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EFFECTS OF LITHOLOGY, STRUCTURE AND STRATIGRAPHY ON SURFACE WATER SPECIFIC ELECTRICAL CONDUCTANCE; SOUTH FORK OF THE FLATHEAD RIVER, MONTANA

By

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Abstract Title: Effects of lithology, structure and stratigraphy on surface water specific electrical conductance; South Fork of the Flathead River, Montana

Chairperson: Perry Brown

Committee Member: F. Richard Hauer, Scott Woods

In the South Fork watershed of the Flathead River the two main determinants of electrical conductivity appear to be lithology and structure (faults). Limestone and dolomite produce high electrical conductivities (150 to 300 mS·cm-1), shale medium conductivities (70-150 mS·cm-1) and quartz, siltite, argillite low conductivities (0 to 70 mS·cm-1). Conductivity measurements from tributaries of the South Fork ranged from 40 to 290 mS·cm-1. South Fork River conductivity values ranged from 132 to 198 mS·cm-1. Longitudinally, the South Fork Rivers' electrical conductivity values exhibited diurnal fluxes, but overall decreased with distance from the headwaters. In general, electrical conductivity was greater (> 150 mS·cm-1) east of the South Fork Fault, which runs parallel with the east bank of the South Fork River. The geology that covers the greatest percentage of a watershed may determine the drainages' conductivity, however all geologies and their percent of cover should be considered when no one geology appears to dominate. This study generally assessed surface groundwater interactions in the South Fork watershed and in doing so, demonstrated how electrical conductivity, lithology and structure can be used to simplify our understanding of complex hydrologic systems. Electrical conductance data and spatial patterns identified in this study provide resource managers clues as to where aquatic biota might and do thrive.

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1. Introduction

The complexity of river systems is in part expressed through spatial and temporal variances in surface and groundwater constituents. Many studies have illustrated that every stream can be differentiated from every other stream, thus each stream has a unique character. Hynes' (1975) seminal paper provides some of the earliest understanding of complex interactions between a stream and its valley and various water interactions occurring throughout the river corridor from headwaters to the ocean. Research has shown that naturally occurring dissolved constituents in stream water are a function of individual rock type within a watershed and therefore streams can be classified or distinguished from each other based on lithology (Davis, 1964; Hem, 1985; Meybeck, 1987; Bluth and Kump, 1993; Cocker, 1999; Grieve, 1999; Clow and Sueker, 2000; Oguchi, 2000; Wanty et al., 2009). Electrical conductance, which measures the ionic strength of a fluid, is a valuable tool that can improve resource managers understanding of hydrogeologic and biological processes in freshwaters. Electrical conductance can spatially identify different rock units and potential mineral solutes (Wantry et al., 2009), locations of structural and physical features (Clow and Sueker, 2000), areas of upwelling or downwelling (Oxtobee and Novakowski, 2002), and microhabitats of stream biota (Hauer and Lamberti, 2007). The goal of this study was to increase understanding of the hydrogeologic processes occurring in the South Fork watershed of the Flathead River using three parameters (1) electrical conductivity, (2) lithology and (3) geologic structrual features. This goal was achieved by answering the following question: Are specific electrical conductance values and patterns within the watershed a result of lithology, structure and stratigraphy? I hypothesize that baseflow specific electrical conductance values throughout the watershed are driven by lithology because most dissolved constituents originate from parent materials that elicit their own geochemical signature. I also hypothesize that baseflow specific electrical conductance values are altered by stratigraphy and structure because both modify hydraulic conductivity and surface area to volume relationships in rock, thus increasing or decreasing the time and amount of rock exposed to the dissolution powers of groundwater.

Historically, streamflow has been described as consisting of a base-flow fraction made up primarily of water that infiltrated as phreatic groundwater into the channel and a direct-runoff fraction that entered the stream during and soon after precipitation (Hem, 1985). Likewise, the stream within its catchment was visualized as a pipe receiving solutes and nutrients and primarily as a conduit for transport of water and materials downstream (Bencala, 1993). This simple model has largely been discredited except where streams flow through canyons and over bedrock. Streams are now viewed as highly interactive systems that penetrate their watersheds and are highly interactive along the longitudinal, lateral and vertical spatial context of material flow (Ward 1992). Indeed, streams and rivers are now seen as integral parts of the catchment system that consist of multiple flow paths which act as bidirectional links (Bencala, 1993). Contemporary research has shown streamflow as the result of complex surface and groundwater interactions shaped by hillslope hydrology, lithology, tectonics, soil, vegetation, stream morphology, and climate (Hynes, 1975; Castro and Hornberger, 1991; Bencala, 1993; Harvey and Bencala, 1993; Stanford and Ward, 1993; Ward and Stanford, 1995; Woessner, 2000; Hayashi and Rosenberry, 2002; Poole et al., 2006; Fetter, 2011).

Ward and Stanford (1989a) identified four dimensions to surface groundwater interactions; a temporal dimension (time) and three spatial dimensions: longitudinal (headwaters to ocean), lateral (river-floodplain), and vertical (surface groundwater/hyporheic). Temporal (diel, seasonal, interannual) variations affect the strength of spatial connections and interactions. Longitudinally, from headwaters to mouth, a river system presents a continuous gradient of physical conditions, which elicit responses from constituent populations resulting in patterns of loading, transport, utilization and storage of organic matter along the length of a river (Vannote et al., 1980). The lateral dimension includes the exchange and storage of surface and groundwater within the fluvial plane. The fluvial plane can be thought of as a relatively planar feature containing the stream channel, floodplain, and associated fluvially derived sediments (Woessner, 2000). The fluvial plane sediments are derived from riverine processes and are stratigraphically complex. Water in the floodplain can flow parallel to, away from and into the river (Woessner, 2000). The vertical dimension includes groundwater or hyporheic water entering/leaving the streambed, banks and floodplains due to pressure gradients. Hyporheic waters exist in the hyporheic zone, which is the interface between phreatic groundwater and surface water in streams where active mixing and interchange occur (Committee on Hydrologic Science, 2001). These vertical, lateral and longitudinal surface groundwater interactions plus lithology and stratigraphy have been known to influence solute dynamics, which ultimately result in distinct geochemical signatures differentiating water flowing from different watersheds.

Lithology is the physical character of a rock or deposit expressed in terms of texture, mineralogy, color and thickness (Stone, 1999). Structural features like fractures, faults, joints, and bedding planes alter hydraulic conductivity, surface area of rock and water residence times (Hurlow, 1999). Stratigraphy is the science of sedimentary rock strata or layers (Hurlow, 1999). The location and nature of these factors within the geologic column is an important source of control on surface and groundwater (Stone, 1999). Combined, these factors create a geologic setting which limits the rate of dissolution and concentration of solutes in surface and groundwater.

Solutes are materials that are chemically dissolved in water (Webster and Valett 2006). Factors which influence solute concentrations are lithology, stratigraphy, tectonics, organic matter, water-dwelling biota, evapotranspiration, rainfall, and atmospheric inputs (Hynes, 1975; Vannote et al., 1980; Hynes, 1983; Hem, 1985; Junk, 1989; Hornung et al., 1990; Lundin, 1995; Billet et al., 1996; Dahm et al., 1998, Hurlow, 1999; Rothwell et al., 2010). Soils and lithology play a major role in solute dynamics (Hornung et al., 1990). Soil is the biologically excited layer of the earth's crust, made of organic and mineral matter. It includes many different horizons derived from soil development **and** underlying unweathered rock, called parent material (Richter and Markewitz, 1995). Through mineral weathering, nutrients and elements are released from primary rock minerals into bioavailable forms, which are then taken up by plant roots and microbes, recombined into secondary minerals, or lost to groundwater and rivers (Richter and Markewitz, 1995). The rate of mineral weathering is often related to soils' or waters acidity, which is the expression of many biological processes that circulate chemical elements in the ecosystems. Organic acid, sulfuric acid, carbonic acid, and ion-uptake dynamics of vegetation are the most common contributors to substances acidity (Richter and Markewitz, 1995). One major pathway used to understand mineral weathering of parent material is attacks of carbonic acid on minerals (Meybeck, 1987). Respiration of plant roots and soil organisms elevates carbon dioxide throughout the below ground atmosphere (Richter and Markewitz, 1995). Water infiltrating through the unsaturated zone reacts with carbon dioxide to form carbonic acid (Meybeck, 1987). As water percolates through the unsaturated zone or varying geolithic layers dissolution of minerals begins and continues until equilibrium concentrations are attained in the water or until all minerals are consumed (Freeze and Cherry, 1979). Depending on the minerals that water has come into contact with during its flow history, groundwater may be only slightly higher is dissolved solids than rainwater, or it may become many times more salty than seawater (Freeze and Cherry, 1979).

The dissolution rate of minerals and elements varies spatially and temporally and depends on temperature, oxygen availability, pH, lithology, hydraulic conductivity, and concentration of dissolved constituents currently in solution (Hem, 1985; Dethier, 1986; Hornung et al., 1990; Billet et al., 1996, Hurlow, 1999). Hydraulic conductivity is a coefficient of proportionality describing the rate at which water can move through a permeable medium (Fetter, 2001). A general relationship between the mineral composition of natural waters and that of the solid minerals with which the water has been in contact is expected. Researchers have identified the mineral origins of dissolved constituents and utilized this knowledge to predict, based on known rock types within a watershed, which chemical properties and constituents will occur in ground and surface waters (Davis, 1964; Hem, 1985; Meybeck, 1987; Grieve, 1999). The absolute and relative concentrations of dissolved constituents have been used to determine hidden or hard to survey geologies within both large and small watersheds (Bluth and Kump, 1993).

It has been demonstrated that during base-flow, groundwater input to a stream will produce a chemical signature of underlying and nearby parent material (Billet et al., 1996; Caissie et al., 1996). The base-flow recession for a drainage basin is a function of the overall topography, drainage pattern, soils, and geology (Fetter, 2001). Indeed, base-flow of a stream is somewhat constant throughout the year, while the total discharge of the stream may fluctuate. Particularly in snowmelt dominated watersheds, as are present in the Rocky Mountains of

Montana, sampling towards the end of the falling limb of the hydrograph ensures base-flow conditions (Billet et al., 1996).

Caissie et al. (1996) found that higher specific electrical conductance values were reflective of groundwater input. A part of the cation content of natural waters may be derived from nonlithological sources, however the importance of this effect on major cation concentrations is rather small and can be ignored (Hem, 1985). The presence of charged ion species or dissolved solids in a solution makes a solution conductive. The ionic strength of water is based on major and trace dissolved components. Major cations found in surface water are Na^+, K^+, Ca^{2+}, and Mg^{2+}. Major anions are HCO_3^-, NO_3^-, SO_4^{2-}, and Cl^-. Trace minor elements include As, Al, Ba, Cd, Co, Cu, F, Fe, Mn, Ni, P, Pb, Sr, Zn (Kyung-Seok Ko et al., 2009). Geogenic elements are easily incorporated into waters via dissolution of geologic material and include Ca, Mg, HCO_3, SO_4, Ba, Sr (Kyung-Seok Ko et al., 2009). As the ion or dissolved solid concentration of water increases, conductance of the solution increases. The ability of a substance to conduct electric current at 25◦C is termed specific electrical conductance and is reported as microsiemens per centimeter (Hem, 1985).

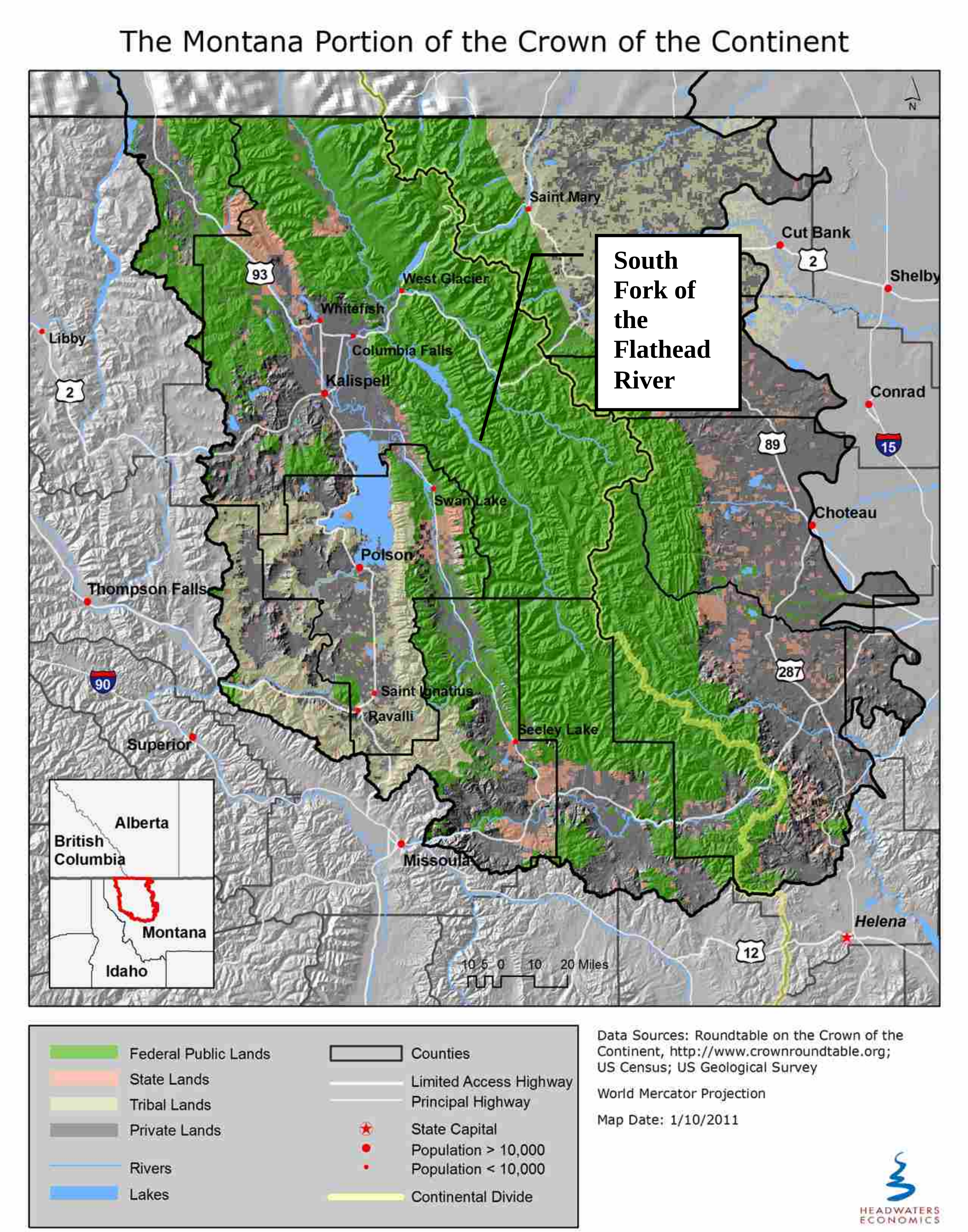
Measures of electrical conductivity are a valuable tool for resource managers. This variable can be measured rapidly and easily. It also can be used to identify locations within a watershed or stream where certain aquatic species may exist or could exist. Studies have shown a threshold of in-stream conductivity exists for fish and that it may influence fish condition (Copp, 2003; Kimmel and Arget, 2010). Leland and Porter (2000) found that ionic composition and major nutrient concentrations of surface waters were the primary factors contributing to benthic-algal assemblages. Interactions between surface water and upwelling groundwater, which is usually full of dissolved ions, were found to affect the distribution and abundance of algae (Wyatt et al., 2008) and aquatic insects (Pepin and Hauer, 2002). Ionic composition of water also was found to explain most diatom assemblages (Potapova and Charles, 2003).

Very little water chemistry data have been collected in the South Fork watershed of the Flathead River above Hungry Horse Dam. This study determines if the location of structural features and distribution of geologic layers within the South Fork watershed of the Flathead River influence specific electrical conductivity. Electrical conductance data and spatial patterns identified in this study may provide resource managers clues to where aquatic biota currently and potentially could thrive.

2. Methods

2.1 Overview of Study

Youngs and Danaher Creeks make up the headwaters of the South Fork River and exist entirely within the Bob Marshall Wilderness, which is east of the Swan Mountains located on the Flathead National Forest in northwestern Montana (Fig. 1). The relationship between lithology, structure, stratigraphy and surface waters' electrical conductivity has not been studied in detail due to its remoteness. Geologic and structural maps, electrical conductivity data collected from 24 tributaries of the South Fork River August 16th-19th, 2011 and data from the PACFISH/INFISH Biological Opinion Effectiveness Monitoring Program (PIBO-EM) database were utilized in the study. These data help determine if lithology, structure and stratigraphy affect surface water specific electrical conductance values and/or create identifiable spatial patterns within the watershed?



Data Sources: Roundtable on the Crown of the Continent, http://www.crownroundtable.org; US Census; US Geological Survey

World Mercator Projection

Map Date: 1/10/2011

Fig. 1: Regional setting of the study area.

2.2 Geologic Framework

The South Fork drainage consists mostly of slightly metamorphosed sedimentary rocks and sedimentary rocks that were uplifted via tectonics and then eroded by glaciers and alluvial processes. Precambrian Belt Supergroup rock made of fine grained, moderately metamorphosed sediment forms the bedrock under the South Fork. The Belt Supergroup was deposited in a large basin bounded on the north, east and south by continental crust during the Middle Proterozoic (Winston and Link, 1993). Facies from the Cambrian, Devonian, Mississipian, Tertiary, and Quaternary time periods are also found in the South Fork drainage on top of Belt rocks (Mudge and Earhart, 1991) (geologies and faults shown in Fig. 2). Thick layers of sandstone, limestone and dolomite were deposited during the Mesozoic. From Jurassic to Paleocene time, Belt rocks along with their Phanerozoic cover, were thrust eastward and were intruded by large batholiths (Winston and Link, 1993). Cenozoic extensional faults cut the thrust plates into large blocks. The South Fork Fault runs parallel with the east side of the South Fork River (Fig. 2). It is a normal fault, which means rocks on the east side of the river were thrust upward, while rocks on the west side of the river dropped (Mudge and Earhart, 1991). Pleistocene glaciation exposed many of the Belt rocks in high alpine areas. The most recent glacial advance receded about 10,000 years ago and left unconsolidated surface sediments in many watersheds that include glacial tills, glacial stream deposits, and fine grained sediments (Ducharme et al., 2001). Sixteen different geologic map units exist within the South Fork watershed above Hungry Horse Dam (Mudge and Earhart, 1991) (Fig. 2).

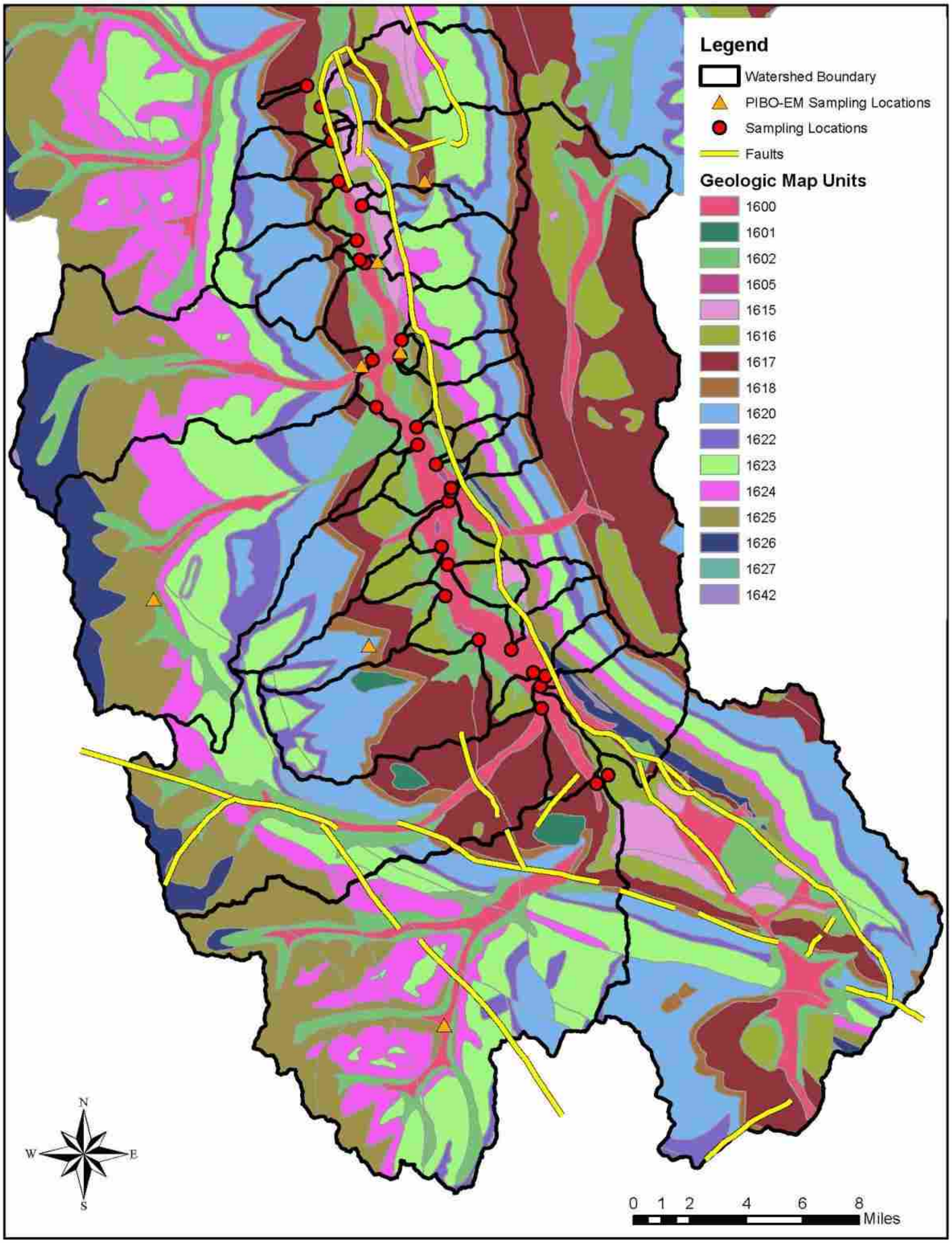


Fig. 2: Map displaying the geologic map units (rock types), faults, and water sampling locations within the South Fork watershed study site (Mudge and Earhart, 1991). Map units are color coded. A summary of geologic map units found within in the South Fork watershed are found in Appendix A.

Major rock types found in the South Fork watershed include argillite, siltite, dolomite, limestone, shale, and quartzite. These rocks are predominantly made up of silicate and carbonate minerals. Sills and dikes of gabbro and monozonite are interspersed throughout the Bob Marshall Wilderness, but few exist within the South Fork valley. Belt rocks have also been found to be rich in lead, zinc, copper and silver deposits (Winston and Link, 1993).

2.3 Hydrologic Landscape

Winter (2001) used land-surface form (slope and area), hydraulic properties of geologic units and climatic settings to identify six different hydrologic landscapes units. Each landscape demonstrates unique hydrologic processes and provides a means for comparing water systems. The South Fork drainage consists mostly of riverine valley and mountain valley landscapes. The main stem of the South Fork exists is a riverine valley, which is wide and can contain other smaller landscape units, such as hummocky terrain from glacial processes. Here regional ground-water is important as it upwells into the floodplain and mixes with water stored in the floodplain or hyporheic zone. Tributaries of the South Fork are mountain valley landscapes. They have steep slopes, confined channels and ground water is dominated by localized precipitation events and/or snowpack. Regional groundwater starts to upwell as tributary stream channels flatten out near the South Fork fluvial plain.

The South Fork is part of the Flathead Subbasin, which constitutes the northeastern-most drainage of the Columbia River. Roughly 57 percent of the South Fork basin is above 6,000 ft (USGS MT Flood-Frequency and Basin Characteristic Data). Hungry Horse Dam drains 1,640mi^2 (Bureau of Reclamation webpage) of the South Fork watershed. The average annual discharge into Hungry Horse Reservoir is 2,300 cfs (Deleray, 1999). No USGS gauging station is located in the study site and no stream flow measurements were made during the sampling period. The closest USGS gauging station is located on the South Fork River above Twin Creek near Hungry Horse, MT (12359800). The average annual peak discharge is 23, 300 cfs and the greatest annual peak discharge ever recorded was 50,900 cfs on June 8, 1964. Summer 2011, peak annual flow occurred June 8, 2011 and was 25,600 cfs. The average flow during the sampling period was 1,250 cfs and depth of water was 6.1 feet (USGS gauging station, South Fork above Twin Creek near Hungry Horse, 12359800).

Due to a La Nina condition, winter and spring 2011 precipitation led to an above average snowpack. This resulted in a hydrograph which peaked later than normal. Large amounts of woody debris were moved / deposited and channel morphology was dramatically altered during this time.

2.4 Soils

Soils are mostly formed from residual and colluvial materials eroded from Belt rocks or from materials deposited by glaciers, lakes, streams, and wind. In many areas, soils formed by glacial till are generally loamy, with moderate to high quantities of boulders, cobbles, and gravels. Although soils within the mountainous regions vary widely in character, most mountain and foothill soils on steep slopes are well drained. Soils tend to have high soil-moisture holding capacity, high fertility, low strength, and high erodability. Rocky outcrops are common (Ducharme et al., 2001). No soil map exists for the wilderness portion of the South Fork River.

2.5 Climate

The climate of the Flathead River Subbasin is strongly influenced by pacific maritime air masses. In winter, moist air dominates, with low-lying, gray clouds in the valleys and mild temperatures ranging from 15- 30 ℉. High-pressure systems occur during the summer causing clear skies and temperatures ranging from the 70-90 ℉ with occasional, short, hotter periods

(Ducharme et al., 2001). Afternoon thunderstorms are common throughout the summer. Fall repeats the unsettled weather pattern of spring; clear skies alternate with periodic cloudy weather (Zackheim 1983). The Swan Mountains, which are west of the South Fork, receive between 80 and 100 inches of precipitation annually, mostly in the form of snow. The mountains to the east of the South Fork receive between 30-60 inches of precipitation annually, mostly in the form of snow (USGS west and northwest regions precipitation map 1941-1970). Mountain ridges have snowpack's of up to 20 feet or more. Valleys annually receive an average of between 15 and 20 inches of precipitation. The rainiest months occur in May and June (Finklin, 1986). Winter snowfalls seldom exceed six inches at a time in the valleys; frequent winter thaws usually keep total valley snow cover at under a foot.

2.6 Vegetation

The South Fork drainage exists within the northwestern forest region of Montana. This region is bounded on the east by the Continental Divide, on the north by British Columbia and on the west and southwest by Idaho and the crest of the Bitterroot Mountains (Arno, 1979). Western and Mountain Hemlock, Fir, Yew, and White Pine are the predominant tree species at higher elevations (> than 3,500 ft). Grasslands exist below 3,500 feet. A variety of habitats exist due to mountains. 90% of the land in the region is potentially forested, and forest covers even the lowest elevation valleys (Arno, 1979).

2.7 Sampling Strategy

Data collection was to commence at the headwaters of the South Fork at the confluence of Youngs and Danaher Creek, and end at Mid Creek approximately 22 miles above Hungry Horse Reservoir (Fig. 3). 31 tributaries were to be sampled and the South Fork River above each tributary. Data were collected August 16-19th, 2011 towards the end of the baseflow recession curve, by raft, from shore, and while standing in the water. The hand held YSI Model-30 Salinity, Conductivity and Temperature Probe was used to collect electrical conductivity (mS·cm-1) and temperature data (°F). For each site one measurement was taken in the thalweg, approximately one foot below the surface of the water. The probe was inserted into the South Fork's thalweg 0.2 miles upstream of where a tributary entered. Each of the tributaries were sampled 0.2 miles upstream from where they entered the South Fork. The YSI meter was calibrated before the trip using a potassium chloride standard (0.13g KCl). A one point calibration was done, as instructed in the manual.

PACFISH/INFISH Biological Opinion Effectiveness Monitoring Program (PIBO-EM) data supplemented my original dataset. The PIBO-EM Program for aquatic and riparian resources was developed in 1998. The primary objective of this program is to determine whether priority biological and physical attributes, processes, and functions of riparian and aquatic systems are being degraded, maintained, or restored in the PIBO-EM area (Montana, Oregon, Washington and Idaho) (Heitke *et al.*, 2009). From 2001-2009 a variety of biological and physical attribute data from rivers within the Upper Columbia River Basin were collected. Water chemistry data were usually collected towards the end of the falling limb of the hydrograph, June-September, and therefore PIBO-EM data were assumed to represent baseflow conditions (Billet et al., 1996). PIBO-EM data metrics were defined and collected based on methods outlined in the PIBO-EM manual (Heitke *et al.*, 2009).

To identify geologies within the South Fork, the United States Geologic Survey's (USGS) Geologic and Structure Map of the Choteau 1°-2 ° quadrangle, of western Montana (Mudge et al., 1982) and companion map unit description compilation database were used (Causey et al., date). For each map unit in the compilation database, the minimum and maximum age of the formation; stratigraphy and mineralogy; and list of information sources is given.

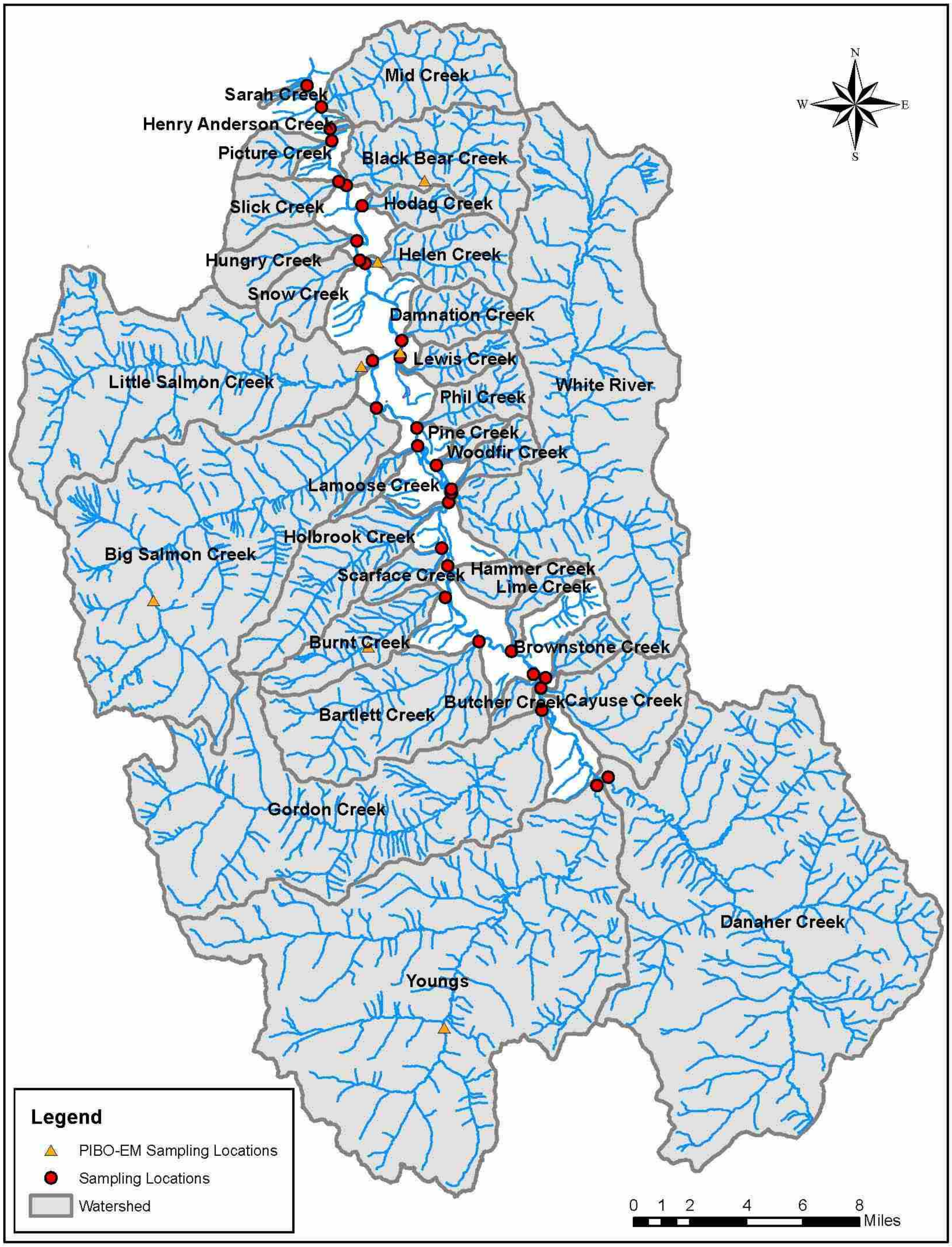


Fig. 3: Map displaying the study area, sampling locations and watershed boundaries of each tributary.

2.8 Data Analysis

To answer my question, unpaired T-test's, ANOVA's, a linear regression and geospatial mapping were utilized. A linear regression was used to determine if watershed size determined electrical conductivity. An ANOVA compared mean electrical conductivity values between different sized watersheds (0-5mi^2; 5-10 mi^2; 10-15 mi^2; 15-25 mi^2; 50-100 mi^2; >100 mi^2). To address the effect of the South Fork Fault on electrical conductivity, east and west bank conductivity values were compared using an unpaired T-test.

Small watersheds (<70 mi^2) were analyzed (ANOVA and figures) to identify a relationship between the lithology that covered the greatest percentage of the watershed and electrical conductivity. Watershed area (mi^2) and the area covered by each lithology in each watershed (mi^2) were calculated. From these two values, percent cover of each geologic unit within a watershed was determined. From this analysis, lithologies were ranked as either producing high (150-300 mS·cm-1), medium (70-150 mS·cm-1), or low (< 70 mS·cm-1) electrical conductivity values. My rating system was verified by past studies which identified the composition (minerals and relative abundance), texture (size, shape and sorting of grains and crystals), and dissolvability of different rocks (Davis, 1964; Hem, 1985; Meybeck, 1987; Bluth and Kump, 1993; Cocker, 1999; Grieve, 1999; Clow and Sueker, 2000; Oguchi, 2000; Wanty et al., 2009). Geologies identified as producing high, medium or low conductivity values were used to predict electrical conductivity values for larger watersheds (>70 mi^2). Electrical conductivity values that did not follow predictions based on geology were investigated one watershed at a time using pie charts. Pie charts were used because they provided a visual means to distinguish between high, medium and low conductivity geologies and they included a numerical value to analyze.

3. Results

Between August 16-19th 2011, 24 tributaries were sampled and 7 were dry. Reach length was 38 river miles. The PIBO-EM database provided eight additional electrical conductivity measurements, collected from five separate tributaries within the study site. Sampled tributary watershed sizes varied from 0.21 to 131 mi^2. Tributary conductivity measurements ranged from 40 to 290 mS·cm-1. South Fork River conductivity values ranged from 132 to 198 mS·cm-1. Longitudinally, the South Fork Rivers' electrical conductivity values exhibited diurnal fluxes, but overall decreased with distance from the headwaters (Fig. 4).

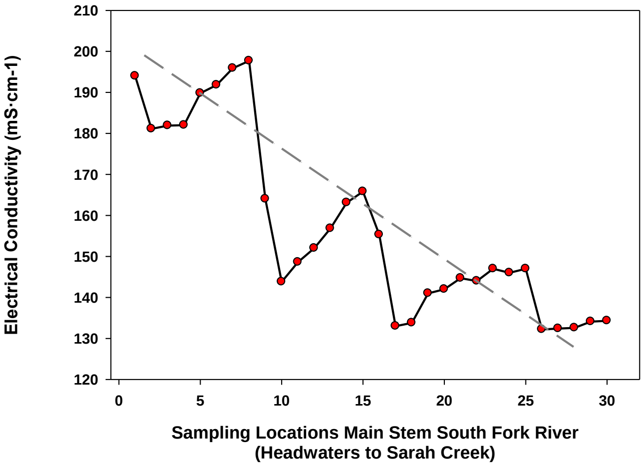


Fig. 4: Longitudinal profile of South Fork Rivers' electrical conductivity decreasing with distance from the headwaters.

3.1 Watershed Size and Electrical Conductivity

Mean electrical conductivity values for six different watershed sized groups (0-5mi^2; 5-10 mi^2; 10-15 mi^2; 15-25 mi^2; 50-100 mi^2; >100 mi^2.) are statistically different (P-value:0.0007) (table in Appendix B). However, a weak relationship exists between watershed size and electrical conductivity (R^2 value: 0.099, P-value: 0.073) (Fig. 5).

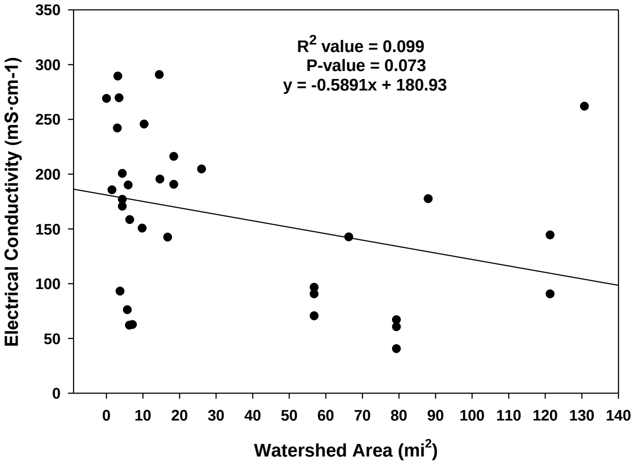


Fig. 5: Linear regression depicting the weak relationship between watershed size and electrical conductivity.

3.2 Structural Influences on Electrical Conductivity

The South Fork Fault runs parallel with the South Fork River on the east bank (Fig. 2). Electrical conductivity values are statistically greater east of the fault (mean: 206 mS·cm-1; P-value: 0.004) when compared to those west of the fault (mean: 120 mS·cm-1) (Fig. 6 and Fig. 7).

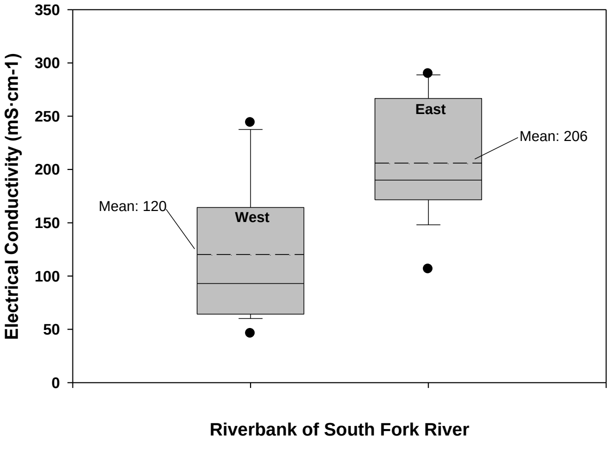


Fig. 6: Comparing electrical conductivity values east and west of the South Fork Fault. East side of valley produces higher electrical conductivity values than the west side.

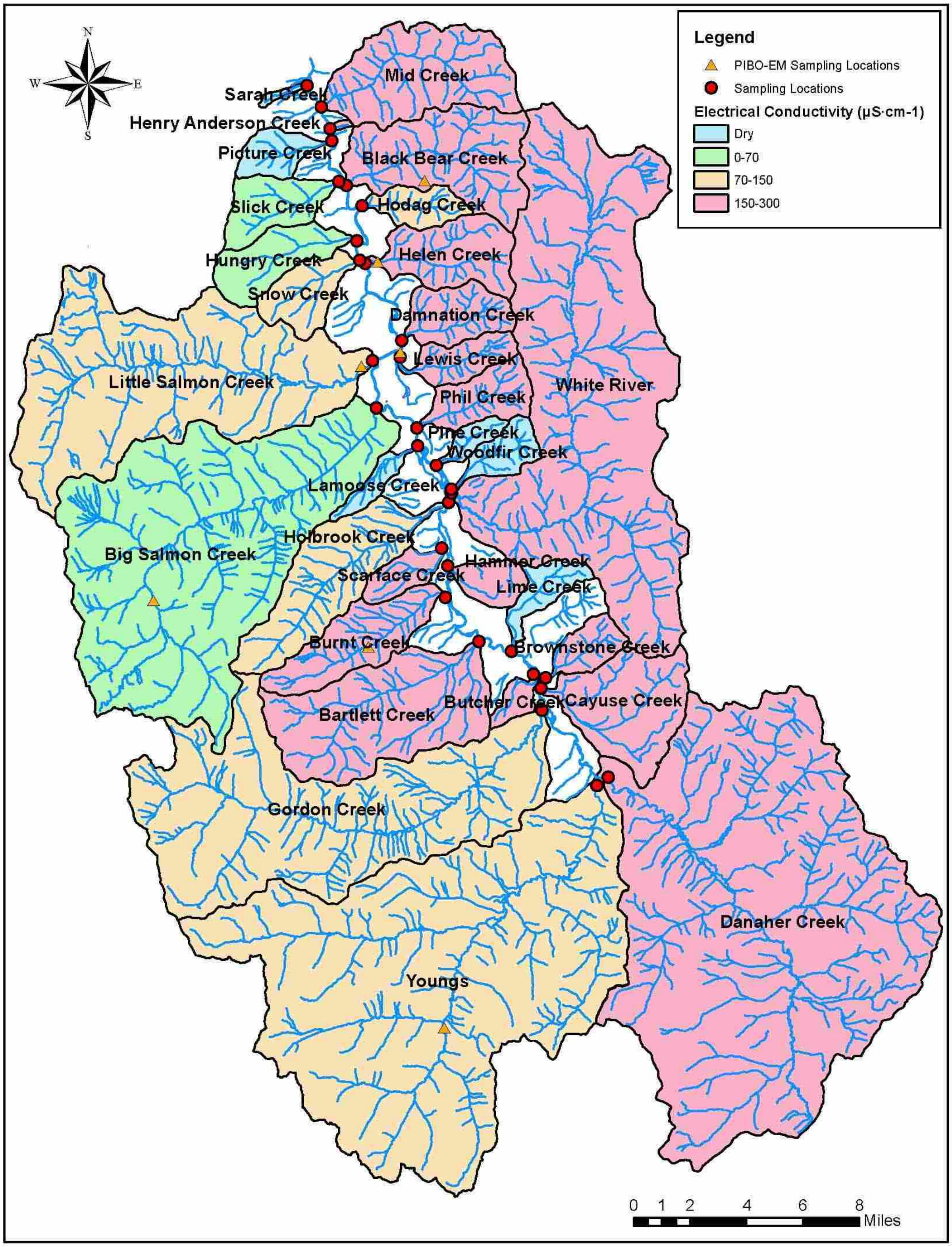


Fig. 7: Map displaying electrical conductivity groups in South Fork watersheds. High electrical conductivity values (150-300 mS·cm-1) mostly occur east of the South Fork Fault.

3.3 Lithological Influences on Electrical conductivity

To identify lithological influences on water chemistry small watersheds (<70 mi^2) were analyzed first. Of the 24 tributaries sampled, 20 of them are less than 70 mi^2. The number of map units per watershed ranges from 2-12, with the average being eight. The geologic map unit that covers the greatest percentage of each watershed was assumed to be the one geology influencing water chemistry the most and used in most analyses. A scatter plot of geology, electrical conductivity and watershed size shows geologic map unit 1623 (mix of argillite, siltite, dolomite, limestone) producing high conductivities; 1624 and 1625 (mostly shale) medium ranged conductivity values; and 1620 (quartz, argillite, siltite) low values (Fig. 8) (see Appendix A and Appendix D for map unit descriptions). Burnt Creek, Phil Creek and Holbrook Creek were anomalies and produced high conductivity values despite unit 1620 covering the greatest proportion of the watershed (Fig.10).

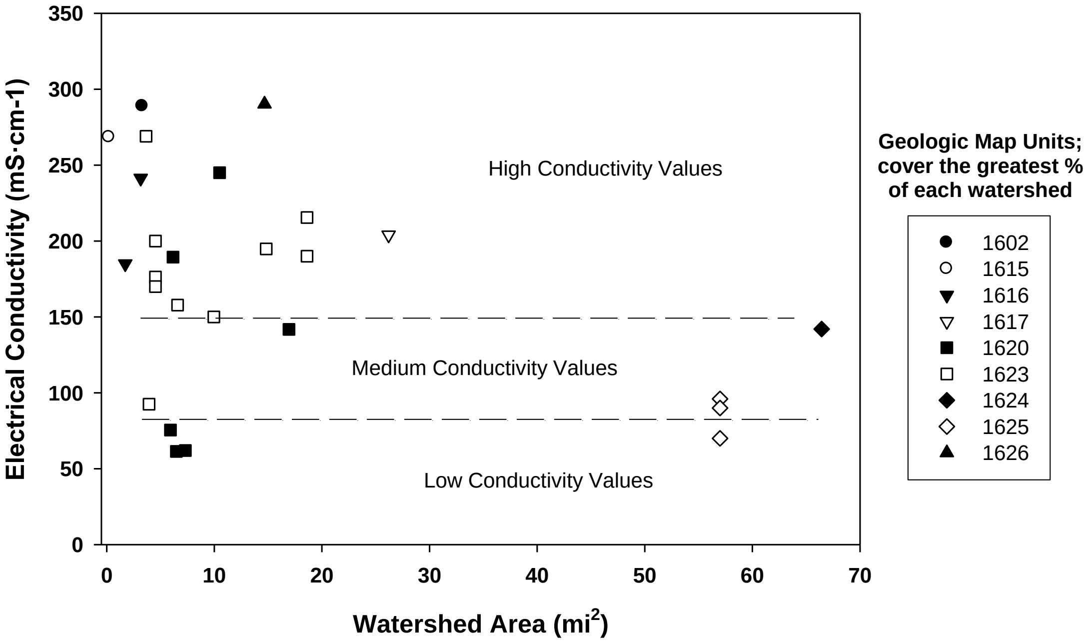


Fig. 8: Comparing geologies and electrical conductivity values for all watersheds < 70 mi^2. 1623 = high values; 1624/1625 = medium values; 1620 = low values.

Electrical conductivity values were statistically different between geologic map units 1623, 1624, 1625, and 1620 (P-value: 0.04) (Fig. 9 and table of data Appendix C). Information such as composition (minerals and relative abundance), texture (size, shape and sorting of grains and crystals), and dissolvability of different rocks gathered from past studies, geologic maps and my findings allow me to predict based on rock type, the range of conductivity values produced (conductivity/geology rating scale –Appendix D).

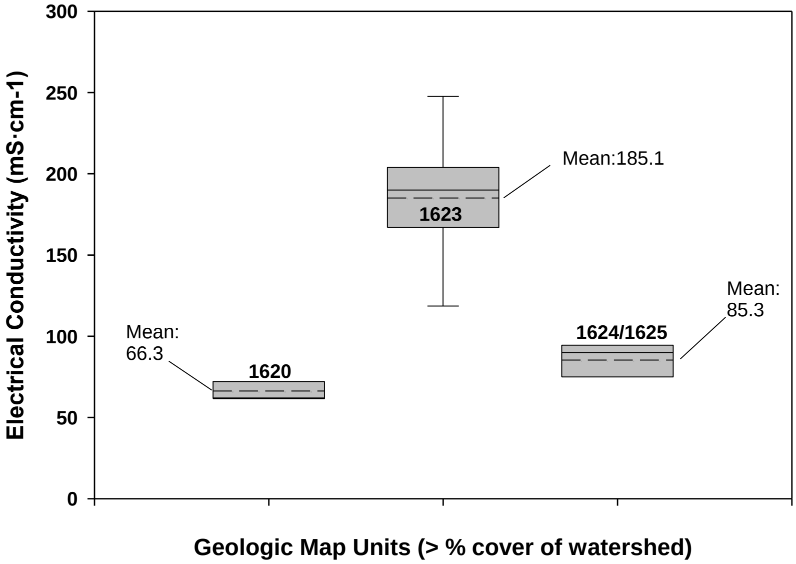


Fig. 9: Comparison of geologic map units 1620, 1623, 1624/1625 electrical conductivity. Outliers removed for 1624/1625 and 1620, no outliers for 1623.

The geology/conductivity rating scale (Appendix D) specifically designed from small watersheds in the South Fork was applied to larger watersheds (> 70 mi^2). Fourteen geologies on average exist within a large watershed. Based on the scatter plot (Fig. 10) three of four large watersheds electrical conductivity measurements did not match predictions based on the geology type that covered the greatest percentage of the watershed. Danaher Creek's conductivity value is higher than expected for unit 1620 (quartz, argillite, siltite); Youngs and Big Salmon Creeks' conductivity is lower than expected for unit 1623 (mix of siltite, argillite, dolomite, limestone).

A total of six watersheds, three small and three large, have conductivity values that do not follow trends noted in scatter plots for smaller watersheds.

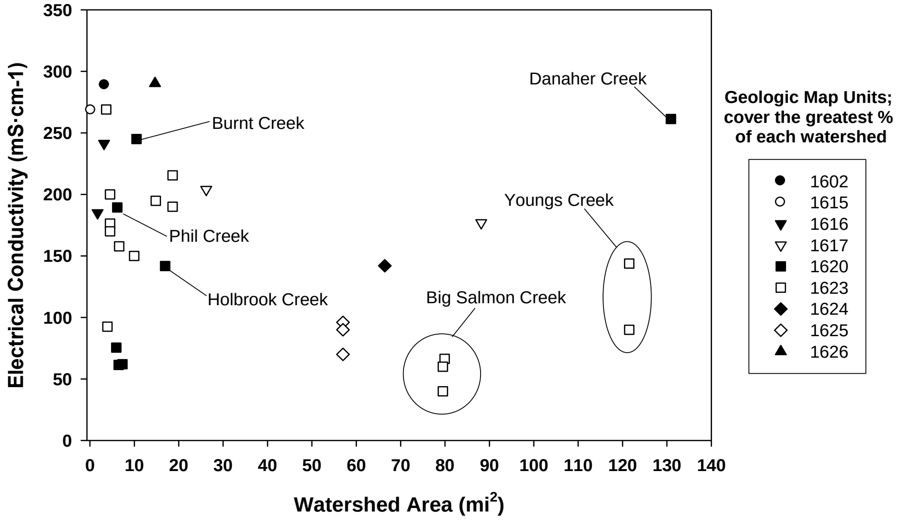


Fig. 10: Comparing geologic type and electrical conductivity for all watersheds. Six watersheds where conductivity values didn't match predictions or other trends are circled.

Breaking down the geologic percent cover of the six watersheds via pie charts shows that for certain drainages the geology covering the greatest area may not determine electrical conductivity. Other geologies within the drainage cumulatively produce high, medium or low conductivities that overpower or lessen the intensity of the most prevalent geology (Fig. 11). For example, in Danaher Creek, unit 1620 (quartz, argillite, siltite) is the most prevalent geology. Based on the analysis of small watersheds unit1620 produces low conductivity values (average: 66 mS·cm-1), therefore it was predicted Danaher would produce low conductivity. However, if one adds up the total area covered by others rocks in the drainage; high conductivity rocks cover more area than unit 1620. Thus Danaher Creeks' electrical conductivity (261 mS·cm-1) is higher than predicted. Burnt Creek's conductivity is similar to Danaher Creeks and can be explained the same way. Big Salmon Creek is also similar to Danaher Creek, except that medium and low conductivity rocks when combined overshadowed unit 1623, a high conductivity rock (mix of argillite, siltite, dolomite, limestone; 182 mS·cm-1). The lake within Big Salmon watershed, could also explain the lower conductivity value.

Youngs Creek demonstrates how some geologies can neutralize other geologies. Two data points exist for this tributary; one from this study and one from PIBO-EM. The PIBO-EM value (90 mS·cm-1) was collected near the headwaters. Nearby geology tends to produce conductivity values in that range, therefore the data point was not included in this analysis. My conductivity value is slightly lower than expected (144 mS·cm-1), based on unit 1623 covering the most area. Equal ratios of high and medium conductivity rocks exist in the watershed, and when combined their waters produce medium range conductivity (144 mS·cm-1). Phil Creek and Holbrook Creek are similar to Youngs and can be explained the same way; however they are predicted to have low conductivity.

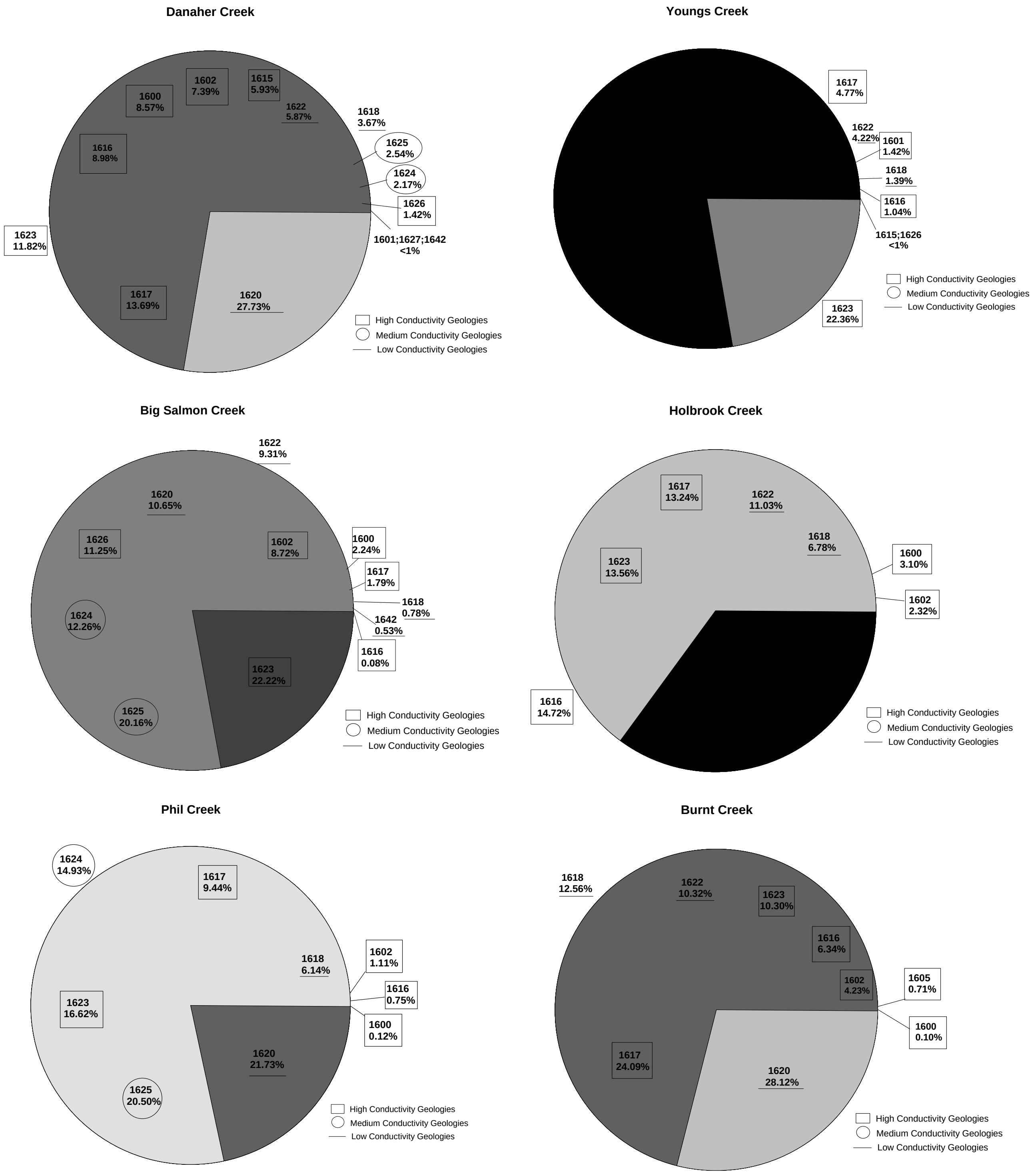


Fig. 11: Evaluation of six watersheds where electrical conductivity measurements didn’t match other geology/conductivity relationships identified in smaller watersheds.

4. Discussion

Electrical conductivity measurements and geospatial patterns in the South Fork suggest lithology, structure, stratigraphy and area of exposure influence the ionic strength of surface water. The effects of stratigraphy, structural features (faults, joint, fractures, bedding planes), and lithology (mineral composition of rock, porosity, surface are to volume ratios), on surface water electrical conductivity are discussed in more detail in the following sections.

4.1 Stratigraphy and Electrical Conductivity

Proterozoic and Paleozoic rocks dominate the South Fork watershed and include argillite, siltite, dolomite, quartzite, sandstone, and limestone (Winston and Link, 1993). Cenezoic fluvial, glacial and lacustrine deposits also occur, which are conglomerates of the fore mentioned rocks. The oldest exposed rocks in the South Fork are Belt sedimentary rocks (Winston and Link, 1993). Many formations exist within the Belt sedimentary basin; however Belt rocks can be lumped into two broad groups. The older group consists of Belt rocks deposited under deep, quite water and consist of varying layers of mudstone, sandstone, limestone and some thin quartzite lenses. Carbonaceous turbidites up to 10 km are also present in spots. The younger group is made of rocks deposited in very shallow water or on dry land (Alt and Hyndman, 1995). Rocks from this group include thick sequences of colorful argillite, thinner intervals of carbonate, sandstone and some quartzite. Both groups contain the remains of primitive plants and bacteria.

Rocks from Proterozoic time are exposed in the South Fork study site; however east of the River Paleozoic rocks cover large proportions of Proterozoic rocks. During Paleozoic time relative sea-level change resulted in transgressions (landward retreat of the shoreline) and regressions (seaward advance of the shoreline) and thus unconformities abound and thick layers of sandstone, dolomite, shale and limestone were deposited on top of Belt sedimentary rocks (Alt and Hyndman, 1995). Glaciers appear to have removed Paleozoic rock layers from the top of the Swan Mountains exposing Belt sedimentary rocks. According to small watershed lithology/conductivity analysis Belt sedimentary rocks produce medium to low electrical conductivity values and Paleozoic rocks produce high electrical conductivity values. Electrical conductivity values are greatest east of the South Fork River where Paleozoic rocks cover a large portion of the South Fork watershed. Combined, lithology and stratigraphy influence electrical conductivity.

During Pleistocene time glaciers grew and then melted during interglacial periods (Alt and Hyndman, 1995). 10,000 years ago the Cordilleran ice sheet covered the South Fork drainage. The southeastern edge of the ice sheet is the eastern portion of the South Fork watershed. The ice sheet left behind moraines made of till, which is a conglomerate of different sized boulders, cobbles, pebbles, sand and clay. Melting glaciers filled valley bottoms with sediments similar to fluvial deposits. Lakes were created from moraine dams (Alt and Hyndman, 1995). The South Fork fluvial plain and tributary streambeds are composed of glacial, alluvial and colluvial deposits, which vary is composition and porosity. Moderate electrical conductivity values of the South Fork main stem probably result from the mixing of surface, ground and hyporheic waters within the fluvial plain and a variety of minerals within glacial/fluvial deposits.

4.2 Structure and Electrical Conductivity

All rock units in the South Fork experienced approximately the same stress history during deformation events, but their physical response to the stress varied according to lithology. Some rocks became densely fractured, whiles others deformed in a more plastic way (Alt and Hyndman, 1995). In the South Fork, structural features (faults, fractures, joints, bedding planes) altered flow paths, permeability and residence times of groundwater. Faults are breaks in rocks along which there has been movement (Stone, 1999). Their impact on groundwater depends on the material of the rock and the nature of the fault. Porosity can increase or decrease, depending on lithology (Stone, 1999). Fractures are vertical orientated breaks, which are the result of overlying or adjacent rocks being removed by erosion (Stone, 1999). Fractures are similar to faults in that the material they exist in determines their hydrologic significance. The Cordilleran ice sheet and other mountain glaciers created many fractures and joints in the South Fork watershed. Joints are smooth fractures that break or interrupt the continuity of rock, but along which there has not been appreciable movement (Stone, 1999). Joints provide the main source of porosity for water movement in well consolidated rocks. Bedding planes are surfaces separating different layers of sedimentary rock (Roberts, 1996). All these features provide secondary porosity, which will influence the dissolution of solutes.

The South Fork normal fault, which runs parallel with the east bank of the South Fork River, was created when the crust stretched apart and the hanging wall (western portion of drainage) moved downward relative to the footwall (eastern portion of the drainage). Today, the east side of the valley is steep. For eastern tributaries, the distance from headwaters to the confluence of the South Fork is almost half the distance of tributaries west of the fault. Small quantities of a variety of rocks are exposed over a short distance. West of the fault, land slopes gradually down to the river. Groundwater flows a greater distance through a variety of rocks. Orientation of a fault to groundwater flow and rock composition influences the occurrence of groundwater (Hurlow, 1999). Water will usually follow the path of the fault (Hurlow, 1999). Within the South Fork fluvial plain, water potentially runs parallel with the South Fork fault.

Moderate electrical conductivity values in the main stem South Fork probably are a result of the parallel flow mixing surface, ground and hyporheic waters.

If a fault is orientated perpendicular to groundwater flow the fault can juxtapose permeable and impermeable materials (Stone, 1999; Hurlow, 1999). If permeable material lies on the upgradient side of the structure, the fault acts as a barrier to groundwater flow. If permeable material is very thick and lies on the downgradient side of the fault, groundwater may cascade down the fault (Stone, 1999). Directly east and west of the South Fork fault rock layers varying in porosity could be offset. I did not determine the porosity of different lithologies or state how or where water is flowing. However, I hypothesize that the elevated electrical conductivity values east of the fault are a result of the fault increasing hydraulic conductivity and surface area of rock exposed to the dissolution powers of groundwater.

The hydrologic influence of fractures and joints depends on the nature of the material in which they occur. They may serve as preferred pathways for infiltration, and ultimately recharge (Stone, 1999). In nonbrittle rocks made of unconsolidated sediments the joints will not be open, and they may have little hydrologic impact (Stone, 1999). Glacial, alluvial and colluvial deposits probably have few fractures and joints. Brittle rock joints are more open and contribute to porosity (Stone, 1999). In the South Fork, sedimentary rocks might have more fractures and joints, and if interconnected hydraulic conductivity would increase. Similar to faults, the more joints and fractures a rock has, the greater the hydrologic conductivity. Increased permeability increases the rate of flow and the amount of rock exposed to groundwater dissolution.

Faults, fractures and joints are rocks responses to physical stress and vary depending on lithology and stratigraphic location. The density and size of these structures, bedding planes, and chemical makeup of each rock varies within the South Fork watershed and so a variety of microgeochemical environments exist within the study site.   Data suggests that the South Fork fault and the area of exposure due to stratigraphy are two of the greatest determinants of electrical conductivity in the South Fork watershed. Smaller structures may also influence conductivity, but their effects are unknown.   With this study I was unable to determine the density or size of structure required to significantly alter electrical conductivity.

4.3 Lithology and Electrical Conductivity

Electrical conductivity values in the South Fork demonstrate how a rock's chemistry, porosity and extent of coverage can elicit a unique geochemical signature based on dissolved ions and trace metals in solution. Rocks within the South Fork are composed of a variety of minerals that differ widely in their stability toward, or solubility in, water. Small watershed analysis suggests ionic strength of water is related to lithology. Porosity is the percentage of a rock that is void of material (Fetter, 2001). Porosity can change with time; intergranular spaces may expand due to the dissolution of minerals or fill in with fine sediment. The ionic strength of water is closely related to rocks porosity. The following two sections explain how the South Forks' main rock types: sandstone, argillite, siltite, shale, dolomite, limestone, and quartzite might influence electrical conductivity.

4.3.a Sandstone, Limestone, Dolomite, Shale, Argillite, Siltite

Sedimentary rocks cover a large portion of the South Fork drainage (Winston and Link, 1993).   The rate of mineral dissolution and ionic strength of water flowing through sedimentary rocks varies greatly. The grains which make up the rock determine its porosity. If a rock is made of granular materials (sedimentary rocks), porosity and permeability are likely primary, meaning intergranular flow. If the rock is made of crystalline materials (igneous or metamorphic rocks) porosity and permeability is secondary, and water will follow fractures and cracks (Stone, 1999). Sedimentary rocks can be classified as resistates, hydrolyzates, precipitates, and evaporates (Hem, 1985).

Sandstone is a resistate, which is made up of relatively unaltered fragments of rocks such as quartz, feldspar, organic materials or carbonates (Wanty et al., 2009). Most sandstone contains cementing materials deposited on the grain surface or within the openings among the grains. Cementing materials include calcium carbonate, silica, and ferric oxyhydroxide (Hem, 1985). Sandstone's porosity depends on the dissolvability of its cement, grain size, shape and size sorting. If the grains are well sorted, permeability will be greater (Fetter, 2001). Sandstone has been found to create a lot of calcium, due to dissoulution of calcium carbonate (CaCo3) or gypsum (CaSO4), depending on composition of sedimentary cement (Oguchi et al., 2000). Precipitation of cementing materials, adsorption and ion exchange all affect major and minor constituents within water (Hem, 1985). Many resistates are permeable and easily receive and transmit solutes, however the ionic strength of water flowing through sandstone usually depends on the cementing materials (Hem, 1985). Calcium carbonate is quick to dissolve, while silicate minerals weather slowly (Clow and Sueker, 2000).

In the South Fork, the porosity of sandstone and the dissolution of its cementing materials appear to create high electrical conductivity values (150-300 mS·cm-1). Unfortunately, the geologic map unit description just lists rocks within a formation. This means sandstone is lumped with other carboniferous rocks, which dissolve easily and produce high electrical conductivity values. With this study it is hard to determine the ionic strength of water coming just from sandstone. The volume of different sandstone cementing materials would provide clues. Overall, the ability of sandstone to influence electrical conductivity values in the South

Fork appears low, but structural features and easily dissolvable cementing materials could create pockets of high conductivity.

Shale and other fine- grained sedimentary rocks are hydrolyzates. These rocks are made of clay minerals or fine-grained particulate matter and are usually cemented together with varying materials, such as silica. Hydrolyzates are porous, but do not transmit water readily because openings are very small and are poorly connected (Hem, 1985). Siltstone and shale were hydrolyzates, but metamorphic processes changed them into argillite and siltite. The heat and pressure which formed argillite and siltite further decreased the rocks primary porosity, slowing the flow of water that can dissolve constituents. In the South Fork, argillite and siltite produced moderate electrical conductivity values and shale produced high values. However, structural features in the South Fork provide avenues of rock dissolution for both metamorphosed rocks and shale. Depending on the location argillite, siltite and shale could be minimally fractured or completely shattered. Faults, fractures and joints will increase the rocks porosity and the rate of dissolution.

In the South Fork, the mineral composition of argillite, siltite, and shale plus secondary porosity create moderate to low electrical conductivity values. Shale produced high conductivity values, but was usually associated with other easily dissolvable rocks such as limestone and dolomite. Overall, argillite and siltite are more resistant to erosion and will not influence the ionic strength of water as much as shale. Drainages dominated by argillite and siltite will produce low electrical conductivities. However, medium to high values can occur if the total ion output of other geologies is high.

Limestone and dolomite are well-known examples of sedimentary rocks of chemical or biochemical origin (Fetter, 2001). Limestone lacks silicate minerals (Hem, 1985; Kyung-Seok

Ko et al., 2009). Limestone is mainly composed of calcium carbonate and calcium-magnesium carbonate (dolomite). Dolomite is composed of magnesium and dolomite the mineral (Oguchi et al., 2000). When limestone produces high levels of magnesium, it is possible the limestone is dolomitic (Oguchi et al., 2000). Porosity is generally similar to hydrolyzates, though the ability of precipitates to dissolve quickly leads to greater porosity with time. Reported values of percent porosity for limestone and dolomite range from less than 1% to 30% (Fetter, 2001). Carbonate bearing minerals such as calcium carbonate, halite, gypsum, and pyrite are major sources of anions (Hutchins et al., 1999). Calcium and carbonic acid dominate in streams near carbonate-bearing limestone (Hutchins et al., 1999). In the South Fork limestone and dolomite produced the highest electrical conductivity values due to their increased porosity and chemical composition.

4.3.b Quartzite

Heat and pressure altered the physical structure of sandstone to produce quartzite (SiO_2). Quartzite is usually composed of quartz grains and appreciable amounts of aluminosilicate minerals such as feldspars and micas (Freeze and Cherry, 1979). Silica and quartz are not easy to dissolve due to the strong chemical bond between silicon and oxygen. Quartzite is a dense rock that restricts water movement to fracture zones. This prevents contact of groundwater with surface areas of minerals as large as is normally expected in sandstone (Hem, 1985). The opportunity for water to dissolve solutes from quartz is small, and therefore water from quartzite usually contains low concentrations of solutes (Hem, 1985). If silica does dissolve, it does not behave like charged ions, nor like a typical colloid. Freeze and Cherry (1979) state groundwater is usually undersaturated with amorphous silica, however it is usually always present (Davis, 1964).

In the South Fork, small watershed assessment found quartzite geologies produced low electrical conductivity values. This probably occurred because quartz is very resistant to attacks by water (Hem, 1985). Watersheds produced low conductivity values if quartzite geologies covered greater than 50% of the watershed. If less than 50% was covered, other geologies in the watershed, when combined usually increased electrical conductivity to moderate or high levels.

Conclusion

Overall, geologic map units with limestone and dolomite produced the highest electrical conductivity values in the South Fork (150-300 mS·cm-1). Map units with shale tended to produce medium conductivity values (70-150 mS·cm-1). Argillite and siltite produced low electrical conductivity values (0-70 mS·cm-1), but medium to high values when mixed with more carboniferous rocks. Units with sandstone and quartzite produced low electrical conductivity values (0-70 mS·cm-1). When carboniferous sedimentary geologies cover more that 50 % of a watershed; high to medium electrical conductivities occur. If quartzite and other silica based rocks cover 50% or more of a watersheds; low electrical conductivity values occur. Sometimes, the geology covering the greatest area may not always determine electrical conductivity. If the one geology which covers the greatest area in a watershed covers less than 50 %, other geologies within the drainage cumulatively appear to produce high, medium or low conductivities that overpower or lessen the intensity of the most prevalent geology. Lithology, porosity, structural features, groundwater flow rate and extent of cover all will influence electrical conductivity. However, lithology and the South Fork Fault appear to be the major two electrical conductivity determinants in the South Fork watershed.

Other factors not addressed in this paper which influence electrical conductivity are precipitation, the hydrologic landscape, surface-ground-hyporheic water interactions, plant cover, aquatic biota, and nutrient cycling. Localized or regional conductivity patterns are created by these factors. The significance of the other factors depends on the watershed, but is usually small (Hem, 1985). In the South Fork drainage, mountains that form the western boundary of the watershed receive twice as much precipitation than the mountains along the eastern boundary. Rainfall is dominated by sodium (Hutchins, date). Increased precipitation also means more water to dilute solute concentrations. Combined, these two factors could cancel the effects of each other, and potentially have very little influence on conductivity. With this study, I was unable to identify the quantity of precipitation entering the system or its chemical composition. This is an area of future study.

The hydrologic landscape creates pockets of varying electrical conductivity values. Studies have shown that concentration of solutes can be determined by different physical features (Hutchins et al., 1999; Clow and Sueker, 2000; Oguchi et al., 2000). Headwaters drain smaller areas and are less influenced by regional groundwater's (Winter, 2001). Headwaters steep tallace slopes lead to short water residence times. Smaller watersheds represent lithological influences the best and are usually less diluted. Riverine landscapes are dominated by surface-ground-hyporheic water interactions (Ward and Stanford (1989a); Woessner, 2000; Winter, 2001). Within the fluvial plane water residence times vary depending on proximity to the stream. The large amount of water in the fluvial plane dilutes incoming groundwater (Winter, 2001) and conductivity values usually represent the watershed average. Glacial deposits become hummocky landscapes that vary in hydraulic conductivity (Winter, 2001). If cracks and pores are filled in with fine sediment, porosity can be slow. However, if cementing materials are easily eroded, porosity will increase with time (Winter, 2001). Comparing electrical conductivity values from different physical features or locations in the South Fork watershed (headwaters v. confluence) is another area for future study. Conductivity geospatial patterns may arise that will aide managers in locating ideal habitat for certain aquatic biota.

Plant cover, nutrient cycling and aquatic biota all potentially influence electrical conductivity. According to Vannote et al. (1980) the river is connected from headwaters to ocean and along this gradient food and energy is used, recycled and transported downstream.

Plant cover in the headwaters limits allochthonous food sources, and autochthonous food, if it blocks out the sun. Plants also decrease soil erosion and decrease water volume during the day due to evapotranspiration. Periphyton, bacteria, diatoms, algae, macroinvetebrates and fish all depend on these food sources. Nutrients and minerals released from these organisms all affect electrical conductivity.

All these factors plus lithology, stratigraphy, area of cover, and structure create the South Fork Rivers unique geochemical signature. Not all factors are equal and some will over power others. In the South Fork the two main determinants of electrical conductivity appear to be lithology and structure. Limestone and dolomite produce high electrical conductivities, shale medium conductivities and quartz, siltite, argillite low conductivities. In general, electrical conductivity is greater east of the South Fork Fault. The geology that covers the greatest percentage of a watershed may determine the drainages' conductivity, however all geologies and their percent of cover should be considered when no one geology appears to dominate. This study generally assessed surface groundwater interactions in the South Fork watershed and in doing so, demonstrated how electrical conductivity, lithology and structure can simplify complex hydrologic systems.

Appendix A: Description of Geologic Map Units within South Fork Watershed Study Site (Causey et al., 2005).

Geologic Map Unit	Map Unit Name	Min Age	Max Age	Description
1600	Alluvial and Colluvial Deposits	Holocene	Pleistocene	Unconsolidated stream-laid sand, gravel, and silt, bouldery, poorly to moderately well sorted. Includes alluvial fan, slope wash, colluvial and glacial outwash deposits.
1601	Landslide Deposits	Holocene	Holocene	Mostly rock debris, locally coarse angular rock fragments in silt or clay matrix. Forms hummocky topography. Produced by rockfall- and rockslide-avalanches, slump, and earthflow.
1602	Glacial Deposits	Holocene	Pleistocene	Drift, heterogeneous mixture of rock fragments in silty clay matrix. Forms hummocky topography. Includes deposits from alpine and continental glaciations; as much as 100 m thick except in Swan River valley where thickness of mostly sand and gravel deposits exceed 300 m.
1605	Lacustrine Deposits	Miocene	Oligocene	Gray, yellowish-gray, gray-brown, sandy silt, silt, clay, shale, marl, and some poorly sorted conglomerate; locally thin coal and carbonates. Locally includes wood and leaf fragments, insects, fish, gastropods, pelecypods, and ostracods.
1615	Castle Reef Dolomite and Allan Mountain Limestone, undivided	Late Mississippian	Early Mississippian	Mississippian rocks are the main cliff former in the eastern part of the mountains and are assigned to the Madison Group. The Madison is divided into two formations, the Castle Reef Dolomite and the Allan Mountain Limestone.
1616	Three Forks Formation, Jefferson Formation, and Maywood Formation, undivided	Late Devonian	Middle Devonian	Mainly limestone and dolomite in upper part; lower part mudstone increases downward.
1617	Devils Glen Dolomite, Switchback Shale, Steamboat Limestone, Pentagon Shale, Pagoda Limestone, Dearborn Limestone, Damnation Limestone, Gordon Shale, and Flathead Sandstone, undivided	Late Cambrian	Middle Cambrian	**Devils Glen Dolomite** (Upper Cambrian) A distinctive, thick-bedded, light-gray, finely to very finely crystalline dolomite. **Switchback Shale** (Upper and Middle Cambrian) Mostly noncalcareous, greenish-gray, thinly laminated clay shale with local thin interbeds of dolomite, limestone, sandstone, and conglomerate. **Steamboat Limestone** (Middle Cambrian) Differs in lithology between western and eastern outcrops. In the west consists of a lower shaly mudstone interval and a much thicker upper limestone interval. In the eastern exposures is about equal parts of alternating sequences of limestone and calcareous shale **Pentagon Shale** (Middle Cambrian) A clastic wedge that consists of very fossiliferous, calcareous, gray to tangray, thick-bedded platy shale that contains some platy, blue-gray argillaceous limestone in the upper part. **Pagoda Limestone** (Middle Cambrian) The upper part consists of yellowish-gray to light-yellowish-brown, thin- to thick-bedded dolomitic limestone and some dolomite overlying very thin bedded limestone. The lower part consists of

				grayish-green, thinly laminated to nodular clay shale with some gray-brown limestone and minor sandstone. **Dearborn Limestone** (Middle Cambrian) Composed of an upper thick limestone unit and a lower thin shale unit. **Damnation Limestone** (Middle Cambrian) Consists of medium- to dark-gray, thin- to thick-bedded, finely crystalline dolomitic limestone and limestone with laminae of grayish-orange to yellowish-gray siltstone that thicken and thin. **Gordon Shale** (Middle Cambrian) Mainly a dark-gray to gray-brown, very thinly laminated shale with a greenish tint and locally maroonish-gray beds. **Flathead Sandstone** (Middle Cambrian) Consists of thin- to thick-bedded and crossbedded, noncalcareous yellowish-gray, poorly sorted, poorly indurated, fine- to coarse-grained quartzose sandstone with scattered quartz pebbles
1618	Garnet Range Formation	Middle Proterozoic	Middle Proterozoic	Olive green to very dark greenish gray micaceous, lensoidal and hummocky cross-stratified quartzite and argillite. Feldspar, detrital mica, and unweathered magnetite grains abound. Cross-stratified arenite.
1620	McNamara Formation	Middle Proterozoic	Middle Proterozoic	Predominantly grayish-green, interbedded and interlaminated argillite and siltite that contain thin chert laminae and chips. Oolites, stromatolites, quartzarenite, and stratabound cooper [sic] minerals present at places. Relatively thin red-bed sequences locally interbedded in the green strata. Small-scale sedimentary features include ripple marks, shrinkage cracks, scours, and cross-beds.
1622	Bonner Quartzite	Middle Proterozoic	Middle Proterozoic	Red to pink, micaceous, arkosic, cross-bedded, fine- to medium-grained quartzite containing red argillite interclasts. Tabular and trough cross-beds and climbing ripple marks common. Interbeds of red, laminated argillite and pink, planar-laminated siltite scattered throughout unit. Rests in sharp contact on Mount Shields Formation. Thickness
1623	Mount Shields Formation	Middle Proterozoic	Middle Proterozoic	Argillite and white or green siltite in upmost unit. Below are blocky, green, dolomitic, silty argillite that shows parallel-laminated graded couplets. Foot-thick carbonate beds are scattered throughout unit, as are rare salt casts. Dolomite present in small amounts.
1624	Shepard Formation	Middle Proterozoic	Middle Proterozoic	Most rocks are carbonate bearing or carbonate rich. The most characteristic lithology is green to gray, dolomitic argillite and siltite in even-parallel to wavy laminae that show graded couplets. Common interbeds a few to a few tens of feet thick include gray dolomitic limestone, stromatolites and oolites, laminated green argillite, gray argillitic siltite, and white quartzarenite.
1625	Snowslip Formation	Middle Proterozoic	Middle Proterozoic	The Snowslip generally consists of two alternating intervals that are each one hundred to several hundred feet thick. One interval consists of thinly laminated, red to purple argillite and siltite interbedded with thinly laminated green argillite and siltite. The other interval consists of couplets of greenish-gray siltite and olive argillite. Within both intervals are beds of stromatolites, arenite, and

				carbonate as layers or cement; certain characteristics of these carbonate and arenite interbeds help to distinguish the various members of the Snowslip.
1626	Helena Formation	Middle Proterozoic	Middle Proterozoic	The most carbonate-rich formation in the Belt Supergroup. Contains abundant beds of dolomite, stromatolitic or oolitic limestone, and molar-tooth limestone and dolomite, and lesser amounts of quartzarenite and black argillite.
1627	Empire Formation and Spokane Formation, undivided	Middle Proterozoic	Middle Proterozoic	Undivided only in the eastern and part of the southern outcrop area. In those areas the unit is pale-red, maroon, green, and gray siliceous argillite and siltite, with minor thin beds of poorly sorted, fine-grained quartzite. Locally in the eastern outcrop also contains some thin beds of dolomite, edgewise conglomerate, and stromatolite beds.
1642	Purcell Sills, above the Prichard Formation	Late Proterozoic	Middle Proterozoic	Mostly diorite and quartz diorite, locally minor diorite-gabbro and monzonite. Dark gray, weathers grayish brown. Widespread throughout map area.

Appendix B: Raw data and ANOVA results; comparing mean electrical conductivity values between different sized watersheds.

Raw Data:

Watershed Groups	**0-5 mi^2**	**5-10 mi^2**	**10-15 mi^2**	**15-25 mi^2**	**50-100 mi^2**	**> 100 mi^2**
Electrical Conductivity (mS·cm-1)	269.0	189.4	290.1	141.8	142.0	143.8
	185.0	157.8	245.0	215.5	176.9	261.3
	288.8	150.0	194.8	190.0	66.4	90.0
	241.3	75.5		203.9	96.0	
	176.3	62.0			40	
	92.5	61.4			70	
	268.4				60	
	170.0				90	
	200.0					

ANOVA Results:

Watershed Groups	*Count*	*Sum*	*Average*	*Variance*	*P-value*
0-5 sq mi	9	1891.3	210.14	3918.43028	0.000729
5-10 sq mi	6	696.1	116.02	3165.64167	
10-15 sq mi.	3	729.9	243.30	2272.69	
15-25 sq mi	4	751.2	187.80	1049.11333	
50-100 sq mi	8	741.3	92.66	2084.55125	
> 100 sq mi.	3	495.1	165.03	7674.06333	

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	94477.34585	5	18895.469	6.01565331	0.000729	2.571886
Within Groups	84808.35597	27	3141.0502			
Total	179285.7018	32				

Appendix C: Raw data and ANOVA results for small watersheds (<70 mi^2); comparing mean electrical conductivity values between geologic map units1620, 1623, 1624/1625.

Raw Data:

Creek Name	Watershed Area (mi^2)	#1 G Map Unit	% Cover #1 Map Unit	Aug 11' Conductivity (mS·cm-1)	PIBO-EM Conductivity (mS·cm-1)	PIBO-EM Conductivity (mS·cm-1)
Burnt Creek	10.49	1620	29	245.0		
Holbrook Creek	16.93	1620	35	141.8		
Phil Creek	6.16	1620	22	189.4		
Snow Creek	5.92	1620	75	75.5		
Hungry Creek	7.31	1620	51	62.0		
Slick Creek	6.47	1620	49	61.4		
				129.2	**Average Conductivity**	
Gordon Creek	66.44	1624	28	142.0		
Little Salmon Creek	56.99	1625	30	96.0	70	90
				99.5	**Average Conductivity**	
Brownstone Creek	3.65	1623	27	269.0		
Lewis Creek	4.53	1623	23	176.3	170	200
Damnation Creek	6.58	1623	48	157.8		
Hodag Creek	3.93	1623	34	92.5		
Black Bear Creek	18.61	1623	28	215.5	190	
Mid Creek	14.82	1623	32	194.8		
				185.1	**Average Conductivity**	

ANOVA Results:

Geologic Map Unit	*Count*	*Sum*	*Average*	*Variance*	*P-value*
1620	6	775.1	129.1833	5837.762	0.043762
1623	9	1665.9	185.1	2241.122	
1624/1625	4	398	99.5	926.3333	

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	23882.72	2	11941.36	3.82914	0.043762	3.633723
Within Groups	49896.79	16	3118.549			
Total	73779.51	18				

Appendix D: Geology/Conductivity rating scale for South Fork Watersheds Study Site. High: electrical conductivity values > 150 mS·cm-1; medium: electrical conductivity values 70-150 mS·cm-1; low: electrical conductivity values 0-70 mS·cm-1. Ratings based on analysis of smaller watersheds and past research.

Geologic Map Unit	**Conductivity Rating**	**General Geologic Description**
1600	High	Alluvial/Colluvial Deposits
1601	High	Landslide Deposits
1602	High	Glacier Deposits
1605	Med	Lacustrine Deposits
1615	High	Dolomite and Limestone
1616	High	Limestone, Dolomite, Shale and Mudstone
1617	High	Dolomite, Shale, Limestone, Sandstone
1618	Low	Argillite, Quartzite
1620	Low	Argillite, Siltite
1622	Low	Quartzite
1623	High	Siltite, Argillite, Carbonate Beds, Salt-crystal casts, Dolomite
1624	Med	Siltite, Argillite, Dolomitic Limestone
1625	Med	Siltite, Argillite, Carbonate Cement
1626	High	Dolomite and Limestone
1627	Med	Siltite, Argillite, some Bedded Quartzite
1642	Low	Quartzite and Diorite

Appendix E: Sampling Location Raw Data and PIBO-EM Location Data

Sample Order	**Creek Name**	**Elevation (ft)**	**Latitude**	**Longitude**	**River R or L**	**Watershed Area (mi^2)**
1	Youngs Creek	4727	47.4446076	-113.1836999	L	121.5
2	Danaher Creek	4721	47.4454880	-113.1833839	R	130.90
3	Gordon Creek	4671	47.4783764	-113.2254507	L	66.44
4	Cayuse Creek	4667	47.4896519	-113.2267102	R	14.66
5	Brownstone Creek	4652	47.4949849	-113.2234134	R	3.65
6	Butcher Creek	4652	47.4975426	-113.2297178	L	1.72
7	Lime Creek	4640	47.5080501	-113.2497943	R	3.62
8	Bartlett Creek	4612	47.5131323	-113.2737521	L	26.20
9	Burnt Creek	4501	47.5352203	-113.2981982	L	10.49
10	Hammer Creek	4487	47.5505124	-113.2990384	R	3.31
11	Scarface Creek	4466	47.5582472	-113.3045234	L	3.16
12	Holbrook Creek	4381	47.5832303	-113.3006489	L	16.93
13	White River	4387	47.5868650	-113.2979919	R	88.16
14	Woodfir Creek	4360	47.5899410	-113.2992339	R	3.63
15	Pine Creek	4360	47.6018929	-113.3109069	R	1.86
16	Lamoose Creek	4320	47.6118922	-113.3250690	L	2.06
17	Phil Creek	4313	47.6217863	-113.3275676	R	6.16
18	Big Salmon Creek	4266	47.6308067	-113.3576393	L	79.50
19	Little Salmon Creek	4211	47.6542356	-113.3631950	L	56.99
20	Lewis Creek	4212	47.6599095	-113.3409584	R	4.53
21	Damnation Creek	4200	47.6652145	-113.3400679	R	6.58
22	Helen Creek	4121	47.7039689	-113.3702174	R	9.96
23	Snow Creek	4134	47.7058269	-113.3733956	L	5.92
24	Hungry Creek	4121	47.7154899	-113.3761811	L	7.31
25	Hodag Creek	4081	47.7334929	-113.3730912	R	3.93
27	Black Bear Creek	4039	47.7431059	-113.3877039	R	18.61
28	Slick Creek	4039	47.7454462	-113.3908034	L	6.47
29	Picture Creek	3999	47.7663168	-113.3974498	L	3.66
30	Henry Anderson Creek	3999	47.7724814	-113.3997202	R	0.21
31	Mid Creek	4016	47.7829151	-113.4069714	R	14.82
32	Sarah Creek	3960	47.7943897	-113.4170151	L	0.46

PIBO-EM Stream Name	**Year Sampled**	**Latitude**	**Longitude**
Big Salmon	2001	47.5284638	-113.5216884
Big Salmon	2006	47.5284638	-113.5216884
Black Bear	2006	47.7445709	-113.3833347
Burnt	2006	47.5082668	-113.3582940
Helen	2006	47.7051282	-113.3595391
Lewis	2001	47.6597197	-113.3403493
Lewis	2006	47.6597197	-113.3403493
Little Salmon	2001	47.6516102	-113.3702302
Little Salmon	2006	47.6516102	-113.3702302
Youngs	2008	47.3150150	-113.2925415

Appendix F: Electrical conductivity raw data for main stem South Fork above tributaries, tributaries and PIBO-EM data.

Creek Name	**Tributary Electrical Conductivity (mS·cm-1)**	**Temp. (C◦)**	**South Fork Electrical Conductivity (mS·cm-1)**	**Temp. (C◦)**	**PIBO-EM Electrical Conductivity (mS·cm-1)**	**PIBO-EM Electrical Conductivity (mS·cm-1)**
Youngs Creek	143.8	11.4			90	
Danaher Creek	261.3	13.2				
Gordon Creek	142.0	13.9	194.0	14.0		
Cayuse Creek	290.1	10.1	181.1	9.4		
Brownstone Creek	269.0	9.8	181.9	10.1		
Butcher Creek	185.0	12.8	182.0	10.2		
Lime Creek	*	*	189.8	13.3		
Bartlett Creek	203.9	13.0	191.8	14.6		
Burnt Creek	245.0	12.4	195.9	14.8		
Hammer Creek	288.8	14.6	197.7	14.8		
Scarface Creek	241.3	13.0	164.0	14.8		
Holbrook Creek	141.8	10.8	143.8	9.6		
White River	176.9	8.1	148.6	9.6		
Woodfir Creek	*	*	152.0	9.9		
Pine Creek	*	*	156.8	10.5		
Lamoose Creek	*	*	163.1	12.3		
Phil Creek	189.4	9.9	165.8	12.3		
Big Salmon Creek	66.4	15.5	155.3	12.9	40	60
Little Salmon Creek	96.0	9.9	133.0	11.2	70	90
Lewis Creek	176.3	6.7	133.8	11.3	170	200
Damnation Creek	157.8	8.0	141.0	13.3		
Helen Creek	*	*	142.0	13.5	150	
Snow Creek	75.5	9.2	144.7	14.1		
Hungry Creek	62.0	9.1	144.0	14.5		
Hodag Creek	92.5	14.0	147.0	15.0		
Black Bear Creek	215.5	15.5	146.0	15.0	190	
Slick Creek	61.4	7.4	147.0	14.9		
Picture Creek	*	*	132.2	10.0		
Henry Anderson Creek	268.4	7.2	132.4	10.0		
Mid Creek	194.8	8.0	132.6	10.0		
Sarah Creek	*	*	134.1	10.2		

* Dry when sampled

Appendix G: The top 5 geologic map units, their areas and percent cover for each watershed; other geologic map units that individually cover less than 10 mi^2 of the watershed.

Creek Name	#1 G Map Unit	#1 G Area (mi^2)	# 1 G % WS covered	#2 G Map Unit	#2 G Area (mi^2)	# 2 G % WS covered	#3 G Map Unit	#3 G Area (mi^2)	# 3 G % WS covered	#4 G Map Unit	#4 G Area (mi^2)	# 4 G % WS covered	#5 G Map Unit	#5 G Area (mi^2)	# 5 G % WS covered	Other geologic map units < 10 mi^2 in Watershed
Youngs Creek	1623	27.19	22.38	1625	26.39	21.72	1624	21.30	17.53	1602	14.51	11.94	1620	8.21	6.76	1620, 1600,1617, 1622, 1601, 1618, 1616, 1626, 1615
Danaher Creek	1620	36.30	27.73	1617	17.90	13.67	1623	15.46	11.81	1616	11.75	8.98	1600	11.21	8.56	1602, 1615, 1622, 1618, 1625, 1624, 1626, 1601, 1627, 1642
Gordon Creek	1624	18.29	27.53	1617	14.30	21.52	1625	14.00	21.07	1623	8.50	12.79	1602	8.07	12.15	1620, 1600, 1626, 1622, 1618, 1601, 1616
Cayuse Creek	1626	2.14	14.60	1623	1.69	11.53	1625	1.60	10.91	1616	1.57	10.71	1600	1.46	9.96	1624, 1620, 1617, 1602, 1622, 1618, 1642
Brownstone Creek	1623	0.97	26.57	1620	0.68	18.63	1624	0.48	13.15	1625	0.46	12.60	1622	0.37	10.14	1618, 1626, 1617, 1600
Butcher Creek	1616	0.99	57.56	1600	0.33	19.19	1602	0.21	12.09	1617	0.18	10.22	none	none	none	none
Lime Creek	1623	0.73	20.17	1625	0.68	18.76	1624	0.64	17.62	1602	0.49	13.40	1622	9.36	258.56	1620, 1615, 1600, 1618
Bartlett Creek	1617	9.60	36.64	1620	7.63	29.12	1622	8.95	34.16	1623	2.19	8.36	1618	1.67	6.36	1602, 1601, 1616, 1600
Burnt Creek	1620	3.05	29.08	1617	2.61	24.88	1618	1.36	12.96	1622	1.12	10.67	1623	1.12	10.65	1616, 1602, 1605, 1600
Hammer Creek	1602	1.45	43.81	1615	0.95	28.70	1616	0.47	14.08	1600	0.43	12.84	1625	0.02	0.54	none
Scarface Creek	1616	2.39	75.77	1602	0.50	15.79	1600	0.18	5.73	1617	0.08	2.65	none	none	none	none
Holbrook Creek	1620	5.96	35.23	1616	2.49	14.72	1623	2.30	13.56	1617	2.24	13.23	1622	1.87	11.03	1618, 1600, 1602
White River	1617	46.90	53.20	1616	19.34	21.94	1600	7.06	8.01	1620	4.97	5.63	1602	3.82	4.33	1623, 1625,1618, 1624, 1626, 1622, 1615
Woodfir Creek	1620	0.72	19.96	1623	0.59	16.13	1625	0.55	15.08	1622	0.50	13.75	1624	0.48	13.15	1618, 1617, 1600, 1602, 1626
Pine Creek	1625	0.80	42.71	1624	0.38	20.26	1623	0.35	18.64	1622	0.15	7.95	1602	0.12	6.66	1620, 1600, 1626
Lamoose Creek	1616	1.28	62.01	1617	0.65	31.64	1602	0.11	5.39	1600	0.02	0.90	none	none	none	none
Phil Creek	1620	1.34	21.71	1625	1.26	20.49	1623	1.02	16.60	1624	0.92	14.91	1617	0.58	9.43	1622, 1618, 1602, 1616, 1600
Big Salmon Creek	1623	17.66	22.21	1625	16.02	20.15	1624	9.75	12.26	1626	8.95	11.25	1620	8.46	10.65	1622, 1602, 1600, 1617, 1618, 1642, 1616
Little Salmon Creek	1625	17.06	29.93	1624	10.27	18.02	1626	9.16	16.08	1623	5.90	10.36	1602	9.23	16.20	1620, 1600, 1622, 1617, 1618, 1642, 1616
Lewis Creek	1623	1.03	22.76	1625	1.02	22.61	1624	0.86	18.88	1620	0.75	16.54	1622	0.29	6.29	1617, 1618, 1602
Damnation Creek	1623	3.18	48.30	1624	1.07	16.32	1620	0.84	12.76	1622	0.52	7.89	1617	0.33	4.97	1625, 1618, 1602, 1600
Helen Creek	1623	3.61	36.19	1620	2.66	26.73	1624	1.32	13.30	1622	0.62	6.18	1617	0.58	5.79	1615, 1618, 1602, 1600
Snow Creek	1620	4.43	74.88	1617	0.61	10.28	1618	0.56	9.51	1602	0.17	2.92	1622	0.13	2.24	1600
Hungry Creek	1620	3.70	50.65	1623	1.96	26.87	1622	0.67	9.11	1618	0.43	5.83	1617	0.37	5.01	1616, 1602, 1600
Hodag Creek	1623	1.34	34.17	1620	1.14	29.08	1622	0.88	22.40	1615	0.27	6.75	1618	0.25	6.26	1602, 1617
Black Bear Creek	1623	5.19	27.90	1620	4.36	23.40	1617	2.77	14.88	1618	1.98	10.66	1615	1.61	8.66	1622, 1616, 1600
Slick Creek	1620	3.19	49.35	1622	1.28	19.86	1623	0.66	10.19	1617	0.59	9.12	1618	0.46	7.13	1616, 1600
Picture Creek	1620	2.12	57.92	1617	0.70	19.28	1618	0.48	13.04	1622	0.20	5.55	1616	0.15	4.16	none
Henry Anderson Creek	1615	0.12	57.14	1616	0.09	41.71	none	none	none	none	none	none	none	none	none	none
Mid Creek	1623	4.72	31.84	1615	2.99	20.14	1616	2.80	18.91	1620	1.22	8.23	1624	1.11	7.48	1622, 1618, 1617
Sarah Creek	1617	0.43	94.41	1618	0.02	5.20	none	none	none	none	none	none	none	none	none	none

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