Hydrology of Big Creek, Idaho: Spatial and temporal heterogeneity of runoff in a snow-dominated wilderness mountain watershed

by

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Hydrology of Big Creek, Idaho: Spatial heterogeneity in snow-dominated mountain watersheds

Abstract

This study was designed to characterize the hydrology of Big Creek, a snow dominated catchment in central Idaho. The hydrology of the main stem Big Creek was characterized in three ways. The past discharge history of the main stem was modeled using a variety of methods so that past flows could be known. The tributaries and mainstem were gaged in order to understand the spatial and temporal variability of snowmelt discharge and the relationship of that variability to watershed topography. Compared to numerous other variables, we found that elevation is a primary control on the timing and magnitude of discharge. Comparing results from Big Creek and its tributaries to other gages in the Salmon River watershed, we improved our understanding of how discharge changes with progressively larger drainage areas. Here too the elevation of a basin controls the amount of snow accumulation and therefore the relation between discharge and drainage area.

Chapter 1: Introduction

1.1Motivation

This project was designed and undertaken to integrate into the research at Taylor Wilderness Research Station (TWRS). Although much work at TWRS has been done on both terrestrial and aquatic ecology and some work on geomorphology and geology, the hydrology of the region has not been studied. The first part of the thesis was designed explicitly to provide a record of past flows of Big Creek that filled in the missing period of record between when the USGS stopped gaging on Big Creek and when I installed a new gage at TWRS. This portion of the study provides context for past studies of biology and geomorphology. The second part of the study was designed to study and quantify the effects of spatial heterogeneity in watersheds. The aim of this portion of my thesis project was to explain what differences exist between tributaries and why those differences exist. In particular, how does topography influence the timing and magnitude of spring runoff? The answers to this can inform us on differences in stream ecology and geomorphology that we observe today as well as help to create new hypotheses about which streams might be most impacted in the future from climate change. Mountain watersheds are of great importance water resources, particularly in the western United States where a majority of precipitation occurs in the mountains. Finally, the results from Big Creek were compared to the larger Salmon River watershed in order investigate the applicability of the results from Big Creek to the larger scale. We evaluate the implications of the topography-induced variability in surface water discharge for scaling relationships between drainage area and discharge.

1.2 Setting

The setting of this study area is the Big Creek Watershed, located in central Idaho. It is a large (1444 km^2) tributary to the Middle Fork Salmon River and a significant contributor to the overall Salmon River watershed. Big Creek is typified by high relief (1800 m) mountainous watersheds, with underlying bedrock composed of Idaho batholith, Challis volcanics, and Proterozoic metamorphic rocks in the Big Creek watershed. The larger Salmon River watershed shares this geology and additionally has some areas of Columbia River basalts in the western part of the drainage and Paleozoic sediments in the eastern part. The area is dominated by mixed conifer in the mid elevations and sagebrush and grasslands in the lower elevations. One of the main attractions of working in the Big Creek watershed was the fact that it is almost wholly contained within the Frank Church River of No Return Wilderness. The wilderness location of this study provides that the hydrology of the watershed is largely unimpaired by human influences, leaving natural processes as the only influence on hydrology.

1.3 Structure of Thesis

This thesis is set up as three stand-alone papers rather than as one larger paper as is typical with many theses. The nature of this project is such that the individual topics are diverse enough that it would have been difficult to integrate the methods and introductions into one coherent document. This format will also improve readability for those who are interested in only one of the three topics of this thesis.

1.4 Key Findings

One key findings from this study is that the multiple linear regression model using a historic station within the watershed and nearby gaging stations in continuous operation provides a reliable method of reconstructing past discharges within the basin. This method provides the most accurate record of discharges and also requires less intensive computer modeling than hydrologic regionalization models or distributed rainfall runoff models. This information is useful for researchers in the area to provide context for past and future research.

The hydrology of the tributaries is dominated by their unique ranges in elevation, and aspect is weakly correlated with the timing and magnitude of spring runoff. The spatial heterogeneity of elevations within the watershed produces predictable variation of the hydrology of the tributaries. Timing of runoff, although comparable, displays a clockwise hysteresis between the tributaries and the main stem, with the tributaries that were studied lower in the basin providing greater flow in the early season while the trunk peaks later.

The spatial variability of topography (and by extension of snow accumulation) produces variations in drainage area/discharge scaling relationships. These variations produce a power law scaling exponent either higher or lower than the expected linear relationship between drainage area and discharge depending on the watersheds selected. This result provides some insight into how higher elevation drainage areas make disproportionately large contributions to mainstem rivers.

Chapter 2: Reconstructing a Record of Historic Flows for Big Creek, ID Using Statistical and Distributed Hydrologic Models

2.1 Abstract

A variety of methods are available to the hydrologist to create synthetic records of flow conditions in a catchment of interest. In this paper, three of these methods are tested for suitability and accuracy in Big Creek, a 1540 km^2 tributary to the Middle Fork Salmon River in central Idaho. An active USGS gaging station was maintained on Big Creek downstream of Cabin Creek between 1944 and 1958. In 2008, a new gaging station was established on Big Creek at the Taylor Wilderness Research Station (TWRS) bridge. The purpose of this study was to evaluate which hydrologic method most accurately bridges the data gap between 1958 and 2008. This synthetic discharge data provides hydrologic context for numerous biological studies that occurred during this period. We evaluated the suitability of three methods: Hydrologic Regionalization, the VIC Distributed Hydrological Model, and a Linear Regression Model. We calibrated and evaluated these methods by comparing modeled flows against the instrumental record. We found that the monthly outputs of the Hydrologic Regionalization model did not provide sufficient detail and lacked the accuracy needed for ecological or geomorphic studies. Though the VIC Distributed Hydrological Model provided flow data at many locations throughout the basin at a daily scale, it did a poor job of matching the finer scale timing and magnitude of spring runoff events. Because the Linear Regression Model explicitly depends on the flow records of nearby active gaging stations, it did a good job of matching both the timing and magnitude of peak flow events. On the basis of

this model comparison, we selected the Linear Regression Model to recreate the last 50 years of discharge in Big Creek.

2.2 Introduction

Extensive utilization of water resources in the West complicates hydrologic analysis. Diversions, withdrawals, agriculture, and impoundments in dams can change the hydrology of a watershed by altering residence times and changing the amount of evapotranspiration (ET) and other losses. In order to evaluate the accuracy of three methods for hydrologic reconstruction, we focused on the Big Creek watershed, a near-pristine stream located almost entirely within the Frank Church River of No Return Wilderness in central Idaho (Figure 1). Because the basin is largely free of anthropogenic alterations of the hydrograph, it is an ideal location for the study of both physical and ecological processes.

Taylor Wilderness Research Station (TWRS), located in the lower reaches of Big Creek (Figure 2), has been a site of active research since 1964. Until 2005, most studies focused on both terrestrial and aquatic ecology, supporting new findings in predator-prey interactions, native salmonid behavior and post-fire stream ecosystem dynamics (e.g. Robinson et al 2000). Despite the long history of ecological research at Taylor, very few streamflow observations have been made. The obvious lack of current and past hydrologic information and the large amount of recent work on streams (i.e. Achord et al., 2005, Malison, 2008) provides the impetus to reestablish a modern gaging station on Big Creek and to reconstruct past flows.

Currently research at TWRS focuses on the potential impacts of climate change. Large scale changes are expected due to warming temperatures. These are anticipated to impact plant communities, stream ecosystems and the snowmelt dominated hydrologic system (Stewart et al., 2004). In order to anticipate future changes, it is important to characterize the current and past variability within the system.

In order to model past flows, a number of techniques are available. These techniques fall into two different broad categories: statistical and spatially distributed models. Distributed models focus on using physical processes, such as Darcy's Law, which are empirically derived laws that govern the movement of water in a landscape. These models range from highly parameterized models to lumped or "black box" type models. Highly parameterized spatially distributed models use inputs such as soil types, land cover, and topography and model rates of infiltration, runoff, and evapotranspiration for each unique combination of soil land cover and slope. Lumped models only differ in the level of detail they go into compared to the more parameterized models. Both of these are driven by climate data that contains at a minimum temperature and precipitation data but may also include dew point, cloud cover, and wind speed and direction.

Process based models have gained great popularity recently because they give scientist the ability to put in differing climate change scenarios and predict potential responses (i.e. Knowles and Cayan, 2004, Tague et al., 2008, Hamlet and Lettenmaier 1999). Models such as DHSVM, BASINS, ArcSWAT, VIC and many more use digital elevation models (DEMs) and climate data in order to calculate mass and energy balances for each grid cell of the model, with routing through the landscape to the channel (Wigmosta et al., 1994).

Statistical models focus on the use of known water discharge from gaged basins and the interpolation of those hydrologic characteristics to basins without gages. These methods can produce either continuous estimates of discharge or can model longer time period measurements such as flood recurrence intervals or monthly exceedance values. A statistical model may be wholly reliant on the hydrologic data of the known basin or it may incorporate basin characteristics such as mean elevation and slope into the analysis. One example of the former is a regression model whereby a statistical correlation between one long term gaging record and one short term gaging record is established and used to extend the record of the short term record (Matlas and Jacobs, 1964; Hirsch, 1982; Nawaz and Khan, 2006). One example of the latter type of model is a Hydrologic Regionalization model in which streams are lumped into similar groups and hydrologic characteristics are interpreted from basin characteristics (Hortness 2006; Kjelstrom 1998).

In this study, we compare the performance of models as presented above to reconstruct the past 50 years of flows in Big Creek in order to fill in the gap between gaging records. The purpose of this study is not to forecast future changes due to projected climate change, but rather to fill in a knowledge gap for a period of time when research took place at TWRS. This longer record will provide better context for the ongoing research at TWRS. In this paper, I use data from VIC to test the quality of a spatially distributed model, the Hydrologic Regionalization model of Hortness and Berenbrock (2001) and a Multiple Linear Regression Model.

2.3 Setting

Big Creek is located within the Frank Church River of No Return Wilderness and as such, has minimal diversions and no dams. It is an unimpaired stream that is currently free from many of the land use changes experienced by other watersheds, including forest harvest, mining, and road construction.

The Big Creek Watershed has an upstream drainage area of 1540 km^2 at the point that it meets the Middle Fork Salmon River, and 1444 km^2 at TWRS, where a new stream gage was established in April of 2008. The basin has a drainage density of 0.67 km/km^2 and an overall dendritic shape. Channels are generally confined within steep canyons, and little floodplain exists. The highest point in the basin is 2908 m and the lowest is 1031 m where Big Creek joins the Middle Fork Salmon River. The gage at TWRS is located at an elevation of 1165 m.

The geology of the basin is comprised of Proterozoic meta-sediments, Tertiary batholiths, and Tertiary volcanics (Lund, 2004). A shallow depth to bedrock is observed throughout the basin. Vegetation is dominated by Ponderosa Pine/Douglas Fir forest and sagebrush/grassland. Upper elevations are subalpine forested and have exposed ridgelines. This land cover has changed significantly in local regions due to the recent fires in 2000 and 2006 which burned much of the canopy. Little re-forestation has occurred following the fires. Prior to the recent fires, there had been few large scale fires in the area in the historical period of record. Recent fires are of concern because the frequency of fire is expected to increase with warming climate (Meyer and Pierce, 2003).

Big Creek, like much of central Idaho is characterized by a precipitation regime that is dominated by winter snowfall, with mixed snow/rain precipitation falling in the lower elevations. A climate station at TWRS has been in operation since 1980. Yearly precipitation is 14.3 inches with 2.73 inches of water equivalent in winter months (December January February). The highest total months of precipitation are April, May and June. The station also records some snow during April and May, indicating that some of these spring storms fall as snow in the high elevations. This scenario leads to a buildup of snow in the winter and spring months that then starts to melt in late April and early May when daily low temperatures remain above freezing.

USGS gage 13310000, Big Creek nr Big Creek, was located just downstream of Cabin Creek at a spot where the river leaves a wide floodplain region and reenters the canyon (Figure 2). The gage was installed in September of 1944 and ceased operation in October of 1958. The gage was manually operated until 1948 and replaced with an automated recorder consisting of a 36" corrugated well. The gage was installed through cooperation with the US Army Corps of Engineers and partially funded by the Corps (Wells, 1960). In April 2008, a new gage was located at TWRS, on a Forest Service bridge where a hiking trail crosses the creek. The modern location is located 7.8 km downstream of the old gage location and incorporates the flow of two additional tributaries, Rush Creek (243 km^2) and Pioneer Creek (16 km^2). The new gage consists of an OTT Radar Level Sensor and is connected to a Campbell Scientific CR1000 data logger which records average stage height over 10 minute intervals. Data is accessed through a satellite internet connection or manual download. There is currently no automated method of data retrieval. A stage-discharge rating curve for the new location was established over the course of two years using a combination of Acoustic Doppler Profiler and wading techniques (Rantz et al., 1983; Blanchard, 2004,). In addition to providing modern flow values for researchers at TWRS, this new gage record also provides a means of checking the accuracy of various flow reconstruction methods.

2.4 Methods

2.4.1 Observed Records of Discharge

Historical flows for USGS gaging station 13310000 Big Creek nr Big Creek were obtained in tab separated format from the USGS (http://waterwatch.usgs.gov accessed 9/5/2009). Flows were reported in daily mean discharge values in cubic feet per second (cfs) for the period of record from September 1944 to October 1958 when the gage was discontinued. Ice-affected periods as denoted by the USGS were removed and the data was brought into Matlab for analysis.

Modern flows were obtained from a new gaging station that was installed in April 2008 as part of infrastructure development at TWRS. The modern gage consisted of a radar level sensor connected to a data logger that records stage at 10 minute intervals. Once a stage discharge relationship was established for this new location, the 10 minute discharge record was averaged on a daily basis in Matlab for comparison to the old record.

Nearby gaging records were accessed from the same USGS site and downloaded as daily mean discharges in cfs. Ice-affected periods were removed and records were temporally aligned so as to overlap and be of the same length as the Big Creek record so that they could be used for the Linear Regression Model discussed below.

2.4.2 Modeled Records of Discharge

2.4.2.1 Hydrologic Regionalization

For this study, I used the Hydrologic Regionalization of Hortness and Berenbrock (2001), the VIC model (Wigmosta et al., 1994) and a multiple linear regression model (Matlas and Jacobs, 1964). These three methods provided area-specific information in the case of Hortness and Berenrock, or have a history of use in snow-dominated mountain catchments in the case of VIC. Also, development of the VIC model for the greater Salmon River Area was currently under development by Tang, Crosby and Wheaton (in prep). The Linear Regression Model was used for its simplicity and universality of application.

Hortness and Berenbrock (2001) used a suite of basin characteristics such as basin slope, elevation, land cover etc. and multiple linear regressions with known hydrographs to derive monthly predictions of flow for ungaged basins within Idaho. This method is readily accessible using publicly available GIS data sets, and can be applied to any basin within Idaho. The Hydrologic Regionalization model required extraction of the following parameters using ArcGIS: watershed area (A), percent of watershed area with slopes above 30 percent (S30), percent forested area (F), mean elevation (E), and mean basin slope (BS). Slope and elevation were derived from a 10m DEM derived from the USGS (seamless.usgs.gov) and forested area was derived from the 2000 National Land

Cover Dataset (NLCD) from the same source. These values were inserted into the equations for monthly exceedance values from Hortness and Berenbrock (2004). These equations were derived via linear regression between gaged basins flow values and their respective basin characteristics. Basins were grouped into regions that reflected similar lithology, topography and land cover so that variability was minimized. Big Creek lies within region 5, which is defined by the Idaho Batholith area of the Salmon River Mountains. The equations only produce exceedance values, which are defined as the flow value which is exceeded x percent of the time in a given time period. Equations were derived for 20, 50 and 80 percent exceedance values for each month. For ease of presentation, 50% exceedance values are used from here in. An example of the types of equations used is given by the equation for average annual discharge:

$$Q_a = 1.07 \times 10^{-2} \times A^{0.831} \times BS^{7.25} \times S30^{-5.42} \times F^{0.448} \qquad (2.1)$$

A complete list of equations used is given in the appendix.

2.4.2.2 Spatially Distributed Hydrologic Model

The Variable Infiltration Capacity model (VIC) is a spatially distributed hydrologic model that was developed by Liang et al., (1994). It operates on 1/16th degree grid cells, which at the latitude of Big Creek translates to cells sized approximately 5 x 7.5 km. It uses weather, vegetation and soil character inputs from the Climate Prediction Center and applies a simplified mass and energy balance equation to each cell and a routing algorithm that passes water into the channel and a shallow groundwater layer. Dr. Chunling Tang, a Post Doctoral Researcher at ISU, 2008-2010, calibrated and ran the model for the entire Salmon River watershed as part of the ongoing research in the area

(Tang et al. in preparation). It should be noted that the VIC model results used here are calibrated to the Middle Fork Salmon River, not Big Creek itself. Also, Big Creek is a smaller watershed than VIC is typically run for, and results may be biased by the small number (43) of grid cells involved in the model.

2.4.2.3 Linear Regression Model

The third flow reconstruction method was to create a linear regression model between the historic ‘Big Creek nr Big Creek’ gage and nearby, contemporaneous gages. As mentioned above, I downloaded gaging records that overlapped the historic period of record for Big Creek. These gages were Johnson Creek, Salmon River at Whitebird, and Salmon River at Salmon, Idaho. Johnson is the closest gage spatially to Big Creek, and also has similar topography and land cover to Big Creek (Table 1). Although the mainstem Salmon River sites, Salmon and Whitebird are further away spatially and also incorporate a wider variety of lithology, topography and land cover, their hydrograph shape and climate forcings matched closely those observed at Big Creek.

Using this model, I tested whether a single nearby stream or a combination of all three nearby streams provided the best modeled fit to observed data from Big Creek. Because both the Big Creek and nearby gage records have missing data, I wrote a Matlab code that identified the days in the Big Creek record that had matching daily flow values at the other gages. With all discharge records temporally aligned, I plotted the flow at Big Creek on a given day against the discharge of the nearby river on that same day (Figure 3). The equations for the linear correlations between the flows at Big Creek and at each nearby gage were used to model flows in Big Creek. These modeled Big Creek flows were then differenced against the observed Big Creek flows during the period of historic record to produce model residuals (Figure 4). Following the same methods as above, I also ran a multiple linear regression using all three sites and calculated the model residuals.

Compared to the other nearby stations, flows at Big Creek tended to increase earlier in the season and recede earlier in the season, producing a slight hysteresis between flows at Big Creek and the other gages. To account for this, flows were divided into two separate groups, early and late season and separate regressions were run for each time period. The Big Creek record was extended by using the correlation coefficients derived from the multiple linear regression analysis and applying them to daily mean discharge values for the nearby gages derived from USGS websites given in the equations

$$Q_{bce} = Q_j * 0.29 - Q_s * (-0.020) + Q_w * 0.035 - 25.51 \qquad (2.2)$$

$$\mathrm{Q_{bce}} = Q_j * 0.295 - Q_s * 0.021 + Q_w * 0.037 + 11.86 \qquad (2.3)$$

Where Q_{bce} is early season Big Creek discharge, Q_{bcl} is late season Big Creek discharge, Q_j is discharge at Johnson Creek, Q_s is discharge at Salmon at Salmon, Idaho, Q_w is Salmon River at Whitebird, Idaho discharge. All values are in cubic feet per second.

Because of the change in drainage area from the old to the new gaging station on Big Creek, a correction needed to be applied to this modeled discharge in order to compare to the new gaging station. Because discharge is expected to scale with drainage area, the modeled data could be manipulated as follows

$$Q_{new} = \frac{Q_{old}}{A_{old}} \times A_{new} \tag{2.4}$$

where Q_{new} is the discharge in cubic feet per second at the new location, Q_{old} is the discharge in cubic feet per second at the old location, A_{old} is the old drainage area in km^2 and A_{new} is the new drainage area in km^2.

2.5 Results

A comparison of the monthly Q50 exceedance values for all three models is seen in Figure 5. The Q50 exceedance value is the equivalent to the monthly median flow value for each month in the period of record from 1944-1958. Median flow values were calculated for all three models for the period of 1944-1958 for each month. The Hydrologic Regionalization method does not produce a time series of data and because of the large errors in its predicted vs. observed values for Big Creek (Figure 5). Hydrologic Regionalization does not give a continuous time series of data, and only reports back monthly exceedance probabilities.

The VIC models data from 1944-1958 works well in some respects and not as well in others. Spring snowmelt runoff is captured, but the timing of the peak flow tends to arrive earlier than the actual peak, winter runoff events are predicted that never occurred and the magnitude of summer rainfall-driven events are greatly exaggerated (Figure 6). When comparing observed versus predicted flows (Figure 7a) it is apparent that there is scatter in the two data sets. Root Mean Square Error (RMS) for the VIC model vs. observed was 534.49 cfs.

In comparison, the linear regression model produces a very tight fit against the observed flow values without increasing variability at increasing discharges (Figure 7b), residuals appeared to be evenly distributed around the zero line and not show a systematic bias (Figure 4). When viewed as a time series (Figure 6), the model matches up well with the observed record with only minor variations. The RMS for the multiple linear regression model was 98.6 cfs, compared to the RMS of Johnson Creek (140.7cfs), Salmon (218.7cfs) and Whitebird (103.7cfs). Because the RMS was smallest for the multiple linear regression I selected this approach to model the Big Creek record (Figure 8, (supplemental data). A comparison of model results to modern flow values confirms that the same relationship established in the 1940's and 50's remains true today and there has not been a significant shift in the relationship between the streams. Figure 9 shows two years worth of modern data and the timing and magnitude of the flows are matched well. Mean flows for the period over which the two records overlap are 831 cfs for the new gage and 850 cfs for the extended record, only a 2% difference. Maximum flows are 5493 cfs for the observed and 5129 cfs for the linear regression model, only a 6% difference. RMS for the new site against the predicted values is 170.3 cfs for the two years of data so far.

2.6 Discussion

Past, present and future studies into the physical and ecological processes in the Big Creek area depend on hydrologic data. The purpose of this study was to create a daily time series of flows in a well-studied area. Given the models presented here, the linear regression model serves the best function here given the relative strengths and weaknesses of each model. Other models may be more appropriate in other circumstances.

2.6.1 Weaknesses of the Three Models

A variety of modeling techniques are available to recreate past flows and all of these methods have various benefits and drawbacks. Distributed models have gained favor because of their predictive, process based capabilities. However, because of their heavy reliance on spatially sparse weather, soil and vegetation data, they can be somewhat difficult to implement in remote settings where measurements often are sparse and may miss important but not widespread events such as thunderstorms. This problem is exacerbated when in a mountain setting because the weather patterns experienced at valley floors (where most weather stations are located) are significantly different than those at high terrain where most of the snow and precipitation accumulates due to orographic effects (Kunkel and Pierce, 2009). This can lead to an underestimation of the total volume of water in a system and/or a difference in the timing of peak runoff. Additionally, distributed models are reliant on spatially insensitive parameterization of some variables such as soil conductivity which might not reflect real world conditions (Kirchner 2006). Spatially distributed models often require large amounts of data inputs. For some regions, this can be an unrealistic expectation because not all weather stations record potential evapotranspiration, cloud cover, and other weather variables. Although calibrated model runs may produce a hydrograph that is similar in magnitude and timing to the real hydrograph, the model processes producing this hydrograph may not reflect real world processes (Grayson et al., 1992). In this study, the VIC model results suffer from the aforementioned problems of volume and timing, visible in Figure 6. For these reasons, the VIC model was not used to reconstruct all past flows.

The Hydrologic Regionalization is not temporally continuous and does not account for year to year variability for the stream of interest. A drawback of this method is that it is does not reflect year to year variability. High and low snow years are not reflected. It also assumes a stationary relationship over time between basins in the same region. In addition, the authors themselves give large error estimations for their method, with some errors of over 100% of flow values. Although the exceedance values produced from this method could have been calculated from the existing flow record, it was hoped that the method could shed some light on tributary processes. However, model performance as measured by RMS was so poor that this method was rejected for that application. The negatives of this method outweigh the positives and therefore it is only applicable as a means of describing a watershed at a very coarse level.

A drawback of the Linear Regression method is that it requires some record of flows within in the basin of interest as well as a contemporaneous record of flow in a nearby basin. The method also assumes a linear and stationary relationship between the two records. In addition, it is a statistical model rather than a physically based model. The model relies on the strength of the linear relationship of the two gages, and cannot be adjusted to known differences in the physical processes within the watershed. Other drawbacks of this method are that it requires the existence of a gage in the watershed at some time, and preferably for multiple years to get a better fit of the regression. Also, there must be at least one nearby continuous operating gage that experiences similar climate forcing and has similar vegetation, geology and topography. It also only informs investigators about flows for a given point in the watershed, and not for all points in the watershed. This can be overcome to some degree by setting up a correction for drainage area, but this correction may fall apart when moving to radically different drainage areas.

2.6.2 Strengths of the Three Different Methods

The method of Hydrologic Regionalization has the benefit of providing a set of descriptive statistics for a basin using readily available data sets such as DEMs and Land Cover datasets. Once a small number of basin characteristics are extracted, it is relatively easy to implement and is not computationally very expensive and requires no calibration of the model. Some benefits of the method are that it does not require the establishment of a gage at any time period. It is also applicable for any point within the watershed within reason. Given that the regression equations were developed with basins of a certain range of characteristics (size, slope, forested area etc) basins that lie at the edge of these values or outside them may not hold true to these relationships.

The VIC model has some of the same advantages as the Hydrologic Regionalization method. It can be used to garner information about hydrology for many points within the basin, and does not require the establishment of a gaging station within the basin of interest. Though it does require calibration against a number of gages for the model, these gages do not need to be within the basin of interest and they can be at pre-existing USGS gage locations. The main advantage of spatially distributed models is their predictive capability. This is the only category of models presented here that is capable of taking modeled changes to future weather patterns and using those to drive the hydrology, informing us of potential future changes to the hydrological system. However, because that is not the purpose of this study, it is not applicable here.

The Linear Regression model does the best job of filling in the gap between the past gage and current gage by matching the timing and magnitude of flows. The estimation of flow values through a two-gage correlation is beneficial because it does not require the use of a Geographical Information System and is computationally very simple. In addition, it does a good job of capturing the total amount of water in the system in a given year and also shows the year to year variability. For this reason, the Linear Regression model serves the purpose of this study best.

With a modeled record of discharge values during the period in which biological measurements were taken, it is possible to correlate these biological measurements to flow values such as the magnitude of the spring flood and hypothesize what impacts changing flow regime might have on the biological processes (Richter et al., 1996). Such correlations are only available when all aspects of the system, including the hydrology, are known.

2.7 Conclusions

Although it does not provide a means of prediction of future climate change, the multiple linear regression method provides a quick and easy technique to model past flows in a basin. Assumed in this method are the stationarity and linearity between discharge values in the gaged basin and ungaged basin. Assuming that no large scale land use changes occur in either basin, this can usually be a safe assumption. It is also possible that a finer spatial scale hydrological model such as DHSVM could possibly do a better job at modeling discharge than a large scale model such as VIC, but the return in model accuracy would be small for the amount of additional model calibration. It is also unlikely that results would surpass those of the linear regression model. In general, distributed hydrologic models are useful to investigate processes and potential changes in hydrologic systems, but for simple historical modeling of discharges at a formerly gaged location, linear regression modeling provides an effective means to do so. This method has already produced additional data for further studies of the Big Creek system (Cornell et al., 2010).

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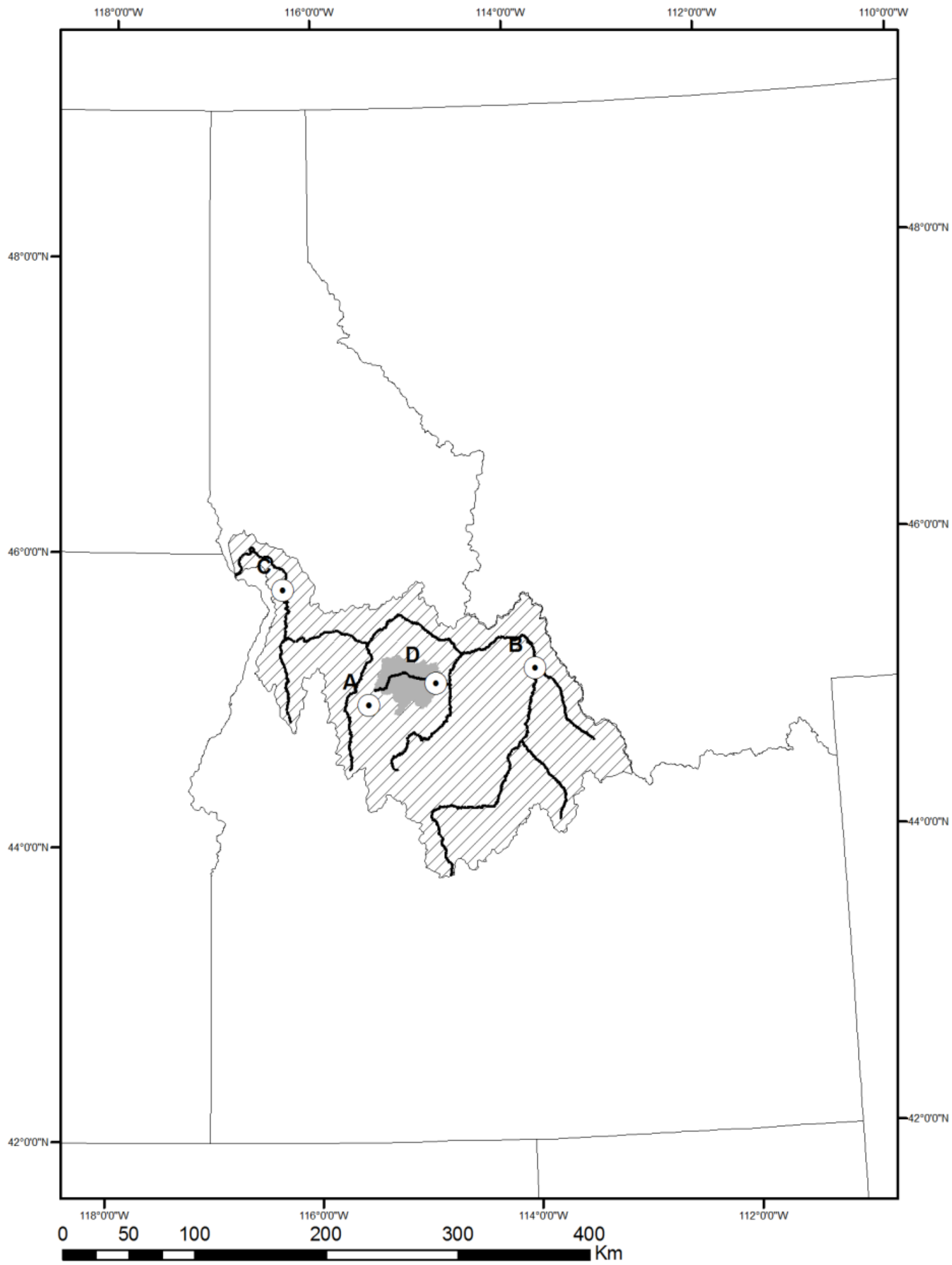

Figure 1. Regional setting of Big Creek and surrounding gages. Big Creek (gray) lies within the greater Salmon River basin (hashed). Circles show locations of long term gages. Their names and basin characteristics are shown in Table 1.

Map	Creek Name	USGS #	Drainage Area [km^2]	Mean Basin Elevation [m]	Distance From Big Creek[km]	Start/End Date
A	Johnson Creek	13313000	561.2	2174.1	54	1928-09-01/ present
B	Salmon @ Salmon	13302500	9738.4	2255.0	76	1912-10-01/ present
C	Salmon @ Whitebird	13317000	35094.3	2053.7	137	1910-09-01/ present
D	Big Creek	13310000	1444.1	2117.1	NA	1944-09-05/ 1958-10-31

Table 1. Names and attributes of the gages used in the Linear Regression Model. Distances from Big Creek is the straight line distance from each gaging station to the Big Creek gaging station.

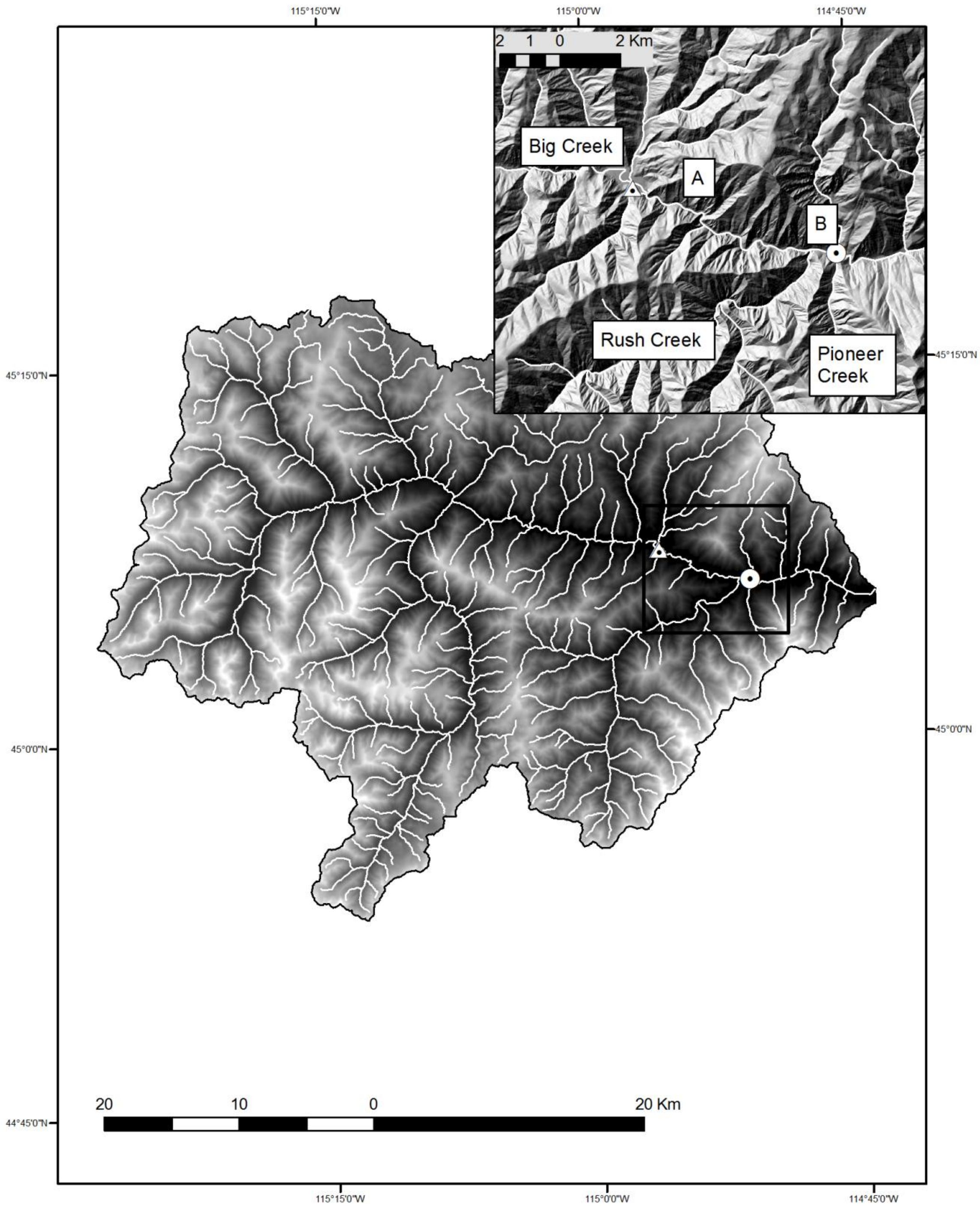

Figure 2. Big Creek watershed with inset of location of old USGS gaging site, Big Creek nr Big Creek, ID (A) and new gaging site, Big Creek at Taylor Ranch Bridge (B). Rush and Pioneer Creeks are additional tributaries to the new gaging site, accounting for an additional 260 km^2 of drainage area.

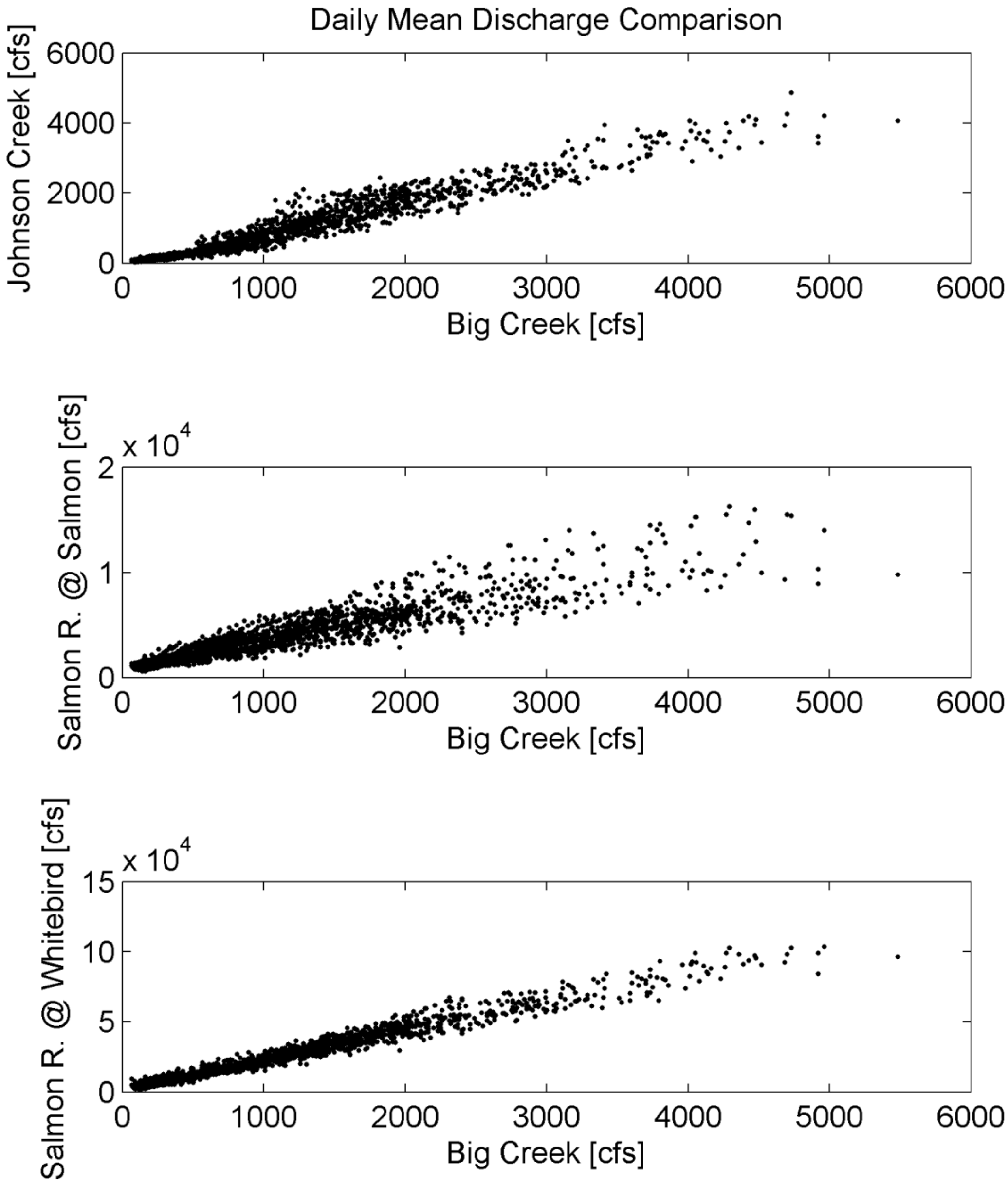

Figure 3. Comparison of observed discharge values at Big Creek nr Big Creek against other long term gages in the area for the period 1944-1958. All comparisons show a linear trend. Observations on both axes are in cubic feet per second.

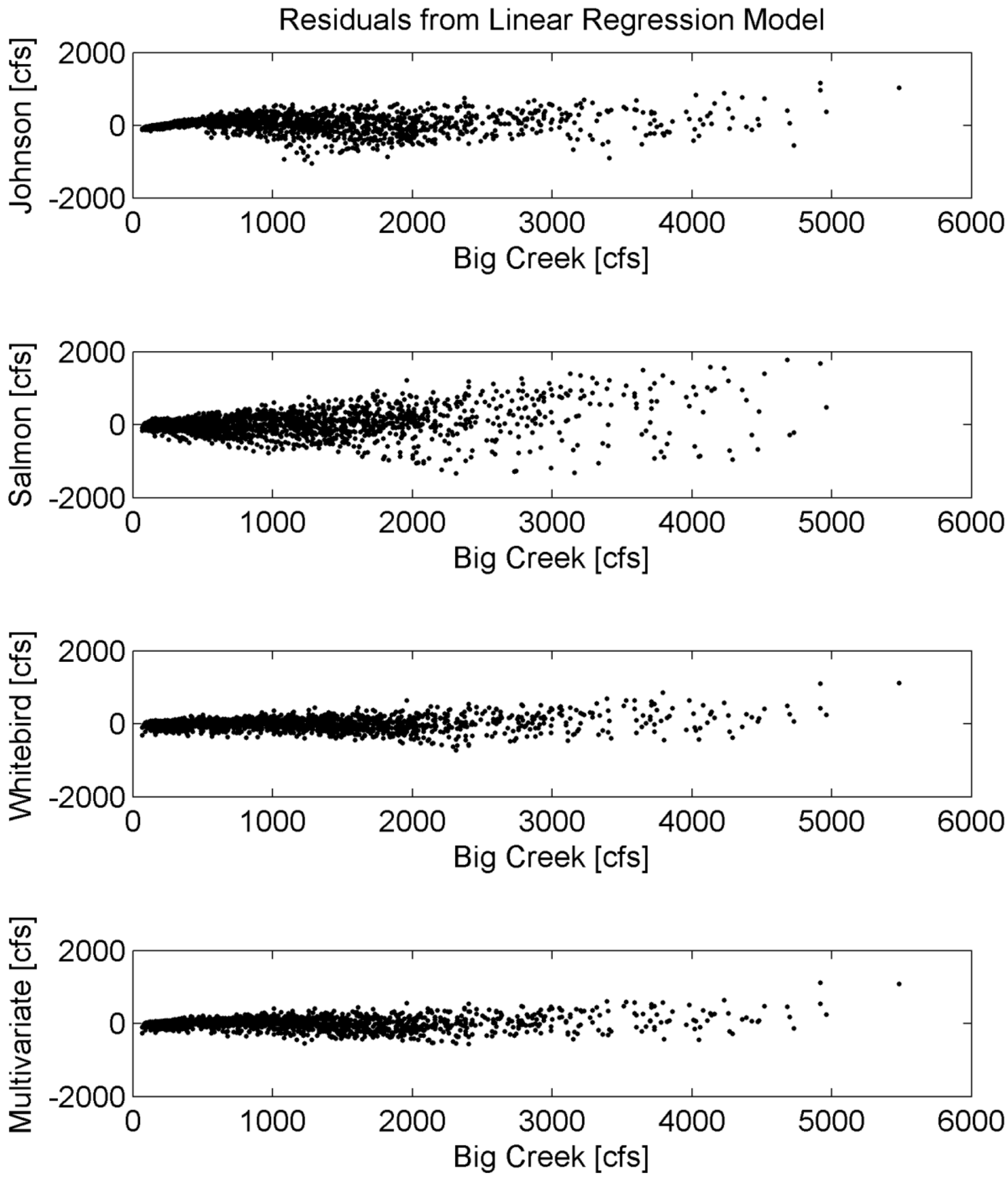

Figure 4. Differences in the observed minus the modeled results for linear fits for the three components of the linear regression model and the multivariable fit. Residuals are evenly distributed around the 0 value

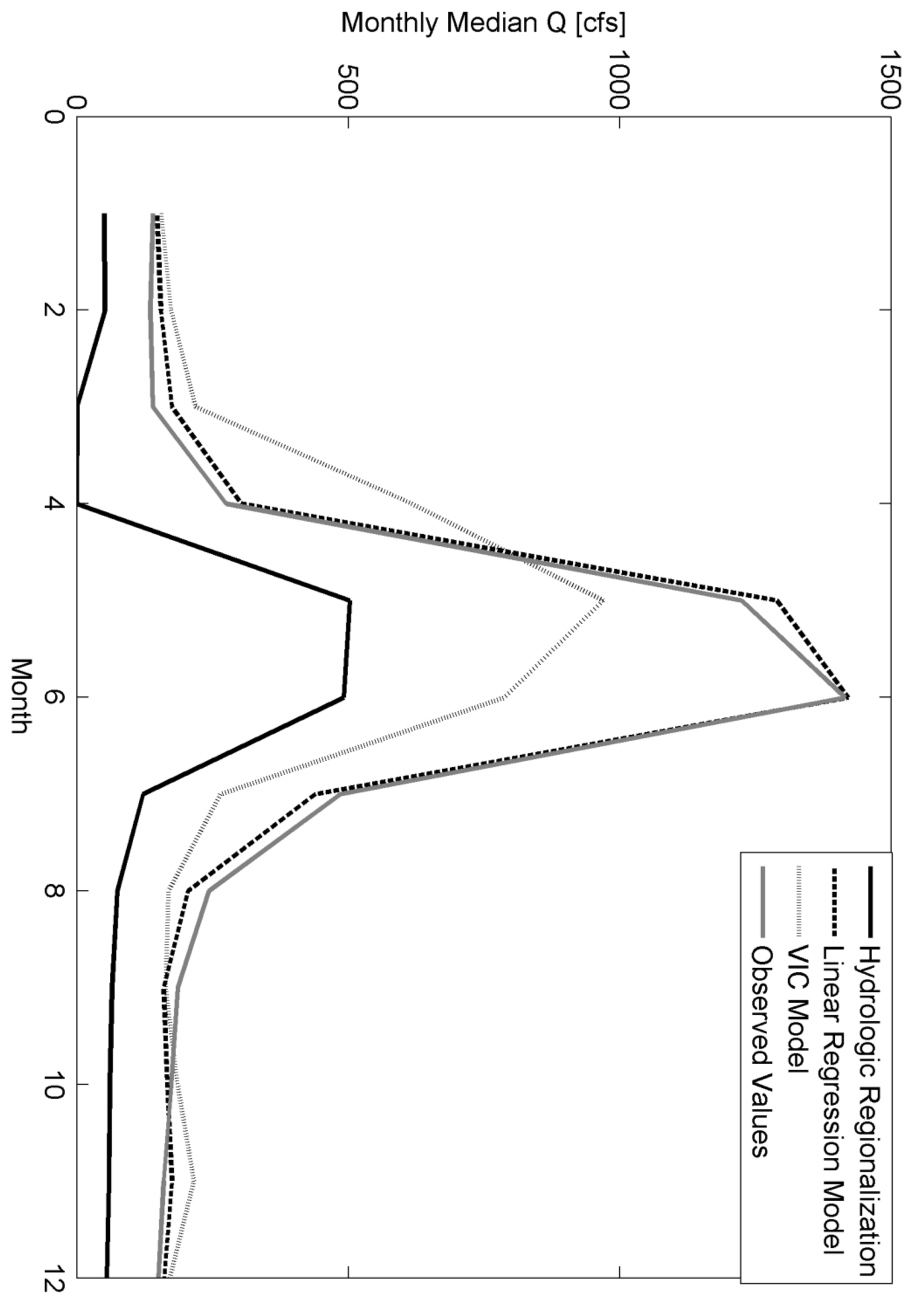

Figure 5. Comparison between all 3 models and the observed water discharge at Big Creek downstream of Cabin Creek from 1944-1958. Plots show median monthly flows in cubic feet per second.

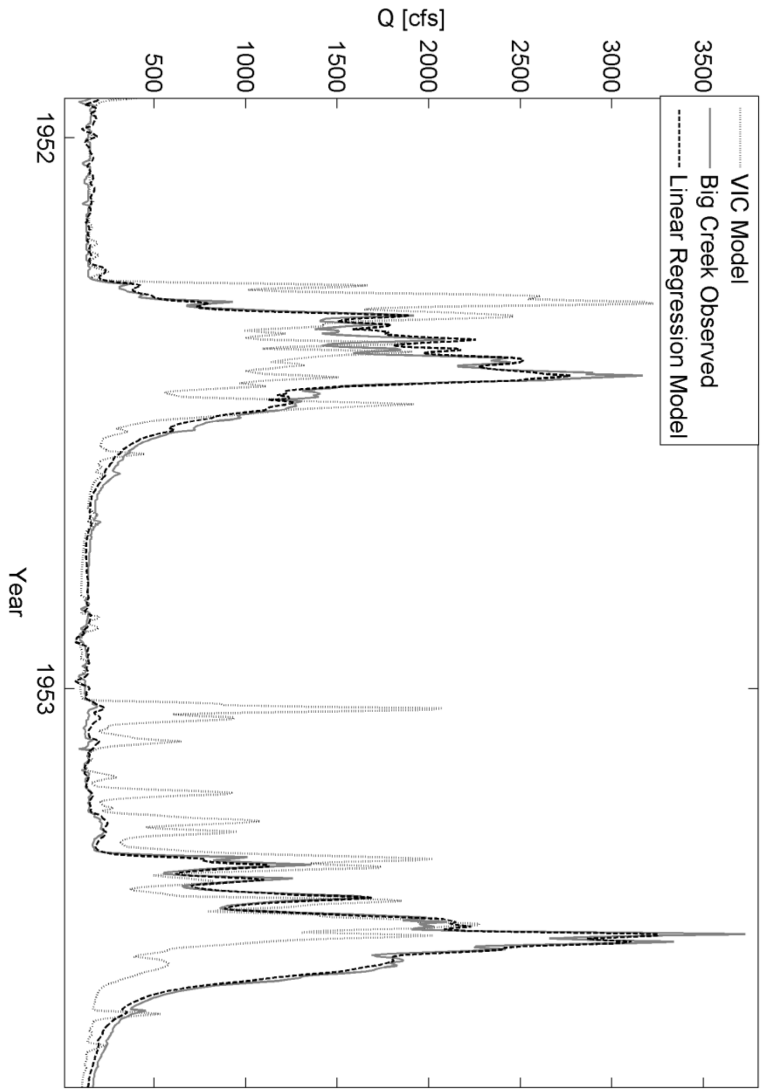

Figure 6. Comparison of two years (1952-1953) of model results for the VIC model and the Linear Regression model compared to observed discharge of Big Creek near Big Creek. The VIC model overestimates the intensity of summer flows and misses the timing and magnitude of spring flows, while the linear regression model follows the observed timing and magnitude closely.

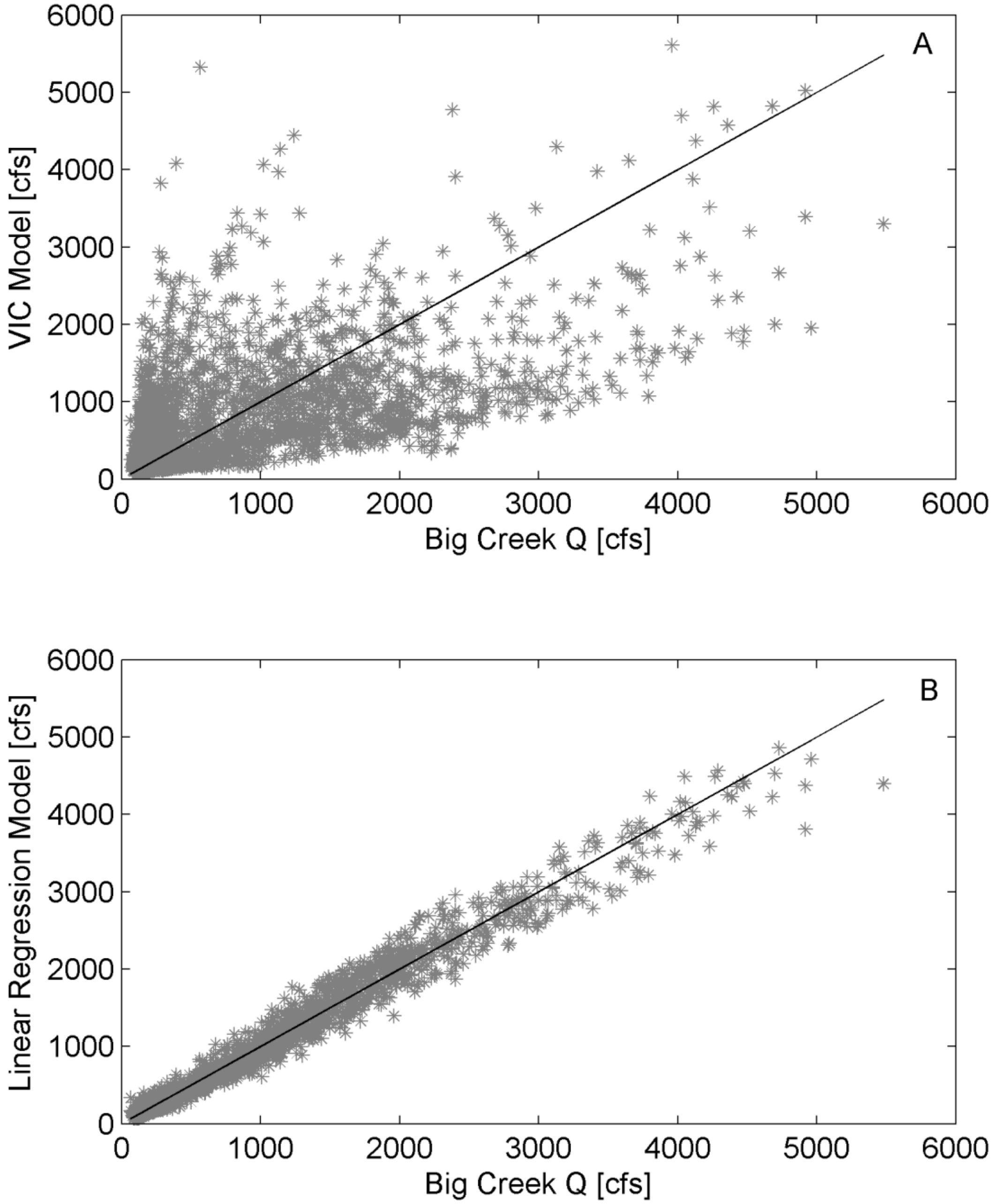

Figure 7. Plots of Big Creek observed discharge (1944-1958) and VIC modeled discharge (A) and Big Creek observed discharge (1944-1958) and Linear Regresission modeled discharge (B). The black line on both graphs shows a 1:1 line that would be expected with a perfect fit of the model.

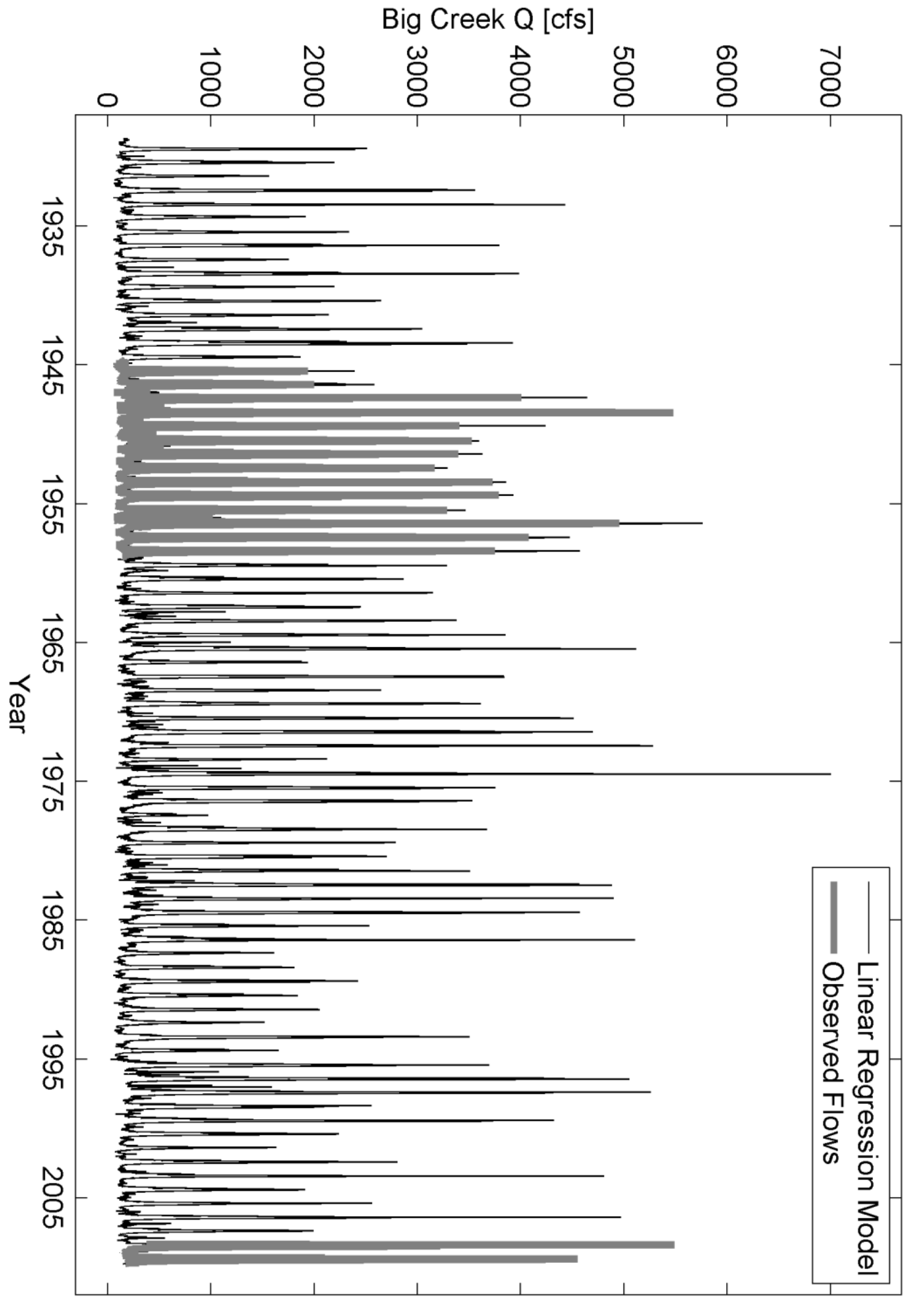

Figure 8. Reconstruction of the long term gaging record using the Linear Regression Model. Since the gages used to develop the linear regression extend further into the past than the original Big Creek gage, flows were modeled for the entire period of record of the nearby gages. Modeled flows have been corrected for the change in drainage area that occurred when the gaging location was moved.

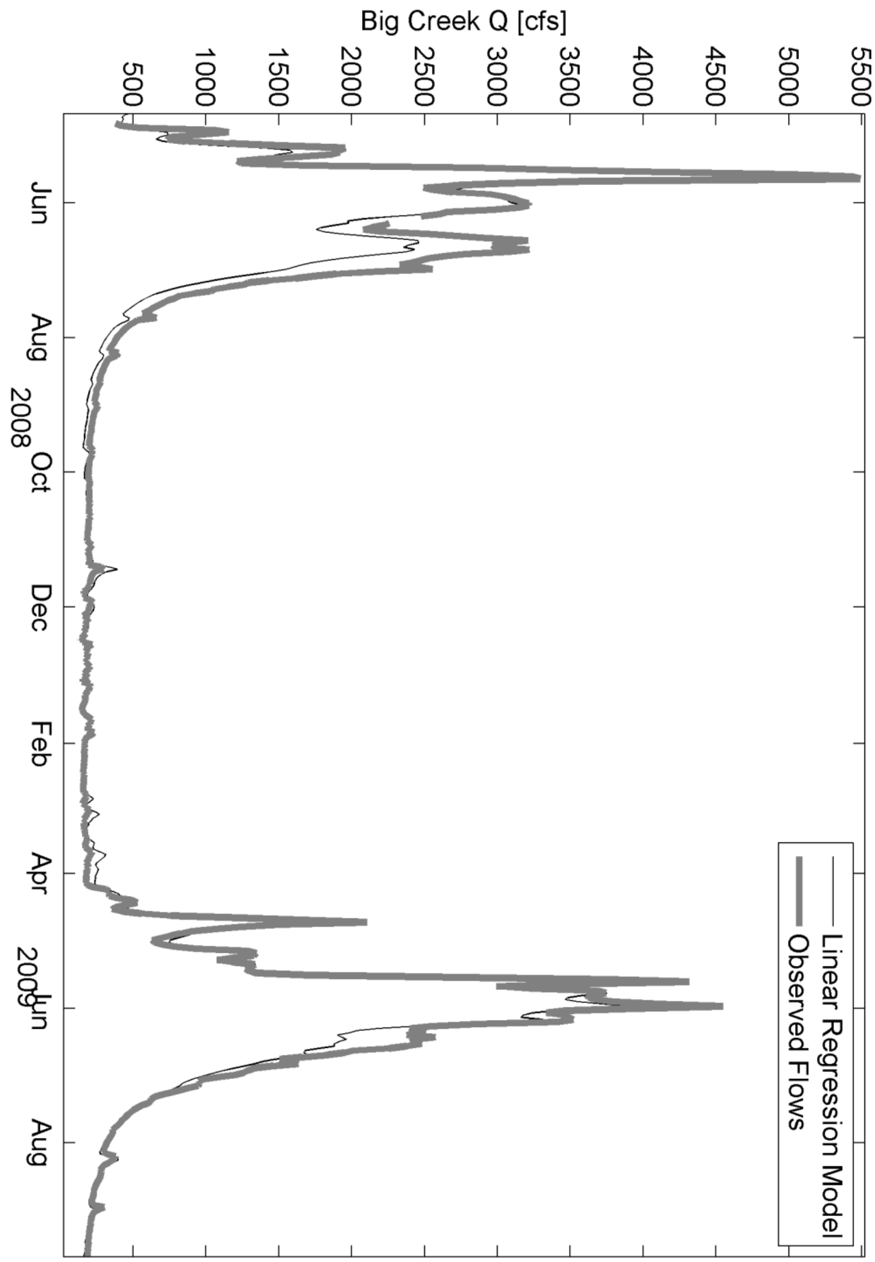

Figure 9. Comparison of modern day discharge of Big Creek at Taylor Ranch Bridge with Linear Regression model corrected for the change in drainage area. Agreement between observed and modeled values of the timing and magnitude of peak spring runoff is still strong.

Chapter 3: Topographic Influences on the Hydrologic Characteristics of Run-Off in a Snow-Dominated Mountain Catchment

Abstract

An improved understanding the spatial heterogeneity in watershed processes (the accumulation, storage and release of water) is essential for predicting how contemporary changes in climate will impact snow-dominated catchments. In order to address how differences in elevation and aspect affect the timing and magnitude of runoff, we collected two years of water discharge data in ten tributaries and the main stem of Big Creek, a tributary to the Middle Fork Salmon River. These catchments provide an ideal location to test the effects of elevation and aspect on runoff because of the large range in elevations and the overall orientation of Big Creek, which produces pronounced differences in aspect between tributaries on the North and South sides of the river. Our results reveal that basins do not produce the same amount of water per unit area, despite relatively close spatial proximity, similar topographic and other basin characteristics. Timing of peak runoff in tributaries was closely spaced between tributaries, occurring each year within one week of each other. Some variation was found in other aspects of timing including a clockwise hysteresis such that tributaries experienced relatively higher discharges than the main stem earlier in the season. Results of linear regression analysis showed that elevation is a first order control on the total water yield of a basin. When, compared with spatially distributed models of Snow Water Equivalent (SWE), elevation still remains a better predictor of total water yield. Water is not produced equally across the landscape and high elevation mountain catchments provide the majority of water to the system. This work shows that further investigations must be done to understand the

heterogeneity that currently exists in watersheds if we are to predict the impacts of future warming.

3.1 Introduction

Understanding hydrologic processes is inherently difficult because of the composite nature of the science. A hydrograph is the end result of a mass balance, where inputs (precipitation) are either fluxed out of the system by processes such as evaporation or stored within the system by groundwater for example. Any change in storage is the output. In this study, the output of interest is surface stream flow. Stream flow integrates all the processes that take place upstream of the basin and is more easily measured than other hydrologic parameters such as mean residence time or groundwater flow rate. Stream flow is also of vital importance to ecological systems and humans that depend on the easily accessible water provided by the stream. Because warming temperatures threaten the availability of water in snow dominated basins by altering the phase of precipitation and the timing of peak flows away from times of high demand, there is a need for better understanding and field studies that can drive models that will inform planners and land use managers (Bales et al., 2006). In particular, increased field observations will inform us on the variability that currently exists in the landscape in order to predict future changes.

3.1.1 Hydrology and Landscape Heterogeneity

Environmental characteristics such as weather, topography, geology and land cover vary across the landscape, producing different hydrologic signals. Weather can change the input to a watershed and the underlying geology and land cover can alter the rates of fluxes through the watershed and the total amount of storage within the watershed. By understanding the effects of each of these factors, we can better predict the responses to changing climate. An effective way to understand spatial heterogeneity at larger scales is to selectively monitor a suite of nested sub-catchments within a larger basin. One can then explore how these different contributions integrate downstream to create the flow of the main stem channel. This makes it possible to distinguish the natural variability within the landscape, allowing the researcher to isolate the effects of selected environmental variables on hydrology (McDonnell et al., 2007). The Big Creek study area has similarity between basins in land cover, underlying geology, and precipitation while the elevation and aspect varies between basins, making it possible to isolate topography as a variable because the other variables are relatively consistent between watersheds.

There is currently a knowledge gap in our understanding of streams at mid-size catchment. USGS gages typically measure large scale rivers that have economic and societal value, either from a water supply or hazard mitigation standpoint (Thomas and Wahl, 1993). These large rivers also provide information on the hydrology of large areas that often span multiple regions. In contrast to the large watersheds, a large amount of work has been done on very small watersheds in order to understand the small scale processes at work within the watershed (e.g. Anderton et al., 2003; Luce et al., 1998; Seyfried and Wilcox, 1995). This paper seeks to bridge the gap between these two scales by focusing on mid-size catchments, which are large enough to be integrative but small enough that the signal from individual processes should still be apparent.

3.1.2 Impacts of Changing Climate on Hydrology

In the coming decades, warming of the climate due to anthropogenic greenhouse gases is projected to have a myriad of impacts. Regions whose hydrology is dependent on snowmelt are particularly vulnerable to warming temperatures (Stewart, 2009; Barnett et al., 2008). Already noticeable differences have appeared in the hydrographs of the Western United States (Mote et al., 2005; Barnett et al., 2005), including a shift in the timing of when 50% of the runoff has passed (Stewart et al., 2004) and a corresponding decrease in April 1 SWE (Hamlet, 2005). As temperatures rise, so too will snowlines. This will create less snow-covered areas and increase the potential for rain-on-snow events. Also, warmer spring and fall seasons will shorten the total time period of snow accumulation and cover.

The effects of warming temperatures will not be felt evenly across the landscape; some streams will be impacted to a larger extent than others. Elevation has a strong effect on accumulation and retention of snow. Models show that future warming will impact mountain zones with lower elevations the most (Knowles and Cayan, 2004). Additionally, elevation and aspect often control the timing of the onset of spring runoff in mountain catchments (Lundquist et al., 2004).

Expected effects of warming temperatures are that the timing of peak runoff will shift earlier in the year, summer flows will be reduced, and total water yields will be reduced (Stewart, 2009). The potential impacts of hydrologic changes would shift the "Natural Flow Regime" (Poff et al., 1997), which could affect in stream ecological processes.

This study was designed to test the hypothesis that differences in topography within a snowmelt dominated watershed lead to differences in hydrology. Specifically, we tested the hypothesis that there are higher peak flows in north-facing, high-elevation basins because of their greater retention of snow cover. The relationship between mean annual discharge and elevation is apparent at large scales (Horton et al., 2006), but this study aims to investigate whether that relationship holds true at smaller spatial scales and in smaller tributary streams. By dissecting the landscape into smaller watershed units, we attempt to understand the topographic heterogeneity and observe the differences in hydrology that arise from this spatial heterogeneity.

3.2 Setting

The Big Creek drainage is an ideal field site due to the wilderness character of the basin, its west-to-east orientation, and its high relief. Because the majority of the Big Creek watershed lies within the Frank Church River of No Return Wilderness (Figure 1), the river lacks the dams, diversions and withdrawals of other rivers. As a result, there are no artificial alterations to the shape or timing of the hydrograph. The location of the Taylor Wilderness Research Station (TWRS) provides easy access to these drainages and logistic support and a legacy of biological investigations in surrounding streams.

The Big Creek watershed is 1540 km^2 at the point where it meets the Middle Fork Salmon River, and 1444 km^2 at TWRS, where a new gage was established in 2008. The only previous continuous gaging in the watershed was at a former USGS gage that existed from 1944 to 1958 and was located ~7 miles upstream downstream of the confluence with Cabin Creek. The watershed has a drainage density of 0.67 and an overall dendritic shape. Channels are generally confined within steep canyons, leaving little room for floodplain formation. Hillslope angles in the watershed average ~25 degrees. The highest point in the basin is 2908m and the outlet at the Middle Fork is 1031m. The current Big Creek gage is located at an elevation of 1165m.

The geology of the basin is comprised of Proterozoic meta-sediments, Tertiary batholiths, and Tertiary volcanics (Lund, 2004). A shallow depth to bedrock (<1 m in many locations) is observed throughout the basin. Land cover is dominated by ponderosa pine/Douglas fir forest and sagebrush/grassland. Upper elevations are subalpine forested, with exposed ridgelines. This land cover has changed significantly in local regions due to recent fires in 2000 and 2006, which burned much of the canopy. Though the riparian shrubs and grasses have recovered following the fires, little re-forestation has yet to occur (Kavanagh, personal communication). Prior to the recent fires, there had been few large scale fires in the area in the historical period of record. This is of some concern because the frequency of fire is expected to increase with warming climate (Meyer and Pierce, 2003).

Big Creek, like much of central Idaho is characterized by a precipitation regime that is dominated by winter snowfall, with mixed snow/rain precipitation falling in the lower elevations during the winter and during the spring and fall in the higher elevations. A climate station at TWRS has been in operation since 1980.

Because the mainstem of Big Creek flows west to east, many of the tributaries have either a predominantly north or south facing aspect, allowing aspect-specific questions to be addressed. In addition to being generally high relief, there is also a fairly wide variety of mean basin elevations (Table 1) as well as a variety of distributions of elevations. Some basins have area concentrated at high elevations and some basins have area concentrated at low elevations. The streams selected for gaging and their characteristics are listed in Table 1 and shown in Figure 2. These sites were selected because of their accessibility from TWRS and because they constitute a wide range of basin sizes from the smallest (Dunce Creek, 6 km^2) to the largest (Big Creek, 1444 km^2).

Big Creek has been studied intensively by ecologists (e.g., Robinson et al., 2000; Malison, 2007) and characterizing the hydrology of the area would provide additional relevance to their studies. Future research in Big Creek will continue to focus on the ecology of the region and combining the hydrology with ecological research will provide a clearer picture of future climate driven changes.

3.3 Methods

This study uses the methods presented in Lundquist et al. (2009) to establish temporary gages using vented water level loggers calibrated using manual measurements of discharge. These continuous records of discharge in the tributaries and the mainstem of Big Creek record the integrated surface water response to spatially variable drivers in the upland territory. Due to difficult winter logistics and access issues, we make no measure of snow depths or melt rates in the study watershed.

3.3.1 Hydrologic Measurements

We recorded stage in tributaries using vented pressure loggers (Level Troll 500 from In-Situ) positioned in 1” diameter PVC perforated stilling wells. Loggers record stage, water temperature and air pressure at 15 minute intervals. Loggers were installed near the start of the spring runoff for two years, 2008 and 2009. The stage in Big Creek is continuously monitored using a radar level sensor (OTT-RLS) mounted to a steel foot bridge at TWRS. In 2008, 10 tributaries and the mainstem of Big Creek were monitored. In 2009, 4 tributaries were eliminated from the monitoring program because results suggested these had redundancy in hydrologic characteristics.

Sites for location of level loggers were selected based on two considerations: (1) good stability of channel bed and banks (Rantz et al., 1982) and (2) finding unobtrusive locations where loggers would not interfere with the wilderness character of the field area. Wilderness regulations did not allow for the installation of permanent structures such as flumes or weirs, hence the need for natural reach controls. Flow measurements were made using a Sontek Flowtracker ADV using the midsection method at 0.4*depth above the bed and averaging intervals of 40 seconds as per USGS methodology (Blanchard, 2004). Rating curves were developed for each tributary (Appendix 1) and a unique rating curve was used for each year to account for possible changes in stilling well position or cross section geometry between seasons.

3.3.2 Hydrologic Analysis

Using the raw stage data and the rating curves calibrated from field measurements of discharge, we generated continuous records of flow. From these records we computed daily mean, maximum and minimum flow values. A one hour smoothing window was applied to account for some of the inherent noise in the original stage data.

Daily mean values of discharge were divided by watershed area (km^2) to normalize stream fluxes so they could be compared between watersheds of varying size (referred to hereafter as yield). Differences in this yield indicate that two tributaries do not yield the same water per unit area. This is a based on the accepted scaling between discharge values and drainage area, given the following equation (Dunne and Leopold, 1978),

$$Q = kA^c \tag{3.1}$$

Where Q = surface water discharge in m^3/s, k is the prefactor in the power-law relation (units depend on value of c), A is drainage area in km^2, and c is the scaling power dependency. Theoretically, c can be equal to 1, implying that each unit area (m^2 or km^2) of land in the basin contributes an equal amount of runoff to the stream. Using flow values from within the Big Creek watershed and other nearby gaging stations, we find that c = 1.1 (Figure 3), indicating that normalizing discharge by drainage area is appropriate for comparing flows from basins within the study area. Total water flows were reported in millimeters. This was done by summing daily mean flow values in m^3/s and multiplying by seconds, minutes and hours to produce a total volume of water measured over the entire period of record. These values were then divided by drainage area and converted to millimeters by dividing by 1000.

3.3.3 Topographic Analysis

The variables chosen for analysis were mean basin elevation and percent of basin facing north or south. These variables were selected due to their relationship with incoming direct solar radiation (aspect) and temperature lapse rate (elevation). Basin attributes were calculated using ArcMap and Matlab from 10m DEM. DEMs were obtained from the National Elevation Dataset at (http://seamless.usgs.gov/ Accessed 2/19/2008). Watershed areas were calculated using GPS locations of gaging stations for pour points and the watershed delineation tool in the Spatial Analyst package of ArcGIS. Aspects were calculated using the Aspect tool in Spatial Analyst and binned into four 90 degree categories, each centered on the four cardinal directions. Mean elevations of the watersheds were extracted in ArcMap.

3.3.4 Snow Water Equivalent Values

Snow water equivalent values were obtained from the National Operational Hydrologic Remote Sensing Center (http://www.nohrsc.noaa.gov/archived_data/ Accessed September 2009-January 2010.). These datasets are generated through a combination of point observations of Snow Water Equivalence (SWE) at SnoTel and snow course sites, remote sensing imagery and spatially distributed mass and energy balance models (Carroll et al., 2001). Data sets cover the lower 48 of the United States and have a 1km grid size. This data was clipped in ArcMap to the boundaries of each watershed. In order to correlate SWE with elevation, the grids of SWE and elevation were converted to point values and joined based on nearest neighbor in ArcMap.

3.4 Results

The general shapes of all hydrographs within the study area are consistent with a typical snow-dominated hydrograph. There is a rapid increase of flows in late April and

May coinciding with increasing temperatures and longer periods of daylight. The average date of peak discharge for all studied streams occurred on May 17 in 2008 and May 23 in 2009. Among the different streams, the standard deviation of the timing of peak flow was 6.3 days for 2008 and 5.8 days in 2009. In both years, the timing of maximum flows appeared to be controlled by synoptic weather patterns rather than a depletion of snow reserves. The peak flow in 2008 and 2009 was interrupted by a rapid cooling that had below freezing temperatures for a large portion of the day. Higher flows were not seen again that water year.

Once discharge was normalized by drainage area (hereafter referred to as yield), the hydrographs separated into three distinct groups (Figure 4). One group, defined by Goat and Dunce Creeks, displayed a very weak peak in late May followed by a gradual decline for the rest of the year. The second group, defined by the remaining tributaries, had a much higher peak in the yield than Goat and Dunce as well as higher yields throughout the remainder of the season. Although tributaries all had general snow-melt hydrographs, a surprising amount of variation existed between hydrographs, with some, such as Goat and Dunce that showed muted signals and others such as Big Creek which showed more drawn-out peaks. Finally the main stem of Big Creek had a higher peak yield than all other tributaries and higher yields throughout the year.

Flow metrics of total runoff, peak flow values, and flow increases were used in linear regressions against topographic variables of elevation and aspect. Linear regression analysis was performed in Matlab, and an alpha value of .10 was used to determine significance. Due to the small sample size involved, a lower alpha value seemed unreasonable. Results of linear regression analysis showed a strong positive linear relationship between flow metrics and elevation. Flow metrics showed a very weak linear relationship with aspect.

SWE showed a strong spatial heterogeneity. Elevation is an important factor for snow accumulation and melt rates. Figure 5 shows how the snowline, defined by the linear regression of SWE and elevation, varied by month. The snowlines calculated in Figure 5 are shown in map form in Figure 6. Overall, there was also a strong west-east gradient of decreasing snow values implying an orographic shadowing for storms moving off the Pacific (Figure 7).

3.5 Discussion

The results of this study are not intended to be used as a predictive model, but rather to test the influence of various topographic variables on hydrology. Results of linear regression analysis showed the strongest correlations between elevation and total runoff (Figure 9). Due to typical lapse rates, basins with a higher mean elevation have overall lower mean air temperatures. These colder temperatures allow for a greater accumulation and retention of snow throughout the winter and early spring season. In turn, this means that there is a greater store of water available to be discharged out of the basin during the time of year that temperatures increase to the point of melting snow at higher elevations. In addition to showing a strong linear relationship for total runoff, the streams maintained the same relationship when monthly mean values are used as opposed to total runoff. This indicates that the positive relationship seen in Figure 9 is not controlled by early season runoff alone, but that it maintains the same observed relationship as groundwater becomes more dominant.

When plotting drainage area versus discharge, we find that the relationship is dependent on the mean elevation of the watersheds that are sampled. Discharges for the small tributaries, Big Creek and nearby larger gages along Middle Fork and Main Salmon River (Figure 3), have a scaling exponent c is 1.087. This is somewhat different than expected from the observed water yields in Figure 4, where two of the smallest tributaries have particularly low water yields. This suggests smaller tributaries have disproportionately smaller water yields which would result in values of c significantly greater than 1. This implies that as drainage area increases, an increasing amount of water is added to stream flow. It is not that some new property emerges that creates more water from one 10 km^2 basin than ten 1 km^2 basins. The 10 km^2 catchment is after all made up of smaller sub-basins. This result suggests that the headwater tributaries, which were not measured as part of my study, provide more water per square kilometer than the tributaries in my study. Part of this is due to the orographic effects of mountains on precipitation. A precipitation shadow is visible from west to east (Figure 7). As a result, a greater overall store of snow exists in the headwater reaches. This same effect is seen within the tributaries themselves, namely, higher elevation basins tend to show higher discharge values and increase rates of increase in flow.

Longitudinal profiles of rivers reveal that tributary basins located closer to the headwaters will have higher mean elevations than their counterparts near the outlet, even if their peak elevations are the same. Assuming a uniform distribution of snow (which is unlikely due to orographic and wind effects in mountainous terrain) it could be assumed that the discharge in high elevation headwater streams will peak later than low elevation streams. As the snowmelt season progresses, the lower elevation tributaries close to the outlet provide a disproportionate amount of water relative to their size as they melt off the majority of their snow early in the season. Figure 6 shows the distribution of SWE by elevation and a map of the tributary basins with these snow lines shown progressively throughout the season. Once the lower elevation outlet tributaries have released most of their water, the higher headwater tributaries begin to contribute their water. These differences in timing can be seen as a hysteresis between the tributary streams and the main stem (Figure 9). This relationship can be represented in another way by showing the relative runoff of each basin as a percentage of the main stem discharge (Figure 10). The timing of the absolute peak flood event is well correlated between basins due to large scale synoptic weather patterns, but smaller differences in their timing are controlled by differences in topography.

A similar correlation is seen between elevation and the rates of change on the rising and receding limbs of the hydrograph. Once again the hydrographs separate into distinct groups based on elevation, with Big Creek experiencing the highest rates of rise and fall, mid tributaries exhibiting medium rates of rise and fall, and Goat and Dunce experiencing the lowest rates of change in discharge. This again implies that elevation is a first order control on the hydrologic characteristic of the tributaries.

Water yields were determined by summing daily mean flow values and multiplying by seconds, minutes and hours to produce total water yield over the entire period of record. These values were then divided by drainage area and converted to millimeters. The resulting total water yields show a strong positive linear relationship with elevation as well (Figure 8).

Results of water yield were compared to SWE observations to evaluate whether the already observed SWE values from remote sensing were a superior predictor of water yield than topographic characteristics of basins. SWE observations are of great use to water managers because despite the positive correlation between elevation and water yield, the amount of water in a basin is determined first by precipitation inputs within the basin, then by transformative processes such as interception or sublimation within the basin. An important observation from this study is that there is a stronger correlation between elevation and water yield than between water yield and April 1st SWE (Figure 10). April 1st is a date often used to characterize the maximum snow accumulation within a basin (e.g. Mote, 2003). This result could be associated with errors introduced by satellite observations or perhaps because topographic controls on the distribution of temperature or solar radiation have large influences on areas of accumulation. In addition the resolution of the SWE (1 km^2) is much coarser than the resolution of the topographic data (10 m^2).

Aspect is weakly correlated to water yield for the tributaries of Big Creek (Figure 11). Although weaker and superimposed on the overall pattern set by elevation, aspect is correlated with the water yield and rates of change within the watershed. Basins with a disproportionately large amount of north facing aspects hold more snow longer than basins with a large portion of south facing aspects as evidenced by the correlation between magnitude of peak yield and aspect. This allows for a greater retention of snow and leads to higher water yields and faster rates of change. These basins retain a deeper snow pack overall until the larger scale weather patterns increase temperatures to a point of consistently staying above freezing. At this point, direct radiative heat from the sun plays less of a role in the melting of snow than longer wavelength heat and convective heat transfer. In addition, north aspects tend to have greater forest cover, which further reduces snowpack amounts because of canopy interception (DeWalle and Rango, 2008).

Certainly other factors than elevation and aspect influence the amount and timing of water transferred from the atmosphere into the stream. Evapotranspiration is one of the major fluxes in the hydrologic cycle, and this study did not make any attempt to account for differences in relative evapotranspiration amounts due to differences in vegetation or burn history. Though beyond the scope of this study, it would be valuable to explore the differences in hydrology and their relationship to different fire history.

3.6 Conclusions

The hydrographs from tributaries and the main stem of Big Creek have important implications for future hydrologic work. This study provides evidence that in snow dominated catchments water yield is not evenly distributed within the basin. Even within regions that receive relatively uniform precipitation, water yields differ depending on the elevation of the basin.

This variable contribution of water implies that basins will not have a uniform response to changing climate. Higher elevation basins are likely to be buffered from change to a greater degree than low elevation basins. Low elevation basins, such as Goat and Dunce Creeks, are particularly vulnerable to rising snowlines because these streams already have very low water yields for their size. Greater reduction in snow covered area could further reduce their water yield and switch these streams and others like them from perennial to intermittent streams.

The implications for geomorphology and biology are important because there is a tendency in these fields to use drainage area as a proxy for discharge, but as can be seen from this study it is not a robust assumption. It is especially true in snow dominated systems where the phase shift in water from solid to liquid can be both elevation dependent and spatially variable.

In addition, these findings have implications for large scale hydrologic models. In order for models to truly be useful and reflect the real world mechanisms at work within a watershed, they must be able to account for these small scale dependencies on elevation that are often not well represented in coarse resolution, distributed hydrologic models.

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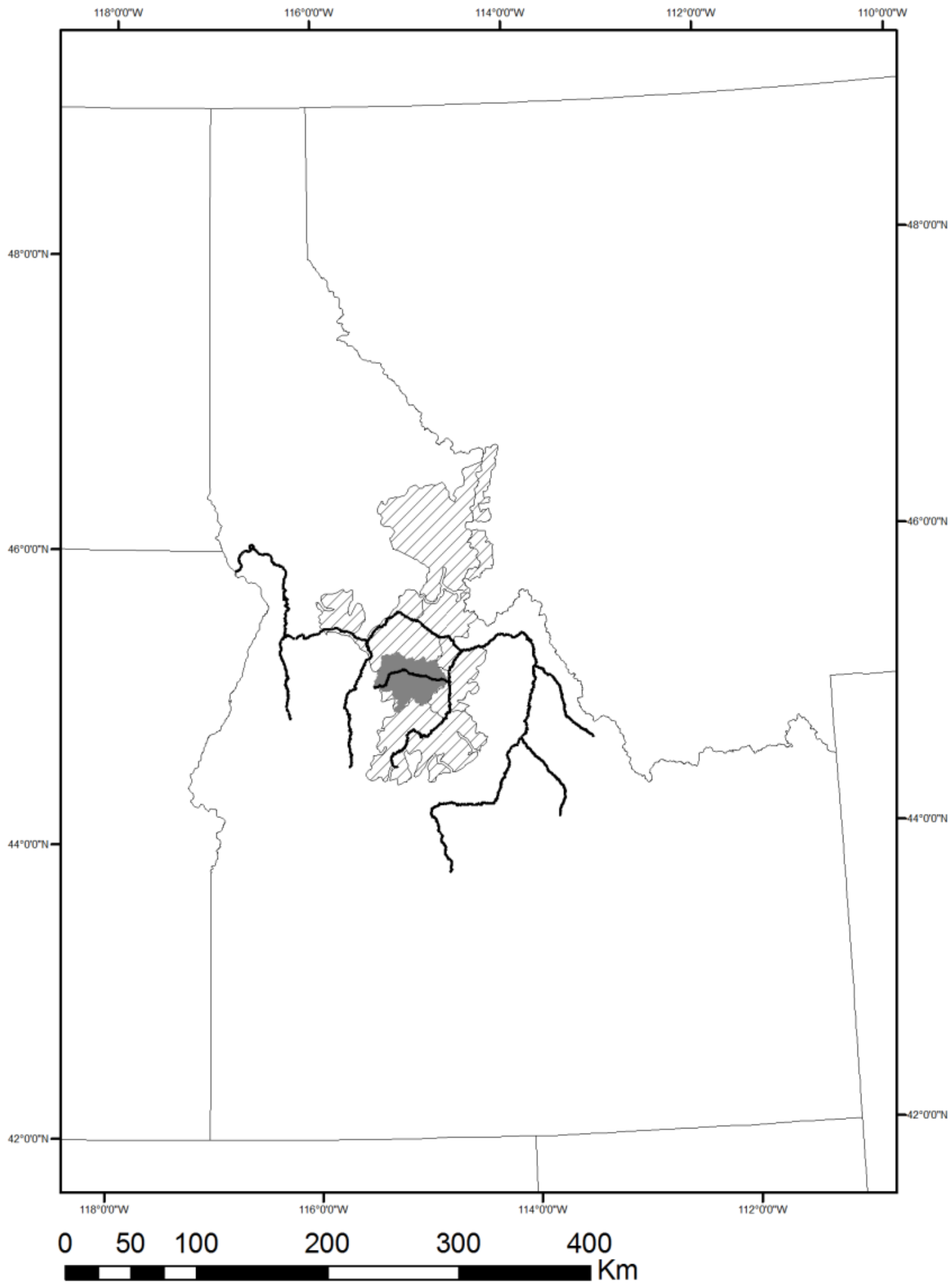

Figure 1. Location map showing the Big Creek watershed in gray. Hashed area is the Frank Church River of No Return/Selway Wilderness and the black lines are the Salmon River and its main tributaries

Creek Name/Figure 2 labels	Mean Elevation [m]	% North	% South	Area [km^2]	Maximum Elevation [m]	Relief [m]
Big (A)	2117.06	24.73	23.22	1444.15	2908.14	1743.24
Cabin (B)	2037.08	15.57	25.81	64.43	2713.23	1482.25
Canyon (C)	1929.39	36.08	16.86	13.64	2524.87	1306.17
Cave (D)	1986.98	16.32	26.11	47.12	2695.99	1461.46
Cliff (E)	2114.02	5.36	31.03	18.81	2652.41	1458.01
Cougar (F)	1990.35	7.42	28.20	21.41	2589.59	1419.43
Cow (G)	1977.40	16.01	26.13	16.13	2648.12	1300.72
Dunce (H)	1832.03	1.24	34.94	6.48	2467.42	1338.28
Goat (I)	1888.95	2.99	26.58	7.86	2465.89	1168.16
Pioneer (J)	2060.67	30.85	7.70	15.87	2834.19	1618.25
Rush (K)	2101.55	27.47	21.64	243.39	2908.14	1731.21

Table 1. Basin attributes of Big Creek and its tributaries. Letters next to the basin names denote locations on Figure 2.

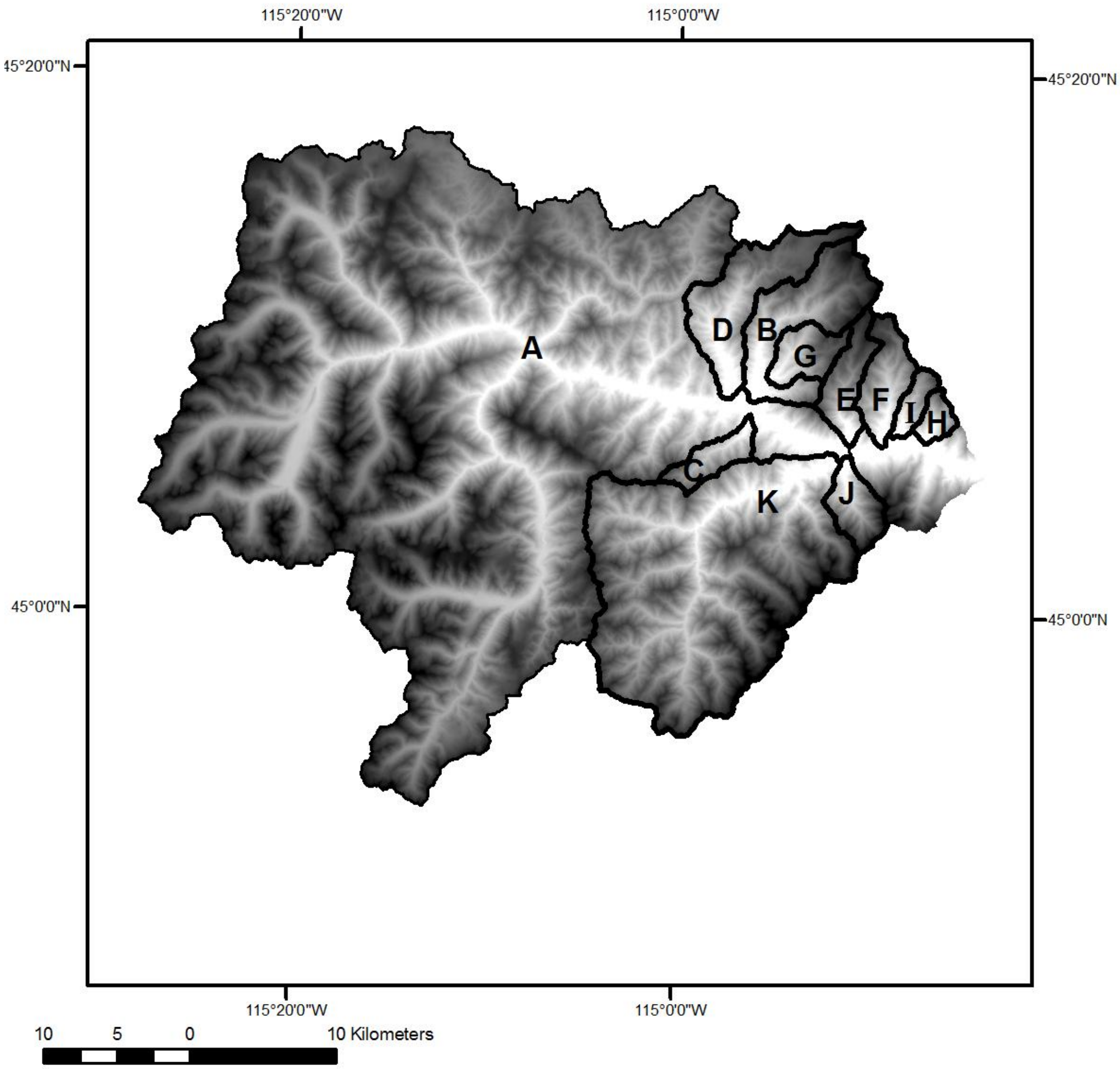

Figure 2. Location map and DEM of Big Creek watershed. Basin names are listed in Table 1. Because of the west to east drainage of Big Creek, tributaries draining from the north have predominantly south facing aspects and tributaries draining from the south have predominantly north facing aspects. Elevation also varies along the axis of Big Creek, with higher elevations on average existing in the western portion of the basin, with the exception of a ridge of high elevation peaks along the south-east watershed boundary.

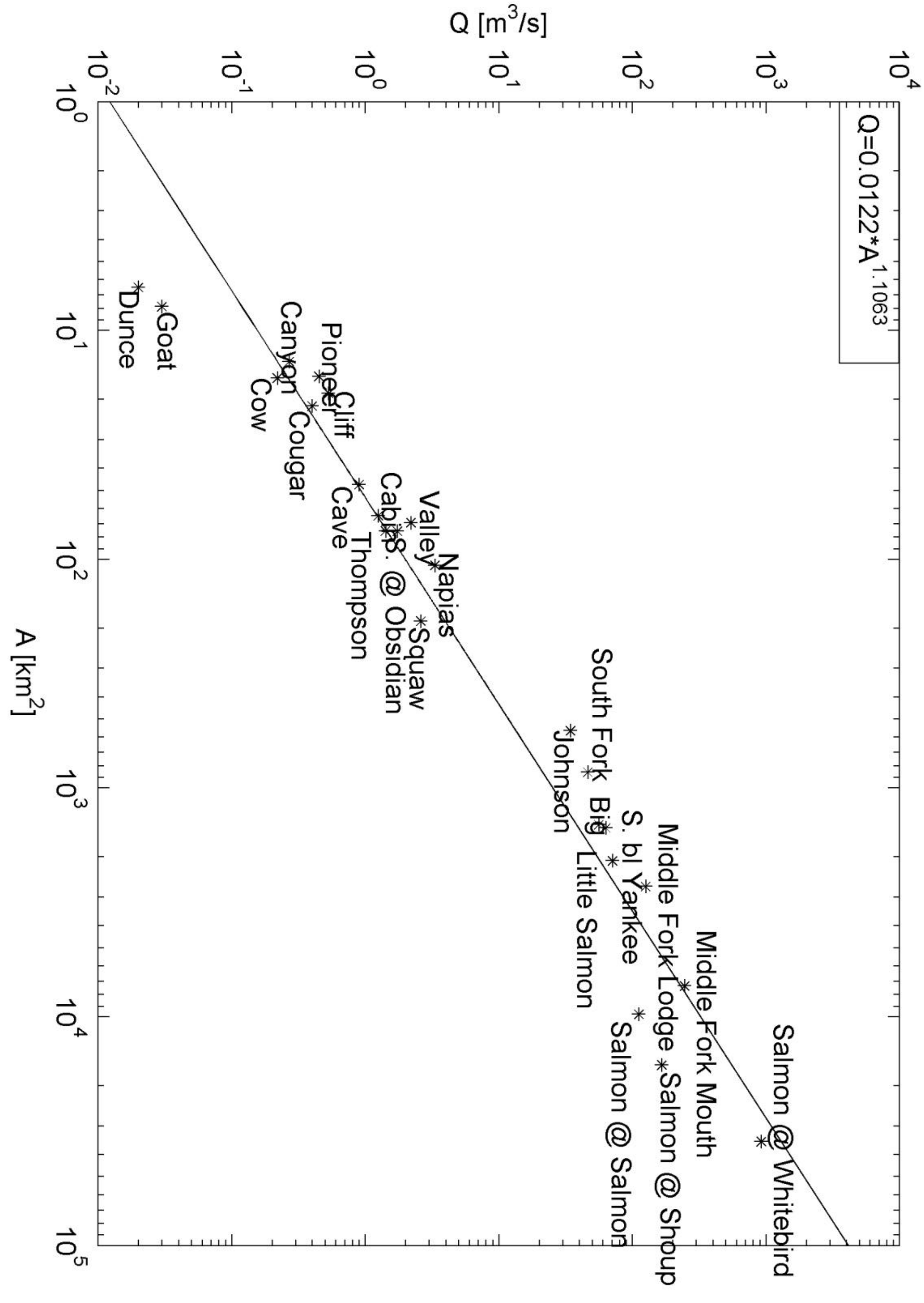

Figure 3. Scaling of mean spring discharge (4/27/08-7/31/08) for Big Creek and its tributaries as well as nearby USGS gaging stations. An exponent of 1.1 on the area term in the equation $Q = kA^c$ means that it is reasonable to expect close correlation of discharge between basins of different sizes once divided by drainage area.

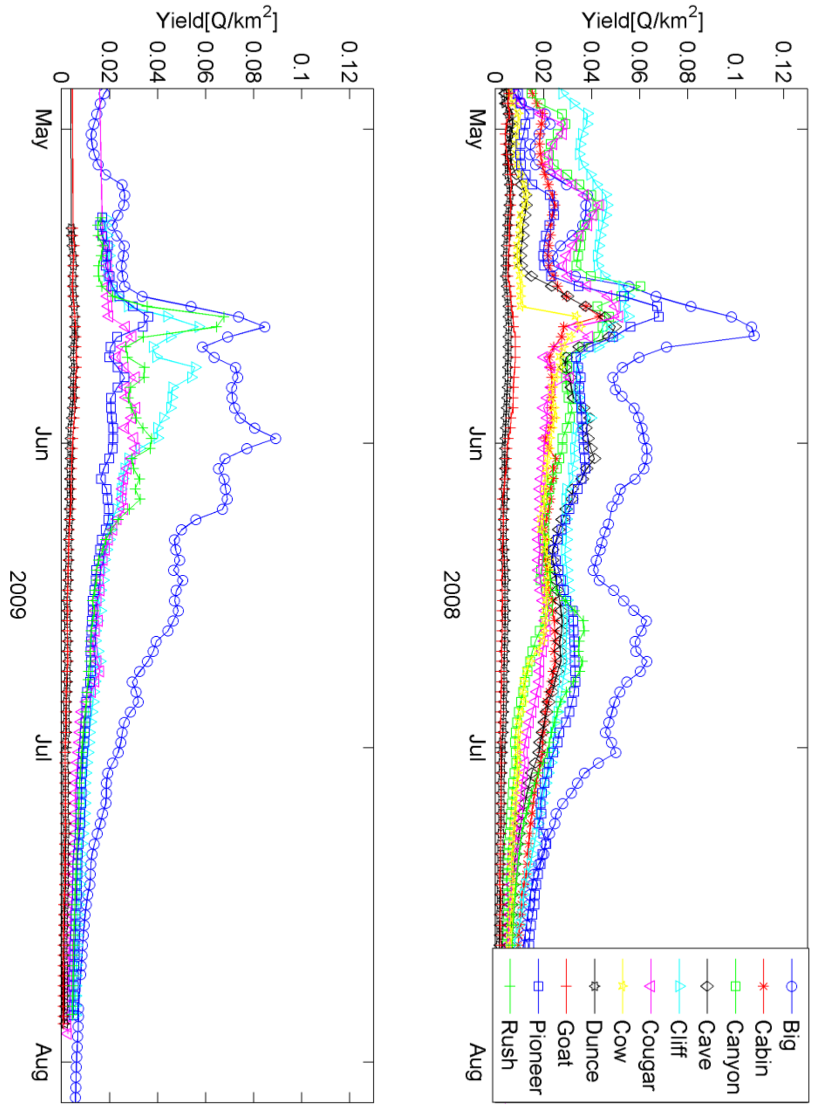

Figure 4. Water discharge of Big Creek and its tributaries normalized by drainage area. Big Creek has a higher water yield than the tributaries and two of these tributaries, Goat and Dunce, had exceptionally low water yields compared to other tributaries within the study area.

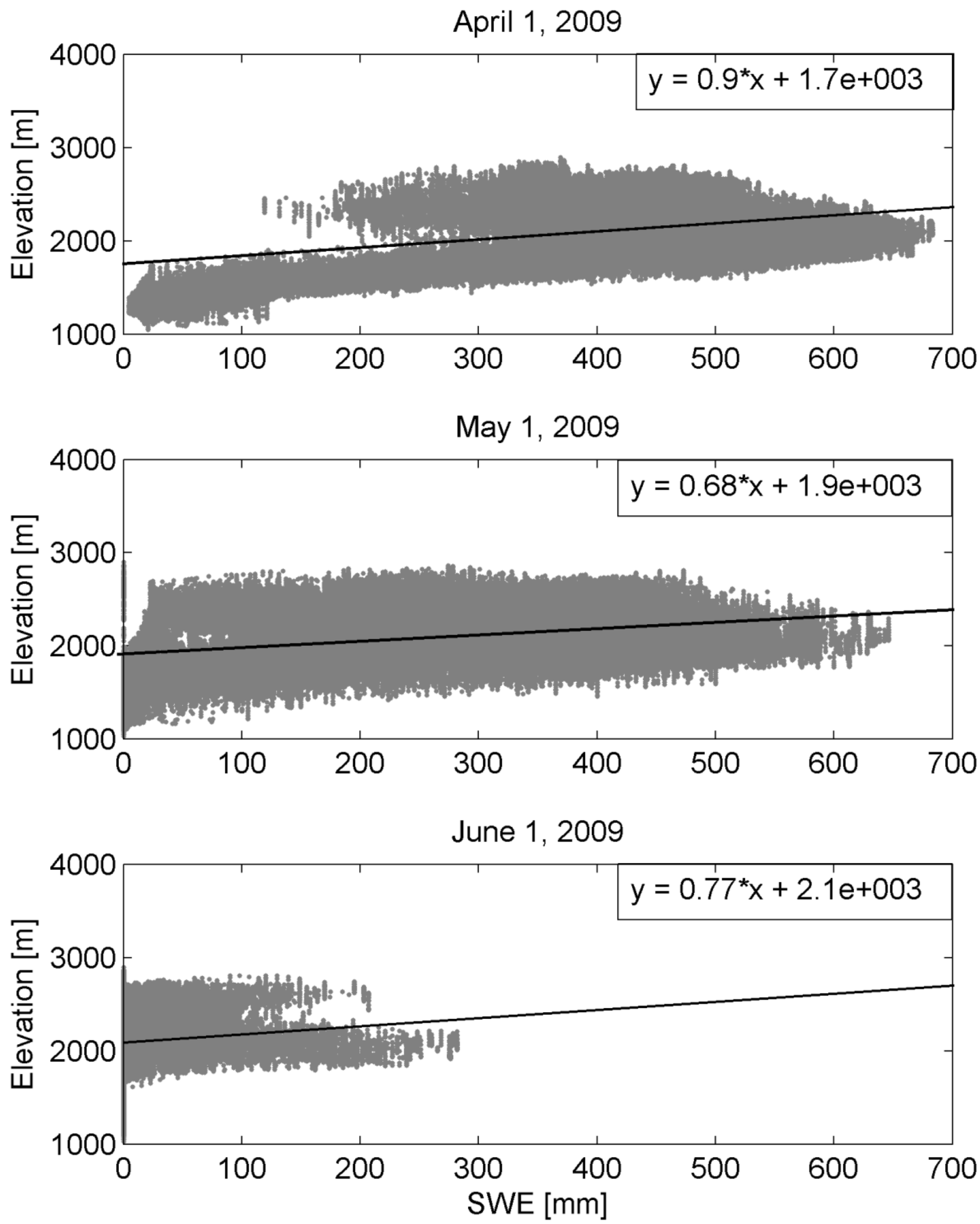

Figure 5. Plots of SWE against elevation for the first of April, May and June of 2009. Average snowline moves up 200 meters per month during this time period defined by the y intercept of a linear regression of the data. This implies that basins with low mean and max elevations will discharge water prior to higher elevation basins. The split population visible in April and June is due to the decreasing west to east precipitation gradient visible in Figure 7.

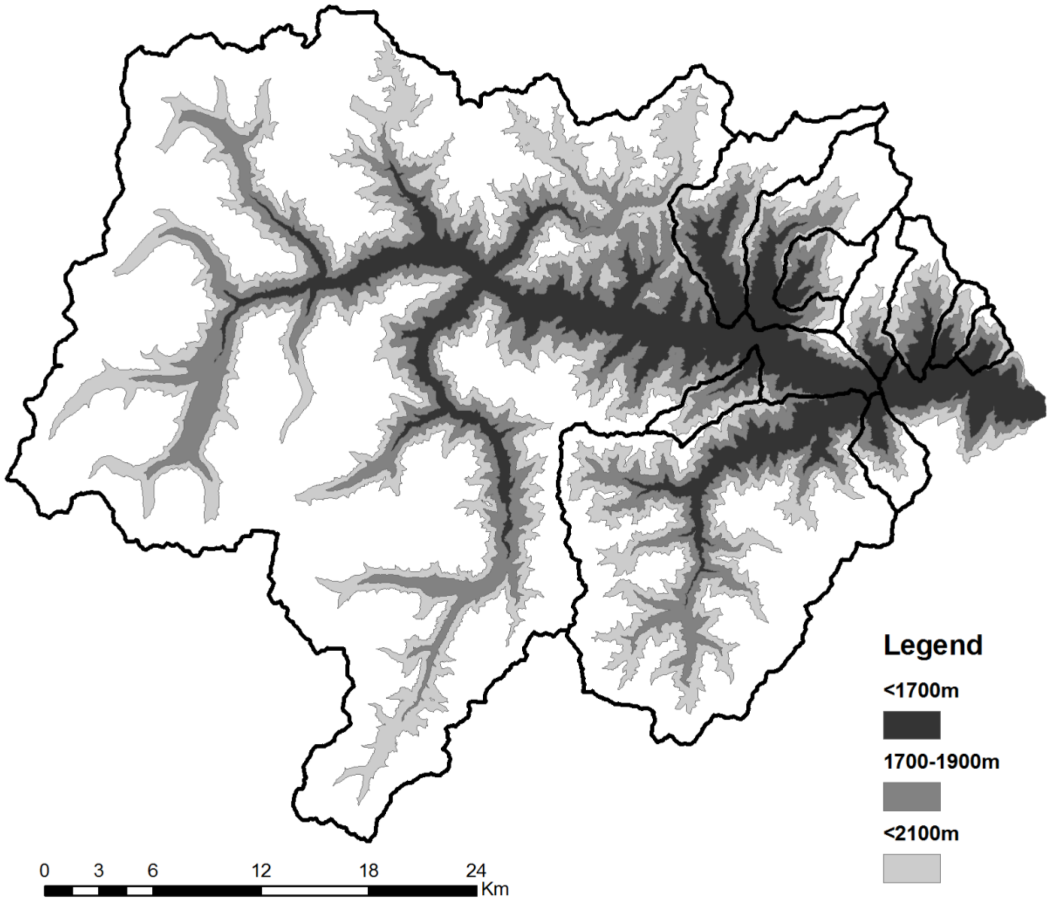

Figure 6. Map view of the Big Creek watershed and elevation bands defined in Figure 5 shown. Lower elevations are concentrated near the outlet of the basin while the western portion of the basin contains large areas of high elevation land that can hold snow late into the season. White regions are those greater than 2100 m in elevation

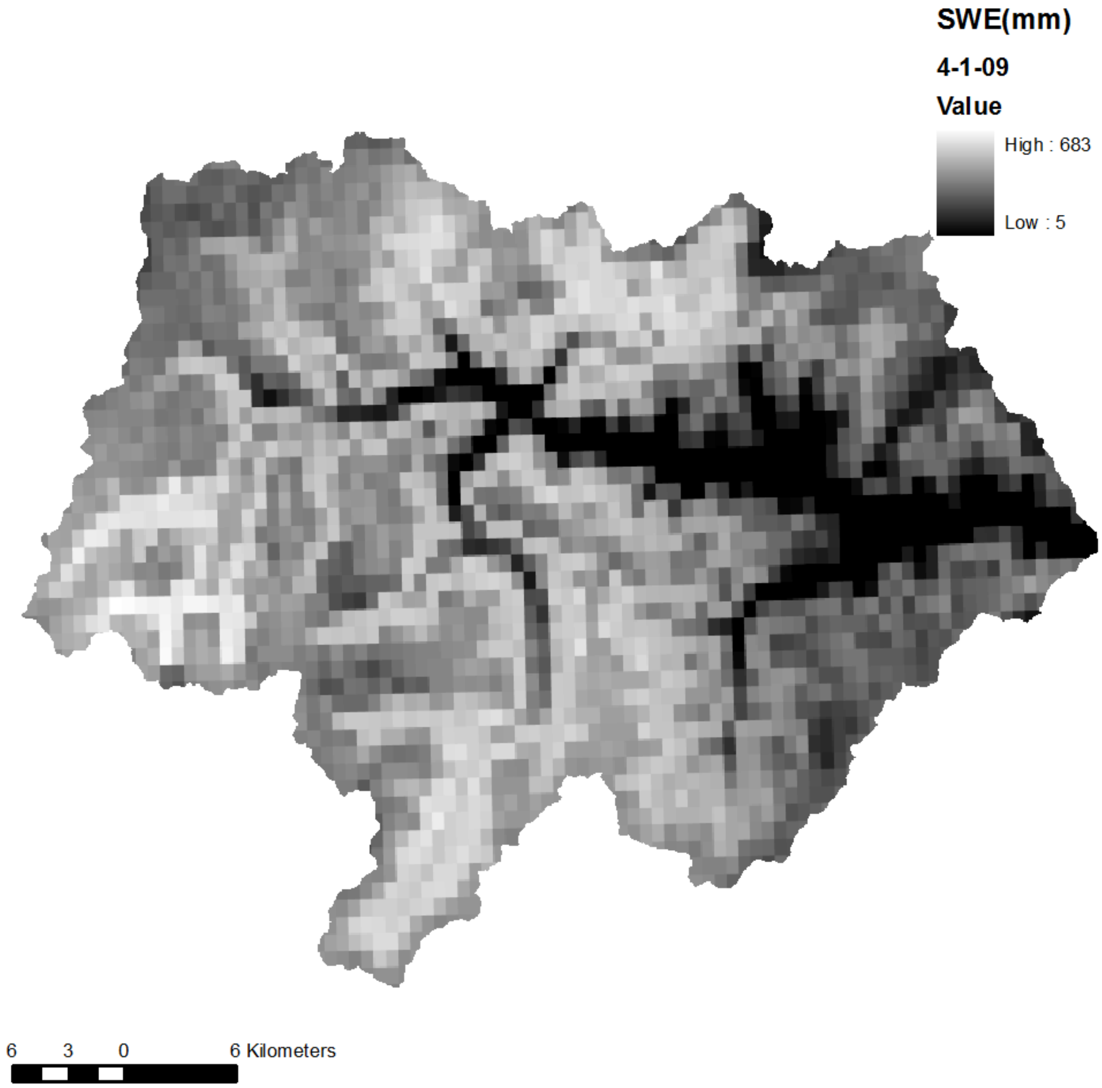

Figure 7. Map of April 1 2009 SWE for big creek. In addition to the elevation dependence of snow, there is also an orographic shadowing that affects the region. Precipitation is concentrated in the western portion of the basin, while the high elevations of the southeast watershed boundary do not receive as much precipitation as their western counterparts (NOAA, 2009).

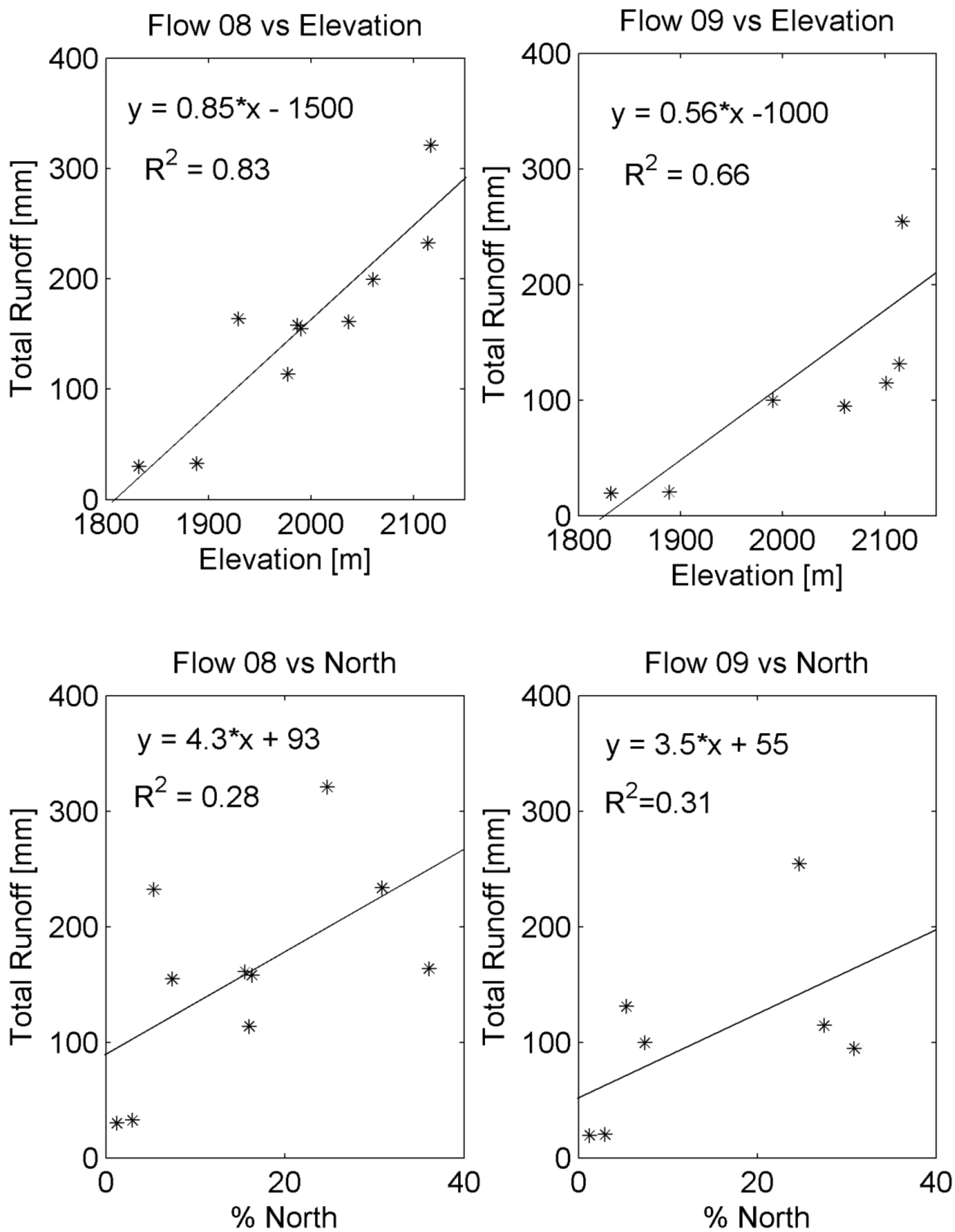

Figure 8. Regressions between total water yield from May through June against north aspect and elevation. Elevation provides the best fit against water yield and is supported by the results of plotting elevation against SWE. Aspect, represented by percent North does have a weak positive relationship. The effects of aspect are superimposed on and partially obscured by the effect of elevation.

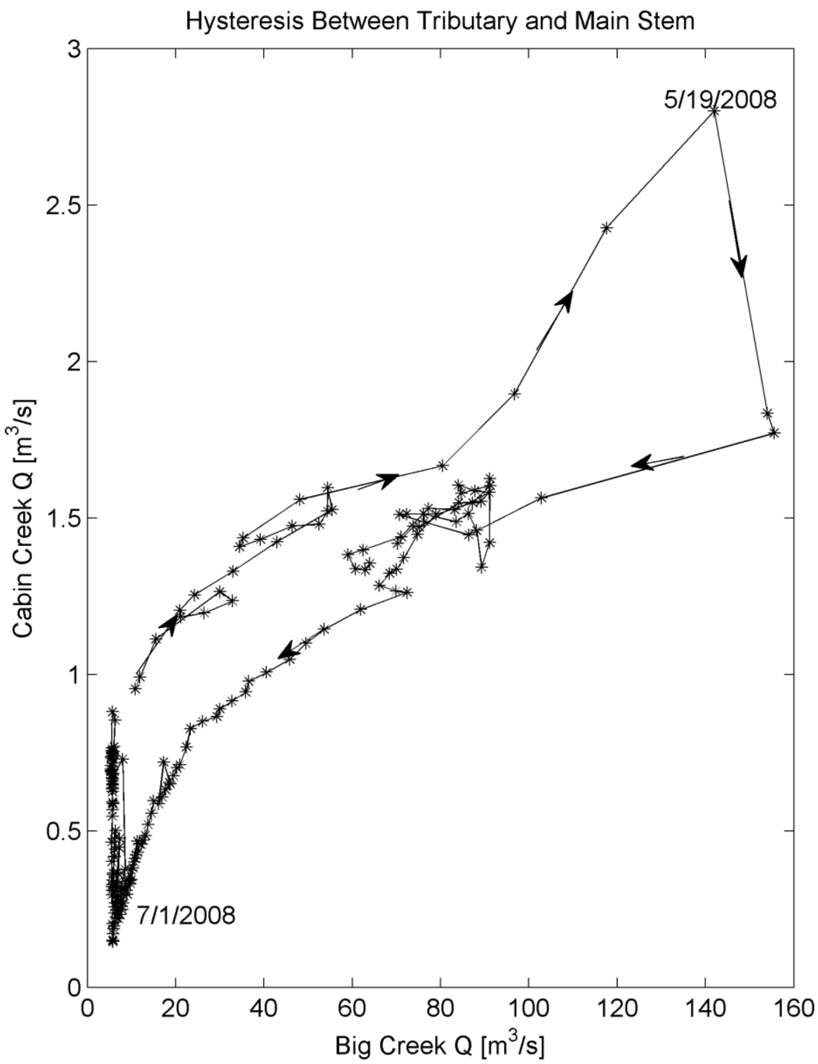

Figure 9. Clockwise hysteresis between Big Creek and tributary Cabin Creek, indicating that the peak flow for Cabin Creek occurs before Big Creek's peak flow. This type of hysteresis is typical of all tributaries within the Big Creek drainage. Tributaries typically have higher flows on the rising limbs of their hydrographs, and lower flows on falling limbs before discharges rise later in the season. This comparison is superimposed on the overall pattern in Figure 10 that shows that Big Creek always has a higher yield, but this shows that that difference is greatest during the falling limb of the tributaries hydrograph as Big Creek maintains relatively high flows.

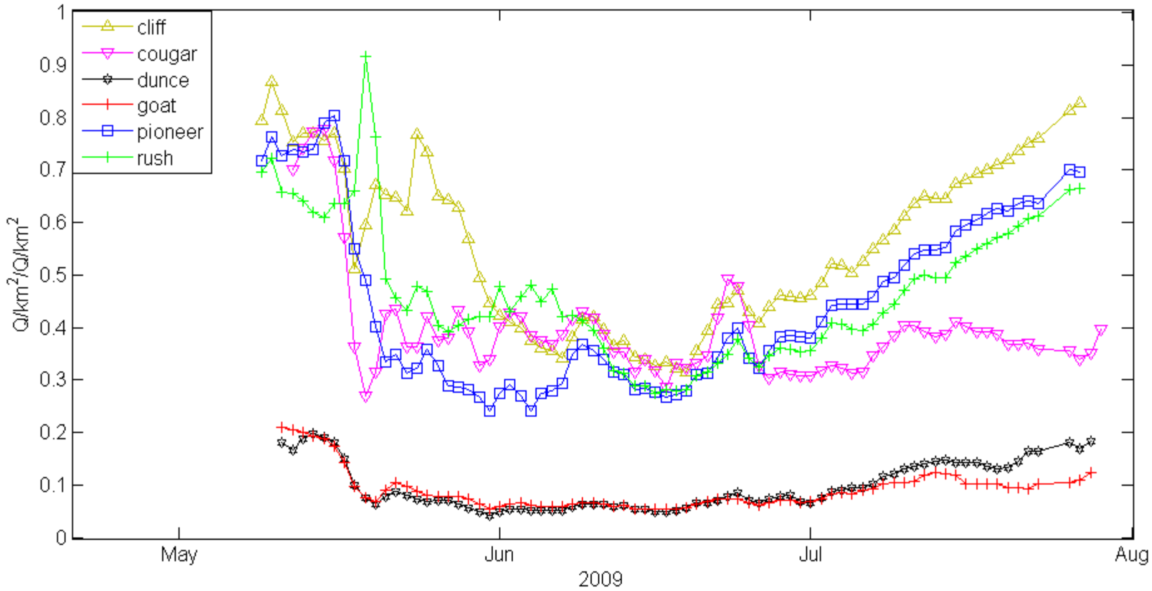

Figure 10. Normalized discharges of tributaries divided by normalized discharges of Big Creek. These y-axis values are a unitless number that is a proxy to the value of C in the equation $Q = kA^c$. During the early runoff season, the larger tributaries approach a value of 1, indicating an equal yield of water per drainage area. In the middle of the season, Big Creek produces much more yield than the tributaries, driving their values down. Towards the end of the season as Big Creek flows decrease, values rise back towards one.

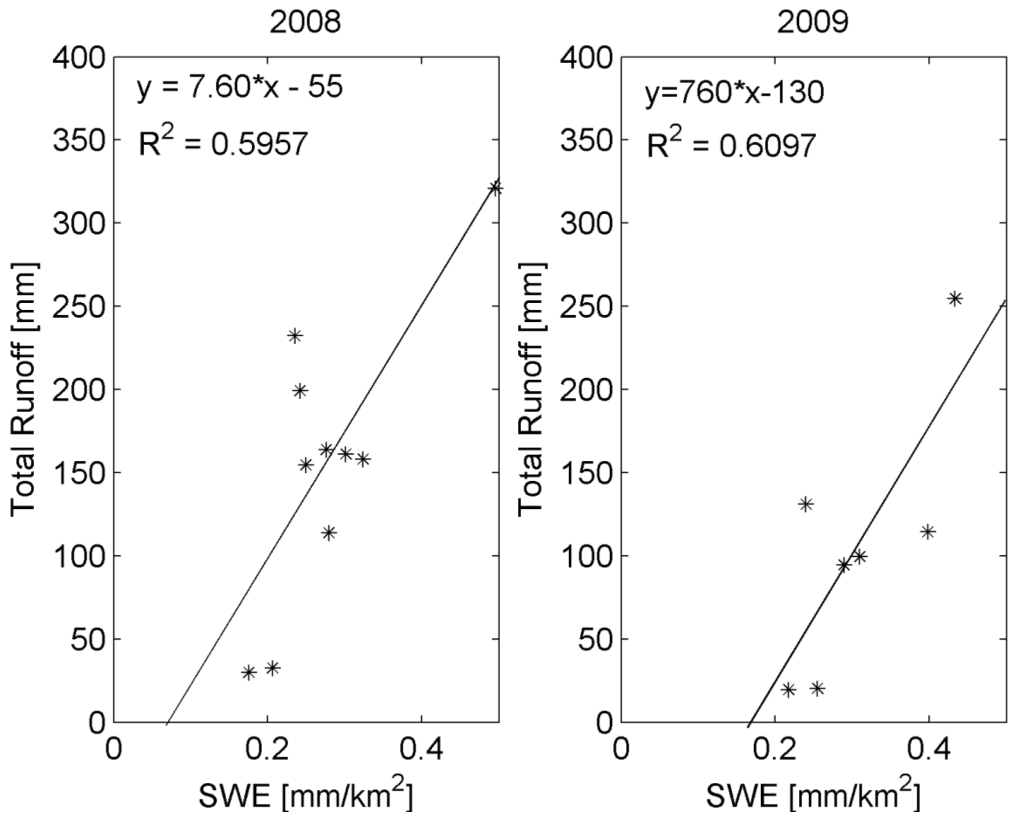

Figure 11. Regression between total basin SWE normalized by basin drainage area (km^2) and total runoff. The results for this are less accurate than the results of regressions from elevation. This means that topographic variables are better predictors of basin runoff than SWE.

Chapter 4: The Applicability of Scaling Relationships between Discharge and Drainage Area in Snow-Dominated Watersheds: A view from the Salmon River Basin, Idaho, USA

Abstract

The hydraulic form of a river including the width, depth, and longitudinal profile are tied to the discharge of the river. Because discharge is difficult to measure, it is often scaled to watershed area. Using discharge data from streams ranging in size from 6 km^2 to 35,095 km^2 from the Salmon River watershed in central Idaho, we examine whether a linear scaling of discharge and drainage area is appropriate in large, snow-melt dominated watersheds. By purposefully selecting discharge data from different portions of the watershed, it is possible to manipulate the exponent in the power-law scaling relationship higher or lower than the expected value of 1. This non-linear scaling relationship and its sensitivity to data selection reveals that discharge is not produced uniformly across the landscape in a mountainous, snow-dominated watershed such as the Salmon River. This has implications for hydrologic or geomorphic models that often assume that one can substitute the more easily measured drainage area for water discharge in mechanistic equations for channel incision, sediment transport or flow accumulation. Further work is required to accurately parameterize scaling relations like these when topographic or orographic effects result in non-uniform precipitation over landscapes.

4.1 Introduction

Scaling relationships are particularly useful because they serve as a means of determining an independent variable create a dependent variable. In the case of this study, drainage area is an easily measured variable from maps. By scaling area with discharge, it is possible to estimate the discharge of a river anywhere within a watershed. Scaling relationships have long been used in hydrology and geomorphology in order to provide a relationship between one measurable property of the landscape and another property (e.g. Hack, 1954; Wolman, 1955; Flint, 1977). In studies of fluvial systems, variables such as channel slope, width, depth, and particularly water discharge are often observed to scale as a power law function of the easily measurable variable, drainage area. A good review of the history of such scaling relations is found in Appendix B of Tarboton et al. (1989). As an example,

$$Q_w = kA^c \tag{4.1}$$

where Q_w is water discharge, k is a prefactor whose units are sensitive to the value of c, A is the upstream drainage area, and c is a dimensionless exponent in the power law function. When the value of c is equal to 1, the relationship predicts that each unit area within the watershed should discharge the same volumetric rate of runoff to the channel. This assumes that precipitation and the partitioning between evaporation, transpiration, infiltration, runoff etc is similar throughout the watershed. If discharge scales consistently with drainage area in a basin, it allows an easy substitution of the expression kA^c for Q_w in discharge-dependent equations for erosion, sediment transport, etc.

These scaling relationships are often used in landscape evolution models (e.g. Whipple and Tucker, 2002) and are implicit in hydrological models (e.g. Koren et al., 1999). They are also used extensively in stream restoration projects to predict channel geometries or other fluvial characteristics (e.g. Montgomery and Bolton, 2003). The estimation of discharge through scaling relationships, whether it is mean annual discharge or the bankfull discharge, is often tied to other metrics such as channel width, depth, or suspended sediment load (Leopold and Maddock, 1953). These anticipated stream geometry metrics are then imposed on restoration projects as an ideal to be attained. As such, it is imperative that if scientists are to rely on a scaling relationship to determine discharge (or any other variable) at a given site for restoration or modeling purposes, that we get that scaling value right.

The reason behind the popularity of scaling discharge and drainage area is that it is much simpler to measure the drainage area of a point within a watershed than it is to measure discharge. Drainage area is relatively steady over the timescale of interest and can be computed using a map or basic geographic information system. In contrast, continuous water discharge is unsteady in time and involves a long and field-work intensive process to accurately measure. It is much easier to establish the scaling relationship for a basin using data from preexisting gages and then approximate the discharge at a given ungaged location using this relationship.

Often, the reported scaling relationships are based on the study of data from large scale drainage basins, typified by those that are gaged by the United States Geological Survey (USGS). The position of these existing gage stations often depends on whether the stream was large enough to be of some economic value for irrigation, navigation, or water supply purposes (Messinger, 2009). Another branch of understanding of scaling relationships comes from small micro scale studies in research watersheds. These studies focus on smaller, hillslope scale processes (i.e. Goodrich et al., 1997). Although both scales have aided our understanding of hydrology, a knowledge gap still exists for mesoscale basins that lie between these two scales. Basins that are too small to warrant a USGS gage, but too large to be extensively studies as experimental watersheds present a significant data gap in the understanding of how water discharge scales with drainage area.

A recent study has focused specifically on the along-stream (longitudinal) scaling of discharge and drainage area (Galster, 2009). In this study, the contribution of the headwater discharge is passed on and incorporated into each following discharge measurement. By working with sites that directly flow into each other (e.g. they are considered to be ‘in-series’ with each other), this method does not truly represent the variability in contribution from a variety of different locations in the basin. Rather, it shows the integration of flow in the downstream direction for a particular system.

Another method of relating water discharge and drainage area is done by measuring the discharge of independent tributaries of varying sizes within a region (Chaplin, 2005). In theory, this method should return the same basic relationship as the in-series method if there is similar precipitation, evapotranspiration, and infiltration characteristics throughout the watershed. The benefit of not using an in-series method is that water is not counted twice, and it is possible to look at the true variation of discharge across the landscape.

Within a fluvial system, the number of streams at a given drainage area decreases rapidly with increasing drainage area. There are only a few large rivers, but many small tributary streams. Thus, there are few options for which rivers are used to represent the higher drainage areas and discharges. There is however, quite a bit of choice in the selection of streams with smaller drainage areas and discharges. Depending on whether an interested scientist selects a high or low yield tributary stream, scaling relationship between area and water discharge could be significantly skewed.

In this study, I explored how sensitive the scaling exponent of the power law discharge drainage area scaling relationship is to the character of the streams selected. Using a different set of rivers in central Idaho, I evaluate possible mechanisms that could control the variations in this exponent, *c*. Galster (2007) examined the scaling relationships of several rivers in the Western United states that have minimal impacts from dams on flows. One of the rivers in this study was the Salmon River in Idaho. His study determined, using the along-stream method (stations in a series along the mainstem), that drainage area scales with discharge according to a power law relationship with an exponent slightly less than 1. The goal of this study is to compare Galster's results with those from a larger number of streams within the greater Salmon River basin and to examine the changes to the power law exponent when different streams are used.

4.2 Setting

This study focuses on the Salmon River in central Idaho (Figure 1). The Salmon River is an ideal study site for scaling discharge relationships because the majority of the basin is unimpacted by human use. It has no dams on the mainstem, and few trivial ones on the tributaries. There are also minimal water diversions or withdrawals for agriculture or municipal use. This reduces the number of confounding factors influencing the hydrologic behavior of the basin. The geology of the basin is complex. Basalts and other volcanic rocks from the Columbia River eruptive sequence dominate the Northwest region near the outlet. Crystalline batholiths and meta-sediments dominate in the central section of the watershed. Intrusive and extrusive igneous rocks of the Challis sequence overlay carbonate and silica-clastic sediments in the southeastern corner of the basin. In this same region, Basin and Range extension has created large alluvial basins with significant groundwater storage capacity. Precipitation values are strongly correlated to orographic processes, with more precipitation falling in the west, closer to the moist Pacific air masses. These air masses are progressively desiccated as they travel Eastward across the basin. High elevation zones are forested by conifers while sagebrush/grassland dominates the lower elevations. Land use within the basin is restricted because an extensive proportion of the catchment is within either National Forest wilderness and non-wilderness lands. Some active agriculture occurs in the eastern portions of the basin above the large sedimentary aquifers. There is rugged relief in the region, with the highest elevation at 3841m and the lowest elevation at 274m.

In this study, we include water discharge data collected from tributaries to Big Creek, the largest tributary to the Middle Fork the Salmon River as well as other USGS gages throughout the Salmon River Basin. Basin characteristics of these tributaries and their gaging records are given in Table 1. Big Creek is unimpacted by human use and lies almost entirely within the Frank Church River of No Return Wilderness. The geology of the basin consists of Paleozoic metamorphic rocks, Idaho Batholith rocks and

Miocene Challis Volcanics. Land cover consists of conifer forest and mixed sagebrush/grassland.

4.3 Methods

Because few gaging records exist for small basins in the Salmon River, we established temporary gaging stations on 10 tributaries to Big Creek using vented pressure loggers. Stage discharge relations were established for each of the tributaries in a wide variety of flow conditions in 2008 and 2009. Gages were operational from before peak discharge in late May to end of summer low flows (4/27/08-7/31/08).

Other nearby gaged basins were selected based on the availability of USGS gaging records. These are listed in Table 1. Mean daily flow values were obtained from http://waterwatch.usgs.gov for the period of record that coincided with the spring/summer 2008 field season when I collected data for the Big Creek tributaries. These basins reflect a similar elevation range and climate forcing as the Big Creek tributaries. Mean daily discharge values were reported in cubic feet per second (cfs) from the USGS and were converted to cubic meters per second (cms) for use in this study.

Scaling of discharge with drainage area is often applied to flood events (e.g. Ogden and Dawdy, 2003), bankfull discharge (e.g. Castro and Jackson, 2001) and mean annual discharge (e.g. Thomas and Benson, 1970). Because of the short duration of the tributary records, this study uses mean daily discharge for the spring runoff season, which although not directly comparable between studies, should show similar results to mean annual discharge for this snow dominated area. Flows were averaged over the period of record for the tributaries, which was approximately three months from April 27, 2008 to

July 31, 2008. Mean daily discharges for the streams were plotted in log-log space and a power law regression was fitted in Excel. To justify the comparison between scaling of yearly averages with the seasonal averages used in this study, a subset of streams were scaled using only spring and summer flows and scaling of the same streams using the entire water year. This subset consisted of in-series gages along the mainstem of the Salmon River in order for more direct comparison to Galster (2007).

4.4 Results

The comparison of streams along the mainstem Salmon for seasonal and yearly averages showed little difference in the value of *c* and mostly affected the value of *k*. The results are as follows

$$Q = 0.0092 * A^{0.9933} \tag{4.2}$$

$$Q = 0.0284 * A^{.9683} \tag{4.3}$$

with the former the result for the seasonal scaling and the latter the result for yearly scaling. These values differ slightly from those published by Galster (2007) due to a different set of sites used and different years analyzed.

For all of the basins included in this study, the regression (figure 2) from the smallest (Dunce, 6.5 km^2) to the largest (Salmon at Whitebird, 35,094.3 km^2) yielded a power law equation of,

$$Q = 0.0122 * A^{1.1063} \tag{4.4}$$

The exponent is slightly higher than 1 (figure 2). This is in contrast to Galster (2007) who found an exponent value of $c = 0.82 \pm 0.01$ for peak annual discharge and mean annual discharge over an ~80 year period of record.

When a subset of only the largest drainage area tributaries is used, (>561.2 km^2), an equation of the form

$$Q = 0.5244 * A^{0.6538} \tag{4.5}$$

results, where the value of c is much lower than for all sizes of streams, indicating large reductions in water contributions to the mainstem as the drainage area increases. A subset of data including only the tributaries with the smallest drainage areas (<561.2 km^2) results in an equation of the form

$$Q = 0.0045 * A^{1.3781} \tag{4.6}$$

where the value of c is much greater than 1, implying that more water is being contributed by channels with larger drainage areas.

When basin elevation, rather than basin size or location is used as a selection criterion, the form of the power law equations become

$$Q = 0.036 * A^{0.9501} \tag{4.7}$$

$$Q = 0.0083 * A^{1.1839} \tag{4.8}$$

with the former the equation for the highest elevation basins and the latter the equation for the lowest elevation basins (Figure 3).

4.5 Discussion

The above results suggest that the scaling relationship between drainage area and water discharge is sensitive to the gaging stations selected for analysis. This sensitivity provides insight into the spatial heterogeneity of tributary contributions that is not apparent when simply measuring increases in the downstream direction along the mainstem. In particular, discharge from snow-dominated headwater catchments dominates the hydrograph form (Bales et al., 2006). By only measuring discharge along the mainstem channel from the headwaters to the outlet, we largely see signals that originated in the headwater region dominating downstream behavior, masking some of the heterogeneity in tributary contributions. By selecting various tributaries of different size, elevation and west-to-east position, the selection of different tributaries enables us to identify the source of this variability rather than becoming confused by it.

The exact headwater tributaries selected will alter the slope of the power law regression line depending on these basins' mean elevation, snow accumulation, geologic setting and total precipitation. Inspection of the basin attributes in this study reveals that the small basins located in Big Creek show a lower mean basin elevation than any of the other basins in the study. The effect of the lower mean basin elevation is to decrease the amount of snow accumulation and melt and thereby reduce the average runoff in the spring season (or mean annual discharge). This reduced value at smaller drainage areas has the effect of pulling down the power law regression at low drainage areas (Figure 3). As the network gains area, including areas sourced in higher elevations, the trendline starts to increase due to the increased proportion of snow inputs, bringing c to values higher than 1. Similarly, if a subset of higher elevation tributaries were used, it would have the effect of pulling up the low end of the trendline and decreasing the value of c to less than one.

The variability introduced into precipitation due to orographic effects distorts the assumed uniform precipitation in a basin, which in turn can distort the expected scaling relationship that has been developed in other more uniform precipitation regimes (Roe et al., 2002). The results from the Big Creek tributaries show that the problem of non-uniform precipitation is exacerbated in snow-dominated regions. The scaling relationships were developed in relatively low-relief regions with uniform precipitation, which over-simplify the processes of snow-dominated regions. When these relations are exported to areas that violate the assumptions incorporated into the original scaling relations, the power law function behaves differently.

Rather than assuming a linearly correlated relation between discharge and drainage area in snow dominated mountain regions, it would be more accurate to suggest that the discharge varies as a function of both drainage area and elevation. In a group of lower elevation small tributaries, lower discharges per unit area should be assumed while in higher elevation small tributaries, a higher discharge per unit area should be assumed. The variability of discharge with elevation is also compounded by the uneven distribution of precipitation within a mountain range. Figure 4 shows the discharge of each gage in Table 1 normalized by the drainage area and plotted against elevation. Although there is a trend of higher discharge with drainage area, gages group based on their location within the basin which controls the total amount of precipitation received. Taking this into consideration, we would expect higher erosion rates in high elevation basins, thus influencing our construction of landscape evolution models. These results suggest another potential negative feedback to mountain growth (Roe et al., 2002), independent of glaciers. This information also changes the potential restoration goals or expectations in stream restoration projects. All watersheds should not be treated as equals and differences in the hydrology and by extension geomorphology can arise due to differences in basin elevation.

4.6 Conclusions

Although useful, the assumed linear scaling between discharge with drainage area should only be applied in circumstances which meet the original assumptions of uniform precipitation. In snow-dominated mountain catchments such as the Salmon River, these assumptions are not met. Instead, a range of scaling values bracketed around an observed mean value could be used instead to account for tributaries at different elevations that produce varying discharge per unit area. By accounting for the natural variability within the hydrologic system, restoration projects and landscape evolution models have a better chance of producing realistic outcomes.

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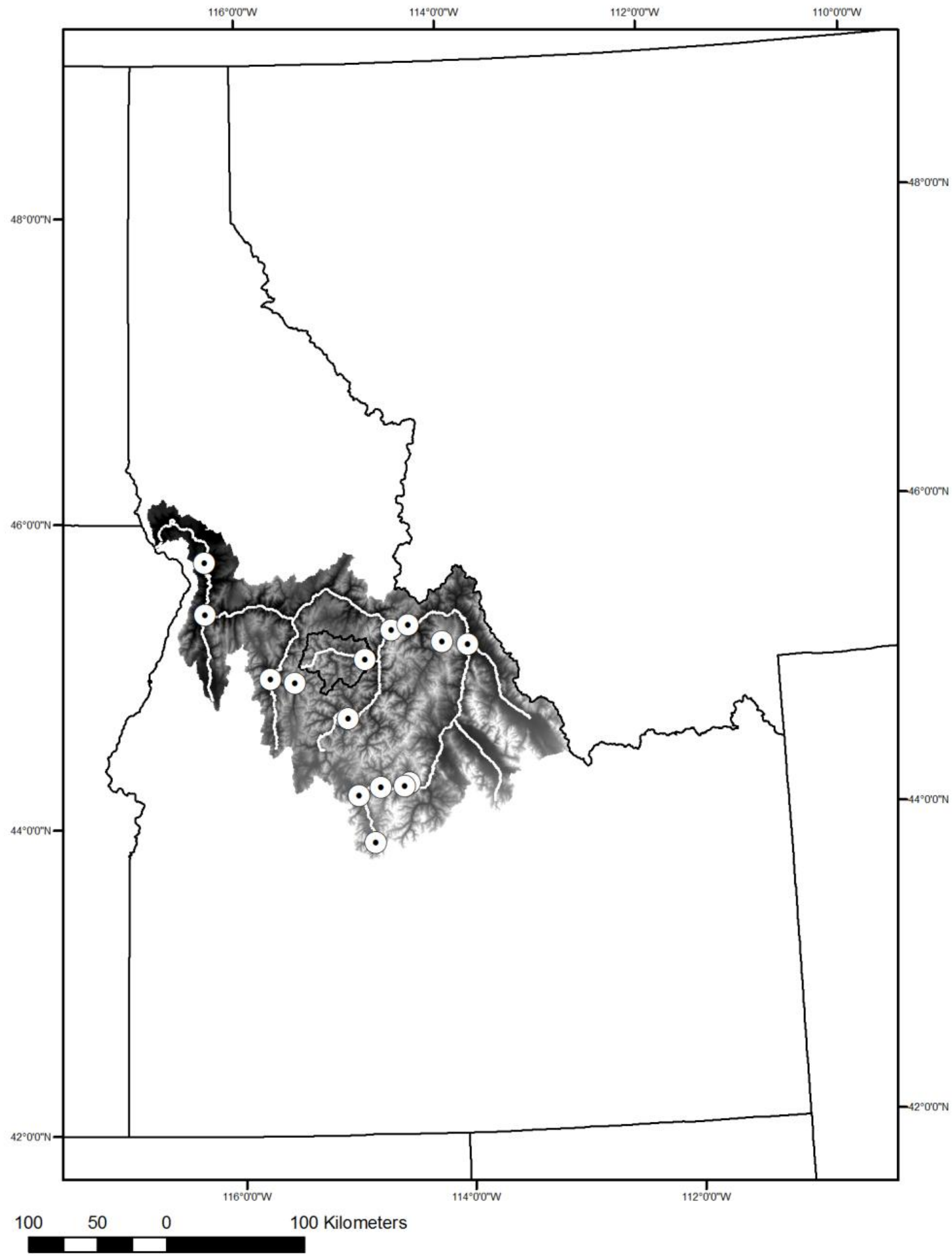


Figure 1. Location map of gaging sites used for this study. Locations span a range of sizes and elevations listed in Table 1. Rather than using numerous sites located along the same single channel, sites are distributed throughout the Salmon River basin for one season (2008) so that the hydrologic signal of one station is not passed on to each successive station. The largest gages unavoidably accumulate the drainage area of smaller upstream gages.

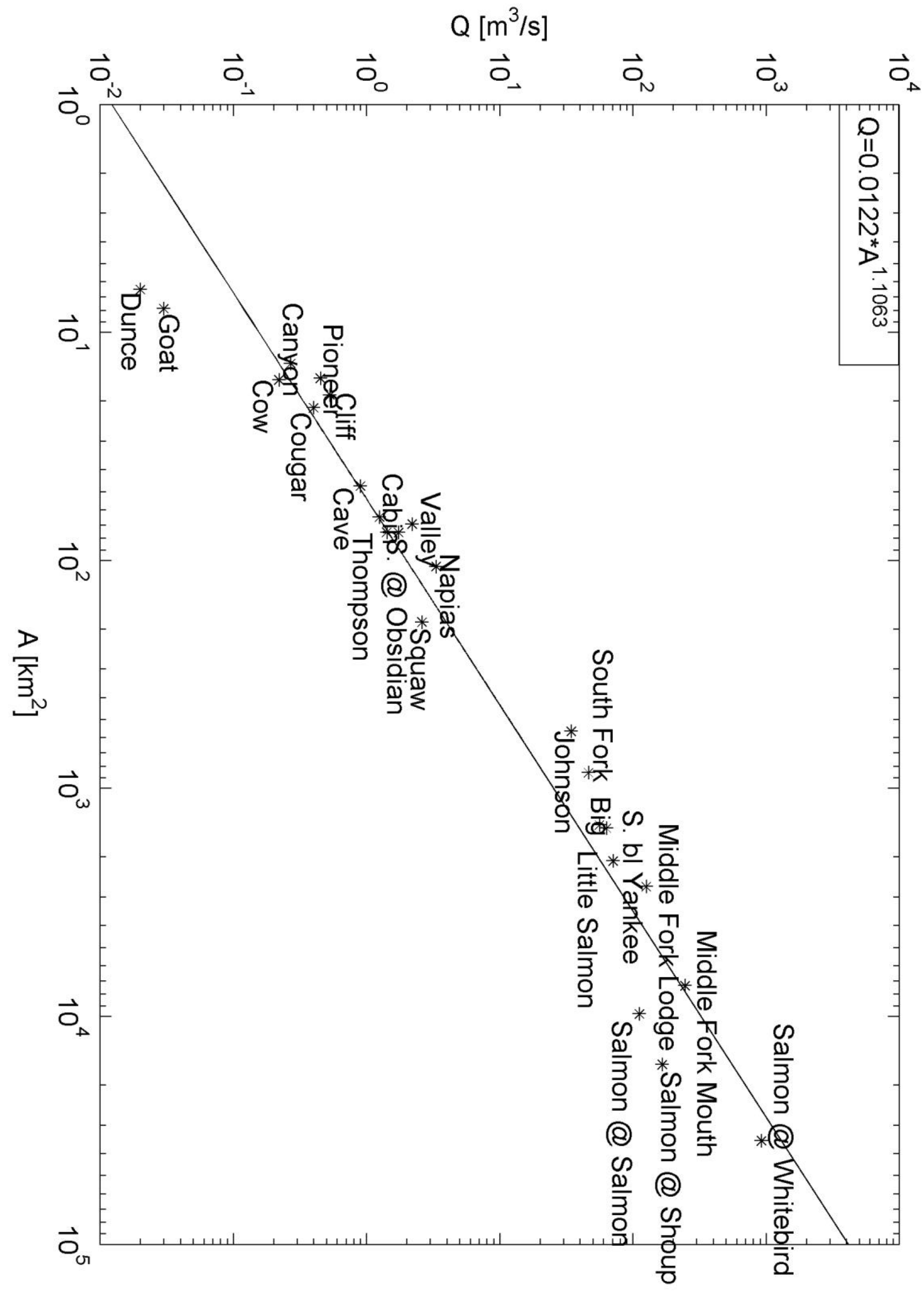


Figure 2. Scaling of drainage area and discharge for the Salmon River basin, Idaho. Using a subset of data of low elevation basins pulls the value of *c* to below 1 while using a subset of higher elevation basins creates a value of *c* above 1. See Table 1 for basin elevations.

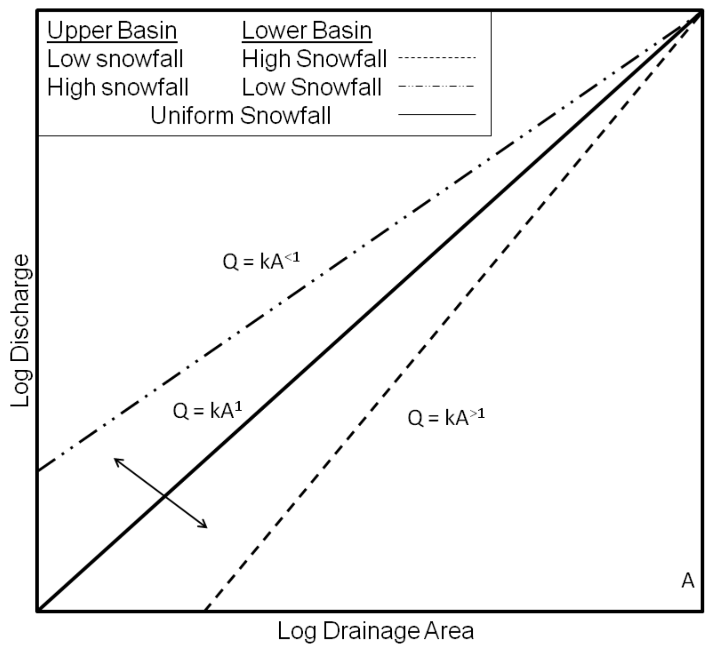


Figure 3. A. Theoretical scaling of drainage area and discharge given three scenarios. In the first scenario, a river moves through a region of low snow fall and then picks up tributaries that tap regions of higher snowfall further downstream, pulling the power law trend line up. In the second scenario, a river starts in a high snowfall region before starting to pick up tributaries that tap lower snowfall regions, pulling the trend line down. In the last scenario, the river picks up a perfect mixture of high and low snowfall areas. This last scenario most closely mimics the scaling of uniform precipitation, but is also the least realistic given the high spatial variability of snowfall. B. Theoretical longitudinal river profile matching the same scenarios as A.

Site #	Name	Mean Q [m^3/s] 4/ 27/08 – 7/31/08	Drainage Area [km^2]	Mean Elevation [m]
TWRS	Dunce	0.02	6.5	1832.0
TWRS	Goat	0.03	7.9	1889.0
TWRS	Canyon	0.27	13.6	1929.4
TWRS	Pioneer	0.45	15.9	2060.7
TWRS	Cow	0.22	16.1	1977.4
TWRS	Cliff	0.53	18.8	2114.0
TWRS	Cougar	0.40	21.4	1990.3
TWRS	Cave	0.90	47.1	1987.0
TWRS	Cabin	1.25	64.4	2037.1
13295000	Valley	2.20	69.2	2255.5
13297330	Thompson	1.42	75.1	2323.9
13292500	Salmon @ Obsidian	1.74	75.4	2194.6
13306385	Napias	3.33	106.2	2308.7
13297355	Squaw	2.60	186.5	2356.5
13313000	Johnson	34.36	561.2	2174.1
13310700	South Fork	46.43	851.7	1944.5
TWRS	Big	55.87	1444.1	2117.1
13316500	Little Salmon	63.08	1491.8	1655.1
13296500	Salmon @ Yankee Fork	70.90	2077.17	2374.4
13309220	Middle Fork Lodge	125.50	2693.6	2192.1
13310199	Middle Fork Mouth	245.66	7329.7	2160.7
13302500	Salmon @ Salmon	111.74	9738.4	2255.0
13307000	Salmon @ Shoup	166.24	16239.2	2180.9
13317000	Salmon @ Whitebird	921.33	35094.3	2053.7

Table 1. Basins used in scaling of Figure 2 and shown in Figure 1. Site # refers to USGS site number. If there is no number listed, it was a temporary gage installed at Taylor Ranch Wilderness Field Station (TWRS).

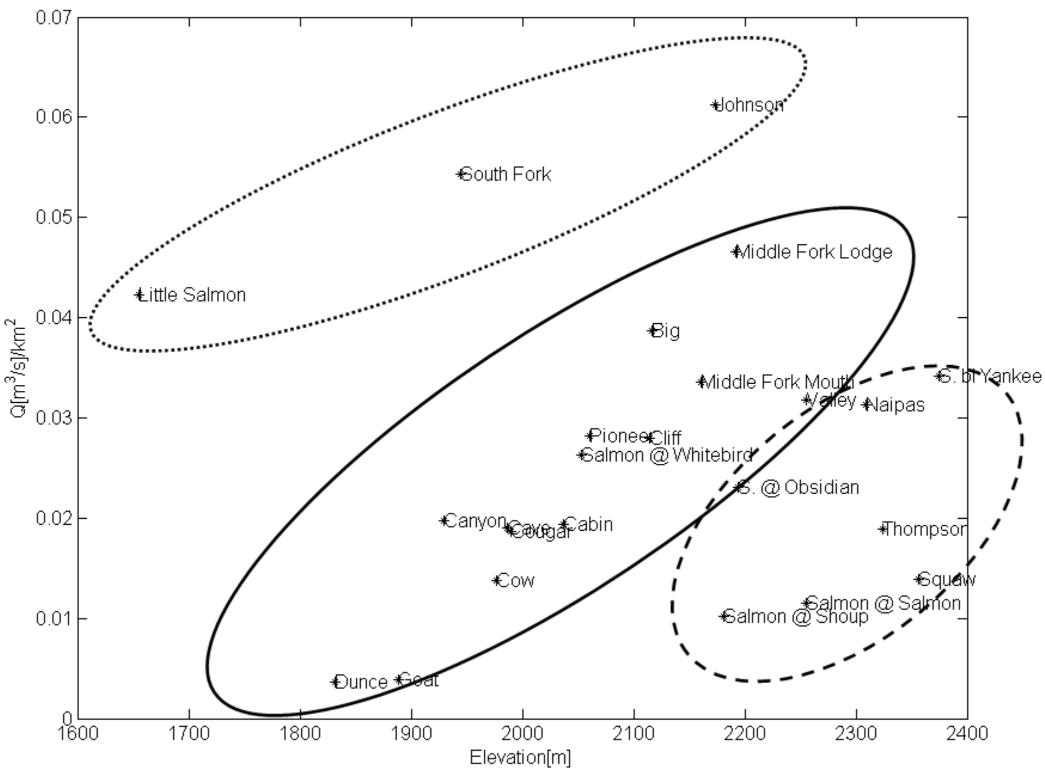


Figure 4. Plot of water discharge normalized for drainage area for the period of study plotted against elevation. The points can be grouped based on their position in the Salmon River watershed, with the dotted circle the points in the western portion of the watershed, the solid circle the points in the central portion of the watershed, and the dashed circle points in the eastern portion of the watershed. This matches well with the observed West-East precipitation shadow caused by the mountain range.

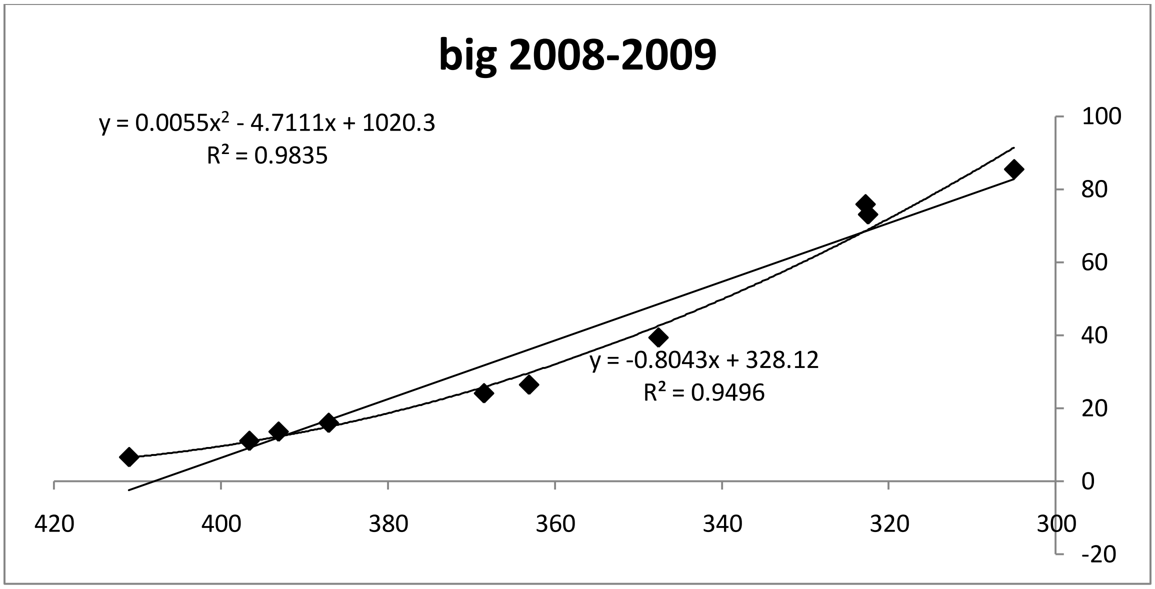
APPENDIX 1.Monthly exceedance values from Hortness and Berenbrock 2001

Table 7. Results of regional regression analysis based on data from 30 gaging stations for region 5

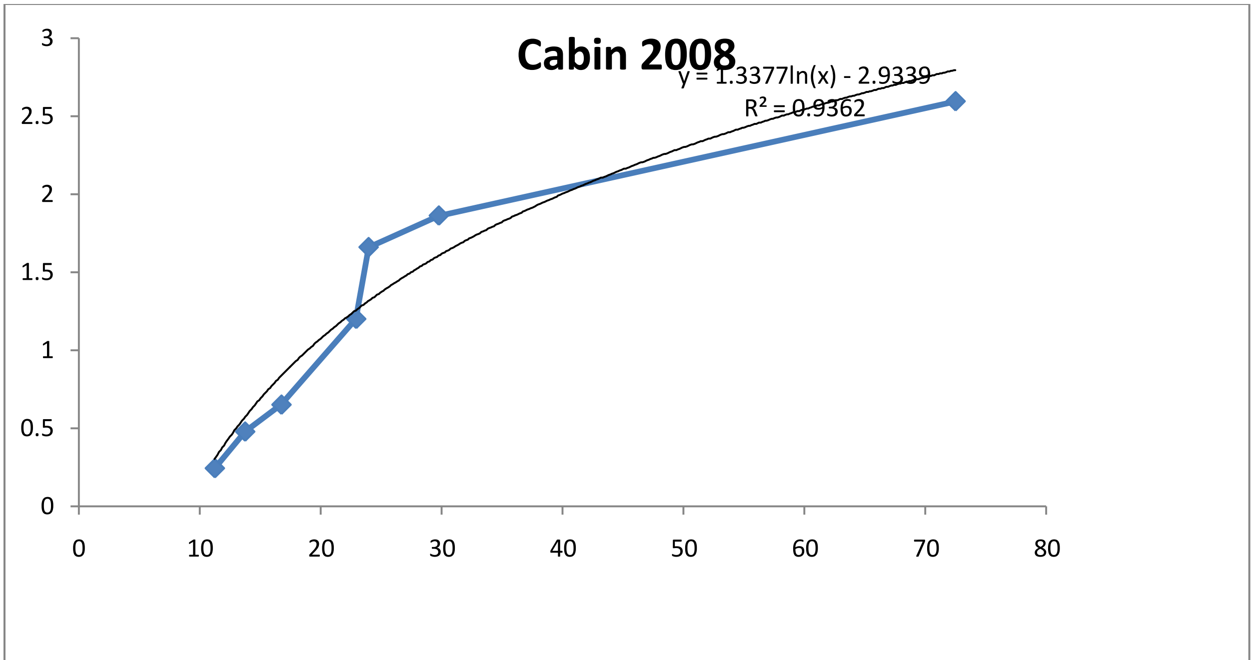
[Q.xx, daily mean discharge exceeded xx percent of the time during the specified month, in cubic feet per second; A, drainage area, in square miles; BS, basin slope in percent; S30*, slopes greater than 30 percent, in percent of drainage area plus 1 percent; F*, forested area, in percent of drainage area plus 1 percent; E*, mean basin elevation, in thousands of feet above sea level; Qa, mean annual discharge, in cubic feet per second]

Region 5			
Month	**Equation**	**Standard error of estimate (log_{10})**	**Standard error of estimate (percent)**
October	$Q.80 = 4.01E\text{-}03\ A^{0.857}\ BS^{5.83}\ S30*^{-4.71}\ F*^{0.847}$	0.244	75.4 to -43.0
	$Q.50 = 7.87E\text{-}03\ A^{0.873}\ BS^{5.89}\ S30*^{-4.56}\ F*^{0.528}$	0.154	42.5 to -29.8
	$Q.20 = 8.91E\text{-}03\ A^{0.863}\ BS^{6.96}\ S30*^{-5.33}\ F*^{0.413}$	0.132	35.4 to -26.2
November	$Q.80 = 8.83E\text{-}03\ A^{0.839}\ BS^{6.07}\ S30*^{-4.98}\ F*^{0.735}$	0.262	82.7 to -45.3
	$Q.50 = 1.07E\text{-}02\ A^{0.867}\ BS^{6.56}\ S30*^{-5.08}\ F*^{0.400}$	0.144	39.3 to -28.2
	$Q.20 = 1.10E\text{-}02\ A^{0.850}\ BS^{7.53}\ S30*^{-5.77}\ F*^{0.325}$	0.128	34.4 to -25.6
December	$Q.80 = 2.05E\text{-}01\ A^{0.773}\ BS^{6.87}\ S30*^{-5.64}$	0.306	102.1 to -50.5
	$Q.50 = 5.22E\text{-}02\ A^{0.834}\ BS^{6.97}\ S30*^{-5.39}$	0.162	45.3 to -31.2
	$Q.20 = 2.96E\text{-}02\ A^{0.832}\ BS^{7.81}\ S30*^{-5.92}$	0.156	43.1 to -30.1
January	$Q.80 = 2.57E\text{-}01\ A^{0.776}\ BS^{6.84}\ S30*^{-5.68}$	0.332	114.6 to -53.4
	$Q.50 = 6.03E\text{-}02\ A^{0.839}\ BS^{6.68}\ S30*^{-5.20}$	0.177	50.2 to -33.4
	$Q.20 = 4.84E\text{-}02\ A^{0.848}\ BS^{7.04}\ S30*^{-5.41}$	0.172	48.5 to -32.7
February	$Q.80 = 2.65E\text{-}01\ A^{0.777}\ BS^{6.71}\ S30*^{-5.57}$	0.345	121.5 to -54.8
	$Q.50 = 6.46E\text{-}02\ A^{0.851}\ BS^{6.44}\ S30*^{-5.02}$	0.178	50.8 to -33.7
	$Q.20 = 5.32E\text{-}02\ A^{0.869}\ BS^{6.35}\ S30*^{-4.86}$	0.181	51.5 to -34.0
March	$Q.80 = 5.07E{+}00\ A^{0.780}\ E*^{-2.08}\ BS^{7.79}\ S30*^{-6.22}$	0.294	96.6 to -49.1
	$Q.50 = 8.06E\text{-}01\ A^{0.871}\ E*^{-1.65}\ BS^{6.59}\ S30*^{-4.97}$	0.178	50.7 to -33.6
	$Q.20 = 2.86E{+}00\ A^{0.866}\ E*^{-2.57}\ BS^{6.81}\ S30*^{-4.95}$	0.189	54.4 to -35.2
April	$Q.80 = 1.07E{+}02\ A^{0.919}\ E*^{-2.45}\ S30*^{-0.00410}$	0.221	66.3 to -39.9
	$Q.50 = 3.66E{+}02\ A^{0.900}\ E*^{-3.07}\ S30*^{0.160}$	0.235	71.8 to -41.8
	$Q.20 = 2.67E{+}02\ A^{0.890}\ E*^{-2.39}\ S30*^{0.103}$	0.231	70.1 to -41.2
May	$Q.80 = 2.29E\text{-}01\ A^{0.790}\ BS^{7.42}\ S30*^{-5.69}$	0.223	67.1 to -40.2
	$Q.50 = 2.77E\text{-}01\ A^{0.798}\ BS^{7.36}\ S30*^{-5.56}$	0.189	54.7 to -35.3
	$Q.20 = 5.37E\text{-}01\ A^{0.802}\ BS^{7.06}\ S30*^{-5.35}$	0.163	45.6 to -31.3
June	$Q.80 = 2.22E\text{-}04\ A^{0.810}\ BS^{10.7}\ S30*^{-7.89}\ F*^{0.993}$	0.170	48.0 to -32.4
	$Q.50 = 5.12E\text{-}04\ A^{0.832}\ BS^{9.84}\ S30*^{-7.28}\ F*^{1.04}$	0.134	36.1 to -26.5
	$Q.20 = 1.27E\text{-}03\ A^{0.824}\ BS^{9.37}\ S30*^{-6.88}\ F*^{0.942}$	0.132	35.5 to -26.2
July	$Q.80 = 9.71E\text{-}05\ A^{0.837}\ BS^{9.44}\ S30*^{-6.88}\ F*^{0.965}$	0.189	54.6 to -35.3
	$Q.50 = 1.91E\text{-}04\ A^{0.824}\ BS^{10.7}\ S30*^{-7.85}\ F*^{0.773}$	0.160	44.7 to -30.9
	$Q.20 = 2.14E\text{-}04\ A^{0.831}\ BS^{11.5}\ S30*^{-8.36}\ F*^{0.705}$	0.145	39.5 to -28.3
August	$Q.80 = 1.04E\text{-}04\ A^{0.864}\ BS^{7.72}\ S30*^{-5.65}\ F*^{1.04}$	0.232	70.7 to -41.4
	$Q.50 = 2.52E\text{-}04\ A^{0.865}\ BS^{8.06}\ S30*^{-5.89}\ F*^{0.848}$	0.200	58.5 to -36.9
	$Q.20 = 4.51E\text{-}04\ A^{0.855}\ BS^{8.50}\ S30*^{-6.21}\ F*^{0.736}$	0.175	49.8 to -33.2
September	$Q.80 = 4.59E\text{-}04\ A^{0.872}\ BS^{6.50}\ S30*^{-4.98}\ F*^{1.03}$	0.243	75.0 to -42.9
	$Q.50 = 1.83E\text{-}03\ A^{0.876}\ BS^{6.33}\ S30*^{-4.77}\ F*^{0.710}$	0.162	45.2 to -31.2
	$Q.20 = 3.51E\text{-}03\ A^{0.863}\ BS^{6.63}\ S30*^{-4.98}\ F*^{0.569}$	0.149	41.0 to -29.1
	$Qa = 1.07E\text{-}02\ A^{0.831}\ BS^{7.25}\ S30*^{-5.42}\ F*^{0.448}$	0.139	37.7 to -27.4

Appendix 2 Tributary rating curves, site photos and discharges



date/time	qw(cms)	stage(cm)	creek name
6/7/2008	73.1	322.5	Big
6/27/2008	75.88939	322.8	Big
7/12/2008	24.1064	368.5	Big
7/24/2008	16.0043	387.1	Big
7/29/2008	13.5931	393.1	Big
11/13/2008	11.0709	396.6	Big
11/16/2008	6.6051	411	Big
6/27/2009	39.36745	347.6	Big
7/3/2009	26.44677	363.1	Big
5/22/2009	85.48133	305	Big



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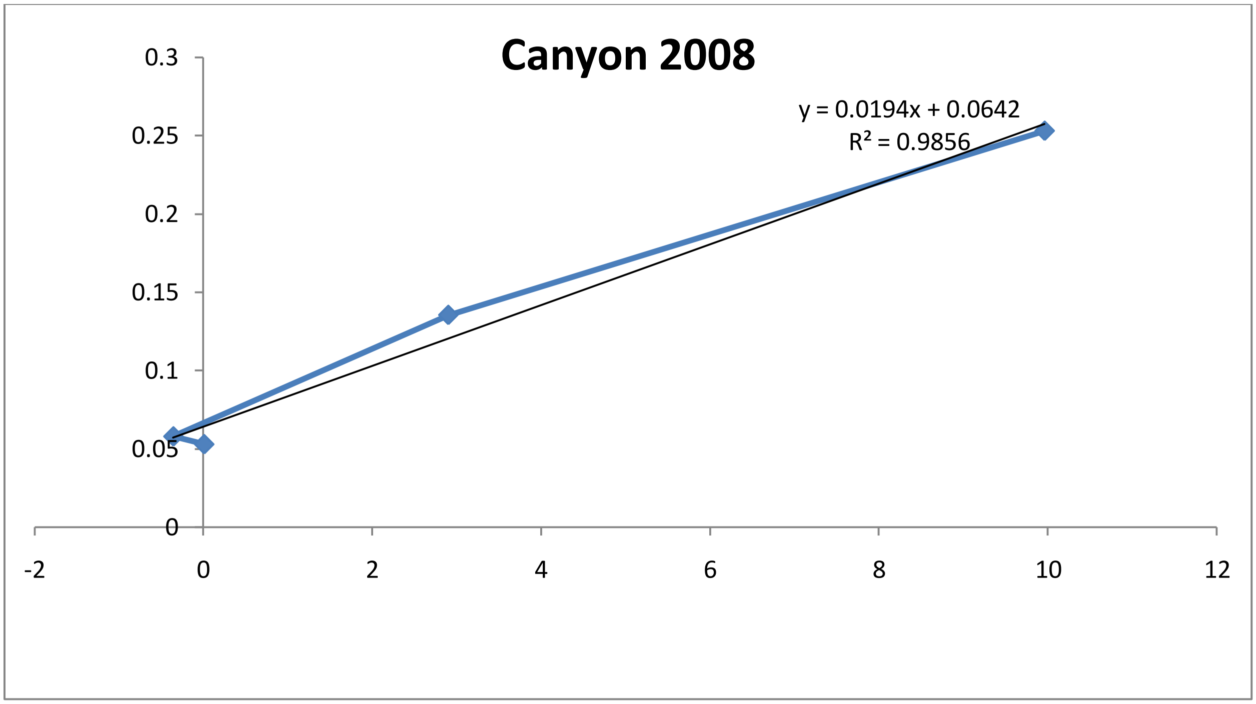
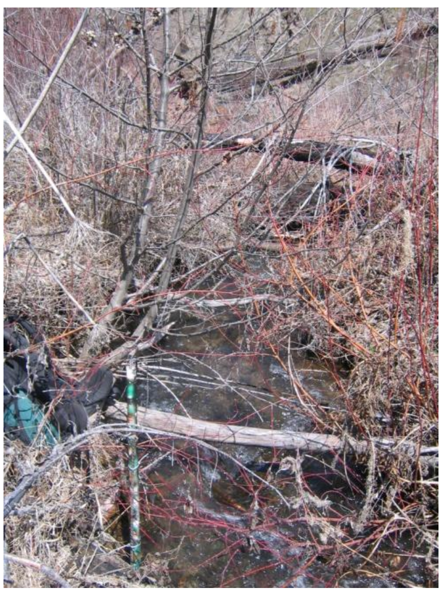
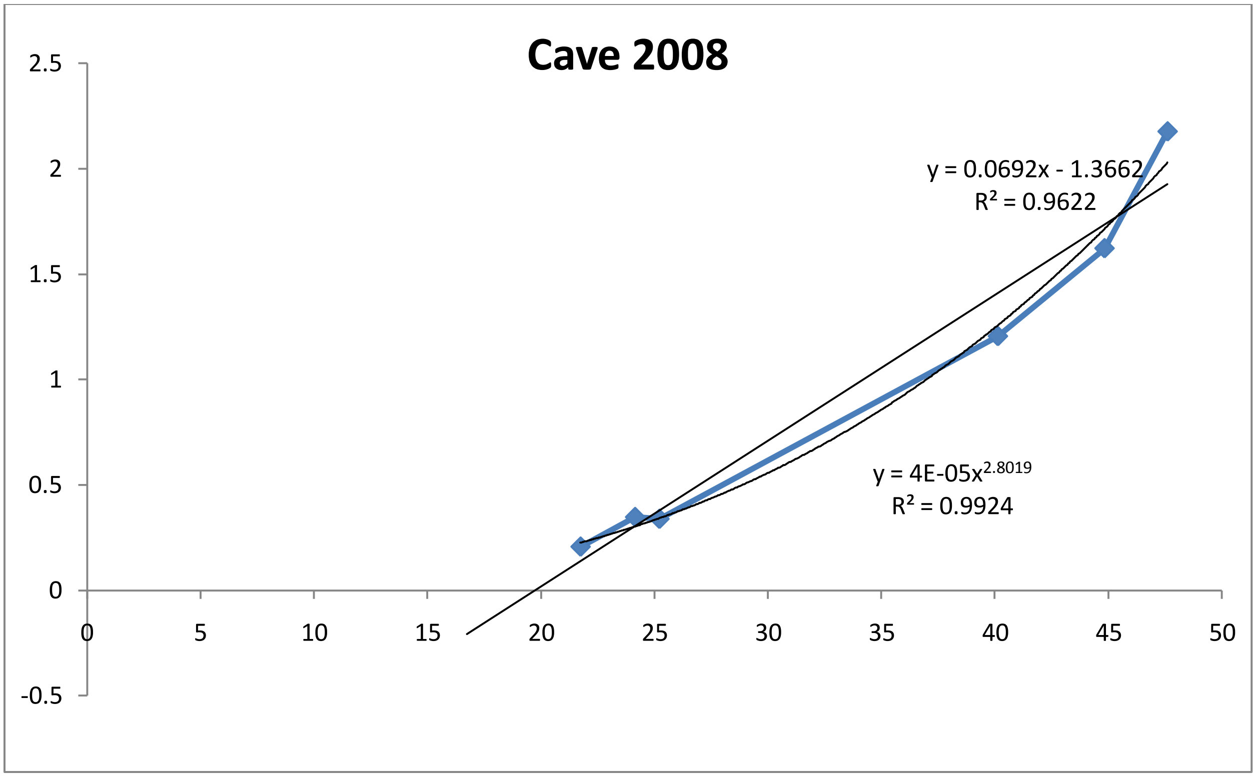
5/19/08 11:30	2.5942	72.484	Cabin
5/28/08 12:00	1.8612	29.752	Cabin
6/9/08 12:37	1.6588	23.944	Cabin
7/2/08 10:50	1.1984	22.919	Cabin
7/14/08 11:50	0.6486	16.74	Cabin
7/27/08 10:26	0.4759	13.736	Cabin
11/15/08 14:45	0.2411	11.229	Cabin

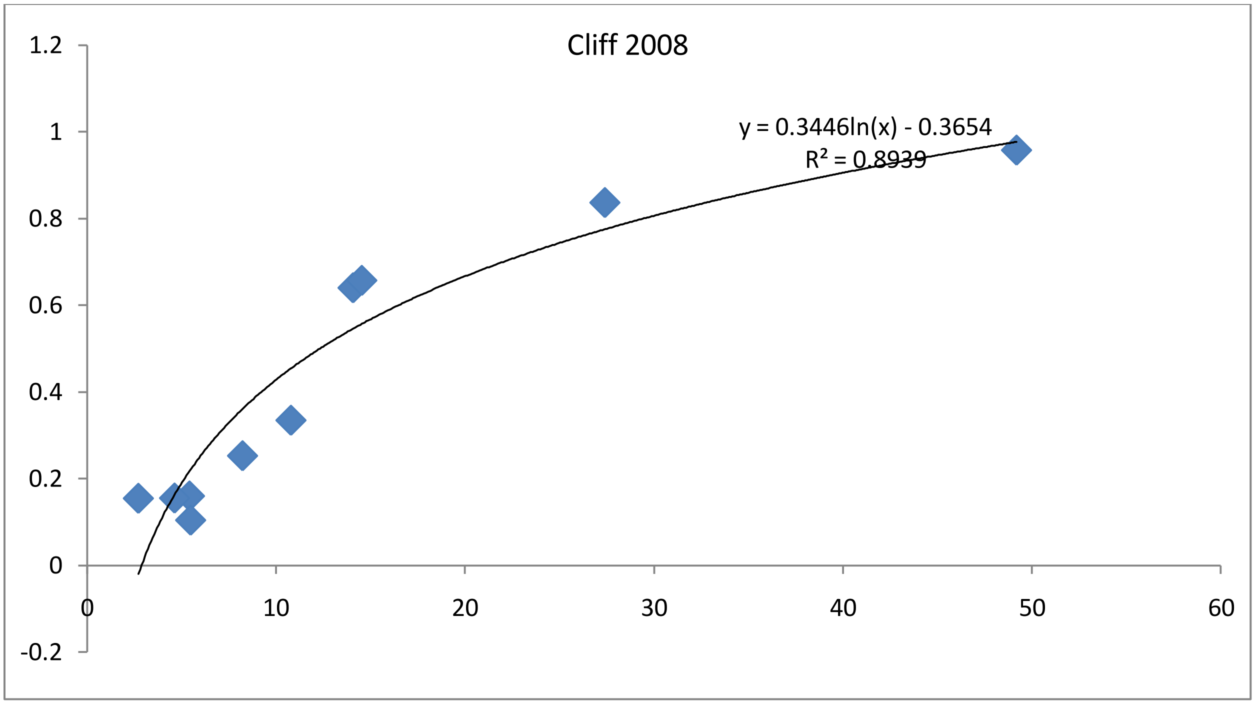




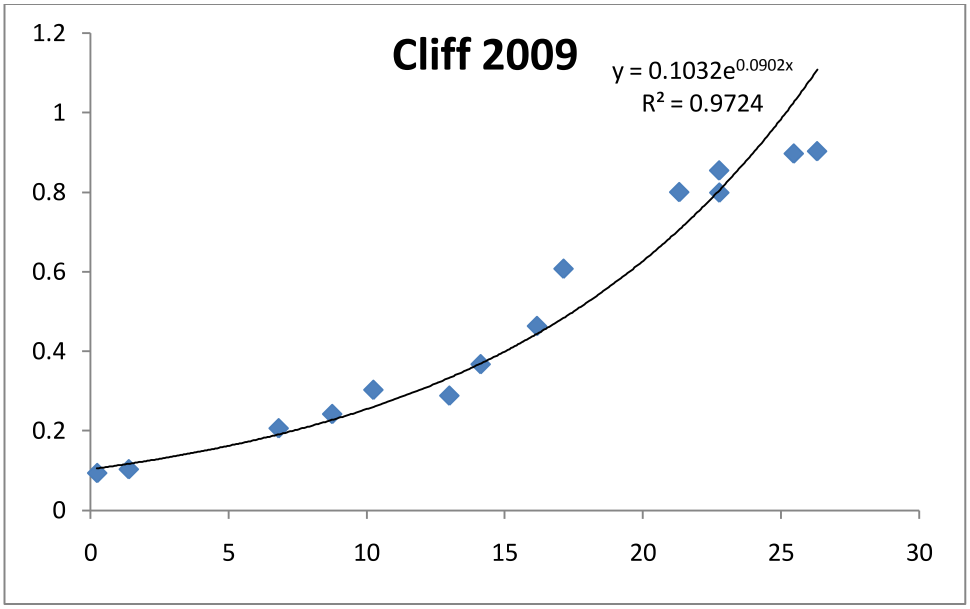
6/13/08 15:37	0.253	9.962	Canyon
7/2/08 13:53	0.1355	2.899	Canyon
7/14/08 16:30	0.058	-0.357	Canyon
7/27/08 16:17	0.053	0.008	Canyon
11/15/08 10:27	0.0201	-0.161	Canyon



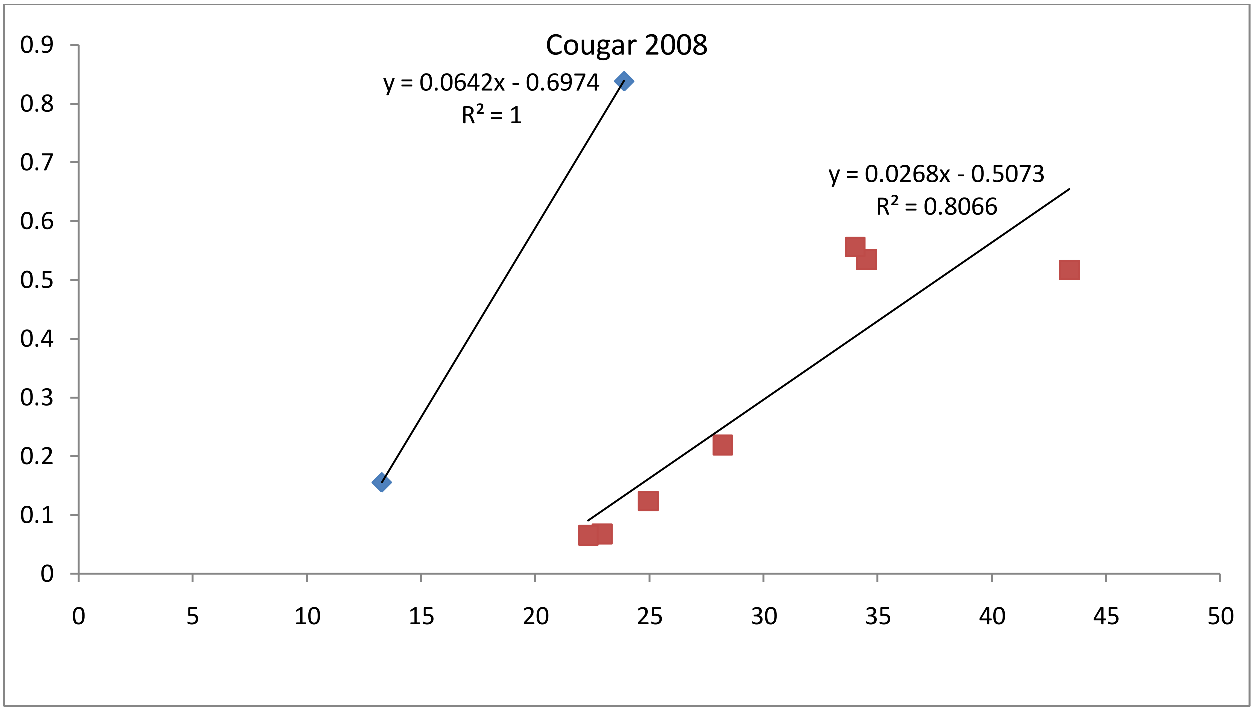
5/19/2008	2.1761	47.619	Cave
5/28/2008	1.6216	44.838	Cave
6/9/2008	1.2048	40.138	Cave
7/14/2008	0.3377	25.219	Cave
7/19/2008	0.3463	24.147	Cave
7/27/2008	0.2058	21.744	Cave
11/15/2008	0.1125	19.498	Cave



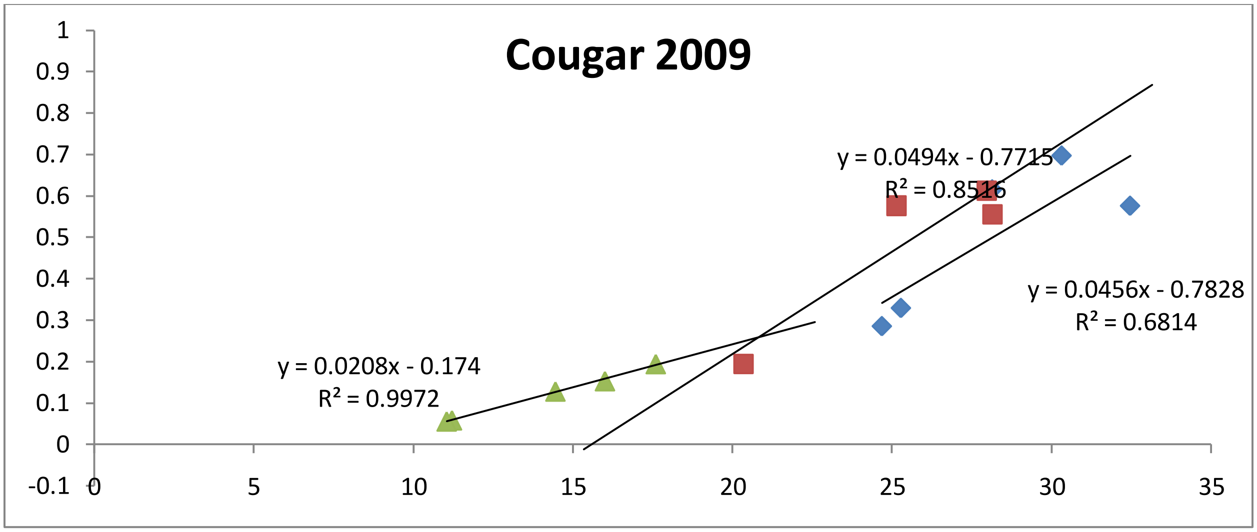
5/18/2008	0.9581	49.168	Cliff
5/20/2008	0.8371	27.4	Cliff
6/3/2008	0.963	14.106	Cliff
6/11/2008	0.6404	14.082	Cliff
6/16/2008	0.6575	14.544	Cliff
7/1/2008	0.3348	10.799	Cliff
7/9/2008	0.2529	8.239	Cliff
7/16/2008	0.1601	5.433	Cliff
7/20/2008	0.1553	4.643	Cliff
7/25/2008	0.1547	2.73	Cliff
11/13/2008	0.1043	5.494	Cliff



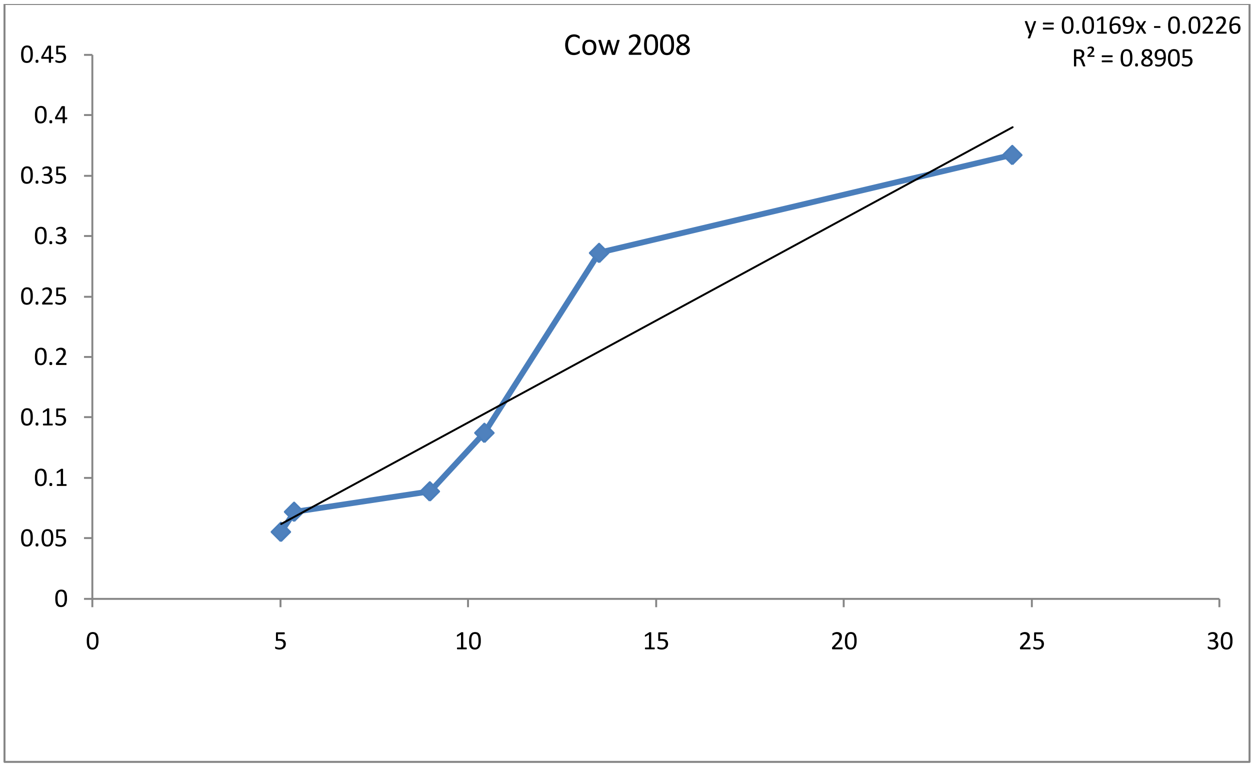
date	Q	stage	name
5/9/09 16:36	0.2881	12.997	Cliff
5/12/09 14:35	0.3671	14.131	Cliff
5/17/09 15:24	0.4631	16.17	Cliff
5/20/09 10:04	0.8966	25.471	Cliff
5/25/09 10:38	0.9025	26.315	Cliff
5/29/09 10:27	0.8542	22.768	Cliff
5/29/09 11:12	0.7984	22.774	Cliff
5/29/09 11:47	0.7997	21.322	Cliff
6/2/09 14:56	0.6071	17.133	Cliff
6/24/09 14:53	0.3027	10.246	Cliff
6/29/09 10:29	0.2419	8.754	Cliff
7/2/09 14:25	0.2061	6.815	Cliff
7/24/09 10:50	0.1031	1.388	Cliff
7/27/09 17:26	0.0936	0.243	Cliff



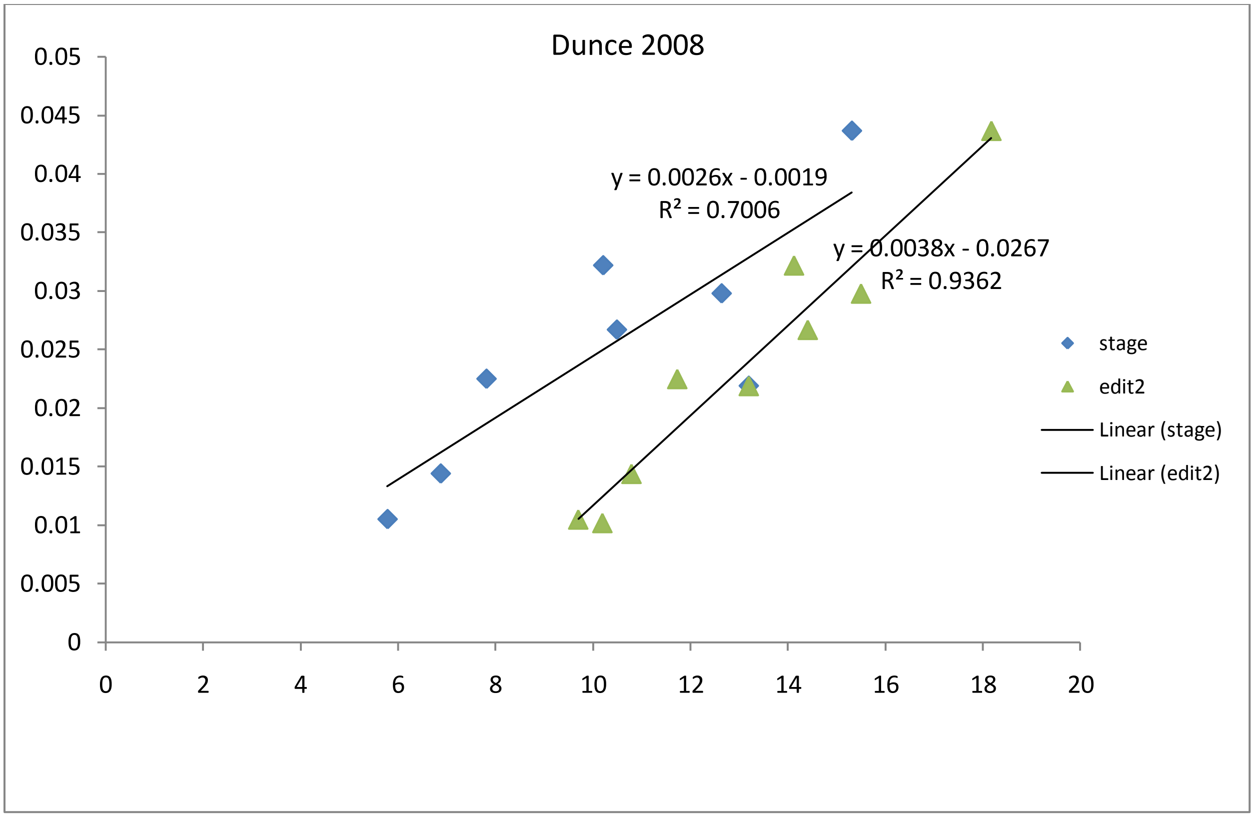
4/26/2008	0.1558	13.281	Cougar
5/18/2008	0.8382	23.903	Cougar
5/24/2008	0.5164	43.405	Cougar
6/5/2008	0.5348	34.516	Cougar
6/15/2008	0.5561	34.019	Cougar
6/30/2008	0.2189	28.229	Cougar
7/10/2008	0.1236	24.957	Cougar
7/21/2008	0.0675	22.937	Cougar
7/28/2008	0.0653	22.327	Cougar
11/14/2008	0.0626	11.847	Cougar



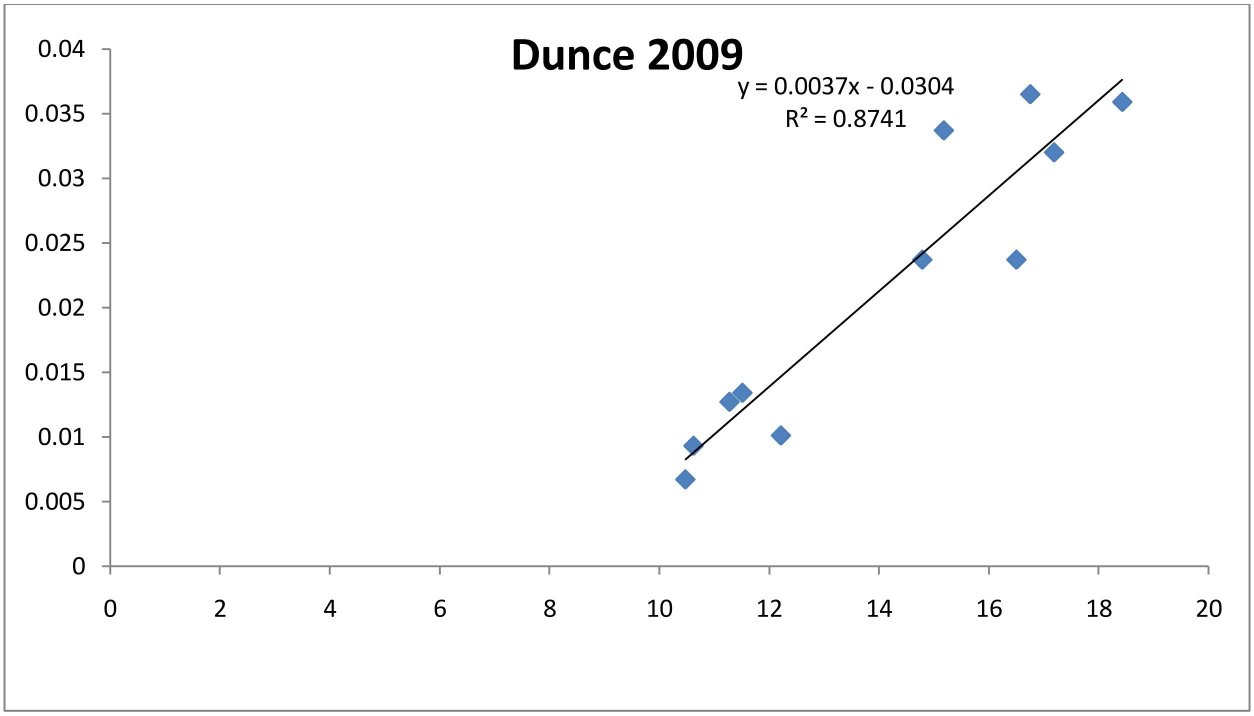
5/10/2009 11:18	0.2862	24.685	cougar
5/15/2009 15:17	0.33	25.283	cougar
5/19/2009 15:05	0.6156	28.144	cougar
5/23/2009 14:54	0.6973	30.32	Cougar
5/28/2009 15:51	0.5763	32.467	Cougar
5/28/2009 16:28	0.5763	25.135	Cougar
5/30/2009 10:11	0.6121	27.961	Cougar
6/1/2009 14:07	0.5554	28.155	Cougar
6/25/2009 15:27	0.1941	20.349	Cougar
6/25/2009 15:27	0.1941	17.589	Cougar
6/30/2009 13:55	0.1529	15.999	Cougar
7/5/2009 14:40	0.128	14.45	Cougar
7/25/2009 13:59	0.0586	11.214	Cougar
7/28/2009 13:47	0.0559	11.048	Cougar



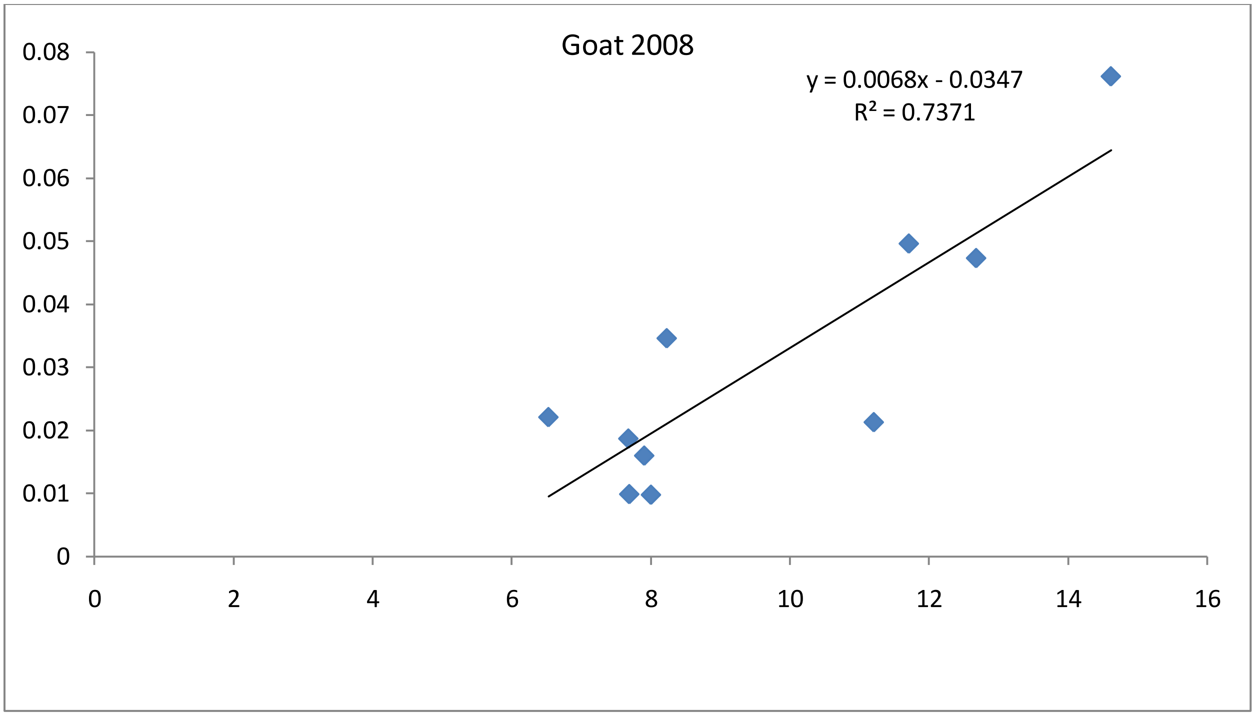
5/19/2008	0.6297	10.901	Cow	10.901
5/28/2008	0.3671	24.487	Cow	24.487
6/9/2008	0.2861	19.572	Cow	13.491
7/2/2008	0.1373	16.52	Cow	10.439
7/14/2008	0.0889	15.068	Cow	8.987
7/27/2008	0.072	11.456	Cow	5.375
11/15/2008	0.0554	11.104	Cow	5.023



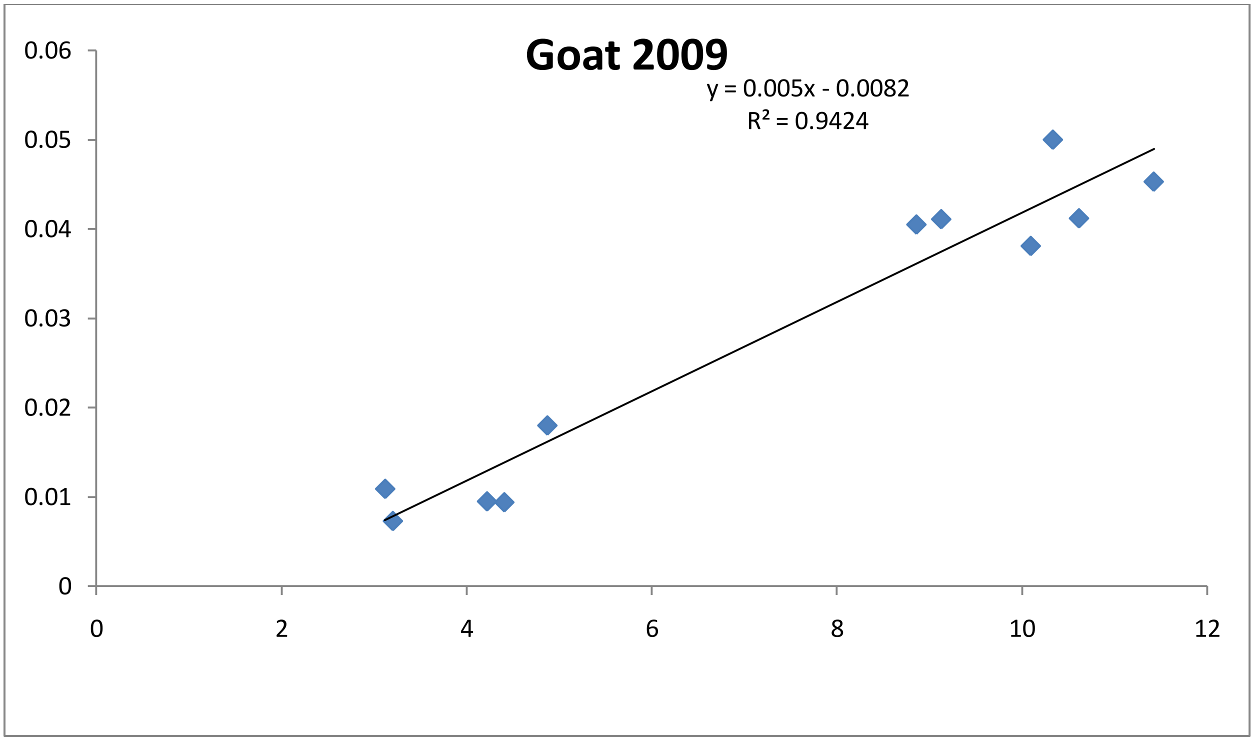
4/26/2008	0.0219	13.197	Dunce	13.197
5/16/2008	0.0437	15.314	Dunce	18.174
5/24/2008	0.0298	12.64	Dunce	15.5
6/5/2008	0.0267	10.49	Dunce	14.407
6/15/2008	0.0322	10.208	Dunce	14.125
6/30/2008	0.0225	7.813	Dunce	11.73
7/10/2008	0.0144	6.874	Dunce	10.791
7/28/2008	0.0105	5.782	Dunce	9.699
11/14/2008	0.0102	6.277	Dunce	10.194



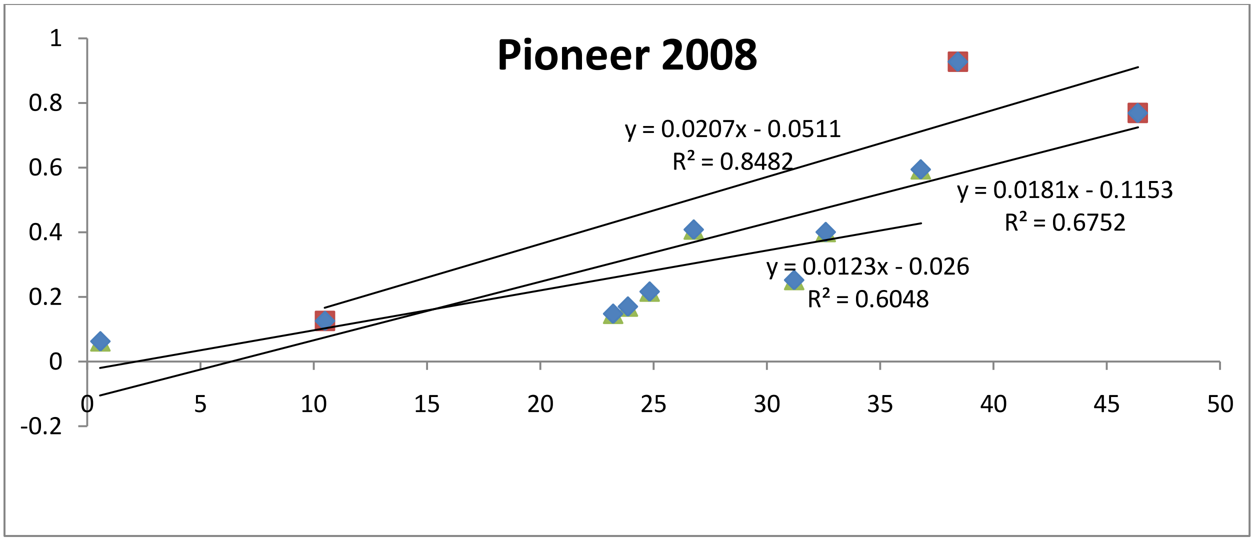
5/10/09 15:28	0.0337	15.18	dunce
5/15/09 13:08	0.0365	16.752	dunce
5/19/09 13:16	0.0359	18.426	dunce
5/23/09 10:58	0.032	17.185	dunce
5/28/09 13:15	0.0237	16.5	dunce
6/1/09 12:09	0.0237	14.788	dunce
6/25/09 13:27	0.0101	12.217	dunce
6/30/09 12:02	0.0127	11.282	dunce
7/5/09 12:59	0.0134	11.517	dunce
7/25/09 12:10	0.0067	10.479	dunce
7/28/09 11:58	0.0093	10.627	dunce



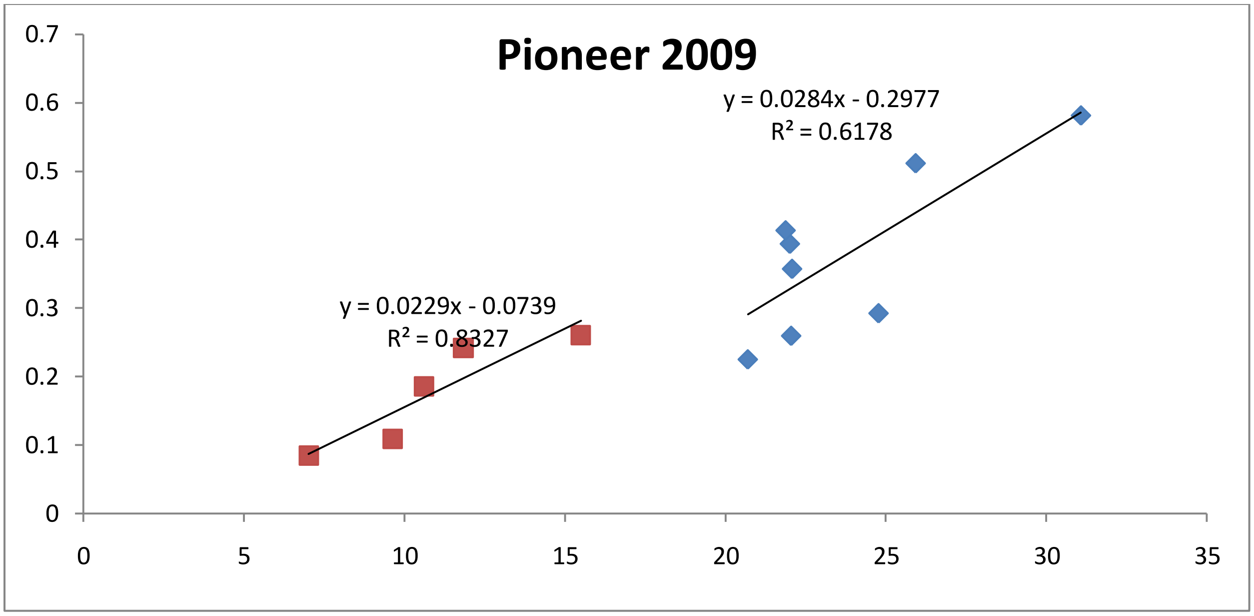
4/26/2008	0.0213	14.979	Goat	11.209
5/16/2008	0.0496	15.483	Goat	11.713
5/24/2008	0.0761	14.619	Goat	14.619
6/5/2008	0.0473	8.781	Goat	12.681
6/15/2008	0.0346	4.331	Goat	8.231
6/30/2008	0.0221	2.629	Goat	6.529
7/10/2008	0.0187	3.779	Goat	7.679
7/21/2008	0.0099	3.792	Goat	7.692
7/28/2008	0.0098	4.104	Goat	8.004
11/14/2008	0.016	4.007	Goat	7.907



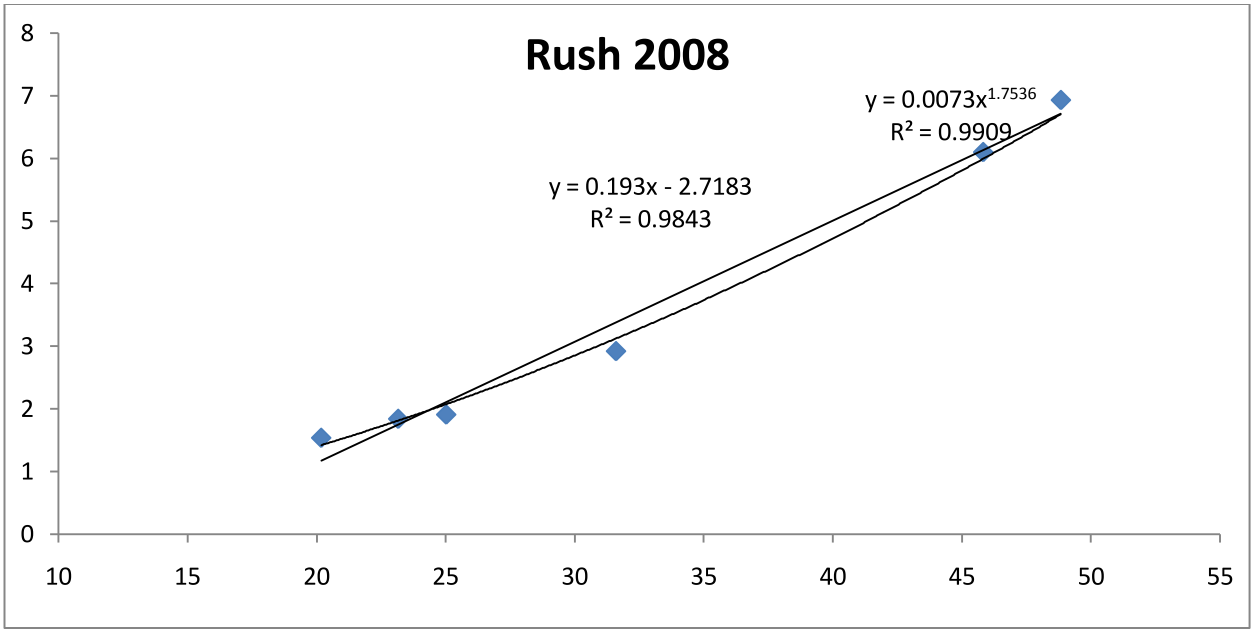
5/10/09 13:38	0.0381	10.096	goat
5/15/09 10:56	0.0411	9.128	goat
5/19/09 11:05	0.0412	10.617	goat
5/23/09 13:33	0.0453	11.425	goat
5/28/09 11:17	0.05	10.335	goat
6/1/09 10:29	0.0405	8.86	goat
6/25/09 11:21	0.018	4.871	goat
6/30/09 10:29	0.0094	4.406	goat
7/5/09 11:17	0.0095	4.219	goat
7/25/09 11:05	0.0109	3.118	goat
7/28/09 10:25	0.0073	3.201	goat



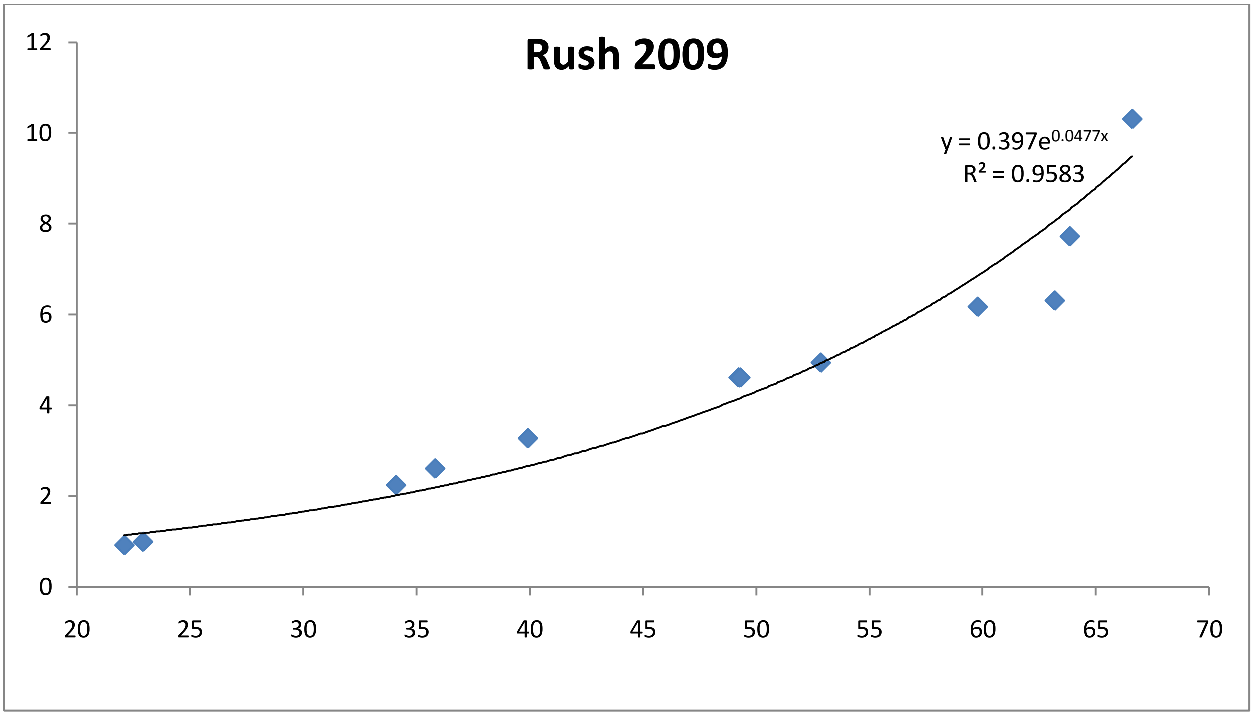
4/25/2008	0.1264	10.5	Pioneer
5/17/2008	0.7692	46.387	Pioneer
5/20/2008	0.9278	38.443	Pioneer
6/3/2008	0.5948	36.806	Pioneer
6/11/2008	0.4089	26.783	Pioneer
6/17/2008	0.5125	7.968	Pioneer
6/28/2008	0.4012	32.611	Pioneer
7/9/2008	0.2529	31.217	Pioneer
7/16/2008	0.2172	24.836	Pioneer
7/20/2008	0.1709	23.876	Pioneer
7/25/2008	0.1486	23.224	Pioneer
11/13/2008	0.0634	0.584	Pioneer



5/9/2009 11:02	0.2252	20.71	pioneer
5/12/2009 11:10	0.2596	22.06	pioneer
5/17/2009 10:52	0.2926	24.775	pioneer
5/20/2009 11:10	0.5814	31.076	pioneer
5/25/2009 11:53	0.5116	25.93	pioneer
5/29/2009 15:38	0.3574	22.083	pioneer
5/29/2009 16:11	0.3940	22.015	pioneer
6/2/2009 13:08	0.4136	21.882	pioneer
6/2/2009 13:23	0.4136	15.492	pioneer
6/24/2009 12:16	0.2610	11.833	pioneer
6/29/2009 11:30	0.2419	10.608	pioneer
7/2/2009 15:25	0.1861	9.629	pioneer
7/24/2009 9:41	0.1092	7.013	pioneer
7/27/2009 19:07	0.0845	6.397	pioneer

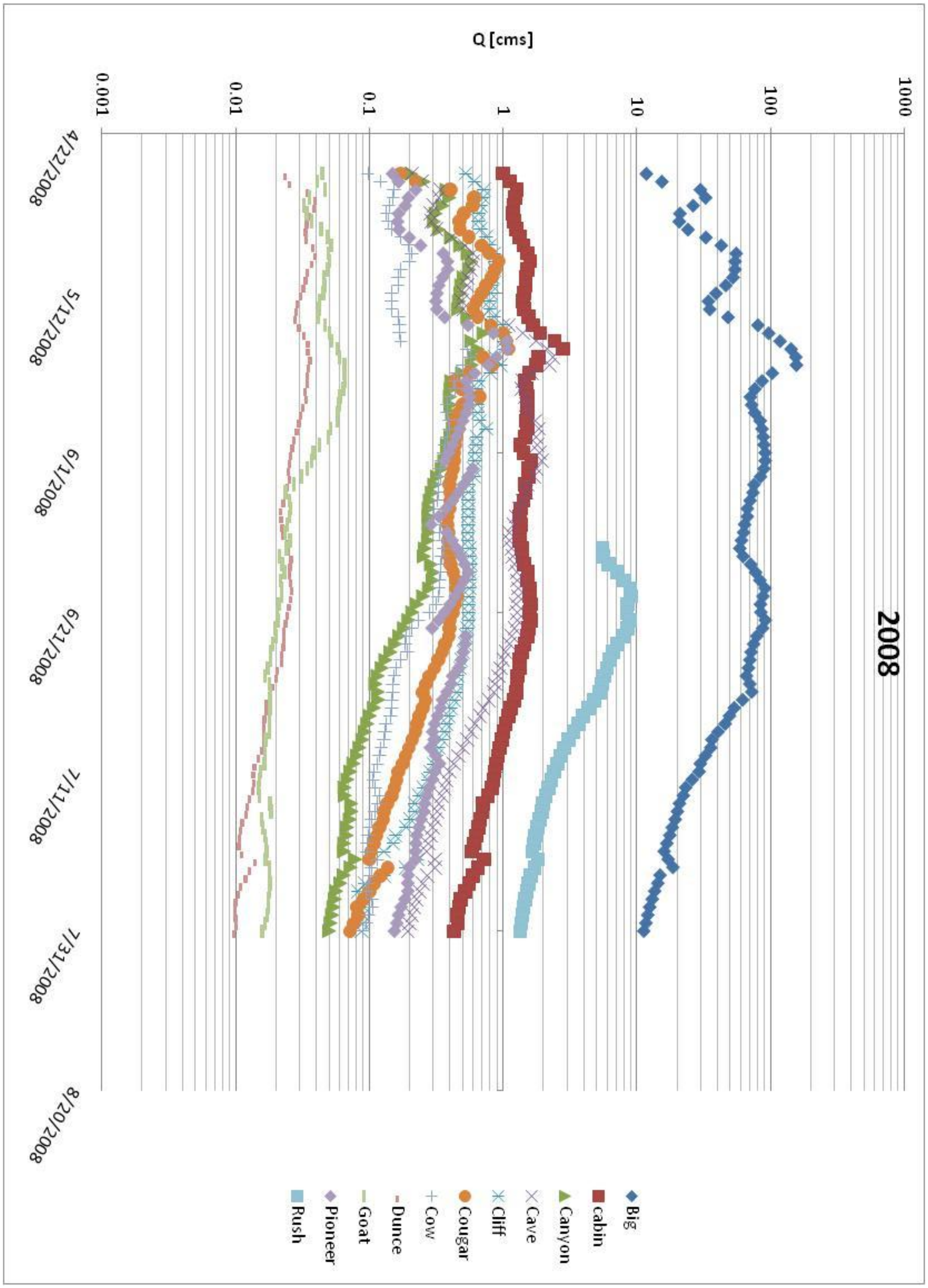


4/25/08 15:05	1.8439	10.099	rush before move
6/16/08 10:53	6.9363	48.84	Rush
6/28/08 10:56	6.1049	45.829	Rush
7/8/08 0:00	2.9246	31.603	Rush
7/15/08 15:17	1.9116	25.023	Rush
7/22/08 9:04	1.8432	23.164	Rush
7/25/08 13:46	1.5399	20.18	Rush
11/13/08 15:48	0.7277	13.935	Rush



5/9/2009 13:05	4.6181	49.211	rush
5/12/2009 9:41	4.6158	49.289	rush
5/17/2009 10:52	4.9459	52.839	rush
5/20/2009 14:35	10.3147	66.601	rush
5/25/2009 17:07	6.3138	63.175	rush
5/31/2009 12:12	7.7289	63.838	rush
6/2/2009 10:19	6.1777	59.775	rush
6/24/2009 13:35	3.2794	39.907	rush
6/29/2009 14:57	2.6131	35.81	rush
7/2/2009 10:03	2.2478	34.086	rush
7/24/2009 13:54	0.9976	22.911	rush
7/27/2009 16:19	0.925	22.087	rush

IDENT	LAT	LONG
Cow	45.14607855	-114.92311257
Cave	45.13413124	-114.95635050
Cab	45.13234749	-114.93587544
Canyon	45.12402610	-114.93675990
Goat	45.11228741	-114.80473705
Dunce	45.10738735	-114.78446642
Cliff	45.10590367	-114.84924830
Cougar	45.10463993	-114.82167972
Taylor	45.10214481	-114.84930849
Rush	45.09974683	-114.86266664
Pioneer	45.09892481	-114.85068371


2008
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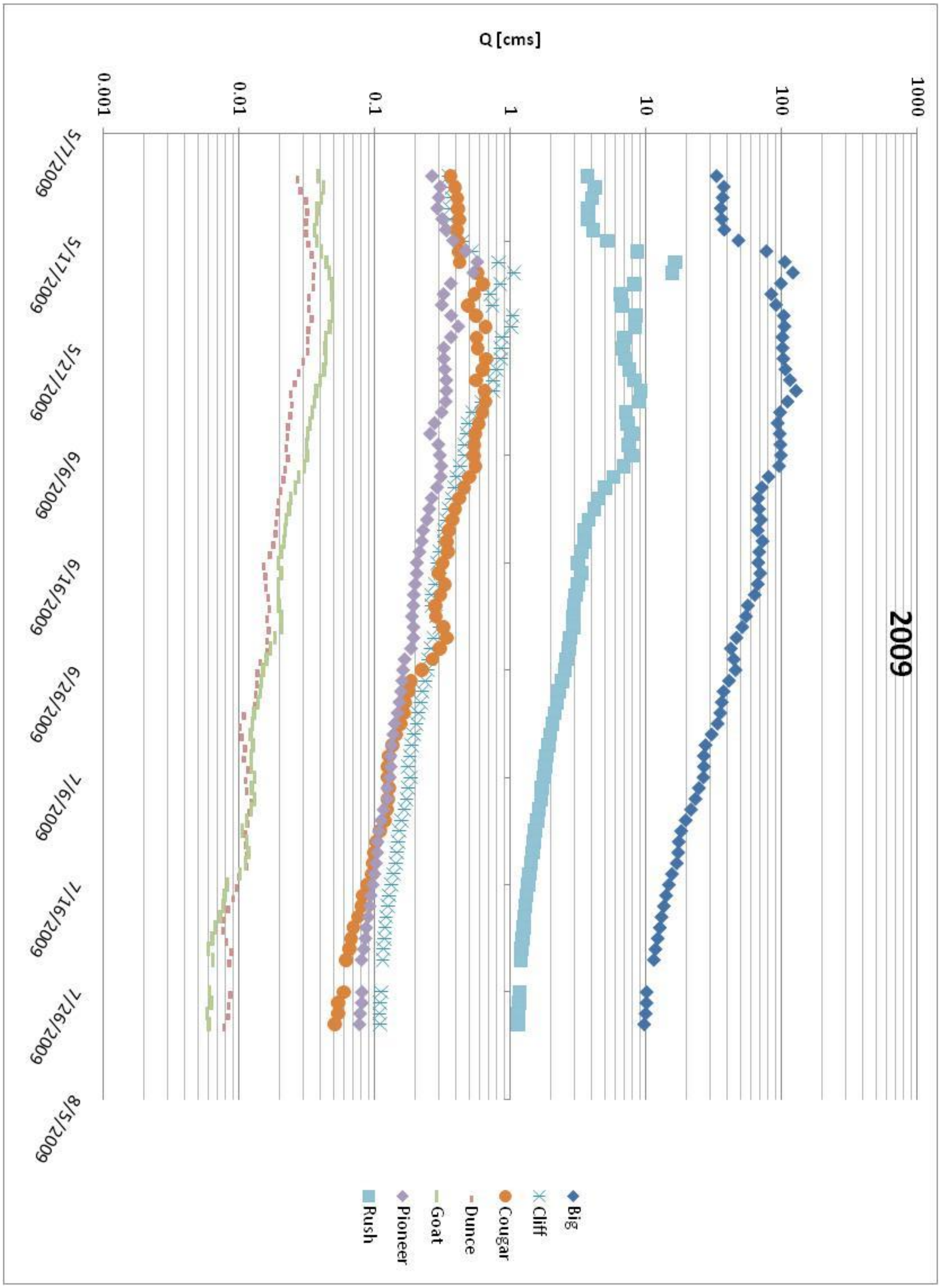
4/22/2008
5/12/2008
6/1/2008
6/21/2008
7/11/2008
7/31/2008
8/20/2008
Big
cabin
Canyon
Cave
Cliff
Cougar
Cow
Dunce
Goat
Pioneer
Rush



2009
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5/7/2009
5/17/2009
5/27/2009
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6/26/2009
7/6/2009
7/16/2009
7/26/2009
8/5/2009
Big
Cliff
Cougar
Dunce
Goat
Pioneer
Rush