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SHORT TERM EFFECTIVENESS OF HIGH DENSITY LARGE WOODY DEBRIS IN ASOTIN CREEK AS A CHEAP AND CHEERFUL RESTORATION ACTION

by

Reid Camp

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Watershed Science

Approved:

Joseph Wheaton Major Professor	Philip Bailey Committee Member
Brett Roper Committee Member	Mark R. McLellan Vice President for Research and Dean of the School of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2015

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ABSTRACT

Short-Term Effectiveness of High Density Large Woody Debris

in Asotin Creek as a Cheap and Cheerful Restoration Action

by

Reid J. Camp, Master of Science

Utah State University, 2015

Major Professor: Dr. Joseph Wheaton
Department: Watershed Sciences

In response to human impacts, river restoration and rehabilitation actions have become a priority in the United States. In the Pacific Northwest, most restoration actions are focused on repairing degraded freshwater habitat to increase or improve Pacific salmonid production. However, traditional river restoration actions remained largely unchanged for over 100 years despite a lack of definitive evidence that the actions were effective. Recently, we have been developing “cheap and cheerful” restoration actions that are low impact, cost effective, can be implemented over large scales, and target degraded processes. However, because cheap and cheerful restoration is a relatively new method, and restoration effectiveness monitoring is universally lacking, the success of these types of projects has not been assessed.

To address this issue, I studied the short-term physical effectiveness of a type of cheap and cheerful restoration that uses high density large woody debris ($_{HD}$LWD) to restore instream habitat complexity in two wadeable tributaries to Asotin Creek in

southeast Washington State. Additionally, I developed a mobile database application to facilitate data collection using a novel rapid restoration effectiveness assessment survey.

Results indicate that the structures are effective at imposing several immediate hydraulic responses following installation. These hydraulic responses increase hydraulic roughness, which results in predictable geomorphic responses following high flow events. Following restoration, the number and area of pools and bars significantly increased within treatment sites, while the number and area of planar units decreased. Likewise, it appears that the addition of the structures has encouraged a 25% increase in depositional volume at treatment sites compared to control sites.

Results from the rapid assessment approach supported the more vetted approaches used to assess the efficacy of the treatment. However, my results indicate that inter-observer variability when using the rapid protocol may be high, and visual estimates of geomorphic unit area are inflated. Analysis of the rapid assessment approach revealed pertinent improvements to the application and rapid protocol that will be made before the approach can be broadly applied

(198 pages)

PUBLIC ABSTRACT

Short-Term Effectiveness of High Density Large Woody Debris in Asotin Creek as a Cheap and Cheerful Restoration Action

Reid J. Camp

In response to human impacts, river restoration and rehabilitation actions have become a priority in the United States. In the Pacific Northwest, most restoration actions are focused on repairing degraded freshwater habitat to increase or improve Pacific salmonid production. However, traditional river restoration actions remained largely unchanged for over 100 years despite a lack of definitive evidence that the actions were effective. More recently, there has been a surge in process-based restoration actions, which aim to reestablish the physical and biological processes that maintain fluvial and floodplain environments by targeting the root causes of degradation in a watershed. Cheap and cheerful restoration projects focus on restoration actions that are low impact and cost effective, can be implemented over large scales, and target degraded processes. However, because cheap and cheerful restoration is a relatively new method, the success of these types of projects has not been assessed.

To address this issue, I studied the short-term physical effectiveness of a type of cheap and cheerful restoration that uses high density large woody debris ($_{HD}$LWD) to restore instream habitat complexity in two wadeable tributaries to Asotin Creek in southeast Washington State. My specific research objectives included (1) assessing hydraulic and geomorphic responses in the stream channel imposed by restoration structures, (2) quantifying the changes to geomorphic channel unit assemblages post

restoration, (3) quantifying changes in sediment storage post restoration, and (4) developing a geomorphic condition assessment of Asotin Creek using the River Styles Framework. Additionally, I developed a mobile database application (app) to facilitate data collection using a novel rapid restoration effectiveness assessment survey.

Through analysis and a thorough review of the land use history in Asotin Creek, I determined that much of the watershed is in poor geomorphic condition based on the River Styles Framework for river classification. Many stream reaches have been degraded from their historic condition and often lack habitat complexity associated with suitable rearing habitat for juvenile salmonids. My results indicate that the structures are impose several immediate hydraulic responses following installation. These hydraulic responses increase hydraulic roughness, which results in predictable geomorphic responses following high flow events. Following restoration, the number and area of pools and bars significantly increased within treatment sites, while the number and area of planar units decreased. Likewise, it appears that the addition of the structures has led to a 25% increase in depositional volume at treatment sites compared to control sites.

Results from the rapid assessment approach supported the more vetted approaches used to assess the efficacy of the treatment. However, the viability of the app and rapid protocol indicate that inter-observer variability may be high, and estimates of geomorphic unit area are not entirely consistent with the vetted approaches. Analysis of the rapid assessment approach revealed pertinent improvements to the app and rapid protocol that will be made in the future.

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Funding for this project was provided by Eco Logical Research, Inc. (ELR) in Logan, Utah. My research was completed in conjunction with the Asotin Creek Intensively Monitored Watershed (IMW) project, a long-term watershed experiment. The IMW is funded by the Snake River Salmon Recovery Board.

I would like to thank my advisor, Joe Wheaton, for his guidance and support during my research. Joe taught me the invaluable skill of reading the landscape, that there is truth in arm-waving, and gave me the flexibility and resources to pursue every research question I had, no matter how tangential. I would also like to thank my committee members, Philip Bailey and Brett Roper, for their helpful feedback and continuous interest in my research. Additionally, I would like to thank Nick Bouwes and Stephen Bennett for allowing me to temporarily leave my position at ELR to attend school, for their feedback, and constant support of my research. I would also like to make special mention of the graduate students and researchers in the Ecogeomorphology and Topographic Analysis Lab, and the Fluvial Habitats Center for their help along the way. In particular the GC members, Nate Hough-Snee, Alan Kasprak, and Eric Wall, for keeping me within the realm of sanity while at USU.

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CHAPTER 1

THESIS INTRODUCTION

In response to human impacts, river restoration and rehabilitation actions have become a priority in the United States. In the Pacific Northwest, much of the restoration is focused on repairing degraded freshwater habitat for Pacific salmonids [*Bernhardt et al.*, 2005; *Roni et al.*, 2008]. However, despite over 100 years of in-channel restoration actions [*Bayley*, 2002], traditional techniques have changed very little [*Thompson*, 2005; *Whiteway et al.*, 2010]. The high cost and low documented success of traditional techniques has led to a focus on process-based restoration which aims to "reestablish normative rates and magnitudes of physical, chemical, and biological processes that create and sustain river and floodplain ecosystems" [*Beechie et al.*, 2010]. However, the most common techniques include engineered structures focused on designs that are highly durable, allowing them to persist for upwards of 20 years [*Roni et al.*, 2002], but their effectiveness at improving salmonid populations is inconclusive [*Thompson*, 2006]. Restoration actions involving static engineered structures tend to provide pockets of improved habitat, but do not fix the root causes of fish habitat degradation [*Thompson*, 2005]. By targeting the root causes of degradation, tailoring actions to local potential, implementing at appropriate scales, and sufficiently monitoring implemented actions, funds for restoration can be spent more effectively [*Wohl et al.*, 2005; *Beechie et al.*, 2010; *Brierley and Fryirs*, 2012; *McMillan and Vidon*, 2014]. However, attaining this knowledge requires extensive investigation into the land use and evolutionary history of the watershed [*Brierley and Fryirs*, 2005].

The need to advance restoration in terms of scale, effectiveness, and decreased cost is apparent. This has led to the development of cheap and cheerful restoration approaches (e.g. [*Zeedyk et al.*, 2009; *Pollock et al.*, 2012; *Wheaton et al.*, 2012; *Camp and Wheaton*, 2014]). By definition, these types of projects are implemented using novel approaches that substantially reduce the cost per unit of implementation (cheap) without reducing the efficacy of the actions (cheerful). Cheap and cheerful projects have the potential to have a more substantial effect on slowing or reversing habitat degradation, because they focus on the disconnected processes that lead to the initial problems. Additionally, due to relatively lower cost, these projects can restore a much larger area, potentially resulting in a larger treatment effect. For example, a group working on the Bridge Creek Intensively Monitored Watershed (IMW) in Oregon recruited beavers (*Castor canadensis)* to target channel incision processes [*Pollock et al.*, 2012, 2014] and have seen success in increased bed aggradation. By following similar principles, restoration can target disconnected processes over larger scales to meet restoration goals.

Additionally, strategies for effectively monitoring the success of river restoration need to advance. The success of restoration is directly related to the initial goals of a project [*Jähnig et al.*, 2011]; however, projects are rarely accompanied by standardized, before-and-after, long term monitoring [*Bernhardt et al.*, 2005; *Roni et al.*, 2008]. Despite an average of >$1 billion per year being spent on restoration [*Bernhardt et al.*, 2005], projects often forego effectiveness monitoring, and thus neglect the opportunities to learn about natural processes, adapt methods, and improve our ability to effectively rehabilitate salmonid habitat [*Bernhardt et al.*, 2005; *Thompson*, 2006]. Unfortunately, increasing project monitoring is often not a choice for practitioners because funding for

monitoring is dismal compared to funding for restoration [*Bernhardt et al.*, 2007; *Roni et al.*, 2008].

In addition to cheap and cheerful restoration, there is a need for cost effective monitoring, especially if appropriate levels of funding continue to be absent. To be sufficient, monitoring must take place over many years, at broad scales, and must be consistent [*Roni et al.*, 2005, 2008]. However, current techniques for monitoring over broad scales are inherently expensive, which limits the spatial extent of monitoring. For example, to assess geomorphic changes to river channels and floodplains, high resolution spatial data is often collected using total stations, real time kinematic global position systems, and terrestrial or airborne laser scanners. While these methods are robust and standardized, they come with a large price tag (equipment, specialized training), which often limits monitoring to the reach scale [*Kondolf et al.*, 2007].

Cheap and cheerful monitoring can be achieved by decreasing the amount of time spent collecting data and/or decreasing the detail of the data collected; however, this does not have to be at the cost of addressing restoration hypotheses. If restoration projects begin with clear objectives and hypotheses [*Roni et al.*, 2005], then monitoring can be better targeted to assess those questions [*Fernández Cortes et al.*, 2011]. This principal has been used in many region-wide stream assessment protocols to evaluate fish habitat and water quality [*AREMP*, 2010; *PIBO*, 2012]. Therefore, it is conceivable for all restoration projects to develop individual protocols, using standardized approaches, which focus on answering restoration hypotheses. Additionally, with the aid of mobile electronic devices and customizable database applications, consistency in data collection can be maintained while increasing rapidity [*Camp and Wheaton*, 2014].

In this thesis, I present a method of cheap and cheerful monitoring to assess the geomorphic changes imposed by a high density large woody debris ($_{HD}$LWD) loading project on two small tributaries to Asotin Creek in Washington State. This monitoring method sacrifices some spatial resolution for rapidity, which allows us to monitor a 4 km treatment section and a complete census of physical responses at every restoration structure in as little as three days using one technician. To facilitate data collection, we developed a custom mobile database application (app) for assessing changes in individual structure condition, influence, and geomorphic unit assemblages.

The goal of this thesis is to evaluate the effectiveness of instream restoration structures at inducing hydraulic and geomorphic responses to the active stream channel, resulting in greater habitat complexity for juvenile steelhead (*Oncorhynchus mykiss*). Because holistic restoration assessment requires knowledge of watershed history and geomorphic condition, I begin this thesis with an in-depth review of Asotin Creek's history. The River Styles Framework is a process-informed classification system used to identify reach types (river styles) based on geomorphology and assess geomorphic condition throughout a watershed. Therefore, in Chapter 2, I present a report of stages one and two of the River Styles classification framework for Asotin Creek to investigate the historical and evolutionary potential of the watershed. In Chapter 3, I describe the overall effectiveness of the $_{HD}$LWD treatment on Asotin Creek at increasing geomorphic complexity by identifying explicit channel responses and changes in geomorphic unit assemblages using a combination of topographic surveys and rapid assessments. I examine these differences by comparing treatment and control reaches, pre and post restoration, on two study streams, Charley Creek and the South Fork of Asotin Creek. In

Chapter 4, I examine the feasibility of using an app and protocol I developed for cheap and cheerful restoration effectiveness monitoring by comparing consistency between observers, and assessing the accuracy of the data collected compared to more vetted methods. In Chapter 5, I summarize my results and discuss the management implications of cheap and cheerful restoration and monitoring.

CHAPTER 2

RIVER STYLES CLASSIFICATION AND GEOMORPHIC CONDITION OF ASOTIN CREEK

RIVER STYLES STAGE ONE: INTRODUCTION

In the United States, stream restoration projects have become commonplace to address decades of human impacts [*Bernhardt et al.*, 2005]; however, many projects often fail to meet environmental objectives due to misguided planning [*Beechie et al.*, 2010]. This lack of documented restoration success may be the result of presumptuous actions taken to reverse the damage humans have done to the world's rivers [*Lave*, 2012]. In learning from past successes and failures, we know that a key component to stream restoration success is an in-depth understanding of the target watershed [*Brierley and Fryirs*, 2009; *Beechie et al.*, 2010]. Because we often alter physical structure to meet ecological goals, proper restoration project planning requires knowledge of the dynamic processes and relationships that maintain fluvial environments [*Thomson et al.*, 2004; *Chessman et al.*, 2006]. Therefore, a fluvial geomorphological perspective of watershed condition provides a logical foundation for assessing the need for restoration and the restoration potential within a watershed [*Brierley et al.*, 2011].

The River Styles Framework for river classification is a process-informed, geomorphically centered approach to appropriately describe the controls that govern river character, behavior, evolution, and trajectory [*Brierley and Fryirs*, 2005]. A river's character can be described as the makeup of its morphology including the valley and the

geomorphic formations in its channel and floodplain. Alternatively, a river's behavior is its capacity for alterations which is different across multiple spatial-temporal scales. Climatic and physical controls in the drainage govern the river character and behavior, but also have defined the river's evolutional history that led to its current form and position. Knowing these three key pieces of the processes that give a river its current form, one can make predictions on the river's future trajectory [*Fryirs et al.*, 2012]. This type of information is invaluable to effectively implement, monitor, and learn from stream restoration and rehabilitation [*Brierley and Fryirs*, 2012].

I completed the first two stages of the River Styles Framework to classify the specific reach types (i.e. river styles) and geomorphic condition of Asotin Creek and its tributaries. Asotin Creek is an 847 km^2 watershed in southeast Washington State and a mainstem tributary to the Snake River downstream of Hells Canyon. Asotin Creek is a wild summer steelhead (*Oncorhynchus mykiss*) sanctuary and home to other native salmonids and non-game fishes [*Crawford et al.*, 2011]. However, homogenous habitat and a lack of overwintering refugia (a lack of pool habitat) may be limiting steelhead production in freshwater habitats [*Solazzi et al.*, 2000] such as Asotin Creek [*Bennett et al.*, 2012]. Asotin Creek was selected as an Intensively Monitored Watershed (IMW) in 2008 to determine the effectiveness of stream restoration at increasing steelhead production [*PNAMP*, 2005; *Bennett and Bouwes*, 2009]. Subsequently, a restoration project began in 2012 in three tributaries (Charley Creek and the North and South Forks of Asotin Creek), aimed at increasing geomorphic diversity through the addition of large woody debris (LWD). *Wheaton et al.* [2012] hypothesized that the lack of LWD and poor LWD recruitment decreased the river's ability to cause the geomorphic changes

necessary to create and maintain pool habitat. To assess the effectiveness of high densities of LWD inputs at causing geomorphic change, we must also understand a river's capacity for adjustment.

The Asotin Creek IMW provides an opportunity to explore the interaction between LWD and geomorphic change, and the effect on refugia habitat for steelhead. Monitoring for changes in habitat and steelhead production is ongoing. The purpose of the intensive monitoring is to detect any changes, but more importantly to determine the processes that lead to those changes and learn why certain restoration strategies worked or did not work.

METHODS

The River Styles Framework provides the multi-scalar context necessary to inform us how certain reaches of river may respond to focused restoration activities. It does so by dividing the classification into multiple stages. In **Stage One**, river styles delineation is guided by climate, hydrology, landscape units, basin controls, and geomorphic unit assemblages that determine river character and behavior. Further analysis in this stage determines downstream patterns that may be unique to subbasins. **Stage Two** involves the assessment of the river's current geomorphic condition at the reach scale compared to reference reaches within the drainage that represent a "best condition" for each river style. This provides a basis to assess their evolution and capacity for adjustment. The groundwork in stages one and two pave the way for **Stage Three**, where we make predictions on the river's current trajectory and recovery potential within each river style. Assessing the recovery potential and possible trajectory of

reaches sets the goals for management in the drainage which are laid out in **Stage Four**. Our goal is to use the River Styles Framework to provide basis for contextualizing and understanding the effectiveness of restoration in the Asotin Creek IMW. Equally important, we can use what we learn from intensive monitoring to vet the river styles procedure for future river management and restoration applications. Because the IMW restoration phase is complete, I am only including Stages One and Two; however, I will be completing Stages Three and Four for a final river styles report in conjunction with ongoing Asotin IMW monitoring reports for the Snake River Salmon Recovery Board.

REGIONAL SETTING

Geology

Asotin Creek is located in the southeast corner of Washington State and is a mainstem tributary to the Snake River. The headwaters largely originate from the northern slopes of the Blue Mountains in the west, and the Columbia Plateau in the eastern portions of the watershed. Geology in the region is dominated by multiple basaltic lava flows (Figure 2.1). The basalt layers were deposited and uplifted during the Miocene (5.4-23 million years ago).The channel network has subsequently dissected the basalt during the Pliocene (5.4 to 2.4 million years ago) to create deep, rocky canyons and dissected plateaus [*Gentry*, 1991]. Erosion of plateau basalt is characterized by steep canyon walls that play an important role in contemporary river behavior by restricting the movement and defining the character of the streams in the Asotin Creek drainage. Most of the eastern portion of the drainage is topped by loess soil deposits primarily sourced

from flood sediments of proglacial Lake Missoula during the late Pleistocene (12-18 thousand years ago) [*Muhs et al.*, 2014].

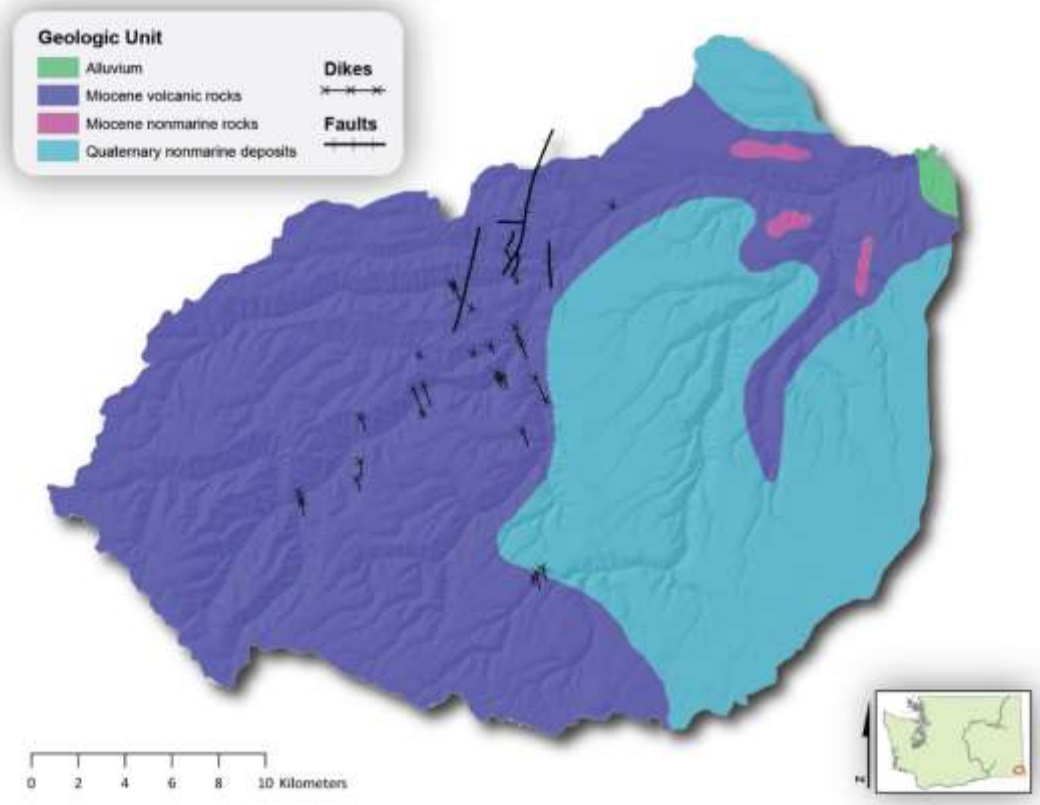

Figure 2.1. Geology within the Asotin Creek drainage.

Land Use History

Grazing by cattle, sheep, and horses began in the 1870s throughout the watershed. Most of the high elevation forestland has been logged at least once since European settlement [*ACCD*, 1995]. A model watershed plan was developed in 1995 for Asotin Creek to address poor land use practices that were linked to 1) high stream temperature,

2) lack of pools with LWD, 3) impairment due to excessive fine sediments, and 4) high fecal coliform levels within the stream [*ACCD*, 1995]. Since the inception of the model watershed plan, land use practices have greatly improved, particularly in upland farming practices, but grazing and logging still occurs in the Umatilla National Forest near Asotin Creek's headwaters. Most of the upper watershed is currently publicly owned and maintained by the Washington State Department of Fish and Wildlife and the United States Forest Service. Most anthropogenic development within the drainage has been agriculture and road construction along the riparian corridor of most of the lower river network. However, the town of Asotin is located at the mouth of the drainage, where the creek has been highly confined by levees, roads, and bridges for the last ~2 km. Exotic grasses (e.g. cheat grass) and forbs (e.g. invasive cinquefoils) are present and their range is expanding throughout the drainage (Figure 2.2). Invasive plant species presence appears to be mostly associated with areas where grazing pressure is the highest.

Euro-American settlement in the region of Asotin Creek began shortly after Lewis and Clark's return from their trans-continental expedition in 1806. By 1811, trappers and hunters established settlements, and by 1861 farms and logging camps were common around forested areas and water [*Gentry*, 1991]. The early establishment of trappers in the inland northwest led to the virtual elimination of beaver (*Castor canadensis*) in less than five decades [*Naiman et al.*, 1986]. Beaver dams historically played a large role in the behavior of small and mid-sized streams by slowing water, increasing wetland area, buffering floods, trapping sediment, among others, and their nearly complete removal has greatly altered evolutionary sequence of streams across North America including Asotin Creek [*Naiman et al.*, 1988; *Hessburg and Agee*, 2003].

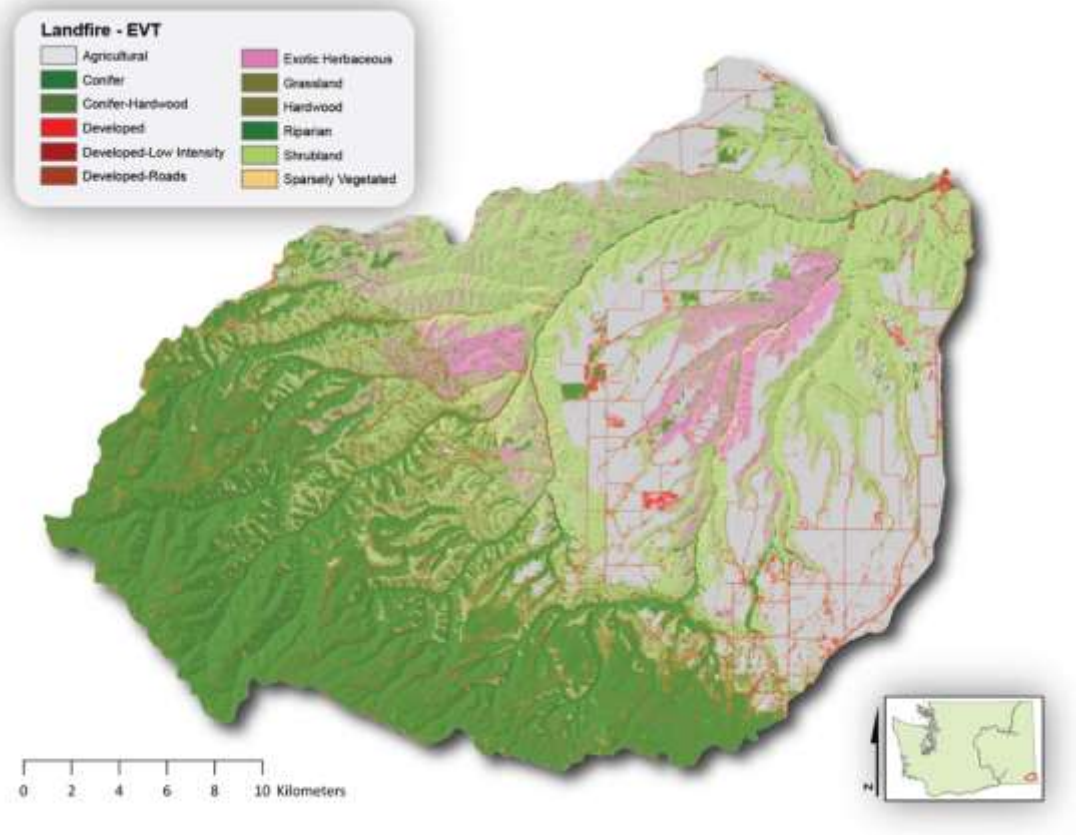

Figure 2.2. LANDFIRE existing vegetation types for the Asotin Creek drainage.

The town of Asotin was founded in 1878 and became the Asotin County seat in 1883, and the area of cultivated and grazed land was increasing significantly [*Gentry*, 1991]. From the late 1800s to the 1950s, timber harvest greatly increased as entire landscapes were stripped of valuable lumber [*Robbins and Wolf*, 1994]. Subsequently, through land management and the alteration of vegetation communities by extensive sheep and cattle grazing, fire regimes in the area changed from frequent low severity fires, to infrequent high severity fires [*Hessburg and Agee*, 2003]. These rapid changes in

the fire regime and land use on the Columbia Plateau and Blue Mountains greatly reduced native grasslands and shrublands [*Hann et al.*, 1998].

Federal legislation in the 1960s and 1970s began a drastic movement towards sustainable and ecologically friendly land use practices nation-wide. Subsequently, in 1995, Washington State's first model watershed plan was developed for Asotin Creek with the goals of implementing land use management practices which promote quality salmonid habitat at multiple scales [*ACCD*, 1995]. Backed by this plan, there have been many successful and ongoing restoration actions and monitoring projects [*Thiessen*, 2000; *Bennett and Bouwes*, 2009; *Bennett et al.*, 2012; *Wheaton et al.*, 2012].

Historical flow records cover roughly the last 110 years at different locations within the Asotin Creek watershed. Large floods in 1904, 1964, 1974, and 1996 exacerbated the problems of incised and degraded channels in Asotin Creek by modifying the substrate composition, geomorphic assemblages, and channel planform, and decimating large sections of riparian vegetation *(NRCS 2001, ACCD 2004)*. Additionally, some reaches on the mainstem were leveed to prevent future damage to urbanized areas during large floods.

Topography

Asotin Creek is comprised of four major tributaries. Three enter the mainstem high in the drainage (North Fork of Asotin Creek, South Fork of Asotin Creek, and Charley Creek), and one is near the mouth of the mainstem (George Creek). The upper tributaries share similar partly confined valley morphologies, but vary in size with Charley Creek being the smallest, and the North Fork covering the largest area (Table 2.1).

Table 2.1. Basic drainage characteristics summarized using the USGS Stream Stats tool for Asotin Creek, George Creek, North Fork of Asotin Creek, South Fork of Asotin Creek, and Charley Creek.

Characteristic	Asotin	George	North Fork	South Fork	Charley
Drainage Area (km^2)	841	332	165	104	58
Mean Elevation (m)	1021	960	1305	1234	1216
Min Elevation (m)	228	287	561	564	521
Max Elevation (m)	1890	1667	1890	1823	1701
Max Relief (m)	1664	1381	1329	1259	1180
Mean Slope	24	15	40	29	34
Percent Area w/ Slope >30%	36	19	68	43	57
Percent Forested Area	21	14	44	30	39
Mean Annual Precipitation (cm)	58	53	76	70	67

In contrast, George Creek is lower in elevation with less steep hillslopes than the other major tributaries. The headwaters of the George Creek drainage cover the loess plateaus and start as shallow, low gradient ephemeral streams. Most of the Asotin Creek network is steep and nestled amid sheer basalt cliffs. As the highlands and uplands have been dissected, the stream has taken a dendritic pattern. The highest point in the drainage is Misery Point at around 1900 meters, but the headwaters typically begin showing defined channels at 1600 meters. There are a few normal faults near the mouth of Charley Creek and Dry Gulch (large drainage north of Charley Creek) and numerous dikes across the North and South Forks that may act as controls on river character (Figure 2.3). Faults in the basin may act as knick points or local controls on base level to upstream reaches.

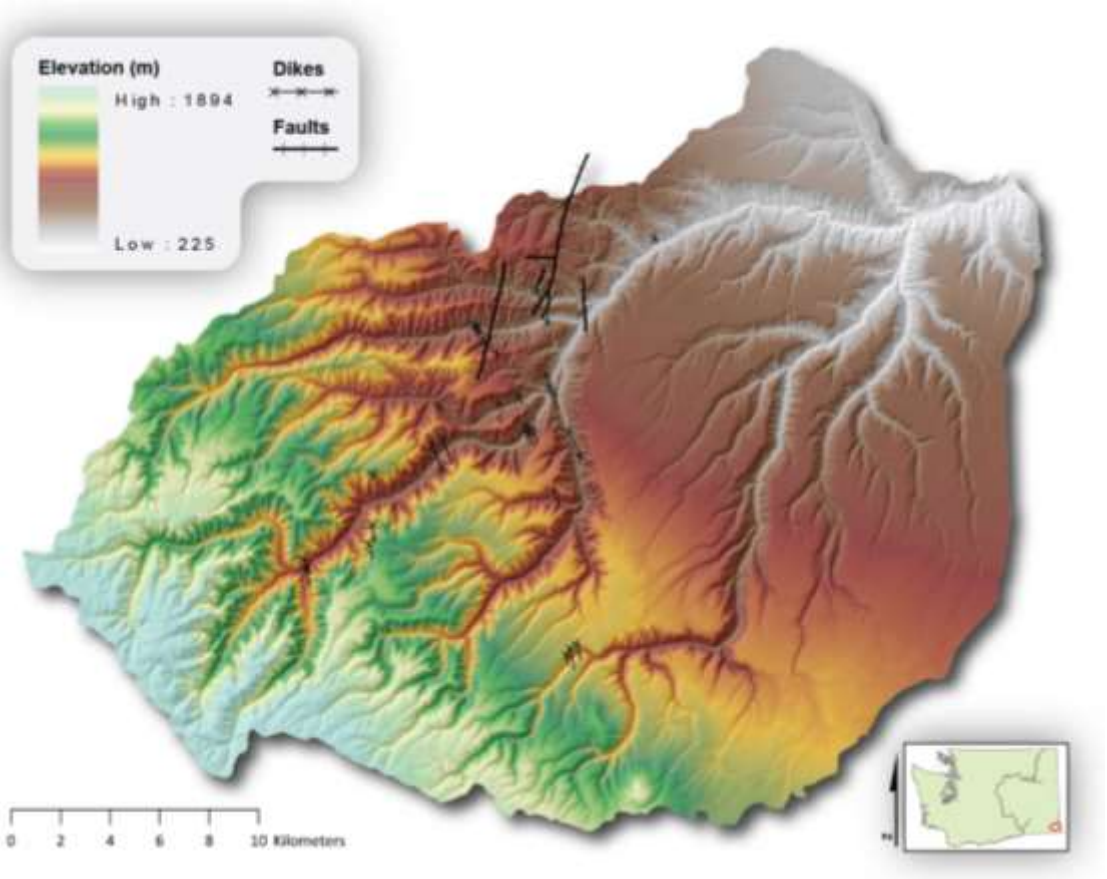

Figure 2.3. Digital elevation model of Asotin Creek drainage and surrounding area. Major dikes and faults are also shown.

The longitudinal profiles of each major tributary have a concave up form, starting with very steep channels in the headwaters, and slowly flattening out (Figure 2.4). There are no major breaks in channel relief, and even though the slopes are decreasing, they are still fairly steep even near the mouth of the mainstem (2-3% gradient). George Creek and the North Fork contribute the most drainage area, followed by the South Fork and Charley Creek (Table 2.1).

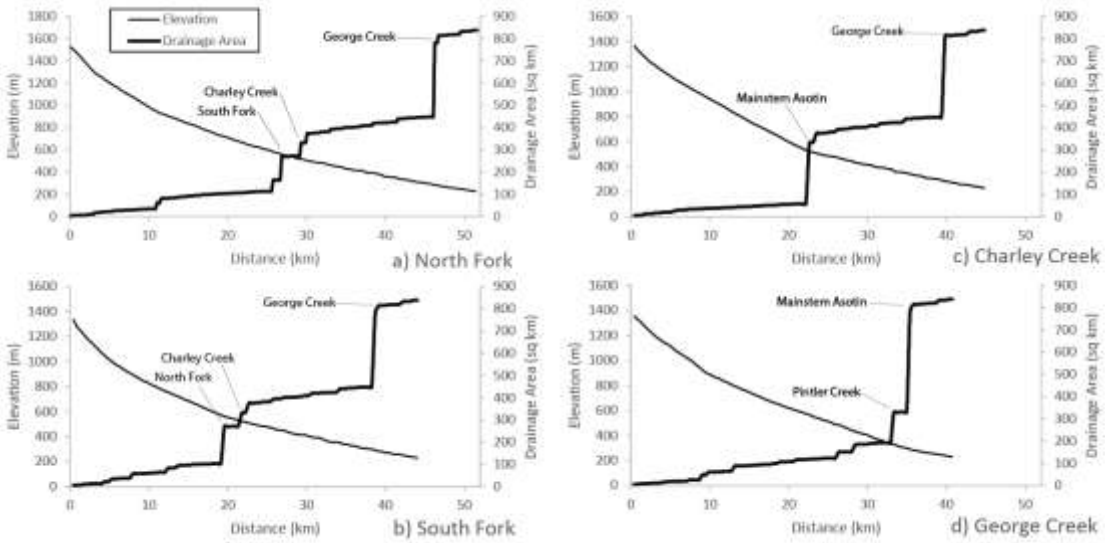

Figure 2.4. Longitudinal profiles and cumulative drainage areas extending to mouth of Asotin Creek and starting in four major tributaries to Asotin Creek: North Fork of Asotin Creek, South Fork of Asotin Creek, Charley Creek, and George Creek.

Climate and Hydrology

Asotin Creek is located in a semi-arid region receiving 115 cm of precipitation at high elevations and less than 30 cm at lower elevations [*Bennett et al.*, 2012]. Most of the precipitation in the winter comes in the form of snow near the headwaters of the drainage; however, large floods can be associated with highly localized, high intensity summer thunderstorms [*Wheaton et al.*, 2012]. Temperatures vary greatly between seasons, with highs in the summer sometimes reaching >38° C, and winter highs <0° C (Figure 2.5).

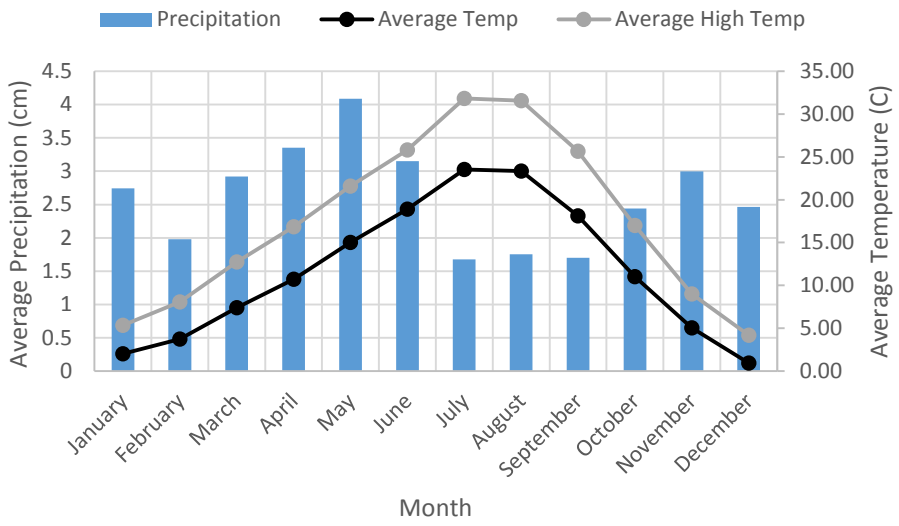

Figure 2.5. Average monthly precipitation and temperature near Asotin, Washington.

The mean annual discharge for the mainstem of Asotin Creek is about 2.21 cubic meters per second (cms) and its pattern is determined mostly by snowmelt in the spring; however, springs maintain base flows in the major tributaries throughout the year. There are multiple historic stream gauges on the mainstem of Asotin Creek, but none of them cover a span longer than 10 years and most have moved locations several times. Therefore, empirical predictions of return interval peak flows are difficult to estimate accurately. However, regionally based regression equations can be used to predict peak flows based on drainage area and precipitation (Table 2.2).

These predictions may be imprecise in terms of the actual potential flow, but they provide context for comparison between subbasins. Overall snowmelt runoff efficiency (the amount of water from snowmelt that reaches the stream network; SRE) for Asotin Creek was 40.9 % (*SD = 29.6)* for all months between 2007 and 2012 where snowmelt occurred. Mean SRE among years was variable, but there was no significant difference

among years (*p=0.60;* Figure 2.6). Likewise, there is a strong positive correlation between monthly snow melt near the headwaters and mean monthly discharge (Pearson's r(34) = 0.846, *p<0.001;* Figure 2.7).

Table 2.2. Estimate peak flows in cubic meters per second for return intervals for Asotin Creek and its major tributaries. Flows are estimated using a region based regression equation and the USGS Stream Stats tool.

Return Interval (Year)	Asotin	George	North Fork	South Fork	Charley
2	42.2	19.9	19.1	12.7	8.3
10	110	58.6	49.3	35.4	24.5
25	154.6	86.4	69.7	51.3	36.2
50	193.1	110.4	87.8	65.4	47
100	235.6	137.6	107.3	81.3	58.9

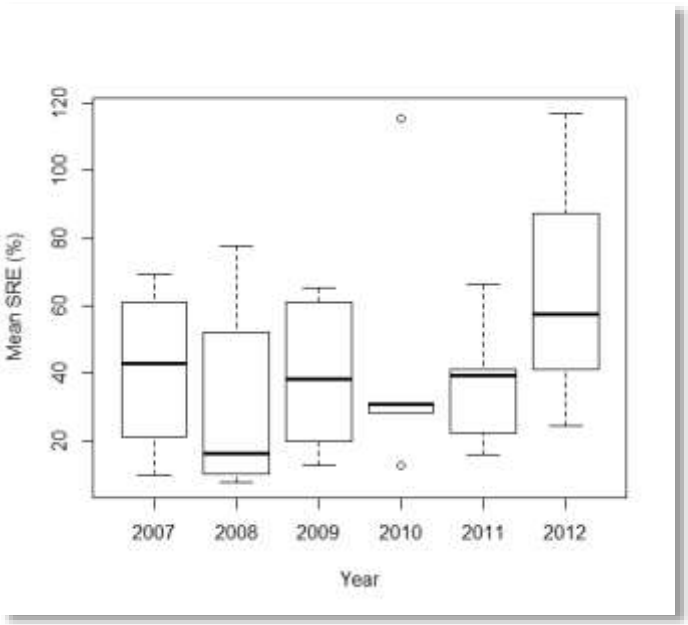

Figure 2.6. Boxplot of mean yearly snowmelt runoff efficiency (SRE) in Asotin Creek from 2007 to 2012.

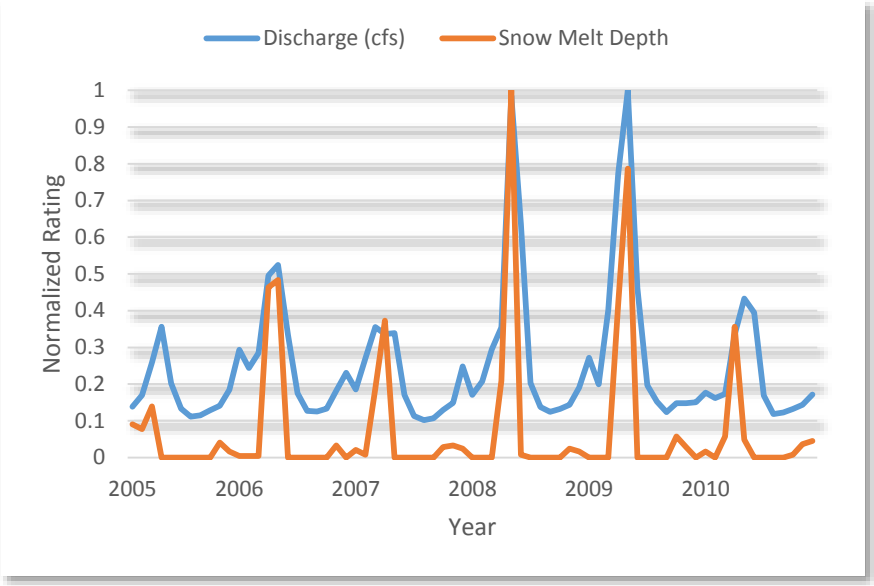

Figure 2.7. Normalized snowmelt depth and discharge by year on Asotin Creek. Discharge is from the Washington Department of Ecology stream gauge #35D1000. Snow melt depth was obtained from the Spruce Springs SNOTEL gauge.

RIVER STYLES IN ASOTIN CREEK

The first stage in the River Styles Framework involves identifying the river styles in the target watershed. River styles delineation is guided by a procedural tree containing defining and characteristic aspects of unique reach types (Figure 2.9). The valley setting is the first branch of the procedural tree and separates reaches by *laterally confined* (abuts valley margin 90-100%), *partly confined* (abuts valley margin 10-90%), or *laterally unconfined* (abuts valley margin <10%) (Figure 2.9). The procedural tree branches further define the planform, floodplain and in-channel geomorphic unit assemblages, bed material texture, and presence of structural elements to delineate specific river styles. River styles are identified using desktop assessments of aerial photography and digital elevation models to provide context and trends, and through in-field evaluations and

validation of office assessments. Landscape units provide the broadest context for controls on river character and behavior, thus acting as a first cut at river style reach breaks. A reach is a distinct section of a stream and valley bottom whose river structure and function is relatively uniform and typically adjusts on a 10-100 year timescale [*Brierley and Fryirs*, 2005].

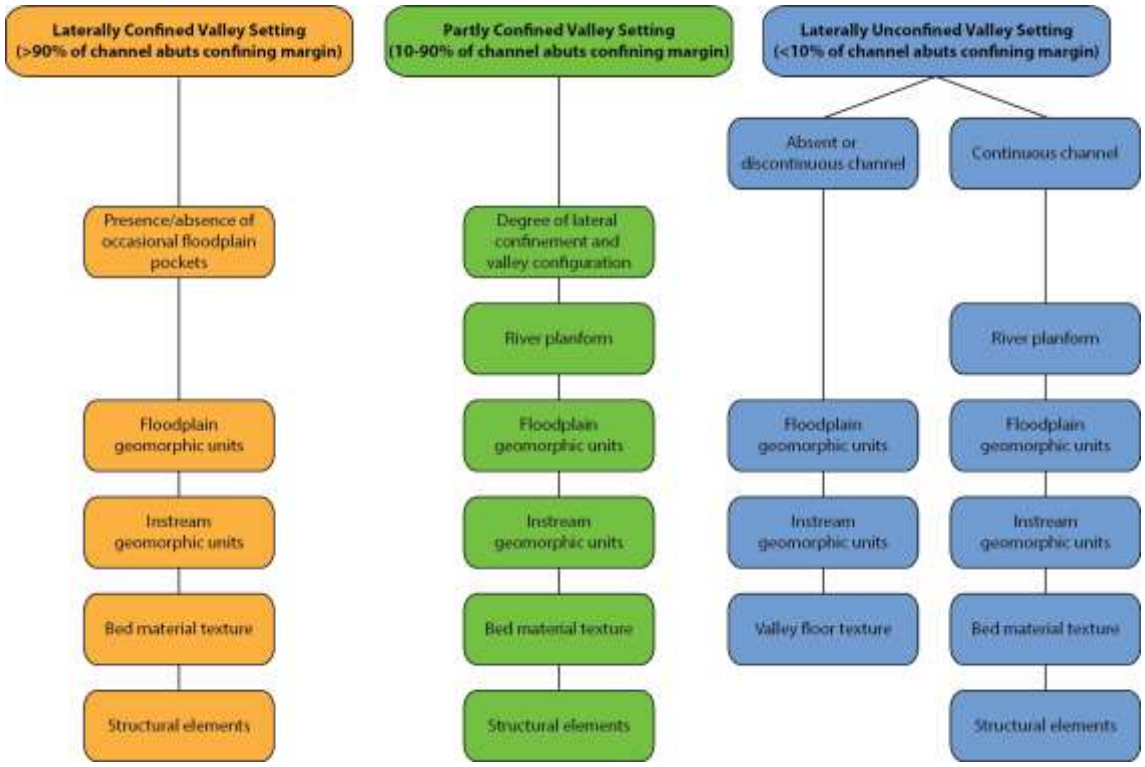

Figure 2.8. River styles procedural tree for delineating reach types adapted from Brierley and Fryirs (2005).

There are four landscape units in the Asotin Creek drainage (Figure 2.11; Table 2.3). The landscape units are largely based off of 1:250,000 scale Level IV EPA ecoregions [*Omernik and Griffith*, 2014]. However, I refined some of the landscape unit boundaries based off of geologic unit mapping at a finer 1:100,000 scale [*Schuster*, 1993]

because geology exerts the greatest control on river character and behavior. The four units are mesic forest zone, dissected highlands, dissected loess uplands, and lower Snake canyons.

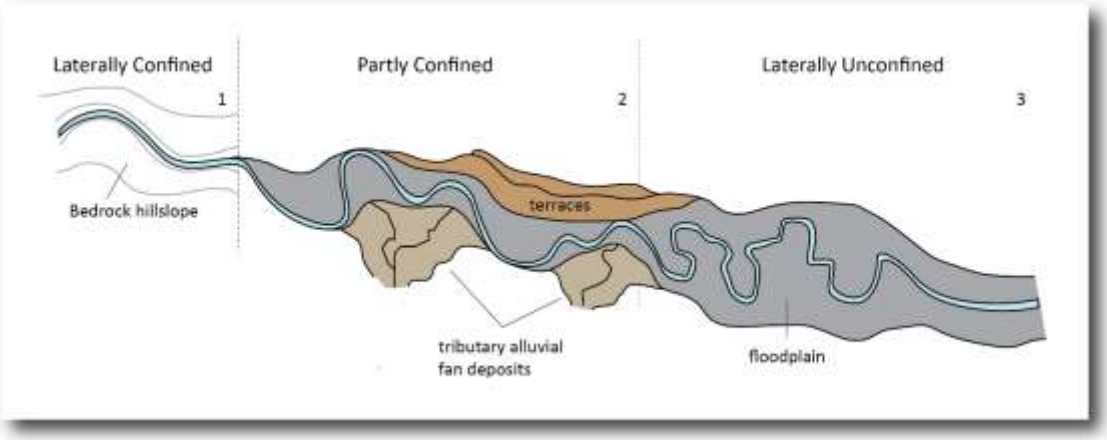

Figure 2.9. Conceptual diagram illustrating the differences between valley settings in the River Styles Framework. The stream channel abuts the valley margin >90% in (1) laterally confined reaches, 10-90% in (2) partly confined reaches, and <10% in (3) laterally unconfined reaches. From Obrien and Wheaton, 2015.

Figure 2.10. Aerial photograph of the study streams in the Asotin Creek Intensively Monitored Watershed study area (yellow) and the landscape units of the Asotin Creek Basin (green).

Table 2.3. Distinguishing characteristics of landscape units in the Asotin Creek drainage.

Parameter	Mesic Forest	Dissected Highlands	Dissected Loess Uplands	Lower Snake Canyons
Landscape Morphology	Steep valleys, largely forested	Plateau dissected to basalt cliffs into deep valleys	Flat plains, dissected by large washes, heavy agriculture	Deep valleys with high relief, often dissected down to basalt formations
Landscape Position	Headwaters of drainage, Blue Mountains	Between Mesic Forest and Lower Snake Canyons	Low in drainage, atop valleys and basalt plateaus	Extends up mainstem and major tributaries, dissecting uplands
Vegetation	Mostly conifers, riparian is often thick with native shrubs	Mix of conifers and deciduous trees, riparian transitions between shrubs and grasses, valley slopes are often associated with semi-arid shrubs like sagebrush	Mostly plains grasses and low shrubs, heavy wheat agriculture	Mostly deciduous trees, upper riparian sections are mostly native shrubs, lower elevations show encroachment of non-native shrubs and grasses
Geology	Basalt	Basalt	Basalt topped with loess	Basalt
Relief	Up to 300 m	Up to 300 m	Up to 150 m	Up to 400 m
Elevation	1200 m - 1900 m	800 m - 1600 m	300 m - 1100 m	200 m - 1300 m
Valley Slope (%)	5 - 15	1 - 4	Flat to <3	1 - 4
Valley Width	10 m - 30 m	20 m - 50 m	Up to 1 km	20 m - 300 m

The mesic forest is characterized by the beginning of dissection of the Blue Mountains, resulting in patches of exposed basalt outcrops. The mesic forest landscape unit is morphologically similar to some parts of the dissected highlands, with frequent basalt canyons, but is largely distinguished by its vegetation and elevation which plays a significant role in characterizing river behavior. The dissected highlands are a transitional zone between the mesic forest and lower Snake canyons. This unit is characterized by steep valley walls with expansive basalt outcrops and dissects a portion of the Blue Mountain section of the Columbia Plateau. The dissected loess uplands are basalt formations topped by deep loess soil deposits. In the last 150 years, the loess uplands

have been converted into agricultural areas with a primary focus on wheat. The lower Snake canyons are large, deep valleys with numerous bands of basalt outcrops along the valley margins. This unit contains mostly high order streams (3rd-4th order) and shows great variability in elevation and valley width.

There are nine distinct river styles in the Asotin Creek drainage based on landscape units and controls, river character, and river behavior. Table 2.4 provides a comprehensive summary of the distinguishing characteristics of each river style. The River styles trees show a multi-tiered representation of each river style (Figure 2.11; Figure 2.12 and Figure 2.13). Each river styles tree describes the defining characteristics of a river style and where those characteristics break off from river styles in a similar valley setting. I delineated the streams of order two and higher in the Asotin Creek drainage using these characteristics (Figure 2.14).

The majority of the river network with defined channels in the Asotin Creek drainage is either confined or partly confined (Table 2.5). The long segments of confined valleys are likely because the basin is dominated by multiple layers of ancient basalt flows, topped by Palouse loess soils on some ridge tops. Most of the higher order stream reaches (3+) are partly confined with intermittent confined reaches mixed in (Figure 2.15, e.g. Figure 2.16). The only instances of laterally unconfined streams are found in the very bottom of the catchment where the valley is uncharacteristically wide. However, about 22% of the drainage network is Upland Swale, most of which has a discontinuous channel. These areas drain most of the dissected loess uplands landscape unit which comprise a large area of the lower basin (Figure 2.15, e.g. Figure 2.17). In contrast, there are very few examples of laterally unconfined valley settings within the Asotin IMW

study streams (Figure 2.18). Nearly every reach in the Asotin IMW study streams is within a partly confined valley setting, with the exception of the mouth of Charley Creek where the channel flows over its own alluvial fan as it confluences the mainstem of Asotin Creek.

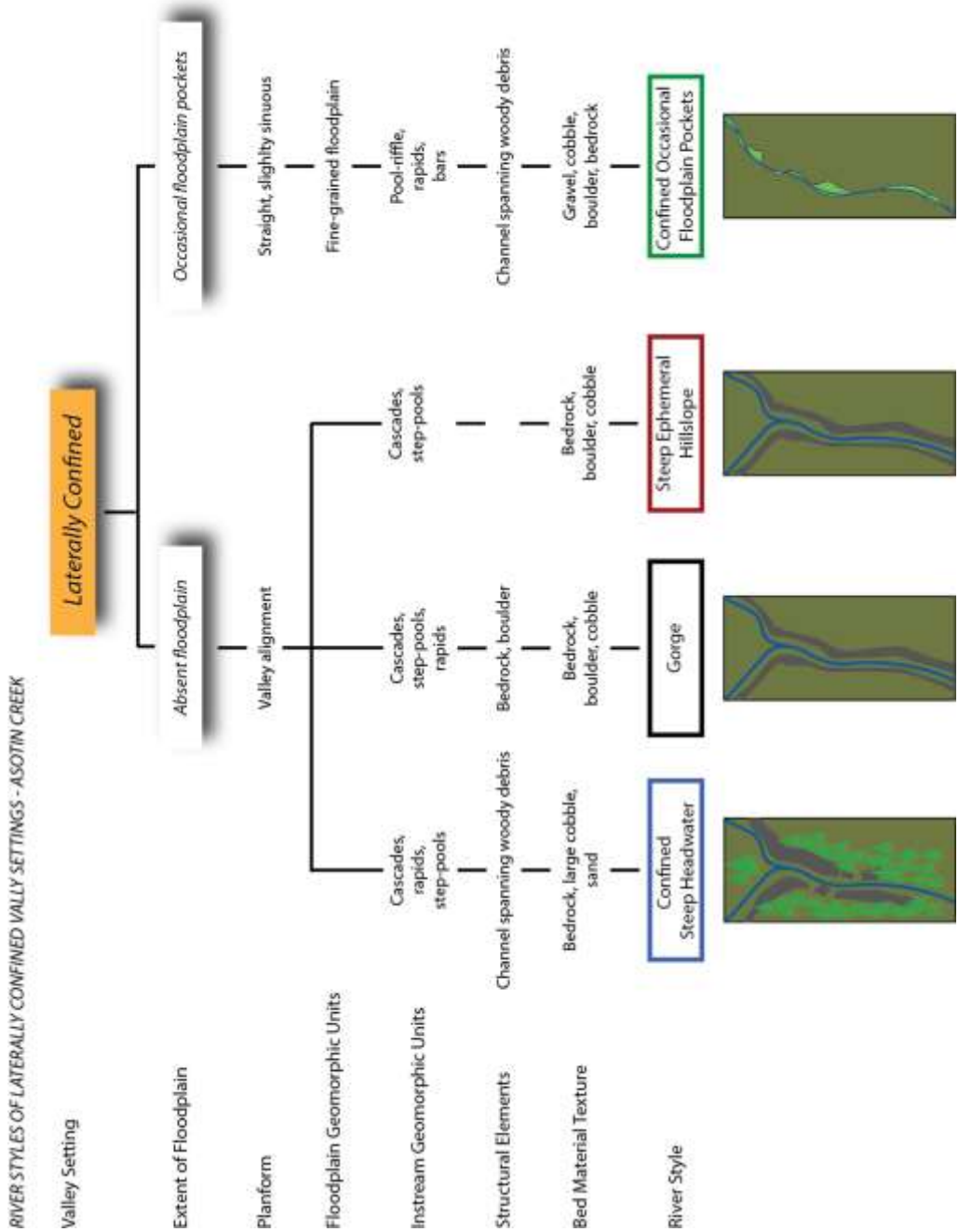

Figure 2.11. River styles tree for laterally confined valley settings in the Asotin Creek drainage.

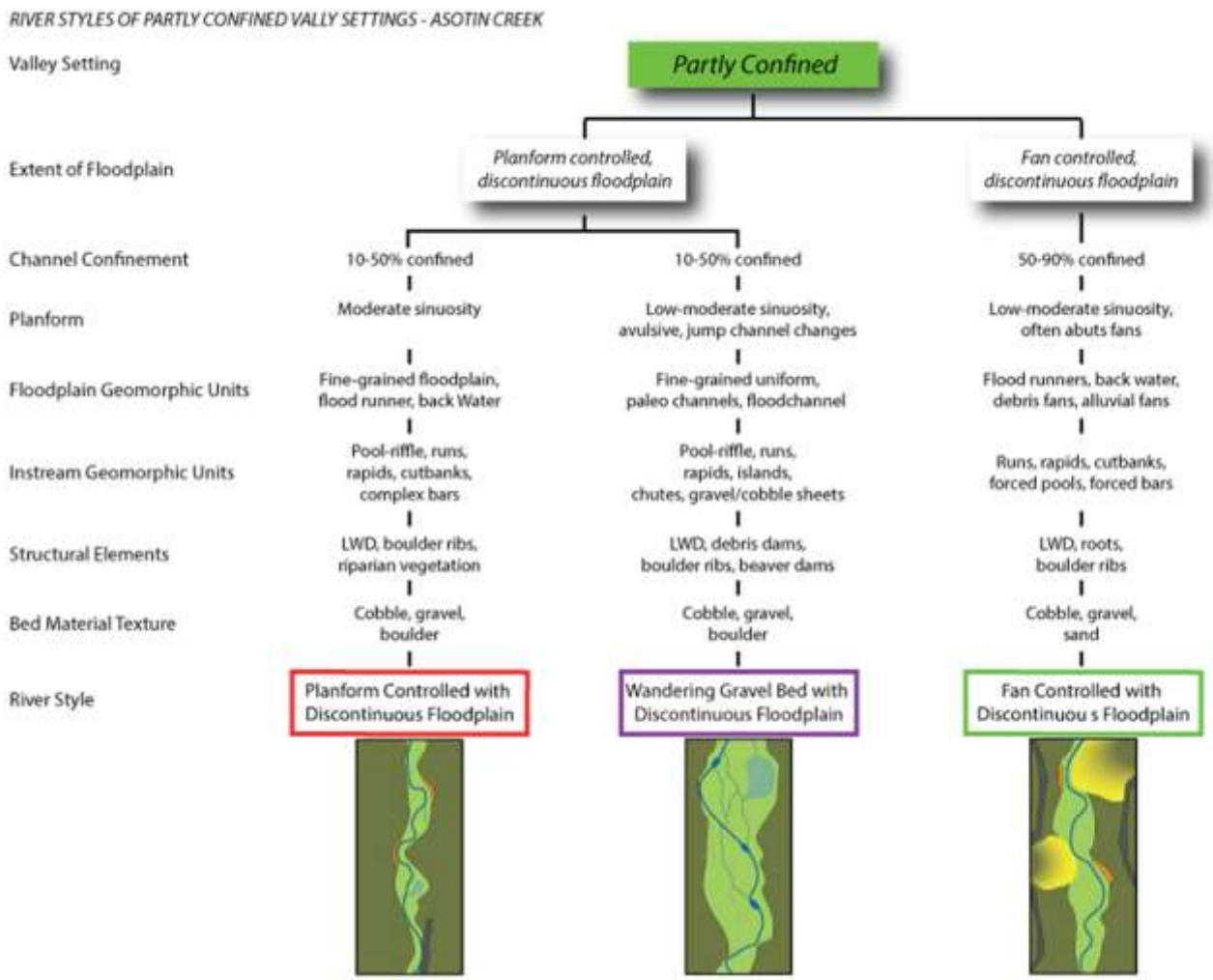

Figure 2.12. River styles tree for partly confined valley settings in the Asotin Creek drainage.

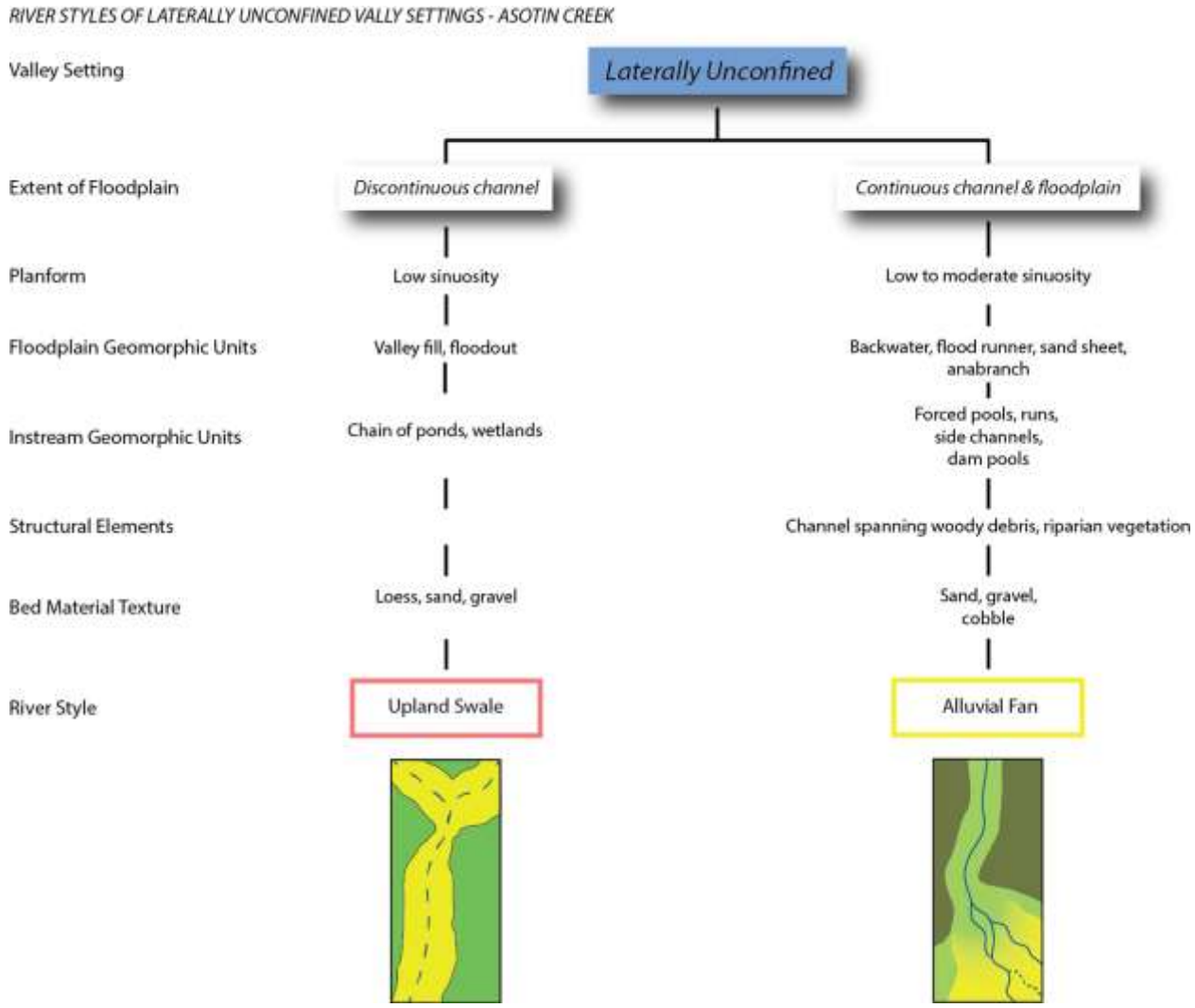

Figure 2.13. River styles tree for laterally unconfined valley setting in the Asotin Creek drainage.

Table 2.4. Characteristics and attributes of river styles in the Asotin Creek drainage.

		River Character			
River Style	**Landscape Unit**	**Channel Planform**	**Geomorphic Units**	**Bed Material Texture**	**River Behavior**
Gorge	Lower Snake canyons	Single channel, aligned to valley, highly stable	Little or no floodplain. Sequence of cascades and rapids	Bedrock-boulder-colluvium at higher elevations	Very steep, incised channel mostly confined by basalt cliffs on both sides. The floodplain is almost entirely absent and there is no opportunity for lateral adjustment. May be present in low order ephemeral and intermittent streams, but is also common in the lower snake canyons.
Confined Steep Headwater	Mesic forest/ dissected highlands	Single channel, aligned to valley, highly stable	Discontinuous floodplain, cascades, rapids, step-pools	Bedrock-boulder-large cobble	Very steep channel, often spring-fed, but flow variability is reliant on snow melt so most of these rivers are intermittent. Limited ability for lateral adjustment. Flushes colluvial deposits from high elevations of the Blue Mountains. Only the large floods extend out of the channel and into the floodplain
Confined Occasional Floodplain Pockets	Dissected highlands/lower Snake canyons	Single channel, low sinuosity, highly stable	Discontinuous pockets of floodplain, bedrock outcrops, pool-riffle, rapids, bars	Bedrock-boulder-cobble	Steep channel, often intermittent at high elevations, with alternating assemblage of bedrock forced pools and pool-riffle-rapid sequences. Floodplain is accessed during bankfull floods, but little work is done to the channel. Found in narrow valleys, largely confined by basalt cliffs and often scoured vertically to bedrock.

Table 2.4 Continued

River Style	Landscape Unit	River Character			River Behavior
		Channel Planform	Geomorphic Units	Bed Material Texture	
Steep Ephemeral Hillslope	Primarily dissected highlands and dissected loess uplands	Single channel, aligned to valley, highly stable	Step-pool, cascade	Bedrock-boulder-cobble-gravel-sand	Ephemeral, bedrock-controlled channel, aligned to the valley, and confined by adjoining hillslopes. Coarse bed material texture with highly angular colluvium eroded and transported downstream from adjacent hillslopes. Dominated by step-pool sequences, cascades, and occasional plunge pools.
Wandering Gravel Bed with Discontinuous Floodplain	Lower Snake canyons	One to many channels, jump channel changes, moderately stable	Discontinuous floodplain, pool-riffle, rapids, bars, frequent paleochannels	Cobble-gravel-boulder	Mostly straight valley. The main channel will suddenly change at greater than bankfull floods, but is otherwise stable. A mostly cobble-gravel bed is reworked often creating multiple bar formations. Paleochannels are very common across the floodplain and are commonly inundated during bankfull floods. Bar forced pool-riffle sequence are common between short sections of rapids.
Planform Controlled with Discontinuous Floodplain	Dissected highlands and lower Snake canyons	1-3 channels, , moderate sinuosity, jump channel changes, moderately stable	Discontinuous floodplain, pool-riffle, runs, rapids, complex bars	Bedrock-cobble-gravel	Channel exhibits low-moderate sinuosity, but can be restricted on occasion by bedrock. Found in wider but still partly confining valleys. Multiple channels may develop in some areas, but one channel will always contain the majority of flow. Larger than bankfull floods will often force sudden alterations to the primary channel. Floodplain is well developed, although discontinuous. Sediment cycles between transport and storage zones, creating complex bars in some areas.

Table 2.4 Continued

River Style	Landscape Unit	River Character			River Behavior
		Channel Planform	Geomorphic Units	Bed Material Texture	
Fan Controlled with Discontinuous Floodplain	Lower Snake canyons	Single channel, straight, highly stable	Discontinuous Floodplain, Rapids, Step-Pool, Occasional cascades or large steps in channel	Boulder-cobble	Found in valleys with frequent large fan deposits that ultimately impose the channel into its current position. The erodibility of the lower Snake canyons has resulted in long sections of river where these fans are abundant and may even force the channel up against the basalt cliffs on the opposite valley margin. They may exhibit localized sinuosity, but are more often straight and are highly stable due to the coarse sediment in the debris fans. The constriction points from these fans create sections of high channel slope.
Upland Swale	Dissected loess uplands, dissected highlands	Continuous channel, moderately stable	Continuous floodplain, cascades, step pools, rapids	Loess soils-sand-gravel	Channel is continuous with intermittent ponds and wetlands. Valleys are unconfined, shallow, and exhibit a rolling hill topography. Flushes loess soils and agriculture land atop basalt formations, but fine sediment is stored as fill in the ponds and wetlands.
Alluvial Fan	Lower Snake canyons	1 to multiple channels, wide valley, avulsive, low stability	Continuous floodplain, forced pools, Runs, side channels, dammed pools	Sand-gravel-cobble	Found at the mouths of some rivers where the main channel is flowing over its own fan. These rivers are at the base of a confined or partly confined valley that acted mostly as a transport zone. When the river enters a wide open valley at its mouth, the bed material is dumped, and the river is forced to frequently rework the material to reach its base level. LWD from upper river sections tend to stack up here, leading to forced pools, dammed pools, and long deep runs. The bed material is highly dependent on the dominant material from upstream reaches.

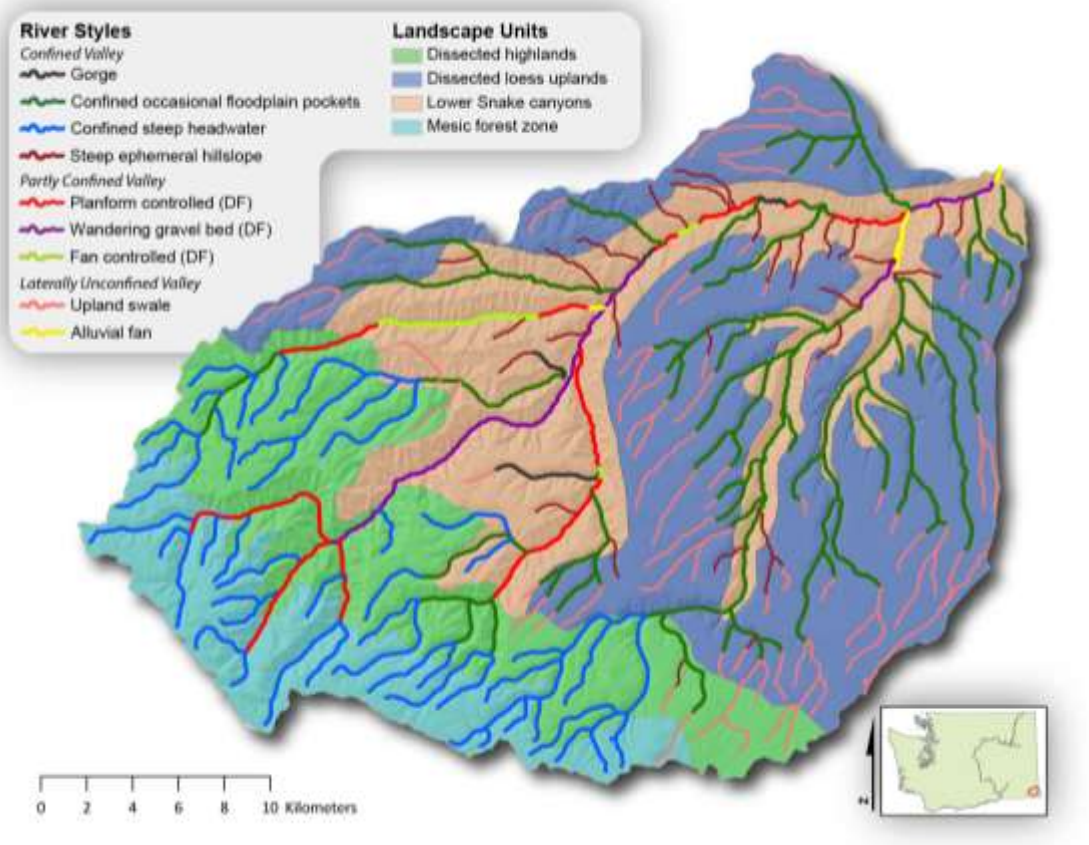

Figure 2.14. River styles classified for 2nd order streams and higher in the Asotin Creek drainage. DF = discontinuous floodplain.

Table 2.5. Total stream lengths of each river style and its proportion to the total length of streams classified in the Asotin Creek drainage.

River Style	**Length (km)**	**Proportion of Length (%)**
Confined occasional floodplain pockets	239	31.6
Confined steep headwater	183	24.2
Steep ephemeral hillslope	65	8.6
Gorge	9	1.3
Upland swale	170	22.5
Alluvial fan	5	0.7
Fan controlled with discontinuous floodplain	9	1.1
Planform controlled with discontinuous floodplain	47	6.3
Wandering gravel bed with discontinuous floodplain	28	3.7
Total	**757**	

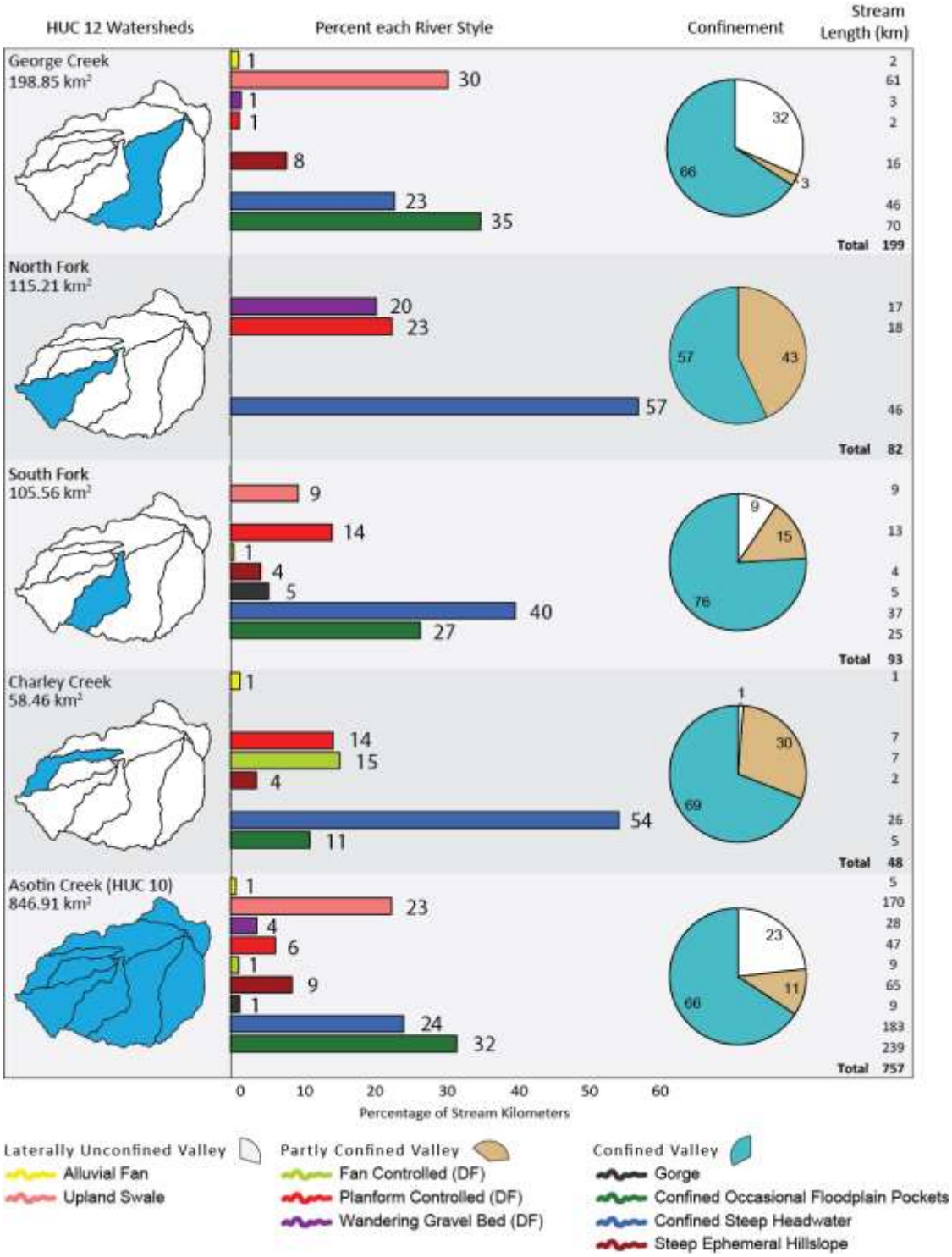

Figure 2.15. Proportion of stream lengths within river styles and valley confinement within the entire Asotin Creek watershed, the Intensively Monitored Watershed study streams (North Fork, South Fork, Charley Creek) and George Creek. DF = discontinuous floodplain.

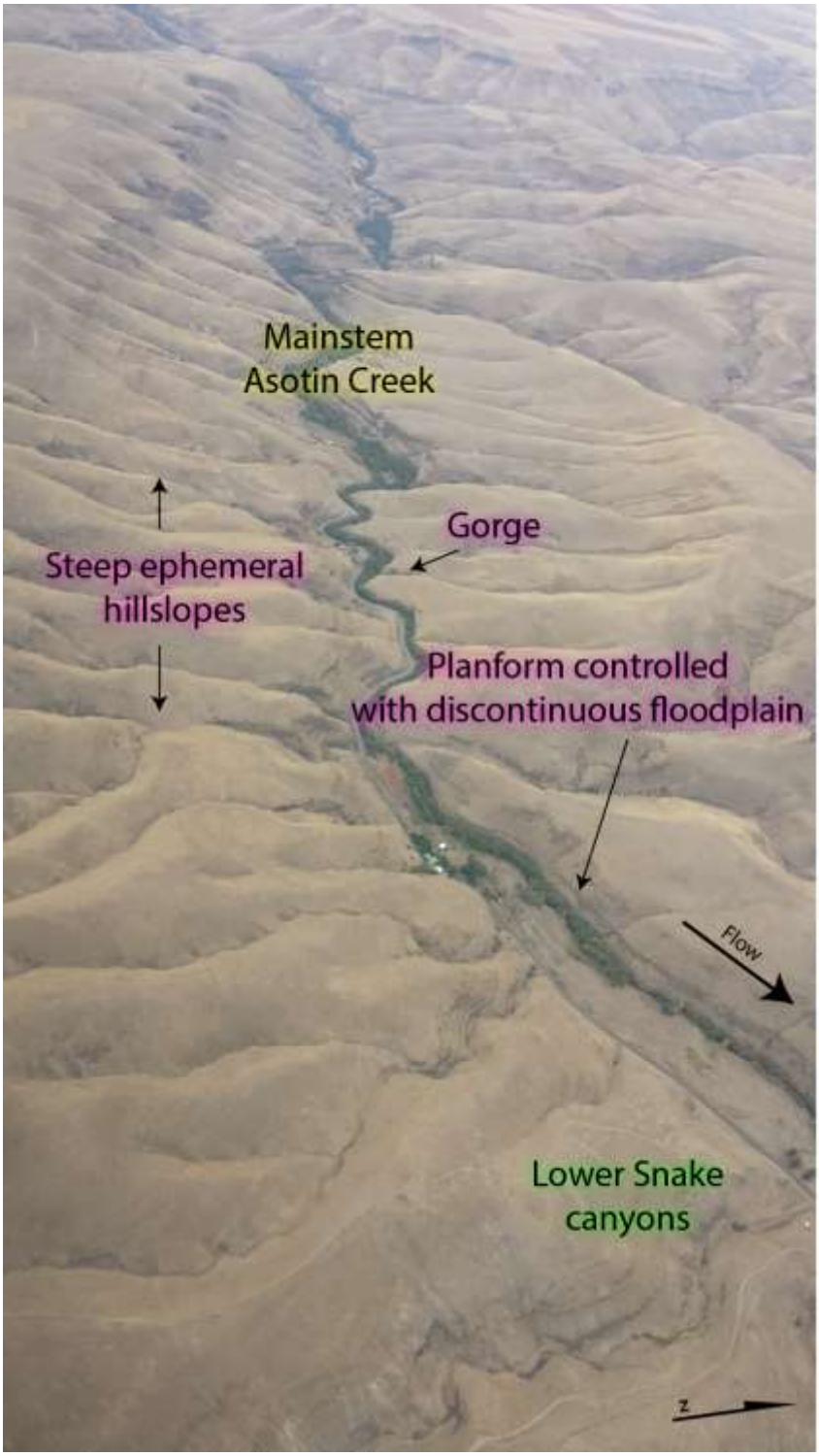

Figure 2.16. Aerial photograph of the mainstem of Asotin Creek located in the lower Snake canyons landscape unit. The Gorge, steep ephemeral hillslope, and planform controlled with discontinuous floodplain River Styles are outlined in pink.

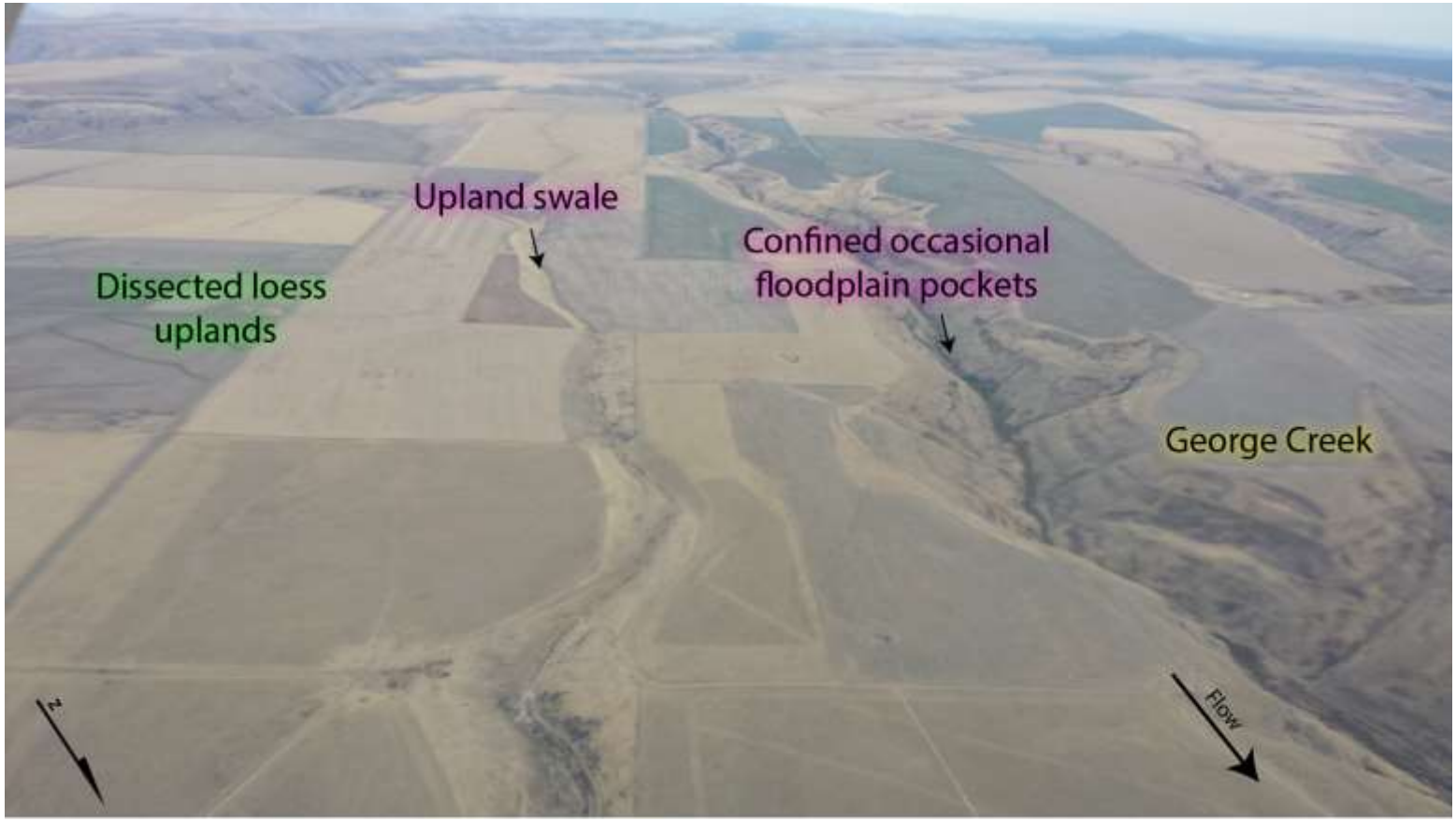

Figure 2.17. Aerial photograph of the dissected loess uplands landscape unit near George Creek in the Asotin Creek watershed. The two contrasted river styles, upland swale and confined with occasional floodplain pockets are outlined in pink.

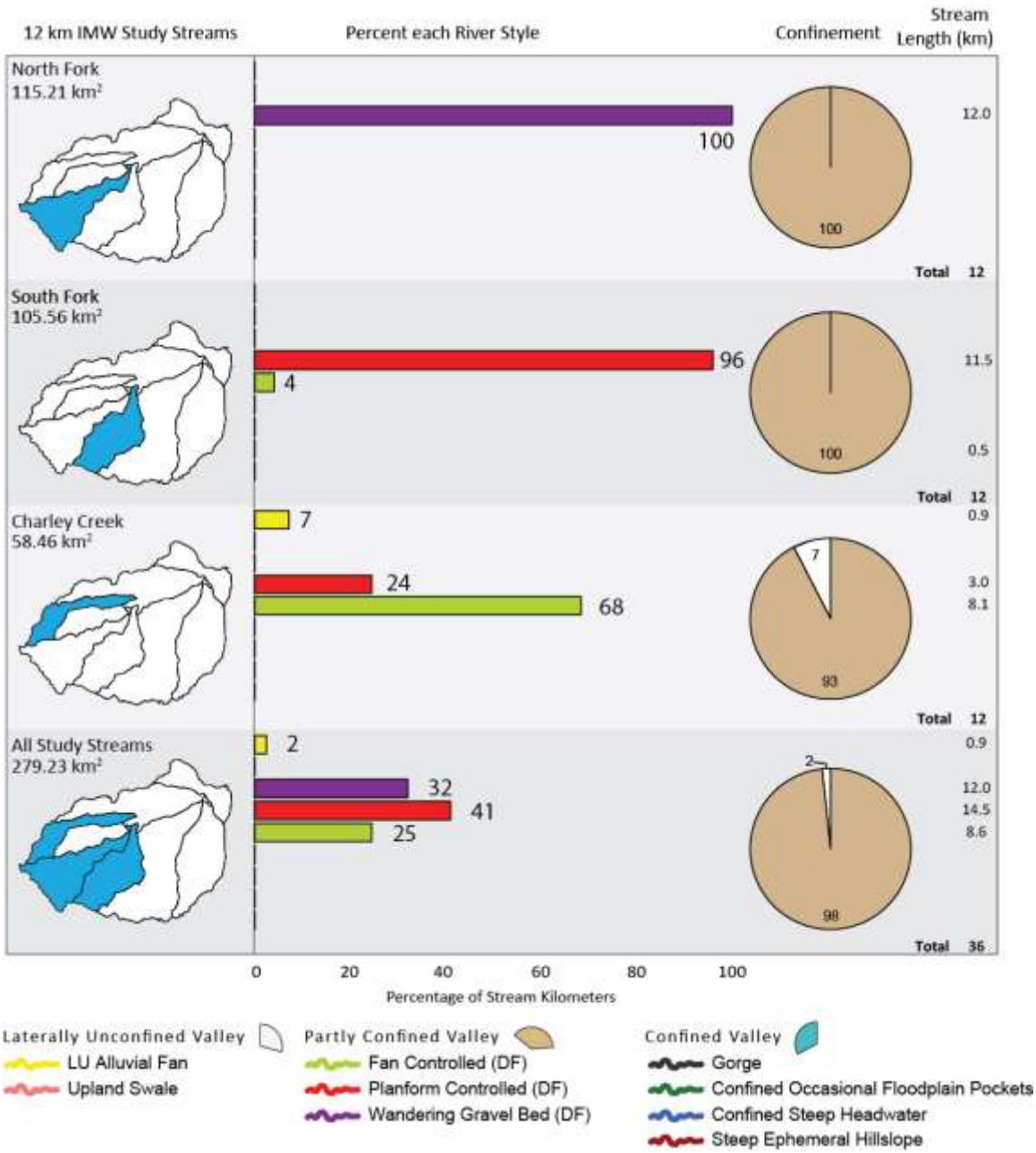

Figure 2.18. Proportion of stream lengths within river styles and valley confinement within the lower 12 km of the Asotin Creek Intensively Monitored Watershed study streams (North Fork, South Fork, Charley Creek). DF = discontinuous floodplain.

RIVER STYLES DEFINITIONS

Confined Valley Setting

River styles in the confined valley setting abut the valley margin 90-100% of their length on one or both sides. Nearly 66% of the stream network in Asotin Creek is within a confined valley setting, with the primary imposition by bedrock. There are four types of confined reaches that occur in Asotin Creek and its tributaries (Figure 2.19).

Figure 2.19. Aerial photograph examples of representative confined river styles in the Asotin Creek drainage.

The ***Confined steep headwaters River Style*** is present only in the upper reaches of the drainage extending from the Blue Mountains. Although most reaches are perennial,

their hydrology is highly dependent on snow melt; however, flows may spike in individual subbasins due to high intensity, localized summer storms. Peak flows in these reaches are short because the upstream drainage area is relatively small. These reaches are very steep (>10%) with regular, localized inputs of colluvium from the surrounding hillslopes. This results in the development of long rapids broken up by brief cascades and forced pools. Most of the reaches are in the mesic forest landscape unit with high LWD loading, which forces most pools and traps sediment. Although there may be occasional pockets of floodplain present, these areas are only accessed in extreme floods. The bed is comprised primarily of boulders and cobble with sands and fines commonly deposited in the wake of in-channel structural elements.

The ***Gorge River Style*** occurs infrequently in the drainage, primarily because one of its defining characteristics is the complete lack of a floodplain. The channel is mostly bordered by bedrock, although the bed usually contains a mixed load of boulder, cobble, and gravel. The gradient is steep (5-10%) and the planform is restricted by exposed basalt outcroppings, forcing the river to align to the valley margin, and become greatly incised. These reaches are found in some minor tributaries and on some sections of the mainstem of Asotin Creek. Aside from the sections on the mainstem, gorges in the Asotin watershed are typically ephemeral and are large sediment sources during intense, local storm events because of the high valley constriction and proximity to loess sediment sources. For example, the ***Gorge River Style*** section on Warner Gulch (an ephemeral tributary to the South Fork) has experienced multiple documented localized storms which brought in large amounts of sediment deposits to the South Fork.

The ***Confined occasional floodplain pockets River Style*** is the most common reach type in confined valley settings of the Asotin watershed. It occurs throughout the drainage where confined valleys have developed floodplain pockets, often downstream of tributaries and fan-forced knick points, but is dominant in George Creek and its tributaries. The floodplain may occur infrequently and in small pockets, but may be well developed and stores fine grained sediment. The most common geomorphic units are rapids, runs, and forced pools. The transport zones and bars that do develop are comprised of coarse substrate and are stable during bankfull floods. Bedrock is the primary control in these reaches, forcing most of the pools at knick points or brief lengths of high confinement in the channel.

The ***Steep ephemeral hillslope River Style*** represents 8.6% of the 2nd order and higher streams in the Asotin Creek watershed. However, many of the 1st order tributaries in the watershed are steep ephemeral hillslopes. These channels are completely confined by the adjacent hillslopes and basalt outcrops and are aligned to the valley. Many reaches begin as ***Upland swale River Styles*** along the tops of the dissected loess uplands and dissected highlands, then rapidly increase in slope and confinement as they dissect the basalt layers to reach the higher order tributaries. The instream geomorphic units are step-pool sequences and cascades, with occasional plunge pools. The bed material texture is coarse and angular, consisting primarily of colluvium from the adjacent hillslopes.

Partly Confined Valley Setting

The partly confined valley setting reaches are the least common reaches by stream length in the watershed; however, most of the salmon-bearing reaches are within this valley type. These rivers typically traverse between both sides of the valley margin or

debris fans. They occur in the main tributaries and mainstem of Asotin Creek and are the primary focus of instream habitat restoration for threatened native fish. There are four types of partly confined river styles in the Asotin Creek drainage (Figure 2.20).

Figure 2.20. Aerial photograph examples of representative partly confined river styles in the Asotin Creek drainage.

The ***Planform controlled with discontinuous floodplain River Style*** occurs where the valley widens slightly but is still partly confining. These rivers abut the valley margin 10-50% of the time, and are moderately sinuous. Multiple high-stage flood channels are common, indicating periodic overbank flows that rework the valley floor. Large floods

often force the active channel to shift in areas where it is not pinned against bedrock. These reaches store local slugs of sediment that are mobilized during high flow events, giving rise to shifting channel topography. The floodplain is discontinuous, but well developed with fine grains and a healthy riparian zone. Large woody debris is the primary forcing mechanism for pool and bar development. Cutbanks are common where the channel is migrating laterally and provide an important source of sediment and LWD.

The ***Wandering gravel bed with discontinuous floodplain River Style*** is only present on the North Fork and mainstem of Asotin Creek. The valley in these reaches is slightly sinuous, and the channel can be moderately sinuous with many side channels and sometimes anabranches. This river style is very dynamic, and the main channel shifts often during floods, sometimes even reoccupying paleochannels in the floodplain during rare flood events. The majority of the floodplain is fine grained and typically has a wide riparian zone. However, gravel and cobble sheets are fairly common as well. These rivers have the sediment load and hydraulic capacity to rework the channel frequently leading to the development of complex bars and habitats. Beaver dams and ponds occur in this reach, increasing the density of side channels and stored fine sediment in some areas.

The ***Fan controlled with discontinuous floodplain River Style*** is most common on Charley Creek where large fans from ephemeral tributaries commonly force the channel to one side of the valley. Most of the debris fans occur on south facing slopes, forcing the channel to the south valley wall, and the river does not have the competence to erode their deposits in typical floods. With debris fans on one side of the valley emanating from tributary sources, and bedrock outcrops on the other, these reaches are confined 50-90% of the time. However, they may exhibit localized sinuosity when given

the lateral freedom, or in some cases, transition into a planform controlled river style. The planform of these channels is highly stable; however, LWD, roots, and bedrock lead to complex instream geomorphology. The imposition of fans also forces the river into the opposite channel margin leading to occasional 5-8 meter high cutbanks into terraces or other fans.

Laterally Unconfined Valley Setting

With the restrictive geology of the Asotin Creek watershed, there are very few perennial reaches that are laterally unconfined. However, 23% of the river network exhibits an unconfined valley setting, but most of these are ephemeral or intermittent streams. Perennial reaches in the unconfined valley settings are only found near and at the mouths of some tributaries and at the mouth of the mainstem of Asotin Creek. There are two laterally unconfined river styles in Asotin Creek (Figure 2.*21*).

The ***Upland swale*** is the most predominant river style within a laterally unconfined valley setting in the Asotin Creek drainage. The channel of this river style is discontinuous with intermittent ponds and wetlands, and the valley is filled with fine sediment. The ***Upland swale River Style*** is found among smooth-sided rolling hills in the dissected loess uplands. Long, shallow swales converge to create larger, smooth-sided

Figure 2.21. Aerial photograph examples of representative laterally unconfined river style in the Asotin Creek drainage.

depressions in the landscape to form this river style. In the Asotin Creek watershed, most of these reaches are within areas of high agricultural use, and some of the naturally occurring wetlands have been converted into ponds.

The ***Alluvial fan River Style*** is specific to the mouths of rivers where the main channel is flowing over its own fan. The stream's own alluvial deposits accumulate at the mouth of streams in reaction to the mainstem's base level. At the mouth, the river may appear as a single channel, or develop multiple distributaries and flood runners as it attempts to rework deposits. Depending on the primary sediment size in the upstream sections of river, large fan-shaped or arcuate sheet deposits act as remnants of past floods (e.g. sand or gravel sheets). Pools are almost always forced by LWD, roots, and riparian vegetation. Long, deep runs are common and usually associated with low gradient sections of the fan and channel spanning LWD. These rivers are battling between reaching a base level at its confluence with the trunk stream, and eroding through massive sediment deposits from large historic floods.

DOWNSTREAM PATTERNS OF RIVER STYLES

There are five unique downstream patterns of river styles represented in nine subbasins in the Asotin Creek drainage. All of the major tributaries to the mainstem of Asotin Creek have their own distinct downstream patterns (Figure 2.22). Documenting downstream patterns is a necessary step in the River Styles Framework to provide a baseline for assessing the geomorphic condition of subbasins within the drainage. Physical controls on geomorphology vary throughout the watershed and ultimately

govern what features and processes should be present in a basin. Among the downstream patterns, there are slight variants due to local controls and geologic features.

Pattern 1: ***The North Fork of Asotin Creek*** and its tributaries extend to the east from the highest elevations in the Blue Mountain range. As the rivers leave the mesic forest zone and dissect the layers of basalt, they are partly confined by bedrock. At the confluence of the North Fork, South Fork, and Middle Fork of the North Fork of Asotin Creek, sediment input is high, and the stream power increases creating a partly confined wandering gravel bed (Figure 2.23).

Pattern 2: ***Charley Creek*** also begins as headwaters extending northeast from the Blue Mountains. It quickly becomes confined as it erodes the basalt layers and enters the canyons of the dissected highlands. The valley widens briefly into a planform controlled section before narrowing again from the influence of large and frequent debris flows in the lower snake canyons. Nearing the mouth of Charley Creek and the confluence with the mainstem of Asotin Creek, the valley becomes even narrower and the primary control on channel planform becomes bedrock. Much of this river is a transport zone, resulting in a large alluvial fan at its mouth. Once it exits its own valley, the sudden change to an unconfined valley setting leads to a large alluvial fan which it dissects before its confluence with the mainstem of Asotin Creek.

Pattern 3: ***The South Fork of Asotin Creek*** begins as headwaters flowing north from the Blue Mountains. Through the dissected highlands, they widen slightly allowing for pockets of floodplain to develop. In the lower Snake canyons, they become partly confined by bedrock and some reaches locally store sediment deposits. There is a small

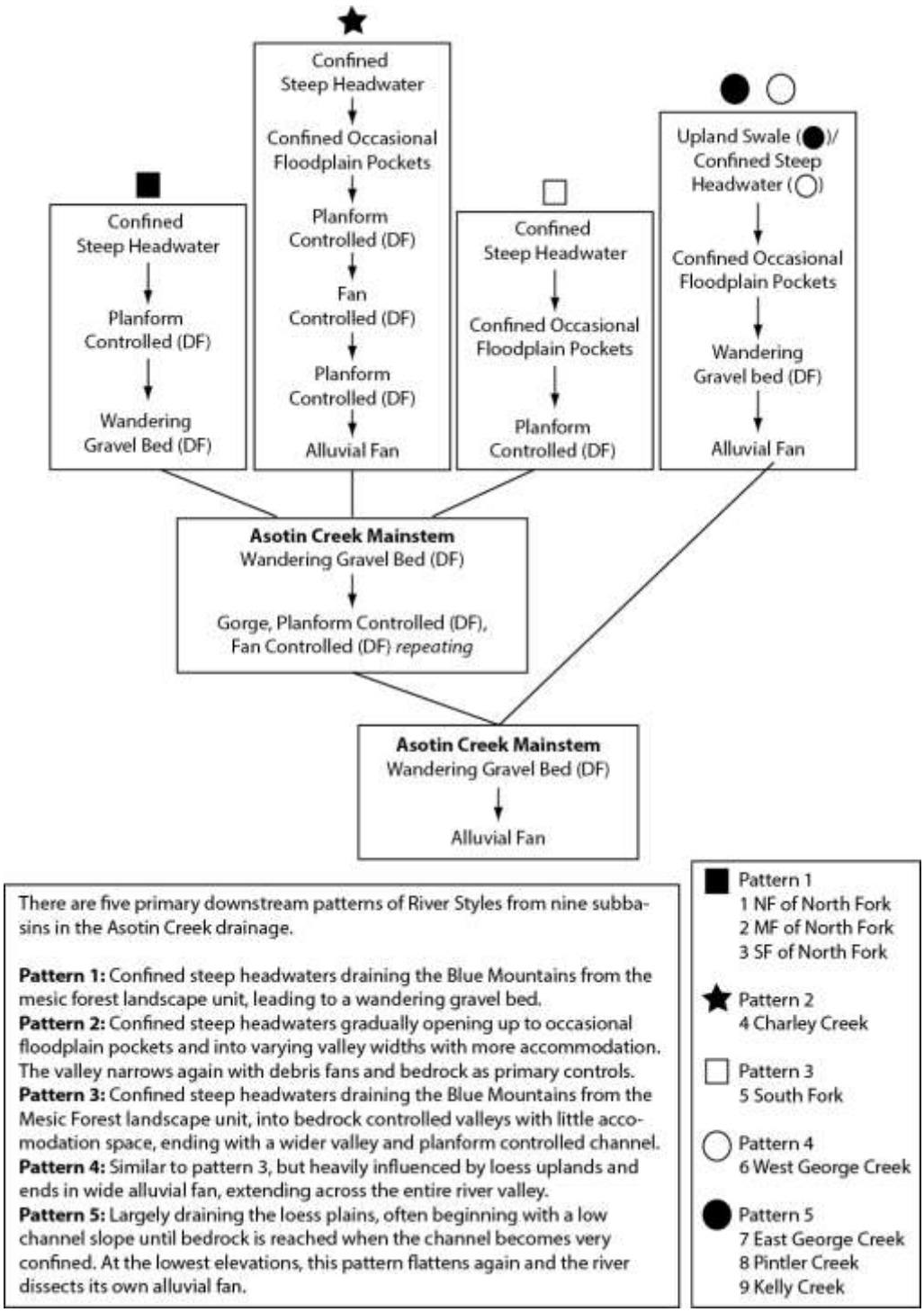

Figure 2.22. Primary downstream patterns of river styles present in the Asotin Creek basin. DF = discontinuous floodplain, NF = north fork, MF = middle fork, SF = south fork.

debris fan controlled section at the confluence of Warner Gulch, a large gorge on river left. The valley then widens, where the river becomes partly confined and planform controlled.

Pattern 4: ***West George Creek*** begins as headwaters flowing north from the Blue Mountains, but some incoming tributaries drain the Columbia Plateau on river left. This river remains confined for most of its length with occasional floodplain pockets before its confluence with East George Creek where it opens up to a valley-wide alluvial fan. This river is almost entirely a transport zone, but wherever the valley widens, large sheets of sediment are deposited and stored.

Pattern 5: ***East George Creek, Pintler Creek, and Kelly Creek*** are similar to West George Creek but their source is entirely from the loess mantled, Blue Mountain section of the Columbia Plateau. Every small order tributary begins as *Upland Swale* until the channel dissects the loess mantel and reaches the first layer of basalt. Once entering the basalt-lined lower Snake canyons, the channel becomes confined until its confluence with West George Creek.

BASIN CONTROLS ON RIVER CHARACTER AND BEHAVIOR

Physical boundaries in watersheds act as controls on river character and behavior, and provide insight into the processes that lead to the river's current form [*Brierley and Fryirs*, 2005]. Understanding these controls and a river's evolution, we can make better predictions on its trajectory and capacity for change. Large scale controls such as climate, hydrology, and catchment extents impact river behavior, but there is little we can do to manage their effects. At finer scales, however, we can identify controls that change over

shorter time periods which govern river behavior such as land use practices within landscape units or geomorphic assemblages within a reach. Explaining how these controls influence a river at multiple scales and evolutionary timeframes leads to well informed river restoration and management decisions.

There are a few major controls on river styles and downstream patterns in Asotin Creek. These controls are summarized in Table 2.6 for each river style, and depicted in Figure 2.23 and 2.24.

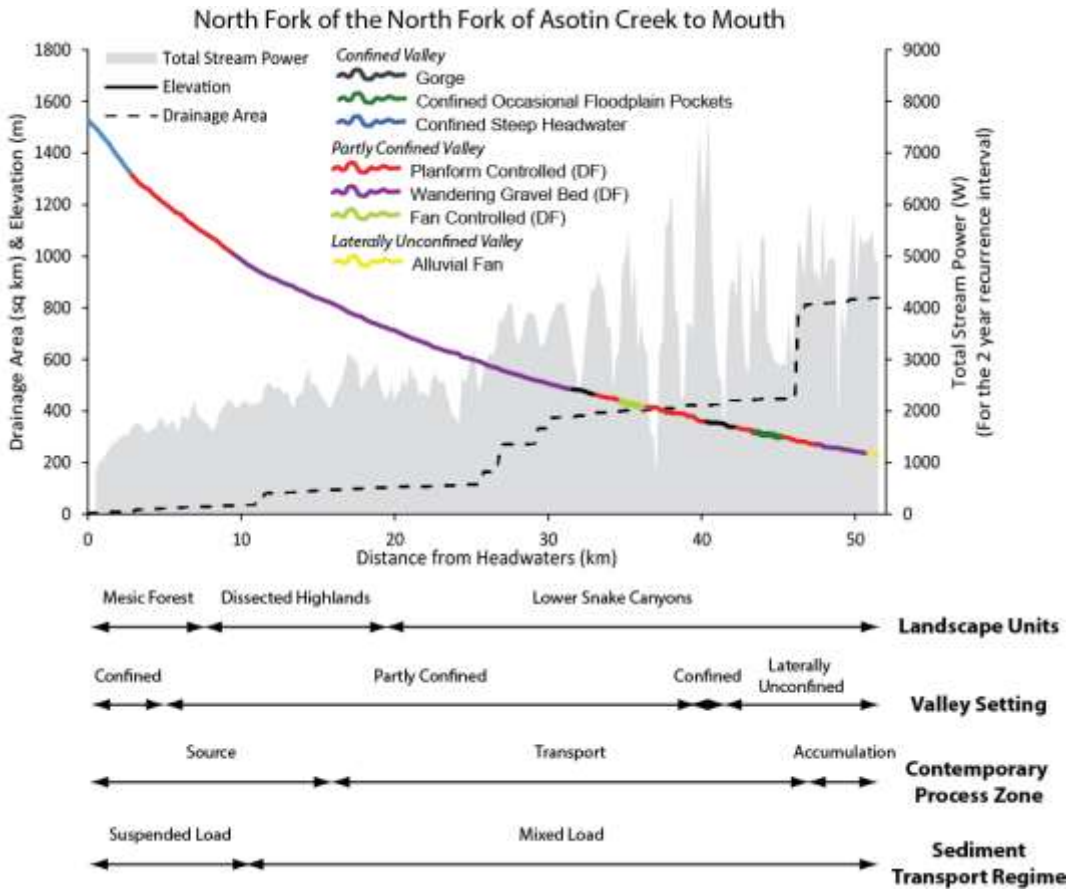

Figure 2.23. Example of longitudinal profile from the North Fork of the North Fork of Asotin Creek to the mouth of the Asotin Creek mainstem. This figure also shows drainage area, total stream power, and various controls. DF = discontinuous floodplain.

Table 2.6. Controls on river character and behavior in the Asotin Creek drainage.

River Style	Valley Slope (%)	Valley Width (m)	Drainage Area (km^2)	Bankfull Recurrence Interval (Years)
Gorge	0.05 - 0.10	<30	<800	N/A
Confined Steep Headwater	>0.10	<15	<30	N/A
Confined Occasional Floodplain Pockets	0.05 - 0.10	<40	<200	10 - 50
Steep Ephemeral Hillslope	>0.10	<15	<30	N/A
PC Wandering Gravel Bed (DF)	<0.02	50 - 100	<300	2 - 10
PC Planform Controlled (DF)	0.01 - 0.03	<100	<800	2 - 10
PC Debris Fan Controlled	0.02 - 0.05	<50	<500	2 - 10
Upland Swale	<0.03	50 - >1000	<50	N/A
LU Alluvial Fan	0.02 - 0.10	>100	<800	2 - 10

Bedrock is a very common control throughout the drainage in the form of basalt outcrops and cliff walls. Many of the valleys are either fully confined by bedrock, or partly confined and traversing between basalt cliffs on both sides of the valley margins. In conjunction with the common valley width constrictions, valley slope and stream

power are likely important controls. The longitudinal profile of the longest continuous river segment in Figure 2.23 shows a concave up form, but remains fairly steep through the entire drainage. Concavity in the longitudinal profile suggests that much of this river acts a transport zone. There are sections of low slope, but even the unconfined river styles will have long sections with a slope around 0.02. The combination of the width constrictions and high slope, causes stream power to fluctuate greatly and shows a general upward trend from the headwaters to the mouth of the mainstem. Short ***Gorge*** sections throughout the drainage greatly increase the stream power and are sources of erosion. These areas of increased valley and channel constriction are evident in the longitudinal profile as steep dips where stream power spikes upward.

The main tributaries all have a similar longitudinal profile (mostly straight and slightly concave up), but local controls and incoming side tributaries result in different river style patterns (Figure 2.24). Each profile shows infrequent decreases in slope; however, George Creek has multiple relatively longer sections of low gradient located at the mouths of incoming washes. The influence of incoming side tributaries appears to be a major cause of transitions between river styles because many of the breaks are located near confluences.

RIVER STYLES STAGE TWO:

INTRODUCTION

The final result in Stage One of the River Styles Framework provides an assessment of major geomorphic patterns among reaches in a river network. However, these patterns represent how a river *currently* behaves based on basin controls and current

flux boundary conditions, and may not always reflect local changes caused by disturbances. Therefore, river styles reaches I delineated in Stage One may include sections of river that appear misrepresentative in the field. Human disturbances cause variability within a river style that force a river to behave differently than it would in its natural geomorphic condition. In Stage Two, I identified the geomorphic condition of reaches that may cause their form to deviate superficially from a river style. I accomplished this by determining each river style's capacity for adjustment and interpreting their evolution to explain the geomorphic condition of reaches in terms of *good*, *moderate*, or *poor* variants.

CAPACITY FOR ADJUSTMENT

The capacity for adjustment of a river style can be defined as "morphological adjustments brought about by the changing nature of biophysical fluxes that do not record a wholesale change in river type." This interpretation is based on three degrees of freedom: the capacity for change of a river's channel attributes, channel planform, and bed character. Thus, the capacity for adjustment wholly represents the river's sensitivity to disturbances that inform the river's evolution. The detailed assessments of each river style in Stage One provide the basis for these interpretations.

River styles with a *low* capacity for adjustment are more resistant to disturbance than those with a *high* adjustment potential. I summarized each river style's sensitivity to the three degrees of freedom to infer their overall capacity for adjustment (Table 2.7). For example, river styles within a confined valley setting are resistant to disturbances due to the impervious physical controls that typically define their valley. Whereas, river styles in

wider valleys (partly confined or unconfined) typically have a greater capacity for adjustment, simply because they have more space to move and develop dynamic features. Likewise, the position in the watershed plays a defining role, with flows typically increasing downstream.

Table 2.7. Summary of the capacity for adjustment of river styles within three degrees of freedom (channel attributes, channel planform, and bed character) in the Asotin Creek watershed. DF = discontinuous floodplain.

River Style	Channel Attributes	Channel Planform	Bed Character	Capacity for Adjustment
Confined Valley Settings				
Confined Steep Headwater				Low
Gorge				Low
Steep Ephemeral Hillslope				Low
Confined Occasional Floodplain Pockets				Low
Partly Confined Valley Settings				
Fan Controlled (DF)				Moderate
Planform Controlled (DF)				Moderate
Wandering Gravel Bed (DF)				High
Unconfined Valley Settings				
Upland Swale				Low
Alluvial Fan				High

Minimal or no adjustment potential

Localized adjustment potential

Significant adjustment potential

Using Geoindicators to define adjustment potential

The summary of river style adjustment potential in Table 2.7 is based on a set of *geoindicators* that relate to each degree of freedom (Table 2.8, 2.9 and 2.10). Geoindicators are used to effectively assess the geomorphic condition of each river style; however, not every geoindicator is used for each river style. Some geoindicators are not

relevant to all river styles. For example, most channel planform geoindicators are not used when assessing the condition of steep headwaters and gorges within confined reaches (Table 2.8). Occasional floodplain pockets also occur within confined reaches, but because the valley width in these reaches is variable, allowing for discontinuous floodplain pockets, more channel planform geoindicators must be considered. Alluvial river styles are naturally more dynamic, therefore, they typically require more geoindicators as lines of evidence to assess their geomorphic condition.

Table 2.8. Geoindicators used to measure the geomorphic condition of river styles in confined valley settings in the Asotin Creek watershed.

Geoindicator/River Style	**Confined steep headwater**	**Gorge**	**Confined occasional floodplain pockets**	**Steep ephemeral hillslope**
Channel Attributes				
Size	No	No	Yes	No
Shape	No	No	Yes	No
Bank	No	No	Yes	No
Instream vegetation structure	No	No	Yes	No
Structural elements (e.g. woody debris loading)	Yes	Yes	Yes	Yes
Channel Planform				
Number of channels	No	No	No	No
Sinuosity of channels	No	No	No	No
Lateral stability	No	No	Yes	No
Geomorphic unit assemblage	Yes	Yes	Yes	Yes
Riparian vegetation	No	No	Yes	No
Bed Character				
Grain size and sorting	Yes	Yes	Yes	Yes
Bed stability	No	No	Yes	No
Sediment regime	Yes	Yes	Yes	Yes

Table 2.9. Geoindicators used to measure the geomorphic condition of river styles in partly confined valley settings in the Asotin Creek watershed.

Geoindicator/River Style	**Fan Controlled (DF)**	**Planform Controlled (DF)**	**Wandering Gravel Bed (DF)**
Channel Attributes			
Size	Yes	Yes	Yes
Shape	Yes	Yes	No
Bank	Yes	Yes	Yes
Instream vegetation structure	Yes	Yes	Yes
Structural elements (e.g. woody debris loading)	Yes	Yes	Yes
Channel Planform			
Number of channels	Yes	Yes	Yes
Sinuosity of channels	Yes	Yes	Yes
Lateral stability	Yes	Yes	Yes
Geomorphic unit assemblage	Yes	Yes	Yes
Riparian vegetation	Yes	Yes	Yes
Bed Character			
Grain size and sorting	Yes	Yes	Yes
Bed stability	No	Yes	No
Sediment regime	Yes	Yes	Yes

Table 2.10. Geoindicators used to measure the geomorphic condition of river styles in laterally unconfined valley settings in the Asotin Creek watershed.

Geoindicator/River Style	Upland Swale	Alluvial Fan
Channel Attributes		
Size	Yes	No
Shape	Yes	No
Bank	Yes	No
Instream vegetation structure	No	Yes
Structural elements (e.g. woody debris loading)	No	Yes
Channel Planform		
Number of channels	No	No
Sinuosity of channels	No	No
Lateral stability	No	No
Geomorphic unit assemblage	Yes	Yes
Riparian vegetation	Yes	Yes
Bed Character		
Grain size and sorting	No	Yes
Bed stability	No	No
Sediment regime	Yes	Yes

RIVER EVOLUTION AND REFERENCE CONDITIONS

Conceptualizing the evolutionary sequence that led to a river reach's current form provides insight into how boundary conditions have responded to human and natural disturbances. To extrapolate timeframes where boundary conditions were constant, major disturbances in the watershed's history must be identified and interpreted. Much of the history of major fluvial disturbances in the Asotin Creek watershed can be linked to human settlement and development starting in the early 1800s.

The combination of human land use and large flood events within the available historic record indicate sustained landscape pressure in the last 200 years in Asotin Creek. Most of the direct human impacts to channel planform have occurred lower in the

basin; however, agriculture, grazing, and logging have influenced river evolution throughout the watershed. Specifically, the lack of organic structural elements (e.g., LWD), is directly related to the historic land use practices. Small, privately owned water diversions still exist lower in the watershed as well. These events and transitions between land use mark important timeframes of geomorphic stability within river styles on Asotin Creek.

EVOLUTIONARY DIAGRAMS OF RIVER STYLES

The geomorphic evolution of a river is characterized by timeframes of consistency, interrupted by major natural and human impacts. By inferring periods of geomorphic consistency, variations of each river style that may have been historically present are revealed. River styles in a watershed appear in different stages of development, equilibrium, and degradation; therefore, historic variations likely still exist at some locations. Developing evolutionary sequences for each river style is necessary to identify a reference condition and the range of condition variants.

An example evolutionary diagram for the ***Planform controlled with discontinuous floodplain River Style*** is shown in Figure 2.24. This diagram shows cross sections of a typical reach as time slices for a given period of relative gemorphic consistency. The first slice is an inferrence of what the channel might have looked like prior to expansive Euro-American settlement. These reaches were mostly single-thread channels with access to the floodplain when traversing between the valley margins. The riparian zone primarily consisted of large cottonwood galleries and a thick understory of native shrubs and grasses. Moving away from the channel, conifer species such as

ponderosa pine and Douglas fir were mixed in, and likely dominated at higher elevations. Large woody debris was abundant in the channel and recruited often. Likewise, beaver colonies were common in the lower gradient sections. This condition is no longer found in the Asotin Creek watershed; however, minimally impacted reaches that are similar to this condition do appear in Charley Creek.

From settlement to the 1950s, logging, grazing, and agriculture in the watershed were booming. Timber was either harvested or removed to make way for houses and small farms on the valley floor, while intensive cattle and sheep grazing likely introduced exotic shrub and grasses that still dominant the vegetative communities today. During this time, fine sediment likely covered the channel bed. As cottonwoods and conifers were removed from the riparian zones, alders took hold, and by 1995, they became the dominant riparian tree species. Three significant floods of record between 1950 and 1996 scoured the channel in some reaches, while laying out large sheets of cobble in others, and completely reworked the geomorphic assemblages that make up these reaches. The floods incised many reaches, and layed down large gravel and cobble sheets that are still present today. With many restoration and recovery actions in the watershed, several of these reaches are currently in recovery. Where the channel was previously a treadmill for sediment, structural elements (from restoration actions or naturally recruited) slowed sediment transfer, created forced bars, and created forced pools.

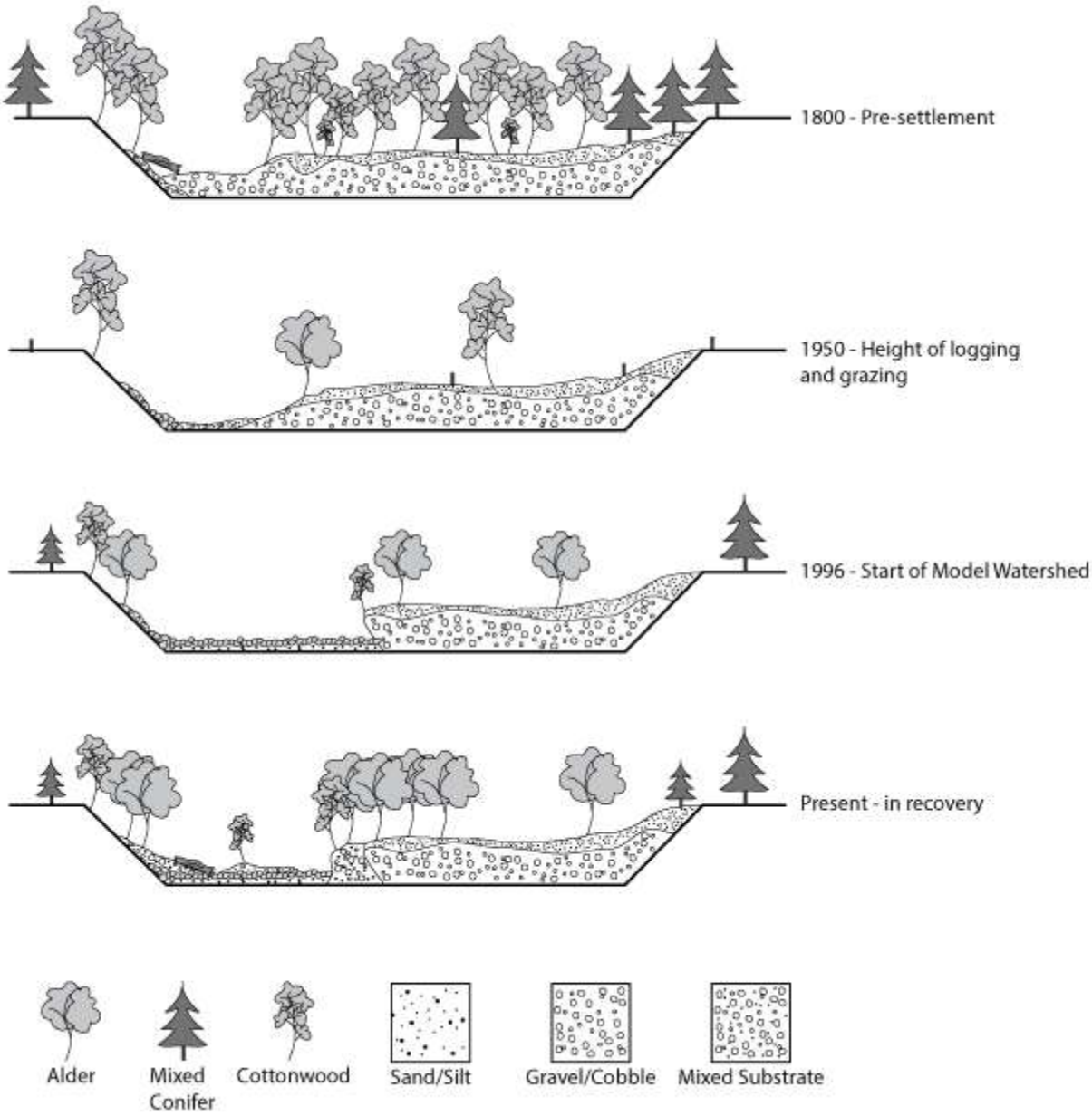

Figure 2.24. Evolution of the Planform controlled with discontinuous floodplain River Style in Asotin Creek.

RELEVANT GEOINDICATORS

Identifying relevant geoindicators for each river style leads to the development of "desirability" questions to help determine a reach's condition. Questions are limited to

those that are relevant to a river style's capacity for adjustment within each degree of freedom. For example, the ***Planform controlled with discontinuous floodplain River Style*** has 13 questions that relate to the condition of a reach's channel attributes, channel planform, and bed character (*Table 2.11*).

The development of River Styles in a watershed is inferred, based on the physical boundary conditions, to define how a given reach "should" be. Under current boundary conditions, variants of each River Style exist due to human and natural impacts that alter the degrees of freedom (Table 2.7). Therefore, to determine a reach's current condition, it is necessary to identify a "reference" reach for each River Style to act as a baseline. A reference reach can either be 1) intact and pristine, 2) the "best" condition reach of that river style attainable under current boundary conditions, or 3) an inferred "expected" condition based on analyses of river character and behavior from Stage One. Pristine conditions do not exist in the Asotin Creek watershed due to extensive grazing, logging, and agriculture throughout the watershed; therefore, reference reaches have been identified and assessed using option two. The decision process for determining an appropriate reference reach is outlined in Figure 2.25.

As stated above, there are no intact reaches of any River Style in the Asotin Creek watershed. Therefore, a reach on Charley Creek, upstream from Zig-Zag Road was assessed and determined to be in good condition under current flux boundaries. This reach was designated as the reference reach for the ***Planform controlled with discontinuous floodplain River Style*** using the reference reach decision tree.

Table 2.11. Desirability questions for assessing good condition reaches of the Planform controlled with discontinuous floodplain River Style in partly confined valley settings in the Asotin Creek watershed.

Degrees of Freedom and their relevant Geoindicators	**Questions to be answered to assess geomorphic condition of each reach of the *Planform controlled discontinuous floodplain River Style*?**
Channel Attributes	**4 out of 5 questions must be answered YES**
Size	Is channel size appropriate for the catchment size, sediment regime, and vegetation characteristics? (i.e. is the width/depth ratio appropriate?)
Shape	Is the channel shape appropriate? (i.e. symmetrical on straight sections, asymmetrical at bends)
Bank	Are the banks eroding in the right places and at the correct rates? (i.e. occasional undercut banks, alternating erosion and deposition along banks)
Instream Vegetation Structure	Is the instream vegetation structure appropriate? (i.e. woody shrubs on bars, native water-loving plants around channel margin, limited macrophytes)
Woody Debris Loading	Is there woody debris in the channel or potential for recruitment of woody debris? (i.e. pools and bars are commonly forced in these reaches)
Channel Planform	**3 out of 5 questions must be answered YES**
Number of Channels	Are the number of channels in this reach appropriate? (i.e. occasional side channels or flood runners)
Sinuosity of Channels	Is the channel sinuosity consistent with the sediment load/transport regime and the slope of the channel? (i.e. moderately sinuous when traversing across valley, not sinuous along valley margin)
Lateral Stability	Is the lateral stability consistent with the sediment texture and channel slope? (i.e. moderately stable with some opportunities for lateral adjustment)
Geomorphic Unit Assemblage	Are the number, type and pattern of instream geomorphic units appropriate for the sediment regime, slope, bed material and valley setting? Are key units of this River Style present (i.e. planar riffles and runs, cutbanks, pools, point bars)?
Riparian Vegetation	Are the appropriate types and density of riparian vegetation present on the banks and floodplain? (i.e. canopy and shrub layers that serve similar function to native vegetation)
Bed Character	**2 out of 3 questions must be answered YES**
Grain Size and Sorting	Is the range of sediment throughout the channel and floodplain organized and distributed appropriately? (i.e. obvious facies units, appropriate sized sediment for each geomorphic unit)
Bed Stability	Is the bed vertically stable such that it is not incising or aggrading inappropriately for the channel slope, sediment caliber, and sinuosity?
Sediment Regime	Is the sediment storage and transport function of the reach appropriate for the catchment position? (i.e. a balanced sediment transfer zone)

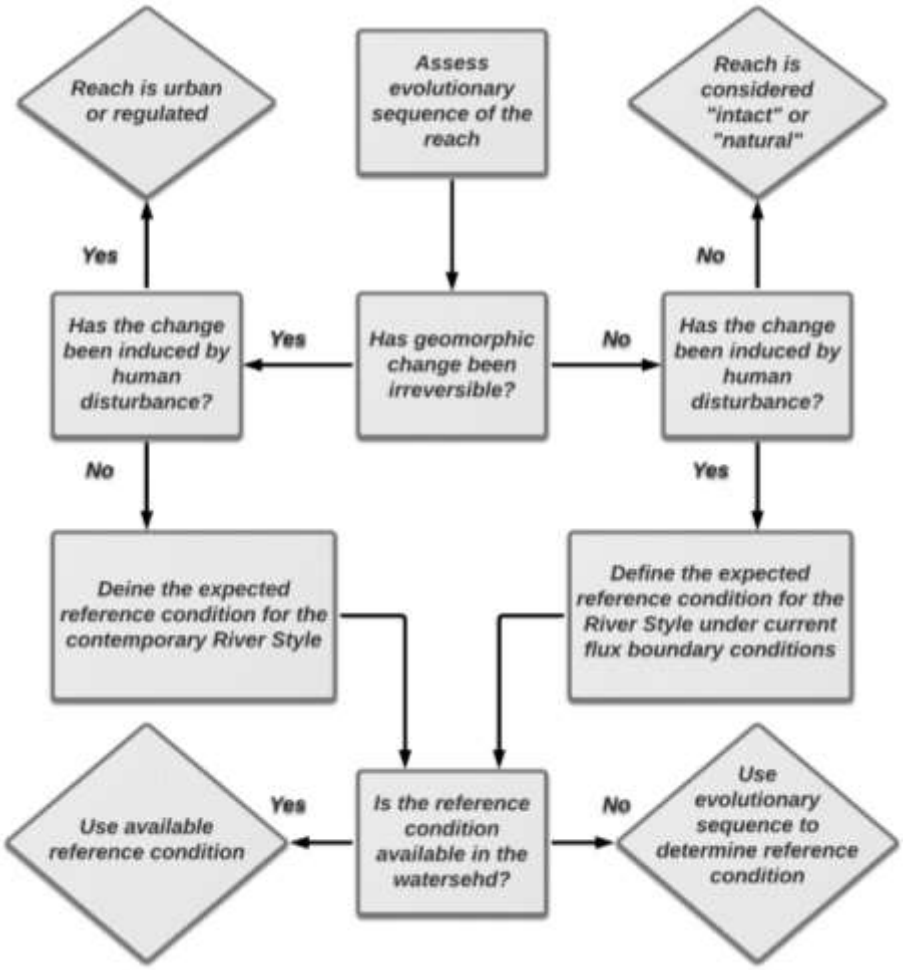

Figure 2.25. Decision tree used to identify a reference reach for a River Style. Modified from Brieryly and Fryirs [2005].

APPLIED GEOMORPHIC CONDITION MAP

Designating and Explaining Geomorphic Condition

The final step to summarizing geomorphic condition is to develop a *condition matrix* for each reach of a river style. The information gained from assessing each reach based on geoindicators and desirability criteria is used to define each reach as *intact* (undisturbed), *good*, *moderate*, or *poor*. If the criteria for degree of freedom is met, a check mark (✓) is placed in the matrix, if the criteria is not met, a cross (X). A reach

receiving three checks is considered to be in good condition, whereas one or two checks would result in moderate condition, and no checks result in a poor condition.

Based on assessment of the geoindicators and the land use history in Asotin Creek, I did not identify any *intact* reaches. There are three "variants" of the ***Planform controlled with discontinuous floodplain River Style*** realized in four separate reaches in the Asotin Creek watershed (

Table *2.12*). A reach upstream from Zig-Zag Road on Charley Creek was assessed to be in good condition, and was used as the reference to which other reaches were compared. There are two *poor* condition reaches on the mainstem of Asotin Creek. Human influence has artificially pushed these reaches and realigned them against the valley margin for most of their length, canopy cover is limited, and straightening of the channel has reduced geomorphic complexity. Results from available geospatial data (LiDAR, soils, historic vegetation maps) reveal that these reaches possessed traits of the ***Planform controlled with discontinuous floodplain River Style*** in its recent history. Geomorphic alteration in some sections of these reaches is irreversible within a management context due to roads, bridges, and other development.

The *moderate* condition reach on the mainstem of Asotin Creek is upstream of Headgate dam and occurs as part of a sequence with the ***Fan controlled with discontinuous floodplain River Style***. This reach is still influenced by human development and it meets three of the five desirability criteria for channel planform. In addition, a small decommissioned dam downstream of this reach has altered the bed character and geomorphic unit assemblages as the channel attempts to rework the large amounts of sediment that historically accumulated behind the decommissioned dam. The

Table 2.12. Geomorphic condition and assessment of degrees of freedom of reaches for the Planform controlled with discontinuous floodplain River Style in the Asotin Creek watershed. Reach names are informal and reference nearby landmarks. They are in order from downstream to upstream within each river. US = upstream, DS = downstream.

Planform controlled with discontinuous floodplain

Reach	Stream	Geomorphic Condition	Channel Attributes	Channel Planform	Bed Character
1. Lower - US of George Cr	Asotin	*Poor*	X	X	X
2. Lower - DS of Headgate	Asotin	*Poor*	X	X	X
3. Middle - US of Headgate	Asotin	*Moderate*	X	✓	X
4. Forks to WDFW Rec Area	South Fork	*Moderate*	✓	✓	X
5. Rec Area to Warner Gulch	South Fork	*Moderate*	X	✓	✓
6. US of Zig-Zag Road	Charley	*Good*	✓	✓	✓

instream geomorphic units in these reaches are comprised largely of glides and runs, with pools almost entirely lacking. The other two moderate condition reaches are on the South Fork of Asotin Creek and meet the minimum requirements for each checked degree of freedom. Reaches four and five have been part of many restoration and rehabilitation projects in the last two decades [ACCD, 1995; Wheaton et al., 2012]. An explanation for each geomorphic condition of the ***Planform controlled with discontinuous floodplain River Style*** is provided in Table 2.13. For the final product of Stage Two of the River Styles Framework, I delineated the river network into condition variants for the Asotin Creek watershed (Figure 2.26). The map reflects apparent downstream patterns where disturbances have affected the channel. The overall increase in the number of *poor* condition reaches moving downstream reflects the downstream culmination of over 200 years of human intervention and increased impacts from rural and urban development lower in the watershed. A relatively small drainage, it is likely that no reach in the

watershed is *intact*. Most of the direct human pressure has occurred on the mainstem of Asotin Creek, especially lower in the watershed. However, logging and grazing has had indirect impacts, especially on reaches extending from the Columbia Plateau which has almost entirely been converted to agriculture. Many of these reaches are also directly impacted by water diversions, sediment traps, ponding, and frequent road crossings. The upper tributaries have all been part of river restoration and rehabilitation projects in the past two decades, and are mostly in recovery.

Table 2.13. Explanations of the geomorphic condition of reaches of the Planform controlled with discontinuous floodplain River Style in the Asotin Creek watershed.

Degree of Freedom	Good Condition	Moderate Condition	Poor Condition
Channel Attributes	Relatively low width:depth ratio with local variability. Most geomorphic complexity is structurally forced by wood, vegetation, and bedrock outcrops when the channel is near the valley margin. The channel is symmetrical when traversing between valley margins, and asymmetrical on bends and against bedrock at the valley margin. Islands and bars are frequent with varying vegetation levels.	Relatively high width:depth ratio, with local variability. Mostly symmetrical channel with occasional high, eroding banks. Bars and islands are rarely vegetated, and mostly comprised of large substrate. Geometry is mostly symmetrical. Limited woody debris. Some exotic macrophytes may be present.	Very high or very low width:depth ratio; channel may be over-widened where banks are unstable, or incised where banks are armored. Slumped or undercut banks are frequent, otherwise is an entirely symmetrical geometry. No woody debris. Limited instream woody vegetation and abundant exotic macrophytes.
Channel Planform	Usually single, but sometimes multiple channels forced by organic structural elements. Low sinuosity along valley margin, moderate sinuosity when traversing to opposite valley margin. Moderate lateral stability, and adjusting when conditions permit. Planar features are separated by forced bar and pool complexes. Riparian zone is relatively wide with mix of cottonwoods, alders, and native conifers.	Almost always single channel and low sinuosity. Laterally unstable with accelerated bank scour, but limited lateral expansion. Mostly planar geomorphology, with some forced pools and bars. Occasional private levees restrict access to floodplain. Limited riparian zone with mixed native and exotic canopy. Much of the floodplain has been converted for agriculture.	Single channel with low sinuosity. Laterally unstable, but no room for expansion. Almost entirely planar channel units with occasional pools. Floodplain has been converted to agriculture or urban use. Very limited riparian cover.
Bed Material	Well sorted bed material with well defined facies typically forced by structural elements. Bars are comprised of gravel and smaller clasts. The channel bed is stable and sediment flux is balanced. Sediment transfer zone with pockets of storage.	Poorly sorted bed material with pockets of defined texture around infrequent structural elements. Limited roughness due to lack of instream vegetation and woody debris. Bed is stable and the sediment flux is balanced. Sediment transfer zone.	Homogeneous bed material, mostly large clasts armoring the bed. Sediment is poorly sorted with limited pockets of defined texture. Unstable bed is incising in most areas. Sediment transfer zone.
Photograph	Upper Charley Creek	Middle of South Fork Asotin Creek	Lower Asotin Creek

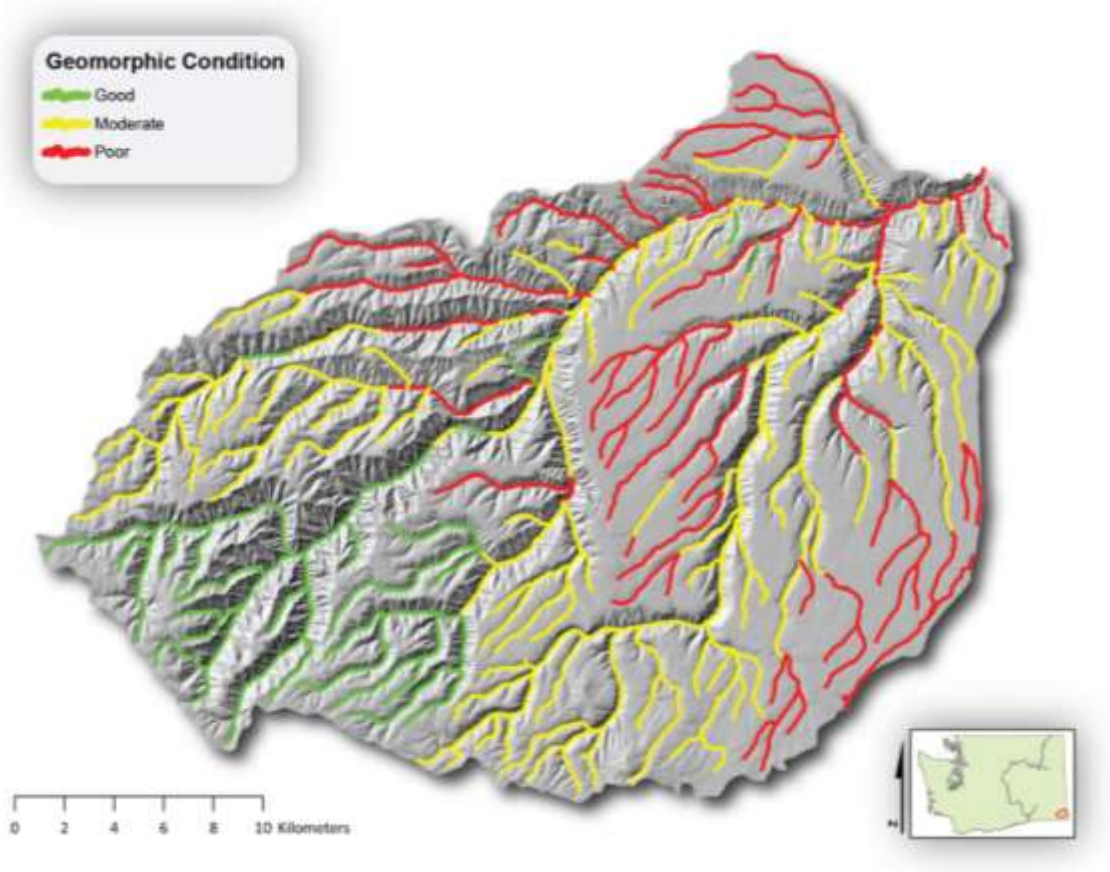

Figure 2.26. Geomorphic condition variants of River Styles in the Asotin Creek watershed.

Good condition reaches are concentrated in the southwest corner of the watershed, and start as the headwaters for the North and South Forks of Asotin Creek. Good condition variants comprise 92% of the North Fork stream length, and 53% of the South Fork stream length (Figure 2.27). That region is within the Umatilla National Forest and has not been developed. However, logging and grazing still occurs, but has had relatively minimal impact on the streams. Due to their isolation from development and rugged geography, many of the reaches on the North Fork are near *intact* condition. The low

density of instream LWD as structural elements reserves their condition as *good.* In contrast, the majority of Charley Creek and George Creek are in moderate condition (81% and 65%, respectively; Figure 2.27). Although they are uncommon in Asotin Creek, there are no *good* condition variants of the laterally unconfined river styles reaches (Figure 2.28). Likewise, river styles in partly confined valley settings are mostly *poor* and *moderate* condition variants, with the exception of a large portion of the North Fork, and part of Charley Creek.

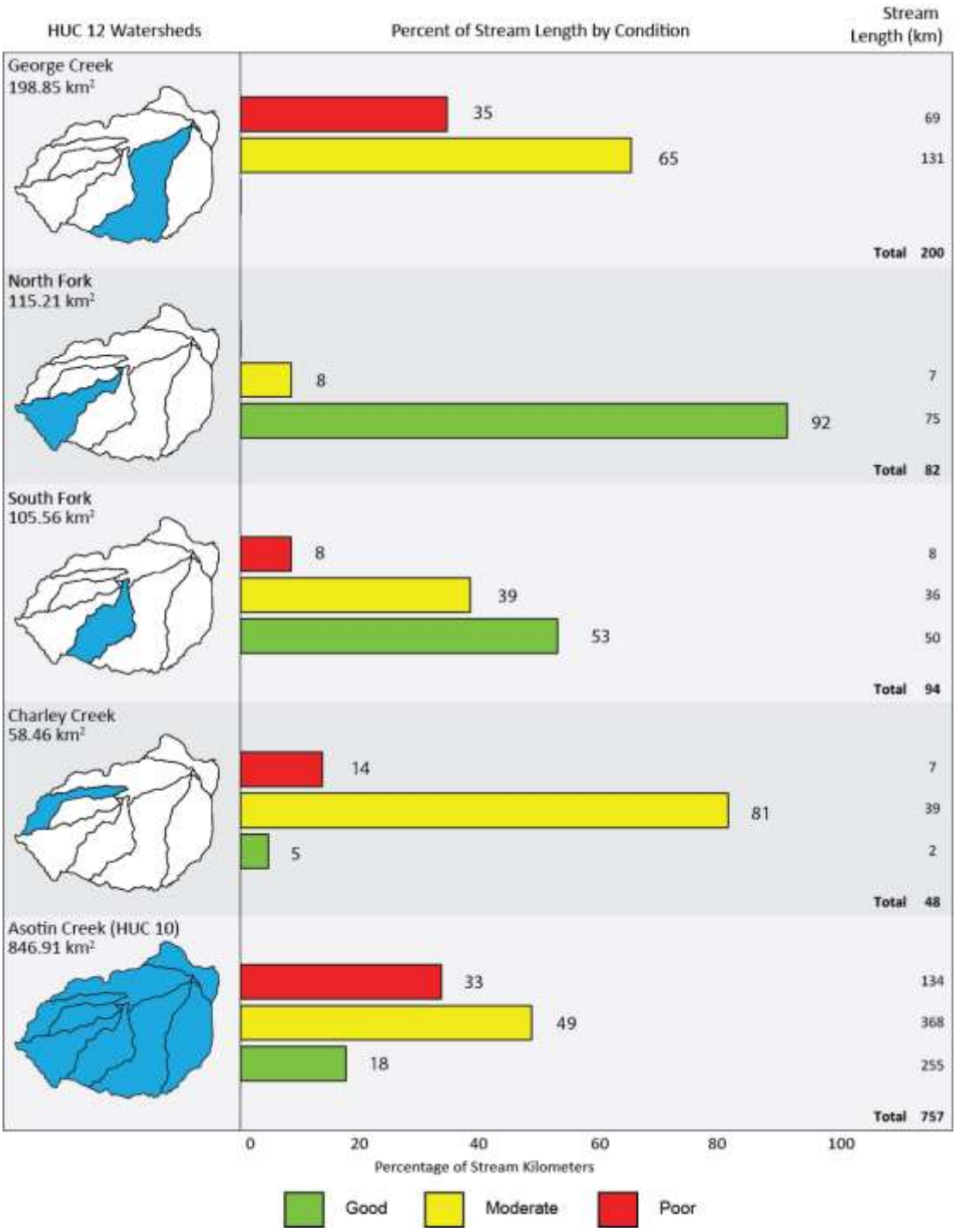

Figure 2.27. Geomorphic condition of streams in Asotin Creek summarized by Intensively Monitored Watershed study streams, George Creek, and the whole basin.

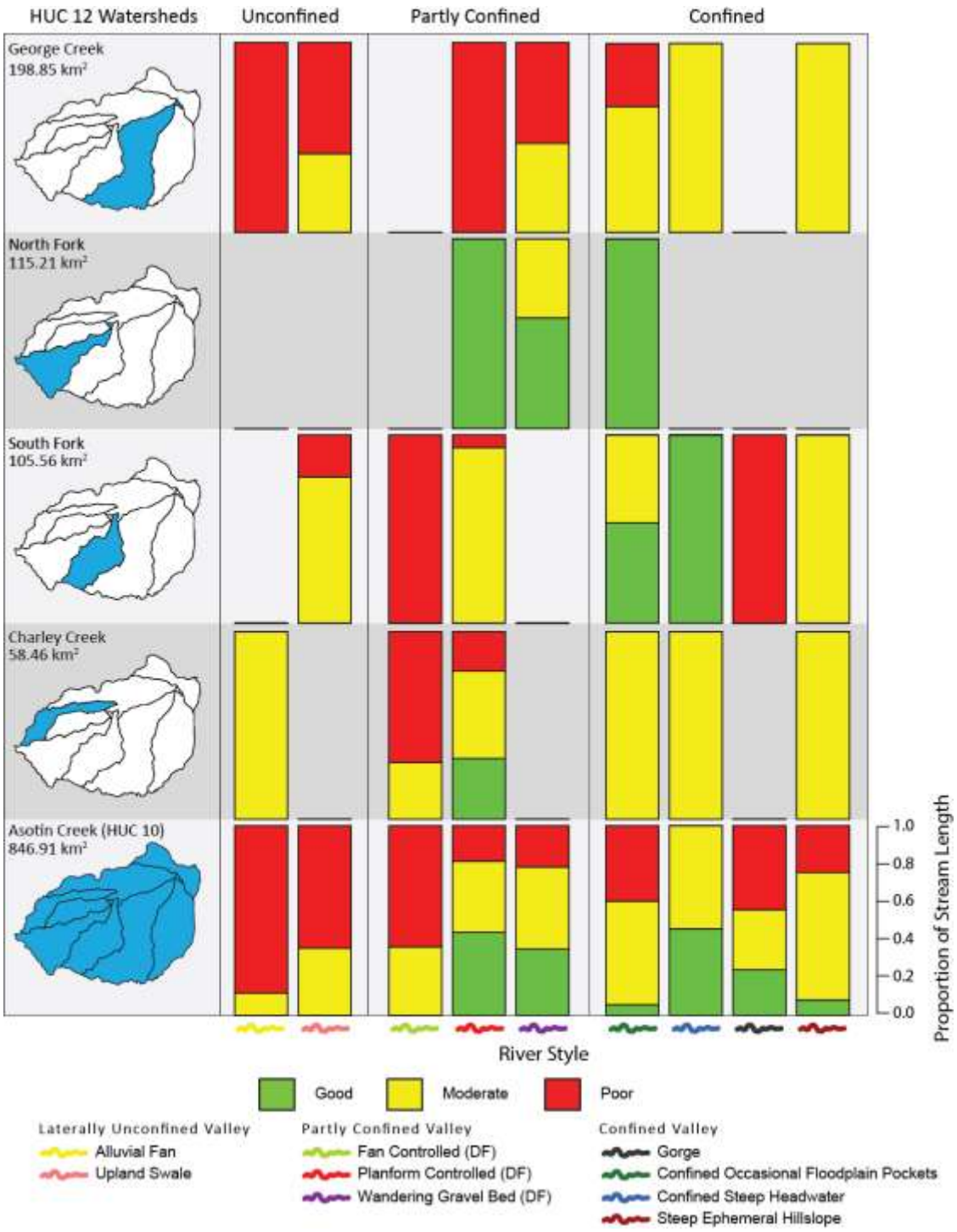

Figure 2.28. Geomorphic condition of streams in Asotin Creek summarized by Intensively Monitored Watershed study streams, George Creek, and the whole basin by river style.

CHAPTER 3

SHORT TERM EFFECTIVENESS OF CHEAP AND CHEERFUL STREAM RESTORATION USING HIGH DENSITY LARGE WOODY DEBRIS

INTRODUCTION

The geomorphic condition of many riverine systems have become highly degraded through human impacts, disrupting natural fluvial processes at a global scale [*Beechie et al.*, 2010]. Restoration and rehabilitation efforts have become standard practices in the United States to mitigate over 200 years of disturbance [*Roni et al.*, 2008]. In the northwest U.S., most stream restoration actions are focused on improving hydraulic and geomorphic conditions in freshwater ecosystems that increase and/or improve salmonid production [*Thompson*, 2006; *Stewart et al.*, 2009; *Whiteway et al.*, 2010]. Commonly, engineered instream structures are placed in the channel with the goals of increasing complexity and promoting spawning and rearing areas while increasing refugia from predators and velocity [*Stewart et al.*, 2009; *White et al.*, 2011]. Engineered large woody debris (LWD) structures are typically built to be static by cabling or burying LWD [*Abbe et al.*, 2003]. While securing LWD increases structure longevity and potentially the predictability of hydraulic and geomorphic effects [*Abbe et al.*, 2003], the dynamism of naturally recruited wood in intact systems is lost which may defeat the purpose of holistic restoration. However, despite static engineered structures being the dominant approach for 80 years, evidence for their success remains inconclusive [*Bayley*, 2002; *Roni et al.*, 2002; *Thompson*, 2006; *Stewart et al.*, 2009]. An

alternative to direct manipulation of habitat pockets using engineered instream structures is to reconnect the processes that led to the initial degradation [*Beechie et al.*, 2010]. Disconnected processes can be assessed by performing an initial watershed assessment to target the root causes of degradation, such as deforestation, urbanization, water diversions, or disconnected habitat [*Beechie et al.*, 2010]. Once the processes that maintain fluvial ecosystems have been restored and/or the impairments that link them addressed, instream structures may be more effective [*Roni et al.*, 2005; *Thompson*, 2005].

Although making a definitive link between restoration and salmonid communities is difficult, it is clear that habitat diversity generally has a positive influence on aquatic ecosystems [*Smokorowski and Pratt*, 2007]. Habitat diversity in streams includes reaches with variable channel depth and width, which reflect a variety of hydraulic conditions that may produce diverse assemblages of geomorphic and hydraulic units which provide different niches for aquatic biota [*Lonzarich and Quinn*, 1995; *Zalewski et al.*, 2003]. In many streams, structural elements such as LWD and riparian vegetation often force these conditions [*Larson et al.*, 2001; *Abbe et al.*, 2003; *Montgomery et al.*, 2003; *Rosenfeld and Huato*, 2003]; however, wood retention and recruitment processes are often degraded [*Larson et al.*, 2001; *Nagayama and Nakamura*, 2010; *Collins et al.*, 2012]. [*McBride et al.*, 2010] suggested that it takes many decades for streams to recover from disconnected riparian processes. I postulate that many streams are too disturbed to fully recover, but strategic intervention can kick start recovery, even under current boundary conditions in their respected watershed [*Brierley and Fryirs*, 2012]. Likewise, LWD loading in high

densities may help kick start recovery of instream habitat while riparian areas continue to recover in degraded watersheds [*Davidson and Eaton*, 2013].

What we term high density large woody debris ($_{HD}$LWD) loading is a restoration strategy to reincorporate the structural elements which promote hydraulic and geomorphic complexity to a stream channel. The geomorphic change we expect to impose using the $_{HD}$LWD method requires channel-altering flows; however, it is an active kick start to reconnecting lost fluvial processes. $_{HD}$LWD loading has been used successfully to increase channel complexity, mostly in small to medium sized streams (<20 m channel width) [*Rosenfeld and Huato*, 2003; *Haschenburger and Rice*, 2004; *Brooks et al.*, 2006; *Kail et al.*, 2007; *Nagayama and Nakamura*, 2010]. However, monitoring can be extremely difficult due to the dynamism of LWD movement, and complexity of the physical interactions between LWD and fluvial processes [*Abbe et al.*, 2003; *Kail et al.*, 2007]. Regardless, LWD is effective at scouring pools, forcing bars, and increasing channel width variability [*Montgomery et al.*, 2003].

From 2012 to 2014, we placed over 500 LWD structures within three 4 km long treatment sections on two tributaries to Asotin Creek in southeast Washington at an estimated cost of less than $100 per structure. The restoration strategy is considered $_{HD}$LWD because density was 45 structures per km resulting in wood loading of 132 pieces per km. The long term goal of the project is to restore riparian function by promoting the development of a riparian zone that resembles the behavior of historic condition [*Wheaton et al.*, 2012]. In the short term, the goal is to learn how the addition of $_{HD}$LWD alters the hydraulic and geomorphic conditions within the study streams. In total, we implemented eight different structure types, each with specific expected

hydraulic and geomorphic responses. The majority of the structures are called Post Assisted Log Structures (PALS), and utilize wooden fence posts to temporarily secure LWD to the channel. Our objectives in this study are to 1) determine the efficacy of $_{HD}$LWD at inducing explicit hydraulic responses, 2) determine the effectiveness of $_{HD}$LWD at inducing explicit geomorphic responses, and 3) examine the changes to the geomorphic unit assemblages within the treatment reach. To meet these objectives, I analyzed topography of treatment and control sites before and after treatment at sample reaches representing 20% of all treatments. In addition, I used a novel rapid assessment method to census responses at every structure for complete coverage in the treatment sections.

We developed explicit design hypotheses at every structure. In short, we expected that the addition of a LWD structure would force the local stream hydraulics to change immediately from uniform to complex flows. We expected that structures would also force local geomorphic change following high flows through increased localized sediment erosion and deposition. We also expected that there would be an overall increase in geomorphic complexity and diversity within the treatment reach following one year of high flows. Specifically, we are addressing the short term (1-5 years) hypotheses from our Asotin IMW restoration design [*Wheaton et al.*, 2012]:

A) The uniform flow pattern will shift to a convergent flow pattern concentrated on the opposite side of the channel as the structure and the main zone of convergence will be slightly downstream of the structure. The intensity of this convergent jet will scale roughly with the degree of blockage at the structure.

B) An eddy will form in the wake of the structure and extend downstream on the same side of the structure roughly as far as the jet from the convergent flow extends.

C) Downstream of the main zone of convergence and the eddy, the flow paths will strongly diverge.

D) We do not expect any significant geomorphic adjustment in response to these hydraulic changes at base flows; however, we do expect the overall hydraulic heterogeneity of the flow field to increase.

E) If woody debris is transported by high flows, we expect some of it to accumulate on the structure.

F) We expect scour and formation, accentuation, or maintenance of a longitudinally elongated constriction-forced pool associated with the convergent flow patterns, and the deepest portion of the pool to form directly downstream of the main zone of convergence. The pool will likely persist as long as the structure persists.

G) If any of the convergent flow is directed at the bank opposite of the structure, and the bank is readily erodible, we expect bank erosion and/or an undercut bank to develop. We expect the fine fraction of this source material to be winnowed away quickly and coarse fraction to be deposited in the next 1-4 bars downstream (at the individual flood event time scale), with most being deposited in the first bar.

H) Depending on the flow geometry and sediment load, the eddy may act as a pool, or may become a zone of finer sediment deposition. In the case of an ample sediment load, an eddy bar may form. The size of the eddy and development or persistence

of any eddy bar deposit will depend very much on the porosity and configuration of any woody debris existing or racking on the structure.

I) Where the flow path becomes highly divergent downstream of the convergent flow jet and eddy, we expect an active gravel bar to form. The flow and channel geometry will determine whether the bar is a mid channel bar, a bank attached bar or riffle. If the local coarse sediment supply is adequate, and a riffle forms, the riffle crest may rise and accentuate the pool depth of the upstream pool.

J) Depending on the degree and geometry of the bar growth, this may promote strongly convergent flow patterns downstream of or adjacent to the bar, which may in-turn form, accentuate and/or maintain a bar-forced pool.

K) Variability in channel & flow width will increase.

L) A low-flow water depth distribution with at least a 2-3 fold increase in range, and potentially a 5-10 fold increase in the variability of water depth compared to the pre-treatment condition (i.e., change the mostly uniform depth profile to a highly variable depth profile with shallow riffles, moderately deep runs, and deep pools).

M) There will be a greater diversity in the type of geomorphic units and a larger number of geomorphic units.

N) The amount of erosion and deposition will increase, without necessarily causing a change in the net sediment budget (i.e. relative balance of erosion and deposition).

O) The presence of structural cover for fish provided from deep pools, woody debris and undercut banks will increase.

P) The number, size and proximity of shear zones to important habitat elements (e.g., pools and undercut banks), resulting from structures, LWD, bank irregularities and variation in channel width will increase.

Many of the short-term hypotheses are individual parts of the hydraulic and geomorphic responses we expected to develop after a structure is installed. We also developed long-term hypotheses (5-10+ years) for the channel, valley, and riparian responses to $_{HD}$LWD restoration [*Wheaton et al.*, 2012]. In short, we expect the short-term physical changes will lead to a riparian and floodplain area that resembles the behavior of historic conditions, including natural wood recruitment.

These hypotheses are detailed and I investigated them individually at every structure using a rapid habitat assessment method. Additionally, I sought to detect reach level changes to the channel. Therefore, I used high precision topographic surveys collected using the Columbia Habitat Monitoring Program (CHaMP) protocol to assess the efficacy of the restoration at meeting our hypotheses at a limited number of sites [*CHaMP*, 2013]. Then, I used the data from the rapid assessment approach to expand our coverage of individual structures to the entire sample size. In this way, I was able to assess reach and section level effectiveness of $_{HD}$LWD using the topographic surveys, and the local structure level responses using the rapid assessment method.

STUDY SITES

The Asotin Creek drainage encompasses 847 km^2 in the southeast corner of Washington State (Figure 3.1) and is a wild summer steelhead sanctuary [*Crawford et al.*, 2011]. Elevations in the basin range from 1890 m in the Blue Mountains to 228 m at the

confluence of Asotin Creek and the Snake River. This study focused on two of three treatment sections on Charley Creek and the South Fork of Asotin Creek, which are also study streams in the Asotin Creek IMW [*Bennett and Bouwes*, 2009]. The South Fork drains an area of 104 km^2, is oriented mostly North-South, and has an average annual discharge of approximately 0.43 cms. Charley Creek is about half the size at 58 km^2, is oriented mostly East-West, and has an average annual discharge of approximately 0.28 cms. Most urban development has occurred along the mainstem and mouth of Asotin Creek. The majority of the upper watershed (including the study sites) is owned by the Washington State Department of Fish and Wildlife and United States Forest Service. Annual fish and habitat surveys are conducted by IMW crews to monitor short term and long term trends within the study streams [*Bennett et al.*, 2012]. For a more detailed site description of the Asotin Creek watershed, refer to Chapter 2.

The treatment sections of the South Fork of Asotin Creek and Charley Creek are in moderate and poor geomorphic condition (see Chapter 2). Following roughly 200 years of intensive logging, grazing, and beaver trapping, the study streams are in a degraded state. Several large floods between 1904 and 1996 further exacerbated the degraded conditions of the study streams by modifying substrate composition, geomorphic assemblages, channel planform, and further decimation of riparian vegetation [*NRCS*, 2001; *ACCD*, 2004]. However, in 1995, Washington state's first model watershed plan was developed for Asotin Creek, which improved land use management practices [*ACCD*, 1995]. In 2012, 195 LWD structures were installed on the South Fork of Asotin Creek and 205 structures were implemented on Charley Creek in 2013 (

Table *3.1*).

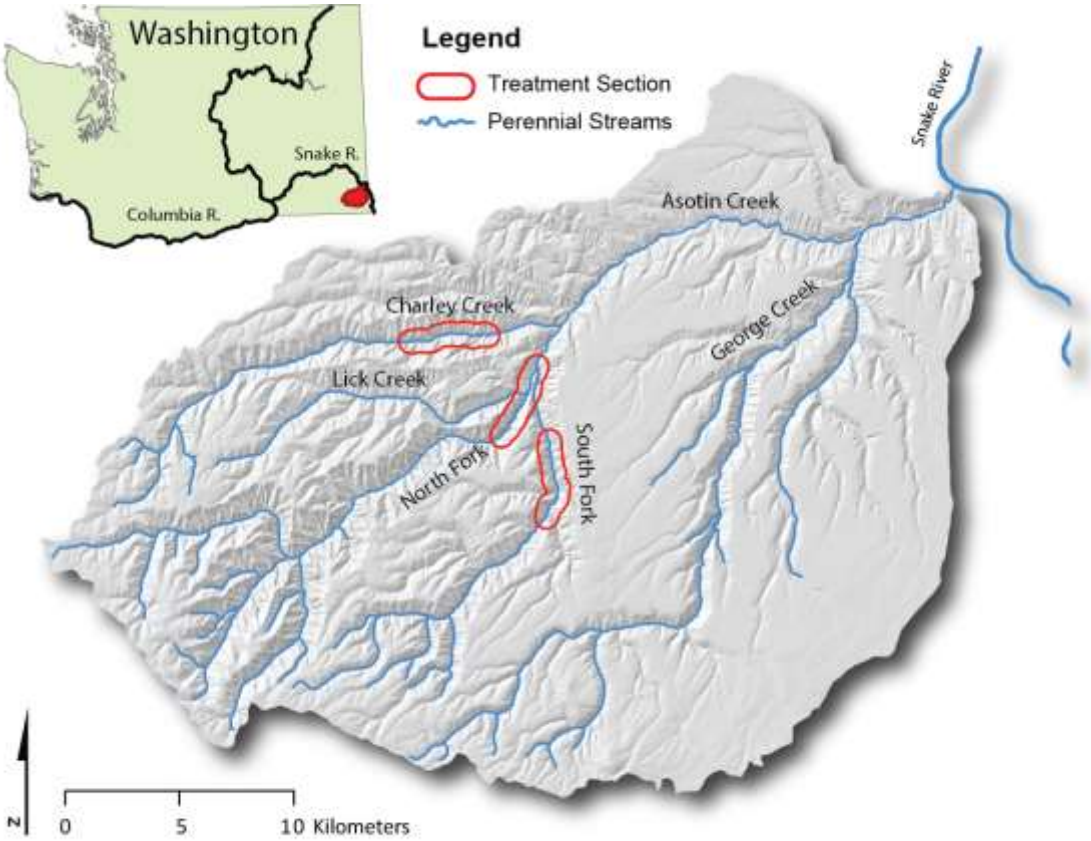

Figure 3.1. Asotin Creek drainage and perennial stream network. Treatment sections of Charley Creek, the South Fork of Asotin Creek, and the North Fork of Asotin Creek are outlined in red.

Table 3.1. Number of each structure type implemented in the South Fork (SF) of Asotin Creek and Charley Creek (CC). PALS = Post Assisted Log Structures.

Structure Type	SF	CC	Primary Objective
PALS - Bank Attached	116	128	Hydraulic and Geomorphic Change
PALS - Mid Channel	17	37	Hydraulic and Geomorphic Change
PALS - Debris Jam	1	10	Hydraulic and Geomorphic Change
Spanner	16	14	Wood Loading
Seeding	23	13	Wood Loading
Cover	11	3	Fish Cover
Key Piece	12	0	Wood Loading, Jam Creation

Although it is outside the scope of this study, an additional 134 structures were placed on the North Fork of Asotin Creek which finalized the implementation stage of the IMW restoration design [*Wheaton et al.*, 2012]. The effects of $_{HD}$LWD on the North Fork will be assessed in future work. Even though the South Fork structures were in place during two spring flood events, only the 2014 spring flows were above the average peak flows (Figure 3.2).

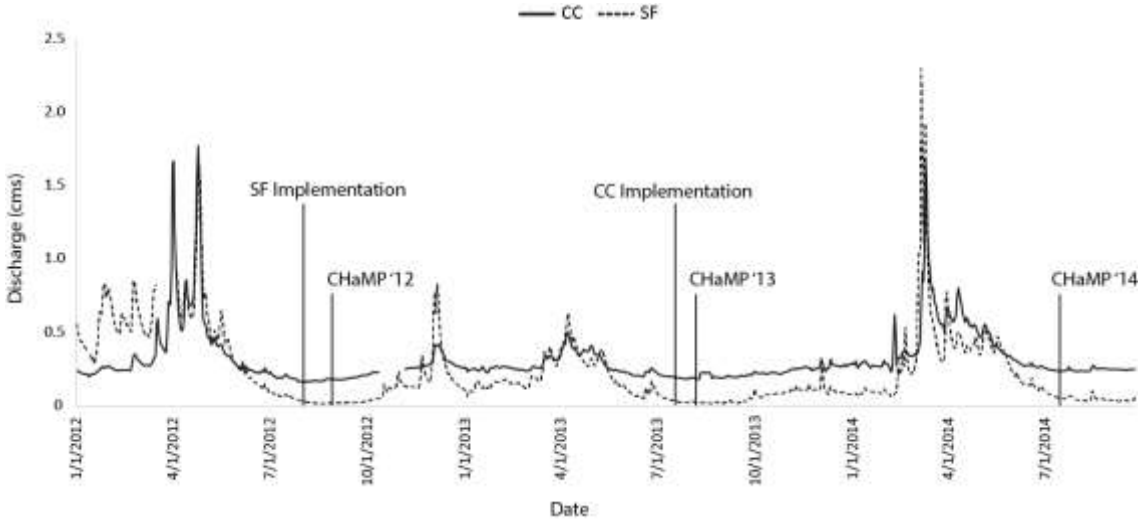

Figure 3.2. Discharge in cubic meters per second at the mouths of Charley Creek (CC) and the South Fork (SF) of Asotin Creek from January 2012 to September 2014. 'Implementation' markers represent the day that restoration started on each creek and the 'CHaMP' markers represent when CHaMP surveys began each year.

METHODS

Restoration Structure Implementation and Hypothesized Responses

Seven different structure types were implemented on the two study streams (Figure 3.3 and 3.4). Regardless of structure type, qualifying LWD (≥10cm diameter and ≥1m long) were used to create each structure. Three structure types are called PALS, because they are primarily supported by wooden fence posts pounded into the stream and can be 1) *bank attached, 2) mid channel*, or 3) *debris jams*. The 4) *spanner* structure type is similar to the *debris jam* but is not supported by posts, rather it is positioned behind trees or large boulders for support. 5) *Seeding* structures were placed opportunistically in stream reaches where PALS were not necessary for increasing stream heterogeneity, but were lacking LWD. Similarly, 6) *cover* structures were mainly placed in pool habits where cover was limited. Each of these structure types are comprised of LWD that can be maneuvered by two or more people. Alternatively, 7) *key pieces* are very large pieces of LWD (30+ cm diameter and >6 m length). *Key pieces* were placed on the South Fork only, using machinery in locations where the riparian zone would be minimally impacted. We designed each structure on-site using nearby structural elements and channel topography to determine what geomorphic results are realistic, and therefore, which structure type to build [*Wheaton et al.*, 2012].

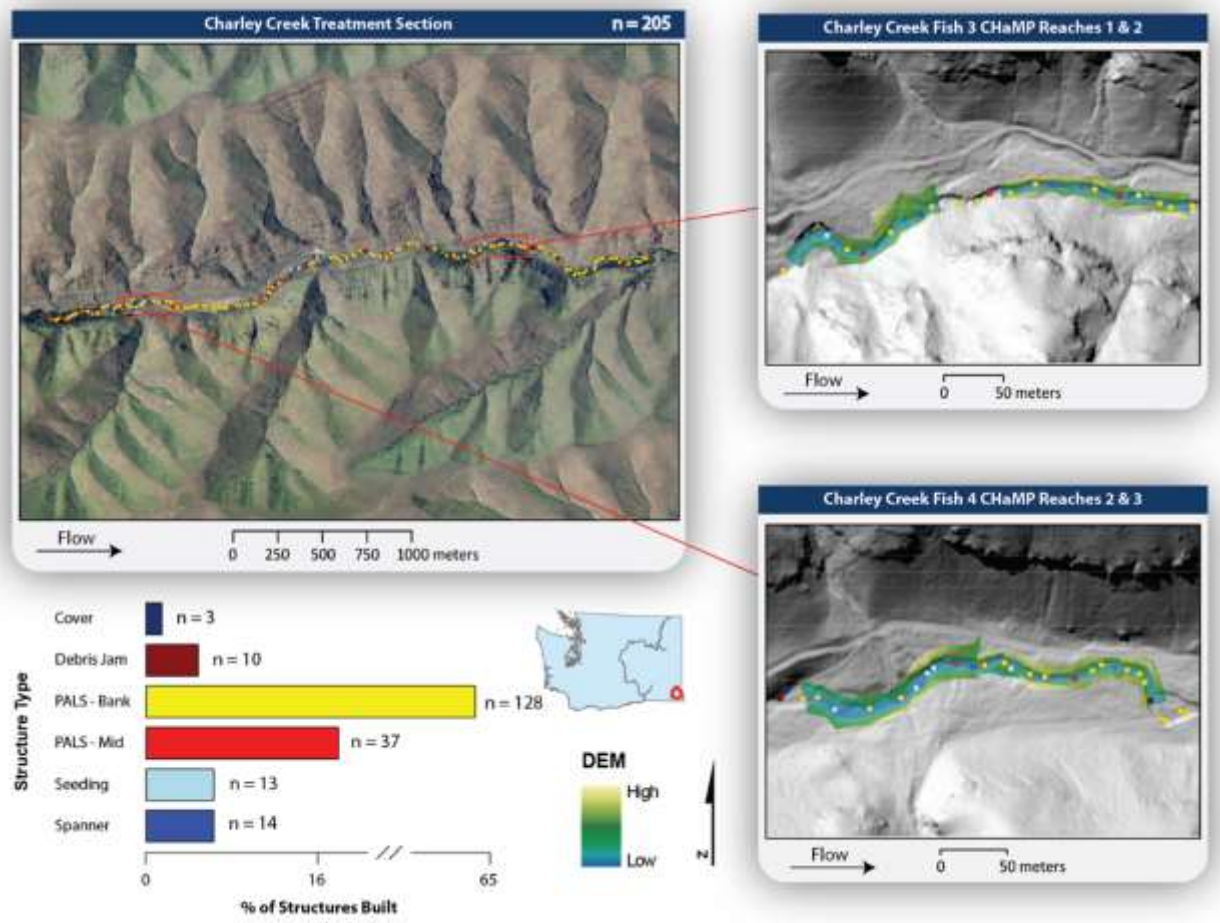

Figure 3.3. Proportion of structure types and their locations implemented on Charley Creek. The inset maps show the overlap of structures within annually monitored habitat reaches. The colors of the dots represent the structure type as indicated in the bar chart.

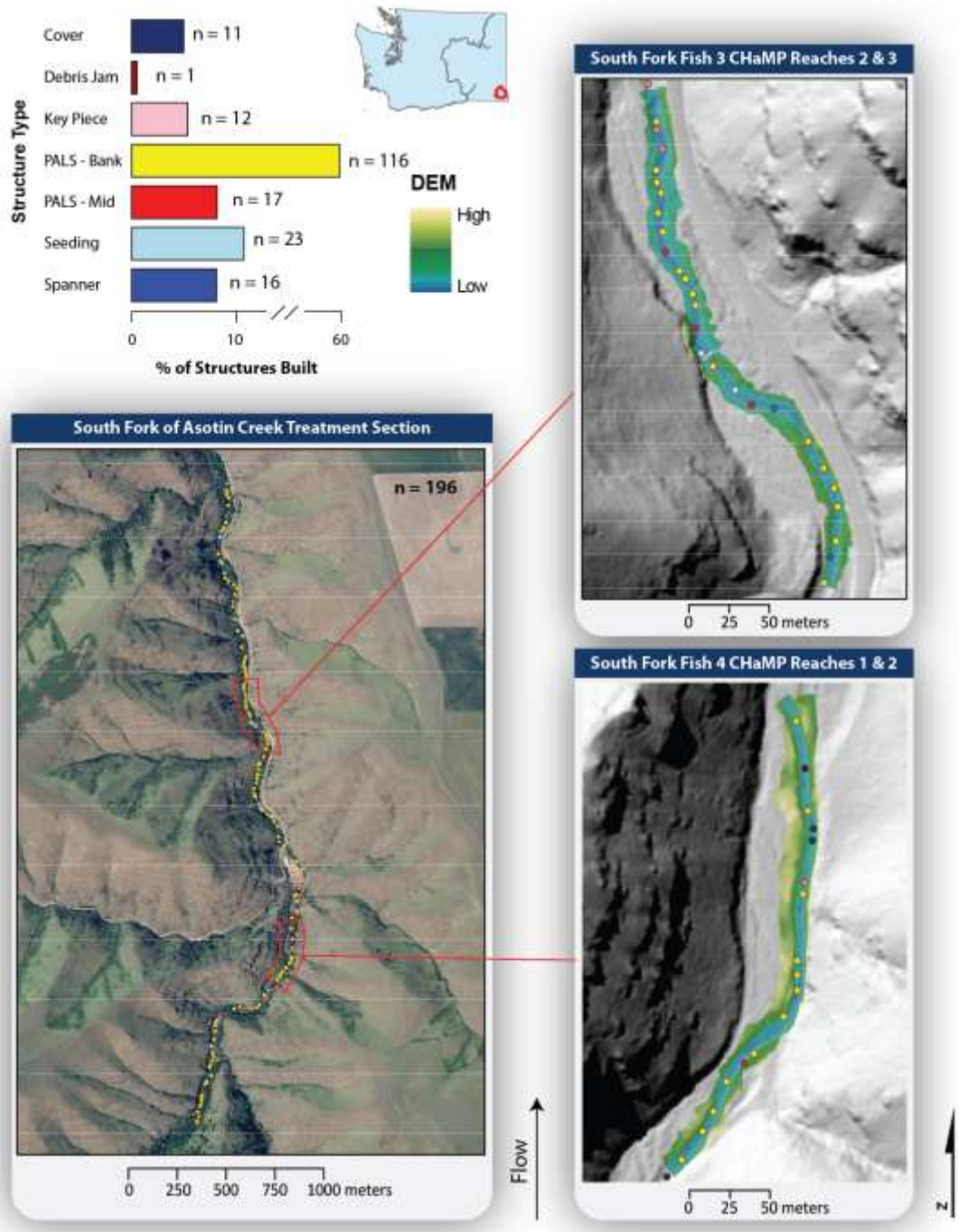

Figure 3.4. Proportion of structure types and their locations implemented on the South Fork of Asotin Creek. The inset maps show the overlap of structures within annually monitored habitat reaches. The colors of the dots represent the structure type as indicated in the bar chart.

I expected specific hydraulic and geomorphic responses to occur in the immediate area surrounding each PALS after being implemented. However, because each structure type affects hydraulics differently, the locations and type of those short-term hypothesized responses differ (Figure 3.5; Table 3.2). *Spanner* and *cover* structures had no expected responses other than to increase LWD density and to provide fish cover; however, all structures provide fish cover in some capacity (i.e. predation refugia). Regardless, I expected that the overall effect of $_{HD}$LWD would increase habitat complexity through the creation and maintenance of forced pools and forced bars at the reach level.

Table 3.2. Short descriptions of the expected hydraulic and geomorphic responses for restoration structures on Charley Creek and the South Fork of Asotin Creek. Label refers to the numbered locations in Figure 2. US = upstream, DS = downstream. Letters A-P reference the hypotheses from Wheaton et al. (2012), and are listed in detail in the introduction.

Response Type	Label	Related Hypotheses	Short Description
Hydraulic	1	A, D, P	Shunting Flow
Hydraulic	2	A, D, P	Splitting Flow
Hydraulic	3	A, D, P	Convergent Jet DS
Hydraulic	4	B, D, H, P	Eddy DS
Hydraulic	5	D	Eddy US
Hydraulic	6	C, D	Divergent Flow DS
Hydraulic	7	J	Convergent Flow DS
Geomorphic	A	H, M	Deposition US
Geomorphic	B	H, M	Deposition in Wake
Geomorphic	C	I, M	Deposition DS
Geomorphic	D	K, G	Deposition Overbank
Geomorphic	E	F, M	Erosion at Convergent Jet
Geomorphic	F	K, G	Erosion by Plunge Hydraulics
Geomorphic	G	J, M	Erosion Forming Chute
Geomorphic	H	N	Erosion of Bar Edge
Geomorphic	I	M, N	Erosion of Outer Bank

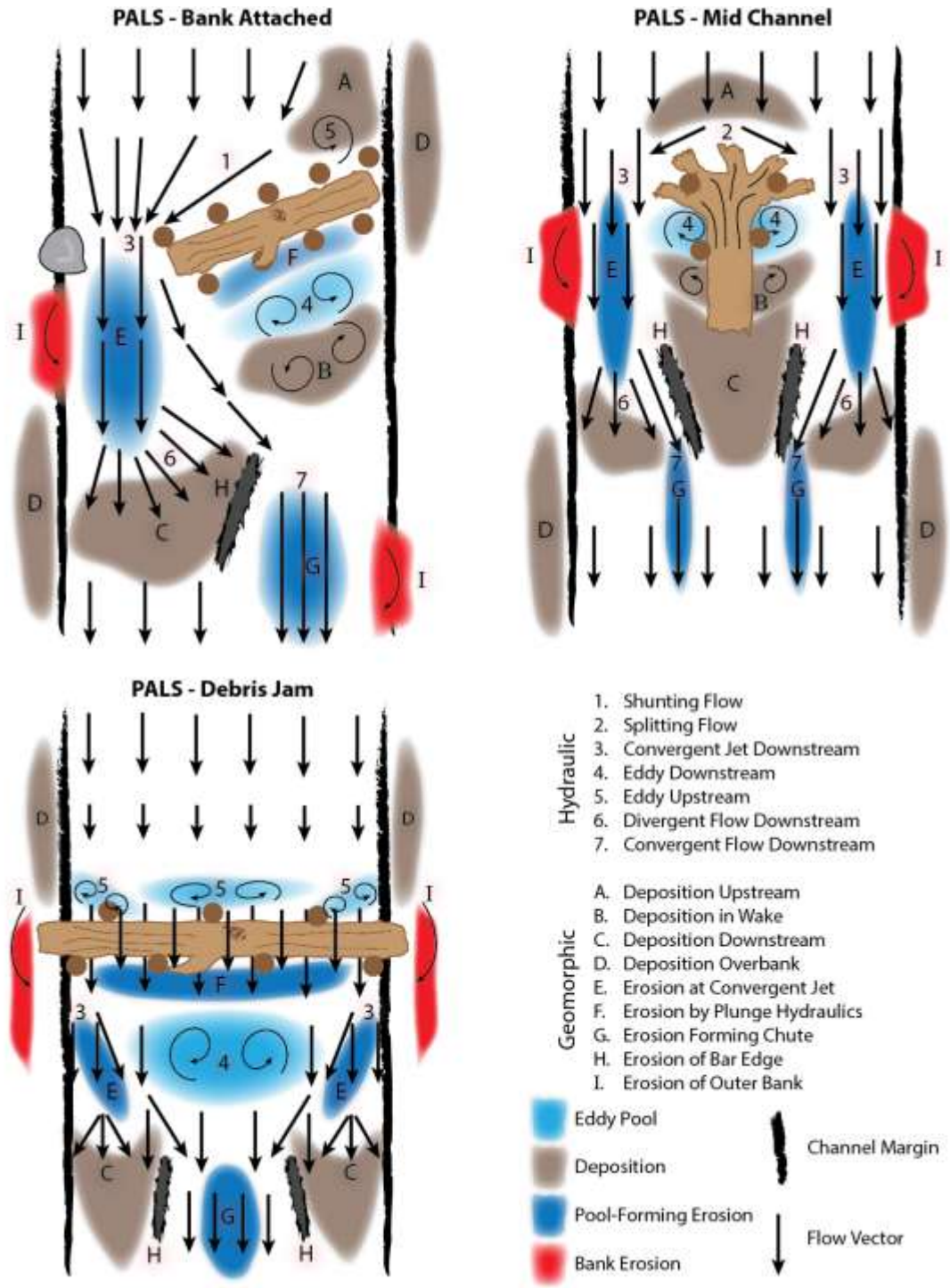

Figure 3.5. Expected hydraulic and geomorphic responses for structures implemented on Charley Creek and the South Fork of Asotin Creek.

Data Collection – Channel Topography

To test the design hypotheses of $_{HD}$LWD at the reach level, I used digital elevation models (DEMs) at annually monitored habitat reaches on the South Fork of Asotin Creek and Charley Creek. During the summers of 2012 to 2014, topographic data was collected by field crews using the Columbia Habitat Monitoring Program protocol [*CHaMP*, 2013]. The crew collected points and breaklines using a total station to describe the channel bed topography. Then, the crew derived 0.1 m resolution DEMs for every site they surveyed using the CHaMP Topo Toolbar in ArcGIS [*ESRI*, 2011; *CHaMP*, 2013]. I used DEMs from 12 sites within the South Fork and Charley Creek. Four sites in each creek are within a restoration treatment section, and two are within separate control sections [*Bennett and Bouwes*, 2009]. Each site is about 160 m long (i.e. 20 times the mean bankfull width) and altogether contained 82 restoration structures (20% of all structures).

Data Processing – Channel Topography

I derived a detrended DEM, surface water elevation DEM, contour lines of the detrended and original DEM (0.1 m intervals), and used site photos as lines of evidence for manually delineating geomorphic units. Geomorphic units are landforms that reflect the processes which determine river structure and function [*Brierley and Fryirs*, 2005; *Wheaton et al.*, 2014]. I drew polygons in ArcGIS around each unit based on the lines of evidence within the bankfull channel to represent three tiers of geomorphic units (Figure 3.6). The first tier is primarily a determination of whether the unit is within the active channel or out of the channel. For the purpose of this study, we only delineated units within the active channel. The second tier describes shape areas as concavities,

convexities, planar features, or transitions. The third tier identifies the specific geomorphic unit based on its in-channel location, morphology, and the process by which it is created or maintained. Transitions are typically short areas where a tier one unit is transitioning into an adjacent tier one unit, and cannot be described by a single tier one unit.

To estimate the error in delineating geomorphic units, I created a 0.1 m buffer on the outside and inside of every unit. The inner and outer areas of the buffered units represent our ability to correctly draw the unit polygons within 0.1 m of the correct location based on the site DEM.

I used pre-treatment and post-treatment DEMs from the 12 sites to create a DEM of difference (DoD), by differencing the elevation values between two sequential DEMS [*Lane et al.*, 2003]. To facilitate the creation of the DoD and account for uncertainty in the elevation differences I used the Geomorphic Change Detection (GCD) Software (http://gcd.joewheaton.org). I derived an error surface using a fuzzy inference system (FIS) model using survey point density, slope, and interpolation error between the original survey points and the triangular irregular network for each survey [*Wheaton et al.*, 2010]. The resulting FIS error surface provides an estimate of elevation error for each cell of the DEM. I then propagated the individual DEM errors together and compared them with the raw DoD. Finally, I thresholded all changes with less than an 80% likelihood of being real [*Wheaton et al.*, 2010]. Additionally, I excluded all change outside of the bankfull union of sequential DEMs. I created DoDs covering three epochs of change, 2012-2011, 2013-2012, and 2014-2013; representing pre-restoration and post-restoration response.

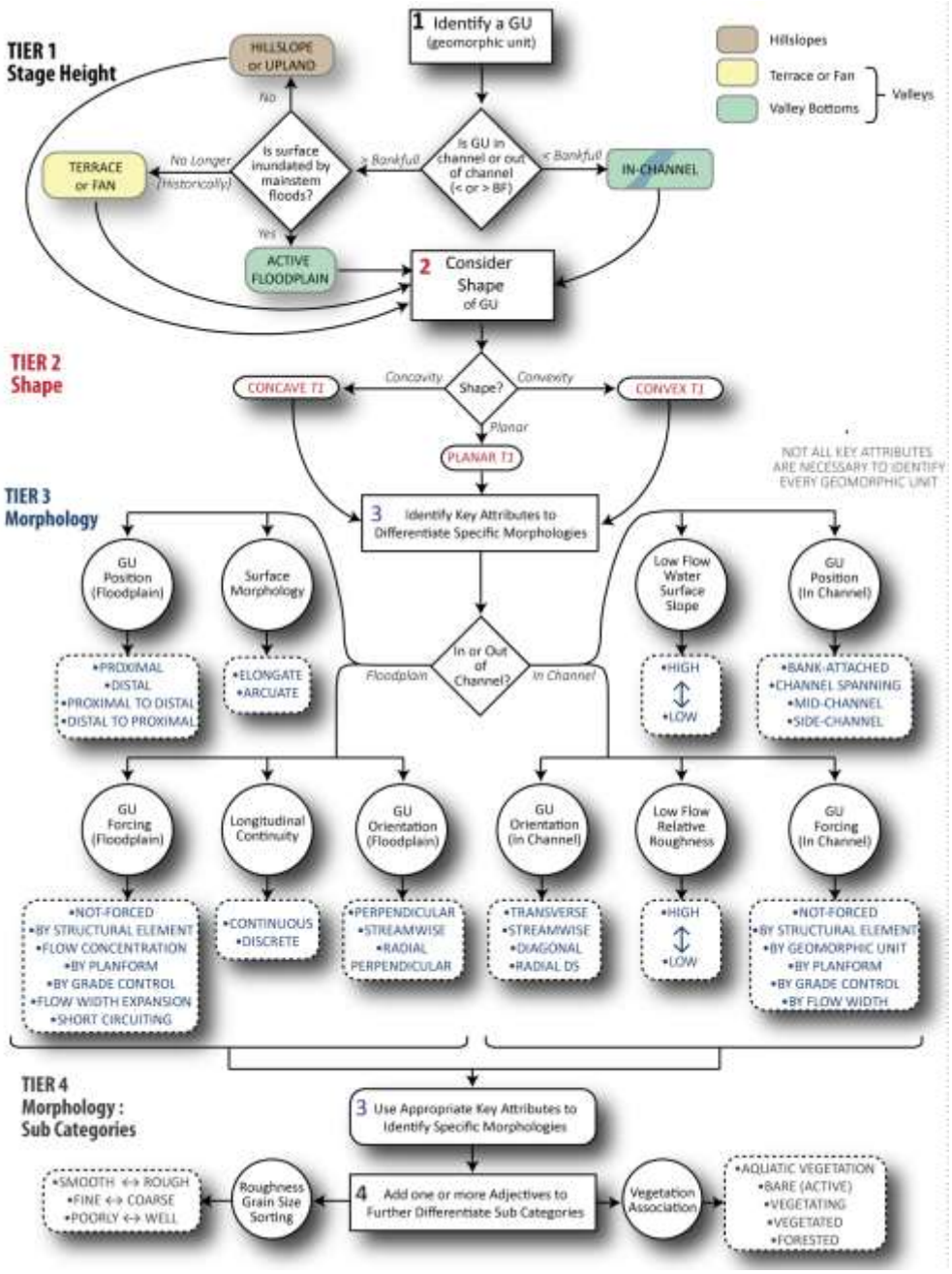

Figure 3.6. Four tier dichotomous key for determining geomorphic units in fluvial valleys. This study delineated units up to tier 3 – the specific morphology of geomorphic units. From [*Wheaton et al., submitted to Geomorphology, 2014*].

Data Analysis – Channel Topography

To test changes in proportional unit areas, I used a two-tailed test of equal proportions. I compared the proportional areas of concavities, convexities, and planar features at the control and treatment sections within each study stream. A significant result ($\alpha = 0.05$) would reject the null hypothesis that there was no change in the proportional area after treatment. I also tested for a significant change in the number of concavities, convexities, and planar features per 100 meters post restoration using a paired t-test. I repeated these tests for all control and treatment sites of each study stream combined to compare overall differences in treatment and control sections.

I derived several metrics to summarize erosion and deposition in each DoD. Volumetric change is calculated for erosion and deposition separately by multiplying thresholded elevation changes by total cell area. Mean thickness is calculated separately for erosion and deposition as the average vertical change in meters. The net change in thickness for an epoch is calculated as the sum of deposition thickness minus the sum of erosion thickness. This represents a standardized form of the net change in sediment storage for that epoch. Total thickness is calculated as the sum of the mean depth of erosion and deposition. The methods used to threshold DoDs in the GCD software help to differentiate real change from noise; however, I am including uncertainty estimates for thickness as ± one standard deviation of the thickness error. This is estimated using the FIS error surface and converting the errors in each cell to thickness errors [*Wheaton et al.*, 2013].

Data Collection – Rapid Assessments

To assess structural-level hydraulic and geomorphic responses to restoration, I used a rapid assessment approach. During every summer since restoration began, I visited each structure on Charley Creek (n = 205) and the South Fork (n=196) to assess their hydraulic and geomorphic influence on the active channel. I recorded whether each response was present within a level of certainty that the response was imposed by the addition of the structure (Certain, Probable, Possible, Unsure, Not Present). I only recorded responses as present if they were identifiable in the expected location relative to the structure (e.g. Figure 3.5). It is important to note that I observed the hydraulic responses during summer low flows.

We developed a custom mobile relational database application (app) to facilitate data collection in the field. The app allows us to track each structure through the design, implementation, and monitoring stages of the restoration project [*Camp and Wheaton*, 2014]. The app creates a new record in the database every time we collect monitoring data at a structure (referred to as a *visit*), storing information on structure condition, channel responses, wood loading, among others.

Data Analysis – Rapid Assessments

To statistically test the presence of the hydraulic and geomorphic responses I used McNemar's Test which converts binomial data into probabilities between each year. The probabilities are applied to a 2 x 2 contingency table (Table 3.3) and tested using a chi-squared statistic calculated using the following equation ($Ho: p_{year1} = p_{year2}$; $Ha: p_{year1} \neq p_{year2}$):

$$\chi^2 = \frac{(year1 - year2)^2}{year1 + year2} \quad (1)$$

I considered a response to be present if it was recorded in the field as certain, probable, or possible, and absent if it was recorded as unsure or not present.

Table 3.3. Generic example of a 2 x 2 contingency table set up for a before/after treatment experiment.

	After Present	**After Absent**	**Row Total**
Before Present	*a*	*b*	*a + b*
Before Absent	*c*	*d*	*c + d*
Column Total	*a + c*	*b + d*	*n*

RESULTS

Structure Condition

The majority of structures are still in place after being in place for 1-2 years. In 2014, 83% of all structures were completely or mostly intact; however, 94% of PALS remained completely or mostly intact. On average, 45% of unsecured structures (e.g. seeds, cover) were mostly or completely removed from their original location by high flows during the study period. Structures that are not mostly intact, have lost enough LWD, posts, or both during flood events to render them incapable of imposing hydraulic and geomorphic responses at their intended location. However, the hypotheses in this study and in the original restoration design do not apply to the non-PALS types.

Wood that was lost from upstream structures drifted past 11 structures on average before it accumulated on a downstream structure. The furthest moving piece of LWD drifted past 99 other structures before stopping on structure #53. Interestingly, structure

#53 accumulated wood from four additional structures as well. In fact, 24 structures in total accumulated wood from two or more other structures creating large LWD jams. Including natural wood recruitment, 18% of the structures have accumulated LWD and 86% have accumulated small woody debris (SWD) since implementation. In total, 1061 pieces of LWD were used to construct the structures on the South Fork and Charley Creek in 2012 and 2013, respectively. In 2014 on Charley Creek 15 pieces of LWD were removed from their original structure by high flows and not recovered. In contrast, on the South Fork, there was a net gain in 42 LWD pieces in the treatment section. Some LWD pieces may still be within the treatment section but were not tagged, or the tag broke off, making them unidentifiable as LWD used in the restoration project. The movement and deposition of wood is an important aspect of this project because, as built, most PALS are porous, restricting the number of immediate hydraulic responses. However, the accumulation of SWD, LWD, other organic material, and sediment clogs the pores in structures, making them more effective at initializing hydraulic responses. A full assessment of LWD movement is currently being assessed in the Asotin IMW study area through a separate project.

Hydraulic and Geomorphic Responses – South Fork

Hydraulic responses at each structure type were variable, but *bank attached* and *mid channel PALS* caused the highest number of significant changes in responses (Figure 3.7). In the first year, immediately after implementation, there was a significant increase in all hydraulic responses except convergent flow downstream at *bank attached PALS*. Likewise, the presence of each response continued to increase in 2013. However, in 2014, there was a significant decrease in shunting flow at *bank attached PALS,* and a

subsequent insignificant decrease in convergent jets and upstream eddies. At *mid channel PALS*, all hydraulic responses except divergent and convergent flow downstream significantly increased immediately after implementation. Since then, the number of *mid channel PALS* splitting flow has remained the same, but the number with convergent jets increased steadily to 100% in 2014. However, while not significant, downstream and upstream eddies decreased between 2013 and 2014. *Key piece* structures showed a significant increase for convergent jets (65%) and shunting flow (42%) between 2013 and 2014, but did not have any significant immediate impacts in 2012. Because there are only two *debris jam PALS* on the South Fork, I was not able to statistically assess any changes between years; however, by 2014 both jams imposed every hydraulic response.

On the South Fork of Asotin Creek, there was a significant increase in all of the geomorphic responses except deposition over the bank and erosion of the downstream bar edge at *bank attached PALS* the first year after implementation (Figure 3.8). In the following year the number of deposition upstream, deposition in the wake, erosion of the outer bank, and erosion by plunge hydraulic significantly increased at *bank attached PALS*. At *mid channel PALS* the presence of deposition upstream, deposition in the wake, erosion at the convergent jet, and erosion of the outer bank significantly increased the first year after implementation (Figure 3.8). The following year, every response increased at *mid channel PALS*, but increases in deposition over the bank, erosion at the convergent jet, chute erosion, and erosion of the downstream bar edge were not significant. At *key pieces*, there was not a significant increase of any of the geomorphic responses. Because there was only one *debris jam PALS* implemented on the South Fork, I was not able to test any differences between years. However, the single structure did invoke the

deposition downstream, deposition upstream, deposition in the wake, erosion at the convergent jet, erosion of the outer bank, and erosion by plunge hydraulics in 2014.

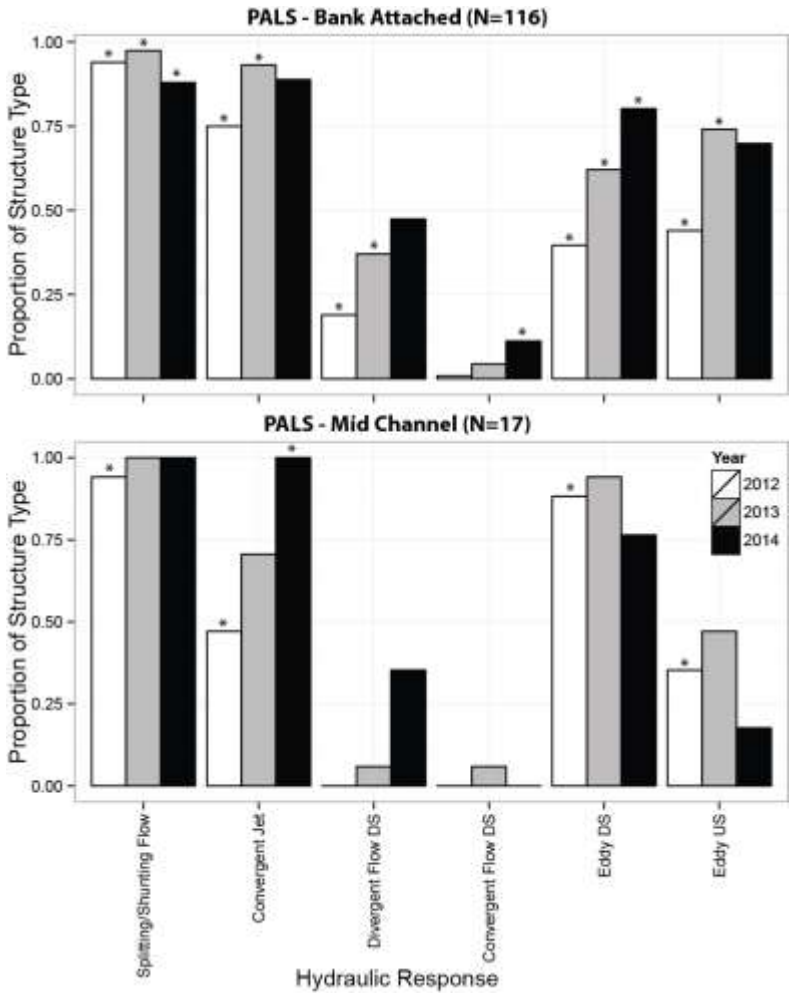

Figure 3.7. Proportion of restoration structures eliciting hydraulic responses during the summers of 2012-2014 on the South Fork of Asotin Creek. An asterisk above a bar represents a significant difference in that response compared to the previous year (* = P<0.05). Responses in 2012 were compared to the initial condition of 0% presence (mu = 0.0). US = upstream, DS = downstream.

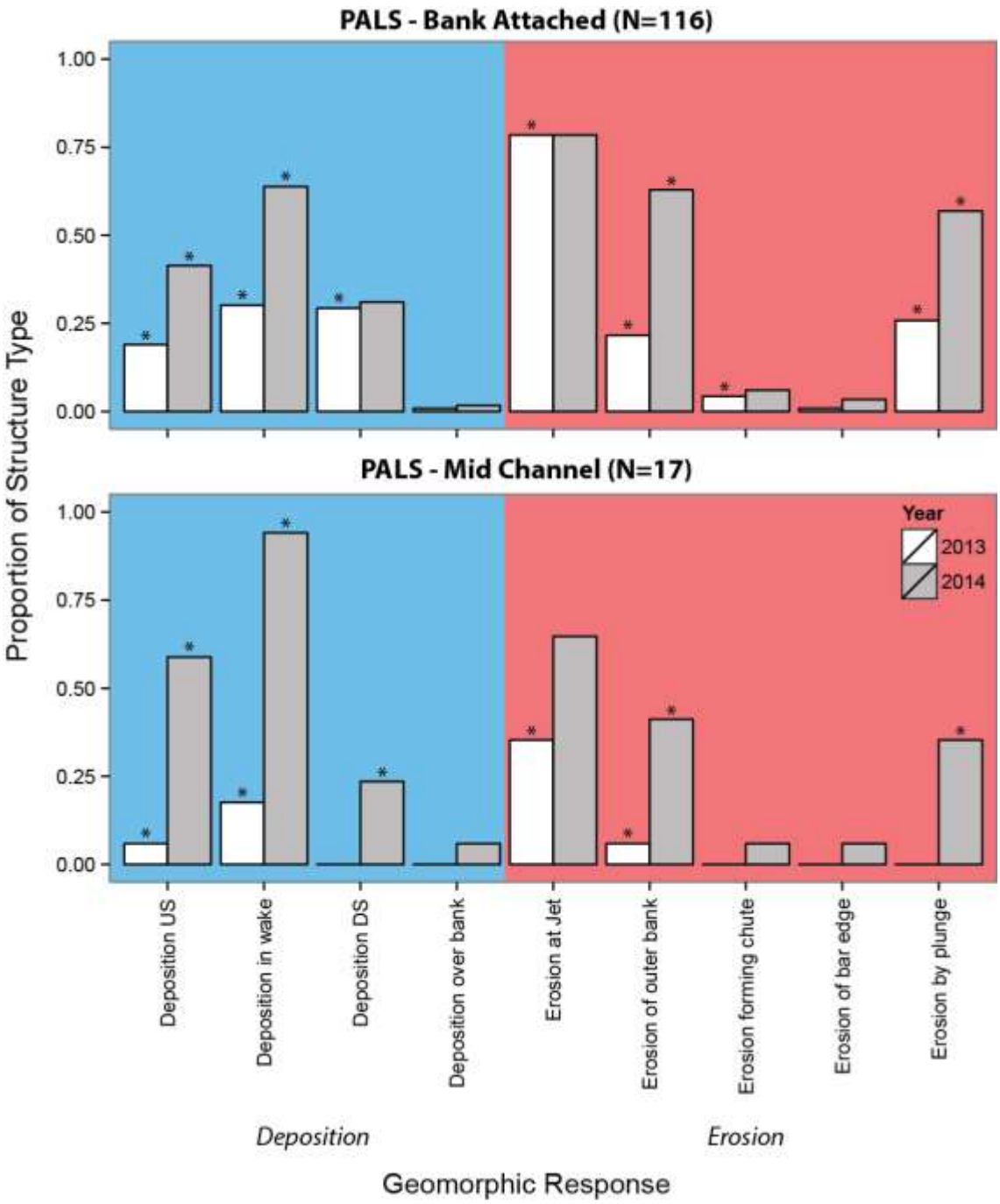

Figure 3.8. Proportion of restoration structures eliciting geomorphic responses during the summers of 2013-2014 on the South Fork of Asotin Creek. An asterisk above a bar represents a significant difference in that response compared to the previous year (* = P<0.05). Responses in 2013 were compared to the initial condition of 0% presence (mu = 0.0). US = upstream, DS = downstream.

Hydraulic and Geomorphic Responses – Charley Creek

Similar to the South Fork, hydraulic responses among structure types on Charley Creek were present by 2014 (Figure 3.9). At *bank attached PALS*, every hydraulic response except convergent flow downstream significantly increased immediately after implementation in 2013. Convergent jets and upstream eddies significantly increased again in 2014, while shunting flow and downstream eddies increased, but not significantly. In contrast, divergent flow downstream decreased insignificantly at *bank attached PALS* in 2014. The presence of splitting flow, convergent jets, downstream eddies and upstream eddies significantly increased immediately after implementation at *mid channel PALS* (Figure 3.9). The following year convergent jets significantly increased again, and, interestingly, splitting flow decreased while shunting flow increased. This decline in splitting flow and increase in shunting flow responses is related to many *mid channel PALS* collecting debris and behaving more like *bank attached PALS*.

Because I have only one year of post-treatment data for Charley Creek, I was only able to assess the first year changes in geomorphic responses. In the first year after implementation on Charley Creek, all of the PALS structures had statistically significant increases in deposition upstream, deposition in the wake, erosion at the convergent jet, erosion of the outer bank, and erosion by plunge hydraulics (Figure 3.10). In addition *bank attached PALS* had a small but significant increase in the deposition over the bank response.

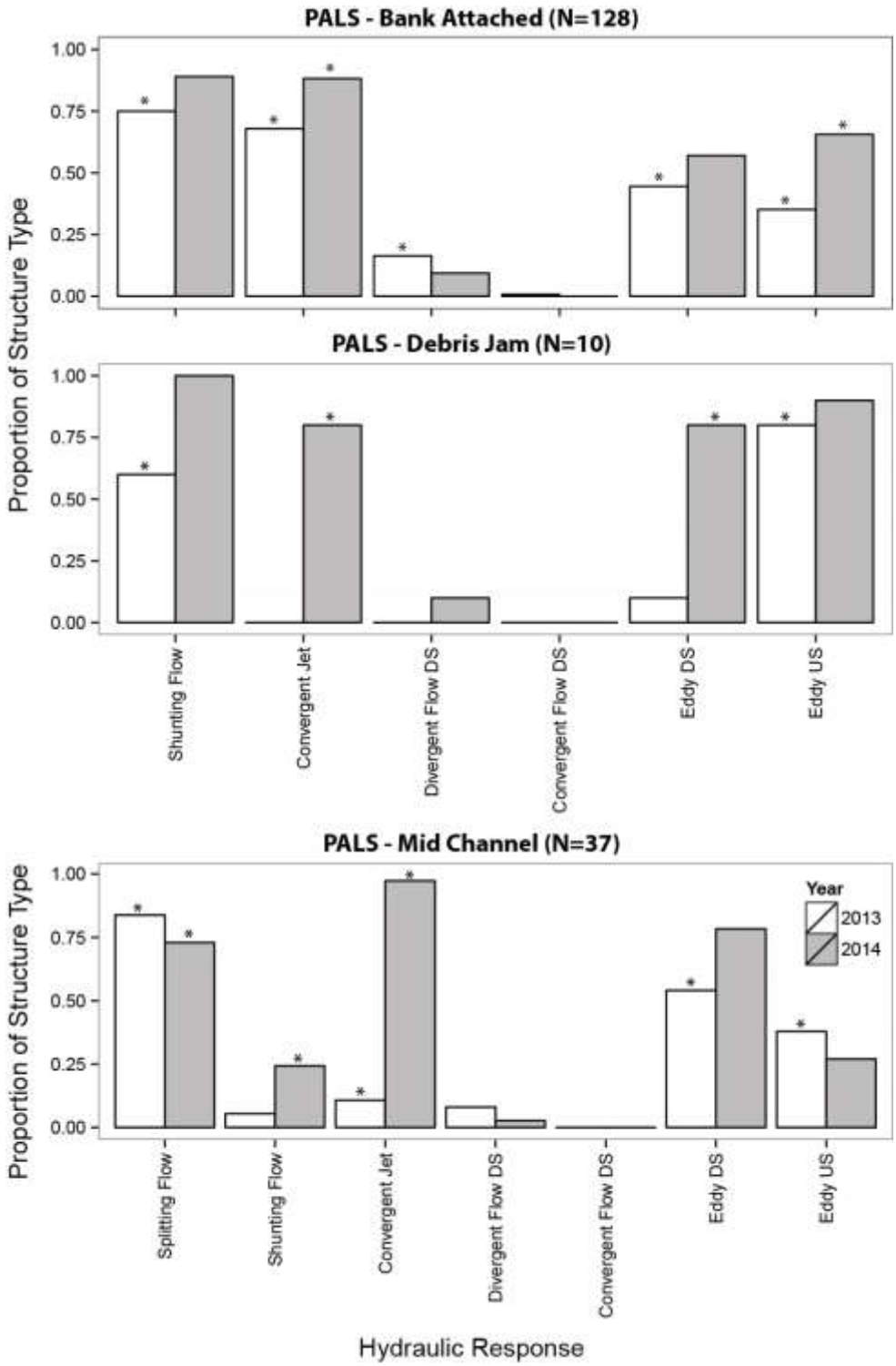

Figure 3.9. Proportion of restoration structures eliciting hydraulic responses during the summers of 2013-2014 on Charley Creek. An asterisk above a bar represents a significant difference in that response compared to the previous year (* = P<0.05). Responses in 2013 were compared to the initial condition of 0% presence (mu = 0.0). US = upstream, DS = downstream.

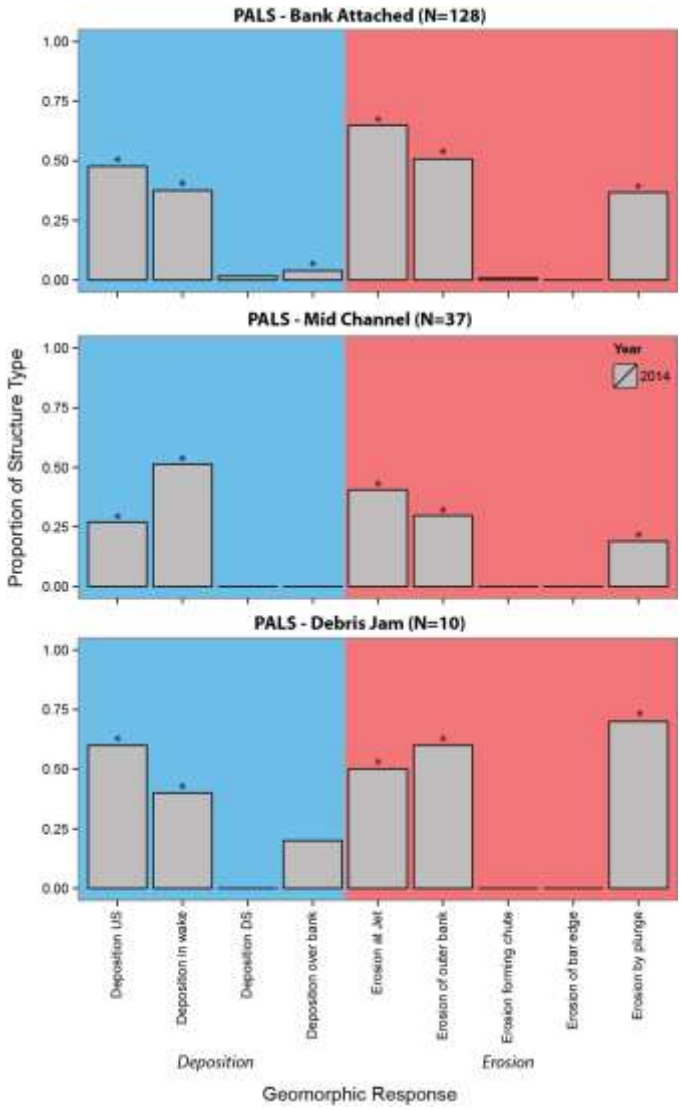

Figure 3.10. Proportion of restoration structures eliciting geomorphic responses during the summer of 2014 on Charley Creek. An asterisk above a bar represents a significant difference in that response compared to the implementation year when no geomorphic responses had developed (* = P<0.05, mu = 0.0). US = upstream, DS = downstream.

Geomorphic Change Detection

Figure 3.11 shows the DoDs for each epoch at one reach on the South Fork of Asotin Creek. Prior to any restoration, there were substantial high flows in the spring of 2012 (Figure 3.2), resulting in a large amount of erosion. The far left DoD for the 2012-2011 epoch shows the result of the 2012 spring flows where 94% of the change was

erosional and the amount of volumetric change was much greater than any year since. Additionally, the treatment reach in Figure 3.11 is the only one that was surveyed in 2011. The lack of 2011 surveys at treatment sites makes it difficult to make definitive comparisons prior to restoration.

The mean thickness of erosion and deposition has decreased over the three epochs (Figure 3.12). Prior to restoration, there was substantially more erosion at the treatment reaches at 0.30 ± 0.14 m, leading to a net thickness of -0.26 ± 0.13 m. Since restoration, erosion thickness has decreased to 0.14 ± 0.09 m in the 2014-2012 epoch, resulting in a net thickness of -0.02 ± 0.08. Likewise, the depth of deposition was lower in the final epoch than prior to restoration. However, there was an increase in deposition in the 2013-2012 epoch resulting in a net positive thickness of 0.10 ± 0.08. The control sites were arguably more stable through each epoch. However, the mean depth of erosion in the 2012-2011 epoch was very similar to the treatment reaches at 0.31 ± 0.14 m. In contrast to the treatment reaches, deposition that year was large enough at control sites to keep the net thickness near equilibrium at 0.05 ± 0.09 m.

Because there was only one treatment site surveyed in 2011, I made pre- to post-restoration comparisons between 2012 and 2014 for the South Fork and 2013 and 2014 for Charley Creek to reflect only elevation changes that have happened since restoration. The combined results comparing mean changes in depth at treatment and control sections are shown in Figure 3.13. The large error bars on all of the results are due to a relatively conservative error estimate in the GCD workflow. Therefore, I cannot determine that any of these differences are significant. It appears that the mean deposition depth is larger at treatment sites (0.35 ± 0.2 m) than control sites (0.2 ± 0.13 m). However, the mean

erosion depths are nearly identical. This results in a slightly negative net thickness at the control sections (-0.02 ± 0.1 m) and a positive net thickness at treatment reaches (0.13 ± 0.13 m). Additionally, the total thickness is larger at treatment sections than control sections at 0.3 ± 0.18 m and 0.21 ± 0.14 m, respectively. The pie charts in Figure 3.13 show the total volumetric proportion of erosion and deposition since restoration at treatment and control sections. Control sections appear to near equilibrium but were slightly depositional, while the treatment sections were dominantly depositional since restoration.

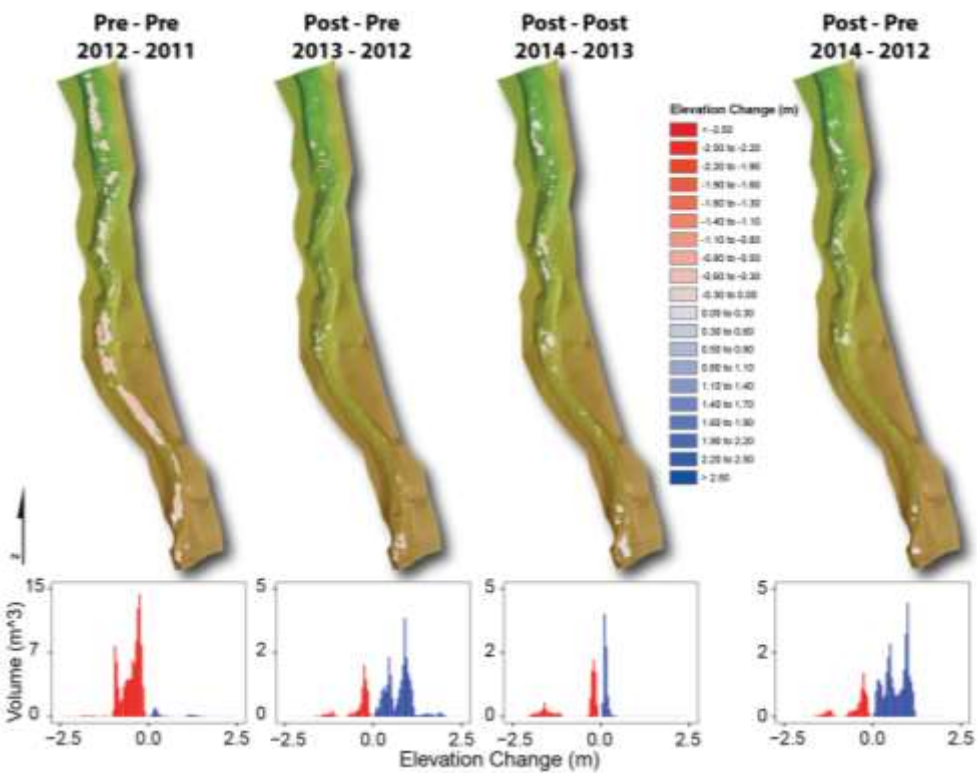

Figure 3.11. Example of thresholded digital elevation models of difference (DoD) and the elevation change distributions at a 160 m reach on the South Fork of Asotin Creek. The DoDs represent change that has a, 80% probability of being real after uncertainty analysis. The volumetric elevation change distributions below each DoD show the thresholded distributions by erosion (red) and deposition (blue).

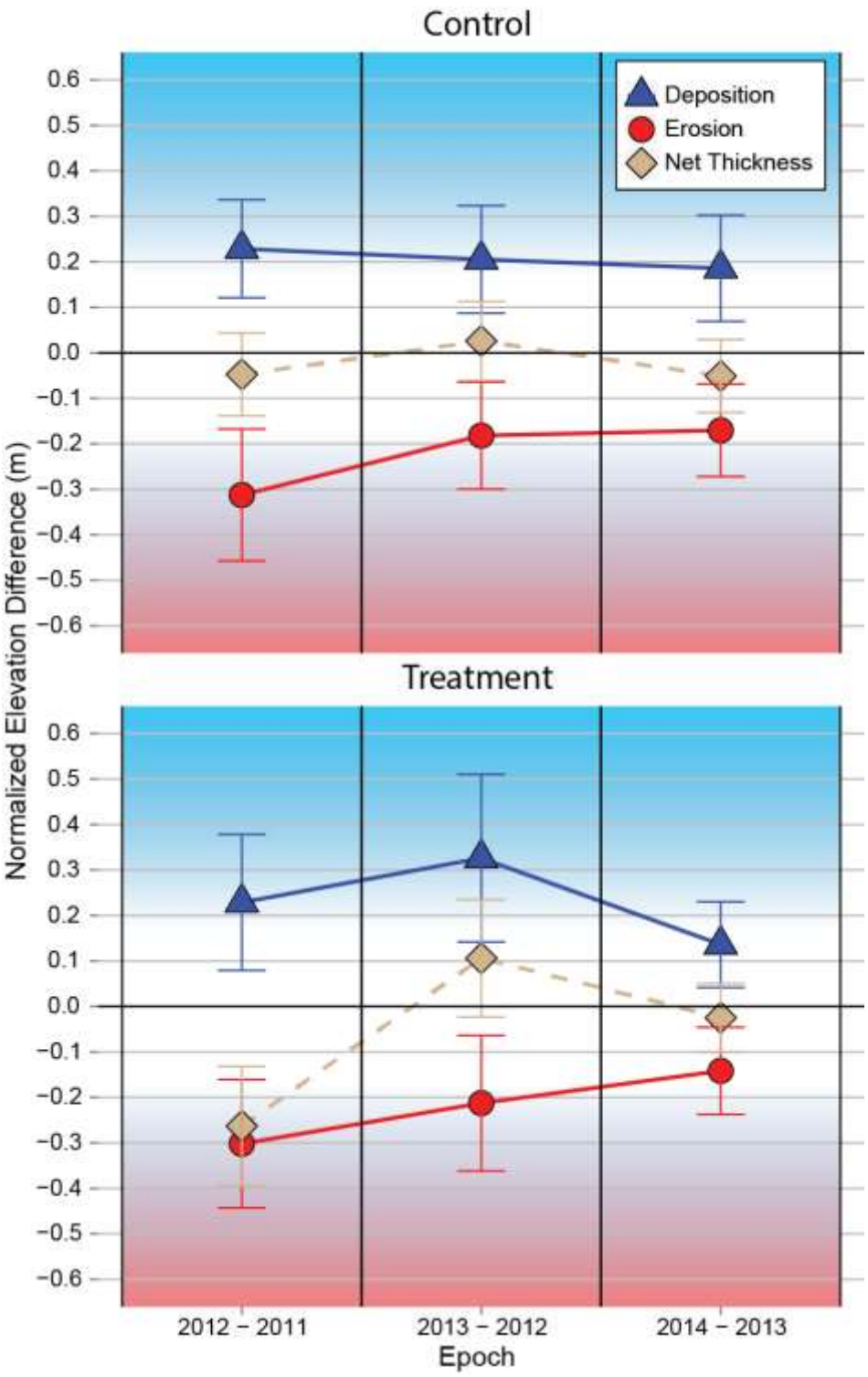

Figure 3.12. Normalized elevation difference of thresholded change in meters across control sites (top) and treatment sites (bottom). The net thickness represents the mean difference in deposition and erosion thickness. The error bars represent the uncertainty from the original DEM of difference estimate.

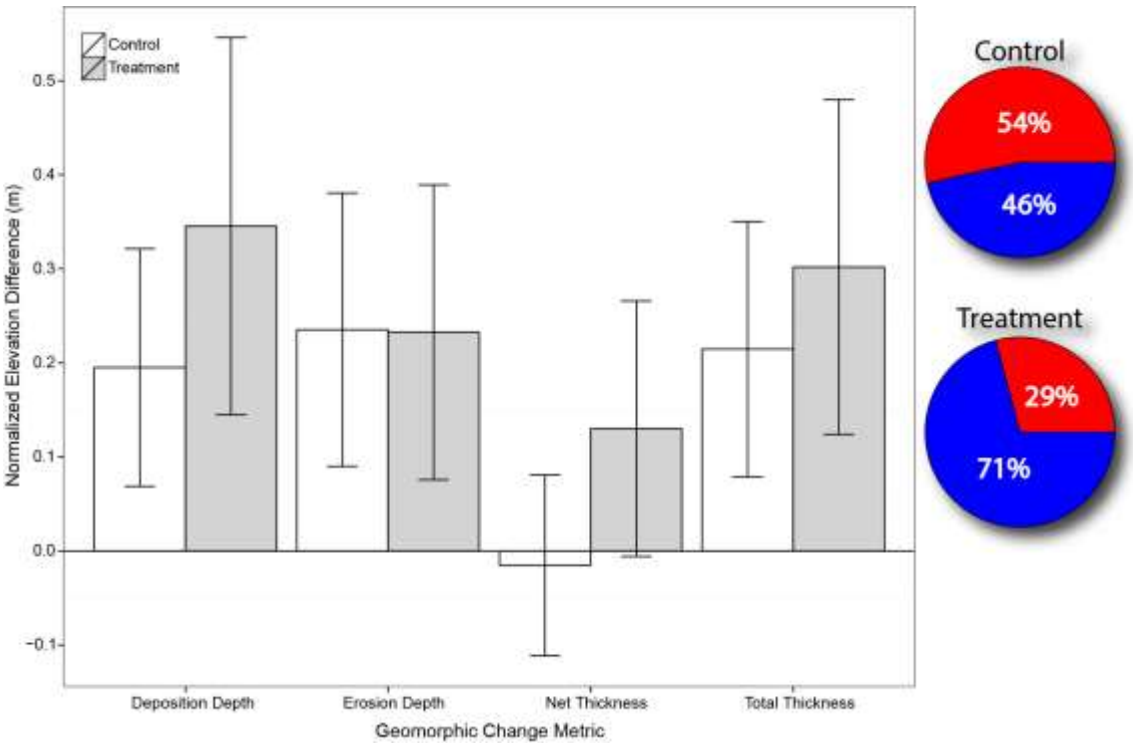

Figure 3.13. Mean differences between deposition depth, erosion depth, net thickness, and total thickness before and after restoration, separated by treatment and control sections. The error bars are the mean error estimates from a fuzzy inference system uncertainty analysis.

Geomorphic Units – South Fork

Among treatment sites on the South Fork there were significant changes in the proportional areas of concavities, convexities, and planar features after restoration (e.g. Figure 3.14). However, concavities at control sites increased as well. At the treatment sites concavity area increased by 3.2%, convexity area increased by 3.6%, and planar features decreased by 4.8% (p <0.0001 in all cases; Figure 3.15). Among the control sites, concavity area increased by 2.3% (p = 0.003), but there was not significant changes in convexity and planar feature area (Figure 3.16). Similarly, there were no changes in the number of any tier two units at control sites. However, at treatment sites the number

of concavities per 100 m increased by 1.9 (p = 0.095) and convexities per 100 m increased by 3.4 (p = 0.08; Figure 3.17). In contrast to proportional area, the number of planar features significantly increased by 3.0 (p = 0.042).

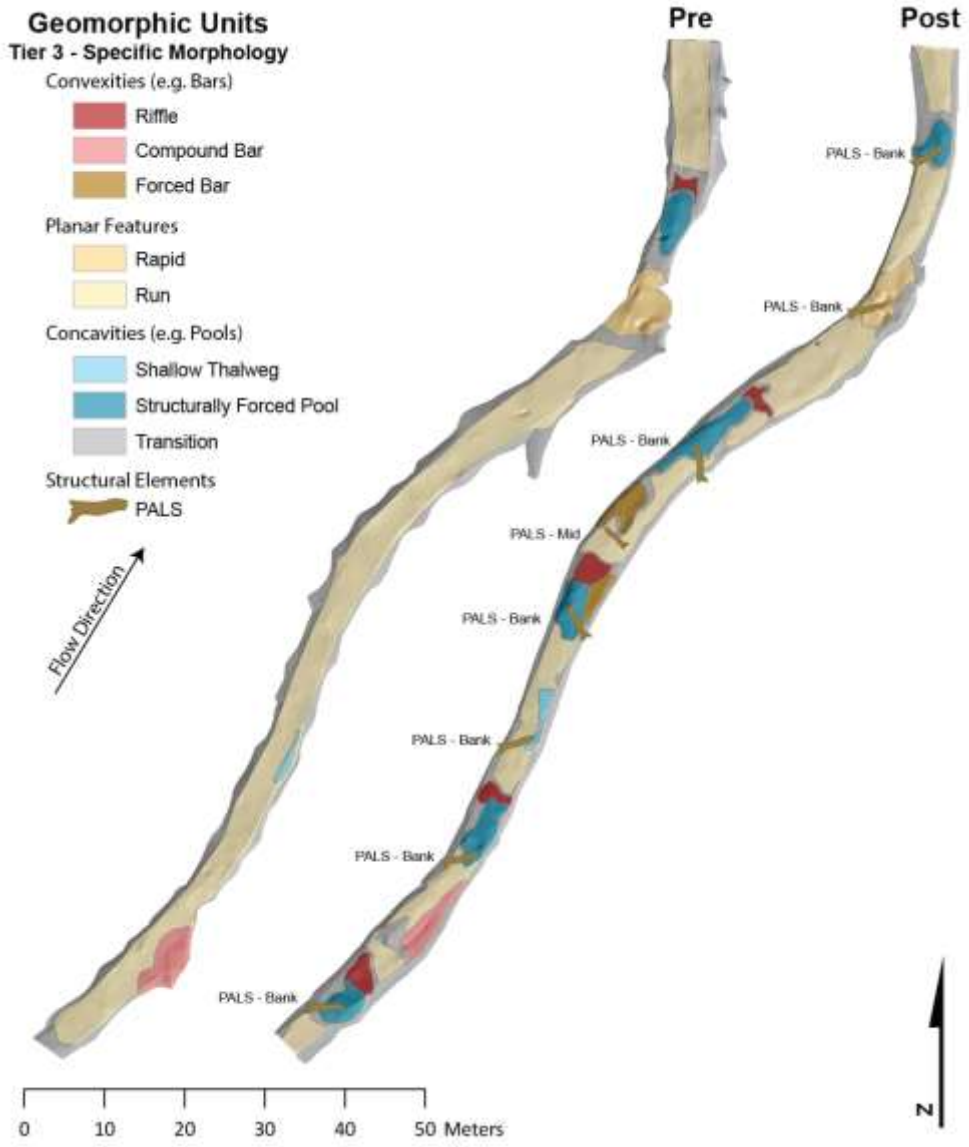

Figure 3.14. Example of geomorphic unit delineation pre- and post-restoration at a treatment reach on the South Fork of Asotin Creek. Pre-restoration, this reach was heavily dominated by runs. Post-restoration, post assisted log structures (PALS) imposed several riffles, forced bars, and structurally forced pools.

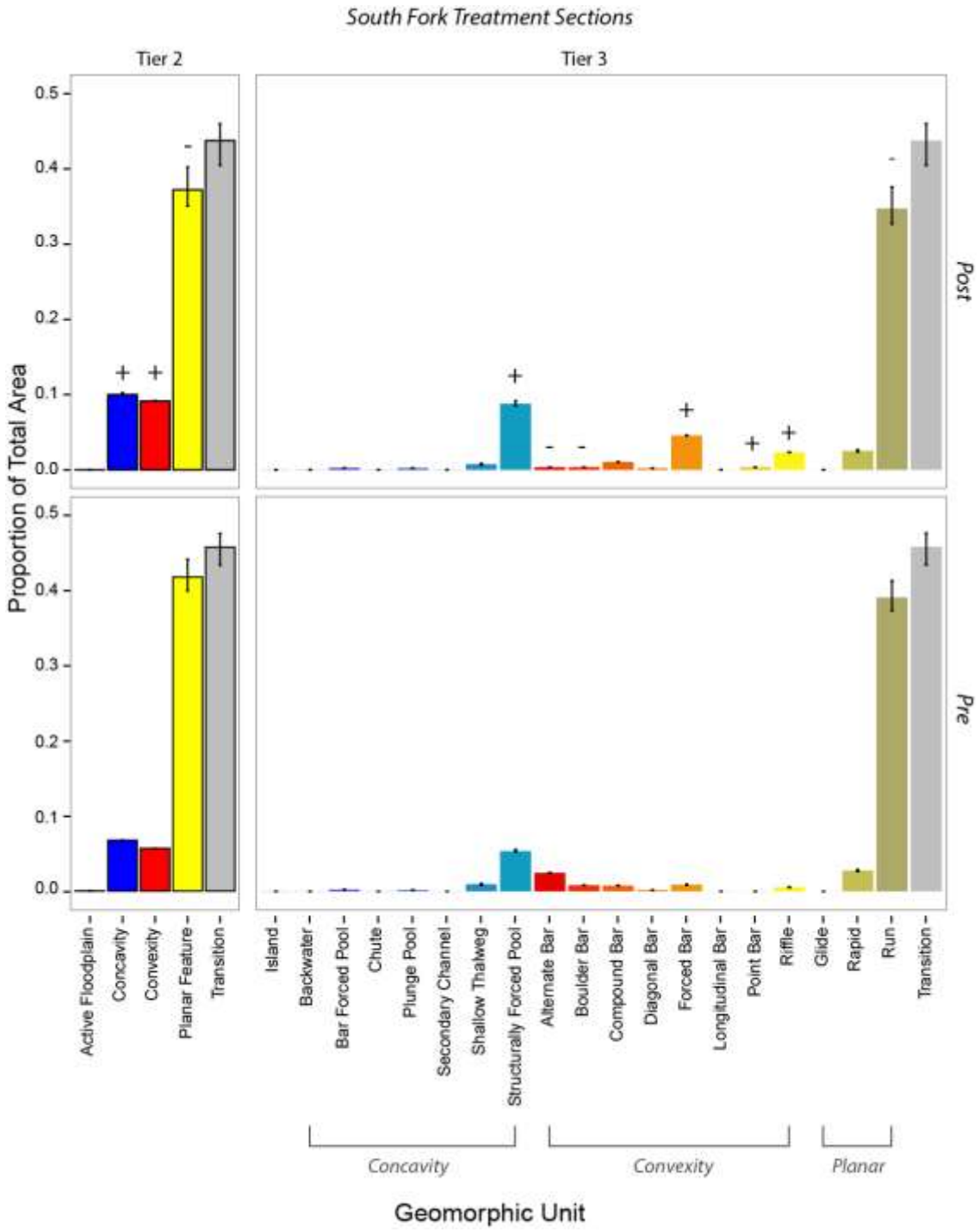

Figure 3.15. Proportional areas of tier 2 geomorphic units at treatment sites within the South Fork of Asotin Creek. Units were manually delineated from topographic data collected at CHaMP sites. Error bars represent the upper and lower area estimates after a ±0.1 m buffer on the original area. A plus (+) or minus (-) sign above a bar indicates the direction of a statistically significant difference in pre- and post-restoration areas ($P<0.05$).

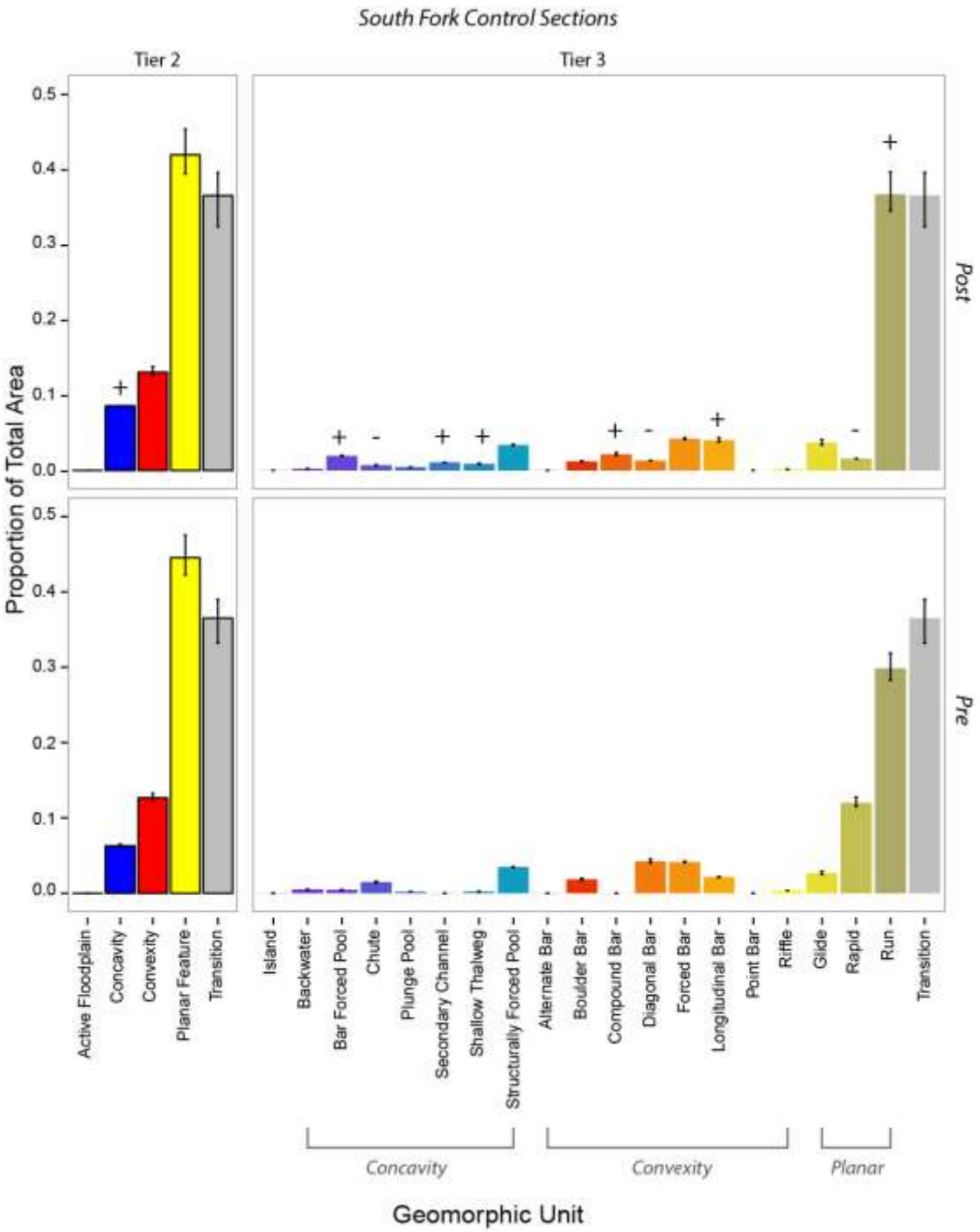

Figure 3.16. Proportional areas of tier 2 geomorphic units at control sites within the South Fork of Asotin Creek. Units were manually delineated from topographic data collected at CHaMP sites. Error bars represent the upper and lower area estimates after a ±0.1 m buffer on the original area. A plus (+) or minus (-) sign above a bar indicates the direction of a statistically significant difference in pre- and post-restoration areas (P<0.05).

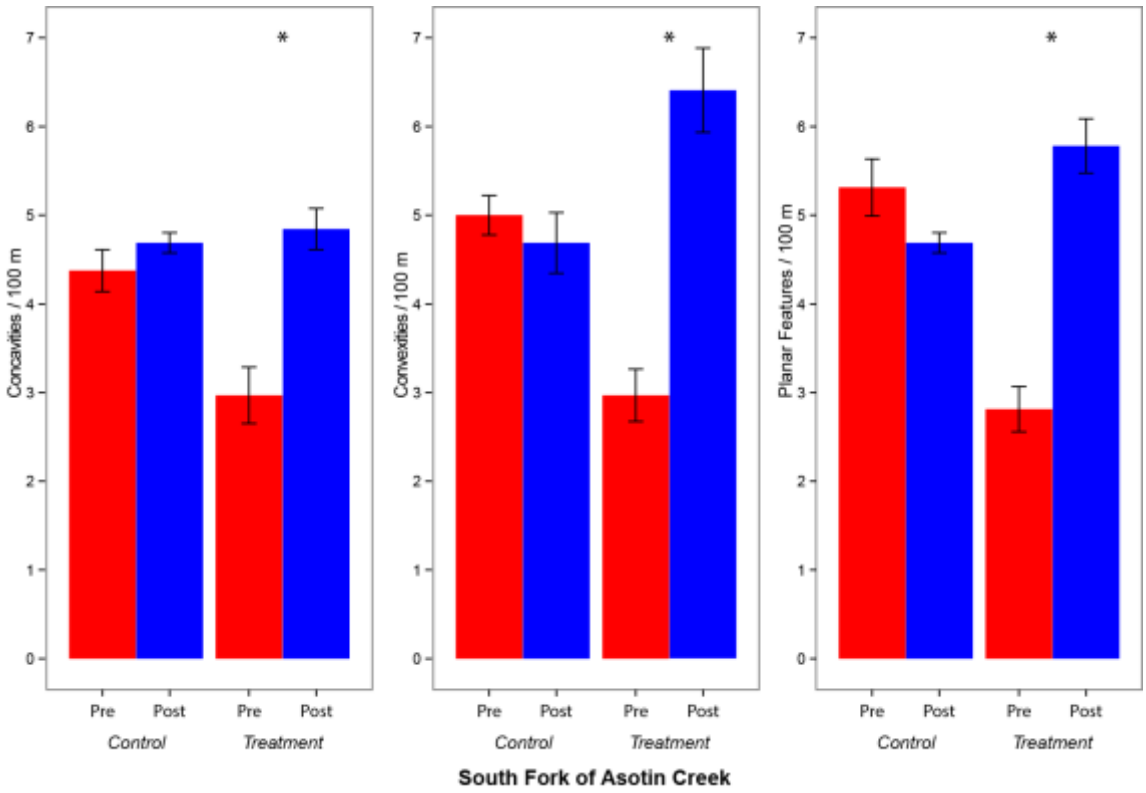

Figure 3.17. Mean concavities, convexities, and planar feature units per 100 meters by pre- and post-restoration and control and treatment sites on the South Fork of Asotin Creek. Units were manually delineated from topographic data collected at CHaMP sites. Error bars represent the standard errors. An asterisk between bars represents a significant difference in the means of unit counts pre- and post- restoration (*=P<0.05).

Geomorphic Units – Charley Creek

All tier two units on Charley Creek treatment and control sections significantly changed after restoration. The proportional area of concavities at treatment and control sites significantly increased by 4.0% ($p < 0.0001$) and 3.4% ($p = 0.006$), respectively (Figure 3.18 and 3.19). Likewise, convexity area increased at treatment and control sites by 2.4% ($p = 0.004$) and 3.1% ($p = 0.006$). Additionally planar feature area decreased at treatment and control sites by 12.5% ($p < 0.0001$) and 10.2% ($p < 0.0001$). There were no statistical differences in the number of tier two units per 100 m at treatment or control

sites (Figure 3.20). However, the changes were greater at treatment sites than control sites.

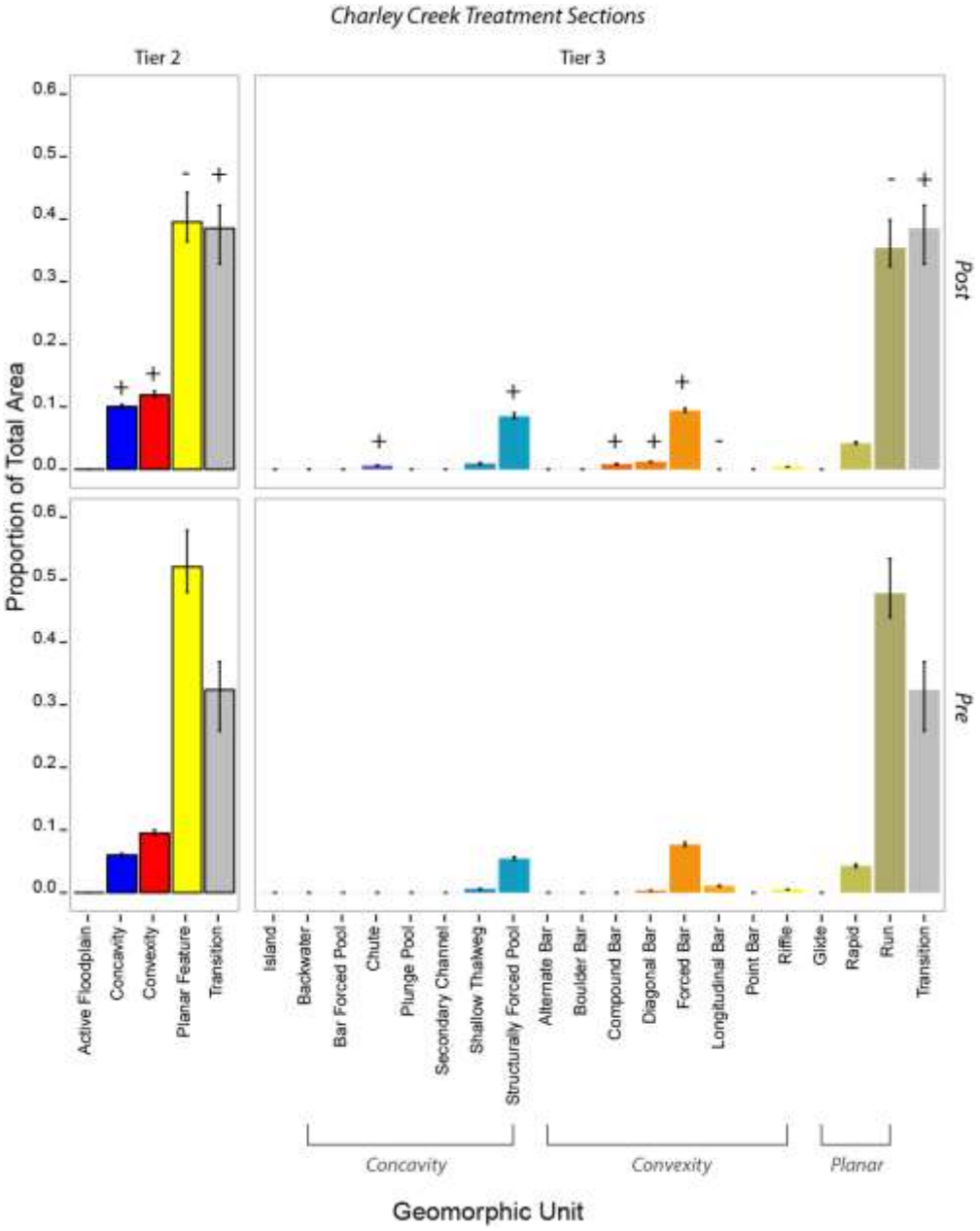

Figure 3.18. Proportional areas of tier 2 geomorphic units at treatment sites within Charley Creek. Units were manually delineated from topographic data collected at CHaMP sites. Error bars represent the upper and lower area estimates after a ±0.1 m buffer on the original area. A plus (+) or minus (-) sign above a bar indicates the direction of a statistically significant difference in pre- and post-restoration areas (P<0.05).

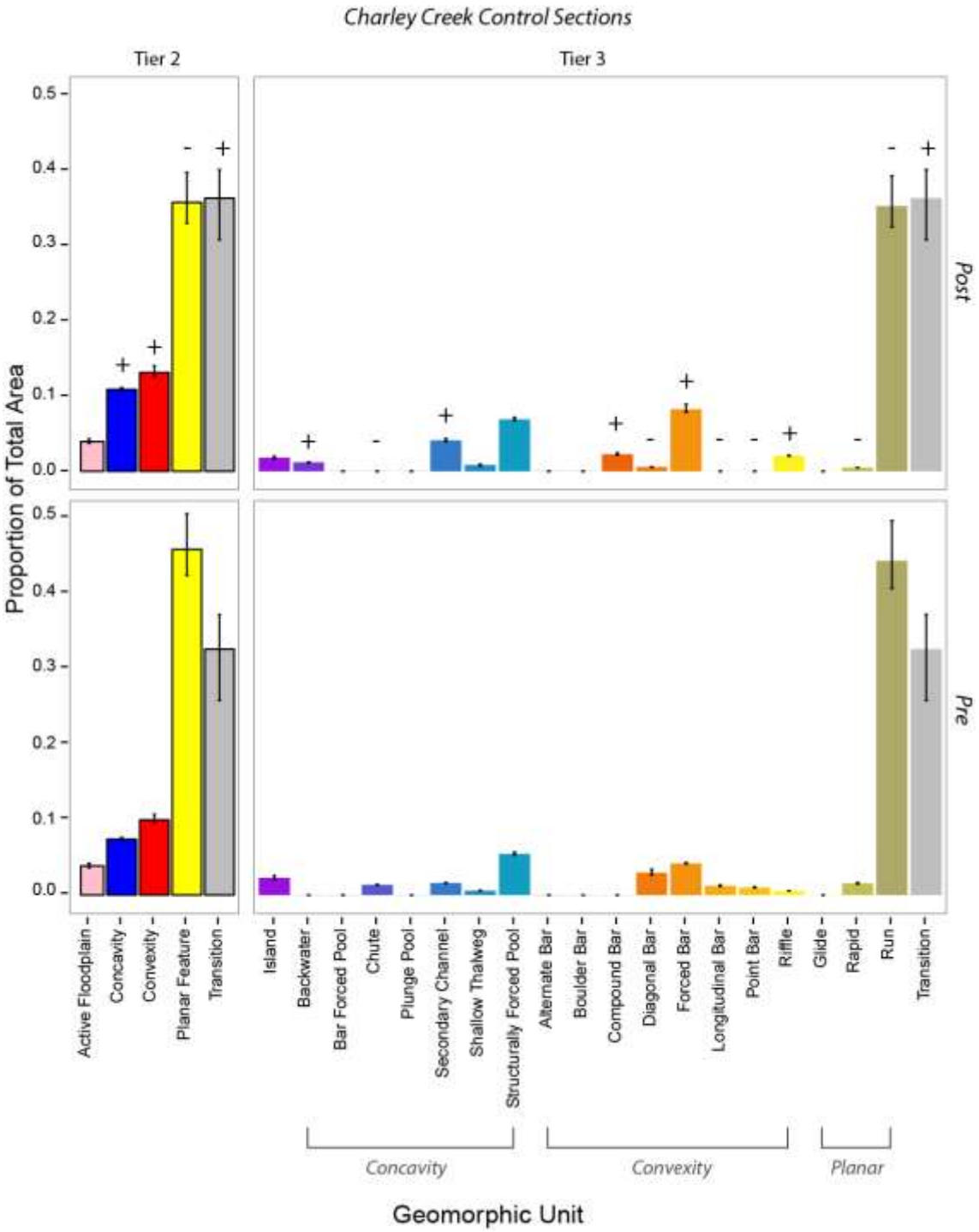

Figure 3.19. Proportional areas of tier 2 geomorphic units at control sites within Charley Creek. Units were manually delineated from topographic data collected at CHaMP sites. Error bars represent the upper and lower area estimates after a ±0.1 m buffer on the original area. A plus (+) or minus (-) sign above a bar indicates the direction of a statistically significant difference in pre- and post-restoration areas (P<0.05).

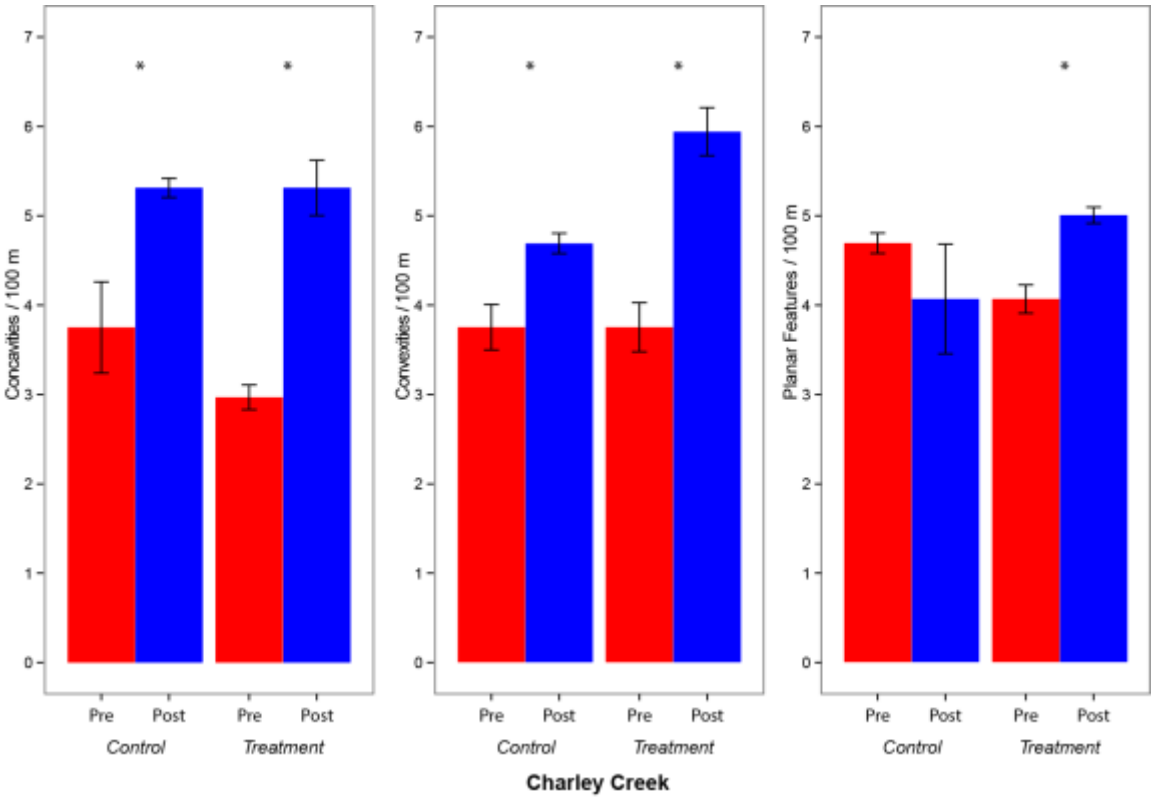

Figure 3.20. Mean concavities, convexities, and planar feature units per 100 meters by pre- and post-restoration and control and treatment sites on Charley Creek. Units were manually delineated from topographic data collected at CHaMP sites. Error bars represent the standard errors.

Geomorphic Units – All Sites

At all of the combined treatment sections, the proportional area of all tier two units significantly changed after restoration. Concavity and convexity area increased by 3.6% and 3.1% and planar feature area decreased by 8.0% ($p < 0.0001$ for all changes; Figure 3.21). However, control sites did not remain the same after restoration implementation either. At control sites, concavity area increased by 3.1% and convexity area increased by 1.5% ($p < 0.0001$ for both changes; Figure 3.22). In contrast, the number of tier two units per 100 m all significantly increased at treatment sites, but did not change at control sites (Figure 3.23). At treatment sites, the number of concavities

and convexities per 100 m increased by 2.0 (p = 0.006) and 2.8 (p = 0.006). Planar features per 100 m also significantly increased by 2.0 (p = 0.01) at treatment sites.

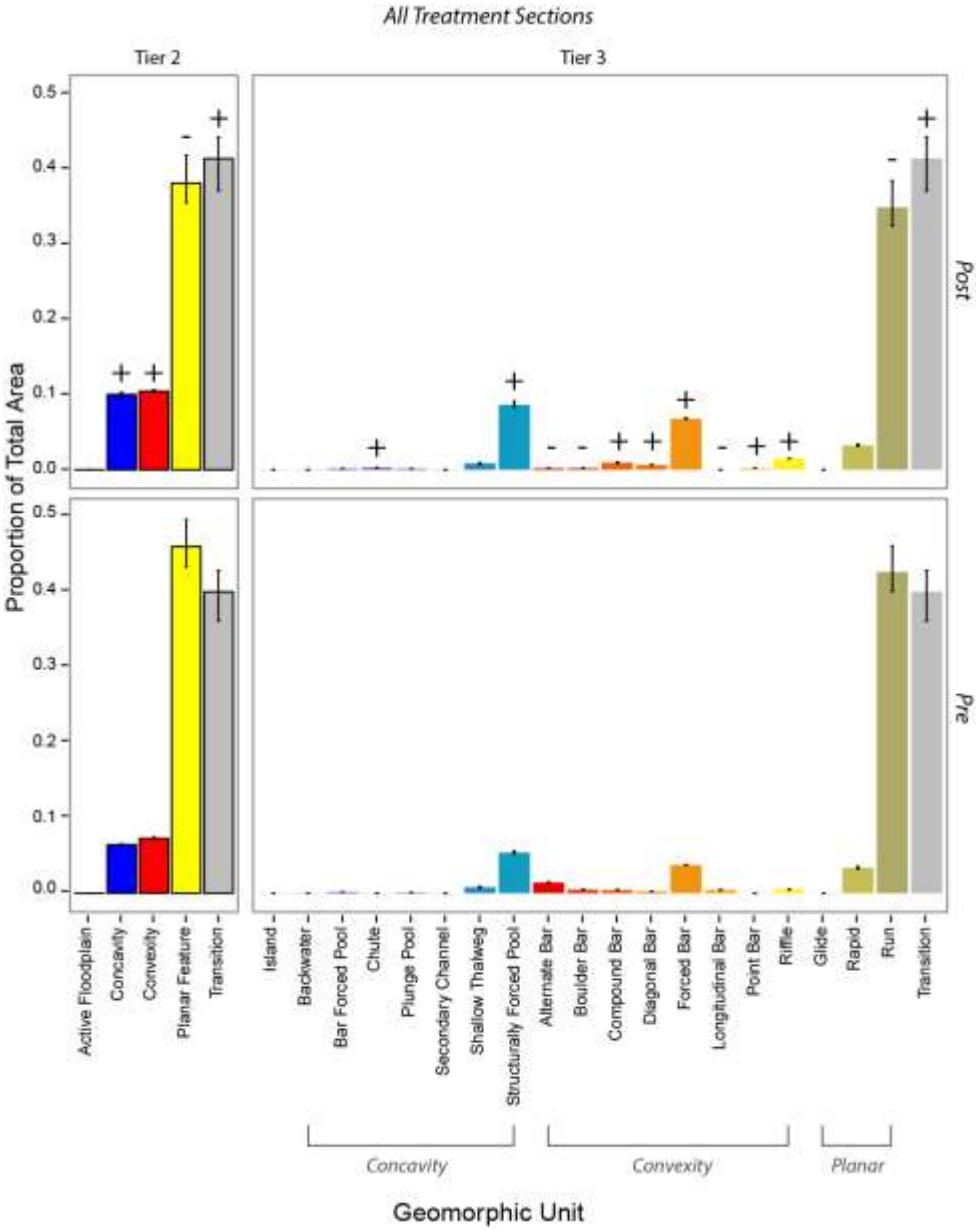

Figure 3.21. Proportional areas of tier 2 geomorphic units at treatment sites within the South Fork of Asotin Creek and Charley Creek combined. Units were manually delineated from topographic data collected at CHaMP sites. Error bars represent the upper and lower area estimates after a ±0.1 m buffer on the original area. A plus (+) or minus (-) sign above a bar indicates the direction of a statistically significant difference in pre- and post-restoration areas (P<0.05).

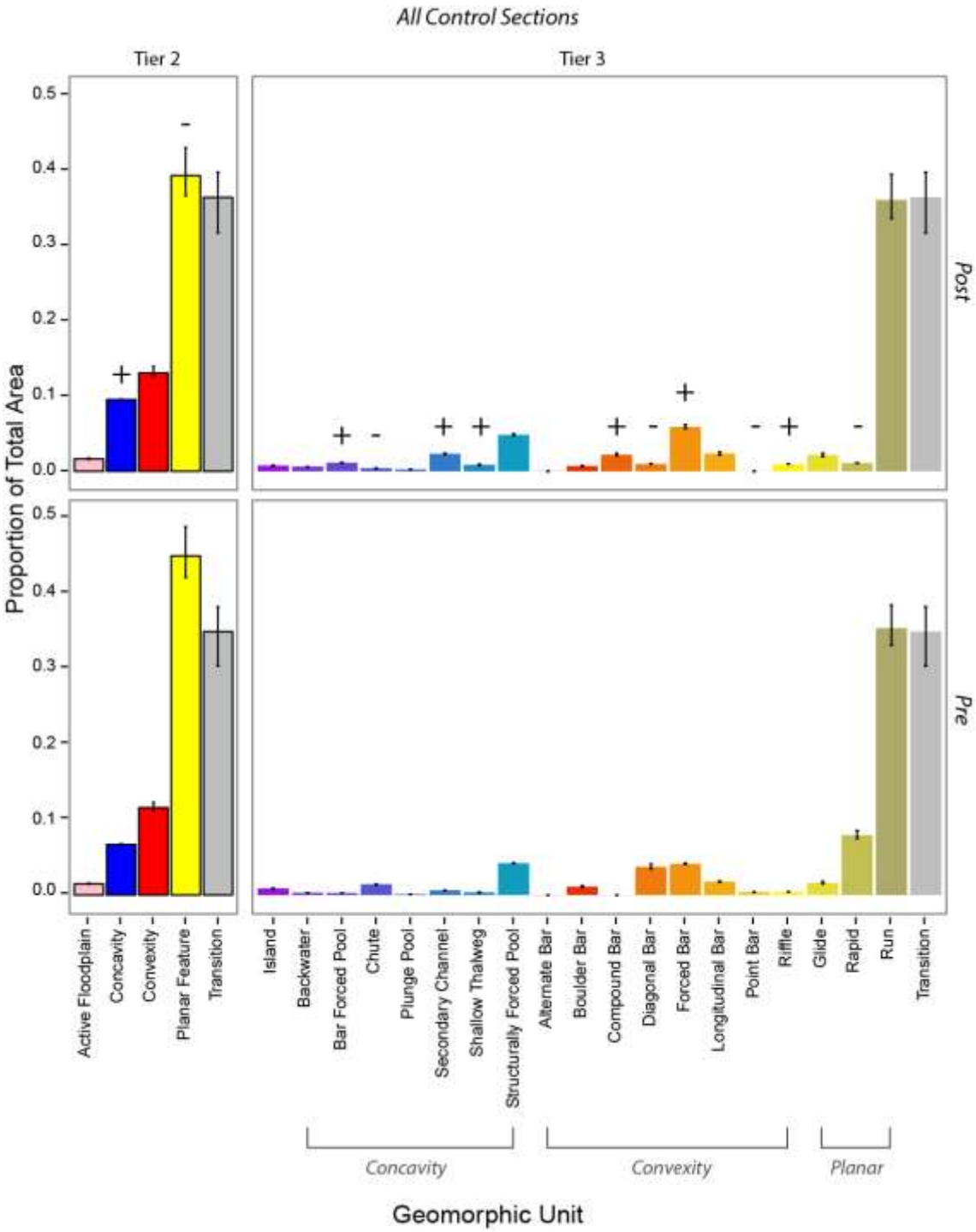

Figure 3.22. Proportional areas of tier 2 geomorphic units at control sites within the South Fork of Asotin Creek and Charley Creek combined. Units were manually delineated from topographic data collected at CHaMP sites. Error bars represent the upper and lower area estimates after a ±0.1 m buffer on the original area. A plus (+) or minus (-) sign above a bar indicates the direction of a statistically significant difference in pre- and post-restoration areas (P<0.05).

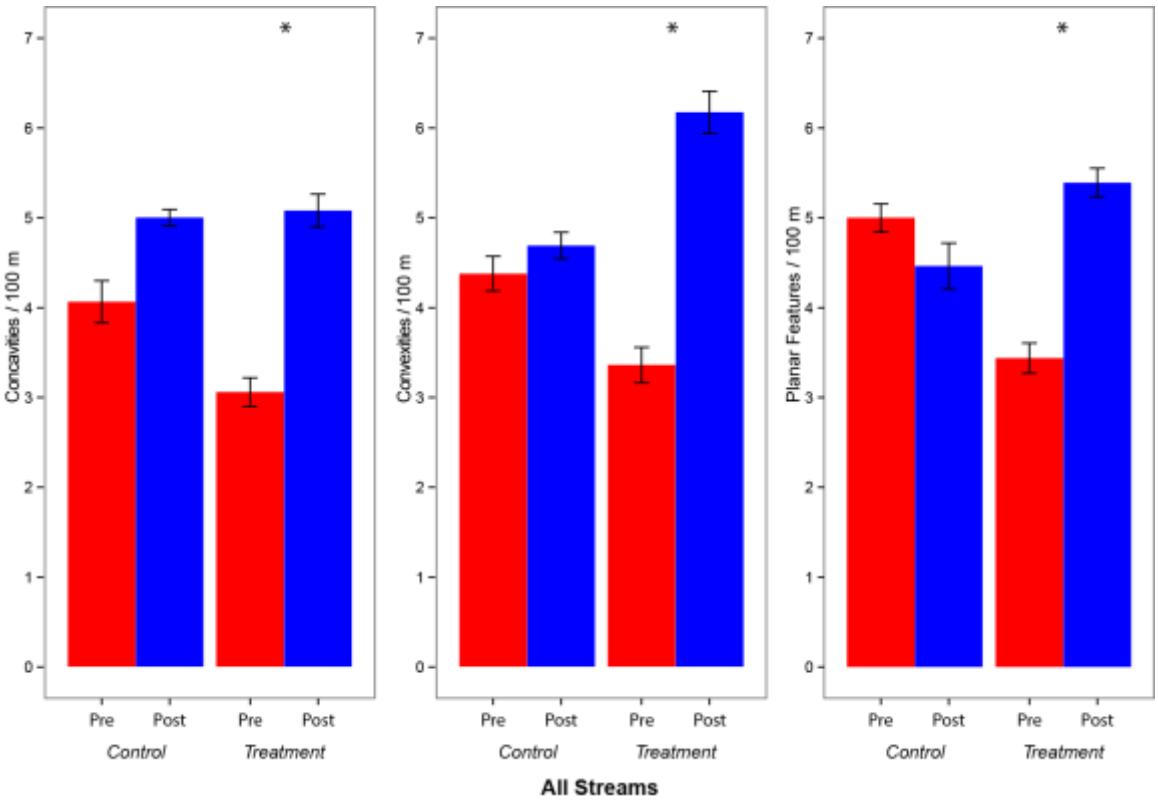

Figure 3.23. Mean concavities, convexities, and planar feature units per 100 meters by pre- and post-restoration and control and treatment sites on the South Fork of Asotin Creek and Charley Creek combined. Units were manually delineated from topographic data collected at CHaMP sites. Error bars represent the standard errors. An asterisk between bars represents a significant difference in the means of unit counts pre- and post-restoration (*=P<0.05).

At treatment sites, the proportional area of structurally forced pools and chutes significantly increased post-restoration (Figure 3.21). In contrast, the proportional area of shallow thalwegs, bar-forced pools, and secondary channels significantly increased at control sites post-restoration (Figure 3.22). Additionally, forced bar area significantly increased at treatment and control sites; however, the increase was 2.1% greater at treatment sites. Although, the proportional area significantly decreased at control sites, the decrease is attributed almost entirely to a decrease in rapid area. At treatment sites, the proportional area of diagonal bars also significantly increased, but significantly

decreased at control sites. The proportional area of riffles also significantly increased at treatment and control sites, but the increase at treatment sites was 1.0% greater.

DISCUSSION

Hydraulic and Geomorphic Responses

Structures on the South Fork of Asotin Creek were implemented in 2012, whereas Charley Creek structures were implemented in 2013. This provides us with the opportunity to interpret the difference in changes between new structures and those that have 'settled in' over multiple years. However, regardless of the time of implementation, the same responses are dominant between the study streams. *Bank attached, mid channel* and *debris jam PALS* appear to be the most successful structure types at inducing hydraulic and geomorphic change (Table 3.4). I cannot make any interpretations on the ability of *debris jam PALS* to induce responses on the South Fork because only one was implemented; however, they appear to be working well on Charley Creek.

Based on the observations and analysis in this study, I developed a conceptual flow chart explaining the process by which each response is imposed (Figure 3.24). Primary responses are more likely to occur quickly within the first year. The secondary responses are heavily dependent on the presence of other responses and higher flows to develop. It is also likely that these secondary responses (e.g. bar edge or erosion forming a chute) require a primary response is stable (e.g. deposition downstream). Additionally, this conceptual pathway is why the presence of some hydraulic responses might decline in subsequent years. For example, there was a decline in the proportion of *mid channel PALS* with the upstream eddy response in 2014. However, there was an increase in

deposition upstream in 2014, which would conceivably further constrict the channel locally, removing space for an upstream eddy at low flows.

Table 3.4. Conceptual effectiveness of structure types at producing expected hydraulic and geomorphic responses based on significant increases of each response on Charley Creek and the South Fork of Asotin Creek. +++ = Highly Effective; ++ = Effective; + = Minimally Effective; - = Not Effective.

Response	Bank Attached PALS	Mid Channel PALS	Debris Jam PALS	Spanner	Key Piece
Shunting Flow	+++	-	+++	-	+
Splitting Flow	-	+++	-	-	-
Convergent Jet DS	+++	++	+++	+	+
Eddy DS	+++	++	++	-	-
Eddy US	+++	+	+++	-	-
Divergent Flow DS	+	-	-	-	-
Convergent Flow DS	+	-	-	-	-
Deposition US	+++	+++	++	-	-
Deposition Wake	+++	+++	++	-	-
Deposition DS	++	+	-	+	-
Deposition Overbank	+	-	+	-	-
Erosion Convergent Jet	+++	++	++	-	-
Erosion Outer Bank	+++	++	++	+	-
Erosion Chute	-	-	-	-	-
Erosion Bar Edge Trim	-	-	-	-	-
Erosion Plunge	+++	++	+++	-	+

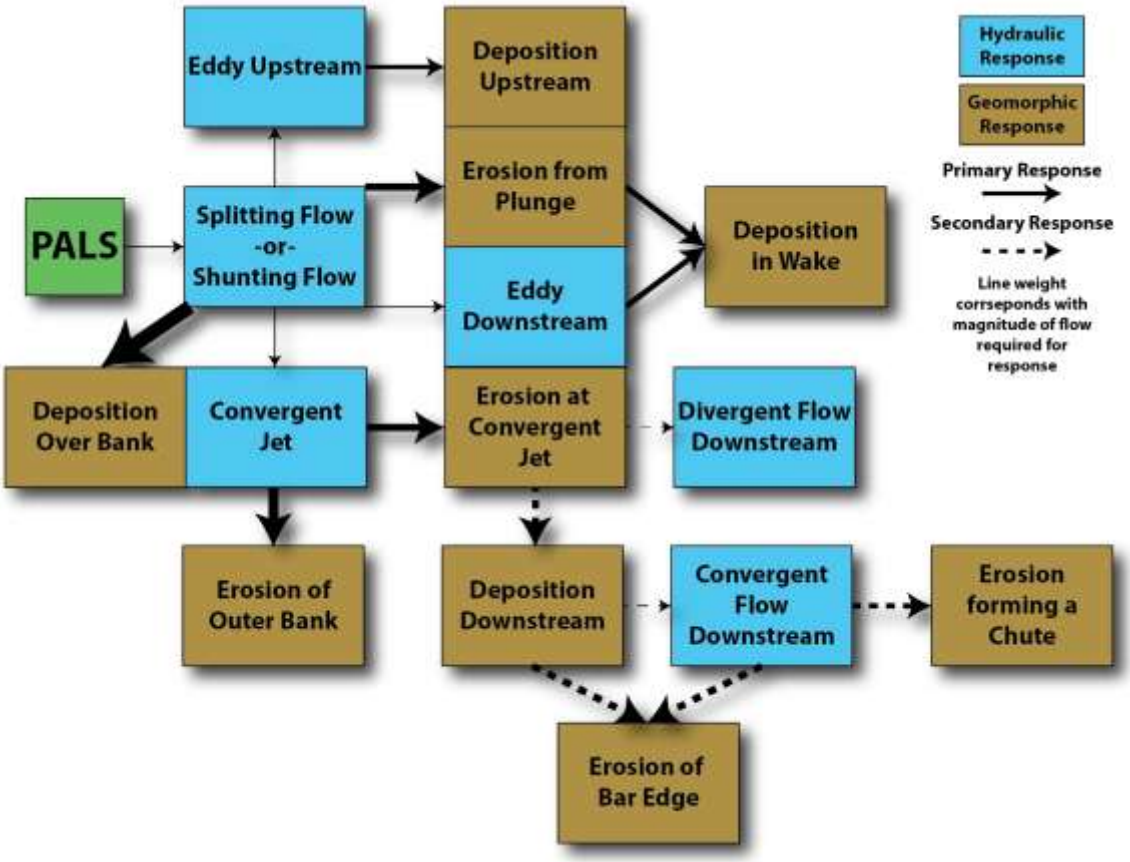

Figure 3.24. Conceptual pathway for expected responses at a post-assisted log structure (PALS) after implementation. Hydraulic responses are blue and geomorphic responses are tan. The line weight between responses corresponds with the magnitude of flow required to elicit the response (thicker = higher flow). Responses connected by a dashed line are secondary, meaning they require the presence of the previous response to form.

Many PALS imposed the primary hydraulic responses immediately after implementation. Downstream eddies provide important velocity refugia for salmonids, and the adjacent convergent jet acts as a feeding lane [*Beechie and Sibley*, 1997; *Nagayama et al.*, 2012] and both of these features significantly increased within two years after implementation at all PALS. These types of variations in hydraulic roughness are also important for generating pockets of sorted sediment [*Haschenburger and Rice*, 2004]. The upstream eddies also provide slower hydraulics that may be beneficial

velocity refugia for salmonids, but may not present during high flows. Likewise, it is important to note that the hydraulic response results are based on summer low flows. Therefore, the behavior of these structures and the hydraulic responses they impose likely go through many changes as flow rises and falls. By that token and based on our conceptual flowchart, I expect that convergent jets, downstream eddies, and divergent flow downstream responses increase during high flows. This is especially important when considering that velocity refugia during high flows can be extremely limited in systems with low densities of structural elements.

The most active geomorphic responses are erosion at the convergent jet, erosion of the outer bank, erosion by plunge hydraulics, deposition upstream, and deposition in the wake. The most prominent erosion response in *bank attached* and *mid channel PALS* is erosion at the convergent jet, which is a common effect of natural LWD [*Beechie and Sibley*, 1997]. In contrast, erosion from plunge hydraulics is the most common at *debris jam PALS*. I did not expect plunge erosion to occur so commonly at any of the structure types. The height of the structures were designed to be just below the bankfull elevation, which would result in water pouring over the top of most structures at the most common recurrent flood interval. So, while I did not expect plunge erosion to be so prominent, it should not be a surprise that it occurred so regularly.

Interestingly, *mid channel PALS* are expected to primarily split flow rather than shunt flow, but many of these structures converted to shunting flow. As debris collected on these mid channel structures, they became bank attached and subsequently were shunting flow rather than splitting flow in 2014. This type of conversion between structure types may occur in other ways, but it is highly unlikely for a bank attached

structure to become a mid channel structure. For this to occur, the posts and LWD nearest to the bank would have to be removed, but these posts are far more secure than those in the middle of the channel. While we have observed some bank scour around the bank attached end of these structures, the complete transition to a *mid channel PALS* would require substantial flows and/or multiple high flow events. This type of structure evolution is important to consider in the long term goals for this style of restoration, especially considering that the development of the expected responses may require many years of channel-modifying floods.

Mid channel PALS show another interesting behavior on the South Fork whereby the presence of downstream eddies significantly decreases. In the year between 2013 and 2014, the presence of deposition in the wakes significantly increased as well, which suggests that the development of this response reduces the occurrence of downstream eddies. The expected location of these two responses overlap, so as sediment is deposited behind a mid channel structure, there is decreased room for eddies to remain directly behind the structure. This may seem like a negative impact because the downstream eddies provide important refugia for juvenile salmonids; however, the scour pools on either side of a mid channel structure become deeper and more pronounced as deposition in the wake increases. Therefore, potential loss in fish habitat by decreased eddies could be overshadowed by the increase in structurally forced pools. Likewise, at higher flows, downstream eddies are likely more prominent than what I observed at base flow.

Geomorphic Change Detection

The results from the geomorphic change detection analysis show that the treatment reaches are aggrading while control reaches are slightly degrading since PALS implementation. Although there is only one treatment reach where a true pretreatment DoD could be made, it was largely degrading. The peak flow in 2014 was larger than the peak flow in 2012 that caused the massive erosion at that site, but there was not a large volume of erosion. This coincides with the change in geomorphic units at treatment sites where the number of convexities nearly doubled. Using the single restoration site as an example, it is plausible that the placement of PALS as structural elements in the stream greatly retards the erosional effect of peak flows by increasing hydraulic roughness. I hypothesized that the lack of structural elements, in part, led to the increased erosion rates that were historically observed on the study streams [*Bennett and Bouwes*, 2009].

The error bars on the GCD metrics are very large due to conservative estimates in the volumetric calculations. They represent the range of uncertainty in the actual mean values of volumetric change, and are carried through to estimates of thickness. However, the differential trends between treatment and control reaches are still informative. Additionally, they act as lines of evidence that $_{HD}$LWD increases opportunities for deposition. Likewise, these results are corroborated by the significant increases in multiple depositional geomorphic responses at structures, and convexities at the treatment sections (e.g., Figure 3.8 and 3.10).

Geomorphic Units

This study has shown that $_{HD}$LWD is an effective approach to increasing in-channel geomorphic complexity in two degraded streams lacking LWD. Within treatment reaches, the proportional area of planar features decreased while concavity and convexity area increased. Changes at the tier two level of geomorphic units within control reaches may be misleading if assessed on their own. Because, even though the proportional area of concavities significantly increased at control reaches, this increase is mostly attributable to one secondary channel and shallow thalwegs. Shallow thalwegs are common geomorphic concavities in low-complexity planar reaches, are only slightly deeper than the average depth, and are typically poor fish habitat [*Wheaton et al.*, 2014]. In contrast, the increase in concavities at treatment sites is almost entirely from structurally forced pools caused by $_{HD}$LWD. Additionally, a larger variety of convexities were created at treatment reaches than in control reaches. Likewise, more forced bars, riffles, point bars, and diagonal bars were created at treatment reaches. The significant increase in compound bars at control reaches is difficult to explain, as their formation processes are implicitly complex. Finally, the significant decrease in planar features at control sites is mostly attributed to a significant decrease in rapid area. In particular, a long rapid on one control site changed into a sequence of runs and shallow thalwegs following the 2014 spring floods. Interestingly, there is a fallen tree and LWD jam at this location which forced these geomorphic changes during the 2014 flows.

The number of concavities and convexities per 100 m significantly increased at treatment reaches, but not at control reaches. The increase in concavities is similar to many previous studies showing that mean pool spacing is generally inversely related to

LWD frequency [*Beechie and Sibley*, 1997; *Montgomery et al.*, 2003]. Therefore, by using $_{HD}$LWD as a restoration tool, I would expect the number of pools to increase. Likewise, convexities increased at treatment sites and LWD can greatly increase a system's capacity to store sediment [*Nakamura and Swanson*, 1993] and increase gravel bars [*Beechie and Sibley*, 1997]. The significant increase in planar features per 100 m is due to an increased number of other units fragmenting the originally uniform channel. This is supported by the fact that planar feature area significantly decreased at treatment sites.

Synthesis

$_{HD}$LWD appears to be a successful restoration method for mimicking the fluvial processes invoked by natural tree recruitment that maintain quality stream and salmonid habitat. The immediate impact of PALS on the hydraulics of the channel may have direct impacts on salmonid habitat. Where PALS are located, the primarily plane-bed channel with uniform flow converted to a channel with multiple feeding lanes, velocity refuges, and structural cover for juvenile salmonids. The availability of variable habitat, such as the changes that PALS impose, has been linked to higher salmonid densities and biomass [*Lonzarich and Quinn*, 1995; *Bayley*, 2002; *Whiteway et al.*, 2010]. Many of the geomorphic responses that these structures impose help to stabilize the structures, and increase the size and presence of hydraulic responses. In addition, PALS have the potential to increase spawning areas. The plane-bed channel that existed before restoration consisted primarily of poorly sorted cobble-gravel matrix. Structural elements such as LWD increase hydraulic roughness, which can create forced patches of well

sorted sediment [*Buffington and Montgomery*, 1999; *Merz*, 2001; *Haschenburger and Rice*, 2004].

LWD restoration projects using traditional techniques cost an estimated $56/m [*Roni et al.*, 2010], whereas the method used in this study costs $3.50/m. This study has shown that $_{HD}$LWD loading is a promising cheap and cheerful restoration method, especially when PALS are used. PALS were much more effective at forcing expected geomorphic and hydraulic change than unsecured structures; however, this result is entirely because this study focused on local change around the initial location of structure. In other words, I did not follow the effects of LWD once it left the original implementation site. Therefore, the accumulation of LWD from "failed" structures downstream has not been fully explored, but is undoubtedly beneficial in a stream lacking structural elements. These structures require 1-5 years for significant responses and shifts in geomorphic unit assemblages to occur. Their effectiveness is highly dependent on flows; therefore, a large flood event in the first year after implementation may be enough to initiate immediate results. Results from this study show the potential impacts of PALS after one effective discharge event.

The 2014 spring flows were likely a 3-5 recurrence event; however, the geomorphic effects of $_{HD}$LWD were less on Charley Creek than the South Fork of Asotin Creek. While Charley Creek is a smaller drainage, and its peak flow was less than the South Fork, the treatment sections of each stream are also located in different river styles. The treatment sections are located within a ***Fan controlled with discontinuous floodplain River Style*** on Charley Creek and a ***Planform controlled with discontinuous floodplain River Style*** on the South Fork (Chapter 2). The treatment section on Charley

Creek is frequently imposed by fans from incoming tributaries that it does not have the competence to erode in its current condition. PALS locally increase competence by artificially constricting the channel, but they may not have been aggressive enough to increase lateral fluctuations in the channel, and locally source sediment to create bars. The higher valley confinement setting in Charley Creek coupled with its lower peak flows, present different challenges to effective restoration than the South Fork. In contrast, the South Fork of Asotin Creek treatment section is generally in a less confined valley, with more frequent access to the floodplain and erodible hillslopes. Despite higher peak flows on the South Fork, there was very little vertical erosion as a result of restoration, due to the coarse substrate and armored bed of this poor condition variant of the ***Planform controlled discontinuous floodplain River Style***. However, because of the higher competence of the South Fork, PALS did increase erosion at the toes of hillslopes and fans, locally sourcing sediment to create more bars and increase the depth of pools. These types of improvements to geomorphic condition may lead to better condition variants of each river style. Regardless, the river style and geomorphic condition of each treatment section provides a starting point and the potential, if not idealized, of typical reaches on these streams.

Because this study is part of the Asotin Creek IMW, a long-term watershed experiment, we will continue to track the effects of $_{HD}$LWD on the stream channel and the wild steelhead population. The short-term hypotheses of the IMW restoration design are expected to reach full fruition in 1-5 years; however, I expect these short-term effects to contribute to the long-term goals of recovering functionality to the riparian area.

CHAPTER 4

VIABILITY OF A CHEAP AND CHEERFUL RESTORATION MONITORING METHOD

INTRODUCTION

Globally, streams have become degraded through centuries of human impact and development [*Karr and Chu*, 1998; *Wohl et al.*, 2005; *Palmer et al.*, 2007]. Although restoration of degraded stream habitat has become a priority in the United States, there is insufficient monitoring to determine restoration effectiveness [*Bernhardt et al.*, 2005; *Roni et al.*, 2008]. Perhaps the most common reason for the lack of monitoring restoration projects is due to insufficient time and money [*Bernhardt et al.*, 2007]. Thus, there is a critical need to create or improve habitat monitoring methods in a manner that decreases cost. The need for cost effective monitoring is exemplified by the need for long term monitoring (10+ years) to successfully determine the outcomes of a restoration project [*Kondolf*, 1995; *Roni et al.*, 2005, 2008]. However, increasing the rapidity of surveys often comes at the sacrifice of consistency and detailed data at large scales.

The loss of survey detail to rapidity can be mitigated by beginning restoration projects with clear objectives and focusing monitoring efforts on answering pertinent questions related to those objectives [*Raven et al.*, 2010; *Fernández Cortes et al.*, 2011]. This principal has been used in the implementation of many region-wide stream assessment protocols which offer the best assessments of rapid protocol evaluations (e.g. [*Larsen et al.*, 2007; *AREMP*, 2010; *PIBO*, 2012]). However, monitoring to meet objectives is a principal rarely incorporated into project planning [*Bernhardt et al.*, 2005;

McMillan and Vidon, 2014]. Regardless, analysis of variability of similar protocols has shown little consistency within and between groups revealing a dire need for improvement in protocol execution [*Roper et al.*, 2010]. Likewise, as methods for monitoring stream habitat become more standardized, there is a need to increase consistency in how groups and individuals implement those protocols. [*Whitacre et al.*, 2007] suggested that clearer attribute definitions and additional training can improve consistency.

Mobile electronic devices (e.g. dataloggers, tablets) are increasingly being used in the field to collect data relevant to stream habitat [*PIBO*, 2012; *CHaMP*, 2013]. The native features of tablets coupled with custom database applications (apps) yield a powerful tool for increasing data collection efficiency in the field [*Camp and Wheaton*, 2014]. Utilizing the power of custom database apps, it is conceivable that consistency in data collection can be increased by real-time data validation. Customizing such apps to collect data that specifically target project objectives may help to mitigate the lack of sufficient monitoring for restoration projects. Likewise, it has become progressively easier to create custom apps without requiring substantial programming knowledge.

We developed a custom database app named the HDLWD Effectiveness App to monitor the physical effect of instream restoration structures in Asotin Creek, Washington [*Camp and Wheaton*, 2014]. We created the app to specifically address pre-defined hypothesis in the Asotin Creek Intensively Monitored Watershed (IMW) restoration design [*Wheaton et al.*, 2012] and have used it since 2012 to perform yearly evaluations of condition and performance of over 530 structures. The data collection methodology behind the app was framed around data relevant to the design hypothesis

while remaining rapid (survey 1-2 km of stream length per day). To do this, much of the data is qualitative; however, some physical metrics are recorded (e.g. wood sizes, water depths, geomorphic unit sizes). As data is recorded into the app, it is validated and run through quality control measures in real time. While the app has met the goal of allowing us to survey up to 2 km of stream in a single day, we have not fully assessed the variability and accuracy of this method.

In this study, I evaluate the feasibility in using the app to consistently and accurately collect data to assess restoration effectiveness. I do so by comparing inter- and intra-observer variability of the capstone data collected using the app. Additionally, I assess the accuracy of data collected using the app compared to methods that have been previously vetted in the literature and in this thesis. I expect that with little training (<2 hours) and with help inherent in the app, a new user can become similarly adept to a veteran user at collecting the capstone data. I also expect that a veteran user of the app, with ample training, can collect data consistent with a vetted protocol. The primary goal of this study is to determine problems and difficulties within the app or protocol so that they can be mitigated through future app development.

STUDY SITES

The South Fork of Asotin Creek drainage is 104 km^2, and one of three study streams for the Asotin Creek Intensively Monitored Watershed [*Bennett and Bouwes*, 2009]. The overall treatment method for the IMW is referred to as high density large woody debris ($_{HD}$LWD), in reference to the large amounts of LWD that is placed in the stream. However, within a $_{HD}$LWD treatment section, there may be multiple structure

types comprised of LWD pieces. The majority of these are called post assisted log structures (PALS), and we have developed specific hypotheses and geomorphic responses for each PALS. In 2012, 195 instream structures were implemented in a 4 km treatment section of the South Fork [*Wheaton et al.*, 2012]. The observer variability portion of this study takes place on a 600 m reach of the South Fork containing 25 structures (Figure 4.1). I used 25 separate structures within two CHaMP sites on the South Fork for methodological validation of the rapid app protocol because topographic data was available (Figure 4.2).

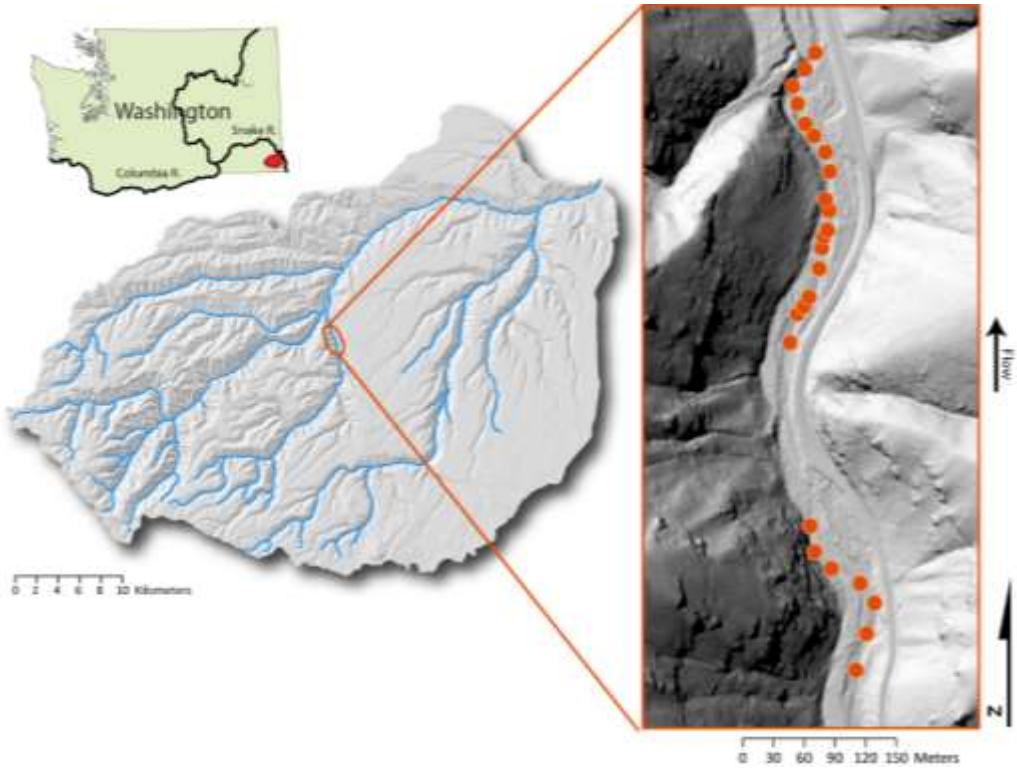

Figure 4.1. Reach on the South Fork of Asotin Creek containing the 25 restoration structures used to estimate observer variability of the HDLWD Effectiveness App.

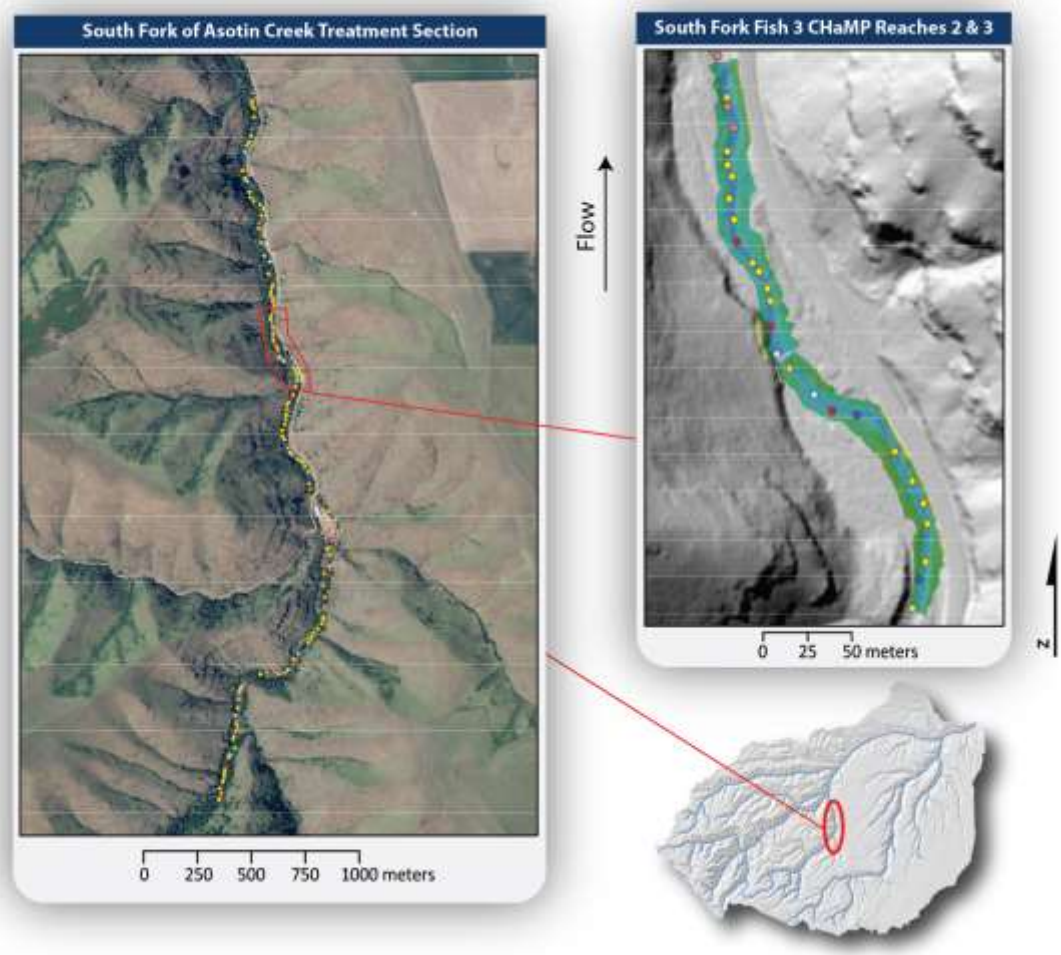

Figure 4.2. Location of the two CHaMP reaches on the South Fork of Asotin Creek containing the 25 structures used for validation of the HDLWD Effectiveness App. Structures are indicated by the colored dots in the channel.

METHODS

We developed a custom database app to monitor the efficacy and condition of restoration structures implemented within the Asotin Creek IMW. The app facilitates data collection for the design, implementation, and indefinite monitoring of individual structures [*Camp and Wheaton*, 2014]. We use the app to collect data every year after

spring flows on the status of every structure, as well as their hydraulic and geomorphic influence on the active channel.

During the summer of 2014, three observers described each structure's condition and influence, counted LWD, mapped geomorphic unit assemblages, and noted the presence of hydraulic and geomorphic responses at 25 structures. One observer surveyed all 25 structures, while the other observers surveyed a combined 25 structures (Table 4.1). I compared each observer's data by identifying the number of matching observations. I then identified the primary reason for those observations that did not match between observers to provide insight into how to improve the app, protocol, and observer training. For this study, Observer 1 is the most experienced in these methods, and Observer 2 received approximately two hours of training before surveying their assigned structures. The secondary observers both had extensive previous experience in data collection and analysis pertaining to fish habitat and geomorphology. In addition, Observer 1 completed two separate surveys of the structures, once in July, and again in October. The purpose of the repeat study by Observer 1 is to enumerate the repeatability of the methods by an experienced user.

Table 4.1. Assignments of three observers to 25 restoration structures on the South Fork of Asotin Creek. Comparisons on observations were made on data collected by Observer 1 and Observer 2.

Structure Number	Observer 1	Observer 2
1	A	B
2	A	B
3	A	B
4	A	B
5	A	B
6	A	B
7	A	B
8	A	B
9	A	B
10	A	B
11	A	B
12	A	B
13	A	B
14	A	B
15	A	B
16	A	B
17	A	B
18	A	B
27	A	C
28	A	C
29	A	C
30	A	C
31	A	C
32	A	C
33	A	C

Observer Variability - Hypothesized Responses

To encourage rapidity of the survey, many observations are qualitative. For example, to indicate the presence of a hydraulic or geomorphic response (Figure 4.3), the user must input their level of certainty that the response exists by picking one of five levels: Certain, Probable, Possible, Unsure, or Not Present. Because of this, it is impossible to make quantitative or statistical comparisons on observer variability.

Therefore, I compared many observations for the presence or absence of features and responses based these factor levels of certainty: Certain, Probable, or Possible = present; Unsure or Not Present = absent. This allows me to compare the consistency of feature and response identification between users. In addition, I created agreement matrices for each response and structure attribute to better understand where observers were diverging from each other. Ideally, observers correctly identify the presence or absence of each response, and do not deviate from each other more than one factor level. For a full description of each variable observed at the structures, refer to Tables B.1 and B.2 in the appendix.

Observer Variability - Geomorphic Unit Assemblages

In addition to identifying hypothesized responses, I also used the app to identify the geomorphic units within the active channel surrounding each structure. Geomorphic units are landforms that reflect the processes which determine river structure and function [*Brierley and Fryirs*, 2005]. Although their presence may be inferred through surface hydraulics, they are first and foremost determined by their geomorphic shape [*Wheaton et al.*, 2014]. I used three tiers of a four tier classification system for identifying geomorphic units in fluvial systems (Figure 4.4). Tier one is primarily a determination of whether the unit is within or outside the active channel. For this study, I only delineated units within the active channel. Tier two separates units by their general shape into three categories: concavities (e.g., pools), convexities (e.g., bars), and planar features (e.g., runs). Tier three breaks units into their specific morphologies. I did not use tier four for this study, because there was not sufficient data to reach this level of detail using the topographic method. I delineated geomorphic units up to tier three within one channel unit width

upstream of the structure and six channel unit widths downstream of the structure (or until the next structure). To compare differences between users and visits, I summarized geomorphic units by tier two and tier three of the geomorphic unit classification system.

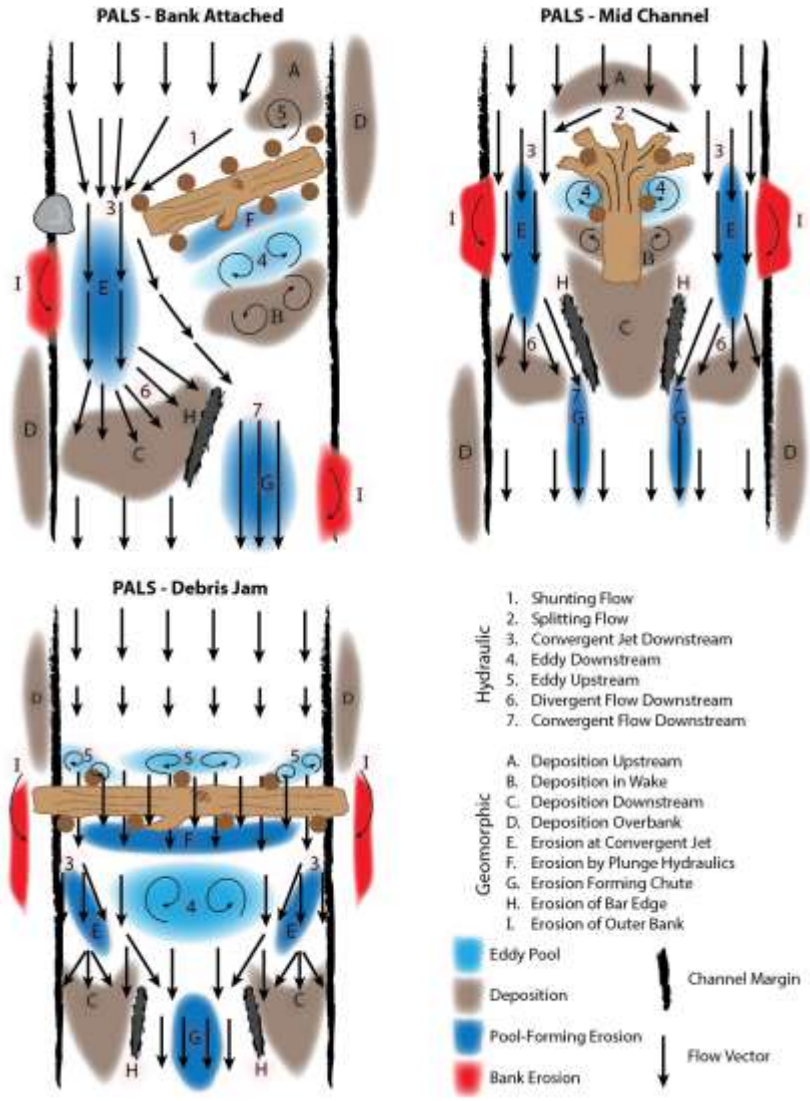

Figure 4.3. Example of expected hydraulic and geomorphic responses for structure types implemented on the South Fork of Asotin Creek. Vectors indicate hydraulic responses, and colored polygons indicate geomorphic responses. Red = bank erosion, blue = pool development, gray = bar development. The noted presence of each response was compared between observers.

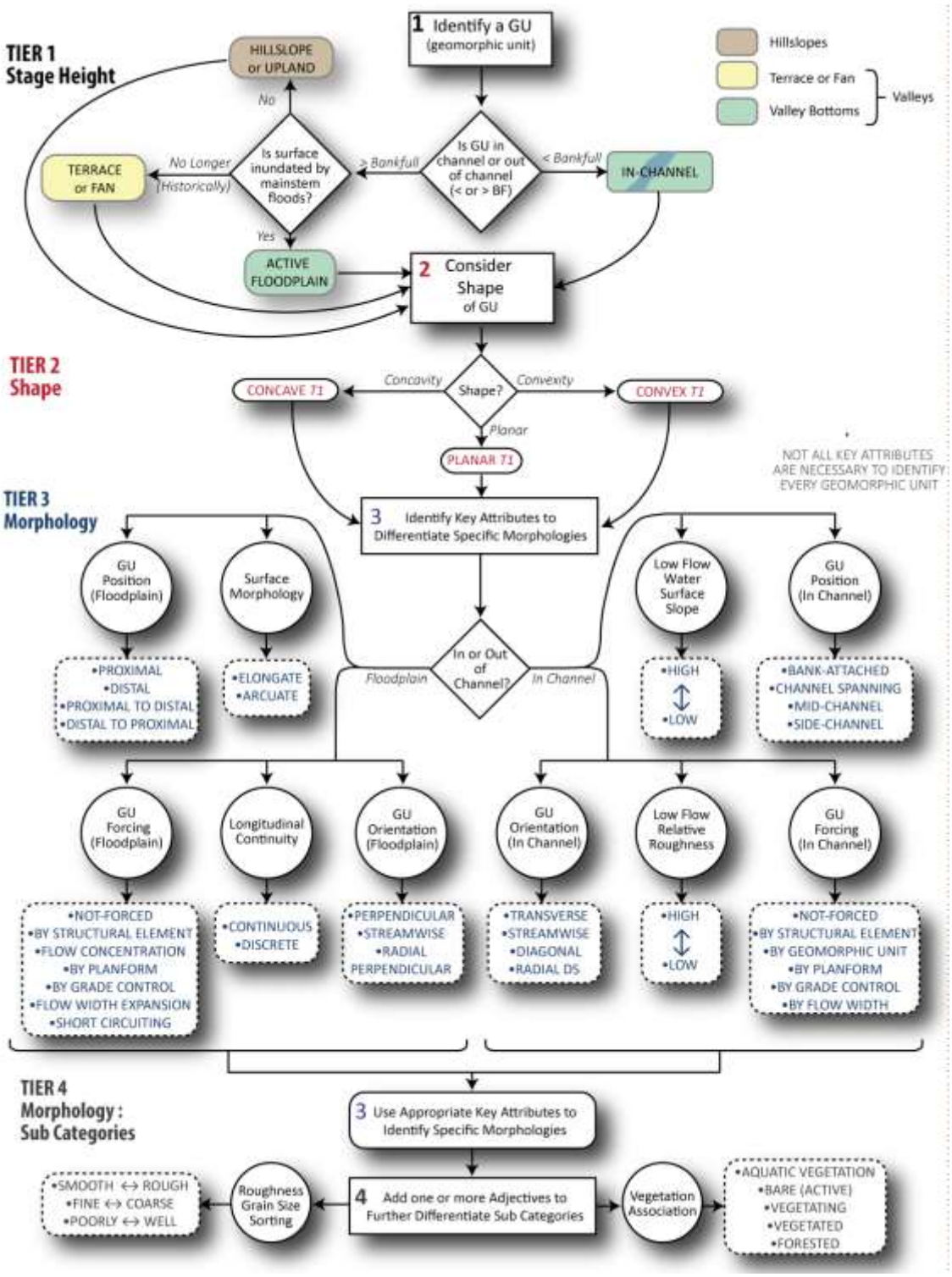

Figure 4.4. Four tier dichotomous key for determining geomorphic units in fluvial valleys. This study delineated units up to tier 3 – the specific morphology of geomorphic units. From [*Wheaton et al., submitted to Geomorphology, 2014*].

To supplement the process-informed delineation of geomorphic units, I also collected each unit's length, width, max depth, and average depth. Lengths and widths were measured visually in relative space as a number of channel unit widths. A single channel unit width is the average width of the active channel within the current reach. For the South Fork of Asotin Creek, this value is about six meters. Therefore, I measured lengths and widths as the number of six meter lengths that could fit inside the attribute (e.g. if the zone of influence downstream is 12 meters, the user would record two as the length). For pool units, I recorded the dominant forcing mechanism and the riffle crest depth instead of the average depth. I also assigned each unit a location relative to the structure. The app uses each unit's size and location to compile the units into a single assemblage around the structure that we call a *tetris diagram.* I exported each tetris diagram from the app as ASCII rasters with each cell (0.06 m by 0.06 m) containing a numeric identifier for a geomorphic unit, water depth, or dominant substrate. I compared the tetris diagrams on a cell by cell basis to determine the most common differences between observers for every structure.

Method Validation – Geomorphic Responses

The Asotin Creek IMW utilizes the CHaMP protocol to assess habitat condition at 18 reaches (160-200 m long) within the IMW study streams. CHaMP field crews collect topographic data using total stations and produce 0.1 m resolution digital elevation models (DEM) of every reach [*CHaMP*, 2013]. I selected two CHaMP reaches within the treatment section on the South Fork of Asotin Creek to identify geomorphic responses of the structures using geomorphic change detection. I used DEMs from the 2013 and 2014 field seasons to create a DEM of difference (DoD) within the bankfull channel of each

reach, by subtracting elevation values of the 2013 DEM from the 2014 DEM. To facilitate the creation of the DoD and account for uncertainty in the elevation differences I used the Geomorphic Change Detection Software (http://gcd.joewheaton.org). I created an error surface using a fuzzy inference system (FIS) model using survey point density, slope, and interpolation error for each survey. The interpolation error surface is equal to the elevation difference between survey points and the triangular irregular network used to create the DEM. The FIS model compounds each surface into an overall error surface represented as depth uncertainty in meters [*Wheaton et al.*, 2010]. I then identified the 16 hypothesized geomorphic responses from the DoD based on their locations relative to the structure, using Figure 4.3 as the conceptual model of responses for each structure type. Finally, I compared the responses which I identified through this GIS exercise to the responses I identified in the field using the app.

Method Validation – Geomorphic Unit Assemblages

To assess the observer's ability to accurately delineate geomorphic unit assemblages using tetris diagrams, I delineated geomorphic units using the topographic data from the same two CHaMP reaches. I used the detrended DEM, 0.1 m contours drived from the detrended DEM and the original DEM, bankfull water depth raster, and in-channel photographs to delineate geomorphic units. I then calculated the proportional areas at tier two and tier three geomorphic units. I compared the proportional area of each unit type derived from topography within the surveyed area, to units derived from the tetris diagrams. I completed this analysis within the survey area of each tetris diagram surrounding a structure (approximately 6 m upstream, and no greater than 36 m downstream). To test for significant differences in proportional areas of geomorphic units

using each method, I used a test of equal proportions (H_o = equal area, H_a = unequal area).

RESULTS

Inter-Observer Variability – Structure Responses

On average, observers identified the presence of the same hydraulic and geomorphic responses 79% of the time (Table 4.2). Separately, the presence of hydraulic responses was matched at 87% of structures, and geomorphic responses were matched at 75% of structures. Some responses are more consistently identified than others (e.g. Shunting Flow vs. Convergent Flow Downstream). All of the unmatched observations appear to be related to inconsistencies in identifying the real responses. Most of the poorly matched responses are difficult to identify or can be easily lumped with a similar response nearby.

The spread of gray to black squares in the agreement matrices represents the deviation between observers when noting the presence of hydraulic and geomorphic responses (Figure 4.5 and 4.6). Ideally, colored squares would only appear within the dark bold lines surrounding the intersecting certainty levels (i.e. observations would be off by one factor level). However, the lightest gray box in the matrices represents a match in factor levels at a single structure. For hydraulic responses, observers were the least consistent in identifying convergent flow downstream (68%) and eddies upstream (76%) of structures (Figure 4.5). When identifying the convergent flow downstream response, Observer 1 always marked “Not Present” or “Unsure”; whereas, the second observer noted it as present with higher levels of certainty for multiple structures. Likewise, the

second observer often marked both upstream and downstream eddies as present with high certainty; whereas, Observer 1 was more variable with those observations.

Table 4.2. The number of matching presence/absence observations for each hydraulic and geomorphic response at restoration structures and an explanation for non-matching observations. The percent matching indicates the proportion of structures with matching presence/absence values between observers (Certain, Probable, or Possible = present; Unsure or Not Present = absent). US = upstream, DS = downstream.

Response	**Response Type**	**Number Matching**	**Number Possible**	**Percent Matching**	**Explanation for Low Matches**
Shunting flow	Hydraulic	23	25	92%	
Splitting flow	Hydraulic	24	25	96%	
Convergent jet	Hydraulic	24	25	96%	
Convergent flow DS	Hydraulic	17	25	68%	Inconsistent ID of response
Eddy DS	Hydraulic	23	25	92%	
Eddy US	Hydraulic	19	25	76%	
Deposition US	Geomorphic	21	25	84%	
Deposition in wake	Geomorphic	18	25	72%	Inconsistent ID of response
Deposition DS	Geomorphic	14	25	56%	Inconsistent ID of response
Deposition over bank	Geomorphic	20	25	80%	
Erosion at jet	Geomorphic	19	25	76%	
Erosion of outer bank	Geomorphic	14	25	56%	Inconsistent ID of response
Erosion forming chute	Geomorphic	20	25	80%	
Erosion of bar edge	Geomorphic	24	25	96%	
Erosion by plunge	Geomorphic	18	25	72%	Inconsistent ID of response

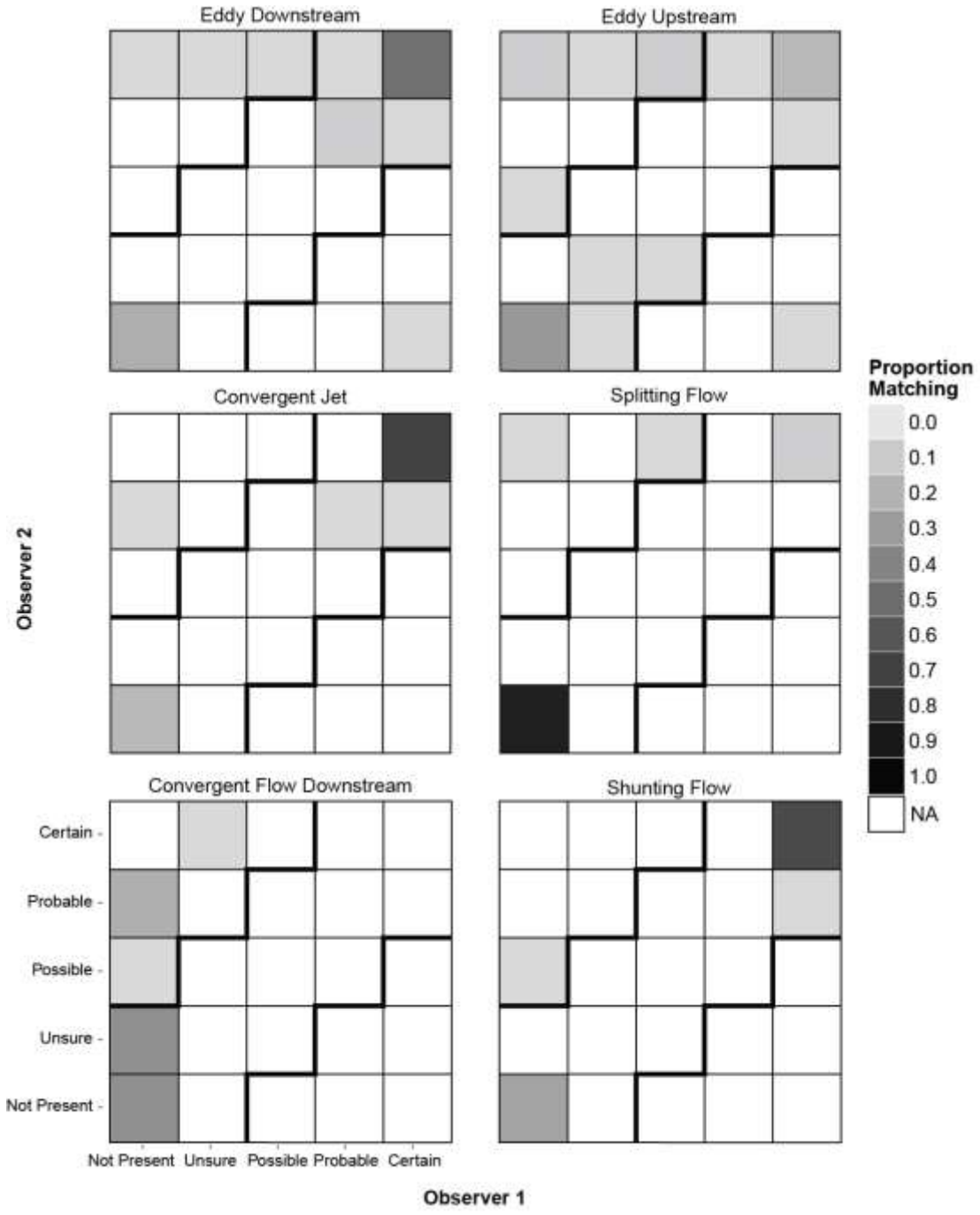

Figure 4.5. Agreement matrices for hydraulic responses comparing observations between observers. The bold black line represents a deviation of one factor level between observers.

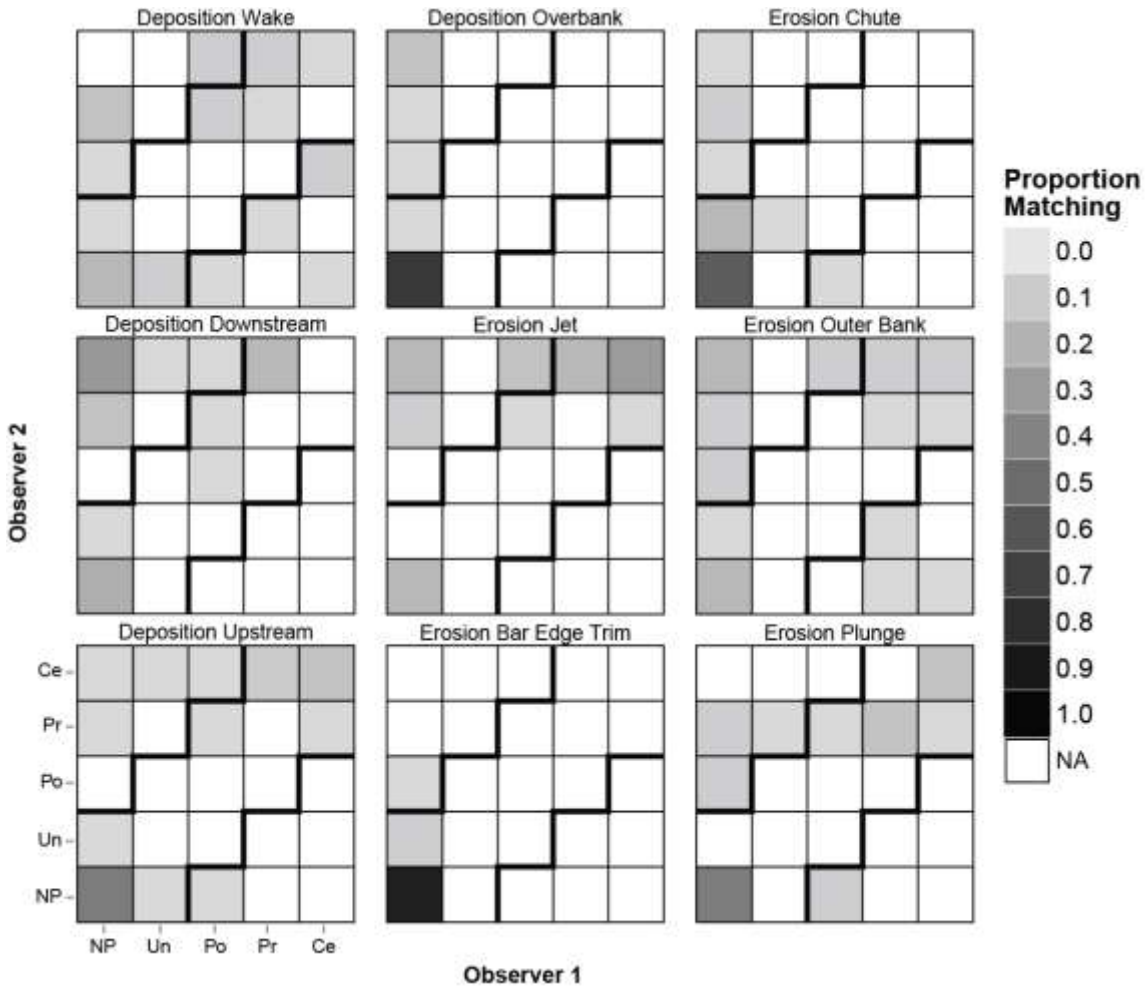

Figure 4.6. Agreement matrices for geomorphic responses comparing observations between observers. The bold black line represents a deviation of one factor level between observers.

For geomorphic responses, the least consistently identified responses between observers were deposition downstream and erosion of the outer bank (both at 56%). This is evident in the agreement matrices which show a lot of spread for both of those responses (Figure 4.6). In contrast to some of the hydraulic responses, Observer 1 appears to have marked many responses as “Not Present” while Observer 2’s observations were more variable (e.g. deposition overbank, erosion chute, erosion outer bank).

Inter-Observer Variability – Geomorphic Unit Assemblages

Among the total surveyed area, 76% of the raster cells from the app-generated tetris diagrams matched between observers. The largest reason for mismatched cells was due to a difference in the area surveyed at structures by each observer, equating to 35.8% of all discrepancies (Table 4.3). The largest discrepancies within overlapping survey areas were between planar features and other tier one units, altogether representing 37.6% of the differences. Most of these discrepancies stem from Observer 1 delineating runs where Observer 2 delineated rapids (14%) or structurally forced pools (10.9%; Table 4.4). The remaining differences stem from inconsistent selection of tier one units. These discrepancies only reflect the consistency between users of creating identical tetris diagrams.

Table 4.3. Differences in tier one geomorphic units assessed by differences in rasters representing geomorphic unit assemblages surrounding structures. The proportion represents the total surveyed area that was different between users because of the associated difference. Only differences that covered more than 4% of the total area are shown here. The combined total of all other differences are represented as "Other."

Observer 1	**Observer 2**	**Proportion**
Size of Surveyed Area	Size of Surveyed Area	35.8%
Planar Feature	Other Planar Feature	14.2%
Planar Feature	Concavity	13.9%
Planar Feature	Convexity	9.5%
Concavity	Planar Feature	7.1%
Convexity	Other Convexity	6.5%
Convexity	Planar Feature	4.7%
Concavity	Convexity	4.3%
Other	Other	4.0%

Table 4.4. Differences in tier two geomorphic units assessed by differences in rasters representing geomorphic unit assemblages surrounding structures. The proportion represents the total surveyed area that was different between users because of the associated difference. Only differences that covered more than 1% of the total area are shown here. The combined total of all other differences are represented as "Other."

Observer 1	**Observer 2**	**Proportion**
Size of Surveyed Area	Size of Surveyed Area	35.8%
Run	Rapid	14.0%
Run	Structurally Forced Pool	10.9%
Structurally Forced Pool	Run	6.0%
Run	Forced Bar	3.1%
Alternate Bar	Point Bar	2.8%
Run	Alternate Bar	2.4%
Run	Point Bar	2.0%
Rapid	Structurally Forced Pool	1.7%
Structurally Forced Pool	Forced Riffle	1.6%
Forced Bar	Point Bar	1.5%
Structurally Forced Pool	Forced Bar	1.3%
Run	Plunge Pool	1.3%
Run	Riffle	1.2%
Structurally Forced Pool	Point Bar	1.2%
Structurally Forced Pool	Rapid	1.1%
Rapid	Forced Bar	1.1%
Rapid	Island	1.1%
Other	Other	9.8%

Among the tetris diagrams, the majority of estimated water depths within units are very similar (Figure 4.7); however, the left skewed histograms of water depths means that Observer 1 was underestimating depths, or Observer 2 was underestimating depths consistently (Figure 4.7a & b). Regardless, 78% of the max depths and 64% of the mean depths are within ±5 cm between observers. The weighted mean of differences between mean and max water depth are -2.25 (SD = 5.44) and -2.84 (SD = 8.37), respectively.

Likewise, the estimated dominate substrate within the tetris diagrams were the same between observers for 76% of the surveyed area (Figure 4.7c). 10% of the differences are related to differences in the surveyed area between observers, 9% is due

to Observer 2 selecting substrate smaller than Observer 1, and 5% is due to Observer 2 selecting substrate larger than Observer 1.

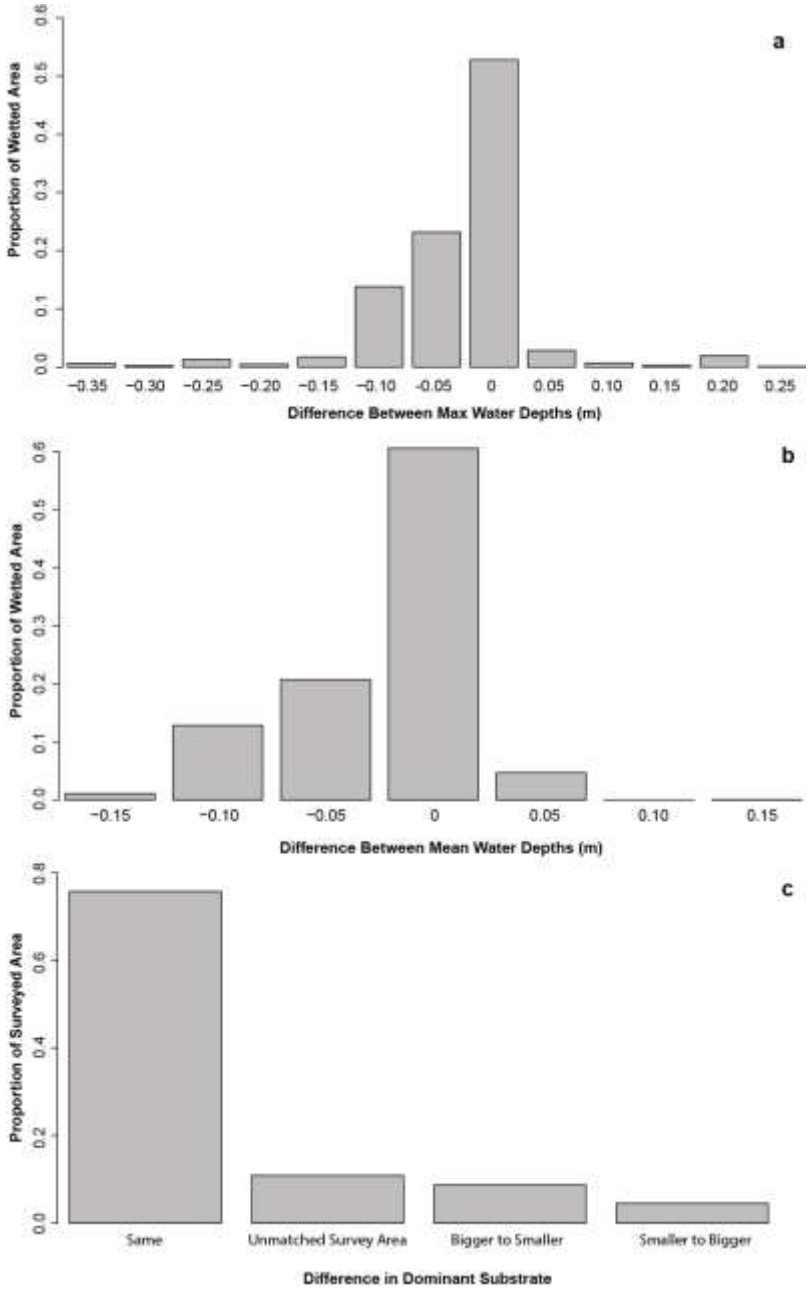

Figure 4.7. Differences in max water depth, mean water depth, and dominant substrate between observers. Differences are calculated by comparing raster cells within each surveyed area around 25 structures.

Intra-Observer Variability – Structure Responses

On average, Observer 1 identified the presence of the same hydraulic and geomorphic responses 92% of the time (Table 4.5). Separately, the presence of hydraulic responses was matched at 95% of structures on average, and geomorphic responses were matched at 90% of structures on average. The least consistent observations were for upstream eddies, deposition upstream, and erosion at the convergent jet (all 80%). All of the unmatched observations appear to be related to inconsistencies in identifying the real responses; however, identifying an upstream eddy is flow dependent. The poorly matched geomorphic responses are difficult to identify or can be easily lumped with a similar response nearby. For example, deposition upstream may be obscured by new vegetation between visits.

The agreement matrices for intra-observer variability in identifying responses are more consistent than those for inter-observer variability. For hydraulic responses, the observer was least consistent in identifying the presence of eddies upstream (Table 4.5). Likewise, the sporadic spread of gray boxes in the agreement matrix for eddies upstream indicates that the response was difficult to consistently identify (Figure 4.8). The consistency in identifying hydraulic responses may be confounded by the timing of each survey. Even though both surveys were completed near base flow, discharge was slightly lower during the October survey; however, leaf debris in the fall decreased the porosity of the structures which may have increased the presence of this response at some structures.

Similar to hydraulic responses, geomorphic responses were more consistently identified by Observer 1 during separate visits than between separate observers. The least

consistently identified geomorphic responses between visits were deposition upstream and erosion of the convergent jet (both at 80%). However, the majority of observations for all geomorphic responses were within one factor level as indicated by the bold lines in Figure 4.9. This indicates that Observer 1 was fairly consistent between visits, but still misidentified the presence and absence of responses at 10% of the structures on average.

Table 4.5. The number of matching presence/absence observations for each hydraulic and geomorphic response at restoration structures and an explanation for non-matching observations. The percent matching indicates the proportion of structures with matching presence/absence values between two different visits made by the same observer (Certain, Probable, or Possible = present; Unsure or Not Present = absent). US = upstream, DS = downstream.

Response	**Response Type**	**Number Matching**	**Number Possible**	**Percent Matching**	**Explanation for Low Matches**
Shunting flow	Hydraulic	24	25	96%	
Splitting flow	Hydraulic	24	25	96%	
Convergent jet	Hydraulic	25	25	100%	
Convergent flow DS	Hydraulic	25	25	100%	
Eddy DS	Hydraulic	24	25	96%	
Eddy US	Hydraulic	20	25	80%	Inconsistent ID of response
Deposition US	Geomorphic	20	25	80%	Inconsistent ID of response
Deposition in wake	Geomorphic	21	25	84%	
Deposition DS	Geomorphic	24	25	96%	
Deposition over bank	Geomorphic	25	25	100%	
Erosion at jet	Geomorphic	20	25	80%	Inconsistent ID of response
Erosion of outer bank	Geomorphic	21	25	84%	
Erosion forming chute	Geomorphic	24	25	96%	
Erosion of bar edge	Geomorphic	25	25	100%	
Erosion by plunge	Geomorphic	22	25	88%	

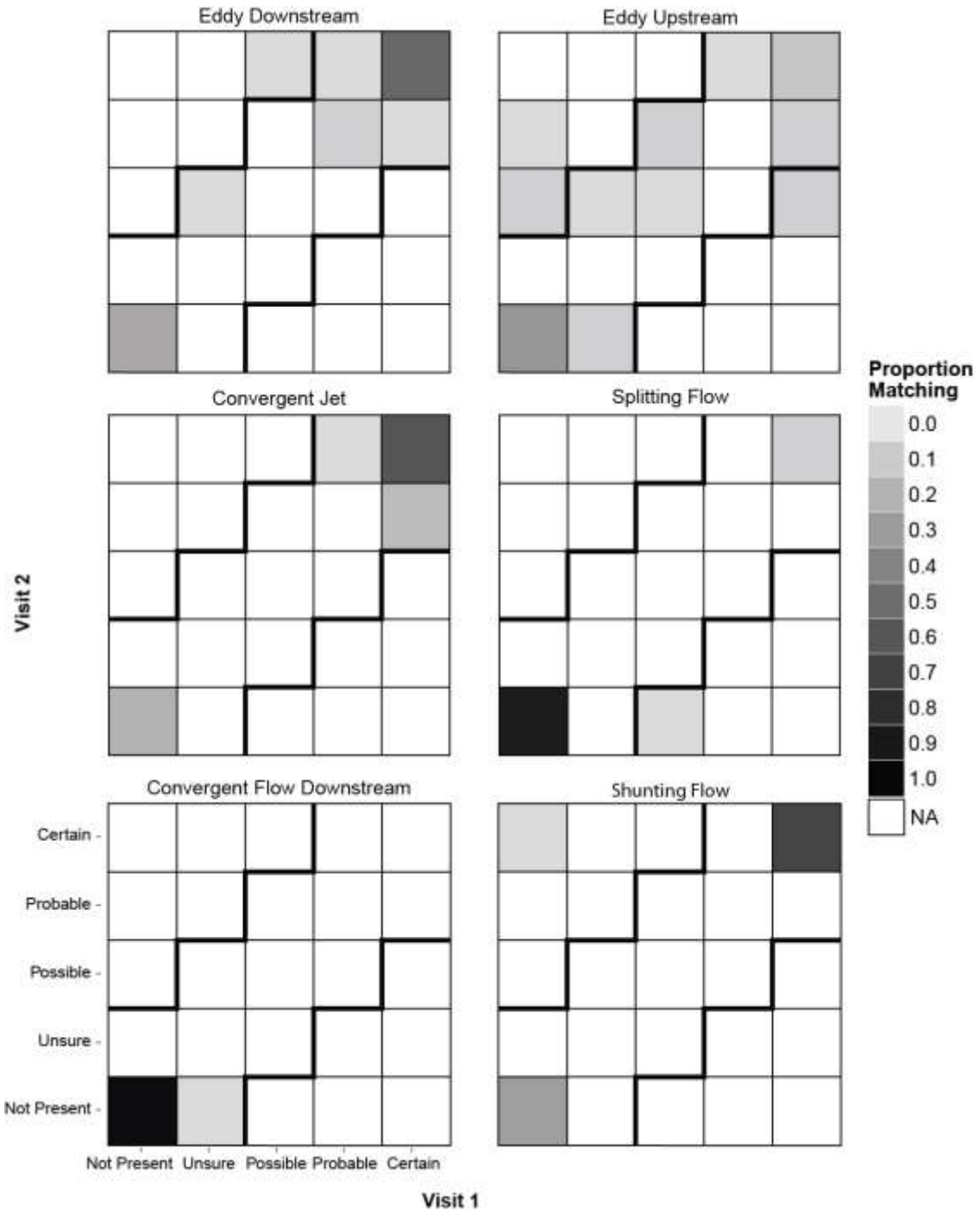

Figure 4.8. Agreement matrices for hydraulic responses comparing observations between two different visits made by the same observer. The bold black line represents a deviation of one factor level between visits.

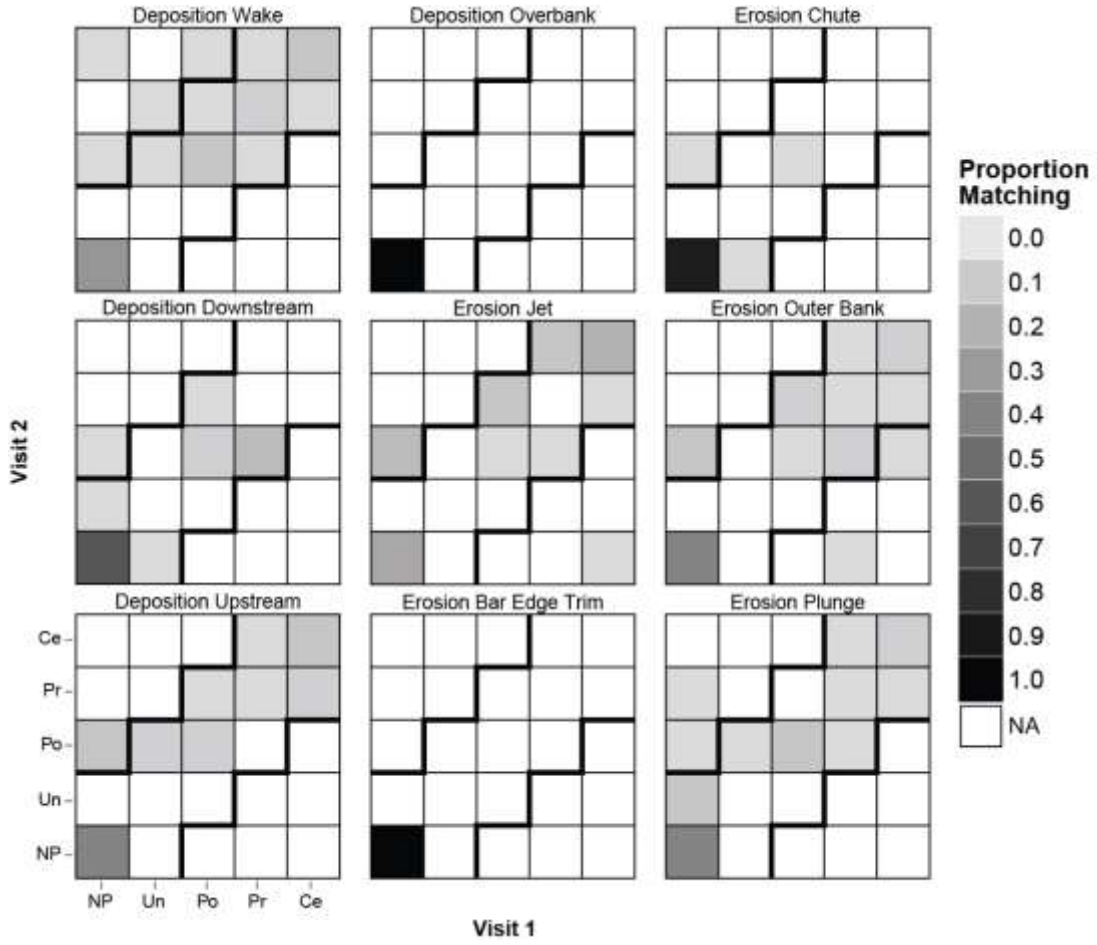

Figure 4.9. Agreement matrices for geomorphic responses comparing observations between two different visits made by the same observer. The bold black line represents a deviation of one factor level between observers.

Intra-Observer Variability – Geomorphic Unit Assemblages

Among the total surveyed area, 86% of the raster cells from the app-generated tetris diagrams matched between visits by Observer 1. Similar to inter-observer variability, the largest reason for mismatched cells was due to a difference in the area surveyed at structures by each observer, equating to 42.7% of all discrepancies (Table 4.6). The largest discrepancies within overlapping survey areas were between planar

features and other tier one units, altogether representing 42.3% of the differences. Most of these discrepancies stem from Observer 1delineating runs on the second visit when they delineated rapids (11.1%) or structurally forced pools (16.6%) on the second visit (Table 4.7). The remaining differences stem from inconsistent selection of tier one units. Again, it is important to note that these discrepancies reflect only the inconstancies in creating an identical tetris diagram between visits by the same observer.

Within the surveyed area, the majority of estimated water depths and dominant substrate were very similar between visits made by the same observer (Figure 4.10). Within the wetted area, 98% and 92% of the differences between mean and max water depth were ±5 cm, respectively (Figure 4.10a & b). The weighted mean differences for mean and max water depths are -0.115 (SD = 4.68) and 0.701 (SD = 9.7), respectively. These mean values for differences in water depth are lower for intra-observer variability than for inter-observer variability. However, the standard deviation is larger for max water depth, suggesting that there was more variability in the depth estimates made by the single observer. The large differences in max depth (>0.25 cm or <-0.25 cm) are related to differences in pool sizes between visits, and are the source of the increase in the data range. Likewise, intra-observer variability is lower than inter-observer variability for estimating the dominant substrate class, resulting in the same estimate for 86% of the surveyed area (Figure 4.10c).

Table 4.6. Differences in tier one geomorphic units assessed by differences in rasters representing geomorphic unit assemblages surrounding structures. The proportion represents the total surveyed area that was different between two different visits by the same user because of the associated difference. Only differences that covered more than 2% of the total area are shown here. The combined total of all other differences are represented as "Other."

Visit 1	**Visit 2**	**Proportion**
Size of Surveyed Area	Size of Surveyed Area	42.7%
Concavity	Planar Feature	18.2%
Planar Feature	Other Planar Feature	12.6%
Planar Feature	Convexity	6.0%
Convexity	Planar Feature	5.5%
Convexity	Other Convexity	4.3%
Planar Feature	Concavity	3.8%
Concavity	Convexity	2.9%
Other	Other	4.0%

Table 4.7. Differences in tier two geomorphic units assessed by differences in rasters representing geomorphic unit assemblages surrounding structures. The proportion represents the total surveyed area that was different between two different visits by the same user because of the associated difference. Only differences that covered more than 1% of the total area are shown here. The combined total of all other differences are represented as "Other."

Visit 1	**Visit 2**	**Proportion**
Size of Surveyed Area	Size of Surveyed Area	42.7%
Forced Pool	Run	16.6%
Rapid	Run	11.1%
Run	Forced Bar	4.0%
Run	Forced Pool	3.5%
Forced Bar	Run	3.2%
Forced Pool	Forced Bar	2.9%
Forced Pool	Plunge Pool	1.7%
Eddy Bar	Forced Bar	1.6%
Alternate Bar	Run	1.5%
Run	Rapid	1.5%
Alternate Bar	Forced Bar	1.3%
Rapid	Forced Bar	1.3%
Other	Other	7.1%

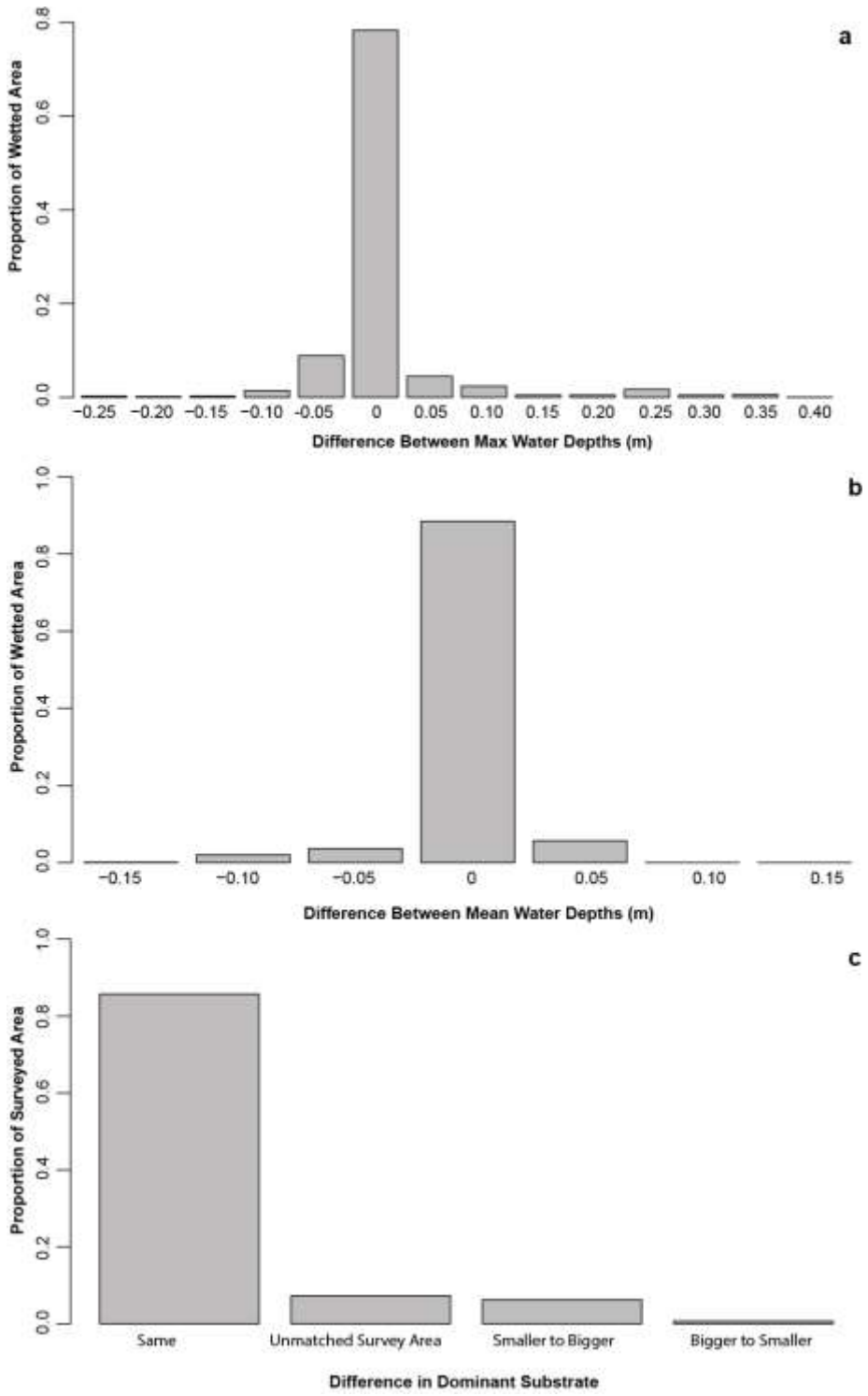

Figure 4.10. Differences in max water depth, mean water depth, and dominant substrate between two different visits made by the same observer. Differences are calculated by comparing raster cells within each surveyed area around 25 structures.

Method Validation – Geomorphic Responses

On average, among 25 structures within the two CHaMP reaches, I was only able to match the presence of 51% of the geomorphic responses between the DoDs and the app. The most consistent matches between methods were for erosion at the convergent jet (71%). However, all of the other responses were matched at >60% of the structures where a response was present. Although there are specific examples where both methods identified the same responses (e.g. structures 74 and 75; Figure 4.11), there appears to be little consistency between the two methods.

Method Validation – Geomorphic Units

There were many significant differences in the proportional areas between geomorphic units derived from topography and tetris diagrams. The total proportional area of concavities was significantly larger in the tetris diagrams (27%) compared to the topographically derived units (18%, $p < 0.0001$; Figure 4.12). The largest difference in concavity area appears to be from a larger proportion of structurally forced pools in the tetris diagrams. However, there were backwaters and dammed pools that were identified in the field, but not in the desktop exercises. Likewise, bar-forced pools and shallow thalwegs were identified in the desktop exercises, but not in the field at these sites. In contrast, convexity area was significantly lower in the tetris diagrams than topographically derived units (9% and 17%, $p < 0.0001$). The only two convexities that were significantly larger in the tetris diagrams were eddy bars and islands, and both were not identified using the topography. Nearly all of the other convexities were significantly smaller in the tetris diagrams, with the largest decreases coming from forced bars and riffles. Riffles were infrequently delineated in the field using the tetris diagrams. Planar

feature area between the two methods was not significantly different (64% and 66%, p = 0.172). However, the proportional areas of rapids and runs were significantly larger and smaller, respectively, in the tetris diagrams. The unit assemblages surrounding structures, however, appear very similar (e.g., Figure 4.13). Therefore, although there are clear inconsistencies in the estimated areas using the tetris diagrams, they appear to create accurate structural representations of the channel.

Figure 4.11. Identification of geomorphic responses using results from a DEM of difference within a reach on the South Fork of Asotin Creek. Elevation differences were calculated from DEMs from 2013 and 2014. US = upstream, DS = downstream.

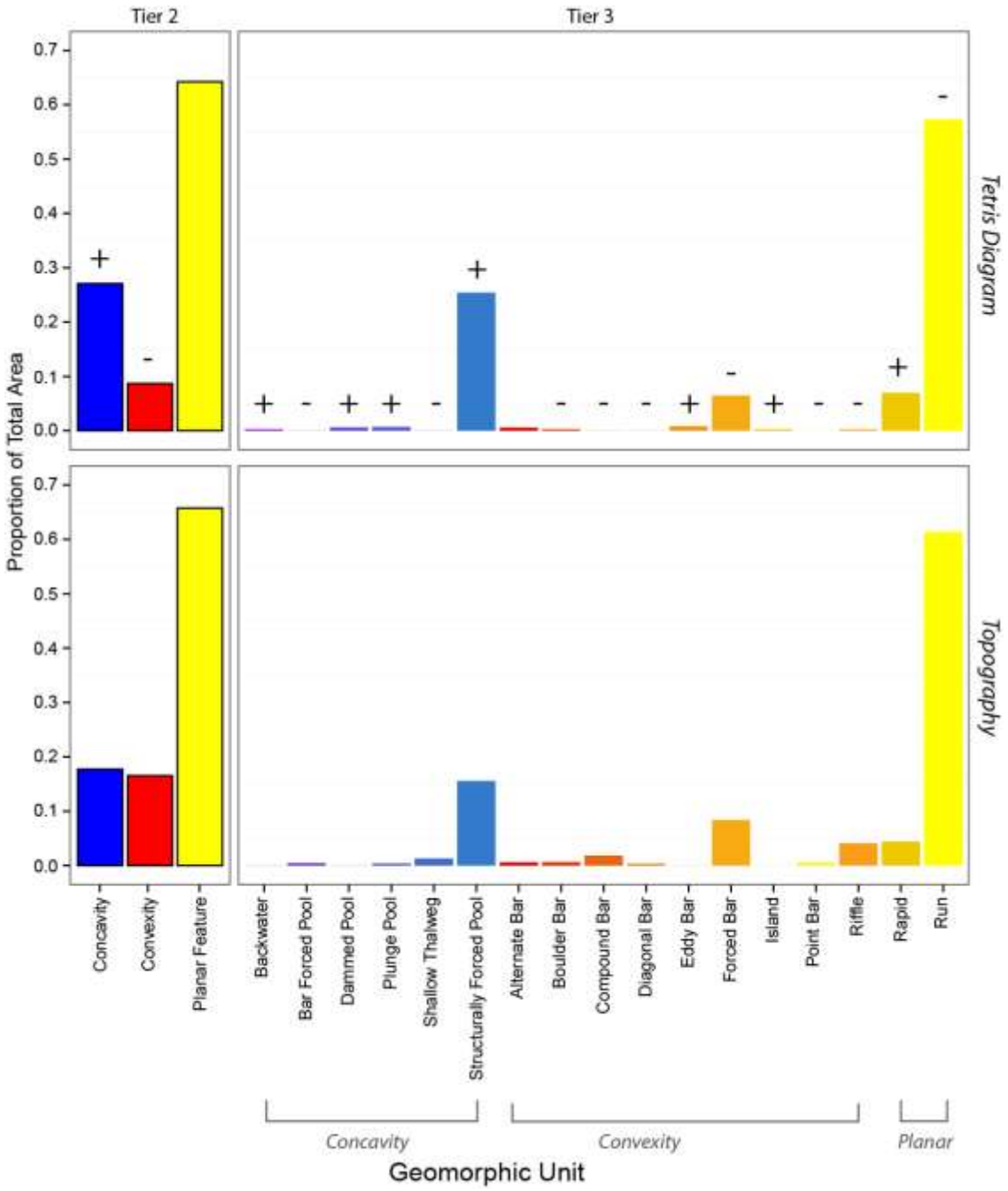

Figure 4.12. Proportion of geomorphic units within surveyed areas around structures within two treatment reaches on the South Fork of Asotin Creek. Units derived in the field using tetris diagrams are shown on the top and units derived from topography using a computer are on the bottom. The direction of significant differences in proportions are shown as plus and minus signs above the tetris diagram bars.

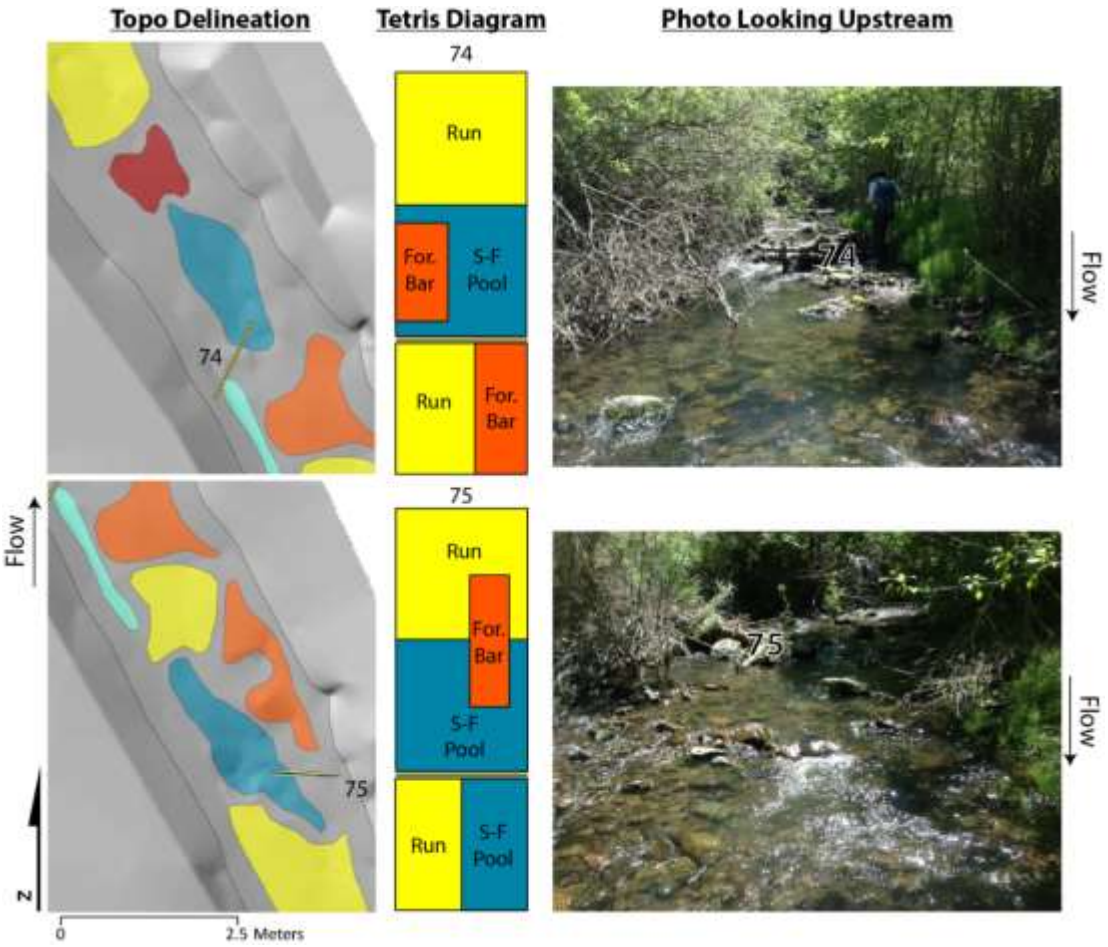

Figure 4.13. Comparison of geomorphic units derived from topography and tetris diagrams of two structures within a treatment reach on the South Fork of Asotin Creek. The photos show the same structures looking upstream. For geomorphic units, yellow = run, dark blue = structurally forced pool (S-F), light blue = shallow thalweg, orange = forced bar, and red = riffle.

DISCUSSION

Using a custom database app to guide users through data collection may increase their ability to collect data consistently and accurately. With only two hours of training, the secondary observer was relatively consistent with the primary observer. However, there is still room for improvement for specific parts of the protocol (in particular,

identifying specific responses), which can likely be mitigated through more thorough training and app development.

Overall, user variability in identifying hydraulic and physical responses appears to be low for the purpose of this particular protocol. The method of allowing the user to select the presence of features and responses using levels of certainty allows for subjectivity. However, in regards to the applicability of this method, we assume that the user is well informed on geomorphic processes, geomorphic units, and the expected responses at structures. Likewise, the major function of this method is to identify year to year changes that may or may not be physically measurable within the error associated with common measurement devices (e.g. fine grain sediment deposits). The most important result of this data is the presence or absence of each feature and response. Therefore, the possibly subjective manor of identifying features and responses is a moot point in reaching our primary goals.

The majority of hydraulic and geomorphic responses were consistently identified between observers. This result is based on the assessment of presence or absence of a response. The few responses that were inconsistently identified are more difficult to differentiate from other landforms in the channel, and their misidentification is likely related to a lack of training. For example, deposition in the wake often occurs near deposition downstream, thus a failure to properly separate these responses will result in an unmatched identification between observers. Likewise, erosion by plunge hydraulics can easily meld into erosion by the convergent jet. These types of mistakes can be easily mitigated through diligent observation by a user with adequate training. This also means providing each user with proper definitions of each response, and expectations on

lumping versus splitting hydraulic and geomorphic properties when identifying responses.

There are, however, differences between observers at individual structures that could affect how we interpret the efficacy of structures at modifying bedform. The majority of the geomorphic unit assemblages at individual structures were at least mostly similar, meaning >75% of the areas within tetris diagrams matched. Many of the discrepancies between observers can also be resolved through adequate training. For example, 21% of the discrepancies were from different delineations of seemingly similar geomorphic units (runs vs. rapids and bars vs. other bars). While the form of a run and rapid are technically different, they can be difficult to differentiate in the field at low flows, and serve similar functions (i.e. sediment transport). Likewise, I expect the user to be able to identify 16 different bars, and the differences in some bars may be subtle. Ultimately, however, bars are all convex bedforms that serve similar functions (i.e. sediment storage).

Discrepancies between unit size and missed units between geomorphic unit assemblages at the structure level is more troubling, however. Estimating unit size based on channel unit widths likely introduces a lot of this variability which can be inferred based on Observer 1 consistently delineating smaller areas than Observer 2. This problem can be alleviated through diligence on the user's part at calibrating their eye with a depth rod or measuring tape prior to starting and during a survey. Regardless, this type of error may not impact the purpose of this method as long as details in geomorphic complexity are not lost or minimized due to a large increase in total area. However, failing to delineate a unit altogether greatly reduces our ability to consistently identify effective

structures. For example 11% of the discrepancies were from pools being delineated by Observer 1 and not Observer 2. One of the expected responses of the structures is the development of pools; therefore, missing these units on any number of structures would be misrepresentative.

The high intra-observer consistency stems largely from quality control and data validation rules that are set within the app. Such quality assurance measures greatly increase the consistency of data because outlying values can be detected during initial data collection [*Camp and Wheaton*, 2014]. Although Observer 1 had substantially more training than Observer 2, the app still provides a guide to keep data collected in a consistent manner. However, there is a lack in consistency between Observer 1 and results from the more vetted methods. The observer consistently underestimated the size of convexities, and overestimated the size of pools compared to the topographically derived channel units. This has obvious implications for a restoration project that is aimed at increasing pool size and density. Based on this study, future improvements of the app protocol will include in-field validation of unit sizes.

Likewise, the most experienced observer did not consistently identify the same geomorphic responses that were present after GCD analysis. However, while GCD has significant promise at improving estimates of sediment flux, the resolution of data from DEMs may be too coarse to be used for verification of this method. CHaMP field crews are trained to survey topographical features and sudden gradient breaks that distinguish landforms [*CHaMP*, 2013], and some of the depositional and erosional responses that we hypothesized sometimes occur at small scales. For example, it is unlikely that a CHaMP crew will notice a relatively small patch of fine sediment near the bank, when their

primary focus is habitat for salmonids. However, in a system such as the South Fork of Asotin Creek, where fine sediment deposits are extremely rare, we key in on those features when they are responses directly related to structure imposition (e.g. deposition upstream). Regardless, the vertical aggradation of such similar deposits may be beyond the certainty bounds of 'real change' when performing GCD analysis. Therefore, elevation differences that may be indicative of the hypothesized responses are removed when thresholding a DoD. Nevertheless, it calls into question the ability of even a veteran observer to consistently identify responses with seemingly explicit definitions. Among future improvements to the app, I will include clear indicators that can help identify responses in the field.

Additionally, the identification of hydraulic responses was not tested in this study. In the future, we plan to use a hydraulic model to simulate flows around structures and compare those results to field-identified hydraulic responses. Likewise, the output of the app can also be used in the program FRAGSTATS to calculate several complexity-related metrics. I did not fully investigate the utility of each metric, but it appears to be a promising and repeatable method for estimating geomorphic complexity at the reach scale (Appendix A).

Ultimately, it may be difficult to make a fair comparison of these two methods. The app relies heavily on expert knowledge and visual indicators in the field to identify responses and delineate geomorphic units. Alternatively, the desktop exercises using topography rely heavily on quantitative measures that sometimes have high uncertainty. Therefore, the desktop exercises leave the user somewhat removed from the real-world area they are studying, and it may be easy to miss indicators that would otherwise be

apparent in the field. That being said, the subjectivity of relying strictly on expert knowledge is not the answer. However, by harnessing the power of mobile electronic devices and mobile database applications, we can begin to put bounds on the uncertainty of this type of data. Likewise, the results from this study will be used to further develop explicit quality control within the app interface.

This study shows promising results for the wide-spread applicability of components of the app for use in restoration or stream habitat monitoring. While the app was customized to suit the objectives of one restoration project, the principal ideas can easily be translated to other projects. The relatively low cost for development of the app and the devices on which it can be deployed is homage to a changing world in the sciences where paper and pencil are becoming obsolete. Similar techniques should be employed by other projects to improve the accuracy and consistency of rapid habitat and restoration surveys.

CHAPTER 5

THESIS CONCLUSION

Traditional stream restoration actions often require heavy machinery to create immediate geomorphic change (digging out pools, constructing side channels, etc). The immediate drawback of this method of restoration is the monetary expense, which greatly limits the scope for many projects. Additionally, these techniques can be temporarily destructive to the riparian vegetation, and have unforeseen consequences [*McMillan and Vidon*, 2014]. We cannot simply call restoration a success by physically altering the channel beyond the capacity of the current boundary conditions (e.g. sediment load, hydrology) without directly targeting the root cause of degradation. We may end up causing more irreversible harm, or the channel may just quickly return to its original degraded state because the initial problem was not addressed. Alternatively, the cheap and cheerful method of restoration I investigated in this thesis is low impact and, in a manner of speaking, gives the river the tools it needs to force geomorphic change within its capacity [*Zeedyk et al.*, 2009; *McMillan and Vidon*, 2014].

My research demonstrates the potential of $_{HD}$LWD and PALS as an effective, low cost alternative to traditional, highly engineered structures. In 2-3 years, concavities increased, convexities nearly doubled, and planar habitats decreased in the study streams after implementing $_{HD}$LWD (Chapter 3). Additionally, the ratio of depositional volume to erosional volume within the treatment areas is 25% higher, suggesting that the treatments support aggradation in the channel. Because many reaches in Asotin Creek have become entrenched over the last 100 years thereby separating many reaches from the floodplain, this increase in aggradation is likely beneficial. Likewise, it reflects that we are disrupting

the previously bimodal residence time distribution of sediment. It supports our postulation that the lack of structural elements in the study streams has exacerbated historic degradation, leading to degrading channels, homogenous substrate patches, and armored beds (Chapter 2). By returning LWD densities to reference levels, creating more temporary storage, sediment sorting and deposition processes are closer to a functional norm. These results are much more evident on the South Fork of Asotin Creek than Charley Creek; however, the structures were installed on the South Fork one year prior to Charley Creek. Additionally, the river style and geomorphic condition of each section controls river behavior, as well as restoration potential (Chapter 2). Therefore, we will continue to monitor these reaches as the Asotin Creek IMW project continues. Likewise, we hypothesized that the short term effects would take 1-5 years to reach full fruition [*Wheaton et al.*, 2012], so we may be just seeing the beginning of the physical effects of $_{HD}$LWD. Long term monitoring is crucial to determining the full efficacy of this restoration technique, and all restoration projects in general [*Roni et al.*, 2008].

Although my work has shown that $_{HD}$LWD is improving geomorphic condition, which presumably improves habitat for juvenile steelhead, we have not yet detected a fish response to the restoration at the watershed scale. [*Johnson et al.*, 2005]) found an increase in winter survival and summer abundance of juvenile steelhead after LWD input. Likewise, LWD forces patches of accumulated gravel that adult fish use for spawning and juveniles use for refuge [*Floyd et al.*, 2009]. However, because freshwater juvenile steelhead populations are also influenced by large-scale processes out of our control, such as migration through the hydrosystem and oceanic conditions [*Bond and Lake*, 2003], it will take time to detect an effect. The growth, survival, abundance, movement, and

production of steelhead will continue to be monitored in the Asotin Creek IMW as $_{HD}$LWD continues to have a physical effect on the channel and instream habitat.

My assessment of the $_{HD}$LWD Effectiveness App demonstrates that we can use the app to rapidly collect consistent and representative data. I was able to survey all 405 structures on the South Fork and Charley Creek in seven days, collecting data directly related to the design hypotheses. The direct identification and tracking of hydraulic and geomorphic responses is essential to understanding the functional behavior of the structures as pools and bars develop (Chapter 4). However, I was able to identify many limitations with the app. Consistency between different users was high; however the non-experienced users received only two hours of training. Therefore, the results in Chapter 4 should be used as the documented testing of the app in its developmental stages. I will use these results to modify the app to include more quality control of the data being collected. Likewise, I will compile examples of visual indicators for each hydraulic and geomorphic response to aid correct identification in the field. While advancements to the app will be beneficial, we must remember to not let the app be a crutch for diligent field work. The crucial modification to the app will be to enhance the reliability of, or quantify the uncertainty in expert knowledge.

In conclusion, $_{HD}$LWD is a promising restoration action and one that should be considered by watershed managers working in streams lacking structural elements such as LWD. The low cost of implementation allows more potential to rehabilitate kilometers of stream instead of meters. We can use the dynamism of streams to our advantage by giving them the tools they need to do geomorphic work. We should move away from highly engineered, static structures that impose strict and unchanging planform,

geomorphic unit assemblages, and are used in limited scope. Likewise, we must pursue monitoring options that are cost and time effective, because every restoration project that goes unmonitored is a lost opportunity. Cheap and cheerful tactics are the future of river restoration.

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APPENDICES

APPENDIX A

Tetris Diagrams and FRAGSTATS: Using Rapid Assessments to Assess Channel Complexity

Research Vignette

NAME: Reid Camp
DATE: August 28, 2014

STUDY SITE(S): South Fork of Asotin Creek
PROJECT: M.S. Thesis

QUESTION / PROBLEM

We developed a custom database application deployable on iOS devices to monitor the efficacy of restoration structures implemented in the Asotin Creek Intensively Monitored Watershed. The app includes a utility to create a spatial representation of geomorphic unit assemblages around structures. We investigated a method leveraging the program FRAGSTATS to quantify complexity of these assemblages.

IDEA / HYPOTHESIS

We installed geomorphic unit assemblages (tetris diagrams) at 196 structures on the South Fork of Asotin Creek and 205 structures on Charley Creek between 2013 and 2014. The data is collected using a mobile database application (app) on a tablet, which converts the tetris diagrams into ASCII rasters in a FRAGSTATS compatible format.

METHODS

During the summers of 2013 and 2014, we visited a combined 401 structures on the South Fork of Asotin Creek and Charley Creek. We identified the geomorphic units within the active channel surrounding each structure. Geomorphic units are bedforms that reflect the processes which determine river structure and function [*Brierley and Fryirs*, 2005]. Although their presence may be inferred through surface hydraulics, they are first and foremost determined by the shape of their bedform. Lengths and widths were measured visually in relative space as a number of channel unit widths. A single channel

unit width is the average width of the active channel within the current reach. For the South Fork of Asotin Creek, this value is about six meters. Therefore, lengths and widths in the rapid assessment approach were measured as the number of six meter lengths that could fit inside the attribute (e.g. if a unit is 12 meters long, the user would record two as the length). We delineated geomorphic units within one channel unit width upstream of the structure and six channel unit widths downstream of the structure (or until the next structure).

To supplement the process-informed delineation of geomorphic units, we also collected each unit's length, width, max depth, average depth, and the dominant substrate size class. In addition, we noted the non-wetted exposure of bars and their level of vegetation. For pool units, we recorded the dominant forcing mechanism and the riffle crest depth instead of the average depth. Each unit is also given a location relative to the structure. The app uses each unit's size and location to compile the units into a single assemblage around the structure that we call a *tetris diagram* (e.g. Figure 1). We exported each tetris diagram from the app as ASCII rasters formatted for the program FRAGSTATS [*McGarigal et al.*, 2002]. FRAGSTATS was originally developed for analyzing spatial patterns within large landscapes by creating adjacency matrices of smaller distinct patches of sub-landscapes. However, the same principles apply to the smaller scale of the tetris diagram. The size and arrangement of each geomorphic unit assemblage are used to create a suite of spatial metrics such as unit area, unit density, unit segregation, assemblage division, and unit diversity (for a full list of the metrics we used and their descriptions, see Table 1).

Table 1. FRAGSTATS metrics used to assess the geomorphic unit assemblages surrounding restoration structures on study streams in the Asotin Creek Intensively Monitored Watershed. In terms of the tetris diagrams, landscape = the whole assemblage, class = aggregation of similar units, patch = single, separate geomorphic unit (adapted from *[*McGarigal et al., *2002]*)

Metric	FRAGSTAT Label	Metric Type	Description	Range	Units
Total Area	TA	Area	TA equals the total area (m^2) of the landscape, divided by 10,000 (to convert to hectares). Note, total landscape area (A) includes any internal background present.	>0	Hectares
Largest Patch Index	LPI	Area	Largest patch index quantifies the percentage of total landscape area comprised by the largest patch. As such, it is a simple measure of dominance.	0-100	Percent
Contagion Index	CONTAG	Aggregation	CONTAG approaches 0 when the patch types are maximally disaggregated (i.e., every cell is a different patch type) and interspersed (equal proportions of all pairwise adjacencies). CONTAG = 100 when all patch types are maximally aggregated. High = few classes; Low = many classes	0-100	Percent
Landscape Division Index	DIVISION	Aggregation	The probability that two randomly chosen pixels in the landscape are not situated in the same patch of the corresponding patch type. =0 when the landscape is a single patch, =1 when the focal patch type consists of a single small patch of one cell.	0-100	Proportion
Number of Patches	NP	Aggregation	Number of patches in the entire landscape	>0	None
Patch Density	PD	Aggregation	Number of patches per 100 hectares in the landscape	>0	#/100 hectares
Patch Richness Density	PRD	Diversity	Standardized measure of patch type richness within the landscape	>0	#/100 hectares
Simpson's Diversity Index	SIDI	Diversity	SIDI is the probability that any two pixels selected at random would be from different patch types.	0-1	None
Simpson's Evenness Index	SIEI	Diversity	SIEI =0 when the landscape contains only 1 patch, =1 when the distribution of area among patch types is perfectly even (i.e. proportional abundances are the same)	0-1	None

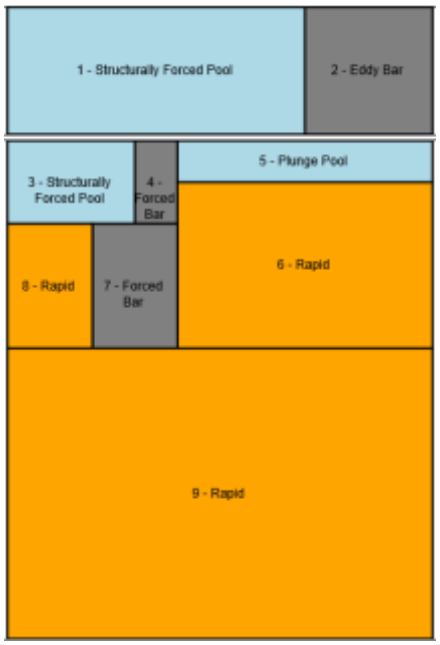

Figure 1. An example tetris diagram showing the geomorphic units surrounding structure 1 on the South Fork of Asotin Creek.

In all practicality, the effectiveness of the structures on Asotin Creek are assessed by the changes that occur over the reach scale. Although we are interested in their condition, longevity, and behavior, the physical responses they impose at the reach scale in concert with each other are likely more relevant to assessing the success of this method as a restoration action. Because we want to assess their cumulative effectiveness, we analyzed geomorphic unit assemblages based on the means of the metrics produced in FRAGSTATS for the 401 structures in this study. This method is a quantitative approach to describing geomorphic complexity and diversity, and therefore a robust measure of habitat complexity. Area metrics within FRAGSTATS are presented as hectares; therefore, we converted the results to square meters for applicability at this smaller scale. We used a two sample t-test to compare the difference in means for each metric between 2013 and 2014 (*Ho:* $p_{2013} = p_{2014}$; *Ha:* $p_{2013} \neq p_{2014}$). We completed the analysis for all

structures, with the exception of the contagion index which requires at least two units in the assemblage. We also separated our analysis by structures that were intact and structures that were not intact in 2014. This method is a quantitative approach to describing geomorphic complexity and diversity, and therefore a robust measure of habitat complexity.

RESULTS

Geomorphic Unit Assemblage Complexity – South Fork

The geomorphic unit assemblages surrounding intact structures on the South Fork of Asotin Creek show deviations towards more complexity. The mean number of units, unit density, unit richness density, and Simpson's diversity index significant increased (Table 2). However, the contagion index significantly increased (although slightly), which suggests that units within the assemblages became more aggregated. The largest unit index decreased which supports the total area remaining the same while the number of units increased. Additionally, there was no significant change in the Simpson's evenness index, suggesting that the proportional abundances of unit types did not change. There were no significant changes in any of the metrics for structures mostly or completely lost to high flows in 2014.

Geomorphic Unit Assemblage Complexity – Charley Creek

The geomorphic unit assemblages surrounding intact structures on Charley Creek showed slight advancement towards more complexity, but do not appear to have changed as much as those on the South Fork. The number of units, unit density, and unit richness density significantly increased between 2013 and 2014 (Table 3). However, the total area surveyed significantly decreased by over 11 m^2. None of the other metrics significantly

changed. Likewise, there were no significant changes in any of the metrics for structures mostly or completely lost to high flows in 2014.

Table 2. Results of student's t-test for complexity metrics based on tetris diagrams of geomorphic unit assemblages surrounding intact structures on the South Fork of Asotin Creek between 2013 and 2014. Bold p-values represent statistically significant differences in the mean of the associated metric.

South Fork of Asotin Creek	INTACT STRUCTURES				
Metric	2013	2014	P value	Direction	N
Total Area (m^2)	105	106	0.796	+	150
Number of Units	2.987	3.780	**<0.001**	+	150
Unit Density (Units/m^2)	0.0247	0.0303	**<0.001**	+	150
Unit Richness (Unit types/100 m^2)	0.0222	0.0258	**0.002**	+	150
Largest Unit Index (% of assemblage)	66.72	61.49	**0.05**	-	150
Contagion Index (% aggregated)	61.24	63.10	**0.045**	+	121
Simpson's Diversity Index	0.375	0.427	**0.041**	+	150
Simpson's Evenness Index	0.583	0.640	0.122	+	150

Table 3. Results of student's t-test for complexity metrics based on tetris diagrams of geomorphic unit assemblages surrounding intact structures on Charley Creek between 2013 and 2014. Bold p-values represent statistically significant differences in the mean of the associated metric.

Charley Creek	INTACT STRUCTURES				
Metrics	2013	2014	P value	Direction	N
Total Area (m^2)	74.63	63.03	**<0.001**	-	178
Number of Units	2.29	2.67	**0.01**	+	178
Unit Density (Units/m^2)	0.029	0.042	**<0.001**	+	178
Unit Richness (Unit types/100 m^2)	0.025	0.036	**<0.001**	+	178
Largest Unit Index (% of assemblage)	76.52	75.99	0.834	-	178
Contagion Index (% aggregated)	62.61	65.07	0.058	+	91
Simpson's Diversity Index	0.255	0.262	0.778	+	178
Simpson's Evenness Index	0.425	0.42	0.898	-	178

PRELIMINARY INTERPRETATIONS

For structures that remained intact, geomorphic diversity increased between 2013 and 2014. The significant increase in the number of units and unit richness density suggest that the geomorphology surrounding structures has become more diverse. Changes in the bedform can be linked to changes in hydraulics (concavities = slow deep water, planar features = faster, shallow water). The availability of variable habitat has been linked to higher salmonid densities and biomass [*Lonzarich and Quinn*, 1995; *Bayley*, 2002; *Whiteway et al.*, 2010]. However, it is important to understand what geomorphological shifts are occurring. For example, while we can say that the number of units in an assemblage significantly increased, we don't know what unit transitions occurred. We do have the data to further explore whether or not FRAGSTATS can be leveraged to meet this goal. Likewise, the FRAGSTATS documentation includes the calculations used to create each metric, so it is feasible to explore the utility of different spatial analysis software.

However, any utility in deriving this metrics using tetris diagrams will come from finding a relationship between the metrics and fish species. Metrics, like unit density and Simpson's diversity index may be good proxies for habitat complexity, but that is outside the scope of this vignette. Additionally, we do not expect that any one of these metrics will be the wholesale answer to linking habitat complexity and fish; however, this method may be an efficient way to unlock one piece of that puzzle.

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APPENDIX B

Table 1. Full descriptions and suggested indicators of the hypothesized hydraulic and geomorphic responses used in the HDLWD Effectiveness App and Asotin Creek IMW restoration design.

Response Type	Label	Description on App	Hypothesis Tested	Long Description - Bank PALS	Long Description - Mid PALS	Long Description – Debris Jam
Hydraulic	1	Shunting Flow	A, D, P	Flow is being shunted laterally across the upstream side of the structure		Flow is being shunted vertically underneath the structure
Hydraulic	2	Splitting Flow	A, D, P		Flow is being split laterally around both sides of the structure	Flow is being split laterally around both sides of the structure
Hydraulic	3	Convergent Jet DS	A, D, P	Flow is strongly converging near the end of the structure furthest from the bank	Flow is strongly converging on either side of the structure	Flow is strongly converging vertically underneath the structure
Hydraulic	4	Eddy DS	B, D, H, P	Flow is circulating directly downstream of the structure near the bank	Flow is circulating directly downstream of the structure in the middle of the stream	Flow is circulating directly downstream of the structure
Hydraulic	5	Eddy US	D	Flow is backed up and circulating directly upstream of the structure near the bank	Flow is backed up and circulating directly upstream of the structure in the middle of the stream	Flow is backed up and circulating directly upstream of the structure
Hydraulic	6	Divergent Flow DS	C, D	Flow is diverging laterally away from the convergent jet downstream of the convergent jet caused by the structure	Flow is diverging laterally away from the convergent jet downstream of the convergent jet caused by the structure	Flow is diverging laterally away from the convergent jet downstream of the convergent jet caused by the structure
Hydraulic	7	Convergent Flow DS	J, M	Flow is strongly converging downstream of deposition (J) as a result of the divergent flow directly upstream (F)	Flow is strongly converging downstream of deposition (J) as a result of the divergent flow directly upstream (F)	Flow is strongly converging downstream of deposition as a result of the divergent flow directly upstream (F)

Table 1. Continued

Response Type	Label	Description on App	Hypothesis Tested	Long Description - Bank PALS	Long Description - Mid PALS	Long Description – Debris Jam
Geomorphic	8	Deposition US	H, M	Deposition directly upstream of the structure near the bank	Deposition directly upstream of the structure in the middle of the stream	Deposition directly upstream of the structure near the bank
Geomorphic	9	Deposition Wake	H, M	Deposition directly downstream of the structure near the bank resulting from an eddy or plunge pool	Deposition directly downstream of the structure in the middle of the stream resulting from an eddy or plunge pool	Deposition directly downstream of the structure near the bank resulting from an eddy or plunge pool
Geomorphic	10	Deposition DS	I, M	Deposition downstream of the convergent jet, associated with divergent flow downstream of structure (F)	Deposition downstream of the convergent jet, associated with divergent flow downstream of structure (F)	Deposition downstream of the convergent jet, associated with divergent flow downstream of structure (F)
Geomorphic	11	Deposition Overbank	K, G	Deposition outside of the active channel upstream or downstream of the structure	Deposition outside of the active channel downstream of the structure	Deposition outside of the active channel upstream or downstream of the structure
Geomorphic	12	Erosion Convergent Jet	F, M	Bed erosion forced by the convergent jet (C) directly downstream of the structure off the end furthest from the bank	Bed erosion forced by the convergent jet (C) directly downstream of the structure on either side	Bed erosion forced by the convergent jet (C) directly downstream of the structure in the middle of the stream

Table 1. Continued

Response Type	Label	Description on App	Hypothesis Tested	Long Description - Bank PALS	Long Description - Mid PALS	Long Description – Debris Jam
Geomorphic	13	Erosion Outer Bank	K, G	Bank erosion forced by the convergent jet (C) directly downstream of the structure off the end furthest from the bank	Bank erosion forced by the convergent jet (C) directly downstream of the structure on either side	Bank erosion forced by flow divergence around the sides of the structure during very high flows
Geomorphic	14	Erosion Chute	J, M	Bed erosion forced by the convergent flow downstream of the structure (F)	Bed erosion forced by the convergent flow downstream of the structure (F)	Bed erosion forced by the convergent flow downstream of the structure (F)
Geomorphic	15	Erosion Bar Edge Trim	N	Erosion of the edge of downstream deposition (J)	Erosion of the edge of downstream deposition (J)	Erosion of the edge of downstream deposition (J)
Geomorphic	16	Erosion Plunge	M, N	Erosion directly downstream of the structure forced at high flows by water pouring over the top of the structure	Erosion directly downstream of the structure forced at high flows by water pouring over the top of the structure	Erosion directly downstream of the structure forced at high flows by water pouring over the top of the structure

Table 2. Additional observations made at individual restoration structures during annual visits.

Variable	Description	Levels
Structure Integrity	The physical condition of the structure. This will change as the structure loses wood or posts	Completely Intact; Mostly Intact; Partly Intact; Completely Gone
Porosity	The general amount of openings between the materials making up the structure	Mostly Porous; Partly Porous, Not Porous; Undetermined
Posts Remaining	The number of posts remaining at a structure	0; 1-2; 3-4; 5-6; 7-8; 9-10; >10
Post Integrity	The physical condition of the posts	Mostly Solid; Mix Solid/Loose; Mostly Loose; Mostly Broken
Width Constriction	Percentage of the channel that is constricted by the structure	100%; 90-100%; 80-90%; 70-80%; 60-70%; 50-60%; 40-50%; 30-40%; 20-30%; 10-20%; 0-10%
LWD Accumulation	Certainty that large woody debris has accumulated on the structure	Certain; Probable; Possible; Unsure; Not Present
SWD Accumulation	Certainty that small woody debris has accumulated on the structure	Certain; Probable; Possible; Unsure; Not Present
MinZOI_DS	The minimum distance downstream that the structure is physically influencing in channel unit widths	0; 0.5; 1.0; 1.5; 2.0; ...
MaxZOI_DS	The maximum distance downstream that the structure is physically influencing in-channel unit widths	0; 0.5; 1.0; 1.5; 2.0; ...
MinZOI_US	The minimum distance upstream that the structure is physically influencing in-channel unit widths	0; 0.5; 1.0; 1.5; 2.0; ...
MaxZOI_US	The maximum distance upstream that the structure is physically influencing in-channel unit widths	0; 0.5; 1.0; 1.5; 2.0; ...