The Influence of Precipitation Phase on Hydrograph Form:

An Investigation of Twelve Tributaries to the Salmon River, Idaho

by

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A thesis submitted in partial fulfillment

of the requirements for the degree of

Masters of Science in Geology

Idaho State University

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June 2011

To the Graduate Faculty:

The members of the committee appointed to examine the thesis of CHRISTOPHER J. TENNANT find it satisfactory and recommend that it be accepted.

Dr. Benjamin T. Crosby, Major Advisor

Dr. Glenn D. Thackray, Committee member

Dr. John A. Welhan, Committee member

Dr. Colden V. Baxter, Graduate Faculty Representative

Acknowledgements

The conception, inception and completion of a thesis are an epic odyssey. To walk this perilous, toilsome, and convoluted path I have had to lean on many fellow sojourners. Those of scientific and technical tact have been of the upmost assistance in their brilliant advice and insight. These tacticians include the following, Benjamin T. Crosby, my main man and advisor from the beginning to the end. Ben is extremely intelligent and has provided thoughtful insights and practical advice into the work presented here. Colden V. Baxter, my graduate faculty representative, has been much more than representative. Colden has added knowledgeable contributions to the experimental design of my project and has opened an entirely new world unto the limited scope of my eyes, the world of life in lotic waters. Glenn D. Thackray, a man prone to cogitate on and likely not to commit one of the top seven mistakes of tea drinking has provided just these assets. Glen and I have shared many good musings over intriguing scientific ideas while enjoying a tasty cup of *Camellia Sinensis*. Finally, John A. Welhan, a wizard of a statistician, has been quite successful in confusing me, enlightening me and then confusing me again and after this mandatory iterative process, enlightening me once more. Much gratitude and acknowledgement are extended to these four people. In addition, I would like to extend my sincere appreciation to the National Science Foundation and the Experimental Program to Stimulate Competitive Research (EPSCoR), which has funded this project (EPS-0814387). To conclude my scientific acknowledgements I must also thank my fellow students, many of whom have been excellent sounding boards and also advisories when my scientific thoughts run afoul.

My greatest acknowledgements are extended to the non-scientific members in my life. Renee and Jude Tennant are the dearest people in my life and mean more to me than anything else. I love both of you very much. I would also like to thank my parents and my brother. You all have been instrumental in shaping me into the person I am today and I extend sincere thanks to all.

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The Influence of Precipitation Phase on Hydrograph Form: An Investigation of Twelve Tributaries to the Salmon River, Idaho, USA

Abstract

Large relief contributes to heterogeneity in the meteorological and hydrologic conditions of mountainous watersheds. In effort to elucidate some of the causes of this complexity we examined the influence of precipitation phase on hydrograph form in twelve tributaries to the Salmon River using an experimental streamflow gaging network that isolated tributaries bounded within distinct elevation ranges. These tributaries are characterized as rain dominated, mixed rain and snow and snow dominated and respectively received the following percentages of rainfall to snowfall between 2003 and 2010: 80:20, 60:40 and 25:75. Streamflow records for two water years provides evidence that differences in precipitation phase causes differences in the magnitude, duration, and timing of hydrologic events. Rain dominated watersheds are contained within low elevations (~ 500-1500 m) and experienced hydrologic events throughout winter and spring months. Their peak, median and baseflow yields were much lower than mixed and snow dominated streams. Mixed rain and snow watersheds are bounded within mid elevations (~ 1500-2500 m) and experienced longer duration hydrologic events of greater magnitude than rain dominated watersheds and exhibited greater peak, median and baseflow yields. Hydrologic events in mixed rain and snow watersheds occurred during early spring and summer. High elevation, snow dominated watersheds (~ 2250-3250 m) had the longest duration and highest magnitude hydrologic events, exhibited peak, median and baseflow yields that were greater than rain dominated and mixed rain and snow watersheds. Melt events in snow dominated watersheds occurred during late spring and early summer. Results from this study demonstrate that high elevation regions yield the greatest volumes of water and that the timing, magnitude and duration of hydrologic events vary considerable across a large elevation range. These findings have important implications for understanding how climate change may alter the frequency and timing of hydrologic events and the availability of water in mountainous catchments throughout the intermountain west. By understanding these heterogeneous sources, we can make stronger predictions about how they are integrated along trunk and mainstem reaches, ultimately affecting aquatic habitat, recreation industries and downstream hydropower production.

Chapter 1: Introduction

1.1 Motivation

There is a growing scientific consensus that human activities are impacting Earth's climate. Work from many researchers clearly demonstrates a concurrent increase in air temperature with the onset of industrialization and anthropogenic production of greenhouse gases such as CO_2 (Keeling et al., 2001, Jones and Mann, 2004, IPCC, 2007, Solomon et al., 2007, Mann et al., 2009). The realization that air temperatures are warming at unprecedented rates and are likely to continue to rise for an unknown period of time has invigorated many members of the scientific community to question the predictability of future conditions. How will changes in air temperatures affect global and regional climate? In turn, how will changes in climate affect the distribution, availability, and sustainability of water resources? Also, if we know that climate drives hydrologic and geomorphic systems how will these systems be altered as temperatures change and landscapes respond?

To help provide answers to these questions we investigated how precipitation phase (rain versus snow) affects hydrograph form and from this infer how climate change could alter hydrologic processes in the Salmon River basin, central Idaho. Specifically, we documented the hydrologic and meteorological characteristics of twelve tributaries to the Salmon River. These catchments are contained within distinct elevation ranges and are subdivided into low, mid, and high elevation zones. These designations are selected based on the hypothesis that low elevation zones are dominated by rainfall, mid-elevations by rain and snow and high elevations are snow dominated. We employed a mixture of field and remote sensing techniques to answer the following questions: 1)

How variable is the amount and phase of precipitation across a large elevation range? 2) If the amount and phase of precipitation vary with elevation, are there significant differences in the seasonality, magnitude, frequency, and duration of hydrologic events and overall streamflow patterns in different precipitation regimes? 3) Can we use observations characterizing diverse hydrologic regimes contained within large mountainous catchments to increase our predictive power of the potential influence of warming temperatures on hydrograph form?

By answering these questions we generate predictive power for understanding how climate change will affect streamflow characteristics. The results of our investigation provide strategic information for water resource managers throughout central Idaho and much of the western U.S. Because the biotic and abiotic components of river systems are inexorably linked to the hydrologic characteristics of a region our work also contributes to the fields of stream ecology and fluvial geomorphology.

1.2 Background

Mountain snowpack is a vital source of water for much of the world. Barnett et al. (2005) estimated that approximately one sixth of the world’s population (~ 1 billion individuals) depend on mountain snowpack for sustained water availability. In areas like the western U.S. and other similar regions throughout the world, the majority of inhabitants live in arid lowlands that rely on snowfall in neighboring areas of high elevation for sustainable water sources. As a consequence, reductions in mountain snowpack and changes in the timing of water delivery to channels are a major concern.

1.2.1 Past Climate and Hydrology

It has long been realized that mountainous landscapes function as a reservoir for water storage during winter months (Dunne and Leopold, 1978). Dai (2008) has demonstrated that temperatures below, at or near freezing (-2 ^{o}C to 4 ^{o}C), will result in solid phase precipitation. This temperature range describes typical wintertime conditions for many mountainous catchments in the western U.S. (Serreze et al., 2000). In snow dominated watersheds, streamflow traditionally peaks in late spring and early summer and sustains water availability through the drier portions of the year when little precipitation falls. However, recent trends (1949 - 2004) demonstrate that mean daily minimum temperatures have increased by 3^{o}C throughout the West and that approximately seventy-five percent of western SNOTEL stations have experienced decreases in snow water equivalent (Knowles et al., 2006).

Fluctuations in spring and winter climate (Cayan et al., 2001) have caused direct and observable changes to the hydrologic cycle. For example, Clark (2010) demonstrated that many of the unregulated watersheds in Idaho, western Wyoming, and northern Nevada have experienced decreases in annual mean and minimum streamflow and that the 25th and 50th percentile of flow are both occurring around twelve days earlier. Luce and Holden (2009) revealed similar trends for streams throughout the Pacific Northwest and show that the driest 25 % of years between 1948 and 2006 are becoming significantly drier. In addition to reductions in streamflow volume, numerous studies indicate earlier peakflow and timing of median streamflow (Regonda et al., 2004; Stewart et al., 2005, Stewart, 2009). Trends of reduced and earlier streamflow are reported by a greater number of researchers and are of great concern for people residing in arid regions that receive water from snowpack.

Problems with changes in the amount and timing of water delivery are amplified by connections between the hydrologic cycle and numerous physical systems. Westerling et al. (2006) demonstrated that there has been an increase in western U.S. wildfire activity associated with increased spring and winter temperatures and earlier snowmelt. In addition, climatic changes have led to alterations in riparian vegetation, stream temperature, species diversity and the overall functionality of aquatic and terrestrial ecosystems (Hauer, 1997; Vitousek, 1994). These observations coupled with the predictions of warmer future temperatures (IPCC, 2007) have spurred many questions. In particular, we ask, how will future climate change affect the hydrologic cycle and the critical ecosystems that it supports?

1.2.2 Future Climate and Hydrology

There is extensive debate about how much temperatures will warm in the future. However, nearly all models, which generate predictions based on different anthropogenic scenarios, indicate that temperatures will warm. The degree of warming depends on the scenario. If there is low population growth and a decrease in greenhouse gas emissions it is suggested that temperatures may rise in the range of 1 ^{o}C to 2 ^{o}C by 2100 (low growth (B1) scenario IPCC, 2007). If population growth is high and there is little reduction in greenhouse gas emissions then temperatures may increase as much as 4 ^{o}C by 2100 (high growth (A2) IPCC, 2007). Downscaled scenarios for the Pacific Northwest and the state of Idaho suggest similar ranges of warming (Hamlet et al., 2010; Moore and Von Waldon, 2009). While temperatures are expected to increase nearly everywhere, the patterns of precipitation changes are much less predictable. It is suggested that some areas will experience an increase in precipitation, while others are predicted to receive less precipitation (Hoerling et al., 2010). Motivated by these predictions, researchers use hydrologic models with various temperature and precipitation scenarios in effort to understand how climate change will affect streamflow characteristics.

Not surprisingly, model predictions for rivers in the western U.S. suggest that the timing of delivery of the median percentile of streamflow will occur earlier in the year (Elsner et al., 2010) In more aggressive warming scenarios, the median percentile of streamflow could occur as much as two months earlier (Rauscher et al., 2008). Warmer temperatures will not only change the timing of water delivery but also alter hydrograph form and pattern. Elsner et al. (2010) use the Variable Infiltration Capacity (VIC) model to suggest that mid-elevation, transient rain snow watersheds will likely experience reduced peak flows and exhibit characteristics similar to rain dominated systems. Furthermore, they suggest that snow dominated watersheds will experience decreases in spring runoff and that snowmelt will occur earlier in the season. In the state of Idaho, Tang et al. (in prep.) used VIC to explore how flows within the Salmon River, a relatively pristine mountainous basin, will change with warmer temperatures. Their findings suggest that there will be an increase in wintertime flows and reductions in spring and annual flows. These projections hold serious ramifications for hydrologic systems and spur the need for more research into how hydrologic systems will respond as temperatures warm.

1.3 Project Scope

This project has been supported by Idaho NSF EPSCoR award (EPS-0814387). This grant is a long term award (5 years) and focuses on Water Resources in a Changing Climate (WRCC). The WRCC program is subdivided into three research themes, hydro-climatology, hydro-economics/policy, and hydro-ecology. These subgroups work within the Snake and Salmon River basins and investigate the potential effects of climate change on Idaho's hydrology. The Snake River watershed is a highly managed river that has been dramatically influenced by human activity. In contrast, the Salmon River basin is highly pristine and primarily unaffected by direct human action. These river systems offer complementary, yet unique vantages that will provide key insights to how climate change will affect hydrologic resources for much of the western U.S.

Our work within the Salmon River, which has been directly coupled with efforts of the Idaho State University Stream Ecology Center, contributes directly to the hydro-ecology discipline. It is the responsibility of the hydro-ecology subgroup to compile legacy datasets that reveal long-term physical and ecological change and to generate predictions about how climate change will affect biotic and abiotic aspects of river systems. Within this context, there are three questions that the hydro-ecology discipline addresses: 1) what are the historical relationships among climate, hydrology, geomorphic conditions, and ecology in the Salmon River? 2) How do current ecological conditions in the Salmon River compare with the past? 3) Can observed changes in hydrology, geomorphology, disturbances (fire, insects) and ecological health be attributed to changes in climate? 4) If so, can accurate predictions of future changes in ecological conditions be made for the next century?

By generating observations of tributaries bounded within distinct elevation zones that collectively span a large elevation range, our study sites differ in their hydrologic, ecologic and geomorphic characteristics. This type of experimental design, which observes distinct spatial domains, grants insights into the potential hydrologic changes that mid and high elevations could experience if snowlines rise in elevation. The low elevation rain dominated watersheds we study provide an analogue for the potential hydrologic and ecological conditions that the higher elevation mixed rain and snow and snow dominated watersheds may someday experience. The current conditions of mixed rain and snow watersheds may reflect the characteristics of what lower elevation; rain-dominated watersheds were like when snowlines were lower. This study contributes information regarding both the past and potential future hydrologic and ecological conditions within the Salmon River basin.

1.4 Setting

The Salmon River basin (Ch. 2, Figure 1) was chosen for study because of its high relief and relatively pristine nature. The basin has more than 3000 m of relief and spans temperature conditions that result in regions that are: rain dominated (low elevations), experience rain and snow (mid elevations) and are snow dominated (high elevations). Study sites are bounded within elevation ranges that correspond to the precipitation regimes described above. Four study catchments were selected from each precipitation regime.

An additional benefit of the Salmon River basin is its low population density and lack of any major diversions or impediments of water. This characteristic allows observations of the natural routing of water in tributaries that experience different proportions of rain and snow to be documented. These observations can be used to infer the potential effects that warmer temperatures may have on hydrologic regimes within different portions of the basin. These inferences are complicated by differences in physiographic characteristics of the three precipitation regimes (i.e. lithology, vegetation, precipitation patterns, etc). Specific characteristics of the watersheds are provided in Ch. 2, Table 1.

1.5 Key Findings

The results from our study demonstrate that differences in precipitation phase result in unique hydrologic characteristics for tributaries bounded within different elevation zones. Hydrographs from rain dominated, mixed rain and snow, and snow dominated watersheds exhibited differences in the magnitude, duration, intensity and seasonality of snowmelt and precipitation events and streamflow patterns.

Meteorological records (2003 - 2010) for rain dominated watersheds indicate that 80 % of the total precipitation fell as rain and 20 % as snow (all subsequent rain to snow ratios reflect precipitation observations from 2003 - 2010). Snow accumulation was minimal and short lived in these watersheds. Meteorological and streamflow observations from rain dominated watersheds suggest that rain on snow events or rain during times of high antecedent moisture conditions due to melt events associated with the transient snowpack in these elevations is common and capable of producing frequent flood events during the winter and spring seasons. In addition, streamflow in these catchments exhibited low peak, median and baseflow yields compared to mixed rain and snow and snow dominated catchments.

Mixed rain and snow watersheds are contained within mid elevations and received 40 % of their total precipitation as rain and 60 % as snow. These watersheds exhibited the greatest year-to-year variability in proportions of precipitation phase. Peak, median and baseflow yields in mixed rain and snow watersheds were greater than in rain dominated watersheds. Hydrologic events within these watersheds were dominantly associated with spring snowmelt events. In addition, there were rain events that occurred during late winter/early spring and throughout the runoff season. Some rainfall events in these mixed rain and snow watersheds were intense and contributed significant volumes of water to these catchments. It is important to note that a portion of these events were rain on snow events, which can lead to rapid melting of snowpack and flash flooding. Rain on snow events and warmer temperatures earlier in the spring caused greater complexity in spring runoff patterns in mixed catchments than in snow dominated ones.

Snow dominated watersheds are bounded within high elevations and experienced 70% of their precipitation as snow and 30 % as rain. As a result, snowpack accumulated to greater depths and persisted longer than in mixed rain and snow or rain dominated watersheds. During fall and winter months snow dominated watersheds were at or near baseflow. These conditions were punctuated by spring runoff when hydrographs exhibited long rising and falling limbs and peak discharges that were at or near bankfull. Hydrologic events, which were almost uniquely driven by snowmelt, were longer in duration and greater in magnitude than events in mixed rain and snow and rain dominated watersheds. Exceedance probability plots of streamflow from snow dominated streams demonstrate that peak, median and baseflow yields were greatest in these catchments.

1.6 Thesis Structure

There are three chapters that are presented in this thesis. This chapter serves as a general overview and presents the project motivation, a review of related literature, the study setting and key findings. The second chapter is the core of the thesis and is presented as a standalone paper intended for publication. The last chapter serves as a brief discussion of future directions within this research project and offers general suggestions for the fields of hydro-climatology and hydro-ecology.

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Chapter 2: The Influence of Precipitation Phase on Hydrograph Form and Streamflow Characteristics

2.1 Abstract

Mountainous watersheds are characterized by large relief, non-uniform elevation distributions and exhibit basin wide variations in aspect, vegetative cover, and land use. This topographic complexity leads to diverse atmospheric conditions and differences in precipitation phase over small spatial scales that cause heterogeneity in hydrologic processes. To help elucidate these complexities and to answer how do differences in precipitation phase influence hydrograph form and streamflow patterns, we characterized the precipitation and hydrologic regimes of twelve tributaries to the Salmon River, Idaho. Study sites are bounded within distinct elevation zones that result in precipitation regimes that are classified as rain dominated, mixed rain and snow and snow dominated.

The rain dominated watershed are contained within low elevations and annually receive 473 mm of precipitation; on average 80 % of precipitation falls as rain and 20 % as snow. Snow accumulations were minimal and of short duration. Streamflow patterns for the 2009 and 2010 water years exhibited low peak, median and baseflow yields compared to mixed and snow dominated watersheds. In addition, rainfall and snowmelt events occurred earlier in the year and were of short duration and low magnitude. Rain dominated watersheds had the highest probability of going dry.

Watersheds with mixed rain and snow precipitation are bounded within mid-elevations and experience an average of 862 mm of annual precipitation, 40 % as rain and 60 % as snow. These watersheds exhibited the greatest variability in precipitation phase yet received enough snowfall to accumulate significant snowpack. Streamflow in mixed

rain and snow watersheds exhibited greater peak, median and baseflow yields than rain dominated watersheds. Precipitation and melt events occurred in mixed rain and snow watersheds during early spring and summer and resulted in hydrologic events that were longer in duration and greater in magnitude than any events in the rain dominated watersheds. Snowmelt runoff exhibited the greatest complexity in mixed rain and snow watersheds because of a high number of rain-on-snow and snowmelt events that occurred throughout the spring season.

Snow dominated watersheds are contained within high elevations and receive 984 mm of mean annual precipitation; 30 % as rainfall and 70 % as snowfall. Because of higher amounts of precipitation and snow accumulation, peak, median and baseflow yields were typically greatest in snow dominated catchments and snowmelt events were of longer duration, higher magnitude and occurred later in the year than in mixed or rain dominated watersheds. Observations from this study demonstrate that the overall streamflow patterns and the timing, duration, and magnitude of hydrologic events can vary predictably within mountainous watersheds depending on the phase of the dominant precipitation. These findings hold important implications for understanding how climate change could alter the biotic and abiotic components of fluvial systems.

2.2 Introduction

2.2.1 Motivation

Mountainous catchments have large relief with non-uniform elevation distributions and exhibit complex topography. Variations in the range and distribution of elevations and other characteristics such as aspect, land cover and proximity to storm source exert a strong influence on the meteorological characteristics of these regions. Studies characterizing terrain with diverse elevation distributions demonstrate that air temperatures exhibit complex temporal and spatial variability (Chung et al., 2006; Blanford et al., 2008; Holden et al., 2011). As a consequence, the meteorological characteristics of mountainous catchments can be quite diverse. The phase and volume of precipitation received can differ substantially from low to high elevations and can cause differences in the timing, magnitude, duration, frequency, and overall pattern of streamflow characteristics. These variations complicate our understanding of how future increases in air temperature could affect hydrologic resources that have direct ties to anthropogenic and ecological systems.

2.2.2 Previous Work

The evidence that temperatures in western North America are warming is extensive (Barnett et al., 2005; Hamlet, 2007; Mote, 2006, Westerling et al, 2006). As such, a profusion of studies have documented how climate change is impacting the hydrologic cycle. In the western U.S. researchers have explored dynamics of spring snowpack (Barnett et al., 2008; Mote et al, 2005; Bedford and Douglass, 2008), changes in the timing and magnitude of peak, quartile, and mean annual flows (Hamlet and Lettenmaier, 2007; Luce and Holoden, 2009; Stewart et al., 2005), as well as changes in the ratio of solid to liquid precipitation falling during winter months (Knowles et al., 2006). These studies demonstrate an increase in liquid precipitation during the cold season (Knowles et al., 2006), which have caused decreases in the volume of spring snowpack (Barnett et al., 2008; Mote et al, 2005). Changes in precipitation and decreases in snowpack have resulted in earlier (Stewart et al., 2005) and declined peak flows (Barnett et al., 2008), as well as a long-term reduction of quarterly quintiles of flow (Luce and Holden, 2009).

These problems are further complicated by projections that warming trends will continue (Hoerling et al., 2010; IPCC, 2007; Moore and Von Waldon, 2009). Predictive studies suggest that much of the Pacific Northwest and the Intermountain West will experience increases in January temperatures on the order of 1.4 to 2.8 °C throughout the coming century (Hamlet, et al, 2010; Moore and Von Walden, 2009). Increases in winter and spring temperatures and more precipitation falling as rain rather than snow will cause snow water equivalent (SWE) values to decrease dramatically (Mote and Salathe, 2010). Led by these predictions researchers have used hydrologic models to predict potential changes in streamflow.

In the state of Washington, Elsner et al. (2010) used the Variable Infiltration Capacity (VIC) hydrologic model to predict changes in streamflow for transient rain-snow and snow dominated watersheds. Their findings suggest that by 2080 transient watersheds will have hydrograph forms that mirror rain dominated systems with streamflow peaks during winter months. They suggest that spring runoff in snowmelt dominated watersheds will transition from clear unimodal peaks to lower magnitude, spikier, bimodal peaks that occur earlier in the year. Within the state of Idaho, Tang et al., (in prep.) used VIC to demonstrate that the Salmon River, a snow dominated mountainous catchment, will experience higher flows during winter months, earlier peak flows, and reductions in summer and annual flows as a result of warming temperatures.

2.2.3 Study Questions

Knowledge of how precipitation phase influences hydrograph form is important because it reveals the variability of hydrologic conditions that can exist in different elevation zones within mountainous terrain. Furthermore, understanding how precipitation phase varies with elevation provides predictive power for understanding how climate change will affect the timing, frequency, duration, and magnitude of hydrologic events from the scale of tributaries to whole watersheds. In turn, the hydrologic regime of an area exerts strong control on the form, functionality and overall resilience of the hydrologic and physical characteristics of river systems.

Because many hydrological measurement networks are designed for operational purposes rather than scientific ones (Kirchner, 1995), it is difficult at best to assign causality to the sources of hydrologic heterogeneity. Furthermore, the integrative nature of large rivers (the ones that have been gaged for operation purposes) obscure the unique hydrologic signals produced by smaller tributary basins, making it difficult to understand how climate change will affect these regionally important watersheds. We seek to help elucidate hydrologic heterogeneity and contribute to the understanding of how climate change will impact the hydrologic cycle by documenting the influence of precipitation phase (liquid, solid and mixed phase) on hydrograph form and characteristics. Specifically, we ask the following questions, 1) How variable is the amount and phase of precipitation across extensive elevation relief? 2) If the amount and phase of precipitation vary with elevation, are there significant differences in the seasonality, magnitude, frequency, and duration of hydrologic events and overall streamflow patterns across a rain to snow gradient? 3) How can we use observations characterizing diverse hydrologic regimes contained within large mountainous catchments to advance the science and increase our predictive power of the potential influence of warming temperatures on hydrograph form?

2.3 Setting

The Salmon River basin (Figure 1) was chosen for study because of its high relief, non-uniform elevation distribution, unregulated flows and importance to anadromous fish species. The majority of the Salmon River drainage is protected by wilderness area designations and forest service lands, with much of the remaining area largely unaffected by human activities. As a consequence of the large spatial extent of this investigation, the watersheds chosen for study differ in physical characteristics such as geology, soil types, vegetative cover and land use.

2.3.1 Rain Dominated Watersheds

Rain dominated watersheds are located near Whitebird, Idaho in low elevation (~ 500 m - 1500 m) regions of the Salmon River basin (Figure 1) and drain areas that are completely underlain by Tertiary age basalts (see Table 1 for more detailed watershed characteristics). These watersheds can generally be described as having steep slopes and significant relief with the exception of the Rock Creek watershed, which is primarily composed of a large plateau dissected by tributaries. Vegetation in low elevation watersheds is primarily composed of grasslands and deciduous tree species, with some conifers in the uplands. The rain dominated watersheds have the greatest percentage of agricultural land area and the least amount of forest covered area. Repeated field surveys and interviews with local residents indicate that there is no pumping of groundwater and that dry-land agricultural practice dominates the region. Precipitation amounts are the lowest in rain dominated watersheds with an average annual precipitation of 473 mm.

2.3.2 Mixed Rain and Snow Watersheds

The mixed rain and snow watersheds are contained within mid elevation zones (~ 1500 m - 2500 m) and are underlain by lithology that includes intrusive and metamorphic rocks that are Permian to Cretaceous in age and Tertiary basalts. These watersheds, located near New Meadows and Riggins, Idaho are composed of steep, mountainous terrain and are almost completely forested (Table 1). There is essentially no agriculture practiced within these watersheds and they are largely undeveloped. Average annual precipitation in these watersheds is around 862 mm.

2.3.3 Snow Dominated Watersheds

Snow dominated watersheds, located near Stanley, Idaho, are bounded within high elevations (~ 2250 m - 3250 m) and drain areas that are composed of Cretaceous and Tertiary age intrusive rocks. Several episodes of glaciations from the Pliocene to early Holocene have produced extensive valley fill in the area. These watersheds are generally well forested; however, many of the valley areas are vegetated by grasses and sage, with open valley riparian zones being dominated by various species of willow. Snow dominated watersheds generally have the highest mean slopes and the most area with slopes greater than 50 % (Table 1). There is little to no developed or agricultural land within these basins. Average annual precipitation is 984 mm.

2.4 Methods

2.4.1 Field Hydrology

To test how precipitation phase influences hydrograph form we established streamflow gaging stations in twelve tributary catchments to the Salmon River. Gaging stations are contained within three distinct elevation zones (Figure 1c). These correspond to elevation ranges that we observe to primarily receive precipitation in the liquid phase (low elevations 300 - 1500 m), mixed phase (mid elevations 1500 - 2250 m), and solid phase (high elevations 2250 - 3250 m). There are four gages within each of the three zones. Hypsometric techniques were used to discover the overall range and distribution of elevations of a catchment and designate it as either snow, mixed, or rain dominated. All study basins were identified and delineated in ARCMAP using 10 m resolution elevation data acquired from the USGS National Elevation Dataset (NED) (Gesch et al., 2009). Elevations of individual catchments were exported from Arc Map and processed using custom MATLAB scripts that helped visualize the range and distribution of elevations within.

To monitor surface flow we installed vented pressure loggers (In-Situ Level Troll 500) in two-inch diameter perforated stilling wells that recorded stage level at ten-minute intervals. Wells were installed in the late spring of 2009. Stilling wells were buried approximately ten to thirty centimeters below the elevation of the present stream bed to minimize variations in stage measurements caused by water pileup and turbulence in and around the wells. We used an YSI-Flowtracker Acoustic Doppler Velocimeter to measure discharge within the channel at a variety of flow conditions following the methods outlined by Blanchard (2004). Erroneous stage level data were removed and any offsets in stage level data caused by changes in channel geometry (i.e. scour or deposition) were shifted to match the starting datum. Power law regressions were used to calibrate the relationship between stage and discharge (See Appendix 1) as described by Rantz (1984). To assure robust stage-discharge relations ~18 discharge measurements were made over 2 years at each site. Once hydrographs were calibrated at 10 minute resolution we converted streamflow to mean daily discharge to allow comparability to historic USGS data.

2.4.2 Multiple Linear Regression

Multiple linear regression methods (Matlas and Jocobs, 1964) were used to extend discharge records a few months before gaging initiated and fill gaps in the data created by faulty equipment or data loss due to flood damage. USGS streamflow records used for reconstruction and gap filling were selected based on their mean basin elevation and geographic proximity to our study sites (See Appendix 2). Thus, the basins used to fill gaps and extend records should have experienced similar precipitation events, phases of precipitation and runoff events as our study basins. Streamflow records for all our study sites were extended back to October 2008 using this method.

Correlation coefficients for the multiple linear regression between our study streams and the USGS set were high (mean R^2 of 0.98, the lowest R^2 was 0.73) and the significance of correlation was good in all cases (P values of 0). When compared to measured streamflow, the modeled discharge seemed to capture the timing and frequency of events with high accuracy. The greatest observed discrepancy was that the predicted peak flows in the low and mid elevations for the 2009 water year were higher than we measured.

2.4.3 Hydrologic Analysis

To analyze differences in streamflow patterns in study tributaries we calculated exceedance probabilities of yield and compared the magnitude, duration, intensity and timing of hydrologic events. Exceedance probabilities were calculated using standard methods outlined by Davie (2002).

In addition to describing general streamflow patterns we sought to identify how differences in precipitation phase influence hydrologic events. To identify and isolate individual hydrologic events we used changes in the sign of the derivative of discharge to identify local maxima (peaks) and minima (valleys) within the hydrographs. However, this method also identified events in streamflow records that were not associated with precipitation events, likely caused by instrumental drift or ice buildup, etc. To remove erroneous events we calculated the standard deviation of streamflow over periods of 1 - 2 weeks, which lacked precipitation or snowmelt. Events that were less than or equal to the calculated standard deviation during non event periods were omitted from analysis. This filter was applied on a stream by stream basis and hand checked for accuracy.

Changes in the sign of the discharge derivative were insufficient at identifying the start or end of events that lacked a distinct local minimum. To circumvent these scenarios we performed baseflow separation of hydrograph data using the Web Based Hydrograph Analysis Tool (WHAT) (Lim et al. 2005), which employs a recursive digital filter method (Eckhardt, 2005). By identifying departures between streamflow and baseflow (i.e. runoff from storm events) we were able to identify the beginnings or ends of events.

Though the automated techniques located likely event boundaries, all events were manually checked and modified if there were inconsistencies. In attempts to be as unbiased as possible we would identify the start of an event as either (1) a distinct valley, (2) when streamflow consistently rose above baseflow or (3) when the rate of change in streamflow increased rapidly from the previous day’s flow. To identify the end of an event that lacked a distinct valley, we would either identify points where streamflow returned to baseflow or when the hydrograph returned to flow values that were within a twenty to thirty percent range of pre-event flow values. The combination of methods described above allowed us to identify most hydrologic events with limited bias.

We used the results from our hydrologic event identification to calculate the following streamflow metrics: magnitude, duration, intensity, and timing. We define the magnitude of an event as the total volume of water that is transported past a give point in a channel over the course of some finite timeframe (i.e. the length of time of the hydrologic event). We estimated the volume of water by computing the hydrograph integral associated with a given precipitation or snowmelt event. The duration of an event is simply defined as the time between the start of an event and the end of an event and is reported in whole days. The intensity of an event was defined as the magnitude of the event divided by its duration. The timing of an event was simply defined as the day of the year when the event’s streamflow peaked.

2.4.4 Meteorology

We characterized the precipitation regimes of our study catchments using Snow Data Assimilation System (SNODAS) data products from the National Snow and Ice Data Center (NOHRSC, 2004). SNODAS is a spatially-distributed energy- and mass-balance model that uses observations from ground stations, satellites and airborne platforms to provide estimates of precipitation and snowpack (Carroll et al., 2001; Barrett, 2003). We used daily data for water years 2003 to 2010 at 1 km^2 resolution for liquid and solid precipitation and snow water equivalent (SWE). These data were used to characterize the dominant precipitation phase received by study catchments and the dynamics of snow accumulation. Data were clipped to the extents of our 12 gaged watersheds. The precipitation and SWE values for all pixels for gaged watersheds within a particular precipitation regime were summed and divided by the total number of pixels for those given watersheds. This provided a mean value for each monitored precipitation zone, rather than for each gaged catchment.

2.5 Results and Discussion

2.5.1 Rain Dominated Watersheds

Rain dominated watersheds received 80 % of their total precipitation as rainfall and 20 % as snowfall from 2003 to 2010 (Figure 2a) and have an annual average of 473 mm of precipitation. Due to their overall lower elevation, snow accumulation in these watersheds was minimal and typically had short residence times of one to two weeks (Figure 2b). During high snowfall winters, snow cover persisted up to a month. Although snowpack accumulations were low, they provided a temporary water source that increased the magnitude of wintertime hydrologic events. In fact, observations of SWE and rainfall indicate that rain on snow events were frequent throughout winter months and lead to rapid melting of any snowpack that was present. The yields associated with these events were however, of lower magnitude than that of larger liquid precipitation events that occurred during spring months (Figure 3a).

Streamflow in rain dominated watersheds exhibited patterns that were different from mixed and snow dominated watersheds in the timing of water movement and the duration of hydrologic events. Hydrographs from the 2009 and 2010 water years indicate that baseflow started to increase in early January due to frequent snowmelt and rain events, whereas mixed rain and snow and snow dominated watersheds were essentially inactive during this timeframe. A cycle was observed where snow would fall and accumulate for short time periods. Subsequent rain events would melt the snowpack and rapidly produce surface runoff greater than possible through the rain event alone. Hydrologic events displayed quick rising and falling limbs that started at low baseflow values and quickly returned to low baseflow values. This is contrasted with events in mixed rain and snow and snow dominated watersheds that exhibited much longer rising and falling limbs where baseflow was elevated for extended periods of time.

In addition to hydrograph forms that are unique in the timing and rates of water movement, rain dominated watersheds yielded less water than mixed rain and snow and snow dominated watersheds, reflecting lower precipitation. To address the influence of lower precipitation volumes on watershed yield we calculated exceedance probabilities (Figure 4). The results from this analysis demonstrate that rain dominated watersheds had the lowest yields. In fact, the Q_{10} and Q_{95} exceedance percentiles are an order of magnitude smaller than those in mixed rain and snow and snow dominated watersheds; furthermore, the rain dominated watersheds exhibited the highest probability of low flow conditions (Figure 4). These results are of particular concern for aquatic organisms and for water resource managers and suggest that mixed rain and snow watersheds could exhibit greater variability in flow conditions if freezing elevations increase and more precipitation falls as rain instead of snow.

One of the primary controls on water delivery and subsequent water flux in rain dominated watersheds is their landscape form and orographic position. Much of the topography near these monitoring sites is comprised of a large, low elevation plateau (partially reflected in the spindle plots, Figure 1c). In contrast, regions south and east (locations of our mixed rain and snow and snow dominated watersheds) have much higher elevations. These regions present some of the first major orographic barriers that Pacific storm fronts encounter once past the Cascade Range. A primary consequence of the topographic change and orographic position of rain dominated watersheds is lower precipitation compared to mixed rain and snow and snow dominated watersheds. The pattern of precipitation observed here conforms to predictions of precipitation distribution in mountainous regions (Smith, 1979; Roe et al., 2003; Roe, 2005).

2.5.2 Mixed Rain and Snow Watersheds

The mixed rain and snow watersheds experience 862 mm (Table 1) of annual precipitation, with 60 % of total precipitation falling as snow and 40 % as rain (Figure 2a). Because these watersheds are bounded within higher elevations than rain dominated watersheds, snowpack provides a significant spring and summer water source. Between 2003 and 2010 snowpack was typically present from late November to early June (Figure 2b).

The disparities between the volumes of snow accumulation in rain dominated watersheds and mixed rain and snow watersheds is a strong point of interest because of the stark contrast of precipitation phase in a close geographic proximity (Figure 1 and 2). This results in hydrologic regimes that differ greatly over small spatial scales; these differences are not observed when streamflow observations (i.e. gaging stations) are limited to mainstem rivers that mix signals from individual tributaries. Meteorological observations from our monitoring network illustrate this point.

The mean elevation of mixed rain and snow watersheds is 600 m higher than the mean elevation of rain dominated watersheds. The significant difference in snowfall amounts (Figure 2) indicates that the freezing elevation(s) during winter months must primarily exist above the mean elevation of the rain dominated watersheds (1100 m) and below the mean elevation of mixed rain and snow watersheds (1700 m). Meteorological records suggest that snowlines fluctuate between 1000 to 1200 m throughout the winter season; however, it is not until elevations greater than 1500 m to 1600 m that snowfall accumulates to significant depths and persists for much of the winter. Again, this suggests that topography and orographic phenomenon such as environmental lapse rate are a first order control on precipitation phase (Blanford, 2008; Roe et al., 2003; Roe, 2005; Smith, 1979) and that these factors will exert strong control on the overall streamflow patterns and hydrograph form of tributary catchments.

Streamflow records from 2009 and 2010 for mixed rain and snow watersheds display a much greater snow influence during spring and early summer (Figure 3b). In contrast to rain dominated sites, these watersheds exhibited long rising and falling limbs during spring snowmelt events. During the 2009 and 2010 water year's streamflow was at baseflow throughout the winter months and started to increase during March and peaked in late May. Although mixed rain and snow watersheds exhibited a strong snow influence it is important to note that these sites experienced a greater number of spikes in spring runoff and earlier increases in streamflow than snow dominated watersheds (Figure 3b). The high frequency of rain on snow caused by warm temperatures early in the spring season suggests that catchments receiving rain and snow could experience high magnitude flood events that occur early in the year.

To analyze the volumes of water yielded from mixed rain and snow watersheds we calculated exceedance probabilities (Figure 4). For all exceedance percentiles these watersheds show higher yield than rain dominated watersheds. Compared to snow dominated watersheds, these catchments typically have lower peak yields. Baseflow and median yields are comparable between mixed rain and snow and snow dominated watersheds. One stream within the mixed rain and snow watersheds exhibited the highest yields, which suggests that factors besides elevation and precipitation phase can also influence water yield. The results from the streamflow data and meteorological analysis demonstrate that mixed rain and snow watersheds are located at a landscape position that is conducive to higher amounts of precipitation and more snowfall than rain dominated watersheds.

2.5.3 Snow Dominated Watersheds

The snow dominated watersheds are bounded within high elevations, receive the greatest amount of average annual precipitation (984 mm) and the highest proportion of snow to rain, 75:25 (Figure 2a). Between the years of 2003 and 2010 these watersheds typically experienced snow cover from mid October to early July and exhibited a small number of rain-on-snow events compared to the mixed rain and snow watersheds (Fig. 2b). The snow dominated watersheds typically had the greatest peak SWE values and the longest temporal extent of snow cover.

An interesting, yet slightly paradoxical meteorological characteristic of these watersheds is reflected in their landscape position. Because snow dominated watersheds are contained within high elevations it is not surprising that they receive high amounts of precipitation. However, the proximal, high elevation topography directly west of these watersheds would be expected to cause a rain shadow that is not quantitatively observable in meteorological data (Table 1). The snow dominated watersheds are located nearly 120 km east and south of the mixed and rain dominated precipitation regimes; yet, on average, they receive 122 mm greater precipitation than mixed rain and snow watersheds and 511 mm greater precipitation than rain dominated watersheds. This is slightly surprising considering the dominantly western wind and storm track patterns (Finklin, 1988) and the high elevation orographic barriers that intercept storm fronts before reaching our snow dominated watersheds. The disparities in precipitation volumes suggests that local differences in elevation have a strong affect on air uplift and localized precipitation and that slight differences in mean elevation (i.e. between precipitation regimes) can result in significant differences in precipitation amounts. However, comparisons of SWE in the Salmon River basin between areas of equal elevation but different longitude demonstrate that high elevations in the western portion of the basin had greater accumulations of SWE than their eastern counterparts. Thus, some length scale threshold must exist where orographic barriers are able to significantly decrease the overall amount of precipitation.

Because of the high proportion of snow to rain, snow dominated watersheds exhibited streamflow patterns that have high volumes and unimodal peaks with long rising and falling limbs (Figure 3c). Spring runoff during the 2009 and 2010 water years started in early May and peaked near late June/early July and was less spiky than snowmelt in the mixed rain and snow watersheds reflecting a lower frequency of rain-on-snow events. Except for the late spring and early summer, these streams are typically at baseflow and exhibited little variability. The hydrograph forms of snow dominated watersheds are controlled by the reservoir of snow that accumulates during winter months and the synoptic weather patterns that control the rate and style of water release from snowpack.

The pulse of water that is released by spring runoff in snow dominated watersheds is of high magnitude and demonstrates that streams in this region delivered the greatest amount of water per unit area (Figure 3c and 4). Exceedance probabilities demonstrate that these watersheds had the highest peak and median yields. Baseflow yields for these streams were greater than rain dominated watersheds and comparable to mixed rain and snow watersheds. Peak flows for snow dominated watersheds group closely together and exhibit little divergence, however, baseflows amongst these watersheds exhibit much greater variability (Figure 4). This suggests that peak flows in snow dominated watersheds are largely controlled by similar runoff processes (i.e. spring snowmelt) and that baseflows are more strongly influenced by local variations in ground water levels and flow pathways.

2.5.4 Comparison of Hydrologic Events

In addition to describing the overall yield and streamflow patterns of watersheds that experienced differences in precipitation phase, the timing, magnitude, duration and frequency of hydrologic events were characterized. Because warming temperatures will likely alter the phase of precipitation that many mountainous watersheds receive, it is important to understand how differences in precipitation phase affect stream response to storm events. Flood frequency and magnitude can be quite variable depending on the amount and intensity of precipitation (Pitlick, 1994), in turn, these characteristics of precipitation are directly influenced by the phase of precipitation. Differences in flood frequency and intensity play a large role in shaping the dynamics of lotic ecosystem habitats. Flow regime characteristics such as, magnitude, frequency, duration, timing and the rate of change of hydrologic events are of critical importance to aquatic organisms (Poff and Ward, 1989, Richter et al. 1996, and Walker et al. 1995).

2.5.4.1 Magnitude, Duration and Intensity

The snow dominated and mixed rain and snow watersheds experienced the highest magnitude and longest duration events (Figure 5a). These events were a combination of snowmelt and rain events that occurred during the spring season. The long temporal extent of these events reflects the large snow reservoirs that accumulate in these watersheds and the high amount of energy needed to melt and process water from solid form in snowpack to a moving liquid within channels. Rain dominated watersheds exhibited hydrologic events that were much shorter in duration and lesser in magnitude. Rain events within this study area do not typically deliver an amount of water that is equivalent to a season of snow accumulation. Furthermore, since precipitation events in rain dominated watersheds typically do not require a phase change, water is quickly processed and is delayed only by flow pathways and groundwater storage.

The intensity of events was also calculated to see if the short temporal extent of flood events in rain dominated watersheds increased the intensity of the hydrologic response. The mixed and snow dominated watersheds exhibited events that were an order of magnitude greater than intensities in rain dominated watersheds. In addition, this analysis also demonstrated that the mixed and snow dominated watersheds experienced high intensity events that were temporally close (Figure 5b). These observations suggest that the higher amounts of precipitation received by mixed and snow dominated watersheds result in higher intensity flood events.

2.5.4.2 Timing

In addition to testing the magnitude, duration and intensity of events in the different precipitation regimes, we also investigated the timing of hydrologic events. Two important findings were that rain dominated and mixed rain and snow watersheds exhibited hydrologic events of moderate intensity and duration during winter months (Figure 6a and b). This reflects the influence of the transient freezing line that migrated in and out of the rain dominated and mixed rain and snow watersheds during the winter season. Furthermore, this demonstrates that there are a greater number of liquid precipitation and melt events occurring earlier in the year in these watersheds. Thus the timing of water movement varies with elevation and precipitation phase. These results demonstrate that the timing of events within mountainous watersheds can be quite different and is of great concern because of the delicate balance between the timing of hydrologic events and life cycles of aquatic organisms.

2.6 Implications

This study attempted to answer how differences in precipitation phase influence hydrograph form and streamflow patterns. Qualities, such as the rate of change in flow, as well as the timing, magnitude, duration and frequency of hydrologic events and the physical characteristics of watersheds determine the geometric form of each hydrograph. These aspects of streamflow and the precipitation characteristics of a region are in turn, what define a hydrologic regime and the magnitude-frequency distribution of potential streamflows. This study demonstrates that differences in precipitation phase, amount and intensity cause differences in the timing, magnitude, duration and intensity of hydrologic events. It is also suggested that precipitation phase, amount and intensity control the rate and subsequently, the intensity of a hydrologic a response.

It is expected that different physiographic areas that receive varying amounts and proportions of rain and snow will exhibit differences in their streamflow, magnitude-frequency distributions. Work from Pitlick (1994) demonstrated that regions with differing climate yet similar physiography exhibited significant differences in flood frequency distributions. For example, in foothills region of the Colorado Front-Range, where floods are produced by intense thunderstorms, the 100 year flood may be more than ten times the mean annual flood. This is contrasted with Alpine regions in Colorado where runoff is generated by snowmelt and the 100 year flood is less than two times the mean annual flood (Pitlick, 1994). These results suggest that precipitation intensity, which can be thought of as a measure of the amount of annual precipitation likely to fall on 1 day, is a primary control on the magnitude of flood response. It can be expected then, that regions dominated by snowfall will exhibit less variability in their flood frequency distributions than areas dominated by rainfall. This occurs because snowfall precipitation, no matter how intense, requires a phase change before water is available for transport. This is contrasted with regions that experience intense thunderstorms, which are far more likely to concentrate more of the annual precipitation into a single storm event that is impeded only by flow pathways and storage and does not require a phase change to be available for transport.

The influence of precipitation phase, amount and intensity on hydrograph form and flood magnitude-frequency distributions is of concern because of the prediction of increased temperatures for much of the intermountain West throughout the coming century (Hoerling et al., 2010; IPCC, 2007; Moore and Von Waldon, 2009). If temperatures continue to warm and wintertime freezing lines move to higher elevations then more precipitation will fall as rain instead of snow over a greater areal extent in many western U.S. watersheds. Furthermore, the timing of water delivery and transport will likely occur earlier in the year. This study has demonstrated that the rain dominated watersheds experience hydrologic events in winter months while snow dominated watersheds are at baseflow conditions (Figure 3 and Figure 6a). The results from this study and the consideration of Pitlick's (1994) findings suggest that many of the mountainous watersheds throughout the western U.S. will likely experience higher magnitude floods and that these flood events will occur earlier in the year. This will be caused by higher intensity liquid precipitation events occurring during the seasons of high precipitation (winter and spring). Thus mapping precipitation regimes (rain, snow and mixed) will help elucidate heterogeneity in hydrologic processes by providing an understanding of the spatial distribution and areal extent of a watershed that is or isn’t affected by rain or snow.

Furthermore, we suggest that these changes (i.e. more rain than snow and higher precipitation intensities) will amplify the magnitude of flood events across large scale basins that drain areas containing multiple precipitation regimes (rain, mixed rain and snow and snow dominated). This is a consequence of the distribution of elevations within a watershed. For example, the elevation range of the mixed rain and snow watersheds characterized in this study have the smallest total relief, yet comprise the majority of the area (> 50%) within the Salmon River basin (Figure 1). This is likely typical of many mountainous watersheds unless there are extensive low elevation valleys or large, high elevation erosional surfaces. Thus, because many of the mid elevations zones compose large areal extents of watersheds and because these elevations will likely experience the greatest changes in the proportions of rain to snow, it is probable that the intensity of flood events will increase at the scale of large basins. The likelihood of more extreme events is even more probable when considering the high probability of rain on snow events in mid and high elevation zones. Rain on snow events have been shown to cause extreme, high magnitude flood events (Marks et al. 1998) and also have been demonstrated to be more frequent at mid and high elevations (McCabe et al. 2006). These hypotheses are supported by the work of Elsner et al. (2010) who used the Variable Infiltration Capacity hydrologic model for the state of Washington to suggest that mixed rain and snow watersheds will transition into hydrologic regimes that are much more rain dominated and that snow dominated catchments will experience melt events earlier in the year.

In this study we explored the influence of precipitation phase on hydrograph characteristics such as the magnitude, duration, timing and frequency of hydrologic events. However, it is important to emphasize that determining how precipitation phase influences hydrograph form, and especially specific hydrologic events, is complicated by the physical characteristics of a basin. For example, patterns of runoff are not only tied to precipitation phase and intensity but are also strongly controlled by soil thickness and permeability (Kirkby, 1978). Freeze (1980) and Wood (1990) found for hillslopes and small watersheds that the distribution of peak flows and shapes of flood frequency curves are influenced by variations in hydraulic conductivity and soil moisture. It is important to note however that the results from Freeze (1980) and Wood (1990) are for small watersheds and hillslopes that are less than 1km^2. Kirkby (1976) suggests that for larger catchments (> 1 km^2) hillslope travel times are negligible when compared to travel times through the channel network. Thus at the scales of our investigation (watersheds > 10km^2), the magnitude and variability of peak flows more strongly reflects precipitation characteristics than topography (Burt, 1989).

2.7 Conclusions

This study demonstrates that differences in precipitation phase result in streamflow patterns and hydrologic events that differ in frequency, magnitude, intensity, duration and timing. It also demonstrates the important role that topography plays in influencing precipitation phase and subsequent streamflow patterns. The high elevations in snow dominated watersheds result in greater amounts of precipitation and higher magnitude floods, whereas the lower elevations in rain dominated watersheds experience lower volumes of precipitation and subsequently lower magnitude floods. The timing, rate of water movement and resulting hydrograph form of rain dominated watersheds provides an analogue for the potential changes in streamflow characteristics (i.e. higher rates of transport, which would result in higher intensities) that snow dominated watersheds could transition to if temperatures warm. Our results suggest that floods would become more frequent, be of higher intensity and occur earlier in the year for large portions of mountainous watersheds. These types of hydrologic regime changes will stress aquatic organisms and land users alike as much of the western U.S. is strongly adapted to a spring flood pulse. We stress here the importance of basin-wide observations when characterizing the meteorological and hydrologic characteristics of watersheds with high relief. The hydrologic regimes that exist within mountainous catchments are diverse and cause heterogeneity in hydrologic and physical processes that warrant further study.

2.8 Acknowledgements

This work has been supported by the National Science Foundation and the Experimental Program to Stimulate Competitive Research (EPS-0814387). In addition, I would like to extend thanks to Benjamin Crosby, Glenn Thackray, Colden Baxter and John Welhan for their insights and helpful review.

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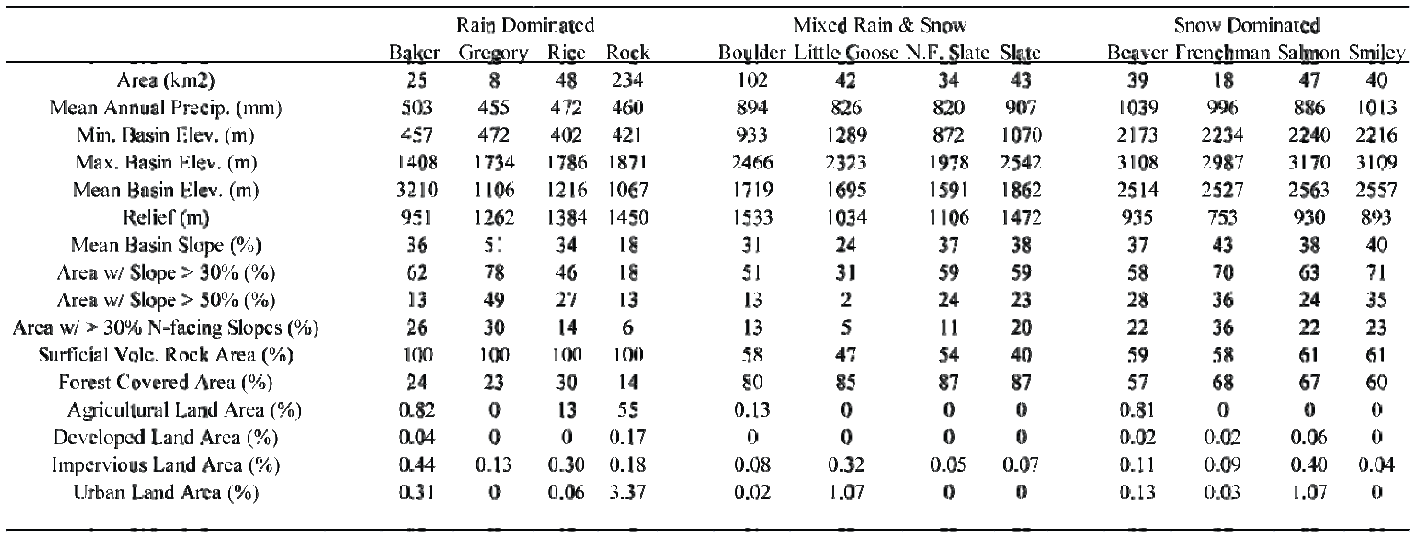
2.10 Figures and Tables



	Rain Dominated				Mixed Rain & Snow				Snow Dominated			
	Baker	Gregory	Rice	Rock	Boulder	Little Goose	N.F. Slate	Slate	Beaver	Frenchman	Salmon	Smiley
Area (km2)	25	8	48	234	102	42	34	43	39	18	47	40
Mean Annual Precip. (mm)	503	455	472	460	894	826	820	907	1039	996	886	1013
Min. Basin Elev. (m)	457	472	402	421	933	1289	872	1070	2173	2234	2240	2216
Max. Basin Elev. (m)	1408	1734	1786	1871	2466	2323	1978	2542	3108	2987	3170	3109
Mean Basin Elev. (m)	3210	1106	1216	1067	1719	1695	1591	1862	2514	2527	2563	2557
Relief (m)	951	1262	1384	1450	1533	1034	1106	1472	935	753	930	893
Mean Basin Slope (%)	36	51	34	18	31	24	37	38	37	43	38	40
Area w/ Slope > 30% (%)	62	78	46	18	51	31	59	59	58	70	63	71
Area w/ Slope > 50% (%)	13	49	27	13	13	2	24	23	28	36	24	35
Area w/ > 30% N-facing Slopes (%)	26	30	14	6	13	5	11	20	22	36	22	23
Surficial Volc. Rock Area (%)	100	100	100	100	58	47	54	40	59	58	61	61
Forest Covered Area (%)	24	23	30	14	80	85	87	87	57	68	67	60
Agricultural Land Area (%)	0.82	0	13	55	0.13	0	0	0	0.81	0	0	0
Developed Land Area (%)	0.04	0	0	0.17	0	0	0	0	0.02	0.02	0.06	0
Impervious Land Area (%)	0.44	0.13	0.30	0.18	0.08	0.32	0.05	0.07	0.11	0.09	0.40	0.04
Urban Land Area (%)	0.31	0	0.06	3.37	0.02	1.07	0	0	0.13	0.03	1.07	0

Table 1. Precipitation and physical characteristics of the rain, mixed and snow dominated watersheds. Metrics were determined using StreamStats a public service provided by the United States Geological Survey (Ries et al. 2008).

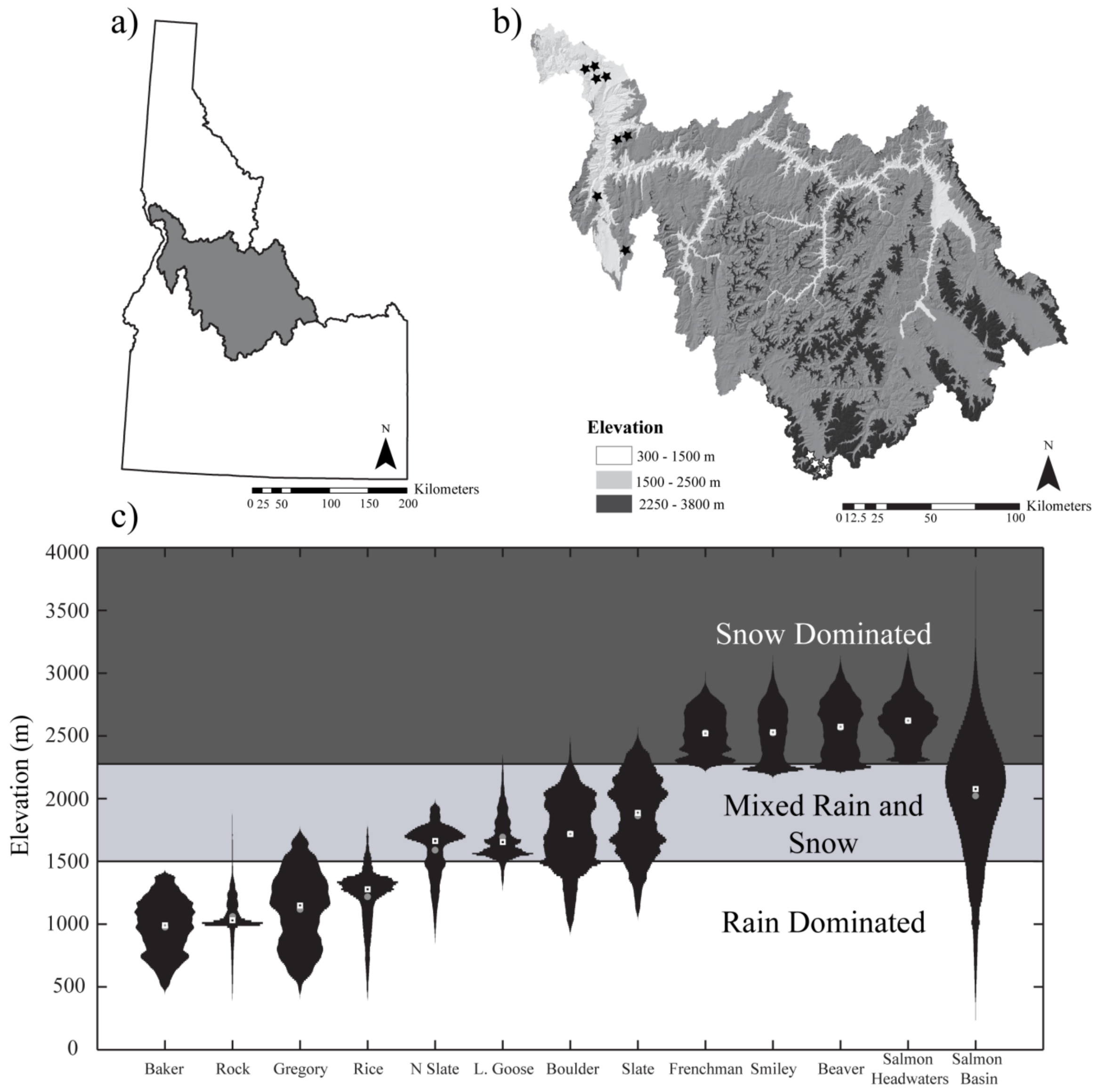


Figure 1. Regional setting of the Salmon River basin (a), in central Idaho and (b) relief map of the Salmon River basin with study sites and elevation zones. Rain dominated and mixed rain and snow sites are indicated by black stars, snow dominated sites are denoted by white stars. Spindle plots (c) reveal the range and distribution of elevations for the 12 study sites. Mean and median elevations are noted by grey circles and white squares respectively. Note that even though the mixed rain and snow elevation range is the smallest, that range composes the majority (> 50 %) of the Salmon River basin's area.

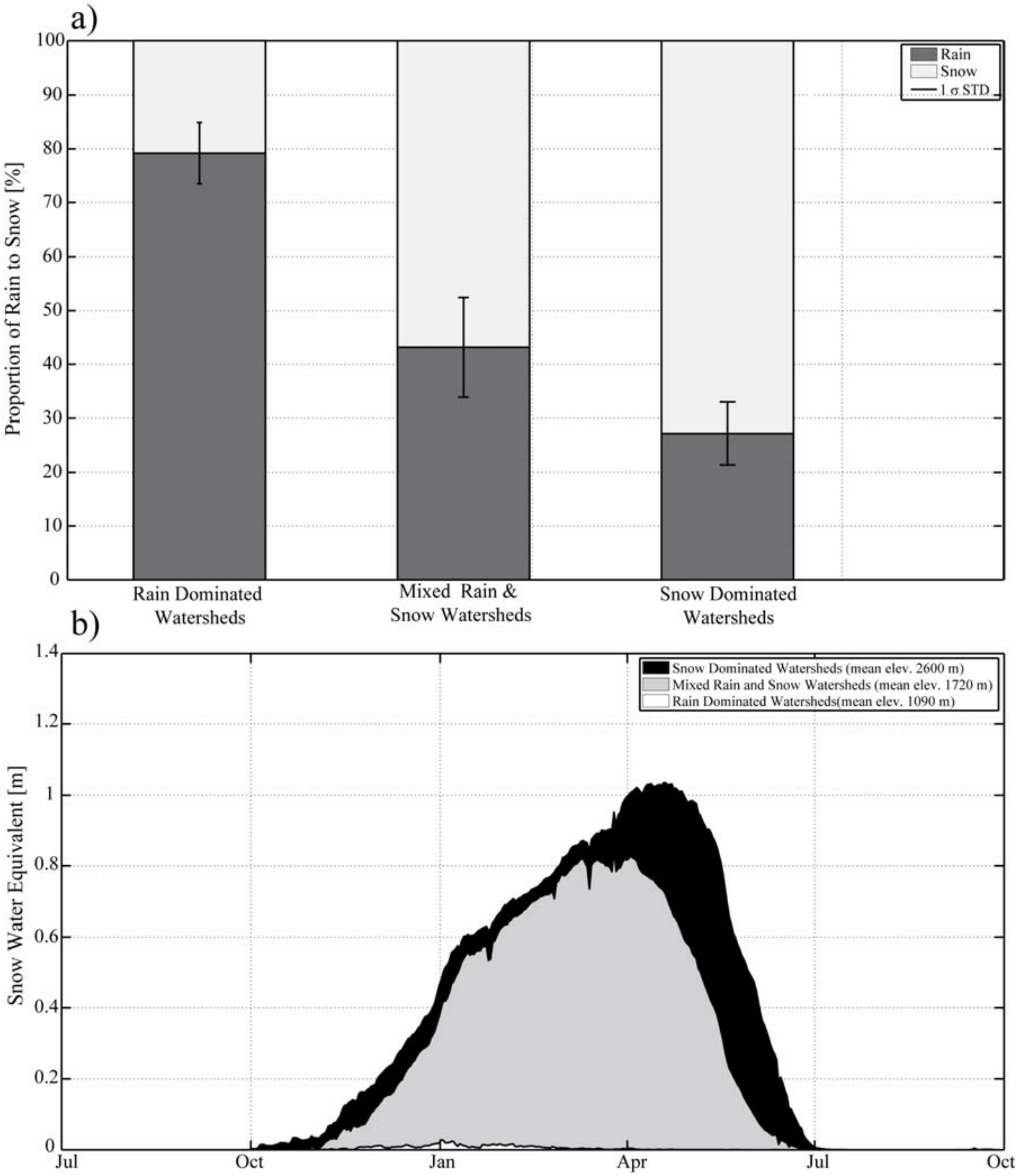


Figure 2. Meteorological comparison of the three precipitation regimes. (a) Ratio of rain to snow and (b) mean daily snow water equivalent averaged between 2003 and 2010. Note that no site is exclusively one phase of precipitation and that rain dominated watersheds do experience very low magnitude, transient snow cover. Data are extracted from NOAA’s SNODAS modeled predictions (NOHRSC, 2010).

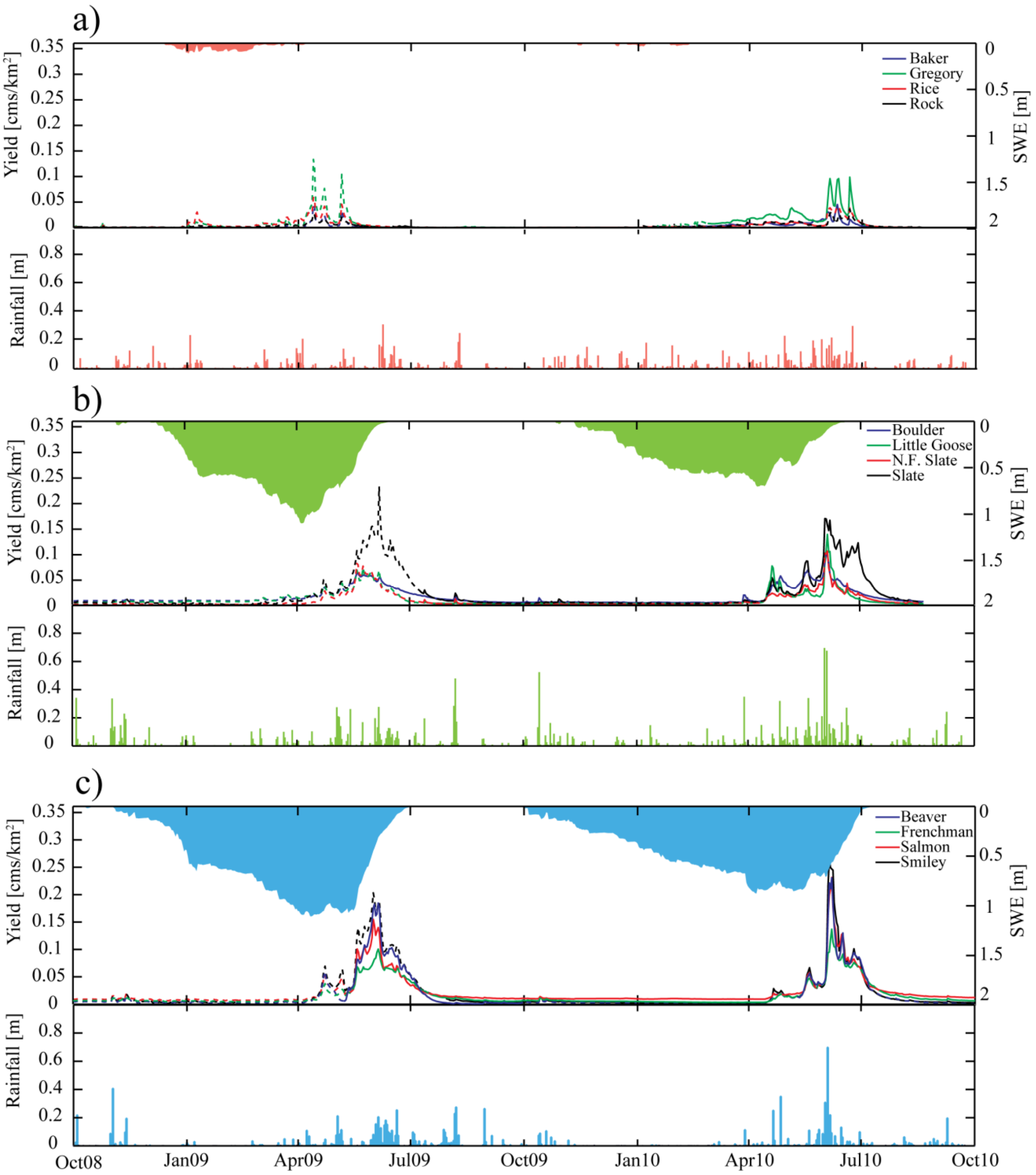
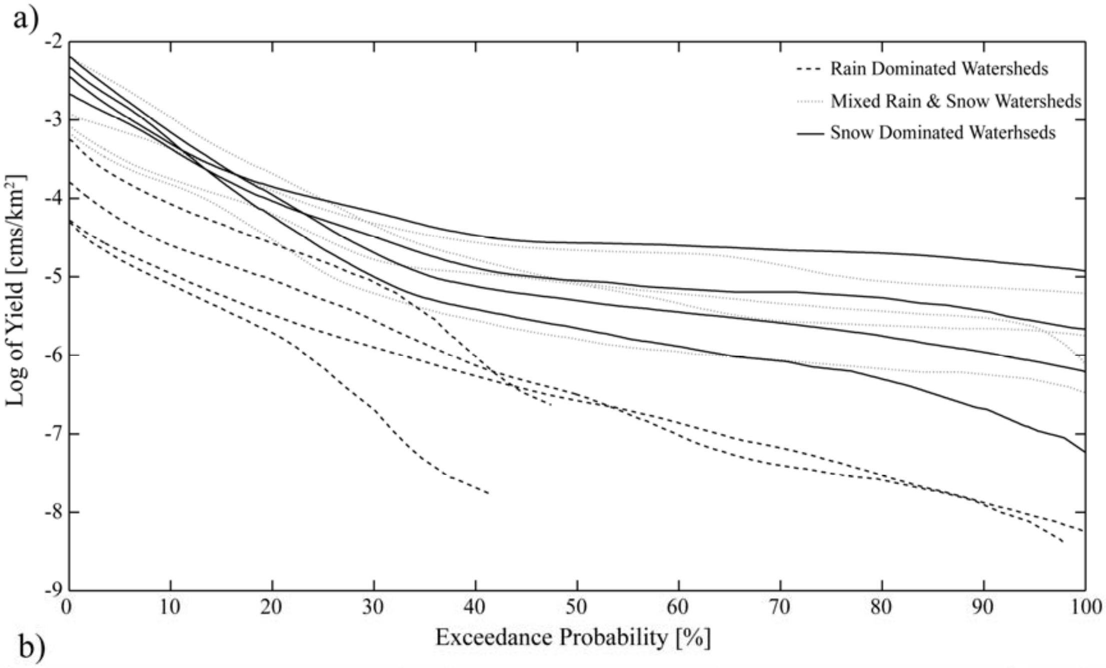
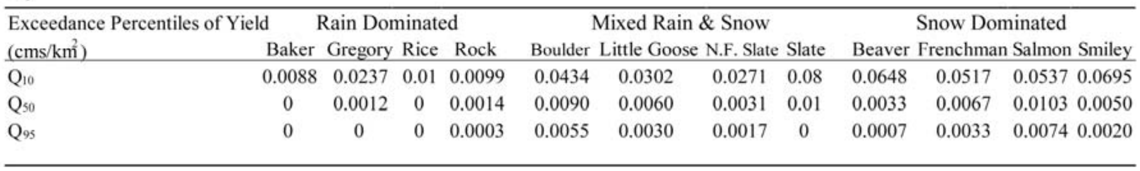


Figure 3. Streamflow yield, rainfall, and snow water equivalent (SWE) for the 2009 and 2010 water years for our 12 sites in (a) rain dominated watersheds, (b) mixed rain and snow watersheds, and (c) snow dominated watersheds. Dashed lines indicate hydrograph data modeled using multiple linear regression analysis. Note that the magnitude of precipitation and hydrologic events and the temporal extent of snowpack vary significantly amongst the precipitation regimes.



b)



Exceedance Percentiles of Yield (cms/km^2)	Rain Dominated				Mixed Rain & Snow				Snow Dominated			
	Baker	Gregory	Rice	Rock	Boulder	Little Goose	N.F. Slate	Slate	Beaver	Frenchman	Salmon	Smiley
Q_{10}	0.0088	0.0237	0.01	0.0099	0.0434	0.0302	0.0271	0.08	0.0648	0.0517	0.0537	0.0695
Q_{50}	0	0.0012	0	0.0014	0.0090	0.0060	0.0031	0.01	0.0033	0.0067	0.0103	0.0050
Q_{95}	0	0	0	0.0003	0.0055	0.0030	0.0017	0	0.0007	0.0033	0.0074	0.0020

Figure 4. (a) Exceedance probabilities for the natural logarithm of streamflow yield for the three precipitation regimes. Table (b) reports the high (Q_{10}), median (Q_{50}) and low (Q_{95}) flow percentiles of yield. Note that the snow dominated watersheds generally have the highest peak yields and that rain dominated streams have the highest probability of extreme low flows. Two streams within the rain dominated group have approximately a 50% probability of going dry (where 2 of the dashed lines end).

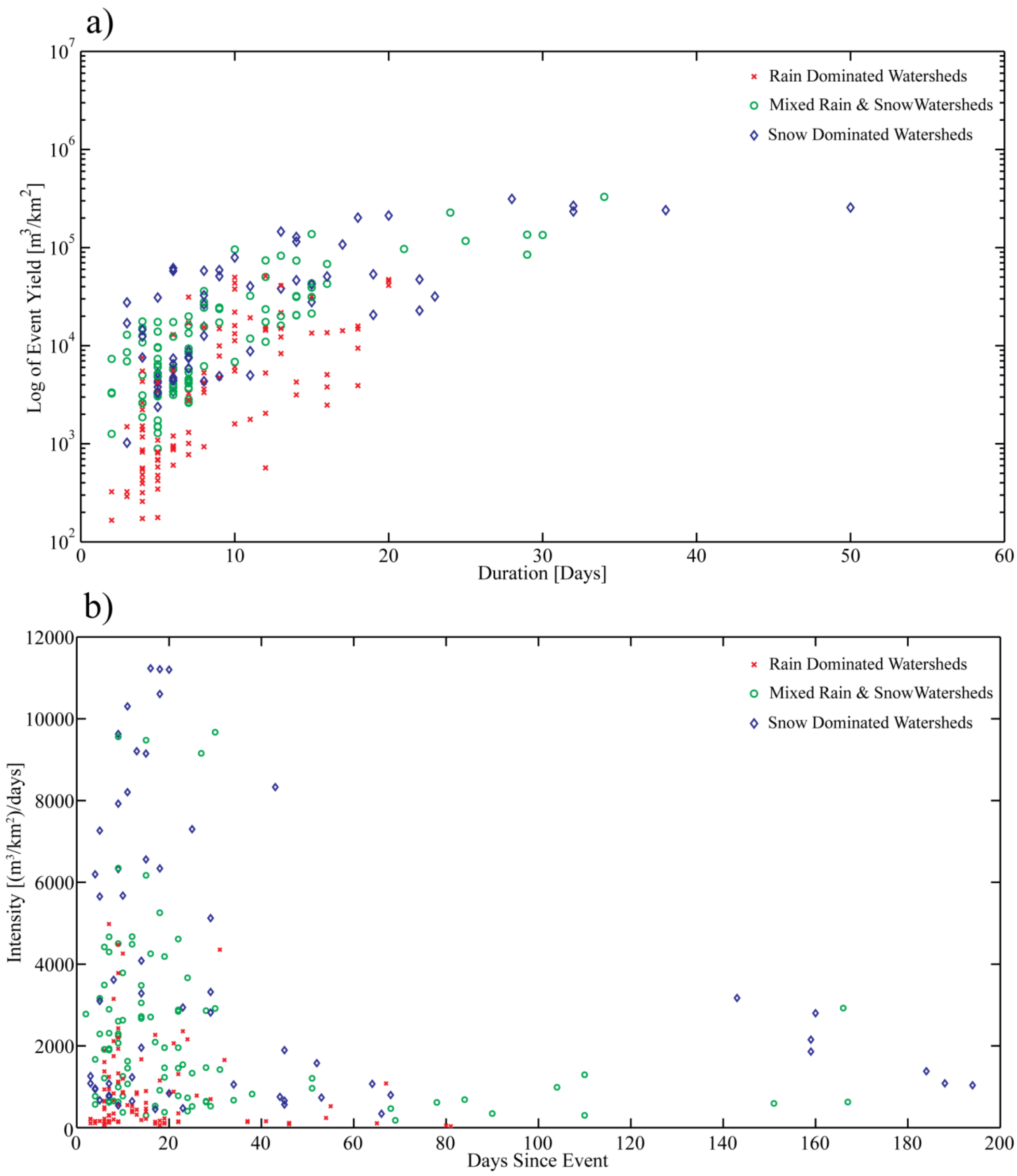


Figure 5. Log of event yield against duration (a) and event intensity against days since last event (b) for liquid precipitation and melt events during the 2009 and 2010 water years. Snowmelt and mixed rain and snow had the longest duration events with the highest yield and the most intense events that occurred closely in time.

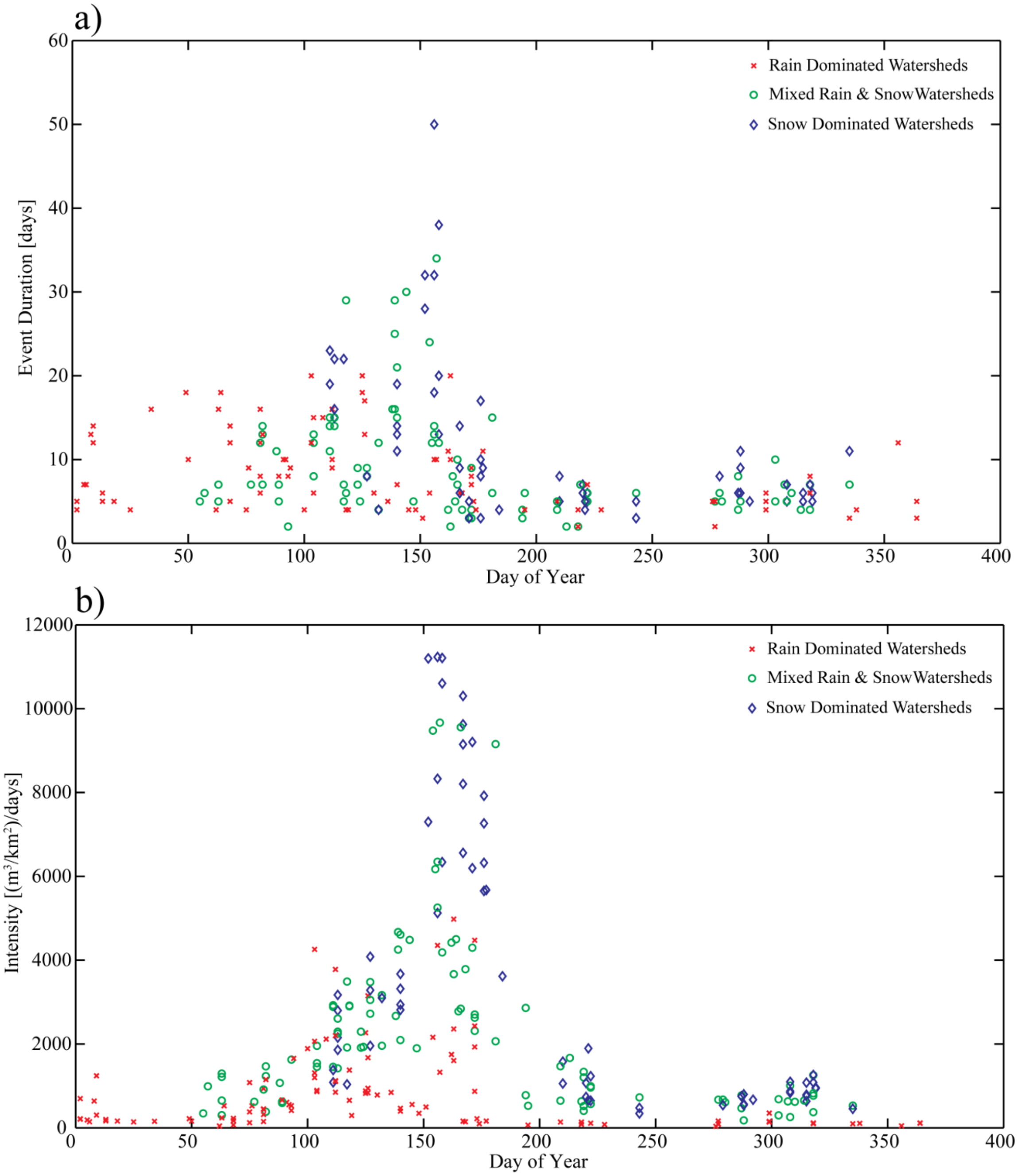


Figure 6. Event duration (a) and intensity (b) for liquid precipitation and melt events for the 2009 and 2010 water years plotted against day of the year. Note that the duration and intensity of hydrologic events in snow dominated and mixed rain and snow watersheds are greatest during the spring months, whereas the high duration and high intensity events in rain dominated watersheds occurred throughout the winter and spring months.

Chapter 3: Conclusions and Future Directions

3.1 Summary

In this project twelve tributaries to the Salmon River were selected and instrumented with stream gaging equipment. These tributary basins are contained within distinct elevation zones that receive different proportions of rain and snow. Rain dominated watersheds received 80 % of their total precipitation as rain and 20% as snow. Mixed rain and snow watersheds received 40 % of precipitation as rain and 60 % as snow and exhibited the greatest variability in the phase of precipitation received. Snow dominated watersheds received the least amount of rain (25 %) and the greatest amount of snow (75 %). These proportions are from meteorological observations from 2003 to 2010 (NOHRSC, 2010).

The rain dominated watersheds are characterized by events of low magnitude. During winter months these watersheds exhibited the longest duration hydrologic events, suggesting that snow accumulated for small periods of time and then melted and that there were frequent rain events during winter months. The delivery of rain and snow and melting of snow during winter months caused the rain dominated watersheds to have the highest probability of going dry or having very low baseflow conditions during late summer. Mixed rain and snow watersheds experienced events that were longer in duration, greater in magnitude and occurred primarily from early spring to early summer. Snow dominated watersheds had the highest magnitude and longest duration events and occurred from late spring to mid-summer. Meteorological and hydrologic analysis suggests that mixed rain and snow watersheds are close to the fluctuating freezing elevation. Thus, these watersheds are at the greatest immediate risk for changes in snow accumulation amounts and hydrologic characteristics if snowlines rise. If temperatures warm these watersheds will likely experience higher proportions of rain which would alter the timing and frequency of flood events and the timing of water availability. Furthermore, since approximately 50 % of the Salmon River basin is comprised of mid elevations there will likely be large basin wide changes in hydrologic characteristics if temperatures warm. These changes are of concern for native aquatic species and local anthropogenic systems.

3.2 Future Work

3.2.1 Motivation

The motivation for this project has centered around two questions that I will continue to pursue as part of my doctoral dissertation work, 1) what is the influence of precipitation phase on hydrograph form and characteristics? 2) How do differences in hydrograph form, caused by differences in precipitation forcing (i.e. rain versus snow), affect the physical and ecological characteristics of a channel?

The question regarding the influence of precipitation phase on hydrograph form is one of practical concern and largely originates in the interests of how hydrograph characteristics affect the mechanical characteristics of hydraulics and in turn, the physical form of channels. For example, it has been proposed by Wolman and Miller (1960) that ‘effective discharge’, the discharge that transports the greatest proportion of sediment, is a relatively frequent event (recurring every ~1.5 years) and corresponds to the bankfull discharge. Therefore, knowledge of the relationship between bedload transport, the dominant control on channel maintenance (Leopold, 1992), and water discharge, allows calibration of channel forming flows (Emmett and Wolman, 2001). The frequency of occurrence and variation in the magnitude of channel forming flows is controlled by the climatic and physical characteristics of a watershed and is reflected in hydrograph form. I define the form of a hydrograph as the number of spikes, rates of change in flow, and the overall shape and pattern of the hydrograph.

Work presented in Chapter 2 demonstrates that differences in the dominant precipitation phase result in differences in the magnitude, duration, intensity and seasonality of hydrologic events. However, determining how precipitation phase influences hydrograph form, and especially specific hydrologic events, is complicated by the physical characteristics of a basin. For example, patterns of runoff are not only tied to precipitation phase and intensity but are also strongly controlled by vegetation, drainage network form, bedrock permeability and soil characteristics (e.g. Kirkby, 1978). The physical characteristics (bedrock, vegetation, soil types and depths) of our study catchments differ significantly between the precipitation regimes (see Chapter 2, Table 1). These factors undoubtedly exert some influence on runoff characteristics and are confounding to our interpretations. In light of the considerations stated above, as well as curiosity inspired by field observations and literature review, I will present some hypotheses and questions that I will pursue in future work.

3.2.2 Hydrology

The movement of water through a landscape, sourced from rainwater or melting snowpack, drives many geomorphic processes and directly impacts ecological and anthropogenic systems. Monitoring the timing, amount and pathways that water takes through a landscape are fundamental for advancing our understanding of hydrologic processes and other coupled systems.

In a rather passionate appeal to the scientific community, Kirchner (1995) identifies the need for hydrologic monitoring networks that explicitly recognize the spatial and temporal heterogeneity of hydrologic processes. This need is largely driven by the fact that many hydrological measurement networks are designed for operational purposes rather than scientific ones (Kirchner, 1995). The Salmon River basin provides an ideal natural laboratory for answering questions about hydrologic heterogeneity at multiple spatial and temporal scales for the following reasons. 1) It is a large basin (~ 32,000 km^2) with extensive relief (300 m to greater than 3500 m) that regionally and temporally experiences variations in precipitation phase (liquid, mixed and solid phases). 2) It has a downstream progression of mainstem streamflow gages maintained by the USGS that allow assessment of hydrologic signals over large spatial scales and time periods. 3) Mid elevation catchments (1500 m to 2250 m) comprise more than fifty percent of the basin area and are close to current snowline elevations, thus the Salmon River is hydrologically sensitive to warmer temperatures and changes in snowline. 4) It is a relatively pristine basin and has experienced much less anthropogenic impact than many other mountainous basins within the U.S. This combination of factors suggests that hydrologic observations from the Salmon River have a high probability of contributing to the knowledge base of disciplines working to understand the problems of hydrologic heterogeneity and the impacts of warmer temperatures on snow dominated watersheds.

The work presented here is based on one and one half water years, thus representation of the range of potential hydrologic conditions is poor (Huh, 2004).

Because of these opportunities and justifications presented above we plan to maintain our monitoring network with the Salmon River basin. Further data collection will allow us to generate additional insights into the influence of precipitation phase on hydrograph form. Ultimately there will be a total of four water years of flow data collected from our monitoring sites. These data will allow better statistical description of the similarities and differences between watersheds that receive varying proportions of liquid and solid phase precipitation. In addition, streamflow data is a critical component for understanding the results of the geomorphic and ecological work we are performing at these study sites.

One of the interesting results of the work presented in this thesis reveals that while there are definite differences in streamflow patterns and differences in the magnitude, duration, intensity and seasonality of hydrologic events, the respective precipitation regimes are not as unique as expected. This may reflect that fact that the end members, the low and high elevation catchments, are not totally dominated by rain or snow respectively. The rain dominated watersheds experienced some amount of snow and the snow dominated watersheds experienced some amount of rainfall. In addition, these differences may result from differences in the physiography of these watersheds (i.e. drainage density, substrate type, geology, etc.). These characteristics may affect the validity of the interpretation of our results. In light of these thoughts it is logical to identify and analyze streamflow characteristics of catchments that are either completely snow or rain dominated. Ideally, these catchments would experience similar amounts of precipitation, have similar drainage areas and similar morphometric characteristics (i.e. channel networks, slope-area relationships, etc.). Obviously natural experiments are constrained by the characteristics of a landscape, however, identification of representative catchments that are entirely snow dominated and those that are entirely rain dominated would be an important next step in improving our understanding of how precipitation phase influences hydrograph form and characteristics.

3.2.3 Fluvial Geomorphology

The idea of hydrologic regime influencing the frequency of effective discharge or the physical characteristics of a channel is by no means a new idea (e.g. Ackers and Charlton, 1970; Inglis, 1968; Pickup and Warner, 1976). For example, Pickup and Warner (1976) explore the effects of hydrologic regime on the magnitude and frequency of dominant discharge. The idea of dominant discharge is somewhat confounded by the variety of ways it is defined. For example, Pickup and Warner (1976) identify three different definitions of dominant discharge. Dominant discharge is the range of flows that over some selected period of time transport the greatest amount of bedload (Marlette and Walker, 1968; Prins and De Vries, 1971). Drury et al. (1963) define effective discharge in a statistical sense as the 1.58 year flood. In addition, dominant discharge has been defined as the "natural" bankfull discharge as measured in the field (Drury et al., 1963; Harvey, 1969). Since the work of Pickup and Warner (1976) numerous authors have added definitions for estimating the most effective or bankfull discharge (Biedenharn, 1994; Biedenharn, 2000; Williams, 1978). For example, Williams (1978) details a method that utilizes stage-discharge calibration curves for calculating bankfull discharge. Using our study sites in the Salmon River basin we will have a unique opportunity to test how differences in precipitation phase influence the frequency and magnitude of effective discharge employing a variety of techniques (e.g. Williams, 1978). This knowledge will provide significant contributions to how hydrograph form affects channel characteristics and will help reveal the potential geomorphic changes that could accompany changes in the dominant phase of precipitation received by a catchment as temperatures continue to warm.

In addition to the ability of identifying potential differences in the frequency and magnitude of effective discharge associated with differences in the dominant phase of precipitation we will be able to calibrate these results in a manner that is typically unavailable to most researchers. This opportunity is provided by the deployment of more than four hundred rocks that have been characterized and equipped with Passive-Integrated-Transponder (PIT) tags into sixteen streams within the Salmon River basin. Twelve of these streams are streams selected for the investigation of precipitation phase on hydrograph form (Chapter 2, Figure 1); the other four, are tributaries to Big Creek which have been sites of ecological and hydrologic investigation for multiple years. Tracking PIT tagged rocks and calculating the frequency and magnitude of effective discharge will allow us to highlight the influence of hydrologic forcing on physical processes occurring within channels.

During the first campaign of rock tracking (summer of 2010) some interesting field observations were made. At some of our sites I noticed that the overall characteristics of the cross-section where the rocks were deployed played an important role in their entrainment or lack thereof. For example, when radio rocks were deployed in channel cross-sections that contained large substrate (i.e. boulder sized substrate) the radio rocks were sheltered and did not experience as much downstream transport as streams where rocks were deployed on a less coarse, more homogenous substrate. Initial observations suggest that selective transport occurred; sheltered rocks were not transported, whereas exposed rocks were transported. These observations have interesting implications and present unique opportunities to investigate some prominent ideas including equal mobility (Parker and Klingeman, 1982), selective entrainment (Komar, 1986), and bed microtopography (Brayshaw, 1985), in the field of sediment transport.

The idea of equal mobility (Parker and Klingeman, 1982) is based on the observation that bedload and typical bed material (referred to as subpavement) are of similar size distributions. Thus the authors assume that the coarse portion of the load must move through a reach at the same rate as the finer portion of the load. If coarse grains are intrinsically more resistant to transport, that is, the critical shear stress required to transport coarse grains is greater than stress needed to transport smaller grains (e.g. Shields diagram, as presented by Bagnold (1941)). It follows then that there is some mechanism that acts to nearly equalize mobility (Parker and Klingeman, 1982). Parker and Klingeman (1982) proposed that equal mobility occurs by proportionally exposing more coarse grains than finer grains to flow through a process caused by vertical winnowing that ultimately produces what they refer to as a pavement (pavement can be thought of as an armor layer, where the bed surface of a river is considerably coarser than the sub-surface). The process of vertical winnowing (not to be confused with downstream winnowing) can be visualized as follows. Imagine that a large grain is dislodged from the bed surface; as a result there is a ‘hole’ of a size roughly equal to the size of the dislodged grain. When this occurs smaller grains may work their way below the pavement and reduce their probability of reerosion. Parker and Klingeman (1982) suggest that this process will occur to the extent necessary to realize equal mobility.

The idea of selective entrainment was most notably presented by Komar (1987) and is strongly related to the relationship revealed by the Shields diagram, where coarse material requires a greater shear stress to be entrained than fine material. Komar (1987) used observations from placer deposits to indicate that coarse material was more resistant to transport than fine material.

The idea of bed microtopography is focused on clusters which are defined as groups of interlocking clasts that form around larger bed particles that present obstructions in an otherwise planar bed (Brayshaw, 1985). There are three principal components to clusters, 1) a large obstacle clast, 2) an upstream stoss deposit and 3) a downstream wake or lee deposit. The obstacle clast is much larger than the grains within either the stoss or lee deposits and the grains within the stoss deposit are typically coarser than grains in the lee deposit (Brayshaw, 1987). Brayshaw (1987) found that threshold velocities required to entrain clast from clusters was greater than velocities needed to entrain ‘exposed’ particles not found within clusters and suggests that bed microtopography can play an important role in delaying incipient motion.

In light of field observations and the potential to contribute to prevalent ideas in the field of sediment transport (equal mobility, selective transport, and bed microtopography) I propose an experiment that involves selective emplacement of radio rocks in a number of our current study streams. Surveys of the channel bed can be performed during times of low flow and patches that contain varying grain size distributions can be identified. Ideally the patch/cluster would contain evidence, through the presence or lack of algal material, of mobility or immobility. With patches identified, strategic grain size distributions of radio rocks can be deployed into the patch. By a strategic grain size distribution I mean a distribution that includes grain sizes that match the distribution of the patch as well as grain sizes that are slightly finer and slightly coarser than the native material of the patch. These patches can be surveyed with some frequency to determine whether or not selective entrainment is occurring. In addition this study would allow us to contribute to the idea of patch dynamics, as stated by Townsend (1989), to the stream ecology community. Townsend (1989) identifies the critical role of refugia (i.e. stable substrate) as sources for recolonization after spates. In the experimental design reviewed above we would likely have the unique opportunity to answer the long sought after question, does moss grow on a rolling stone and if it does or does not, how does this affect stream community dynamics and structure?

3.2.4 Stream Ecology

In effort to answer some of the questions above, the Idaho State University Stream Ecology Center has collected serber and periphyton samples for all study sites (Chapter 2, Figure 1). Preliminary results suggest that the average mass of chlorophyll –a for a given stream is strongly influenced by the time between the sample date and the flood peak (Figure 1). Furthermore, variability in mean annual streamflow and the median distance of travel of tracer rocks seem to generate variation in the mean amount of chlorophyll-a (Figure 2). For example, rain dominated watersheds display the greatest variability of Interannual mean streamflow (mean annual streamflow from one year to the next) and median distance travelled by tracer rocks. We posit that the variability in hydrologic conditions and sediment transport resulted in the greatest variability in Interannual mean chlorophyll-a values. An initial hypothesis is that greater variability in hydrologic and geomorphic forcings in rain dominated watersheds will result in greater variability in primary resources for aquatic organisms, which will have important consequences for aquatic community structure in rain dominated streams. This hypothesis is confounded by many environmental aspects (stream temperature, stream riparian zone density, land use practices, etc.) and has a variety of implications for aquatic organisms in low elevation streams. Although these results are preliminary and warrant further investigation, there are interesting opportunities that arise when monitoring streams that experience differences in the frequency and magnitude of disturbance.

For example, the intermediate disturbance hypothesis predicts that an intermediate level of disturbance results in the greatest species diversity (Connell, 1978; Grime, 1973; Resh et al. 1988; Ward and Stanford, 1983), however, at the extreme ends of the disturbance continuum, competitive exclusion and physical elimination will result in diversity loss. Although this hypothesis has been widely accepted by the lotic community (Resh et al. 1988; Ward and Stanford, 1983) experimental manipulation of substrate patches does not lend support to the intermediate disturbance hypothesis (Reice, 1984; Robinson and Minshall, 1986). In their review of the role of disturbance in stream ecology, Resh et al. (1988) suggests that the dynamic equilibrium model is the hypothesis most applicable to stream communities. The dynamic equilibrium model (Huston, 1978) suggests that stream community structure reflects a balance between the rate of competitive exclusion, which is a function of the productivity of the environment and the frequency of population reduction (i.e. disturbance). If the interval between disturbances is shorter than the time needed for competitive exclusion then diversity levels should be maintained at a high level, if however, disturbance is infrequent, increases in the growth rates of strong competitors within the population will likely result in a loss in species diversity. Although Resh et al. (1988) suggest that the dynamic equilibrium model is the most applicable for understanding the structure and dynamics of stream communities they provide no convincing evidence in its support (Russel, 1995).

The sites that we study in the Salmon River experience differences in the magnitude, duration, intensity, and seasonality of hydrologic forcings (i.e. disturbance), thus we have a unique opportunity to contribute to the long-term debate over the role of disturbance in stream ecology.

3.2.5 Hypsometry

Hypsometry is the study of the distribution of elevations over some discernible finite area. The shape of a hypsometric curve, its rate of change and its integral reflect the erosional history of the region and, if elevation is normalized, its relative age (Schumm, 1956; Strahler, 1974). Hypsometry has the potential to be a very useful tool for predicting the areal percentage of a basin that could be affected by an upward migrating snowline (Fig 3.). This concept is not necessarily a new idea as it has been used by glaciologist in analysis of equilibrium line altitudes (Anderson and Anderson, 2010). However, with the availability of high spatial resolution (1km^2) physically modeled meteorological data from the Snow Data Assimilation System (SNODAS, (NOHRSC, 2004)) and the widespread availability of high resolution elevation data (i.e. National Elevation Dataset (NED, (Gesch et al. 2009)) new opportunities arise for understanding how complex topography, with non-uniform elevation distributions, influences the accumulation of snow and subsequent hydrologic processes.

Using meteorological data from SNODAS and elevation data from the NED we are able to evaluate the controls of elevation range and distribution on the accumulation of snow water equivalent. In addition, by using meteorological data in conjunction with hypsometric techniques we have the ability to understand and predict how changes in snowline elevations could affect the phase and amount of precipitation that a given elevation zone receives. Understanding the elevation distribution of a watershed and its influence on meteorological processes affords unique insights into the potential evolution of hydrologic systems with expected warmer temperatures. I suggest that the analysis reviewed above be applied to large mountainous watersheds throughout the western U.S. The coupling of high resolution meteorological and topographic data with hypsometric techniques allows evaluation of the “hypsometric” sensitivity of a catchment to rising snowlines.

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3.4 Figures

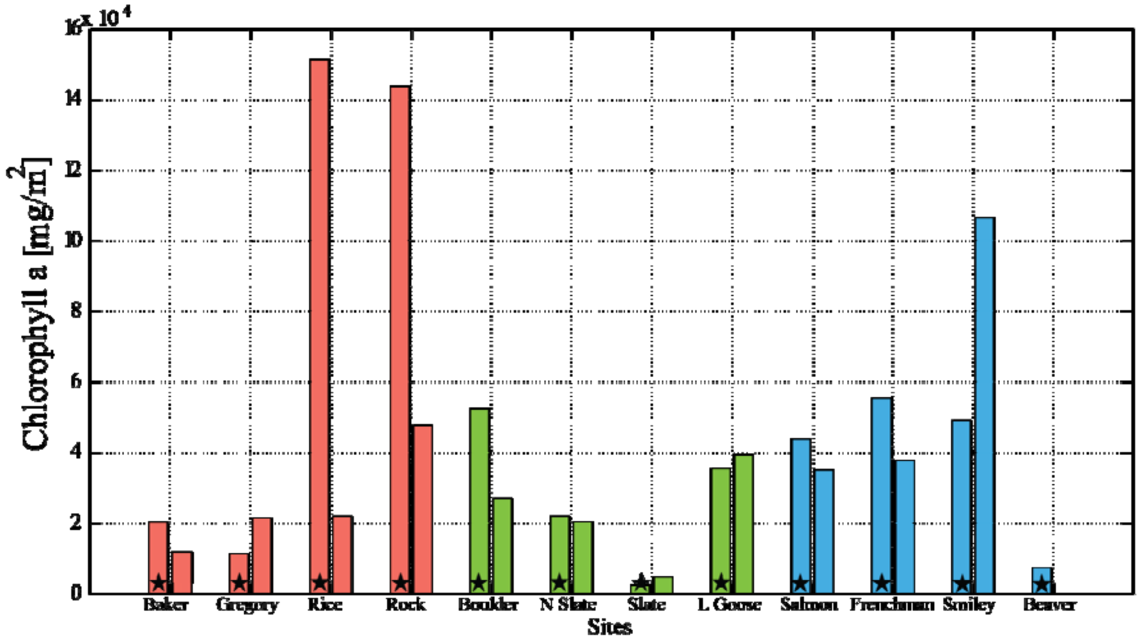


Figure. 1. Mean chlorophyll-a mass for study sites for 2009 and 2010. Stars indicate 2009 sampling. Red bars are rain dominated streams, green are mixed rain and snow and blue are snow dominated. The time between peak flows and sampling was much greater for rain dominated sites in the 2009 year than during 2010 sampling.

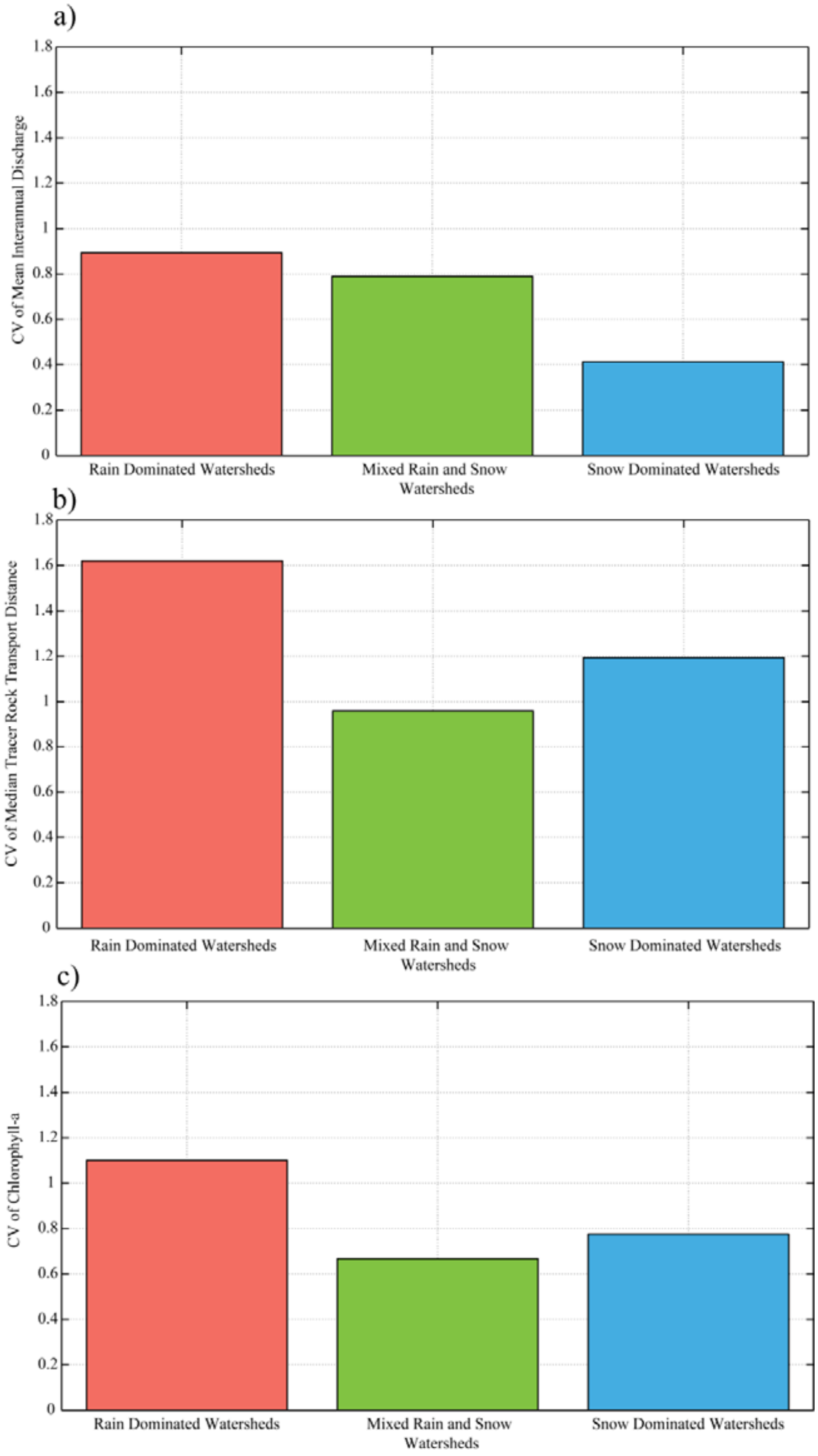


Figure 2. Coefficient of variation for (a) Interannual mean streamflow, (b) median distance travelled by tracer rocks, and (c) Interannual mean chlorophyll-a for 12 study sites. Variation in the hydrologic and geomorphic conditions generates variations in chlorophyll-a mass.

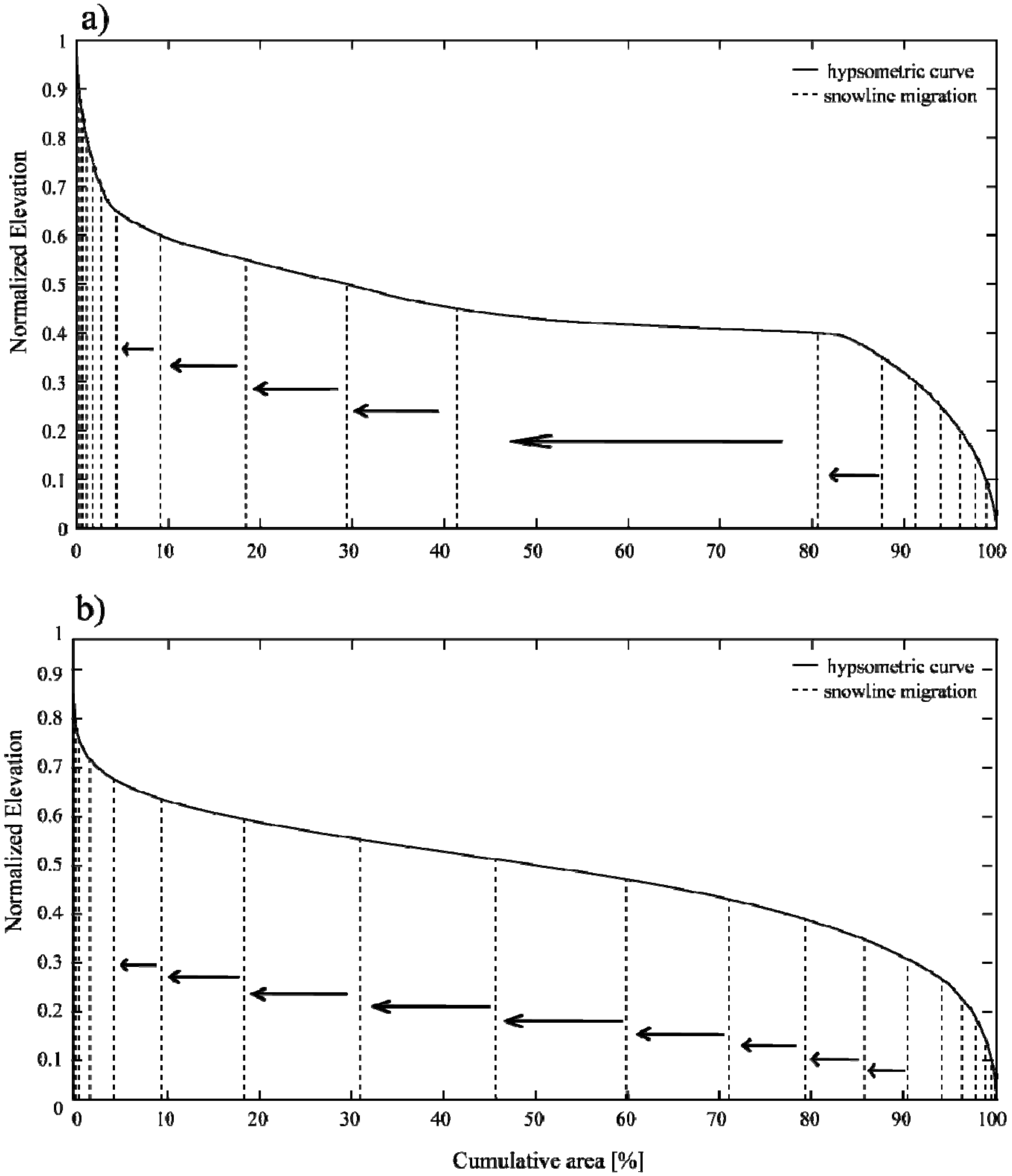
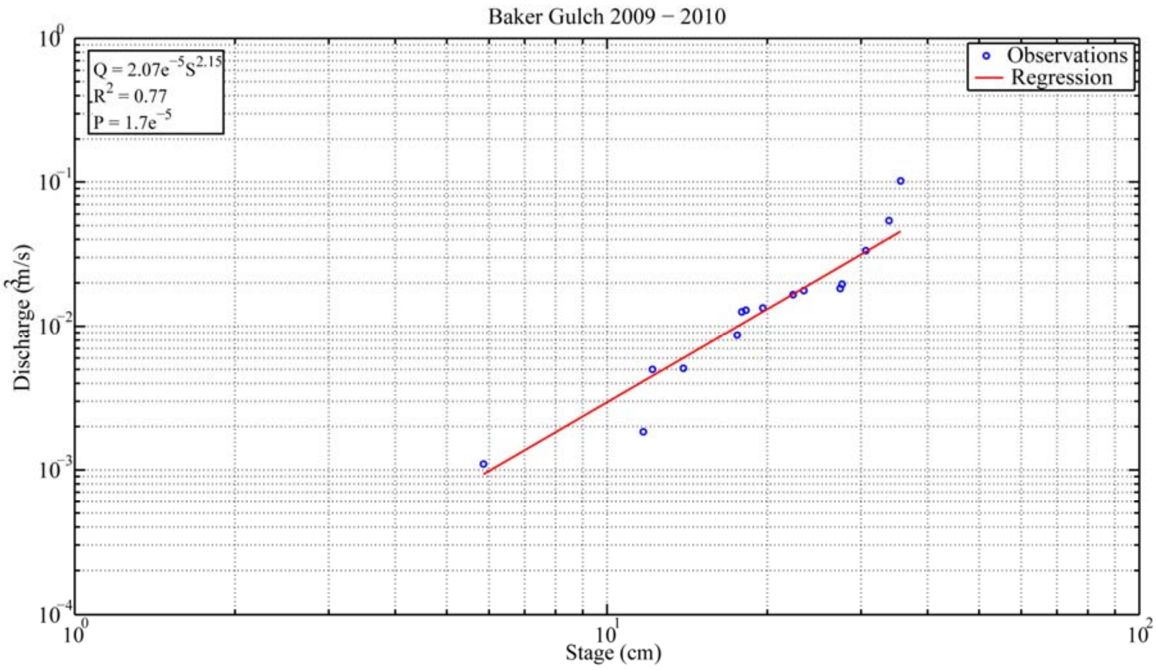


Figure 3. The elevation distribution of a watershed influences its sensitivity to rising snowlines (a). Note how the areal change in snow cover is greatest for regions of low slope on the hypsometric curve. The lower hypsometric curve (b) is for the Salmon River basin. Snowline steps are 0.05 units.

4 Appendix 1: Discharge rating curves for study tributaries

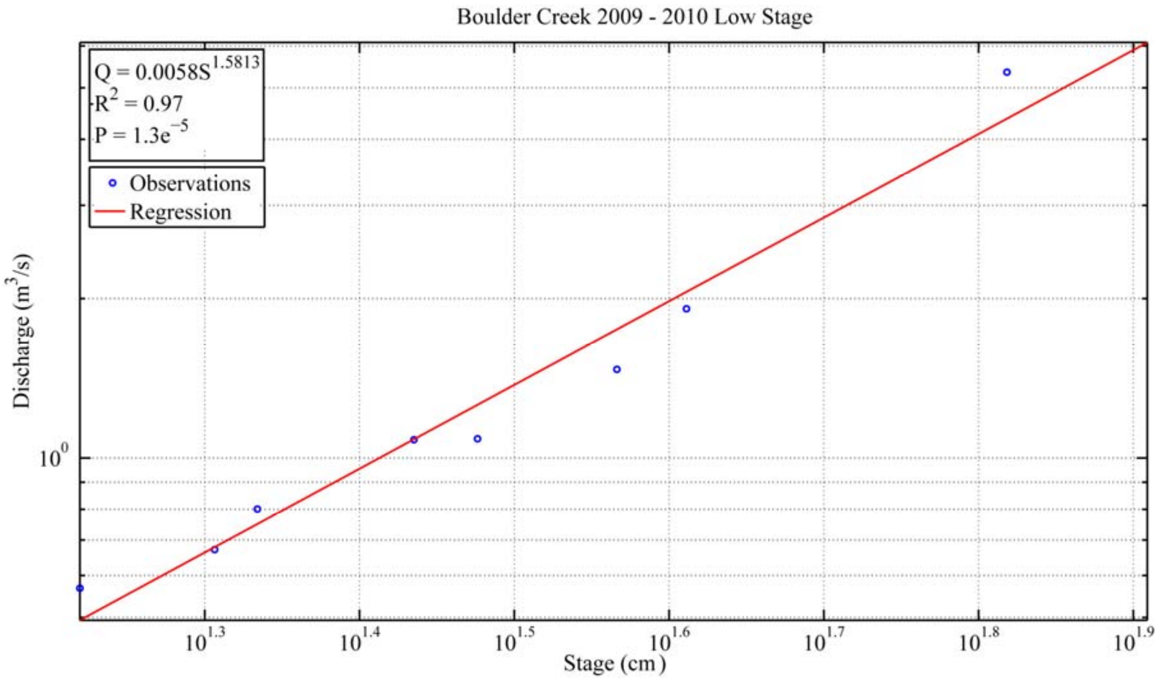
This appendix provides the stage - discharge relationships for the streams we monitored. Plots provided display the stage and discharge values used to produce the regression equation(s) that were used for discharge calibration. The regression equation(s) are provided for all streams and use the variables Q (discharge) and S (stage). Both the stage and discharge data are presented as the log of stage and the log of discharge. Discharge is on the y-axis and stage level is on the x-axis for all streams. In addition the R^2 and P statistics are provided. A table follows each graph that provides the stage and discharge data for that stream.

Baker Gulch

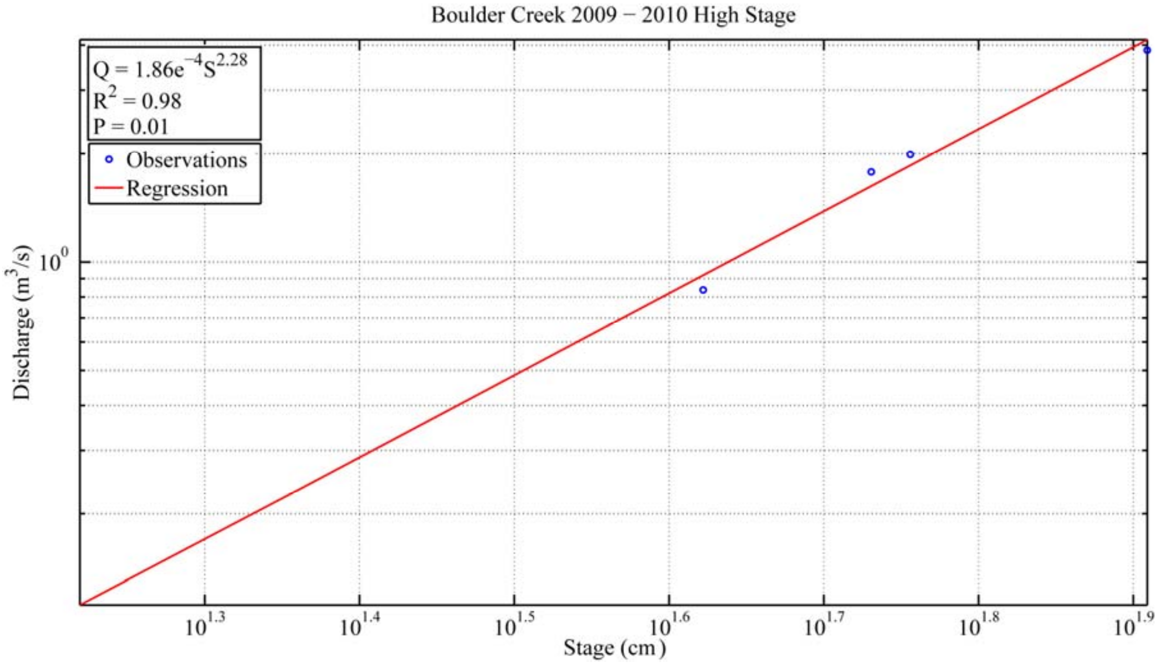


Date	Discharge (m^3/s)	Stage (cm)
5/14/09 15:30	0.1015	35.5989
5/17/09 15:36	0.0539	33.8560
5/25/09 12:38	0.0177	30.6164
6/1/09 16:11	0.0166	27.4274
6/2/09 13:04	0.0196	27.6453
6/10/09 11:04	0.0334	23.4119
6/16/09 16:23	0.0134	19.6096
6/25/09 16:42	0.0087	17.5549
6/29/09 9:41	0.0050	17.9063
7/9/09 10:55	0.0051	13.9090
7/15/09 10:39	0.0018	12.1639
2/26/10 18:17	0.0129	18.2293
5/6/10 14:22	0.0183	22.3624
6/3/10 12:22	0.8683	35.0079
6/29/10 8:42	0.0909	21.0153
7/18/10 15:20	0.0126	11.6957
8/13/10 14:46	0.0011	5.8597

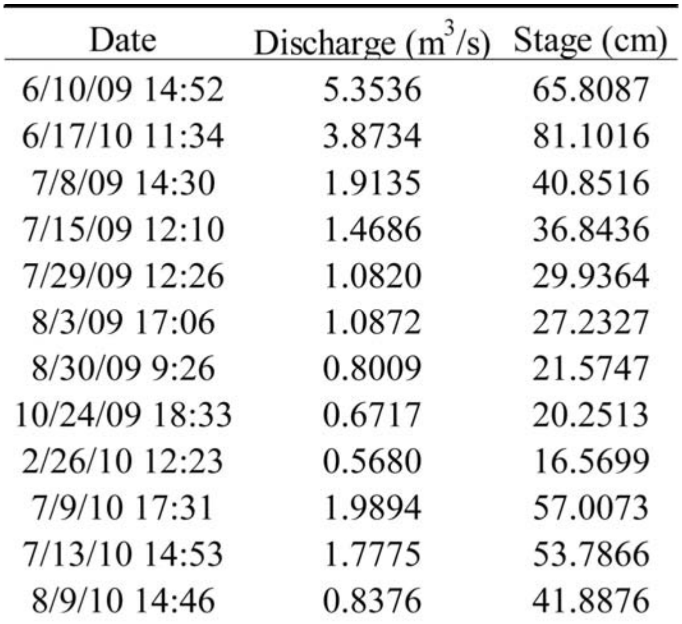
Boulder Creek



Boulder Creek 2009 - 2010 Low Stage

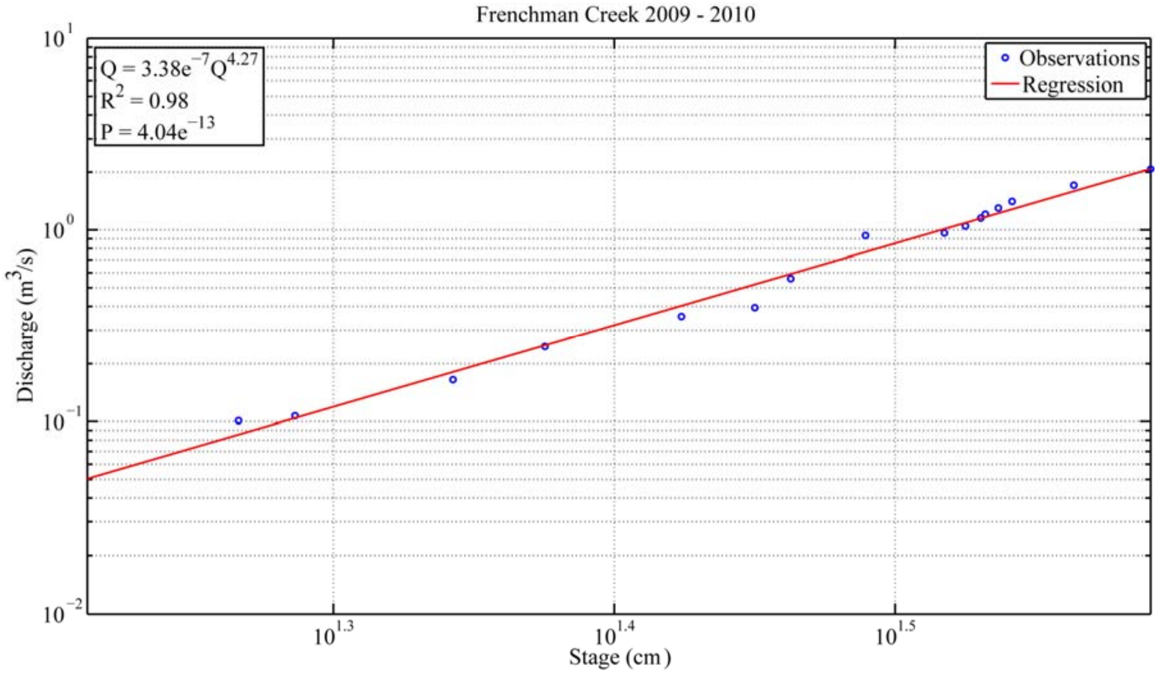


Boulder Creek 2009 − 2010 High Stage



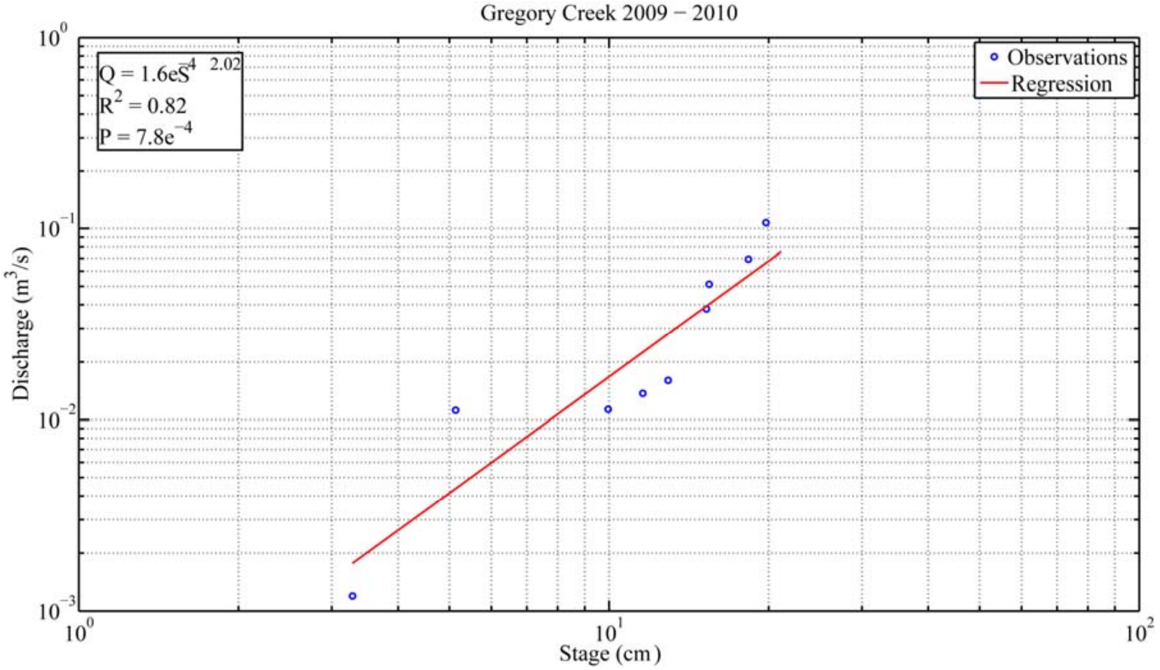
Date	Discharge (m^3/s)	Stage (cm)
6/10/09 14:52	5.3536	65.8087
6/17/10 11:34	3.8734	81.1016
7/8/09 14:30	1.9135	40.8516
7/15/09 12:10	1.4686	36.8436
7/29/09 12:26	1.0820	29.9364
8/3/09 17:06	1.0872	27.2327
8/30/09 9:26	0.8009	21.5747
10/24/09 18:33	0.6717	20.2513
2/26/10 12:23	0.5680	16.5699
7/9/10 17:31	1.9894	57.0073
7/13/10 14:53	1.7775	53.7866
8/9/10 14:46	0.8376	41.8876

Frenchman Creek



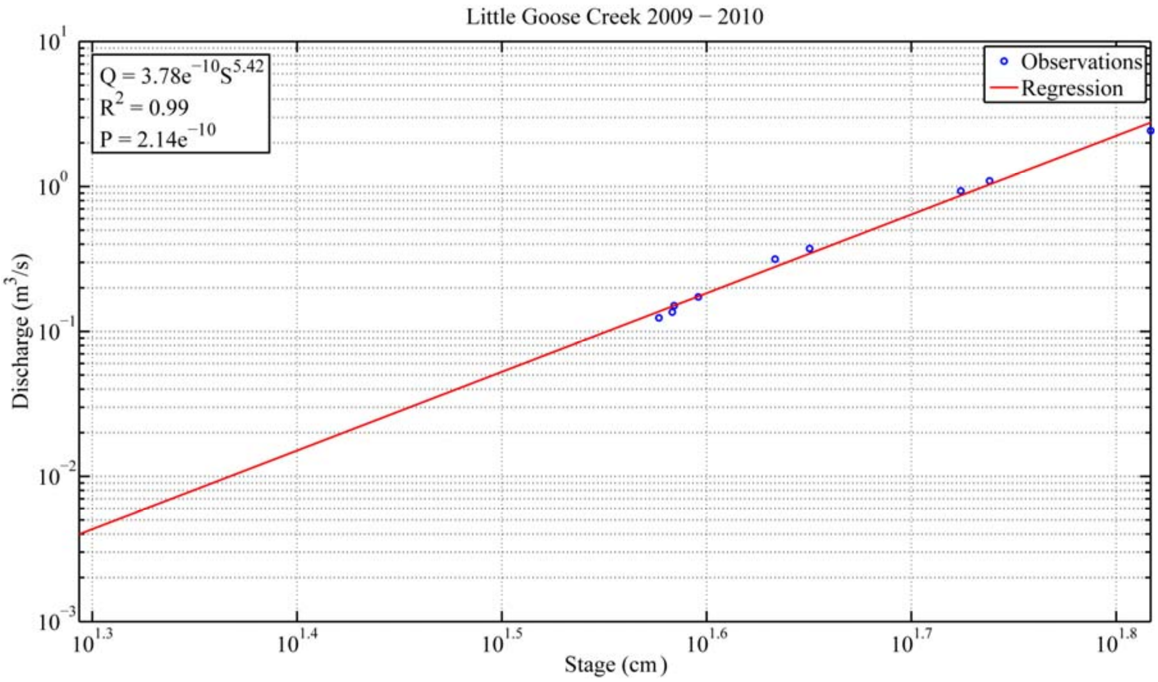
Date	Discharge (m^3/s)	Stage (cm)
5/15/09 19:40	0.5580	28.1860
5/16/09 11:30	0.3540	26.5397
5/21/09 11:47	0.9359	32.9294
5/23/09 19:14	1.2994	34.4160
5/27/09 9:42	1.2076	34.0506
6/3/09 15:00	1.7088	36.6127
6/8/09 13:51	1.4074	34.8089
6/17/09 17:29	1.1508	33.4987
7/1/09 10:34	0.9647	30.8653
7/7/09 10:24	0.3941	29.0312
7/18/09 20:10	0.2467	23.7336
8/28/09 20:25	0.1009	18.4614
10/23/09 19:04	0.1071	19.3339
2/5/10 9:26	0.1646	16.3074
6/9/10 12:28	2.0800	38.9900
7/1/10 11:22	1.0473	33.9254
8/5/10 18:16	0.1652	22.0070

Gregory Creek



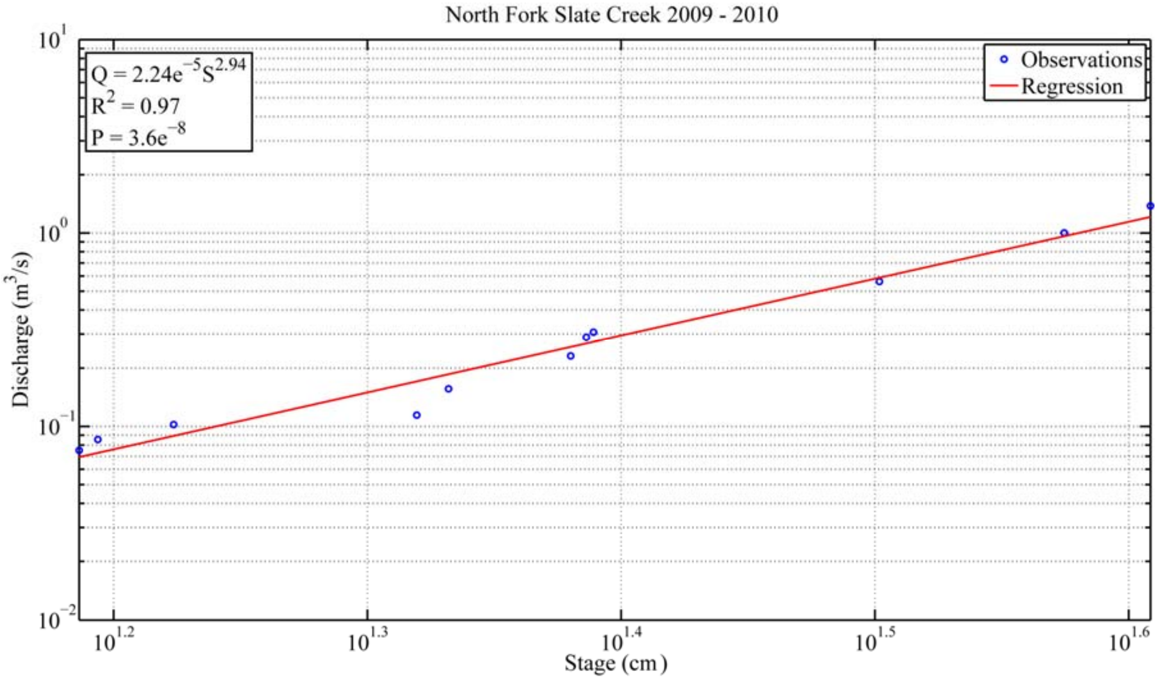
Date	Discharge (m^3/s)	Stage (cm)
5/14/09 18:30	0.1073	19.7677
5/17/09 16:11	0.0513	18.3197
5/25/09 11:27	0.0380	15.2740
6/1/09 19:32	0.0137	12.9326
6/10/09 9:56	0.0160	9.9614
2/26/10 17:33	0.0112	11.5861
5/16/10 15:01	0.0694	15.4506
6/3/10 11:23	0.2520	21.1237
6/29/10 7:52	0.1329	13.3910
7/18/10 10:41	0.0113	5.1361
8/13/10 11:04	0.0012	3.2819

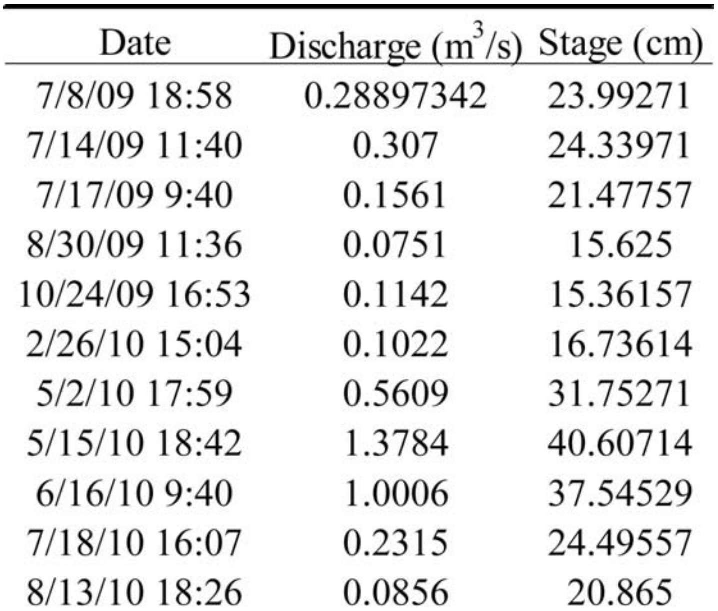
Little Goose Creek



Date	Discharge (m^3/s)	Stage (cm)
5/14/09 10:50	1.3994	24.9913
5/16/09 16:31	1.3541	21.6217
5/24/09 11:16	1.4120	28.1109
5/26/09 11:30	0.9930	23.5493
6/1/09 15:35	0.8446	20.0377
6/2/09 15:52	0.7807	19.6595
7/23/09 19:48	0.1728	39.4427
8/29/09 12:46	0.1361	37.7361
10/25/09 8:23	0.1506	38.3026
2/26/10 11:06	0.1241	38.3829
5/2/10 15:03	1.0920	54.7223
5/15/10 14:50	0.9297	52.9823
6/10/10 13:41	2.4295	65.5829
7/7/10 17:27	0.3737	44.6987
7/13/10 9:17	0.3153	42.9931

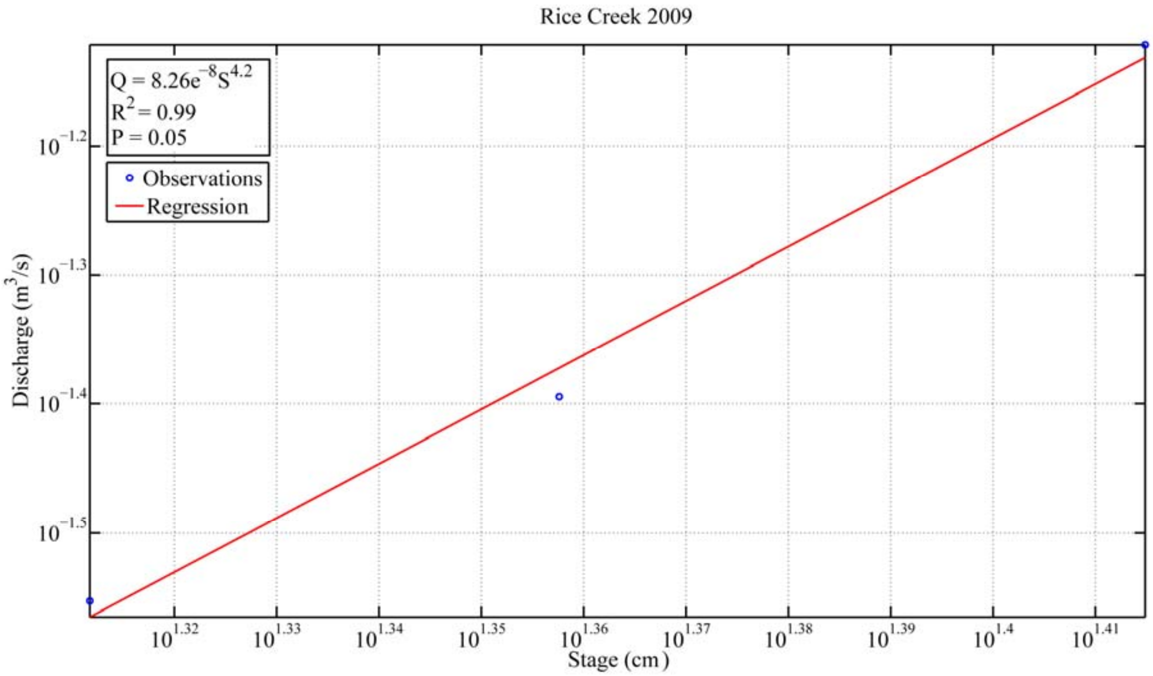
North Fork of Slate Creek

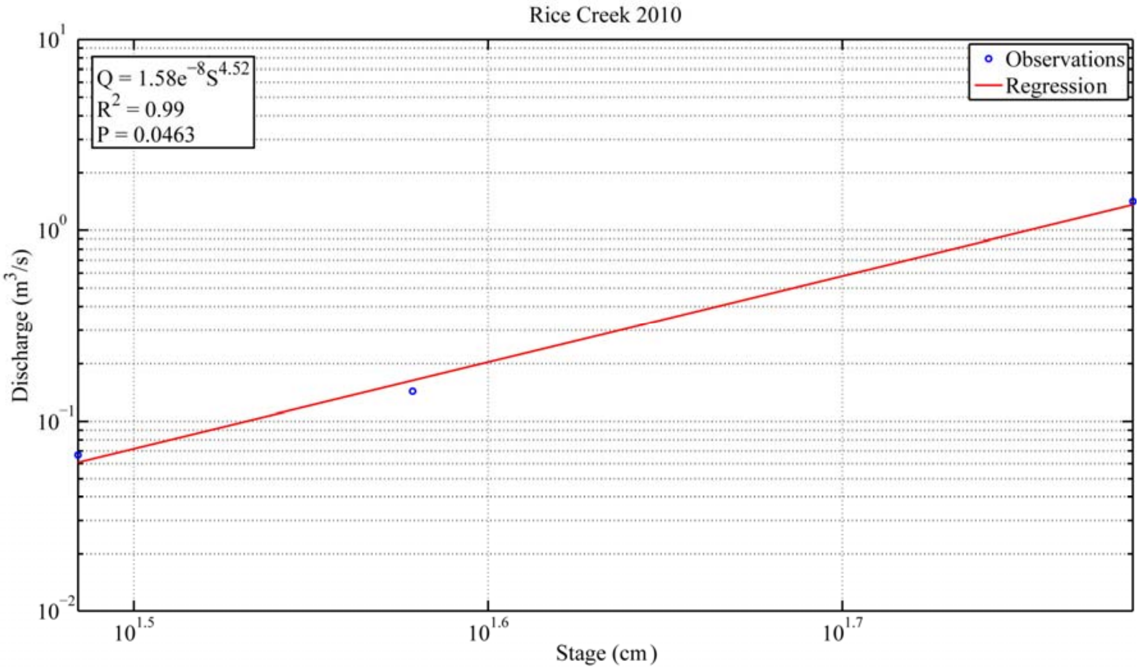


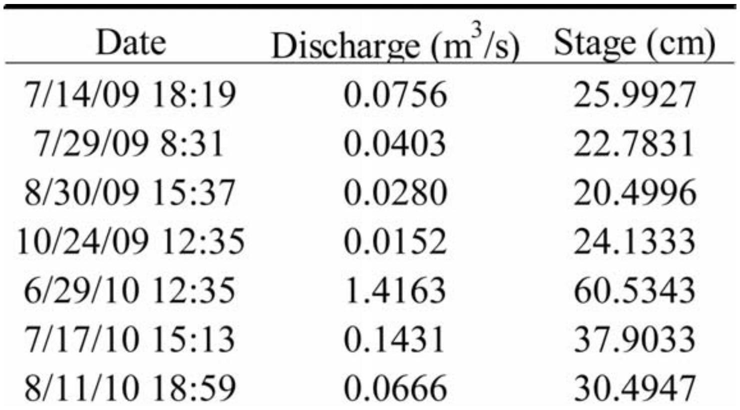


Date	Discharge (m^3/s)	Stage (cm)
7/8/09 18:58	0.28897342	23.99271
7/14/09 11:40	0.307	24.33971
7/17/09 9:40	0.1561	21.47757
8/30/09 11:36	0.0751	15.625
10/24/09 16:53	0.1142	15.36157
2/26/10 15:04	0.1022	16.73614
5/2/10 17:59	0.5609	31.75271
5/15/10 18:42	1.3784	40.60714
6/16/10 9:40	1.0006	37.54529
7/18/10 16:07	0.2315	24.49557
8/13/10 18:26	0.0856	20.865

Rice Creek

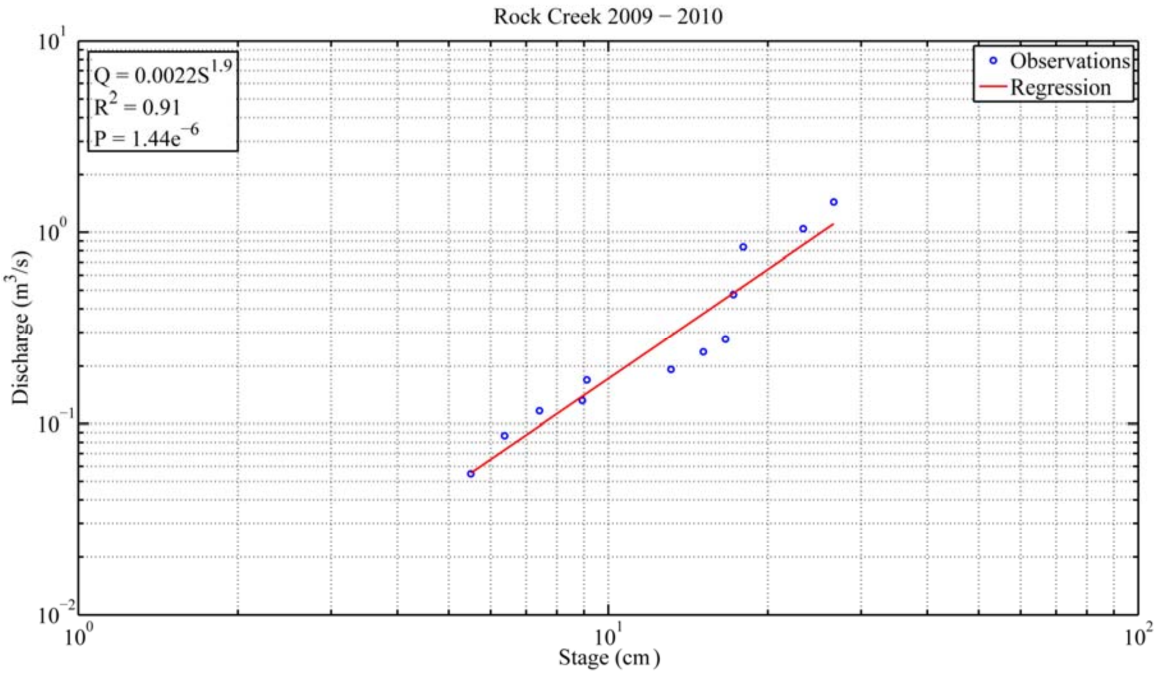

Rice Creek 2009

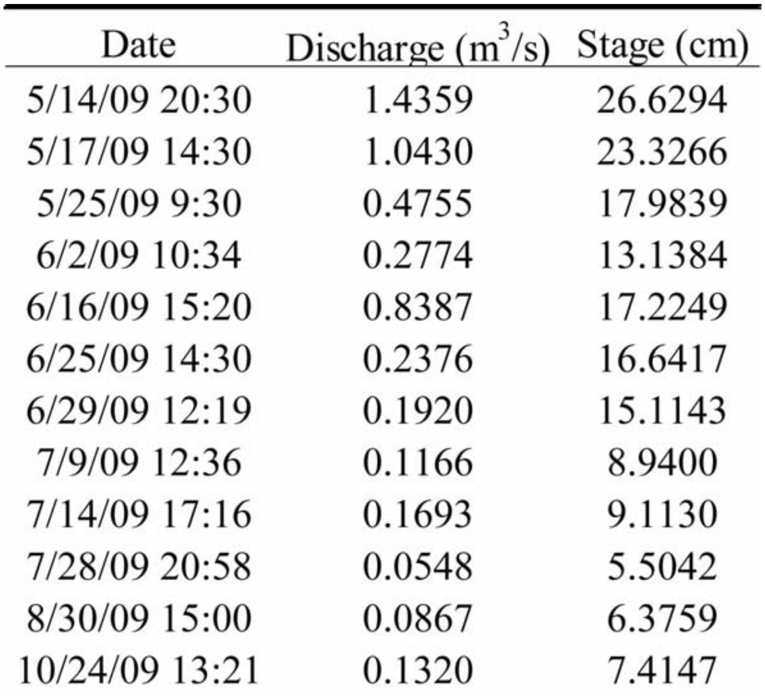

Rice Creek 2010



Date	Discharge (m^3/s)	Stage (cm)
7/14/09 18:19	0.0756	25.9927
7/29/09 8:31	0.0403	22.7831
8/30/09 15:37	0.0280	20.4996
10/24/09 12:35	0.0152	24.1333
6/29/10 12:35	1.4163	60.5343
7/17/10 15:13	0.1431	37.9033
8/11/10 18:59	0.0666	30.4947

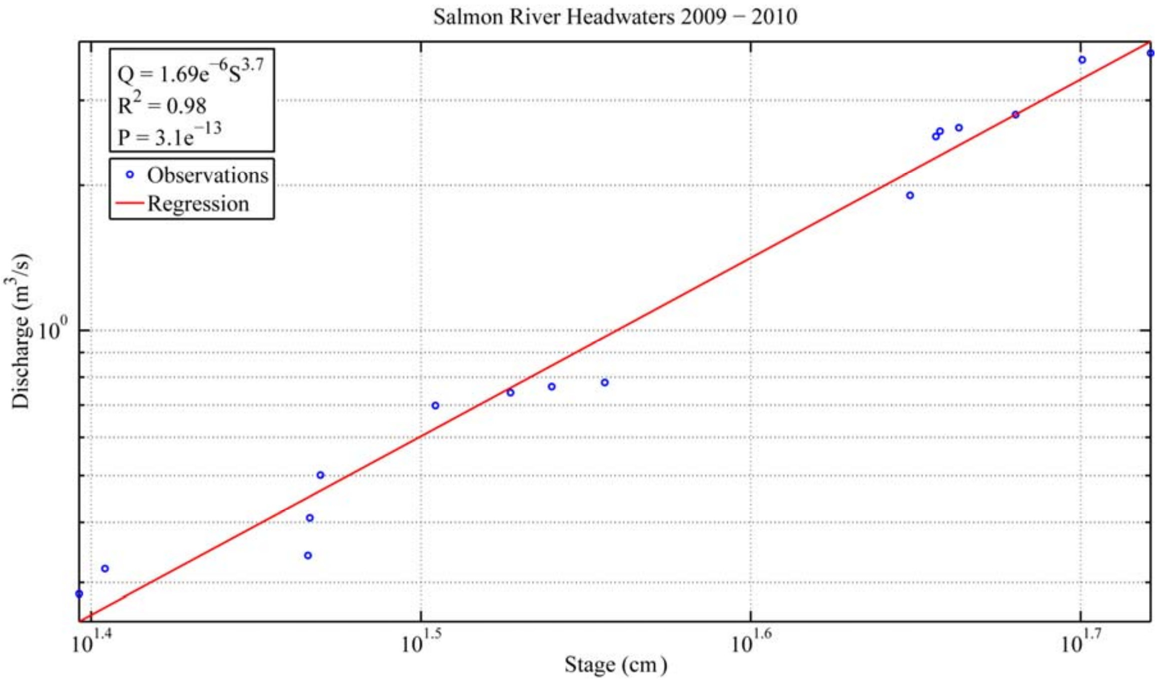
Rock Creek

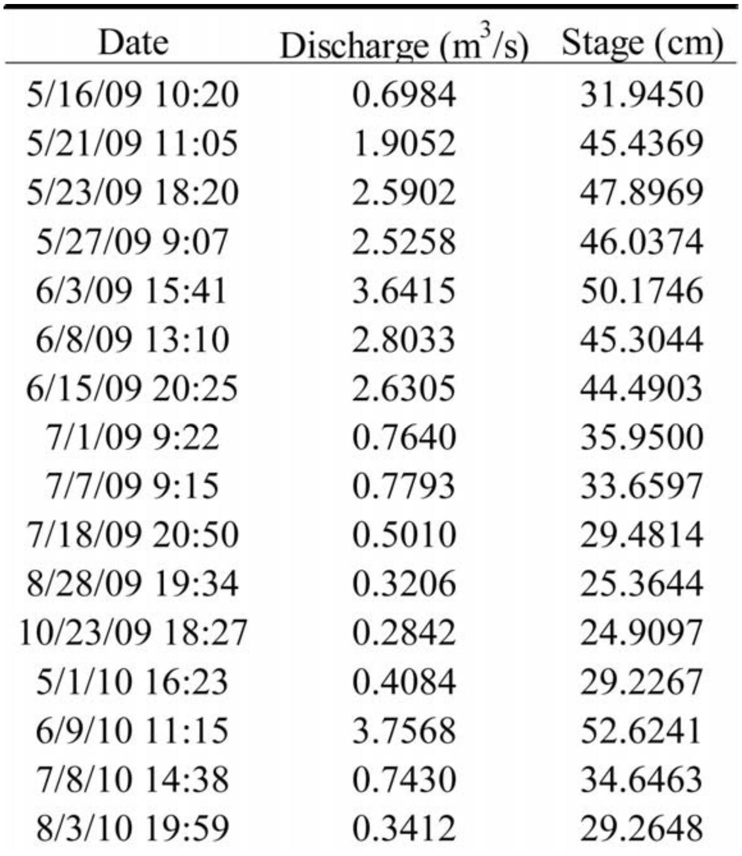




Date	Discharge (m^3/s)	Stage (cm)
5/14/09 20:30	1.4359	26.6294
5/17/09 14:30	1.0430	23.3266
5/25/09 9:30	0.4755	17.9839
6/2/09 10:34	0.2774	13.1384
6/16/09 15:20	0.8387	17.2249
6/25/09 14:30	0.2376	16.6417
6/29/09 12:19	0.1920	15.1143
7/9/09 12:36	0.1166	8.9400
7/14/09 17:16	0.1693	9.1130
7/28/09 20:58	0.0548	5.5042
8/30/09 15:00	0.0867	6.3759
10/24/09 13:21	0.1320	7.4147

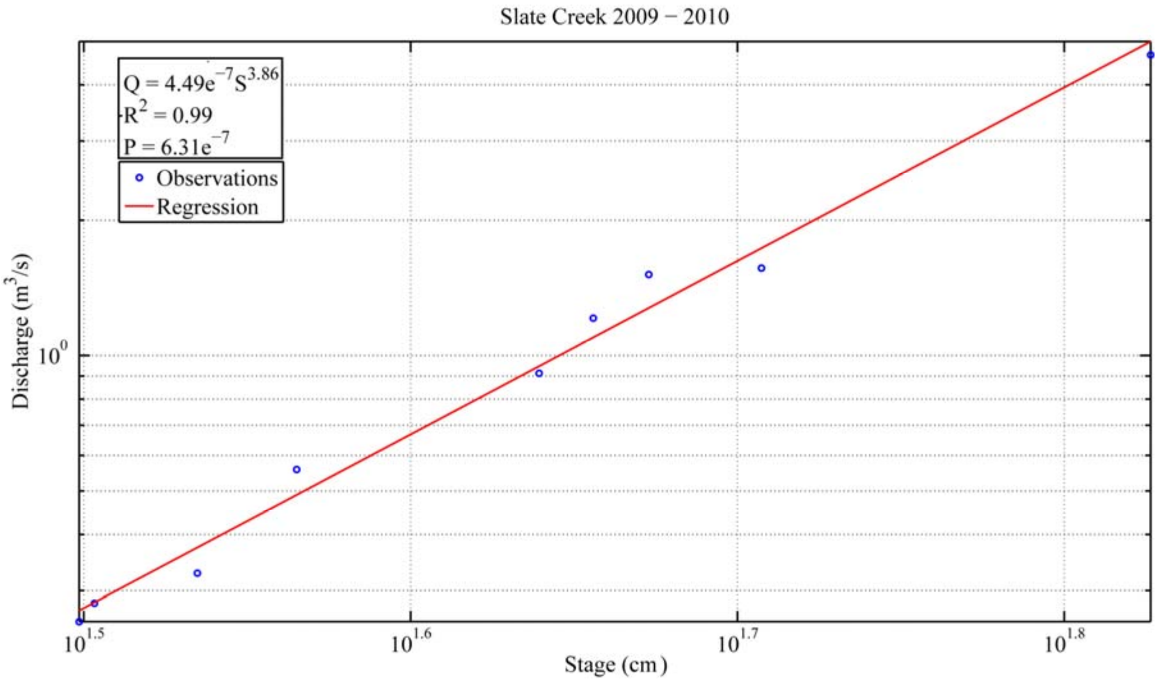
Salmon River Headwaters

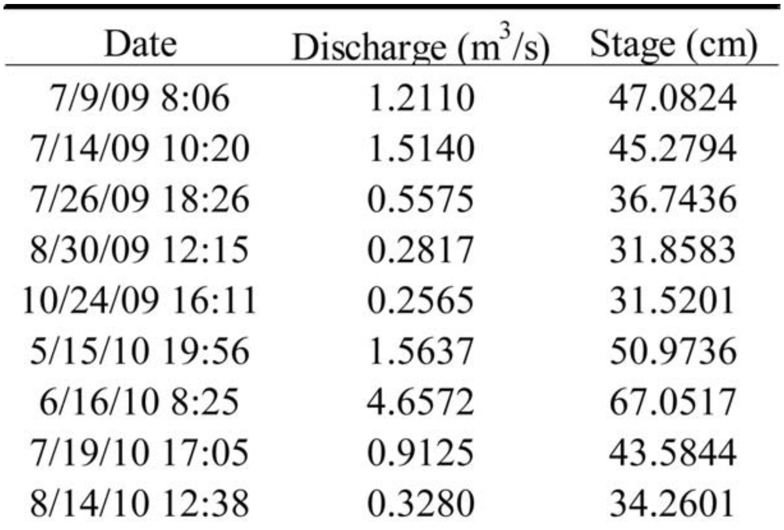




Date	Discharge (m^3/s)	Stage (cm)
5/16/09 10:20	0.6984	31.9450
5/21/09 11:05	1.9052	45.4369
5/23/09 18:20	2.5902	47.8969
5/27/09 9:07	2.5258	46.0374
6/3/09 15:41	3.6415	50.1746
6/8/09 13:10	2.8033	45.3044
6/15/09 20:25	2.6305	44.4903
7/1/09 9:22	0.7640	35.9500
7/7/09 9:15	0.7793	33.6597
7/18/09 20:50	0.5010	29.4814
8/28/09 19:34	0.3206	25.3644
10/23/09 18:27	0.2842	24.9097
5/1/10 16:23	0.4084	29.2267
6/9/10 11:15	3.7568	52.6241
7/8/10 14:38	0.7430	34.6463
8/3/10 19:59	0.3412	29.2648

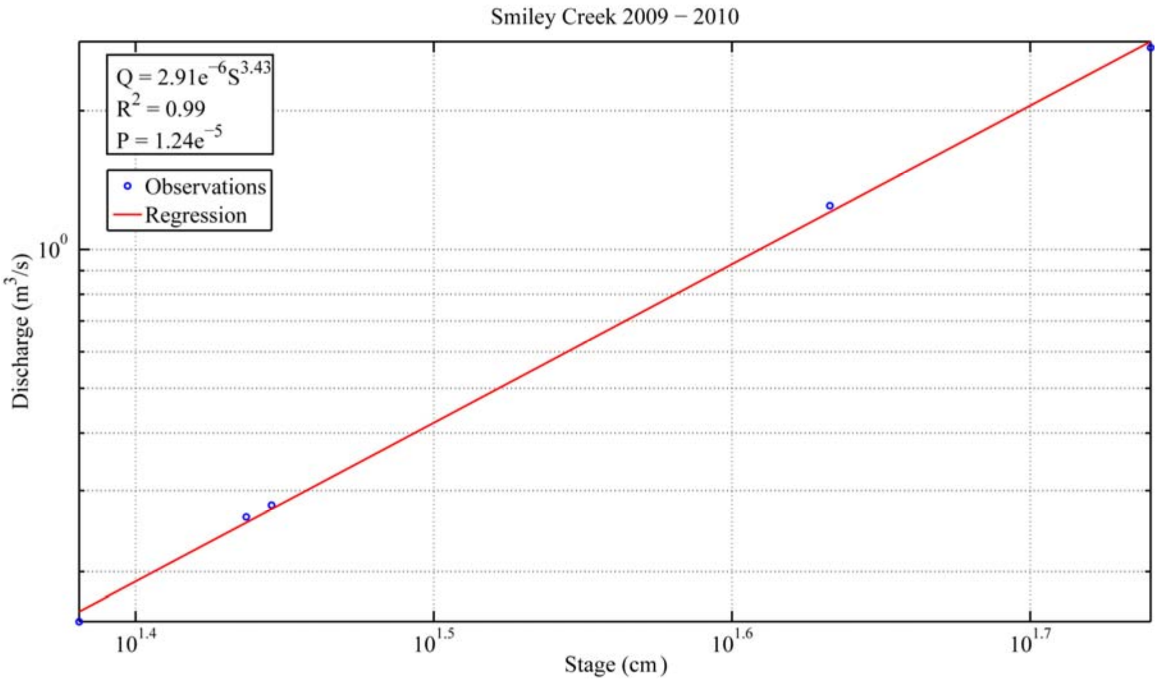
Slate Creek

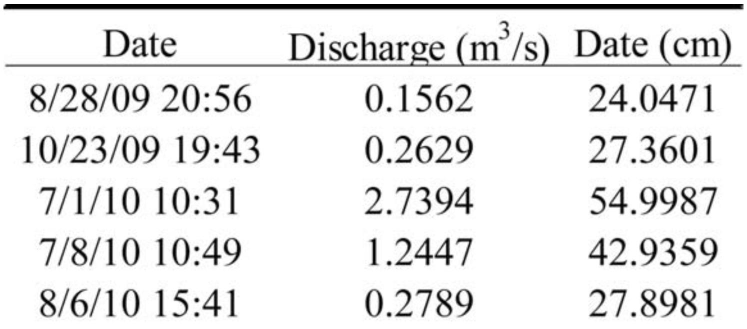




Date	Discharge (m^3/s)	Stage (cm)
7/9/09 8:06	1.2110	47.0824
7/14/09 10:20	1.5140	45.2794
7/26/09 18:26	0.5575	36.7436
8/30/09 12:15	0.2817	31.8583
10/24/09 16:11	0.2565	31.5201
5/15/10 19:56	1.5637	50.9736
6/16/10 8:25	4.6572	67.0517
7/19/10 17:05	0.9125	43.5844
8/14/10 12:38	0.3280	34.2601

Smiley Creek





Date	Discharge (m^3/s)	Date (cm)
8/28/09 20:56	0.1562	24.0471
10/23/09 19:43	0.2629	27.3601
7/1/10 10:31	2.7394	54.9987
7/8/10 10:49	1.2447	42.9359
8/6/10 15:41	0.2789	27.8981

5 Multiple Linear Regression Error Analysis

This appendix provides the methodology used to assess the error associated with the multiple linear regressions used to fill gaps and extend streamflow records. The initial step in the analysis was to identify streams near our study sites that had more complete/longer discharge records. The streams with more complete records were plotted against the stream to be modeled to examine the strength of correlation (R^2) and its significance (P value) (Figure 1). In nearly all cases the multiple linear regression was chosen over a bivariate relationship between single streams (Table 1). Plots of the predicted discharge (from multiple linear regression) values were plotted against measured discharge to ensure high correlation (Figure 2). In addition, we calculated residuals between the modeled and observed discharge to identify where the relationship exhibited the poorest correlation (Figure 3). Not surprisingly the model exhibited the greatest inaccuracy at higher discharge values. The final step was to use the multiple linear regression equation and the streamflow records without gaps to generate discharge values (Figure 4). A table follows the error analysis example plots that details the time periods and streams used to fill gaps/and or extend records (Table 1).

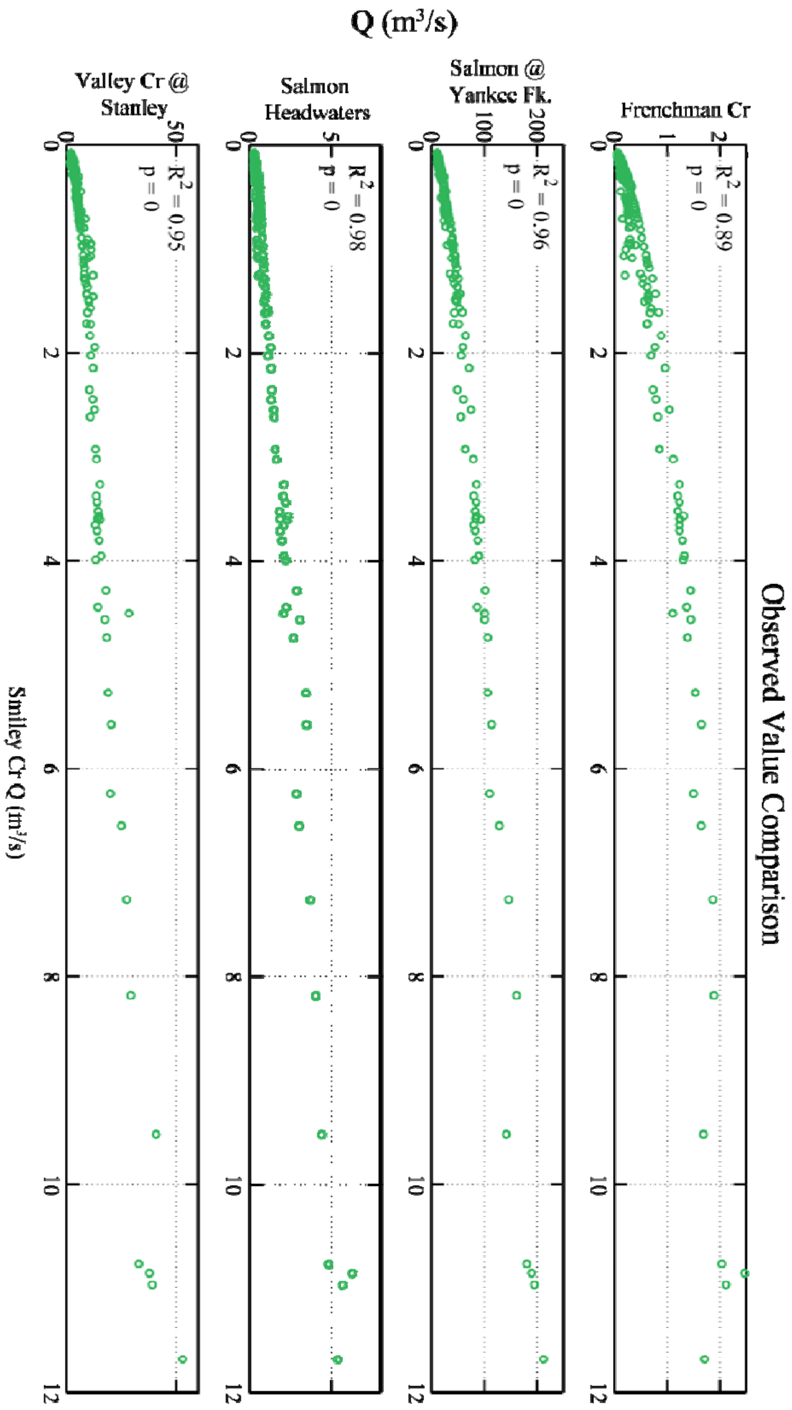


Figure 1. Smiley Creek discharge plotted against discharge of nearby streams with more complete records. The first step for generating a multiple linear regression was to ensure that there was a linear relationship with high correlation between the stream with gaps and the predictor streams. Note that the correlation (R^2) is high in all cases and significant (P value).

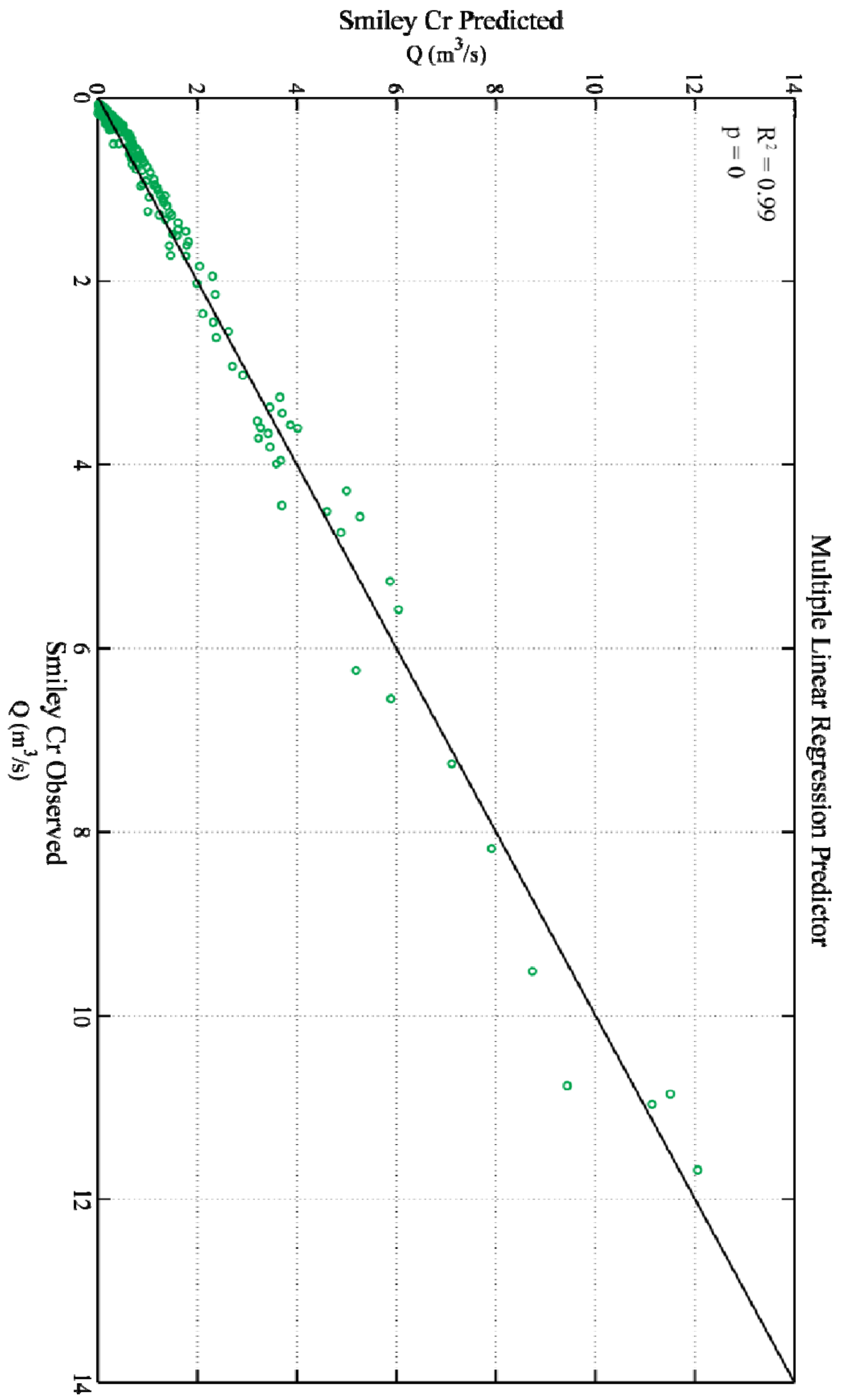


Figure 2: Smiley Creek predicted discharge plotted against Smiley Creek observed discharge with one to one line shown. Note that the correlation is strong and statistically significant.

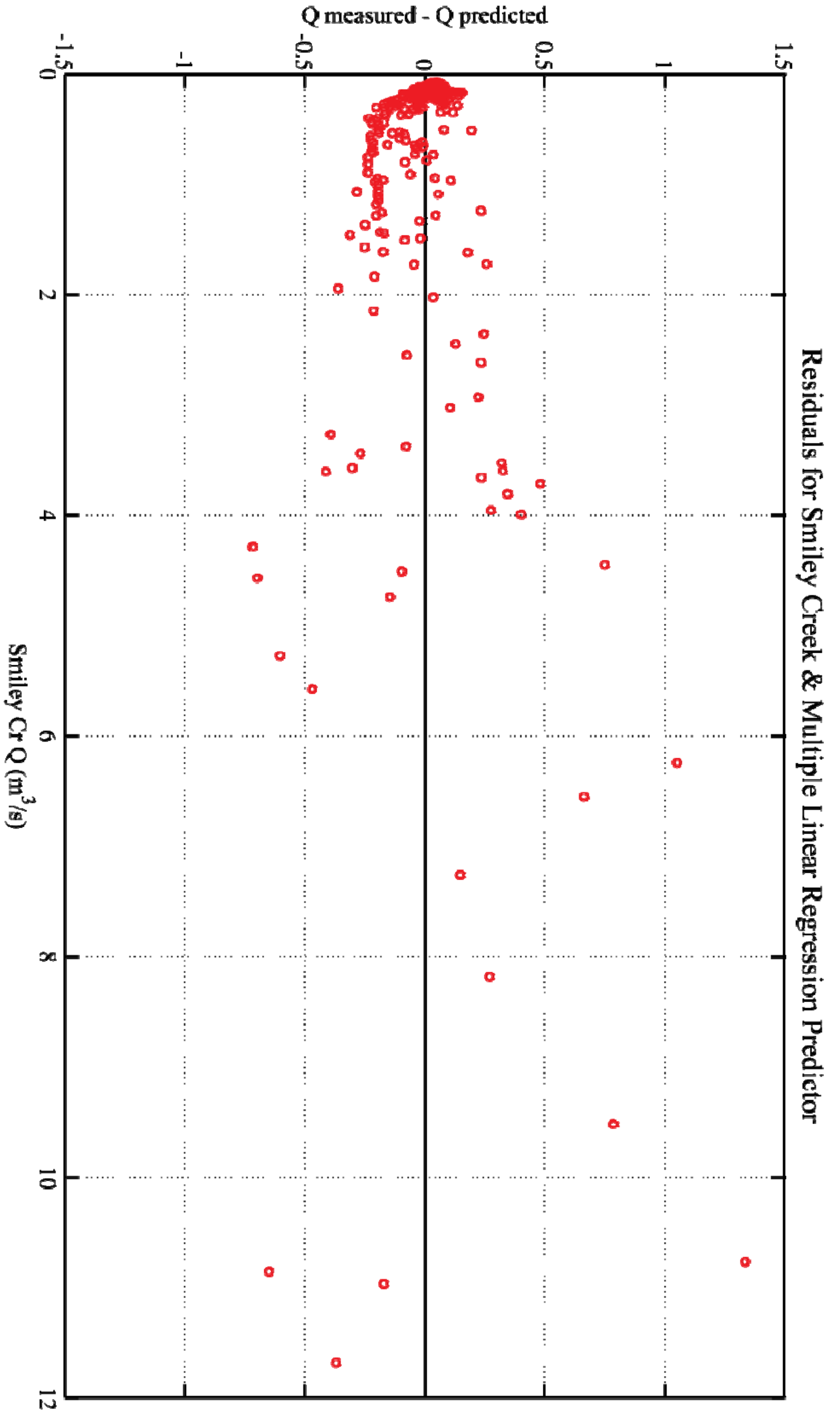


Figure 3: Residuals for Smiley Creek multiple linear regression (Smiley Creek measured discharge - Smiley Creek predicted discharge). Positive values indicate that the regression equation is under-predicting the discharge value and negative values indicate that it is over-predicting.

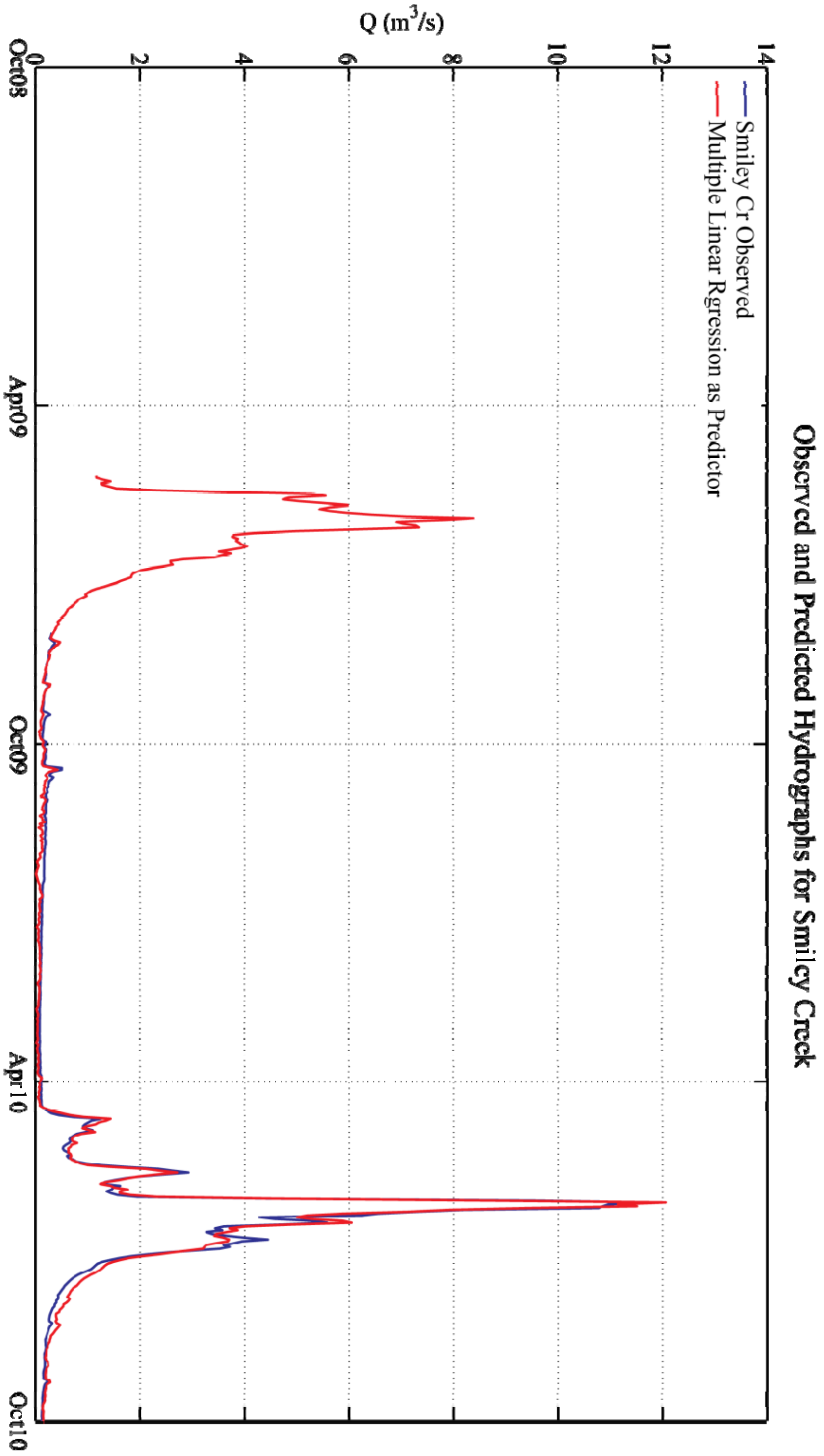


Figure 4: Observed hydrograph (blue line) and predicted hydrograph (red). Note that the predicted timing of events matches the timing of observed events well; the predicted hydrograph over-predicts peak runoff for spring 2010.

Baker Gulch Regression Details		
Streams Used for Regression	**Start Date**	**End Date**
Tucannon River Near Starbuck, WA	10/1/2008	5/14/2009
Webb Creek Near Sweetwater, ID	10/1/2008	5/14/2009
Sweetwater Creek at Sweetwater, ID	10/1/2008	5/14/2009
Tucannon River Near Starbuck, WA	8/1/2009	2/26/2010
Webb Creek Near Sweetwater, ID	8/1/2009	2/26/2010
Sweetwater Creek at Sweetwater, ID	8/1/2009	2/26/2010
Rice Creek	8/1/2009	2/26/2010
Rock Creek	8/1/2009	2/26/2010

Beaver Creek Regression Details		
Streams Used for Regression	**Start Date**	**End Date**
Valley Creek at Stanley, ID	10/1/2008	5/16/2009
Salmon River BL Yankee Fork NR Clayton, ID	10/1/2008	5/16/2009
Valley Creek at Stanley, ID	9/30/2009	5/9/2010
Salmon River BL Yankee Fork NR Clayton, ID	9/30/2009	5/9/2010
Frenchman Creek, ID	9/30/2009	5/9/2010
Salmon River Headwaters	9/30/2009	5/9/2010
Smiley Creek	9/30/2009	5/9/2010
Valley Creek at Stanley, ID	7/7/2010	10/1/2010
Salmon River BL Yankee Fork NR Clayton, ID	7/7/2010	10/1/2010
Frenchman Creek	7/7/2010	10/1/2010
Salmon River Headwaters	7/7/2010	10/1/2010
Smiley Creek	7/7/2010	10/1/2010

Boulder Creek Regression Details		
Streams Used for Regression	**Start Date**	**End Date**
Johnson Creek at Yellow Pine, ID	10/1/2008	5/13/2009
Lake Fork Payette River AB Jumbo Cr NR McCall, ID	10/1/2008	5/13/2009
Little Salmon River at Riggins, ID	10/1/2008	5/13/2009

Frenchman Creek Regression Details		
Streams Used for Regression	**Start Date**	**End Date**
Valley Creek at Stanley, ID	10/1/2008	5/9/2009
Salmon River BL Yankee Fork NR Clayton, ID	10/1/2008	5/9/2009

Gregory Creek Regression Details

Streams Used for Regression	**Start Date**	**End Date**
Tucannon River Near Starbuck, WA	10/1/2008	5/14/2009
Webb Creek Near Sweetwater, ID	10/1/2008	5/14/2009
Sweetwater Creek at Sweetwater, ID	10/1/2008	5/14/2009
Tucannon River Near Starbuck, WA	8/1/2009	2/26/2010
Webb Creek Near Sweetwater, ID	8/1/2009	2/26/2010
Sweetwater Creek at Sweetwater, ID	8/1/2009	2/26/2010
Rice Creek	8/1/2009	2/26/2010
Rock Creek	8/1/2009	2/26/2010

Little Goose Creek Regression Details

Streams Used for Regression	**Start Date**	**End Date**
Johnson Creek at Yellow Pine, ID	10/1/2008	7/23/2009
Lake Fork Payette River AB Jumbo Cr NR McCall, ID	10/1/2008	7/23/2009
Little Salmon River at Riggins, ID	10/1/2008	7/23/2009
Boulder Creek, ID	10/1/2008	7/23/2009

North Fork of Slate Creek Regression Details

Streams Used for Regression	**Start Date**	**End Date**
Johnson Creek at Yellow Pine, ID	10/1/2008	5/13/2009
Lake Fork Payette River AB Jumbo Cr NR McCall, ID	10/1/2008	5/13/2009
Little Salmon River at Riggins, ID	10/1/2008	5/13/2009
Little Salmon River at Riggins, ID	5/13/2009	7/8/2009
*Little Slate Creek **	5/13/2009	7/8/2009
Boulder Creek	5/13/2009	7/8/2009

Rice Creek Regression Details

Streams Used for Regression	**Start Date**	**End Date**
Tucannon River Near Starbuck, WA	10/1/2008	7/10/2009
Webb Creek Near Sweetwater, ID	10/1/2008	7/10/2009
Sweetwater Creek at Sweetwater, ID	10/1/2008	7/10/2009
Tucannon River Near Starbuck, WA	6/3/2010	6/29/2010
Webb Creek Near Sweetwater, ID	6/3/2010	6/29/2010
Sweetwater Creek at Sweetwater, ID	6/3/2010	6/29/2010
Baker Gulch	6/3/2010	6/29/2010
Gregory Creek	6/3/2010	6/29/2010

Rice Creek Regression Details

Streams Used for Regression	Start Date	End Date
Tucannon River Near Starbuck, WA	10/1/2008	5/14/2009
Webb Creek Near Sweetwater, ID	10/1/2008	5/14/2009
Sweetwater Creek at Sweetwater, ID	10/1/2008	5/14/2009
Tucannon River Near Starbuck, WA	6/19/2010	8/28/2010
Webb Creek Near Sweetwater, ID	6/19/2010	8/28/2010
Sweetwater Creek at Sweetwater, ID	6/19/2010	8/28/2010
Baker Gulch	6/19/2010	8/28/2010
Gregory Creek	6/19/2010	8/28/2010
Rice Creek	6/19/2010	8/28/2010

Salmon River Headwaters Regression Details

Streams Used for Regression	Start Date	End Date
Valley Creek at Stanley, ID	10/1/2008	5/9/2009
Salmon River BL Yankee Fork NR Clayton, ID	10/1/2008	5/9/2009

Slate Creek Regression Details

Streams Used for Regression	Start Date	End Date
Johnson Creek at Yellow Pine, ID	10/1/2008	5/13/2009
Lake Fork Payette River AB Jumbo Cr NR McCall, ID	10/1/2008	5/13/2009
Little Salmon River at Riggins, ID	10/1/2008	5/13/2009
Little Salmon River at Riggins, ID	5/13/2009	7/8/2009
Little Slate Creek *	5/13/2009	7/8/2009
Boulder Creek	5/13/2009	7/8/2009

Smiley Creek Regression Details

Streams Used for Regression	Start Date	End Date
Valley Creek at Stanley, ID	10/1/2008	5/9/2009
Salmon River BL Yankee Fork NR Clayton, ID	10/1/2008	5/9/2009
Valley Creek at Stanley, ID	5/9/2009	8/2/2009
Salmon River BL Yankee Fork NR Clayton, ID	5/9/2009	8/2/2009
Frenchman Creek	5/9/2009	8/2/2009
Salmon River Headwaters	5/9/2009	8/2/2009

Table 1. Streams used for multiple linear regressions and the time period of modeled data for all study sites. Italicized streams are gage records maintained by the USGS, streams that are italicized and starred are from the United States Forest Service Slate Creek Ranger Station.