3.0	5.5	1483
045 Bacon Creek Lower	3.9	6.2	1728
046 Foss Creek Upper	3.7	6.1	608
047 FossCreek Lower	15.0	9.5	873
048 Rapid Creek Upper	1.8	4.3	950
049 Rapid Creek Lower	7.5	7.8	1124
050 Skykomish NF Upper	4.8	6.7	1182
051 Skykomish NF Lower	2.6	5.2	2000
052 Martin Ck	3.6	6.0	212
053 Pilchuck Upper	9.5	8.4	829
054 Pilchuck Lower	4.2	6.4	1350
055 Olney Creek	6.3	7.4	1472
056 Snoqualmie Middle F. Upper	1.5	3.8	625
057 Snoqualmie Middle F. Lower	5.6	7.1	1436
058 Taylor Creek Upper	9.1	8.3	1146
059 Taylor Creek Lower	8.6	8.1	1392
060 Lennox Creek	1.6	4.0	769

Appendix C. Chapter 3
FIGURE 3. Glacial-Fluvial Valley Type "V"

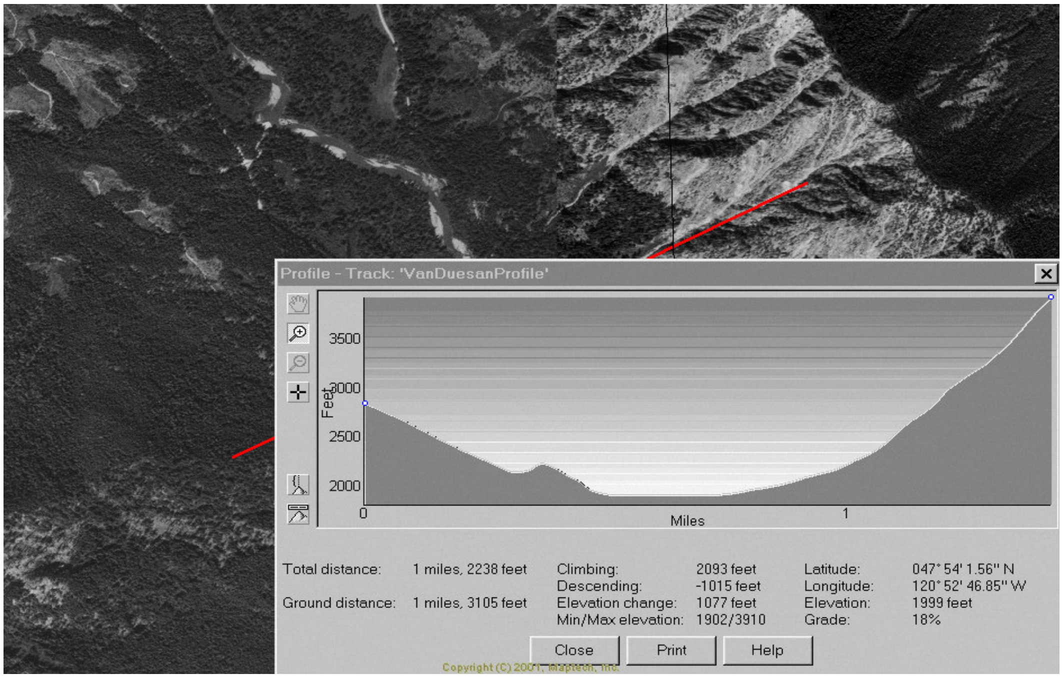
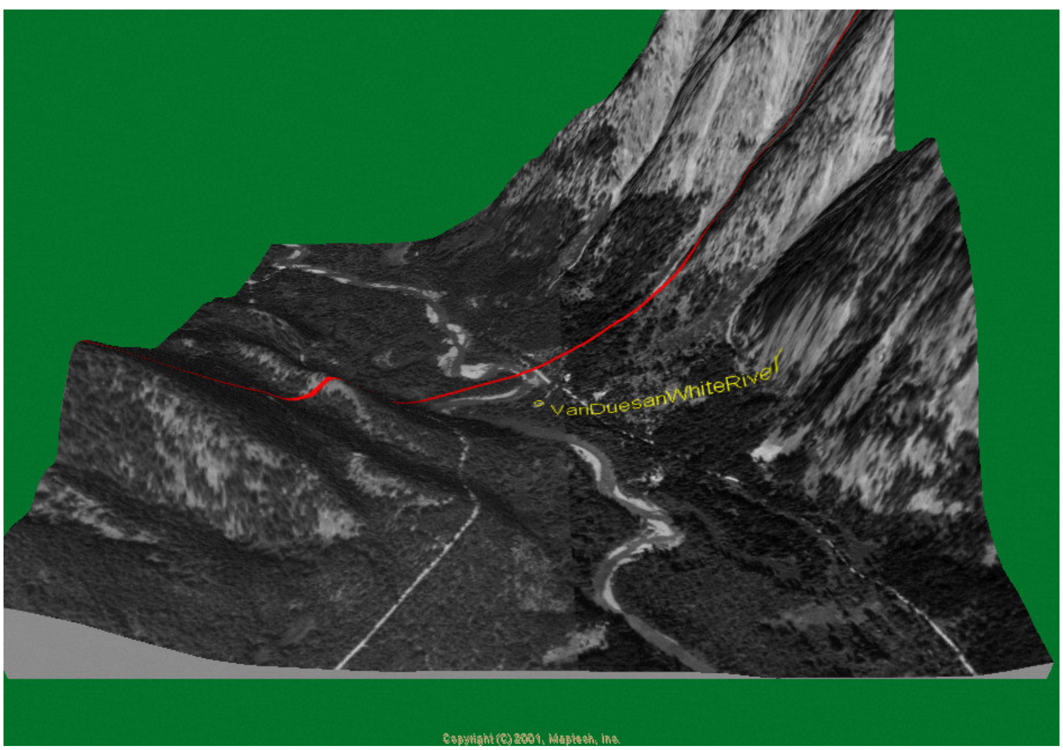


FIGURE 4



Terrain Navigator Pro 2003

Appendix D. Chapter 4

TABLE 1
Basic Stream Reach Stability Analysis

Reach Name:			**Profile Feature: Pool or Riffle**
Location:			**Photo Ref: Y or N ?**
Reference Reach: Y or N?	**Stream Classification (if known)**		
Measured Feature	**Field Measurement**	**Measure**	**Value** Low, Moderate, High, etc.
Bank Height Ratio (BHR)	**Max depth Top of Bank (TOB):**	**TOB/MBF:**	
	Max depth of bankfull (MBF):		
Root Matrix	**Root Depth:**	**RD/BH:**	
	Bank Height:		
Root Density Use carpenter ruler or grid count	**% of 4 square feet of bank covered by roots**	**% Roots/ % Total Space w/i ($4ft^2$):**	
Use Staff and tapes and rulers in Photos for scale. Attach Photos of three field measurements and cross-section of this form.			

Categorical Hazard	BHR	Root Depth/ Bank Height (Root Matrix)*	%Streambank Cover, Root Density %	Other Features Noted i.e. bank material texture(s)
LOW (STABLE)	1.0 - 1.1	1.0 - 0.9	100 - 80	
LOW	1.11 - 1.19	0.89 - 0.5	79 - 55	
MODERATE	1.2 - 1.59	0.49 - 0.3	54 - 30	
HIGH	1.6 - 2.0	0.29 - 0.15	29 - 15	
VERY HIGH	2.1 - 2.8	0.14 – 0.05	14 – 5.0	
EXTREME	>2.8	<0.05	< 5.0	

Ratings are based on Low, moderate, high and extreme values as defined by Rosgen (1996). Includes list of changes in latest printing (1/15/01).
*** Include cover such as lodged woody debris integrated with root area.**

Measured Feature (Apex of meander)	Reference Reach	Reach of Interest	Rating Index	Percent Departure
Bank Height Ratio	1.07	1.25	Moderate	17%
Root Density	70%	25%	High	64%
Root Matrix	.78	.30	Moderate	62%

Measured Feature (Riffle)	Reference Reach	Reach of Interest	Erosion Potential	Percent Departure
Bank Height Ratio				
Root Density				
Root Matrix				

If any of the three features are high, the stream is subject to rapid channel change
If all three are moderate, stream site may likely be unstable.
If root density and/or matrix has high hazard(s); however, BHR is low, expect lateral movement or migration with a wider and shallow channel, possibly aggradation.
If BHR is greater than 1.2 and root system is entirely fibrous, site is likely to be unstable

Figure 1.

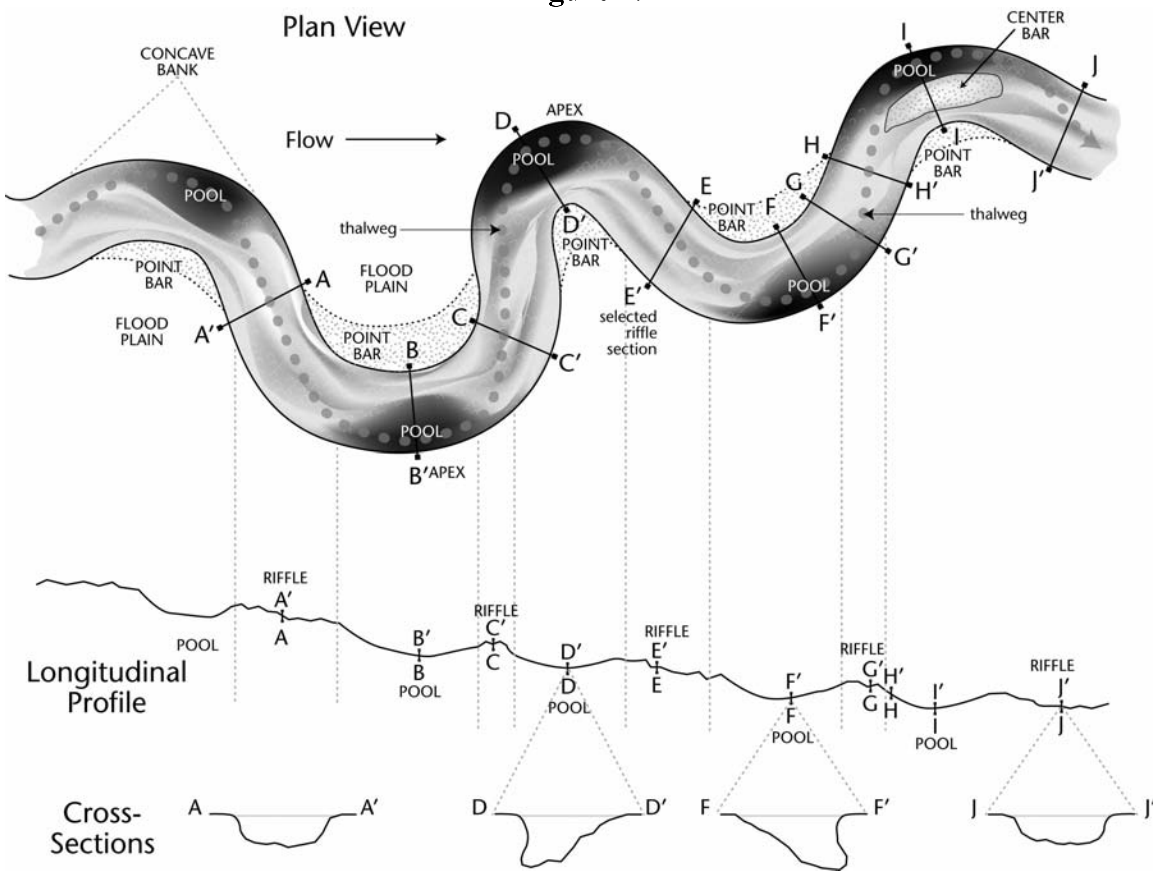


Figure 2

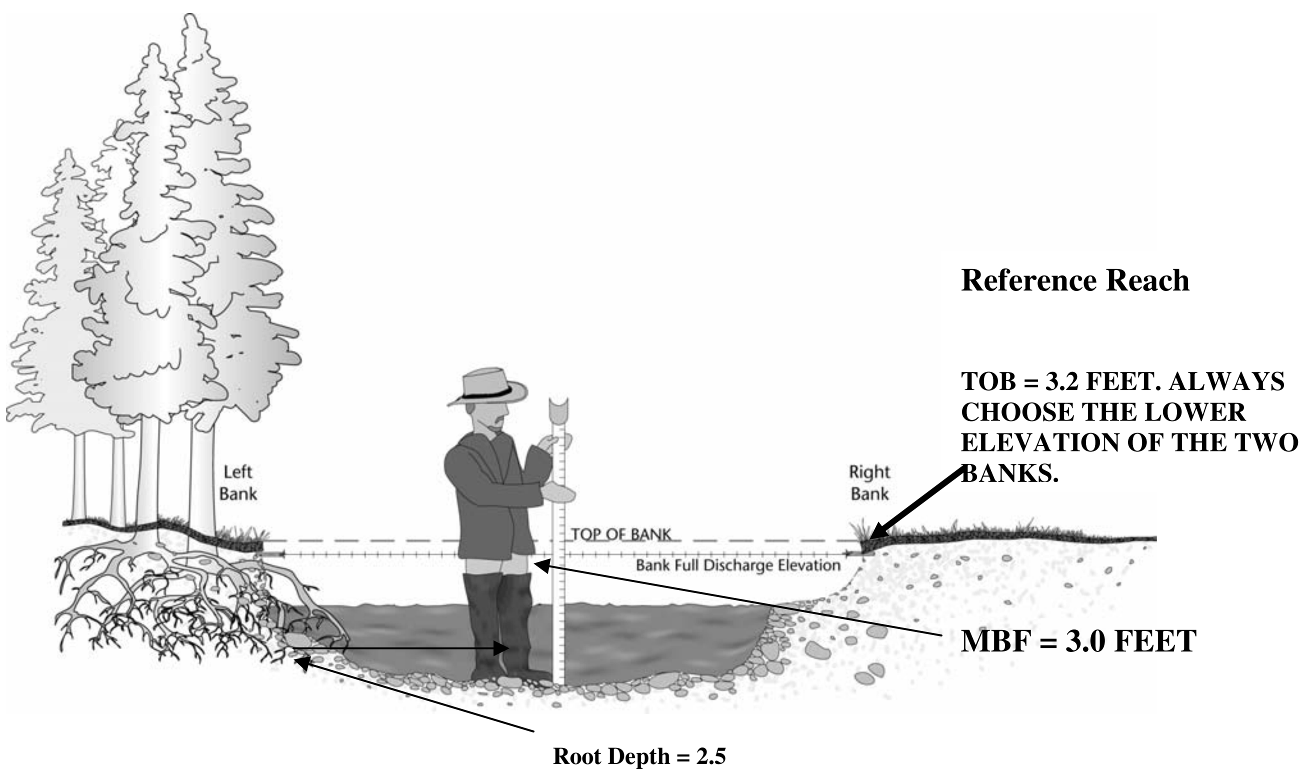


Figure 3

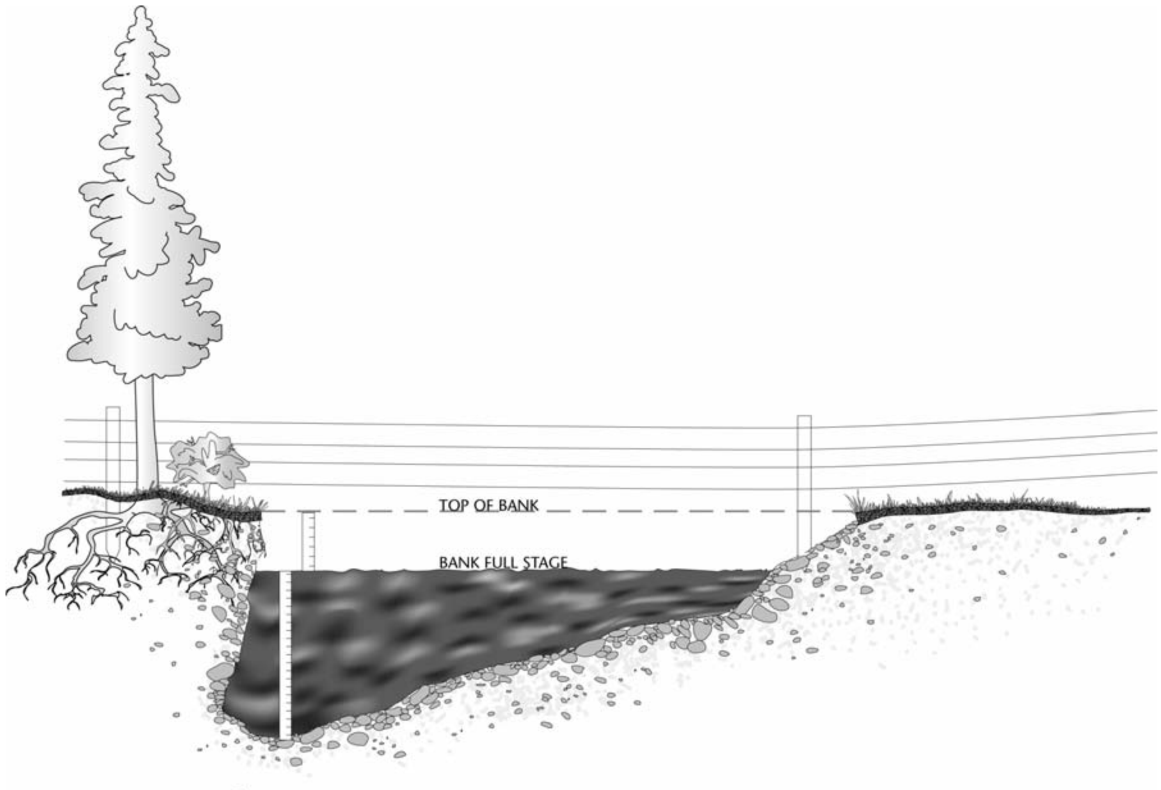
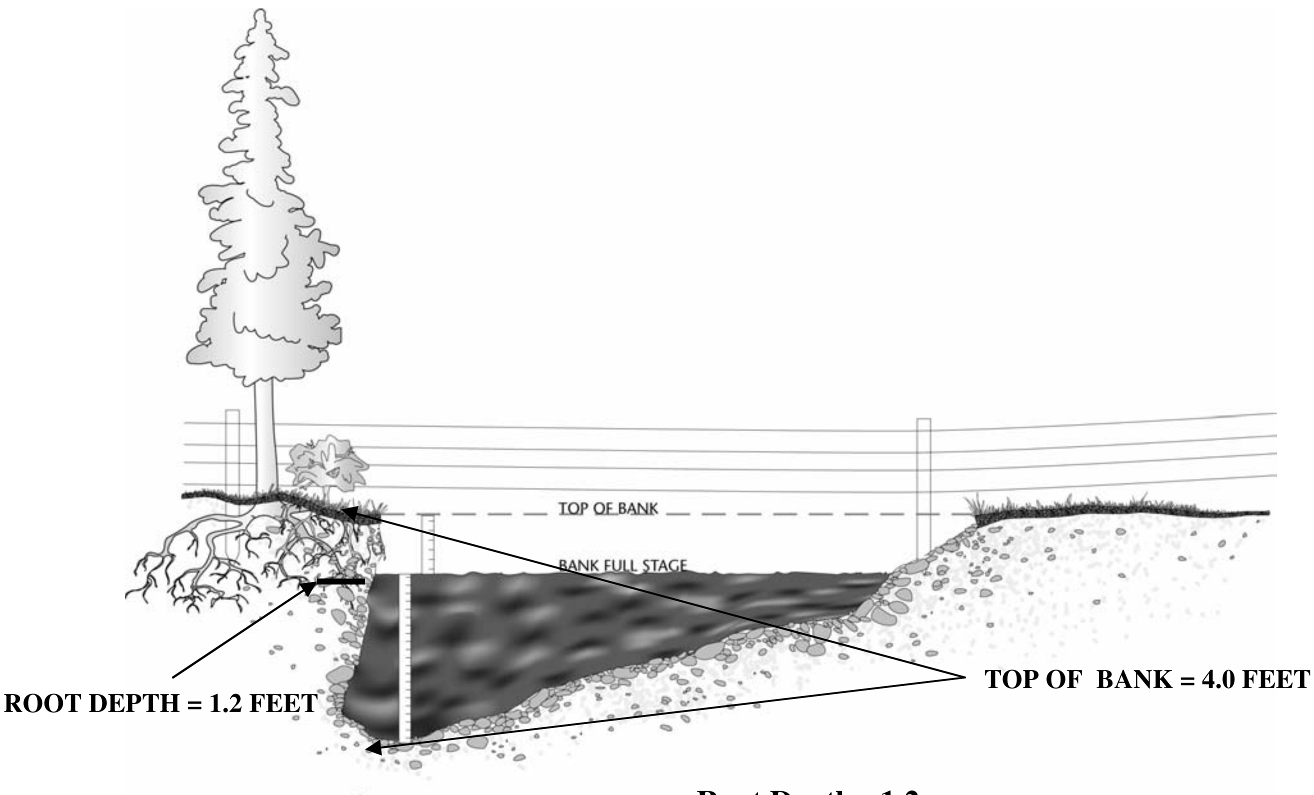
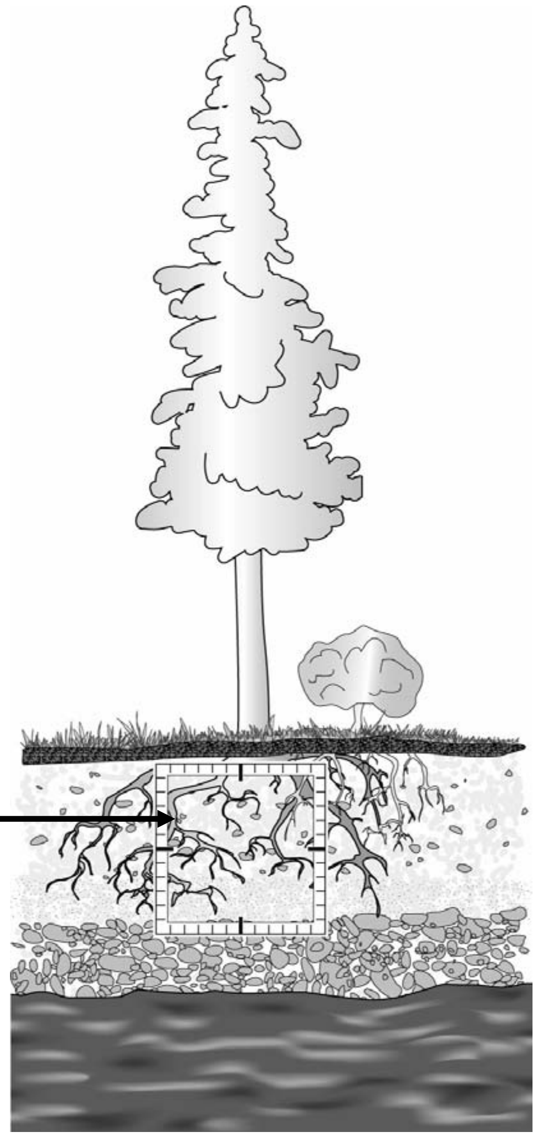


Figure 4



$$\frac{\text{Root Depth: } 1.2}{\text{Top of Bank: } 4.0} = 0.30$$

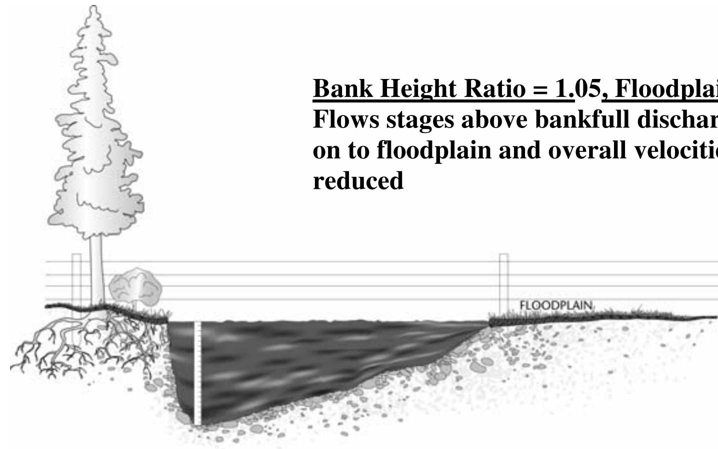
Figure 5



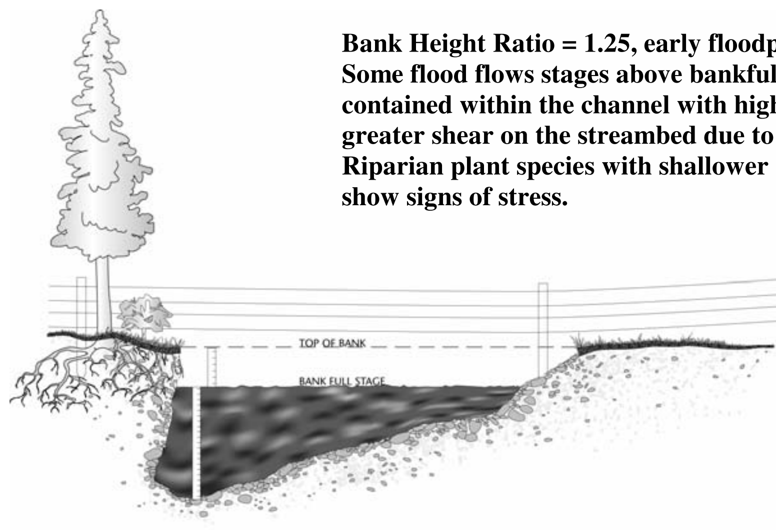
Percent of bank that is made up of roots i. e. 30%

i. e. 70% for reference condition

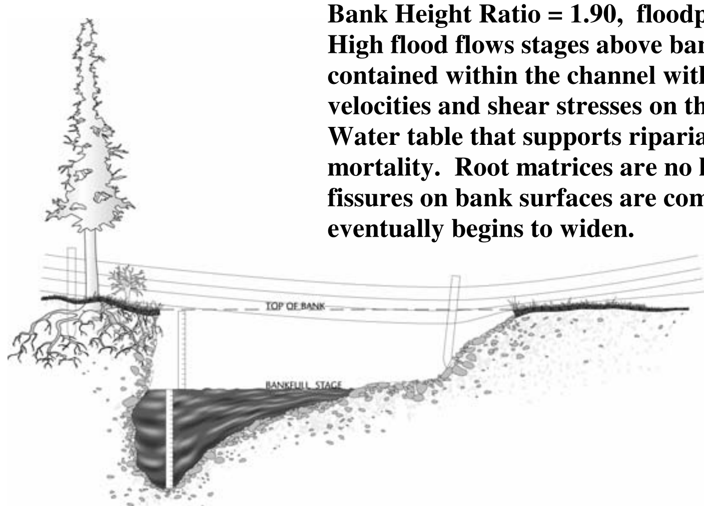
FIGURE 6, INCISION STAGES



<u>Bank Height Ratio = 1.05, Floodplain Attached</u>
Flows stages above bankfull discharge are distributed on to floodplain and overall velocities are substantially reduced



Bank Height Ratio = 1.25, early floodplain departure
Some flood flows stages above bankfull discharge are now contained within the channel with higher velocities and greater shear on the streambed due to deeper water. Riparian plant species with shallower root systems begin to show signs of stress.



Bank Height Ratio = 1.90, floodplain departure
High flood flows stages above bankfull discharge are now contained within the channel with extremely high velocities and shear stresses on the streambed and banks. Water table that supports riparian is gone causing plant mortality. Root matrices are no longer present and fissures on bank surfaces are common as the streambed eventually begins to widen.