THESIS

HEADWATER STREAM MORPHOLOGY AND SENSITIVITY TO DEVELOPMENT IN THE PICEANCE BASIN OF WESTERN COLORADO

Submitted by

Krista K. Garrett

Department of Geosciences

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Master's Committee:

Advisor: Ellen Wohl

Sara Rathburn
Jeffrey Niemann

ABSTRACT

HEADWATER STREAM MORPHOLOGY AND SENSITIVITY TO DEVELOPMENT IN THE PICEANCE BASIN OF WESTERN COLORADO

Headwater streams are important components of watershed networks, but are less studied than larger channels and lack regulatory protection. Despite the small size of these streams, they have a disproportionate impact on the health of the watershed. Development of energy resources in the Piceance Basin of western Colorado is potentially causing significant changes in water and sediment yields to these headwater streams through the construction of roads and infrastructure. Additionally, the importance of headwater streams implies that understanding channel initiation is valuable for delineating and managing headwater stream systems. This research investigates two aspects of headwater streams: the potential impacts of energy development on channel morphology and the characterization of channel heads in western Colorado.

The study focusing on channel morphology and energy development tests three hypotheses: 1) the morphology of headwater streams proximal to energy development is significantly different than otherwise analogous streams, 2) stream sensitivity to development will vary with respect to underlying lithology, and 3) stream sensitivity to development will vary with respect to stream gradient. The study exploring channel heads in western Colorado has two main objectives: 1) examine the effects of surface and subsurface flow, underlying lithology, and local gradient on channel head characteristics, and 2) examine differences between channel heads in diverse study regions by comparing this dataset to published datasets.

A total of 94 stream reaches were chosen for assessing channel response to energy development. Of these, 49 reference reaches have little or no upstream disturbances and 45 impacted streams are located immediately downstream of a road or well pad. Three cross-sections per reach were surveyed to determine gradient and width to depth ratio; this ratio was used to represent channel morphology. A variety of statistical methods, including ANOVA and pairwise comparisons, were used to investigate the influence of energy development on channel morphology. This study found limited connection between energy development and headwater channel morphology. Although the morphology of impacted stream reaches is not significantly different from reference reaches, there is a relationship between channel morphology and distance to impact.

Additionally, 38 channel heads were selected for analysis, including both channel heads with surface and subsurface flow, and channel heads with underlying shale and sandstone lithology. ArcGIS was used to calculate channel head parameters, including contributing drainage area and local gradient. Boxplots and the non-parametric Wilcoxon Rank Sum test were used to compare the variables drainage area, local gradient, and basin length between sandstone and shale lithologies and between subsurface and surface flows. Regression equations and pairwise comparisons were used to compare datasets from differing geographic regions. Channel heads with subsurface runoff have significantly different characteristics than channel heads with surface runoff. Differences are also present between channel heads with different underlying lithologies. No notable differences were found between channel heads located in western Colorado and other study regions.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. OVERVIEW OF THESIS

Headwater streams (first to third order; Strahler, 1952) are increasingly studied as essential components of watersheds, but are still poorly understood. Development of energy resources in the Piceance Basin of Colorado is likely causing significant changes in water and sediment yields to these headwater streams through the construction of roads and other infrastructure. Understanding the morphology, function, and response to disturbance of headwater streams is important for managing and protecting the entire stream network. Furthermore, little is known about the channel initiation of headwater streams, but understanding the formation of channel heads is additionally important for managing headwater stream systems (Jaeger et al., 2007).

This project has two main parts, presented in the following sections; this document is best understood as the report on two separate, but related, projects. The first part addresses the issue of energy development impacts on headwater stream morphology. In order to better understand how energy development affects the stream network, channel response to these potential changes in water and sediment yield is evaluated based on physical characteristics. The second portion of this document examines the formation of channel heads in western Colorado. This study maps channel heads and examines potential surficial controls such as contributing drainage area and local gradient on channel initiation. These data are further compared with existing channel head data sets from other geographic region

2. INTRODUCTION TO ENERGY DEVELOPMENT AND HEADWATER STREAMS

Headwater streams are important components of watershed networks, but are less studied than larger channels. Furthermore, they frequently lack regulatory protection. These headwater channels comprise the majority of the total channel length in a network (Downing et al., 2012) and therefore provide the entry point for most water and sediment in the network (Wohl, 2010). As such, minimizing impacts of surface disturbances at the headwaters is important for mitigating downstream alterations in a river network.

Development of energy resources in the Piceance Basin of Colorado is potentially causing significant changes in water and sediment yields to these headwater streams through surface disturbances due to the construction of roads and other infrastructure. The construction of infrastructure and other development in a watershed can alter channel form and processes by i) altering water and/or sediment yields to channels by changing the land cover (e.g., road construction; Luce and Wemple, 2001), ii) directly altering water and/or sediment yields to channels (e.g., diversions, streamflow augmentation; Ryan, 1997; Caskey et al., 2015; David et al., 2009), iii) directly altering channel geometry (e.g., channelization, bank stabilization; Landemaine et al., 2015; Brookes and Gregory, 1983), or iv) altering base level (e.g., grade control structures; Gregory, 2006). Field and aerial observations in the study area indicate that energy development, which is the focus of this investigation, is typically not associated with channel engineering or alteration of base level. Additionally, there is no evidence of water diversions or augmentation in the vicinity of the study locations. The primary potential influence of energy development appears to be the alteration of land cover through the construction of unpaved roads and drilling pads. This research is based on this assumption and indirectly examines the effects of these surface disturbances by comparing the channel geometry of streams proximal to energy development to otherwise analogous channels that are not adjacent to development. Any significant differences are assumed to be the result of changes in water and sediment yield to these streams; water and sediment yield to channels is not directly measured.

In order to better understand how these changes affect the stream network, this study evaluates channel response to these changes, and seeks to identify correlations between physical characteristics (such as lithology and stream gradient) and channel morphology and sensitivity to disturbance. Factors other than land use and land cover can create differences in channel geometry among channels. These factors include lithology (as this influences substrate resistance, grain size of sediment, and rates of sediment production), drainage area (as this influences discharge), elevation (as this influences precipitation, vegetation, and rainfall-runoff), and stream gradient (which correlates with substrate grain size and stream erosive energy, when other factors are held constant; Knighton, 1998). This study collected a large dataset (94 surveyed channel reaches) with the intent of increasing statistical power and being able to detect land-use related differences within the natural variability of channel reach morphology created by factors unrelated to energy development (e.g., lithology, drainage area). This dataset consists of 49 reference reaches with little or no immediate upstream disturbances and 45 potentially impacted streams adjacent to surface disturbances. Statistical analyses were used to test for significant correlations between independent variables (e.g., lithology) and channel morphology in order to provide context for examining whether there are significant differences between channels proximal to energy development and channels without adjacent development.

3. BACKGROUND

3.1.1. Importance of Headwater Channels

Headwater streams are primarily small, first- to third-order channels (Strahler, 1952), commonly with drainage areas less than 25 square kilometers, and are typically ephemeral and intermittent channels. Despite the small size of these streams, they have a disproportionate impact on the health of the watershed. Headwater channels comprise approximately 90% of the total river length in a watershed (Downing et al., 2012) and are therefore the entry point for most of the water and sediment in the network and consequently affect downstream channels (Wohl, 2010). When headwater channels are altered or compromised, downstream segments of the watershed system may experience eutrophication, lower secondary biological productivity, and reduced viability of freshwater biota (Freeman et al., 2007; Dodds and Oakes, 2008). Headwater streams do not typically have associated floodplains and are closely coupled to the adjacent uplands (Wohl, 2010). Because of this relationship, headwater streams are likely to be sensitive to changes in water and sediment discharge, and quickly transport changed inputs to downstream portions of the watershed. Additionally, headwater streams greatly affect the biodiversity of a watershed. These channels can differ significantly in physical, chemical, and biotic attributes, creating a range of habitats that support a variety of species and increase the biological diversity of the river system (Meyer et al., 2007). Headwater streams support both permanent resident and migrant aquatic and riparian animals (Meyer et al., 2007), and provide invaluable connectivity with downstream portions of the river system (Freeman et al., 2007).

3.1.2. Unpaved Roads

Unpaved roads have been shown to increase runoff, intercept subsurface flows, increase drainage density, increase peak flows, and increase production of fine sediment (Luce and Wemple, 2001). The compaction of roads significantly decreases the infiltration rate of road surfaces, causing most precipitation falling on roads to run off as overland flow that is rapidly delivered to the stream network by ditches and waterbars (La Marche and Lettenmaier, 2001). Furthermore, subsurface flow can be intercepted by road cutslopes, transforming this slower moving flow to faster moving surficial runoff. Unpaved roads have also been shown to significantly increase the drainage density of a watershed through channel initiation and connecting roads directly to streams (Montgomery, 1994; Wemple et al., 1996). This increased drainage density may provide an explanation for the increased peak flows shown by streams proximal to unpaved roads. Lastly, roads have a net effect of increasing sediment production and delivery to streams (Wemple et al., 2001). Ephemeral streams, however, may act as temporary storage for sediment delivered from road surfaces, as these streams do not immediately transport this sediment downstream (Duncan et al., 1987). Increasing discharge due to road construction may cause the headwater streams to experience channel widening, increasing width to depth ratio, and bed material coarsening (Wohl and Dust, 2012). Increases in sediment yield, however, would complicate this response. Lane's Balance ($Q_sD_s \propto Q_wS$) indicates that an increase in both sediment yield (Q_s) and water yield (Q_w) could lead to bed material fining and a decrease in channel slope (Lane, 1955).

In addition to forest access and industry roads, recreational vehicle roads can cause geomorphic changes to streams (Marion et al., 2014). Off-highway vehicle (OHV) usage is a common recreational activity and many public lands have dedicated OHV trails (Cordell et al., 2005). These OHV trails have been shown to have geomorphic impacts on stream channels, including sediment plugs (accumulation of sediment in a channel that at least partially blocks the channel), changes in the width to depth ratio, and bed material fining (Marion et al., 2014).

3.1.3. Geomorphic Response to Disturbance

Channel form, primarily cross-sectional channel geometry, is predominantly controlled by the discharge and sediment load supplied to the channel (Knighton, 1998). Geomorphic changes of width, depth, slope, and sediment load in response to changes in discharge were described by Leopold and Maddock (1953) in their documentation of hydraulic geometry relationships. These relationships predict that the cross-sectional geometry of a channel, including width and depth, will reflect changes in discharge and sediment load. Bankfull width is defined as the width of the channel at the top of the bank (Williams, 1978). The bankfull discharge usually corresponds to the dominant or channel-forming discharge and is frequently defined as the discharge that transports the most sediment (Wolman and Miller, 1960). The concept of bankfull discharge simplifies the process of channel form creation and the bankfull width provides a convenient metric for comparing different channels (Knighton, 1998).

Changes in discharge or sediment yield potentially cause different geomorphic responses. Increases in discharge have been shown to cause channel incision and channel widening (Montgomery and Buffington, 1998). Incision would lead to a decrease in the width to depth ratio and, conversely, widening would lead to an increase in the width to depth ratio. Changes to the sediment load can also affect the width to depth ratio of a channel. The transport capacity of a channel determines the extent of changes in response to an increase in sediment load (Montgomery and Buffington, 1998). An increase in sediment load to a stream without the capacity to transport the sediment would cause aggradation, channel widening, and pool filling (Montgomery and Buffington, 1998). Aggradation and channel widening would both cause an increase in the width to depth ratio of the channel. Measurable changes to the channel morphology may depend on the location of the sediment or water input and the time since the disturbance to the water or sediment yields occurred.

Predicting channel geomorphic responses to changes in water and sediment yields may be complicated by the discontinuous and abrupt patterns of change typically exhibited in streams in the semiarid environment of western Colorado. Streams in this environment commonly demonstrate a complex response to changes in water and sediment yield, and experience alternating periods of incision and aggradation (Patton and Schumm, 1975; Womack and Schumm, 1977). These periods of incision and aggradation can occur independently of changes in sediment yield. Periodic runoff in semiarid regions can transport sediment into channels, but may be insufficient to transport the sediment out of the system. These discontinuous inputs of sediment lead to over-steepening of the channel, followed by the formation of a headcut, incision, and arroyo formation. The formation of arroyos can cause downstream channel segments to aggrade due to the influx of sediment. Despite the complications of complex response, channel response to changes in water and sediment yields should be detectable.

3.1.4. Effects of Lithology and Gradient

The severity of geomorphic channel changes has been shown to depend on the lithology underlying the channel and catchment and the stream gradient. David et al. (2009) demonstrated that streams with underlying lithology that weathers to fine-grain sediment are more resistant to changes in water and sediment discharge, as the fine-grain sediment leads to greater cohesiveness of the banks. In contrast, channels with underlying lithology that weathers to coarser grain sediment are more responsive to changes in water and sediment, as sand and gravel are more easily transported (David et al., 2009). Furthermore, high gradient channels commonly have erosionally resistant channel boundaries formed in boulders or bedrock (Montgomery and Buffington, 1997). These steep channels are also more resistant to changes in water and sediment discharges (Ryan, 1997; Wohl and Dust, 2012) as steep streams have high ratios of transport capacity to supply, moving sediment quickly through the reach without impacting the channel morphology (Montgomery and Buffington, 1997).

3.2. Research Objectives and Hypotheses

3.2.1. Research Objectives

The primary objective of this study is to examine the impacts of surface disturbances due to energy development on headwater channels. This project seeks to identify correlations between physical characteristics (such as lithology and stream gradient) and channel morphology and sensitivity to disturbance by evaluating the physical responses of headwater streams to changes in sediment and water discharge. If correlations exist, secondary objectives include developing a protocol for remotely predicting stream characteristics and creating recommendations for managing the effects of surface disturbances due to energy development.

3.2.2. Hypotheses for Streams Proximal to Energy Development

Changes in water and sediment yield due to road construction and other energy development activities can cause significant changes to the morphology of headwater streams, as discussed in Section 3.1.2. The main hypothesis addresses the potential morphological difference between the reference streams that are not in proximity to energy development or unpaved roads and impacted streams that are proximal to energy development. These two populations are otherwise analogous, with similar elevation, land cover, hydroclimatology, and underlying lithology.

H_0: There is no significant difference between the reference and impacted stream reaches.

H_1: The morphology of headwater streams proximal to energy development (impacted stream reaches) are significantly different than otherwise analogous streams (reference stream reaches).

The morphology of impacted and reference reaches is assessed using the width to depth ratio of each channel reach; reaches were assigned as reference or impacted reaches in the field based on proximity to surface disturbances. The width to depth ratio for channel reaches was calculated using data collected by cross-sectional channel surveys, as described in Section 4.1.

The remaining hypotheses are considered as sub-hypotheses, if the main hypothesis is not rejected. These hypotheses address the controls on channel sensitivity to changes in water and sediment yield. Other studies (e.g., Ryan, 1997; David et al., 2009; Wohl and Dust, 2012) have demonstrated that differences in channel morphology and/or underlying lithology correlate with differences in sensitivity to changes in water and sediment inputs. The responses predicted by Hypotheses 2 and 3 are outlined as a conceptual model in Figure 1. Hypothesis 2 addresses lithology as a control of channel response.

> **H_2:** Stream sensitivity to development will vary with respect to lithology. Channels with underlying lithology that weathers to fine-grain material (silt and clay) will be more resistant than channels with underlying lithology that weathers to coarse-grain material (sand and coarser).

Streams underlain by shale are likely more resistant to changes in water and sediment yield associated with energy development, as the fine-grain material forms more cohesive, less erodible channel banks. Any increases in water and sediment yield would therefore move through the reach either without affecting the channel morphology or with less effect on channel morphology. Stream gradient is also expected to control channel response to changes in water and sediment yield.

> **H_3:** Stream sensitivity to development will vary with respect to stream gradient. Streams with steeper gradients ($\geq$ 4%) will better transport increases in water and sediment discharge without changes in channel morphology.

Impacted streams with steeper gradients will likely be more resistant to changes in water and sediment yield, as they are better able to move water and sediment through the reach without changes to the geomorphology.

The potential effects of energy development on streams with varying lithologies and gradients are summarized in the conceptual model presented in Figure 1. Starting with the assumption that energy development will primarily increase water and sediment yield, this model illustrates how these changes may interact with existing lithology and stream gradient to produce a range of possible channel responses. The channel responses are dependent on the nature of the underlying lithology (fine or coarse grain) and the steepness of the channel gradient (low or high gradient). The variety of these responses is illustrated in Figure 1. Channel response to increased discharge is dependent on the time elapsed since disturbance and is expected to primarily lead to erosion. The initial response to increased discharge is typically incision, producing a smaller width to depth ratio, and channel widening may occur later, producing a larger width to depth ratio (Simon and Rinaldi, 2006). Increasing the sediment yield to headwater streams is expected to primarily lead to aggradation, which may cause the channel to become shallower and result in a larger width to depth ratio, depending on the underlying lithology and channel gradient.

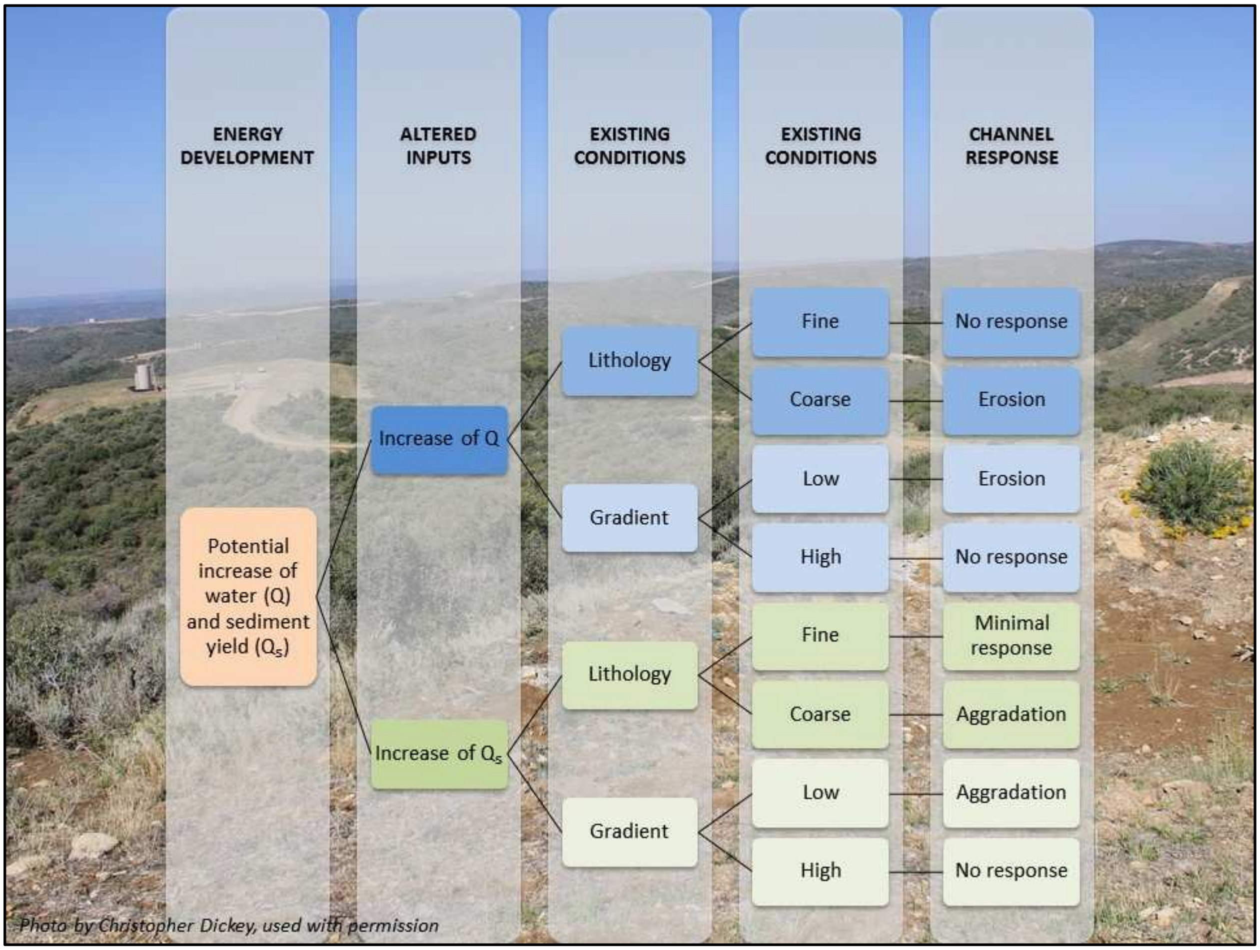

Figure 1: Effects of potential development-driven increases of water and sediment yield on headwater streams, as determined by lithology and gradient.

3.3. Study Areas

The Piceance Basin is a structural basin in western Colorado, extending from Moffat County in the north to Ouray County in the south and from approximately the Colorado-Utah border east to Glenwood Springs, approximately 18,415 km^2 in area (Ground Water Atlas of Colorado, 2003). The basin formed during the Laramide Orogeny and is bounded by major faults (U.S. Geological Survey, 2003). The Colorado River and its tributaries drain the Piceance Basin. Study sites for this project are located on private landholdings of the Chevron Corporation, the

Uncompahgre National Forest (UNF) and Bureau of Land Management: Dominguez Canyon Wilderness Study Area, and the Piceance State Wildlife Area (PSWA; Figure 2). Study sites on the public lands were selected based on similarities in elevation, topography, and lithology to the Chevron property. All study areas are utilized as rangeland for cattle, with light to moderate grazing in each area. Impacted study reaches are proximal to either national forest roads (in the UNF study region) or industry roads and drilling pads (in the Chevron study region). Based on analysis of historical imagery in Google Earth, all features that potentially impact streams were constructed prior to 1993, with the exception of seven impacts. Six of these seven impacts were constructed between 1993 and 2005; the seventh impact was constructed between 2006 and 2011. On the Chevron property, many of these roads appear to have been enlarged, with drilling pads added, between the years 1993 and 2005.

The vegetation in the basin is dominated by sagebrush steppe (Hoelzle et al., 2012). The vegetation community includes big sagebrush (*Artemisia tridentata*), pinyon pine (*Pinus edulis*), Utah juniper (*Juniperus osteosperma*), quaking aspen (*Populus tremuloides*), and perennial grasses (Bonham et al., 1991). Forested areas are also present, especially at higher elevations; forest types include ponderosa pine forests, mixed-conifer forests, and aspen stands (Binkley et al., 2008). The climate of the Piceance Basin is primarily semi-arid, and there are likely multiple flow-generating mechanisms producing surface runoff. There are limited data available about the precipitation patterns of the Western Slope of the Rocky Mountains, but precipitation patterns are likely similar to those on the eastern side of the mountains, where surface runoff is dominated by spring snowmelt at elevations above 2300 meters and by convective rain events at elevations below 2300 meters (Jarrett, 1990).

Mesa County was initially home to the Ute Native American people, who hunted and kept seasonal farms in the region (Museum of Western Colorado). Spanish priests and explorers first entered the area in the late 1700s (Marshall, 2006), but fur trappers and traders were the first to extensively explore the region in the 1820s through the 1840s (Mehls, 1982). The land began to be used as cattle rangeland in the 1870s (Mehls, 1982). After an uprising near Meeker, the Ute people were moved to reservations in 1879 and the first white settlers arrived in Mesa County in 1881 (Museum of Western Colorado). The settlers established farms in the valley bottoms, primarily raising sugar beets and fruit. In addition to farming, cattle ranching remained prevalent in Mesa County, and many of the settlers began ranching sheep. Trapping, mainly of beaver along creeks, also continued to provide some employment.

Mineral resource extraction has also been an important economic factor in the Piceance Basin, as reviewed by Mehls (1982). Soon after settlement began in the Grand Valley, coal mines were developed. Beginning in the early 1900s, minerals such as vanadium and uranium were also mined in the region. The Ute people told the first settlers to the region about the "rock that burns," but it was not until the early 1920s that the first oil shale boom occurred. By the end of the decade, however, the discovery of new oil fields elsewhere in the country caused a decline in interest in the oil shale of western Colorado. Subsequent development of the oil shale has experienced multiple periods of increases and decreases, due to events such as World War II and other economic factors. Development of the natural gas resources in the area remained limited until the 1950s, when this resource became more valuable, and natural gas extraction continues to the present day (Mehls, 1982).

3.3.1. Chevron Corporation Private Property

The private landholdings of the Chevron Corporation in western Colorado are located north of the town of De Beque. The geology of this region consists of Eocene sedimentary rocks, primarily in the Uinta and Green River Formations, with overlying Quaternary sediment (Hail, 1989). In this study region, these formations consist primarily of mudstone and shale with some interbedded sandstone (Hail, 1989). The landholdings of Chevron vary in elevation from 1720 meters in the Clear Creek Valley to 2700 meters on the Roan Plateau. Study sites were selected near the top of the plateau due to access, and the sites range in elevation from 2400 meters to 2600 meters. The climate of the Chevron Property is semi-arid, with a mean annual precipitation of 417 mm (Western Regional Climate Center, Altenbern, 1947-2015). October receives the most rainfall, with an average rainfall of 41 mm. The mean annual minimum temperature is -1 degrees Celsius and the mean annual maximum temperature is 17 degrees Celsius. The area near the Chevron Property also receives an annual average of 1610 mm of snowfall (Western Regional Climate Center, Altenbern, 1947-2015).

Historical imagery in Google Earth was used to assess the age of roads and drilling pads impacting the study reaches. Based on this imagery, all roads and drilling pads were in place by 1993, with the exception of the road impacting study reach Impacted 22, which was constructed between 2006 and 2011. The main roads on the Chevron Property were enlarged between 1993 and 2005, and the majority of the drilling pads appear to have been installed between 2005 and 2011.

3.3.2. Uncompahgre National Forest and Bureau of Land Management: Dominguez Canyon Wilderness Study Area

The Uncompahgre National Forest is located south of Grand Junction and the Dominguez Canyon Wilderness Study Area is immediately adjacent to the Forest along its eastern boundary. Sites in the Dominguez Canyon Wilderness Study Area were located along the border with the Uncompahgre National Forest. Study reaches located in the Uncompahgre National Forest and the Dominguez Canyon Wilderness Study Area are hereafter collectively referred to as Uncompahgre National Forest (UNF) sites. The geology in this region consists of Triassic and Jurassic sedimentary rocks, primarily in the Chinle Formation, Wingate Sandstone, and Morrison Formation (Green, 1992). The elevation of study sites in the Uncompahgre National Forest ranged from 2170 meters to 2700 meters. The climate of the Uncompahgre National Forest is semi-arid, with a mean annual precipitation of 288 mm (Western Regional Climate Center, Gateway, 1947-2015). October receives the most rainfall, with an average rainfall of 32 mm. The mean annual maximum temperature is 20 degrees Celsius and the mean annual minimum temperature is 5 degrees. The Uncompahgre also receives an annual average of 399 mm of snowfall (Western Regional Climate Center, Gateway, 1947-2015).

The Uncompahgre Plateau was first explored by the Spanish, beginning in 1761, and was later traversed by Fathers Dominguez and Escalante in 1776 (Marshall, 2006). European settlement of the area, however, did not begin until after the removal of the Ute Native Americans in 1881 (Marshall, 2006). A handful of homesteaders lived on the plateau, although it was mostly used as grazing land for cattle (Marshall, 2006). Extensive logging also occurred in some areas (Binkley et al., 2008). Overgrazing at the beginning of the twentieth century led to the need for government regulation of the area, and in 1905 President Theodore Roosevelt created the Uncompahgre National Forest (Marshall, 2006). The last major landscape-scale wildfire documented in historic records occurred in 1879 (Binkley et al., 2008).

Both impacted and reference sites were surveyed on the Uncompahgre Plateau; Forest Service access roads and OHV roads affect the impacted sites. Based on historical imagery in Google Earth, all roads impacting study reaches in the Uncompahgre National Forest were constructed prior to 1993.

3.3.3. Piceance State Wildlife Area

The Square S Summer Range Unit of the Piceance State Wildlife Area (PSWA) is located north of Grand Junction. Similar to the Chevron Property, the geology consists of Eocene age mudstones and shales, primarily in the Green River Formation (Roehler, 1972). The elevation of study sites in the Piceance State Wildlife Area ranged from 2500 meters to 2650 meters. The climate of this area is semi-arid, with a mean annual precipitation of 417 mm (Western Regional Climate Center, Altenbern, 1947-2015). October receives the most rainfall, with an average of 41 mm. The mean annual minimum temperature is -1 degrees Celsius and the mean annual maximum temperature is 17 degrees Celsius. The Piceance State Wildlife Area also receives an annual average of 1610 mm of snowfall (Western Regional Climate Center, Altenbern, 1947-2015).

The physical characteristics of the three study areas are summarized in Table 1.

Table 1: Summary of study area characteristics.

	Lithology	Elevation	Mean Annual Precipitation	Land Use
Chevron Corporation Private Property	Shale	2400 – 2600 m	417 mm	Energy development, rangeland
Uncompahgre National Forest	Sandstone, shale	2170 – 2700 m	288 mm	Recreation, OHV use, rangeland
Piceance State Wildlife Area	Shale	2500 – 2650 m	417 mm	Recreation, rangeland

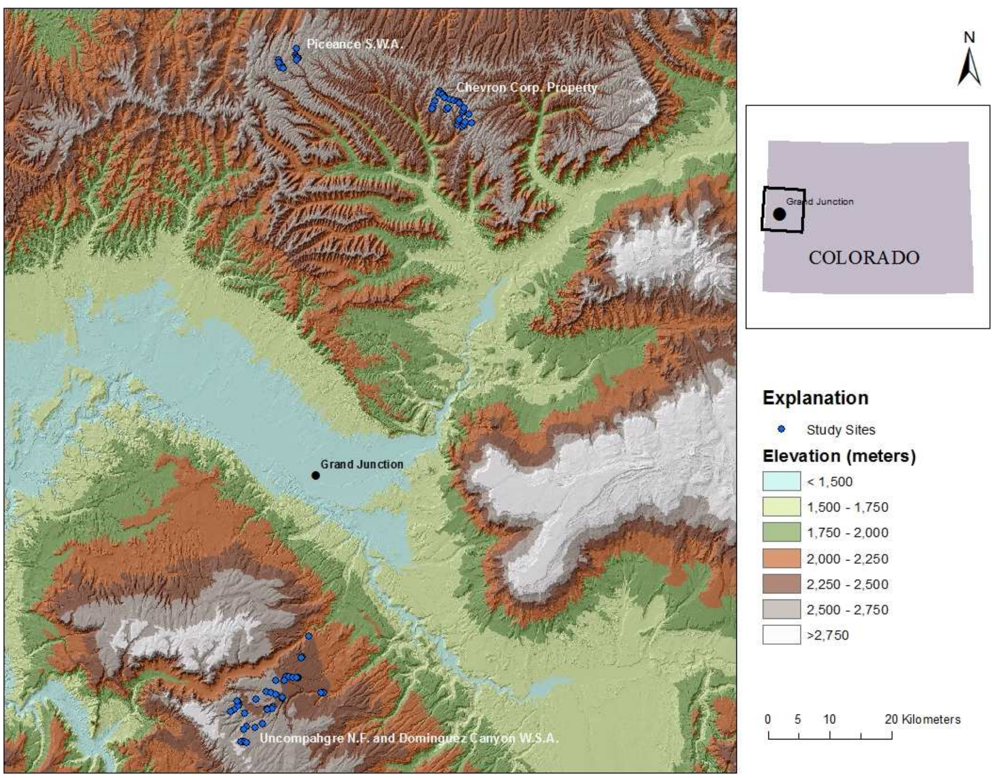

Figure 2: Study regions in the Piceance Basin, Colorado.

4. METHODS

A total of 94 stream reaches between 10 and 35 meters long were chosen for this project. Of these, 49 reference reaches were selected with little or no immediate upstream disturbances. Forty-five impacted streams are located immediately downstream of a road or well pad. Reaches were chosen based on their proximity to development, gradient, and underlying lithology. The following sections describe all the methods used in this project. Section 4.1 describes the field methods used for data collection. The second section, 4.2, details the statistical methods used to analyze these data.

4.1. Field Methods

At each study reach, the channel was characterized through measurement and categorical assessment. The reach length at each site was at least 10 times the average bankfull channel width and no less than 10 meters. Three cross-sections per reach were surveyed (Figure 3). Stream gradient was calculated for each reach using the surveyed elevation of the reach's center of the upstream and downstream cross-sections and the measured reach length. At each reach, the substrate was categorically identified (lithology and dominant grain size), the percent cover and type of vegetation cover of the riparian zone were categorized (trees, shrubs, graminoids, and forbs), the channel was assigned to a category of flow regime (perennial, intermittent, or ephemeral), and the bedform type (cascade, step-pool, plane-bed, pool-riffle, dune-ripple; Montgomery and Buffington, 1997) was identified. At each site, GPS points noting elevation and location were recorded.

Impacted reaches were designated based on the proximity to surface disturbances caused by energy development or recreational activity. The impacts of nearby disturbances on the channel were assessed based on spatial proximity to roads and drilling sites and observed connectivity in the form of evidence of water and/or sediment moving directly from roads and drilling sites into channels. Proximity to roads and drilling sites were measured in the field with a 100-meter tape or calculated using aerial imagery in Google Earth. A channel segment was considered a reference reach if there was no road or drilling site within a lateral distance of 10 times the average channel width or immediately upstream of the study site and there was no evidence of surface runoff or sediment from a road directly into the channel. Additionally, the impacts were characterized as either parallel or perpendicular to the flow direction.

Figure 3: Surveying the channel cross-section. Flow is right to left.

4.2. Statistical Analyses

In order to evaluate stream sensitivity to disturbance, channels affected and unaffected by energy development were compared across diverse lithology, stream gradient, and drainage area within the study areas. All statistical analyses were performed using the R statistical package (R Core Team, 2014). Analyses were performed using a confidence level of 95%.

Survey data collected at each study reach were used to calculate the gradient of each study reach and the width to depth ratio of the reaches' three cross-sections. The width to depth ratios within one standard deviation of the mean were averaged to produce a single representative width to depth ratio for each study reach. The width to depth ratio of the study reaches was the primary response variable for the statistical analyses. The sample population was tested for normality using visual methods, such as histograms and qqplots, and the Shapiro-Wilk test for normality (Royston, 1982). In order to obtain normality for the distribution of the width to depth ratio, a logarithmic transformation of the data was used. Two outliers were removed from the dataset as they appeared as outliers and field notes indicated that there were difficulties in obtaining measurements at these reaches.

ANOVA analysis allows for comparison of continuous response variables with categorical predictor variables to test the equality of the means of the grouped data. An ANOVA is based on the assumptions of normally distributed data, equality of variances, random sampling, and independent observations. The data were organized into groups according to the variables of interest for each hypothesis. A one-way ANOVA with one predictor variable was fitted and the means of the width to depth ratio (a continuous variable) were compared between each of the groups. Additionally, the lsmeans command from the lsmeans package (Lenth, 2015) was used to calculate pairwise comparisons of the mean width to depth ratio between groups with a Tukey adjustment to account for multiple testing. Pairwise comparisons using lsmeans are based on the same assumptions as an ANOVA.

For impacted reaches, the distance to the impact was considered as a continuous variable and relationships between the distance to the impact and the width to depth ratio were analyzed. Lastly, multiple linear regressions were conducted, utilizing all predictor variables and the width to depth ratio as a response variable.

5. RESULTS

All graphs presented in this section use untransformed data; all statistical analyses presented use data transformed using a log transformation. Key analyses are presented in this section. Additional analyses are presented in Appendix A; these analyses included: comparing parallel versus perpendicular impacts, stratifying the data by drainage area, investigating the effects of the type and percent cover of vegetation, analyzing the variances of each group, examining the effects of flow regime, conducting principal components analysis, and interpreting scatterplots of key variables.

5.1. Hypothesis 1

H_0: *There is no significant difference between the reference and impacted stream reaches.*

H_1: *The morphology of headwater streams proximal to energy development (impacted stream reaches) are significantly different than otherwise analogous streams (references stream reaches).*

In order to test Hypothesis 1, the data were initially organized into three groups: 1) study reaches on Chevron property proximal to disturbance (Chevron Impacted), 2) reference reaches in both UNF and Piceance study regions (Reference), and 3) reaches proximal to disturbance located in the UNF study region (UNF Impacted). An ANOVA used to compare the differences in width to depth ratio between the three groups found a statistically significant difference between Chevron Impacted reaches and Reference reaches ($p\text{-value} < 0.05$). Pairwise comparisons between the groups were also made. Statistically significant differences were found between the width to depth ratios of the groups Chevron Impacted and Reference and between the groups Chevron Impacted and UNF Impacted (Figure 4).

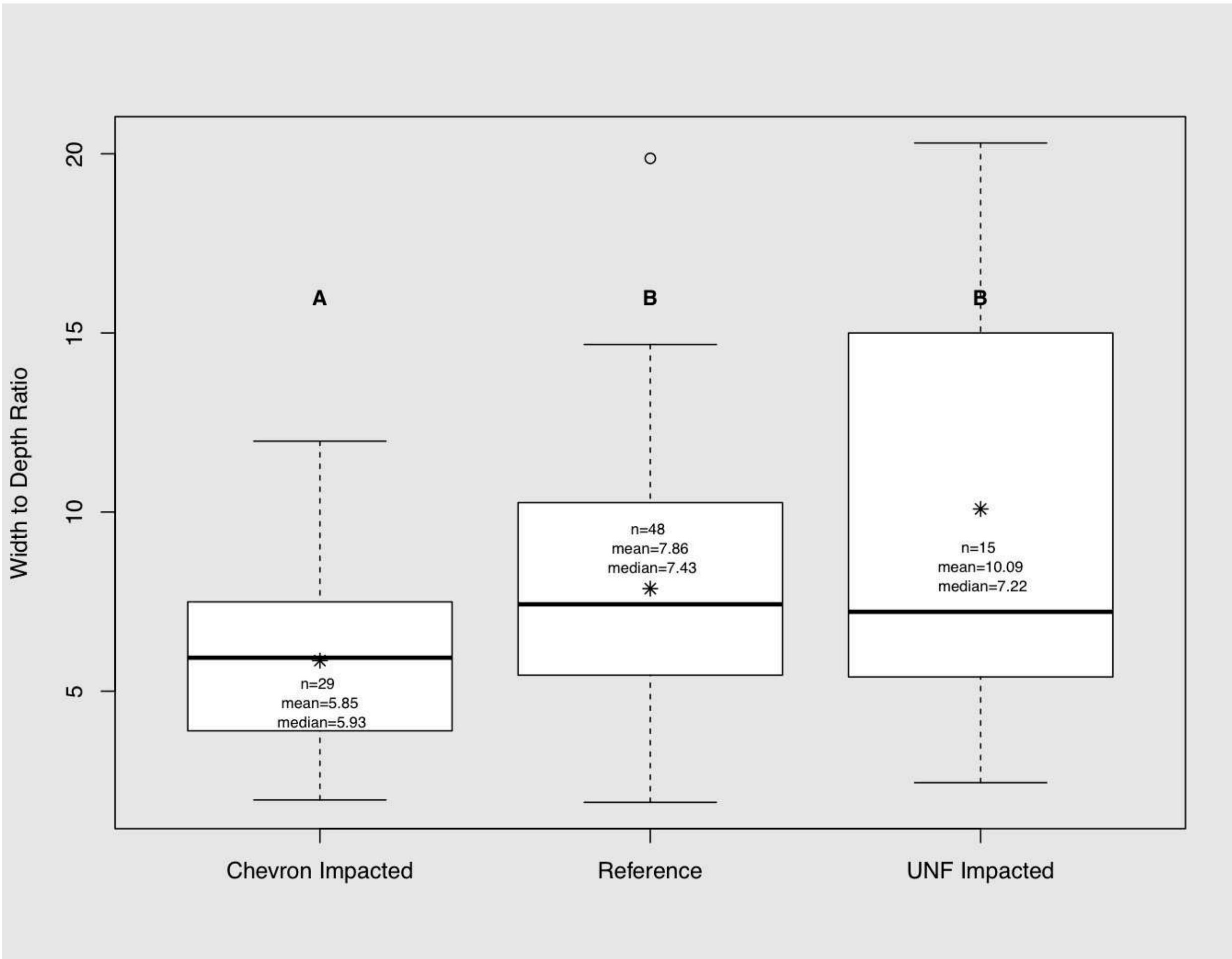

Figure 4: Comparison of width to depth ratios of impacted and reference reaches. The box plots show the width to depth ratio for each study region. The whiskers mark the minimum and maximum values, and the ends of the boxes indicate the 25th and 75th percentiles of the dataset. The bold line in each box represents the median, an asterisk marks the mean of each group, the outliers are shown as empty circles, and the sample size (n) is shown for each group. The capital letters (i.e., A and B) represent statistically similar and different groups; groups with statistically significant differences in width to depth ratios are marked with different letters.

As the Chevron and Piceance study regions are geographically closer together, the data were additionally grouped based on location and whether the reach was proximal to roads or other development in order to examine any trends based on geographic location. Four groups were formed: 1) Chevron Impacted, 2) Piceance Reference, 3) UNF Impacted, and 4) UNF

Reference. An ANOVA was used to compare the differences in width to depth ratio between the four groups. Pairwise comparisons of all the groups were also made. Statistically significant differences (p-value < 0.05) were found between the width to depth ratios of the groups Chevron Impacted and UNF Impacted and between the groups Chevron Impacted and UNF Reference (Figure 5). As differences exist between Chevron Impacted reaches and both Impacted and Reference reaches on UNF, this indicates that the differences are caused by factors other than the impacts of energy development on Chevron's property. Additionally, there is no statistically significant difference between the groups Chevron Impacted and Piceance Reference, which are geographically closer together. If the proximity to roads and other development had a significant influence on the channel morphology, a significant difference between the width to depth ratios of the Chevron Impacted and Piceance Reference sites would be expected. As there is no significant difference between these groups, this indicates that the differences in morphology between Chevron and UNF reaches are not caused solely by the presence of energy development in the Chevron study region.

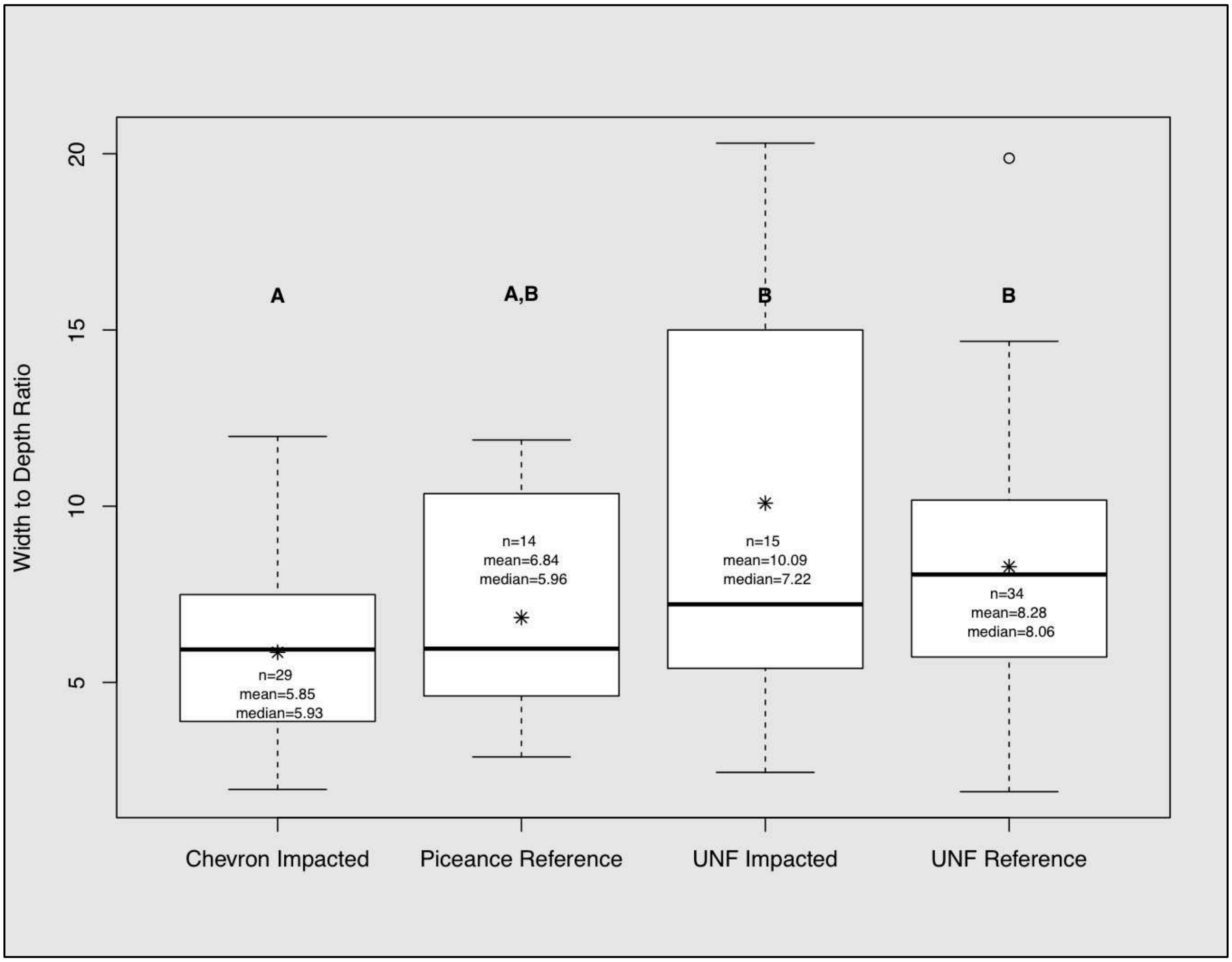

Figure 5: Comparison of width to depth ratios of the study regions. The box plots show the width to depth ratio for each study region. The capital letters (i.e., A and B) represent statistically similar and different groups; groups with statistically significant differences in width to depth ratios are marked with different letters.

5.2. Hypothesis 2

H*$_2$*: *Stream sensitivity to development will vary with respect to lithology. Channels with underlying lithology that weathers to fine-grained material (silt and clay) will be more resistant than channels with underlying lithology that weathers to coarse-grained material (sand and coarser).*

Testing Hypothesis 2 is dependent on rejecting the null hypothesis that there is no difference between streams proximal to energy development and otherwise analogous streams. As discussed in Section 5.1, the data do not fully support a conclusion that streams proximal to development are significantly different than otherwise analogous streams; therefore, it is difficult to test whether streams underlain by shale or sandstone are more susceptible to channel morphology changes in response to human impacts.

In order to fully examine Hypothesis 2, the width to depth ratios of the study reaches were compared based on underlying lithology. The data were grouped according to location, whether the reaches were impacted, and underlying lithology; six groups were formed (Figure 6). An ANOVA and pairwise comparisons were conducted, resulting in evidence that only the width to depth ratios of the groups Chevron Impacted Shale and UNF Reference Shale were significantly different. This indicates the possibility that reaches underlain by sandstone are not sensitive to changes in water and sediment yield as a result of development. As discussed in Section 5.1, however, the difference between the Chevron Impacted Shale and UNF Reference Shale groups is likely due to factors other than the presence of human impacts in the Chevron study region. The fact that the Piceance Reference Shale and Chevron Impacted Shale groups are not significantly different strongly supports rejecting Hypothesis 2. Furthermore, if Hypothesis 2 were supported by the data, statistically significant differences between the impacted reaches underlain by sandstone and shale would be expected; this is not shown in the data (Figure 6).

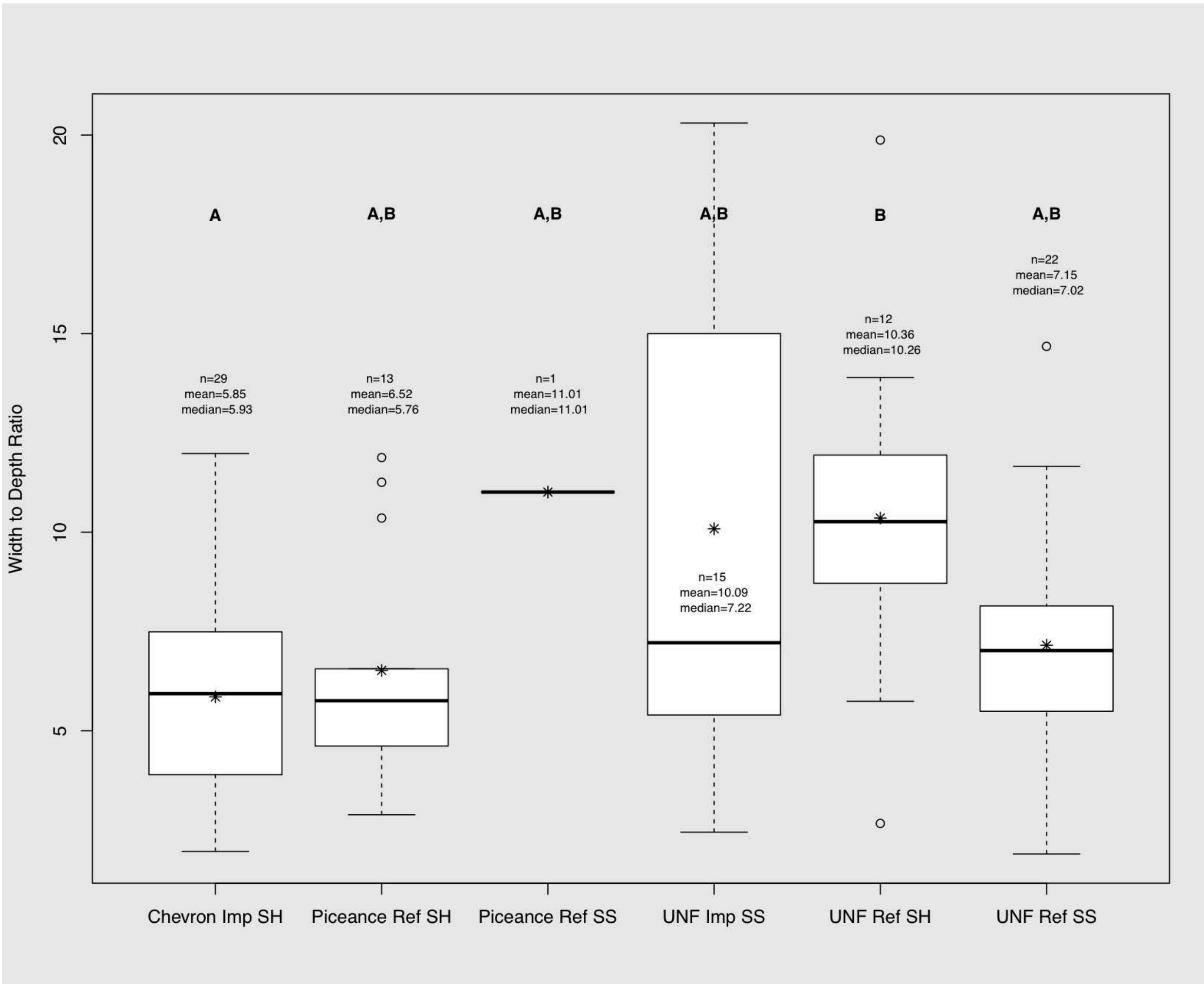

Figure 6: Comparison of width to depth ratios by location and lithology. Imp = Impacted; Ref = Reference; SH = Shale; SS = Sandstone. The capital letters (i.e., A and B) represent statistically similar and different groups; groups with statistically significant differences in width to depth ratios are marked with different letters.

5.3. Hypothesis 3

H₃: *Stream sensitivity to development will vary with respect to stream gradient. Streams with steeper gradients (≥ 4%) will better transport increases in water and sediment discharge without changes in channel morphology.*

Testing Hypothesis 3 was dependent on rejecting the null hypothesis that there is no difference between reaches proximal to energy development and otherwise analogous reaches. As discussed in Section 5.1, the data do not support a conclusion that the morphology of streams proximal to development are significantly different than otherwise analogous streams; therefore, it is difficult to test whether channels with steeper gradients are more susceptible to channel morphology changes in response to human impacts.

The width to depth ratios were compared based on study region and gradient. Study reaches with gradients greater than 0.05 were classified as having steep gradients; study reaches with gradients less than 0.05 were classified as shallow gradients. A gradient of 0.05 was selected as the division point based on the histogram of study reach gradients; 49 study reaches had gradient values less than or equal to 0.05. An ANOVA and pairwise comparisons were used. No statistically significant differences were found among the groups in shallow gradient streams (Figure 7). In streams with steep gradients, the Chevron Impacted and UNF Reference groups were the only groups with statistically significant differences (p-value < 0.05) in width to depth ratios (Figure 8). If Hypothesis 3 were supported by the data, significant differences between impacted reaches and reference reaches would be expected in shallow gradient streams, with no or limited differences between impacted and reference reaches in steep gradient streams. These expected trends are not present, indicating that Hypothesis 3 is not supported by the data.

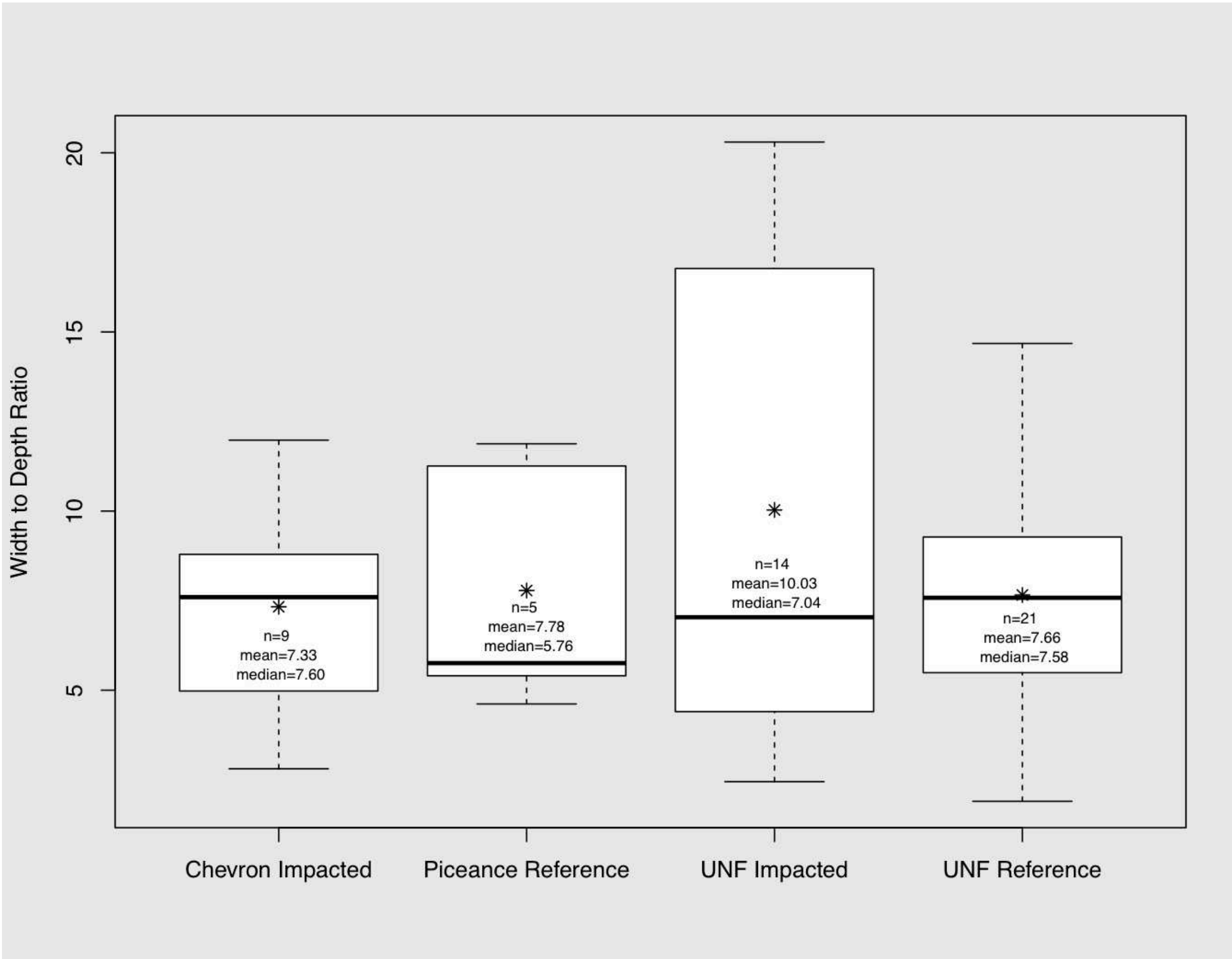

Figure 7: Comparison of width to depth ratios of shallow gradient streams. No statistically significant differences between groups are present.

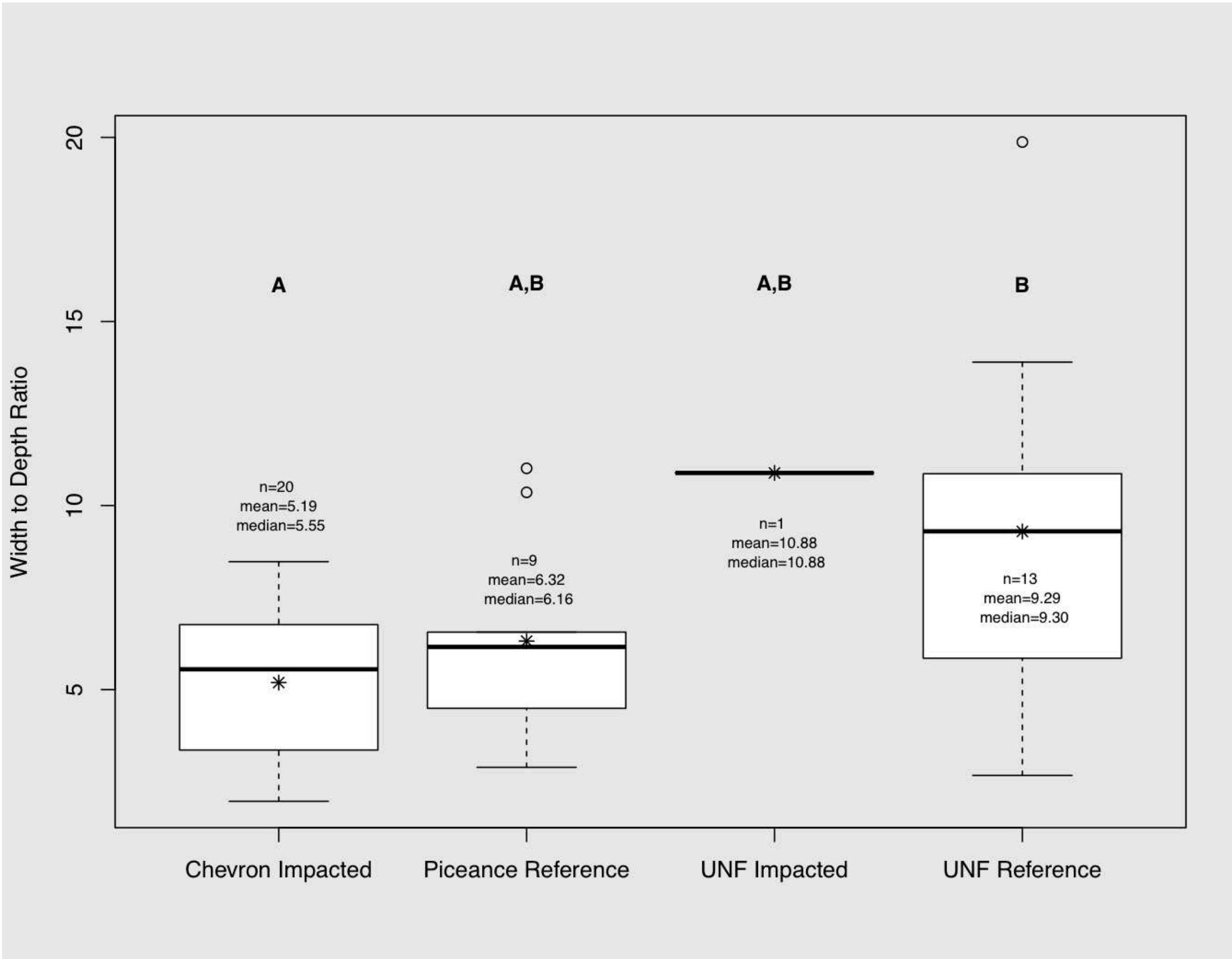

Figure 8: Comparison of width to depth ratios of steep gradient streams. The capital letters (i.e., A and B) represent statistically similar and different groups; groups with statistically significant differences in width to depth ratios are marked with different letters.

5.4. Effects of Proximity to Impact

The distance from impact (road, drilling pad, culvert, etc.) to a given study reach varied from 0 to 140 meters. In order to examine the effect of distance from an impact, the proximity to impact was considered as a continuous predictor variable (Figure **9**). Figure **9** illustrates the trend between increasing distance to impact and decreasing width to depth ratio. Decreasing width to depth ratio indicates that either the width is decreasing, the depth is increasing, or both; in summary, channels close to an impact are wider and shallower than channels farther from impacts. A variety of trendlines were tested on the entire dataset of impacted reaches; apparent outliers were excluded for the purpose of testing trendlines with this dataset. The best fit line is a power function with the equation $y = 14.768x^{-0.306}$. Although this is the best fit line, the R^2 value is 0.256, indicating that a large portion of the variance of the data cannot be explained by this trendline.

The trend of decreasing width to depth ratio with increasing distance is especially noticeable amongst impacted sites on Chevron property (Figure **9**). A two-sample t-test was conducted in order to compare the difference in mean distance from impact between study reaches in the Chevron and UNF study regions. A statistically significant difference (p-value = 0.005) exists between the mean distance from impact in the Chevron study region (mean distance to impact = 34.1 meters) and the UNF study region (mean distance to impact = 13.4 meters). In general, impacts resulting from energy development in the Chevron study region are located farther from headwater streams than impacts resulting from National Forest use and maintenance.

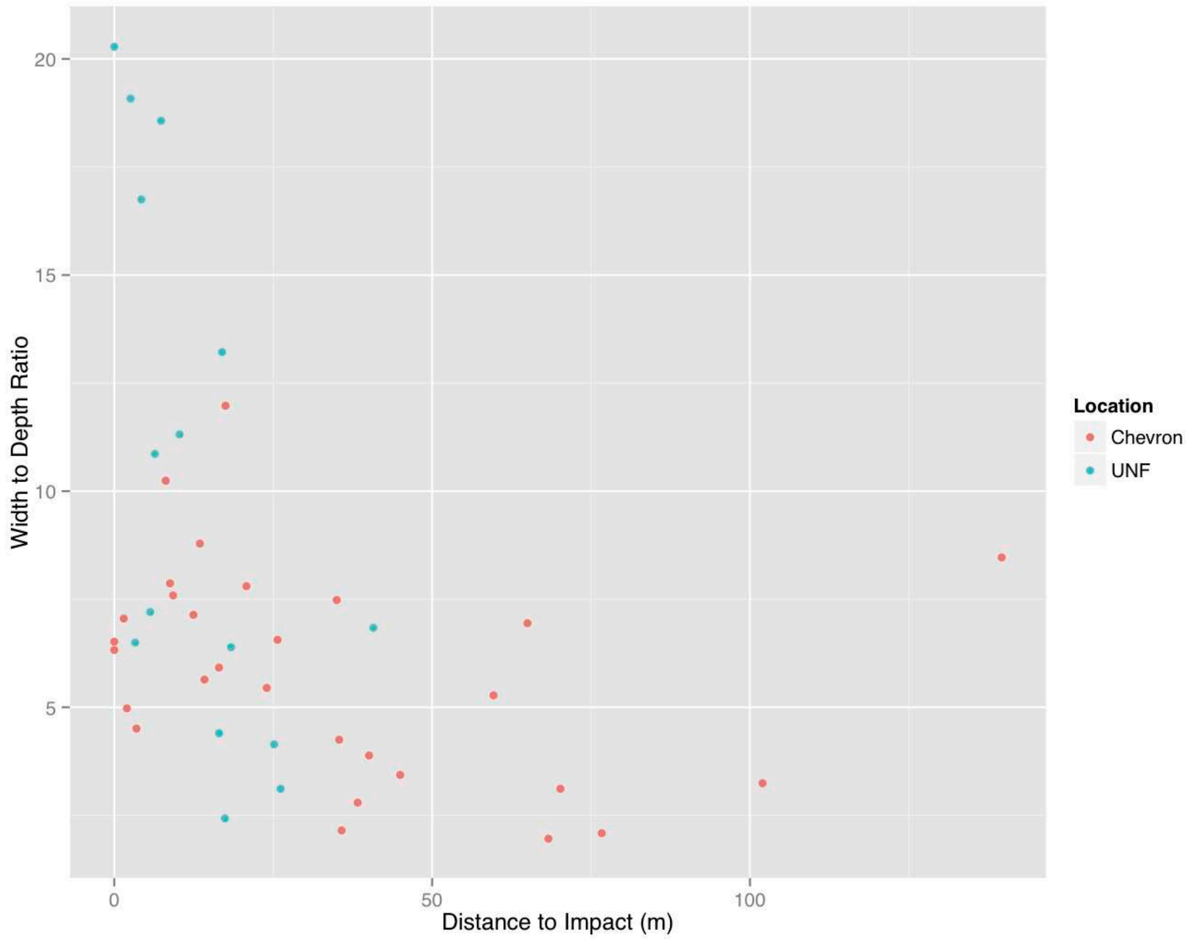

Figure 9**: Distance to impact as a continuous variable.**

It is apparent from Figure **9** that the width to depth ratio of reaches is generally higher when the impact is within 20 meters of the study reach. Additionally, more than half of the impacted streams were within 20 meters of the impact. In order to further investigate the role of proximity to impact on headwater stream morphology, streams with impacts within 20 meters of a study reach were considered "near" impacts, and impacts greater than 20 meters from a study reach were considered "far" impacts. The effects of near versus far impacts on the width to depth ratio of study reaches were examined (Figure 10). The only groups found to have statistically significant differences were Chevron Impacted Far and UNF Impacted Near and Chevron

Impacted Far and UNF Reference. These differences are between sites with distant impacts and near impacts or reference sites, which implies that factors other than the presence of human impacts are causing the differences in channel morphology between these groups. If proximity to roads or other development had the greatest influence on channel morphology, statistically significant differences would be expected between the Chevron Impacted near group and the reference sites at both the Piceance and UNF study regions; no statistically significant differences in width to depth ratio were found between these groups of data. Based on visual assessment of the boxplot comparing near and far impacts (Figure 10), differences may exist between the groups Chevron Impacted Far and Chevron Impacted Near. The pairwise comparison between these two groups is close to statistical significance with a p-value of 0.0525.

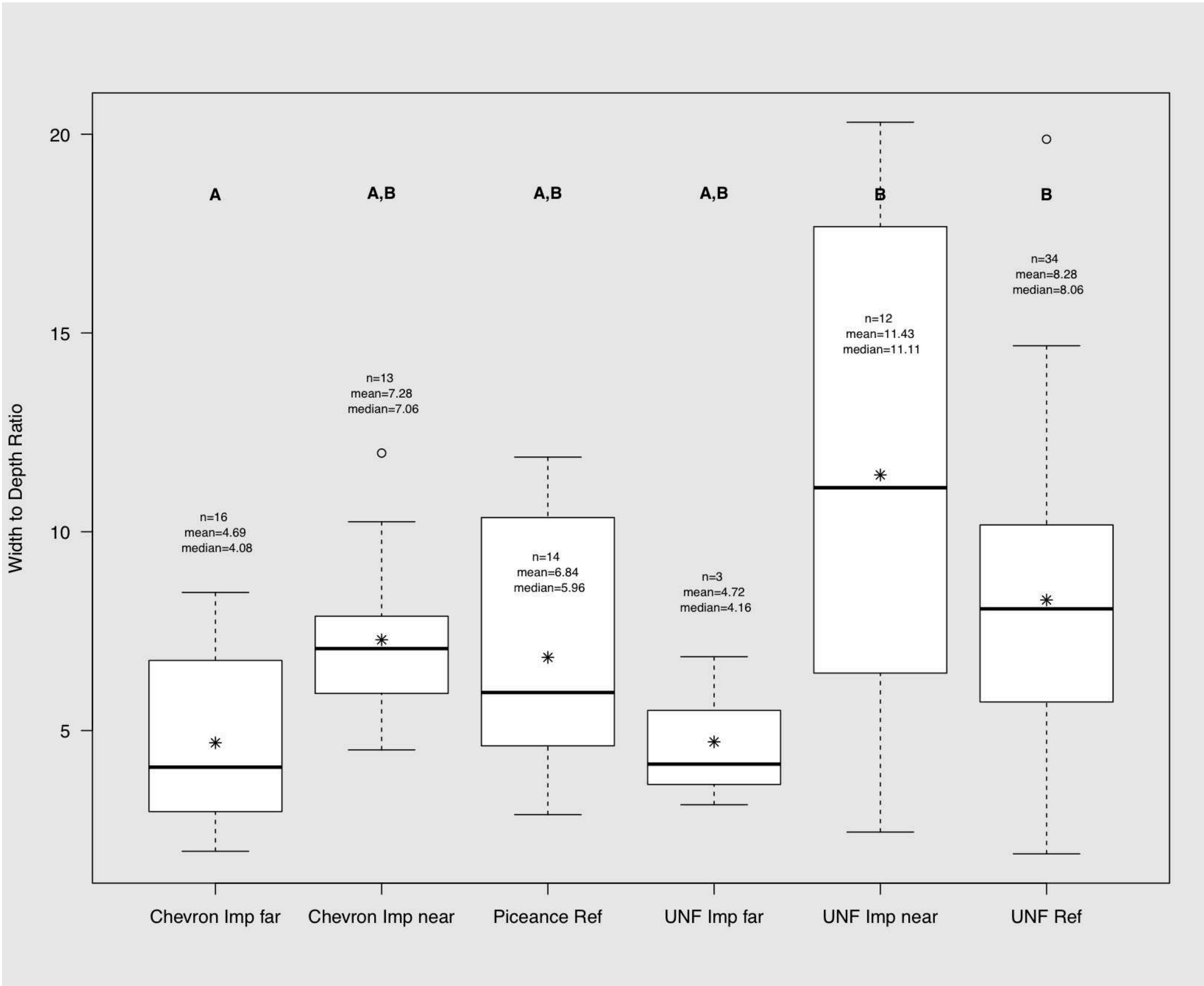

Figure 10: Comparison of width to depth ratios by location and distance to impact. "Near" sites are closer than 20 meters to the impact; "far" sites are greater than 20 meters to the impact. Imp = Impacted; Ref = Reference. The capital letters (i.e., A and B) represent statistically similar and different groups; groups with statistically significant differences in width to depth ratios are marked with different letters.

It is possible that the influence of impacts decreases with distance from a stream. In order to explore this possibility, reaches with impacts at distances greater than 20 meters were classified as “distal” and grouped with reference reaches (Figure 11). Figure 11 illustrates that Chevron Impacted reaches within 20 meters of the impact are not significantly different from either Piceance Reference reaches or UNF Distal and Reference reaches. However, Chevron Impacted reaches within 20 meters of the impact have statistically significant different mean width to depth ratios from Chevron Distal reaches (p-value = 0.0414). This supports the observation from Figure 10 that Chevron Impacted Near and Chevron Impacted Far study reaches appear different, even though they are not statistically different. This indicates that locating industry construction (roads, drilling pads, or other infrastructure) farther from headwater streams may be beneficial in mitigating impacts to these headwater streams.

The grouping of data from the Chevron study region did not change; only the names of the groups changed. The change in results when comparing Chevron Impacted reaches based on distance to impact occurred because of correcting for multiple comparison problems. When pairwise comparisons are made using the R package lsmeans, a Tukey adjustment is used to account for multiple comparison problems. The Tukey adjustment takes into account the number of comparisons made such that when the number of comparisons decreases, the power of the test to detect significant differences increases. The change in the results of pairwise comparisons occurred because when Distal impacts are grouped with Reference reaches for the data from the UNF study region, the number of groups decreases from 6 (Figure 10) to 5 (Figure 11) and the pairwise comparison test had more power to detect differences between Chevron Impacted and Chevron Distal reaches.

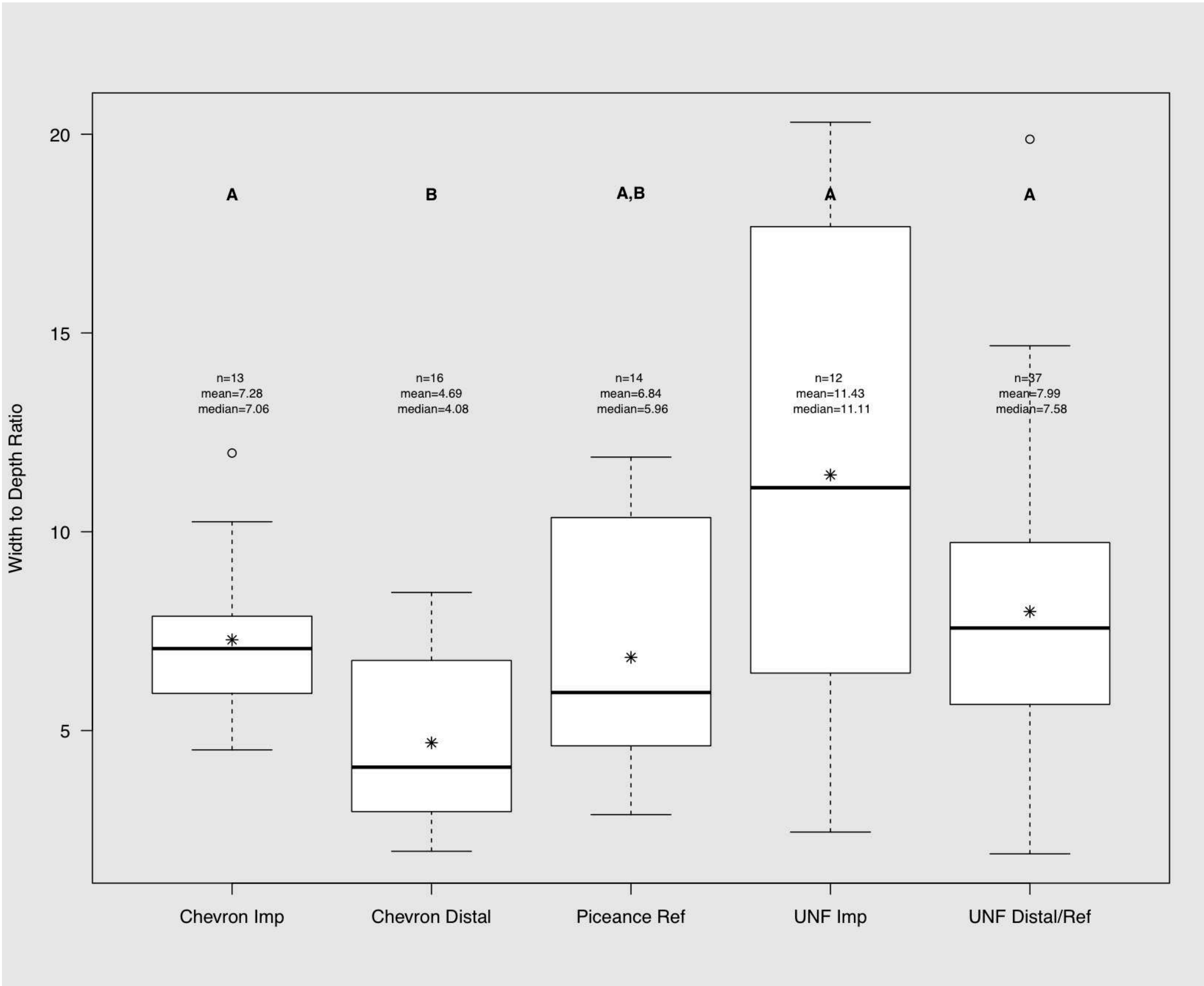

Figure 11: Comparison of width to depth ratios by location and distance to impact. Sites are considered impacted if the impact is located closer than 20 meters to the stream. "Distal" sites are greater than 20 meters to the impact and are grouped with reference reaches. Imp = Impacted; Ref = Reference. The capital letters (i.e., A and B) represent statistically similar and different groups; groups with statistically significant differences in width to depth ratios are marked with different letters.

5.5. Multiple Linear Regression

A multiple linear regression was conducted to explore the importance of the independent variables. A model was produced using the variables drainage area, class (impacted or reference reach), gradient, location (study region), lithology, flow regime, elevation, percent vegetation cover, and type of vegetation cover. The width to depth ratio was used as the response variable. The model was created using untransformed data. The variable of class, specifically whether the stream was a reference reach, was the only significant predictor (p-value = 0.036).

5.6. Summary of Results

Hypothesis 1 was partly supported in that the mean width to depth ratio differed between Chevron Impacted and all Reference reaches. However, the mean width to depth ratio for Chevron Impacted did not differ significantly from reference reaches in the nearest region, Piceance Reference, indicating that Hypothesis 1 is not supported. No evidence of significant differences between the width to depth ratios of impacted streams underlain by sandstone or shale was found, indicating that Hypothesis 2 was also not supported. Hypothesis 3 was not supported, as no statistically significant differences were found among impacted and reference streams with shallow gradients. Additionally, there is a relationship between proximity to impact as a continuous variable and the width to depth ratio of reaches; with increasing distance to an impact, the width to depth ratio decreases. Furthermore, when distal impacts are considered as analogous to reference reaches, the smaller number of pairwise comparisons allowed for increased power of detecting differences. Chevron Impacted and Chevron Distal study reaches have statistically significant different mean width to depth ratios. This indicates that locating development farther from headwater stream reaches is valuable. Finally, the results of multiple linear regression indicate that whether a stream is a reference reach, versus an impacted reach, is the most significant predictor for width to depth ratio.

6. DISCUSSION

This study has shown very limited connection between energy development and altered channel morphology of headwater streams. Initial analysis does show a statistically significant difference between reference reaches and impacted reaches. Although this difference is likely due to regional differences between the UNF study region and the Chevron study region, there is additional limited evidence of the influence of impacts on headwater stream morphology. When distance to an impact is considered as a continuous variable, a noticeable trend is present: as distance to the impact increases, the width to depth ratio decreases. Furthermore, multiple linear regression suggests that whether a stream is a reference reach has the most significance in predicting width to depth ratio. These trends indicate that even though this dataset does not demonstrate statistically significant differences between reference and impacted reaches, differences are present. There are complicating underlying factors that may have affected the outcomes of this study and obscured the investigation of significant differences between reference reaches and those impacted by energy development. Some of these factors are discussed in the following sections. Additionally, the applicability of the conceptual model presented Section 3.2.2 (Figure 1) is discussed. Because this study did not find strong connections between energy development and altered channel morphology, it was not possible to address the study's secondary objectives of developing a protocol for remotely predicting stream characteristics and creating management recommendations.

6.1. Natural Variability Among Headwater Streams

The infinite combinations of morphology, roughness, slope, stream order, and planform lead to the high spatial variability of headwater streams. Additionally, the topography and vegetation cover varied greatly within the relatively small study regions of this project. The data collected represent many different channels, including, for example, ephemeral channels, perennial streams, forested channels, grassy swales, dense riparian vegetation, nearly bare banks, low gradient valleys, and steep hillslopes. Despite the large dataset collected for this study (94 study reaches), this dataset may not fully represent the variability present in the study regions. A larger dataset may have allowed for further stratification of the data in order to compare between increasingly specific channel types or channel characteristics.

6.2. Naturally High Sediment and Water Yields

Due to their location in the uplands, headwater streams are typically bordered by steep hillslopes and characterized by higher rates of precipitation. These areas are known as sediment production zones, where sediment is transported from the hillslopes into the channels (Schumm, 1977). Because of this, headwater streams tend to have naturally high sediment and water yields, delivered to headwater streams episodically (Benda et al., 2005). This may have contributed to the inconclusiveness of the analyses presented in this study. As the natural system has high water and sediment yields, an increase in these yields due to road or drilling pad construction may not have a measureable effect upon the channel form parameters analyzed here.

6.3. Imperfect Reference Reaches

The lack of significant differences between impacted and reference reaches may also be due to imperfect reference reaches. Ability to select and access study reaches of all categories was severely constrained by patterns of land ownership and land use in this portion of western Colorado. Study reaches in the UNF study region were selected and surveyed based on lithology, elevation, and accessibility prior to initial field work in the Chevron property study region. Many of these study reaches are reference reaches. Once field work commenced in the Chevron study region, however, it became apparent that the landscapes in these two study regions differ; for example, the plateau of the Chevron study region appeared much more dissected, with fewer forested regions, than the UNF study regions. This impression was supported by the data analysis. As detailed in the Results section, the width to depth ratios of study reaches located in the Chevron study region were significantly different from the width to depth ratios of both impacted and reference study reaches located in the UNF study region. This indicates a regional difference between these two study regions, rather than differences based on the presence or absence of impacts.

The idea of imperfect reference reaches is also imperfect, however, because reference study reaches were analyzed from the PSWA. The PSWA study region was much closer geographically and looked similar to the Chevron study region. These PSWA study reaches were not significantly different from those located in the Chevron study region. Therefore, the imperfect reference reaches does not entirely explain the lack of statistically significant differences between reaches impacted by energy development and reference reaches. Fourteen reaches were surveyed in the PSWA study region, so this small sample size may have influenced these results. If this study were repeated, it would be worthwhile to consider selecting more reference reaches within the PSWA study region or adjacent public lands.

6.4. Legacy Effects

Headwater streams lacking immediate visible proximity to disturbance were used as reference reaches in this study. Despite this, there are likely no truly undisturbed reaches located in the study regions of this project. European trappers and settlers began altering the watersheds of these regions through beaver trapping, grazing, and other settlement activities in the early 1800s (Mehls, 1982). Furthermore, all of the study regions used in this project are subject to cattle grazing, which has been shown to affect channel morphology through direct changes by trampling, decreased resilience to larger floods, and indirect changes by soil compaction, decreased infiltration, increased runoff, and increased sediment yield (Trimble and Mendel, 1995). As such, it is possible that the channel morphology (width to depth ratio) of the study reaches is most affected by influences other than the presence of roads, drilling pads, and other infrastructure.

6.5. Small Study Regions

Due to safety concerns, accessibility and time restraints, and the number of channels present on the property the reaches sampled on Chevron property came from a limited area and number of streams. Commonly, multiple reaches were sampled along the same headwater stream. When this occurred, attempts were made to collect samples far enough downstream from the previous study reach such that the drainage area approximately doubled, but this was not always possible. Therefore, the limited geographic sampling area and sample size and closely spaced study reaches may have led to the inconclusiveness of the analyses presented here.

6.6. Conceptual Model

The conceptual model presented in Section 3.2.2 (Figure 1) summarized the hypothesized consequences of energy development on headwater stream channel morphology. The data do not support the use of this conceptual model in this region. The inconclusive nature of the results of this study precludes the development of a conceptual model for the impacts of energy development or forest roads on headwater streams.

6.7. Management Recommendations

In the Chevron study region, there are numerous retention ponds located at the edge of roads. These ponds are intended to capture runoff and sediment and provide water for livestock and wildlife. The ponds are dredged periodically. Monitoring and studying the frequency of dredging and the amount of sediment dredged from these ponds could provide valuable information about how much sediment these ponds are accumulating and the effectiveness of this mitigation method. These ponds may be preventing significant water and sediment yields to the headwater channels in the Chevron study region and quantifying the sediment accumulation would provide valuable management information.

Channels proximal to an impact (within 20 meters) tend to be wider and shallower than other reaches. Furthermore, there is a statistical difference between Chevron Impacted reaches within 20 meters of an impact and Chevron Distal reaches that are farther than 20 meters from an impact. This indicates that it is valuable to locate development at distances greater than 20 meters from a headwater channel. Doing so may mitigate any potential impacts to headwater channels. The mean distance from an impact to a channel in the Chevron study region is 34.1 meters; it is likely that locating development at least 20 meters away from streams would not create significant obstacles to property management and operations.

7. CONCLUSIONS ABOUT ENERGY DEVELOPMENT AND HEADWATER STREAMS

This study has shown very limited connection between energy development and altered channel morphology of headwater streams. This may be due to either the simple fact that the emplacement of roads, drilling pads, and other infrastructure has not significantly altered the water and sediment yields or that the headwater streams in this region are resilient to any changes in water and sediment yields. There are numerous complicating factors that may have also affected the outcomes of this study and would warrant further investigation in any future research of the impacts of energy development. Although this study found limited correlation between energy development and altered channel morphology, differences between channels located within 20 meters of an impact and channels with more distal impacts were detected. Placing construction at a distance of 20 meters or greater from headwater streams may mitigate any potential effects of development until further analysis can be conducted. Further research should consider utilizing a larger dataset and more targeted reference reaches, in order to subset the data according to specific characteristics and retain large sample sizes in each subset. Additionally, future research should attempt to survey more reaches on independent channels in the Chevron study region, so that there is no concern about sampling the same stream multiple times. The inconclusiveness of this study and the number of complicating factors impacting this dataset indicates that this research is worth refinement and replication.

8. INTRODUCTION TO CHANNEL HEADS

Delineating and understanding the formation of channel heads is important for understanding and managing headwater stream systems (Jaeger et al., 2007). Previous studies conducted to analyze channel initiation have focused in humid regions of the United States (Montgomery and Dietrich, 1988) or on the eastern side of the Rocky Mountains in Colorado (Henkle et al., 2011). This study maps channel heads and examines potential surficial controls such as contributing drainage area and mean basin slope on channel initiation. These data are then compared with existing channel head data sets from other geographic regions.

8.1. Background

The importance of headwater streams to the health of the watershed network points to the necessity of understanding the location and processes of headwater channel initiation for management purposes. A channel head defines the upstream-most point of a longitudinally continuous channel delineated by the presence of a bed and channel banks, where the unchannelized hillslope changes to the channel network (Montgomery and Dietrich, 1988; 1989). The channel head does not necessarily coincide with stream flow; the stream head is defined as the location below which perennial flow occurs (Jaeger et al., 2007). Channel initiation is driven by either surface or subsurface flow, though in both instances the topography or the stratigraphy concentrates the flow enough to initiate channelization.

Previous research has demonstrated relationships between the channel head location and the contributing drainage area, the valley slope upslope of the channel head, and the length of the contributing basin. Montgomery and Dietrich (1988; 1989) demonstrated inverse relationships between local valley gradient and contributing drainage area and basin length, such that as the local valley gradient increases, both the contributing drainage area and basin length decrease. This relationship was found for steep, humid study regions (Montgomery and Dietrich, 1989). The inverse relationship between contributing drainage area and local gradient is exhibited most strongly in humid regions, although it is also present in more arid regions, such as the semiarid Colorado Front Range (Henkle et al., 2011). Henkle et al. (2011) found a weak inverse relationship between contributing area and local gradient, and no significant relationship between basin length and local gradient. In the semiarid Colorado region, surface topographic parameters such as local slope and contributing area do influence channel initiation, but have less of an effect than in wetter regions. In areas where the inverse relationship between contributing drainage area and local gradient was weak or nonexistent, fractured bedrock, subsurface topography, or other local factors may be controlling channel initiation (Jaeger et al., 2007; Henkle et al., 2011).

In these studies, the inverse relationship between contributing area and local gradient did not hold true upslope of the channel head, indicating that channels only initiate when a drainage area threshold has been passed and there is enough runoff to support a channel (Montgomery and Dietrich, 1988; 1989). Furthermore, Montgomery and Dietrich (1988) posited that, for a given gradient, the contributing drainage area upstream of a channel head would increase as precipitation decreases because runoff increases with contributing area and a larger contributing area would produce sufficient runoff to initiate a channel. In the Front Range, a drainage area of 10,000 m^2 was found to be the threshold of erosion for channel initiation (Henkle et al., 2011).

8.2. Research Objectives

The location of channel head initiation has been shown in some regions to have a relationship with surface topographic parameters such as local gradient, contributing drainage area size, and contributing basin length. These parameters are considered in the objectives presented here. The primary purpose of investigating channel initiation is to map the locations of channel heads and analyze potential controls, such as contributing drainage area and local basin slope, on the formation of channel heads in western Colorado. These data are compared with existing channel head datasets from other geographic regions to test for regionally significant differences in contributing drainage area, basin length, and local slope. Four primary objectives are considered.

8.2.1. Objective 1: Subsurface versus Surface Flow

Objective 1: Examine the effects of subsurface and surface flow on channel head characteristics.

The first objective considers the differences between channel heads with evidence of subsurface flow or surface flow. Jaeger et al. (2007) determined that in some locations subsurface processes can have a greater influence on channel initiation than surface topography and processes. If subsurface topography or processes are controlling channel initiation, contributing drainage area can be much larger as surface runoff is not driving erosion and channel head formation. It is expected that channel heads initiating due to subsurface flow will have larger contributing drainage areas and longer basin lengths. If subsurface flow dominates, this will likely also affect the local gradient of a channel head. If subsurface topography or processes are controlling channel initiation, it is likely that gradient will not control initiation and channel heads can form on much shallower slopes.

8.2.2. Objective 2: Lithology

Objective 2: Examine the effects of the underlying lithology on channel initiation.

The second objective considers whether the underlying lithology, shale or sandstone, has an effect on channel initiation and channel head parameters. Shale tends to have lower porosity and permeability than sandstone, which would lead to higher rates of runoff during precipitation events. This could cause more efficient concentration of runoff, such that the threshold of erosion is reached with a smaller contributing drainage area than in areas underlain by sandstone lithology. Because of this, it is expected that channel heads with underlying shale lithology will have smaller contributing drainage areas and shorter basin lengths than channel heads with underlying sandstone lithology.

8.2.3. Objective 3: Gradient

Objective 3: Examine the effects of the local gradient on the necessary contributing drainage area and basin length for channel initiation.

Previous research has demonstrated an inverse relationship between drainage area and gradient, and between basin length and gradient (Montgomery and Dietrich, 1988; 1989). Although much of this research occurred in more humid regions, it is expected that a similar trend will exist for western Colorado. It is predicted that as gradient increases, a smaller contributing area is required to accumulate enough flow to cause channel initiation. Similarly, it is likely that as gradient increases, the basin length will be shorter. The direction of these relationships between gradient and contributing area and basin length is expected to match previous studies; this relationship, however, is likely to reflect the differences in climate amongst study regions.

8.2.4. Objective 4: Comparison with other datasets

Objective 4: Examine differences between channel heads in different study regions by comparing this dataset to published datasets.

The last objective investigates whether regional differences, primarily climatic influences, causes noticeable differences in the channel head parameters between western Colorado and study regions from previous studies. It is predicted that there will be significant differences between the gradient-contributing area relationships and gradient-basin length relationships in western Colorado and other study regions. The climate of western Colorado is more arid than the climate of study regions from previous investigations. This could lead to differences in the relationship curves for these regions. It is expected that in drier regions, for a given gradient, a larger contributing drainage area, and thus longer basin length, is required to accumulate enough flow for channel initiation. Regional differences based on climate aridity have been found in previous research (Henkle et al., 2011).

8.3. Study Area

All channel head data were collected in the Uncompahgre National Forest study region (Figure 12). Refer to Section 3.3.2 for details of the study area.

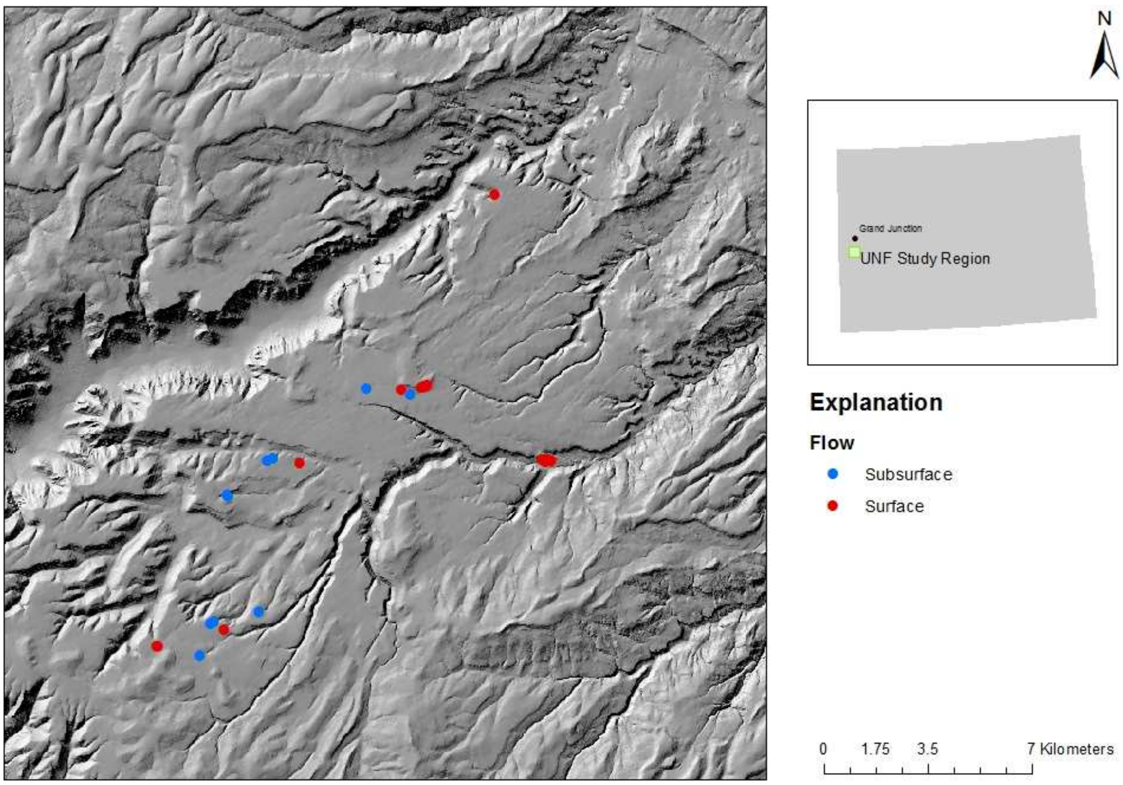

Figure 12: Location map of channel heads in the Uncompahgre National Forest. Channel heads are colored according to the flow type that initiated the channel head.

8.4. Datasets from Published Studies

The channel heads from western Colorado will be compared with channel head datasets from published studies on channel initiation. These datasets are from a variety of study regions that encompass a range of climates and lithologies. The datasets used for comparison are from the Colorado Front Range (Henkle et al., 2011), North Carolina (Jefferson and McGee, 2013), the Mid-Atlantic (Julian et al., 2012), and central California (Montgomery and Dietrich, 1989). Most of these regions receive greater mean annual precipitation than western Colorado. Information about these study regions is presented in Table 2.

Table 2: Study regions of published channel head data. Precipitation values were taken from the published papers.

Dataset	Mean Annual Precipitation (mm)	Number of channel heads
Western Colorado	288	38
Front Range	430-1000	78
North Carolina	1140-1180	100
Mid-Atlantic	--	253
Central California	760	63

9. METHODS

A total of 38 channel heads were selected for analysis. Twenty-five of these channel heads had underlying sandstone lithology; 13 channel heads had underlying shale lithology. Ten of the channel heads had evidence of subsurface flow (e.g., amphitheater headcut); the remaining 28 had evidence of initiation due to surface runoff. The following sections describe all the methods used in this project. Section 9.1 describes the field methods used for data collection and the second section, 9.2, describes the spatial analyses used to attain additional parameter data. Section 9.3 details the statistical methods used to analyze these data.

9.1. Field Methods

At each channel head, a GPS point recording elevation and location was taken. Any evidence of surface or subsurface flow channel initiation, such as "amphitheater-shaped" channel heads or visible surface runoff, was recorded. Additionally, the presence and type of vegetation cover was categorized.

9.2. Spatial Analysis

The GPS coordinates of the channel heads were imported to ArcGIS and overlaid on a 10-meter digital elevation model (DEM) of the region. Sinks in the DEM were filled and the DEM was used to create a flow accumulation raster. The value of the pixel with the channel head point located on it was used to determine the contributing drainage area of each channel head.

Some of the channel head points did not fall exactly on a pixel indicating flow lines. This is likely due to error in the GPS point collection; these points were therefore moved to the closest flow accumulation pixel. The local basin slope was determined by taking the difference between the elevation of the DEM pixel immediately upstream of the channel head and the channel head's elevation, and dividing this by 10 meters, which is the width of a pixel (Jaeger et al., 2007). The basin length, from the drainage divide to the channel head location, was calculated using the flow length tool in ArcGIS. The flow length tool calculates the distance a drop of water would travel from the drainage divide to the selected pixel; this value is used as the length of the basin upstream of the channel head.

9.3. Statistical Methods

In order to evaluate channel initiation, channel heads were compared based on local gradient, drainage area, basin length, lithology, elevation, and surface or subsurface flow. All statistical analyses were performed using the R statistical package (R Core Team, 2014). Analyses were performed using a confidence level of 95%. Eight channel heads were removed, due to inaccurate collection of the GPS location.

The sample population was tested for normality using visual methods, such as histograms and qqplots, and the Shapiro-Wilkes test for normality (Royston, 1982). None of the variables had normal distributions; multiple transformations were considered, but none provided satisfactory normality. Because of this, non-parametric tests were used to analyze the data.

Boxplots and the non-parametric Wilcoxon Rank Sum test were used to compare the variables drainage area, local gradient, and basin length between sandstone and shale lithologies and between subsurface and surface flows. The Wilcoxon Rank Sum test is considered an approximate test of medians to determine whether the two populations are identical.

The data collected from the UNF study region were plotted on a scatterplot of gradient (x-axis) versus contributing drainage area (y-axis). Data from other studies were plotted on the same axes, in order to compare between study regions and examine the data for regionally significant trends. Quantitative relationships between these variables were also considered. Linear regression of the log-transformed data was conducted; the coefficients were then untransformed to yield the relationship equation in the form $Y=aX^b$; the method used for this is described in Section 16: Appendix B. Relationship equations were compared using the 95% confidence intervals of the coefficients. Overlapping confidence intervals indicate no statistically significant difference between the two relationships.

The contributing drainage area, local gradient, and basin length were also compared among the datasets from differing regions, using the R package lsmeans to make pairwise comparisons. Log-transformed data were used for these comparisons. The log-transformation did not achieve perfect normality of the dataset's distribution, but the histograms and qqplots indicated that it was a good approximation.

10. RESULTS

10.1. Objective 1: Subsurface versus Surface Flow

The effects of subsurface flow versus surface flow on channel initiation were examined using boxplots (Figure 13-15) and the Wilcoxon Rank Sum test. Statistically significant differences ($p\text{-value} < 0.05$) were found between the contributing areas, basin lengths, and gradients of channel heads with evidence of subsurface flow and channel heads with evidence of surface runoff. Channel heads with evidence of subsurface flow had statistically larger contributing drainage areas, longer basin lengths, and shallower local gradients than channel heads with evidence of surface runoff.

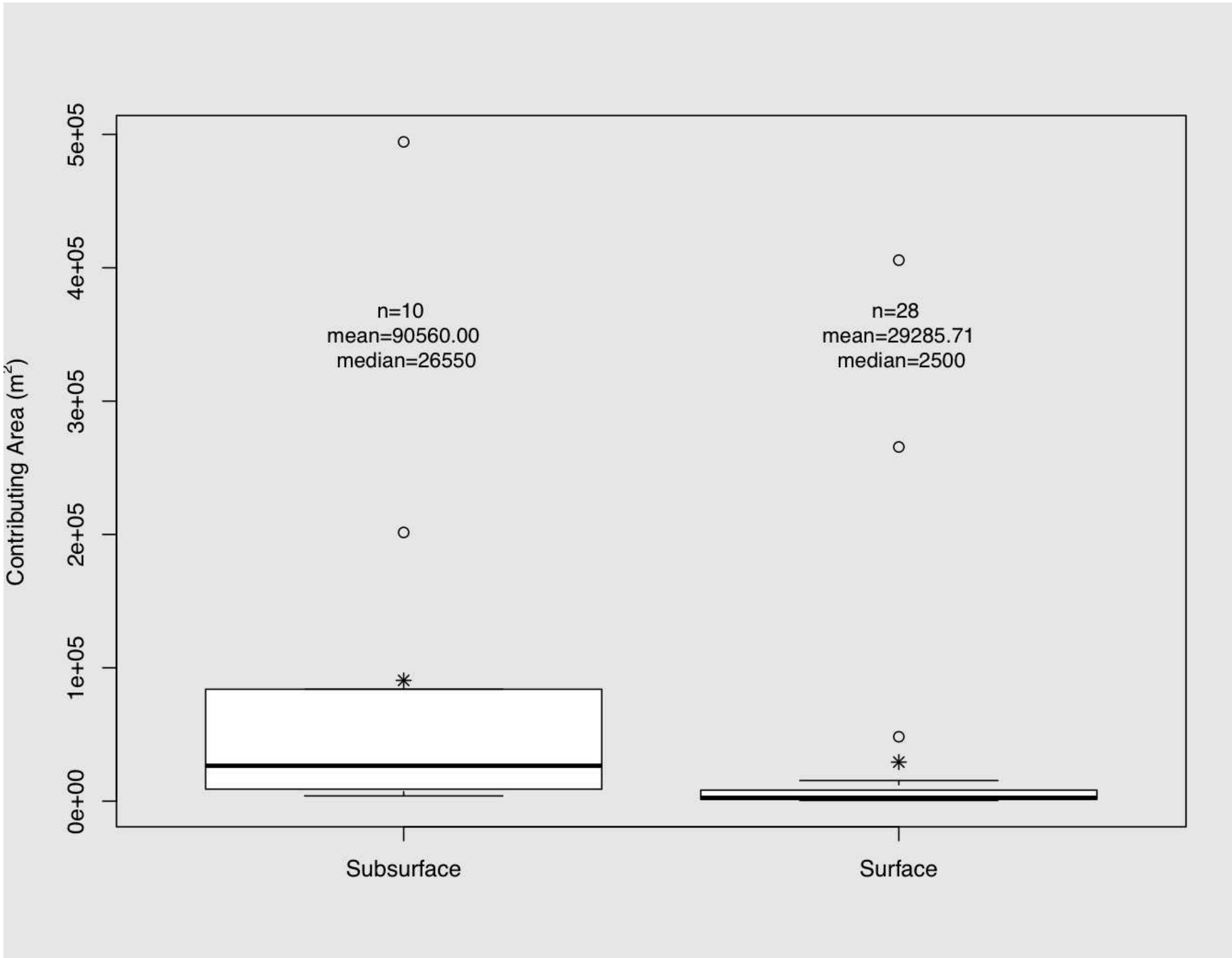

Figure 13: Comparison of the contributing drainage areas of channel heads with evidence of initiation due to subsurface and surface flow. Channel heads were characterized as initiating due to subsurface or surface flow based on field observations.

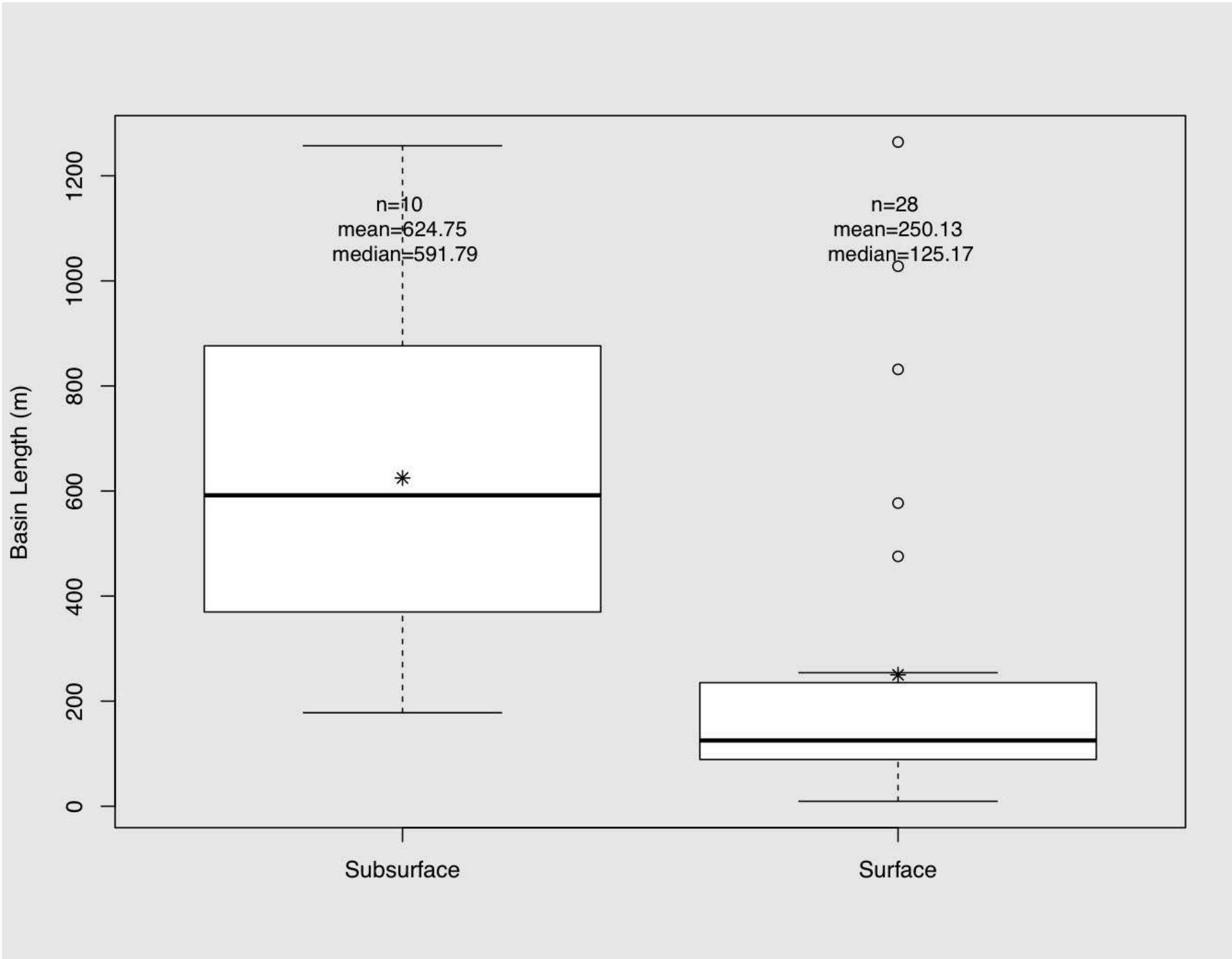

Figure 14: Comparison of the basin lengths of channel heads with evidence of initiation due to subsurface and surface flow. Channel heads were characterized as initiating due to subsurface or surface flow based on field observations.

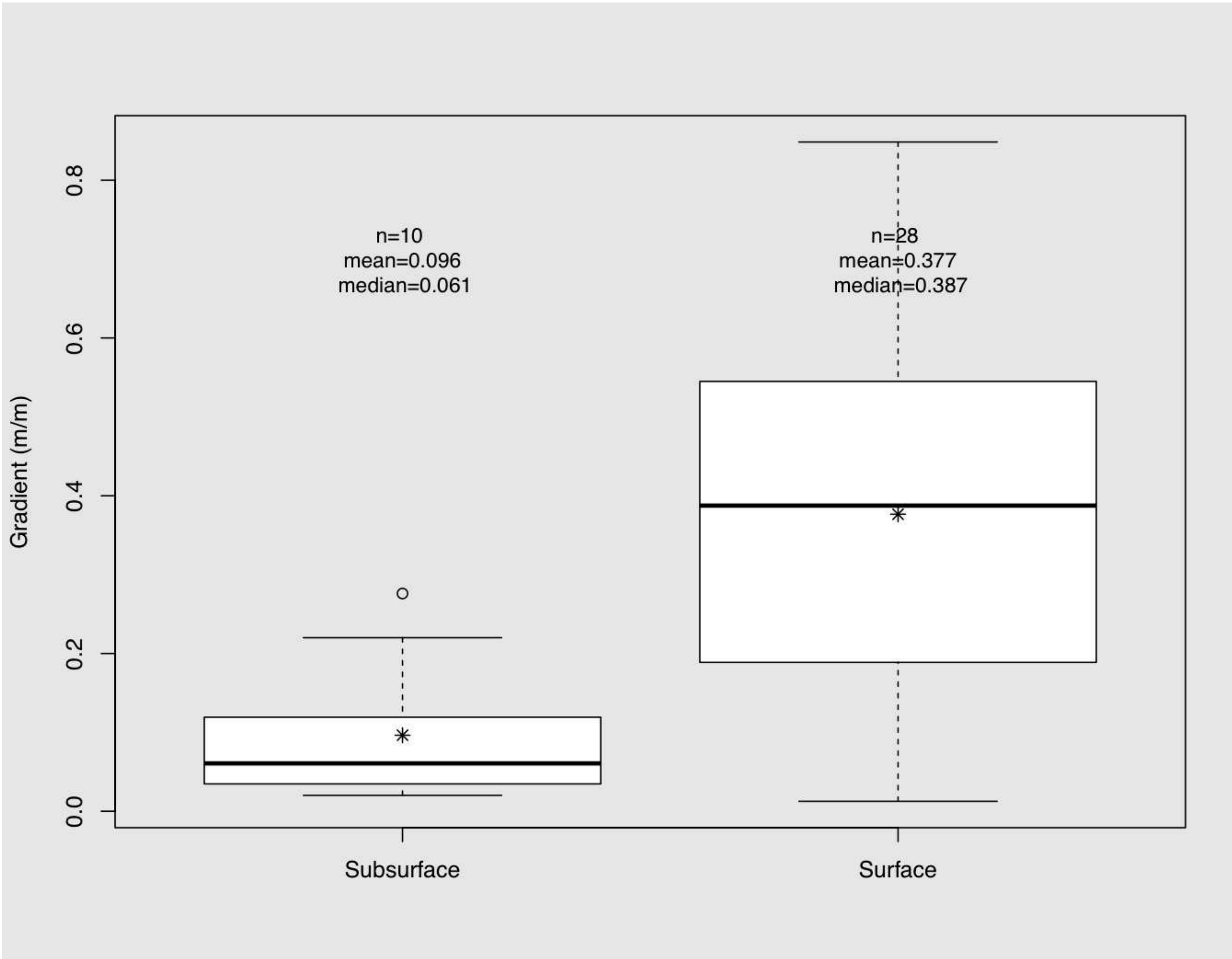

Figure 15: Comparison of the gradients of channel heads with evidence of initiation due to subsurface and surface flow. Channel heads were characterized as initiating due to subsurface or surface flow based on field observations.

10.2. Objective 2: Lithology

Potential differences of channel head parameters between channels with underlying shale and sandstone lithologies were examined using boxplots and the Wilcoxon Rank Sum test. Statistically significant differences (p-value < 0.05) were found between shale and sandstone channel heads for contributing drainage area, basin length, and local gradient (Figure 16-18).

Channel heads with underlying shale lithology had statistically smaller contributing drainage areas, shorter basin lengths, and steeper gradients than channel heads underlain by sandstone.

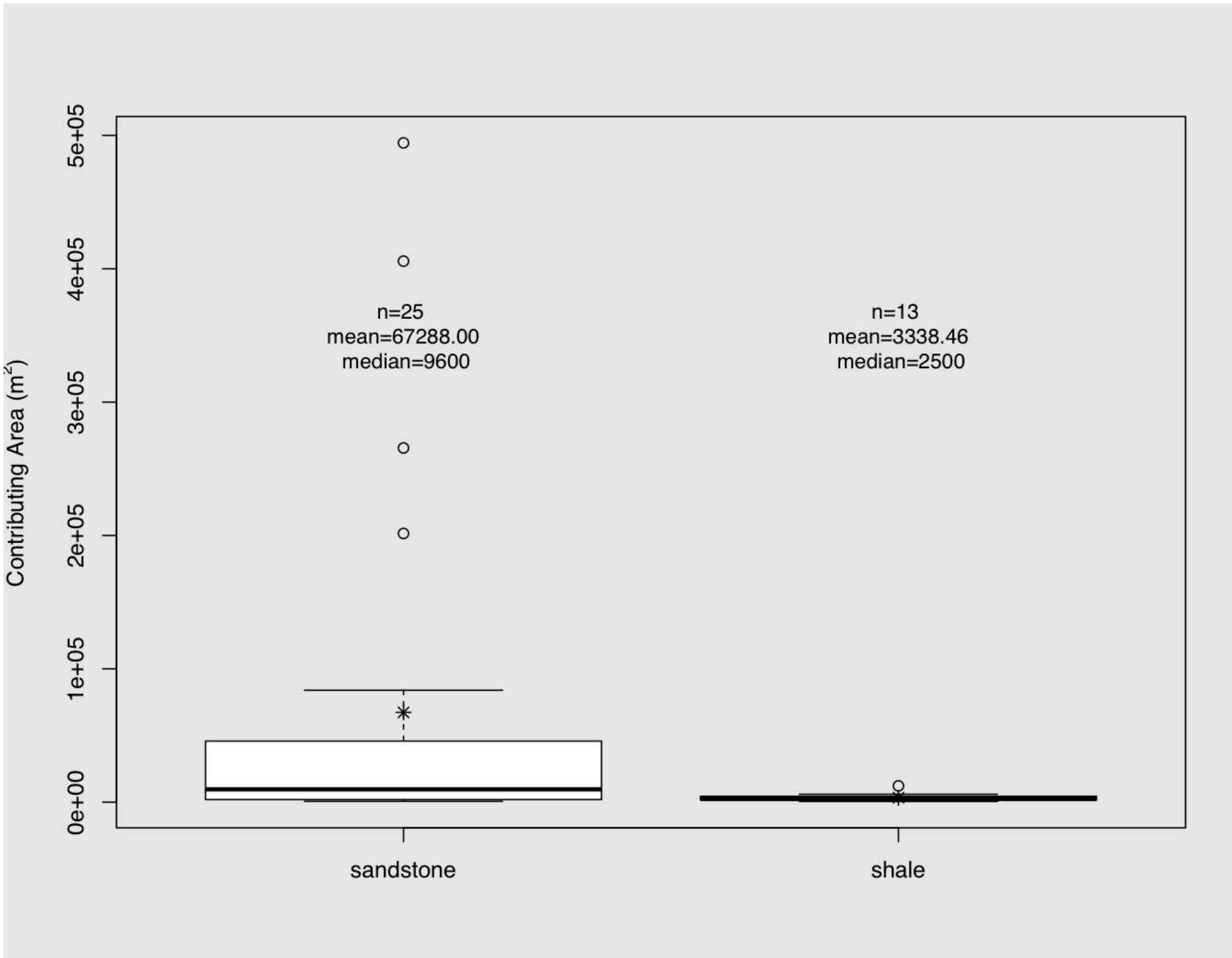

Figure 16: Comparison of the contributing drainage areas of channel heads with underlying sandstone and shale lithology.

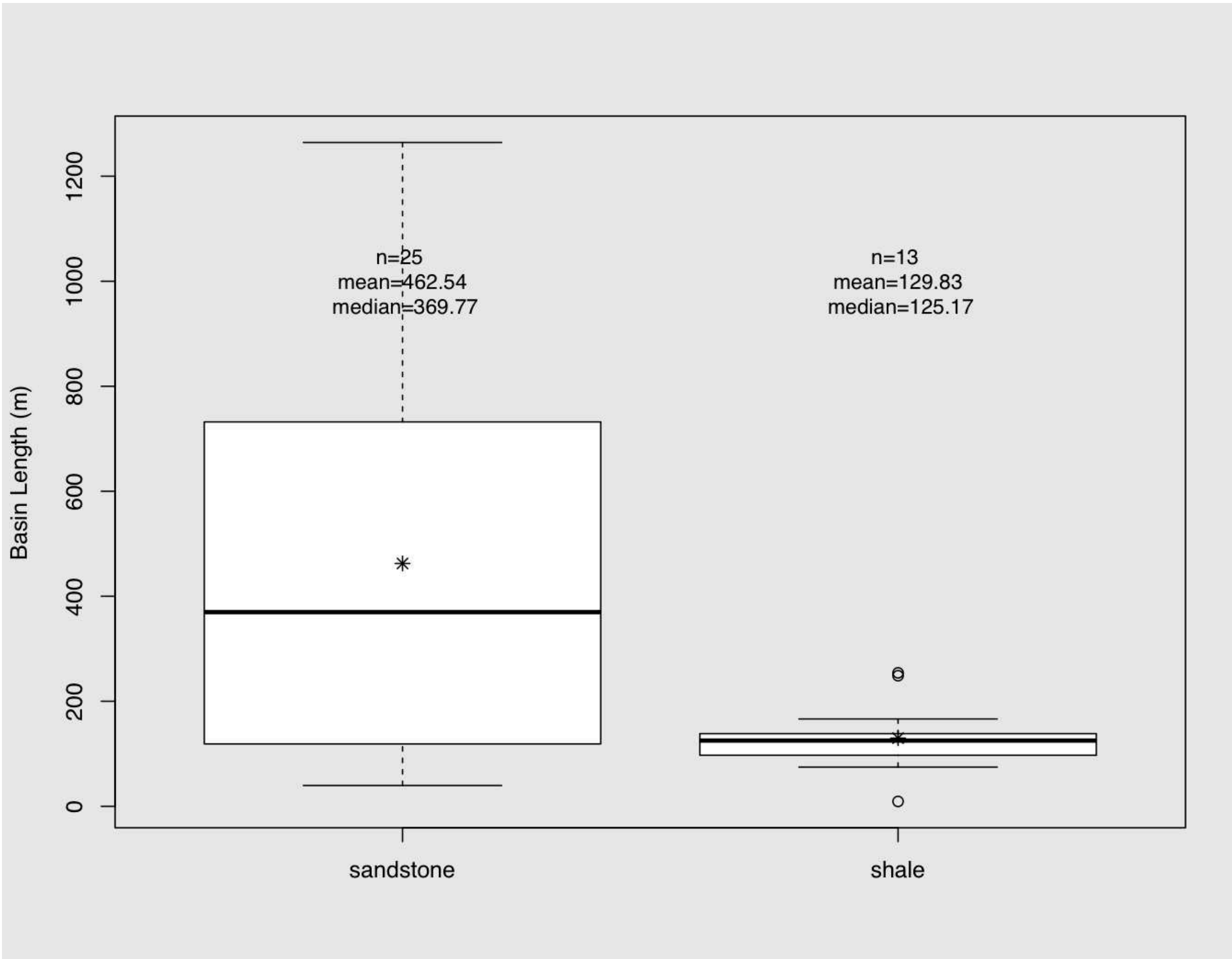

Figure 17: Comparison of the basin lengths of channel heads with underlying sandstone and shale lithology.

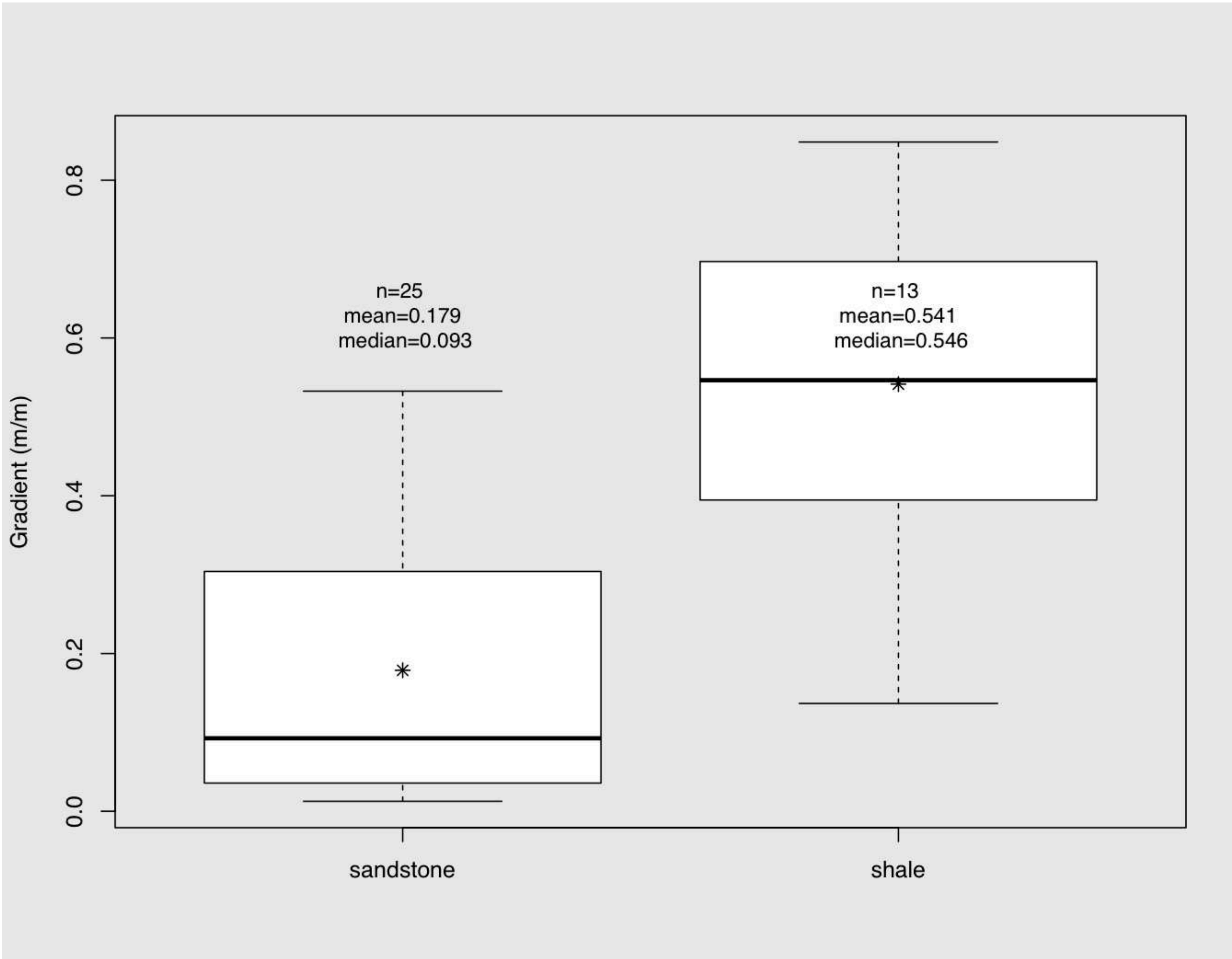

Figure 18: Comparison of the local gradients of channel heads with underlying sandstone and shale lithology.

10.3. Objective 3: Gradient

The effect of gradient on contributing area was examined by plotting the data points on a scatterplot of local gradient versus contributing area (Figure 19). It is apparent from this plot and the slope of the fitted regression line that as gradient increases, the contributing drainage area decreases. This relationship was expected based on previous studies and because a smaller contributing area is necessary to accumulate enough flow to initiate erosion when the gradient is steeper. Similarly, larger local gradients correlate with shorter basin lengths; as basin length is one dimension of contributing drainage area, these observations are closely related.

Regression lines were also fitted to the subsurface flow channel head data and the surface flow channel head data. Visually, it is apparent that channel heads initiated by subsurface flow plot differently than channel heads initiated by surface flow. The regression line for the subsurface data is not statistically significant, likely due to the small sample size (n=10) and wide range of variability. Despite this, the regression line provides a good representation of the differences between channel heads with evidence of subsurface and surface flow. Channel heads with evidence of subsurface flow do not closely follow the expected trend of decreasing contributing area with increasing gradient.

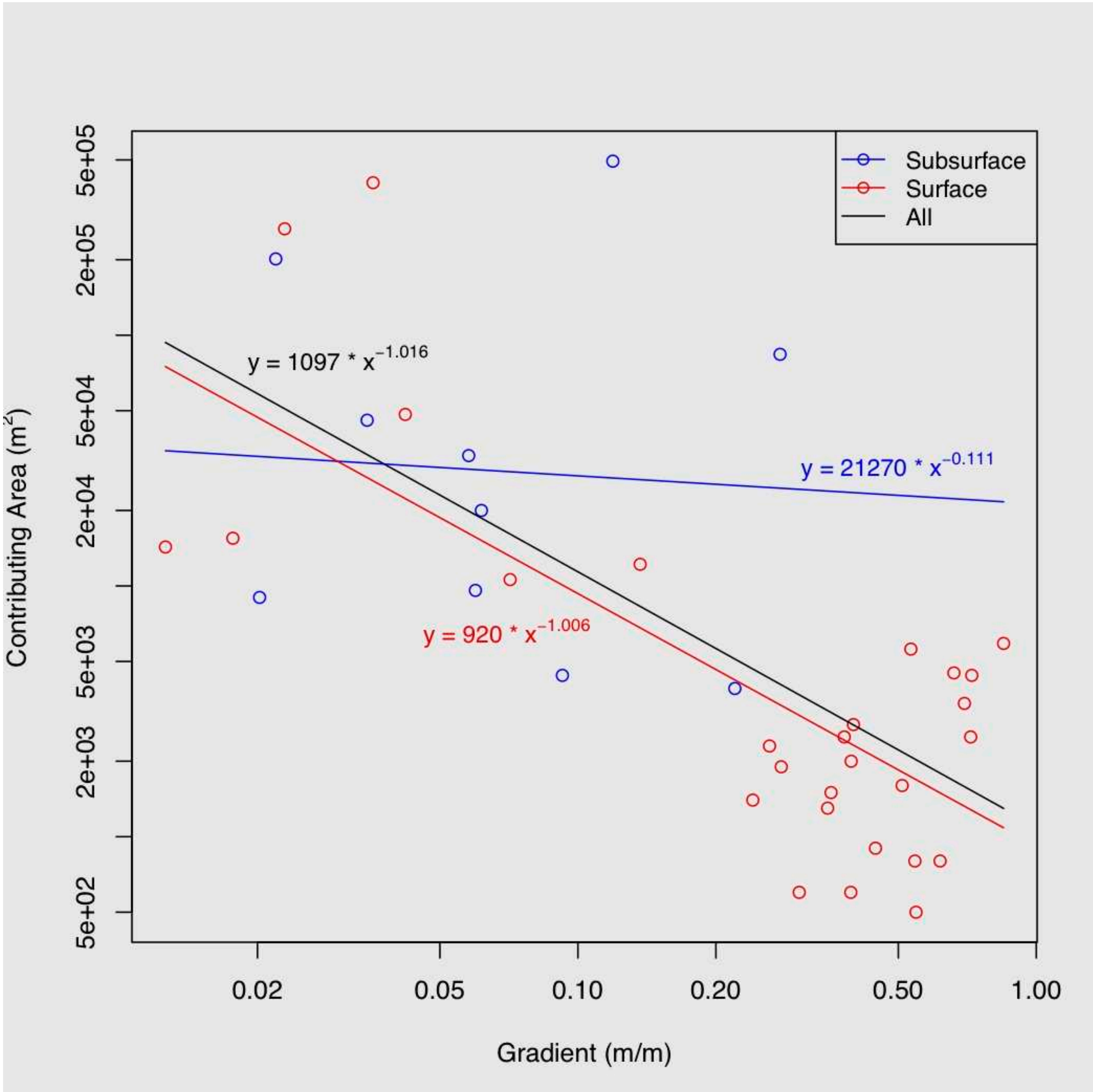

Figure 19: The gradient and contributing drainage areas of channel heads. Steeper gradients correlate with smaller contributing drainage areas. Data points are colored according to the type of flow that initiated the channel head.

10.4. Objective 4: Comparison with other datasets

The channel head data collected in western Colorado are compared with four other datasets from the Colorado Front Range, North Carolina, the Mid-Atlantic region, and central

California. In the following sections, these datasets are compared on the basis of contributing drainage area, basin length, and local gradient. Additionally, previous studies have developed regression relationships for gradient and contributing area, and for gradient and basin length. Similar relationships are developed for the data from western Colorado and compared to existing equations. For many of the comparisons, the western Colorado dataset is treated as two sets of data based on channel heads with evidence of subsurface or surface flow.

10.4.1. Comparison of contributing areas, local gradients, and basin lengths

The contributing area, basin length, and local gradient of each dataset were compared using boxplots and pairwise comparisons (Figure 20Figure 22). The contributing area of western Colorado channel heads with surface runoff is significantly smaller relative to the channel heads with subsurface flow, the Front Range dataset, and the Mid-Atlantic dataset. The channel heads with evidence of subsurface flow have significantly larger contributing areas than channel heads with surface runoff, channel heads in North Carolina, and channel heads in central California.

The local gradient of channel heads initiated by surface flow in western Colorado is significantly different from all other regions. The local gradient of channel heads initiated by subsurface flow is similar to sites in North Carolina and the Mid-Atlantic, but is statistically smaller than the gradient of channel heads located in the Front Range and central California, as well as channel heads in western Colorado initiated by surface runoff.

The basin length was only provided for the datasets from the Colorado Front Range and central California. Pairwise comparison of the log-transformed data indicated that the basin length of channel heads with evidence of surface runoff is statistically shorter than the basin lengths of Front Range and subsurface channel heads. The basin length of channel heads with evidence of subsurface flow is significantly longer than the basin lengths of the channel heads with evidence of surface flow and the channel heads in central California.

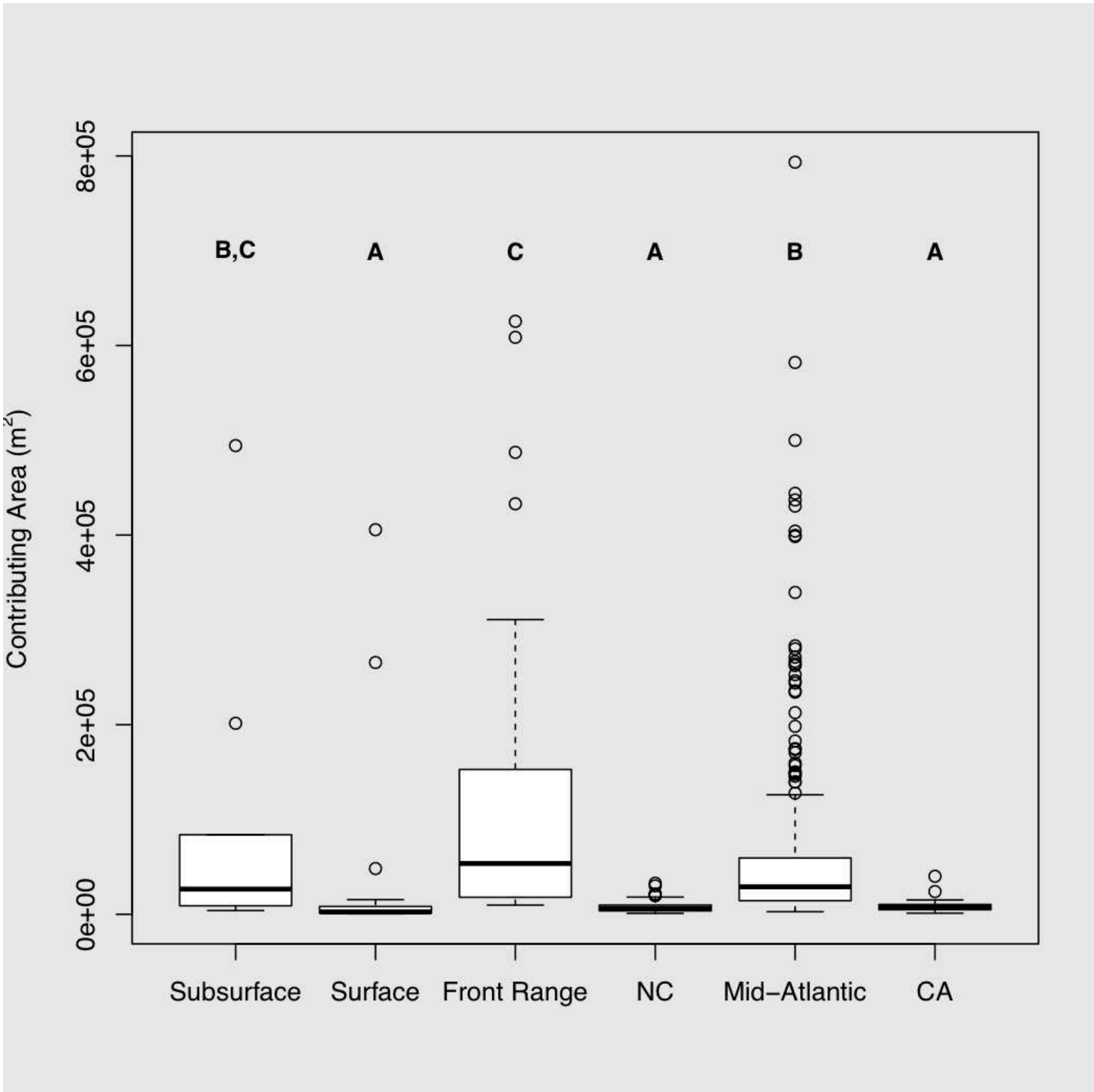

Figure 20: Contributing drainage area for all channel head datasets. The capital letters (i.e., A and B) represent statistically similar and different groups; groups with statistically significant differences in contributing area are marked with different letters. Differences between datasets were determined by pairwise comparisons of log-transformed data.

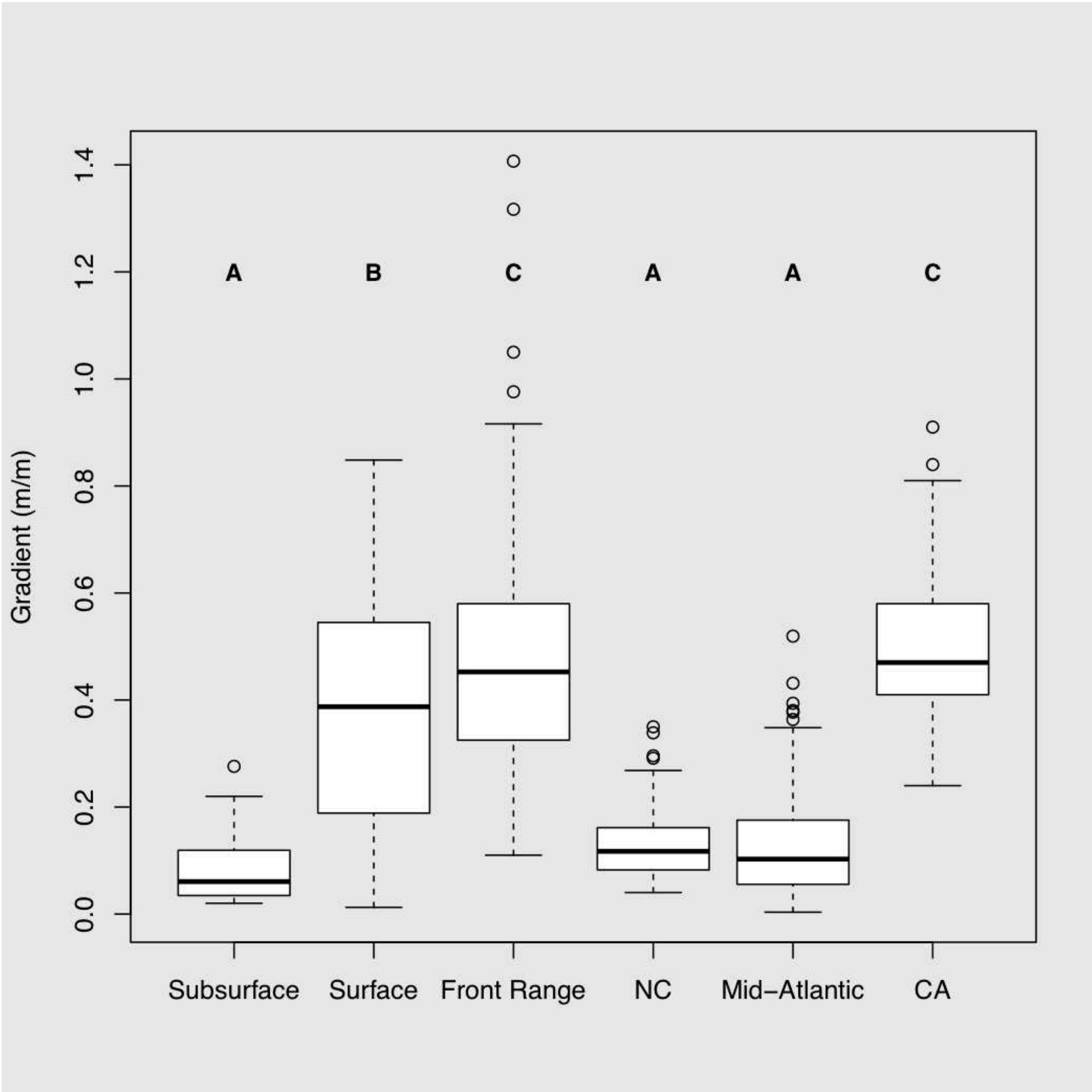

Figure 21: Local gradient for all channel head datasets. The capital letters (i.e., A and B) represent statistically similar and different groups; groups with statistically significant differences in contributing area are marked with different letters. Differences between datasets were determined by pairwise comparisons of log-transformed data.

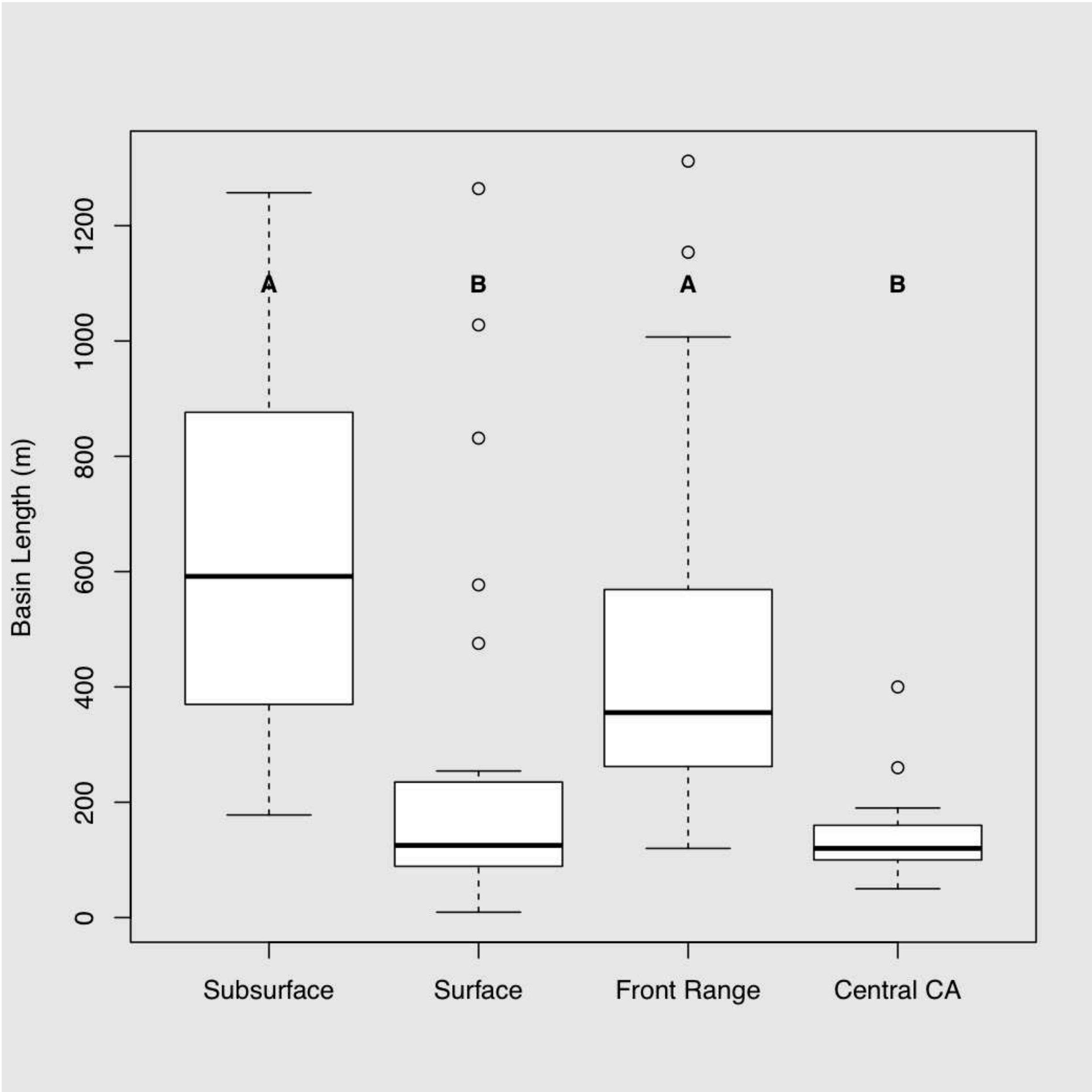

Figure 22: Basin length for all channel head datasets. The capital letters (i.e., A and B) represent statistically similar and different groups; groups with statistically significant differences in contributing area are marked with different letters. Differences between datasets were determined by pairwise comparisons of log-transformed data.

10.4.2. Local gradient and contributing area

The channel head data for all datasets were plotted on a graph of gradient versus contributing area (Figure 23) and regression equations were developed for each of these datasets. For the purposes of comparison, the Mid-Atlantic dataset was divided according to location. Julian et al. (2012) found that only channel heads located in the Appalachian Plateau and the Piedmont had statistically significant relationships between gradient and contributing area; data from these two regions are used in this comparison. The coefficients, exponents, and corresponding confidence intervals are presented in Table 3. The exponent values are most important, as they dictate the slope of the regression line. Comparison of the confidence intervals for the exponent values reveals that the confidence intervals for the exponent of channel heads with both surface and subsurface flow overlap with the confidence intervals for the exponent of equations for all other datasets. This indicates that these relationships are not statistically significantly different based on location.

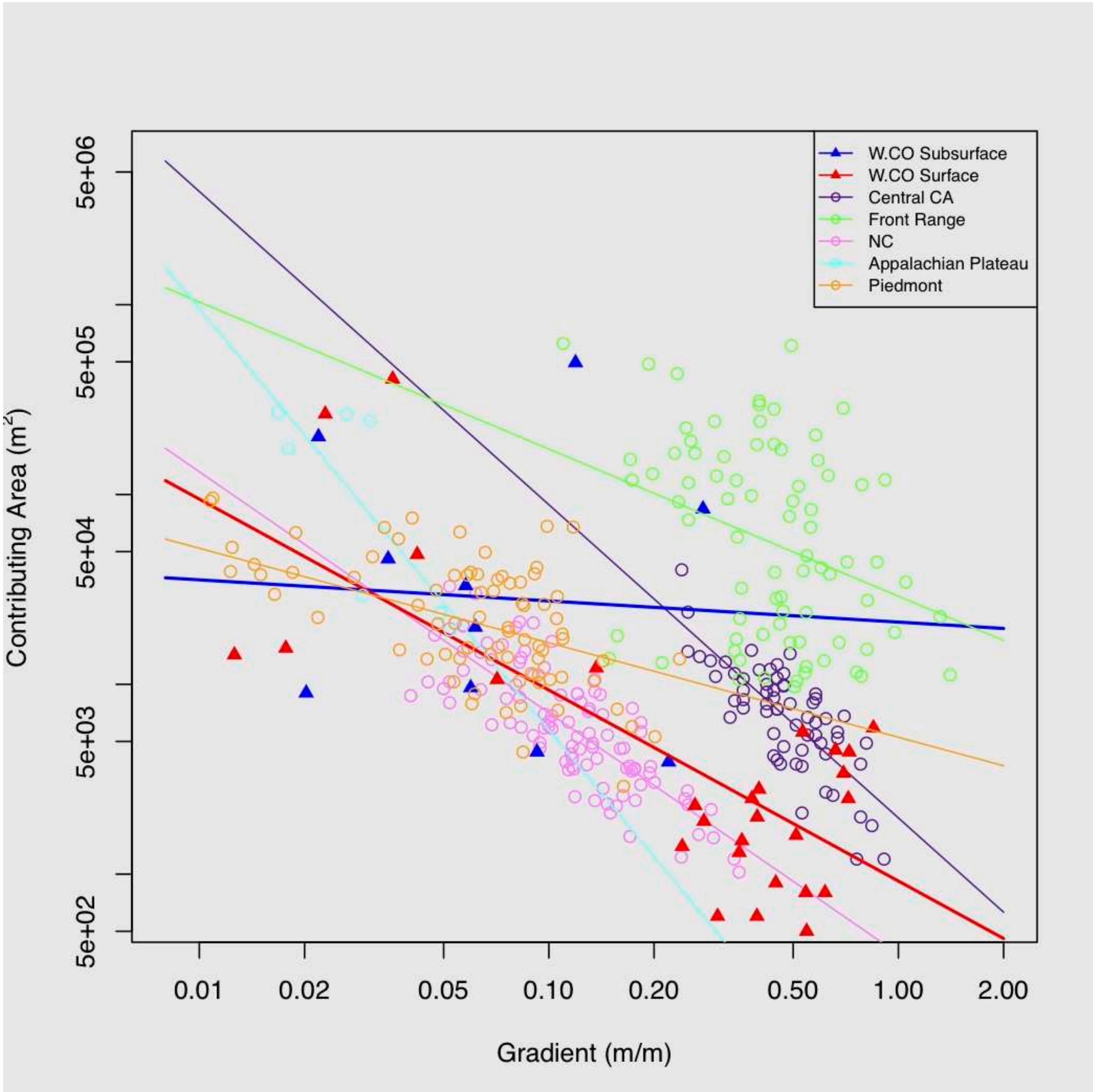

Figure 23: Relationships between gradient and contributing area for all channel head datasets.

Table 3: Values of the coefficients (a) and exponent (b) for the gradient-contributing area relationship equations (in the form Y=aXb) for all datasets. The confidence intervals for the coefficients and exponents are also presented. "Western Colorado" includes all channel heads; "surface" includes only channel heads from western Colorado with evidence of surface flow; "subsurface" includes only channel heads from western Colorado with evidence of subsurface flow.

Dataset	Coefficient	Confidence Interval (Coefficient)	Exponent	Confidence Interval (Exponent)
Western Colorado	1097.20	504.61, 2385.70	-1.016	-1.377, -0.656
Surface	919.67	459.55, 1840.45	-1.006	-1.377, -0.634
Subsurface	21270.08	323.10, 1400219.94	-0.111	-1.600, 1.377
Front Range	28264.99	17272.38, 46253.60	-0.816	-1.316, -0.316
Central California	1977.52	1495.58, 2614.76	-1.647	-1.993, -1.301
North Carolina	380.13	251.90, 573.64	-1.268	-1.453, -1.083
Appalachian Plateau	34.68	0.029, 41516.21	-2.220	-4.214, -0.226
Piedmont	5260.328	2963.636 9336.862	-0.498	-0.694, -0.302

10.4.3. Local gradient and basin length

Information about basin length is only available for the channel head datasets from the Colorado Front Range and central California. The channel head data for these datasets and the western Colorado channel heads were plotted on a graph of gradient versus basin length (Figure 24) and regression equations were developed for each of these datasets. The coefficients, exponents, and corresponding confidence intervals are presented in Table 4. The exponent values are most important, as they dictate the slope of the regression line. Comparison of the confidence intervals for the exponent values reveals that the confidence interval for the exponents of channel heads with surface flow does not overlap with the confidence interval for the exponent of the Front Range channel head equation. This indicates that these two relationship equations are statistically different. All other equations modeling the relationship between gradient and basin lengths for the datasets are not statistically different.

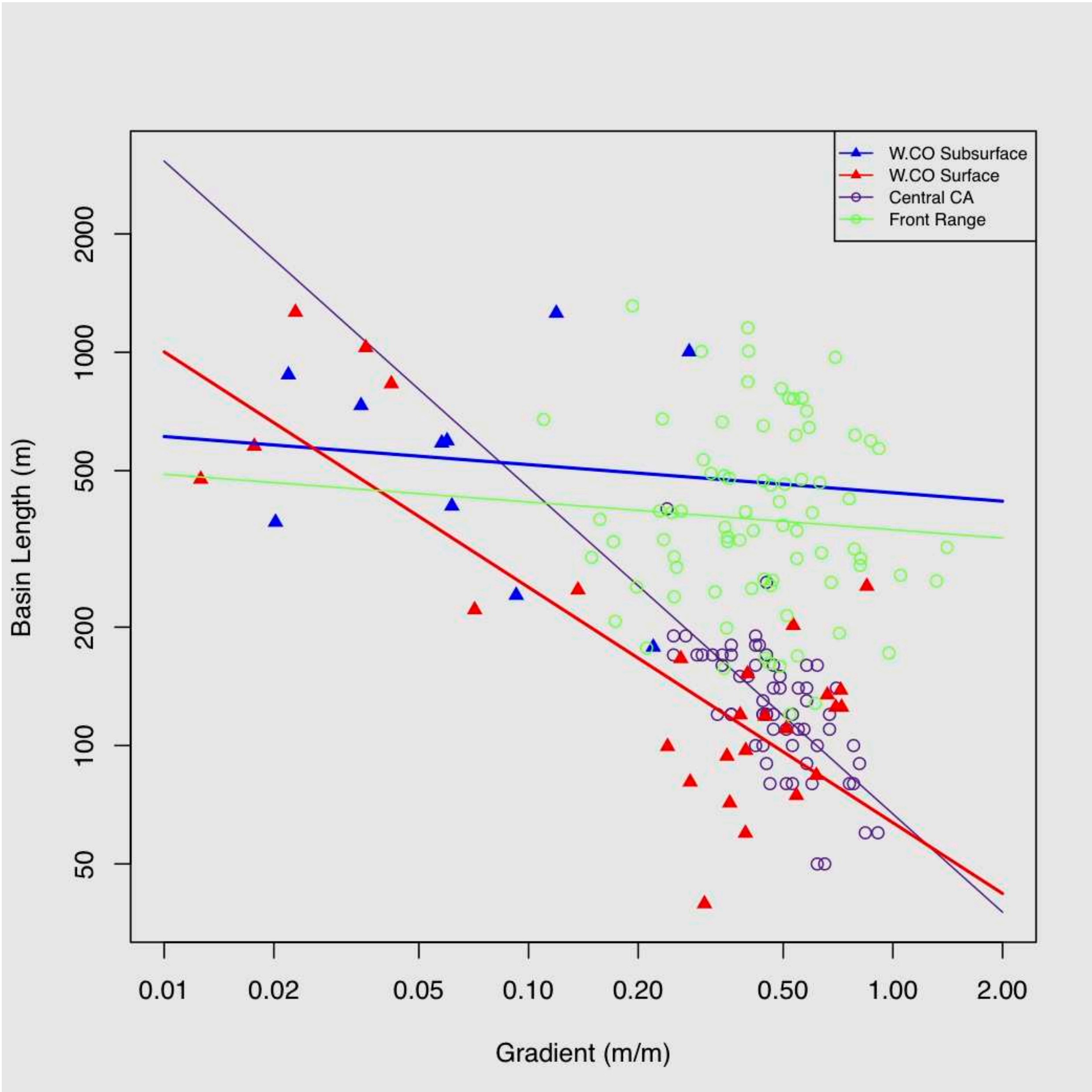

Figure 24: Relationships between gradient and basin length for all channel head datasets.

Table 4: Values of the coefficients (a) and exponent (b) for the gradient-basin length relationship equations (in the form Y=aXb) for all datasets. The confidence intervals for the coefficients and exponents are also presented. "Western Colorado" includes all channel heads; "surface" includes only channel heads from western Colorado with evidence of surface flow; "subsurface" includes only channel heads from western Colorado with evidence of subsurface flow.

Dataset	Coefficient	Confidence Interval (Coefficient)	Exponent	Confidence Interval (Exponent)
Western Colorado	70.57	45.87, 108.56	-0.617	-0.817, -0.417
Surface	63.65	41.36, 97.97	-0.599	-0.830, -0.367
Subsurface	439.38	86.73, 2226.04	-0.071	-0.648, 0.506
Front Range	353.79	278.59, 449.30	-0.071	-0.313, 0.172
Central California	67.10	55.89, 80.57	-0.825	-1.052, -0.599

10.5. Summary of Results

In summary, the results supported predictions described earlier in connection with Objectives 1 through 3. Channel heads with evidence of subsurface flow had significantly larger contributing areas, longer basin lengths, and shallower local gradients than channel heads with evidence of surface flow (Objective 1). Channel heads underlain by shale had significantly smaller drainage areas, shorter basin lengths, and steeper gradients than channel heads with underlying sandstone lithology (Objective 2). Similarly to previous studies, both contributing area and basin length decreased with increasing local gradient for channel heads with surface runoff (Objective 3). Objective 4 investigated potential differences between channel heads in western Colorado and previously published datasets. Although channel heads with evidence of surface runoff in western Colorado have gradients that are statistically different from all other datasets, other metrics indicate that climatic differences do not influence channel initiation as predicted in this study. Notably, the relationship between gradient and contributing area for surface runoff channel heads was not found to be significantly different from the same relationship for other study regions.

11. DISCUSSION

It is apparent from these data that channel heads in western Colorado follow many of the same trends that are present in other study regions. As expected, channel heads with evidence of subsurface flow had statistically larger contributing areas, longer basin lengths, and shallower gradients than channel heads with evidence of surface runoff. Channel heads with subsurface flow did not have statistically significant relationships between gradient and drainage area. These differences likely occur because, when subsurface flow is present, it dominates channel initiation. The subsurface heterogeneity and preferential flow processes are more influential in determining the concentration of flow necessary to initiate erosion and channel formation than runoff generated in the contributing area.

Underlying lithology clearly influences channel head formation in the UNF study region. Channel heads underlain by shale had significantly smaller contributing areas, shorter basin lengths, and steeper gradients. These trends were predicted based on the lower permeability and porosity of shale. The lower permeability and porosity may lead to greater runoff, such that smaller contributing drainage areas are required to concentrate sufficient flow to initiate erosion and channel initiation.

Previous studies have found significant relationships between local gradient and contributing drainage area, such that as gradient increases, the contributing area decreases. This trend was present in the data from western Colorado. When the flow types causing channel head formation were considered separately, the inverse relationship between gradient and contributing area was also present for channel heads with evidence of initiation due to surface runoff. Local gradient and contributing area were not correlated, however, for channel heads with evidence of subsurface flow. This could reflect the small sample size and wide range of variability in the gradients and contributing areas of channel heads initiated by subsurface flow, or could indicate that surface characteristics have minimal influence on location of these channel heads. Although this relationship is not statistically significant, the line of the relationship visually indicates that subsurface channel heads likely behave differently than channel heads initiated by surface runoff. As subsurface flow dominates at these channel heads, the relationships of gradient and contributing area are very different than for those channel heads with evidence of surface runoff.

The relationship between gradient and contributing area for channel heads with surface runoff was compared to the same relationship developed for other study regions. Objective 4 predicted that differences in climate, specifically the higher aridity in western Colorado, would influence the relationship equation. The results did not show this trend, however, as the relationship equation for western Colorado channel heads is not significantly different from other datasets. One explanation for this is the large range of variability in the dataset from western Colorado (Figure 23). Although the relationship equation is not significantly different, differences do exist between the mean gradients, contributing areas, and basin lengths of the western Colorado channel heads and channel heads in other regions. These differences are not systematic, but the presence of these differences indicates that a larger dataset from western Colorado might provide additional insight into the role of aridity in channel head formation.

It is also possible that the lack of significant differences between the gradient-contributing area relationships of western Colorado and other regions indicate that broadly applicable relationships could be developed for channel heads initiated by surface runoff in diverse environments. The published datasets used in this study did not distinguish between channel heads initiated by surface or subsurface flow, but future research should compare gradient and contributing drainage area relationships for channel heads initiated by surface runoff across multiple regions. It is possible that regional differences in climate and lithology have minimal effect on the location of channel heads. Determining whether a broadly applicable relationship exists between gradient and contributing areas of channel heads initiated by surface flow is worth further investigation.

12. CONCLUSIONS ABOUT CHANNEL HEADS

This study has shown significant differences between channel heads with surface flow and channel heads with subsurface flow, as well as differences between channel heads with different underlying lithology. No notable differences were found, however, between channel heads located in the more arid western Colorado and channel heads located in other, more humid study regions. This may be in part due to the small sample size of this study. Any future research of channel heads in western Colorado should utilize a larger sample size, especially a larger number of channel heads with evidence of subsurface flow. Furthermore, it is recommended that local gradient be measured in the field in order to compare the field measurement with the gradient value obtained remotely. The small sample size of this study, the ambiguity of the results, and the importance of channel heads indicates that this research should be replicated on a larger scale in western Colorado. The lack of significant differences between western Colorado and other regions may also suggest that broadly applicable relations between gradient and contributing area can be used to predict the location of channel heads formed primarily by surface runoff in diverse environments.

13. CONCLUSIONS

Headwater streams are essential components of the watershed system, supplying the majority of water and sediment to downstream channels. Understanding these headwater channels and their points of initiation will allow for improved management and protection of watersheds. The two parts of this research examined both the potential effects of energy development on channel morphology and the formation of channel heads in western Colorado. This study showed limited connections between energy development and altered channel morphology. Significant differences were found between channel heads with evidence of initiation due to surface flow and subsurface flow, and between channel heads with different underlying lithology. Comparisons between channel heads in western Colorado and other geographic regions suggested no significant differences in drainage area-gradient relations for initiation of channels by surface runoff in diverse environments, indicating that a broadly applicable relationship could be developed. Both portions of this research, focusing on headwater streams and channel heads, had aspects that could be refined to obtain more complete data. The importance of channel heads and headwater streams and the inconclusiveness of these studies indicate that this research is worth improvement and replication. Management of water resources is an intricate and indispensable task. Increasing and improving the knowledge about watershed networks through studies such as these will enhance and support the management and protection of these resources.

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15. APPENDIX A: OTHER RESULTS FOR HEADWATER STREAMS

15.1. Other Results

In addition to all of the statistical tests detailed in Section 5, other analyses were attempted to explore all possibilities. None of these analyses produced remarkable results, and are summarized briefly here.

In general, impacts were either parallel or perpendicular to the study reaches; for example, a road either crossed the reach (perpendicular impact) or ran alongside the reach (parallel impact). Impacts were classified as either parallel or perpendicular in order to explore the possibility that the angle of impact affected the results. The data were grouped according to location, whether the stream was impacted, and the angle of impact. Pairwise comparisons using the R package lsmeans found no additional or noteworthy trends were discovered in the data.

The data were stratified according to the size of the drainage area. Half of the study reaches had drainage areas larger than 0.5 km^2; these drainage areas were classified as “large.” The data were grouped in various ways according to drainage area size and compared using Welch’s Two Sample t-tests. There was no statistically significant difference between the width to depth ratios of study reaches with small or large drainage areas. Similarly, there was no statistically significant difference between the width to depth ratios of reference and impacted reaches with large drainage areas. There was a statistically significant difference between the width to depth ratios of reference and impacted reaches with small drainage areas (<0.5 km^2). Pairwise comparisons by location and whether a reach is impacted, however, indicated that there is no statistically significant difference between Chevron Impacted and Piceance Reference reaches with small drainage areas. This matches trends previously noted in the dataset. Drainage area was also considered as a continuous variable and width to depth ratio was plotted versus drainage area; no noticeable relationships between variables were observed.

The type of vegetation cover and percent vegetation cover were considered as the main predictor variable, in the place of location or whether the stream was impacted. The type of vegetation cover was considered as a categorical predictor variable, and pairwise comparisons using the R package lsmeans were conducted. Percent vegetation cover was considered as a continuous variable; width to depth ratio was plotted against percent vegetation cover and analyzed visually. No noteworthy trends or statistically significant differences were discovered in either analysis.

15.2. Comparison of Variances

Comparisons of the variances of width to depth ratios between location groups were completed using Levene's Test. Unequal variances indicate that comparisons of means between two groups may not provide accurate information; if the variance within one group is significantly different than the variance of the other group, this may explain differences between the two groups. Table 5 shows that the variances of width to depth ratios were unequal between the groups UNF Reference and UNF Impacted, UNF Impacted and Piceance Reference, and UNF Impacted and Chevron Impacted. None of these pairwise comparisons test Hypothesis 1, that headwater streams affected by energy development are morphologically different than otherwise analogous streams.

Furthermore, these variance tests were performed on untransformed data. When the log-transformed data were tested, no unequal variances were found.

Table 5: Variances.

Locations		p-value	Equality of variance
UNF Reference	UNF Impacted	0.01647	*Unequal*
UNF Reference	Piceance Reference	0.5462	Equal
UNF Reference	Chevron Impacted	0.1861	Equal
UNF Impacted	Piceance Reference	0.03587	*Unequal*
UNF Impacted	Chevron Impacted	0.001177	*Unequal*
Piceance Reference	Chevron	0.6718	Equal

15.3. Effects of Flow Regime

The data were also subdivided based on flow regime (perennial, intermittent, and ephemeral) and lithology to create six groups, as shown on Figure 25: Comparison of width to depth ratios by flow regime and lithology. SH = shale; SS = sandstone. Boxplots are colored according to flow regime; i.e., the boxplots representing ephemeral streams are a different color than the boxplots representing perennial streams.. The width to depth ratio was compared between groups using an ANOVA and pairwise comparisons with the R package lsmeans. There were no statistically significant differences among these groups.

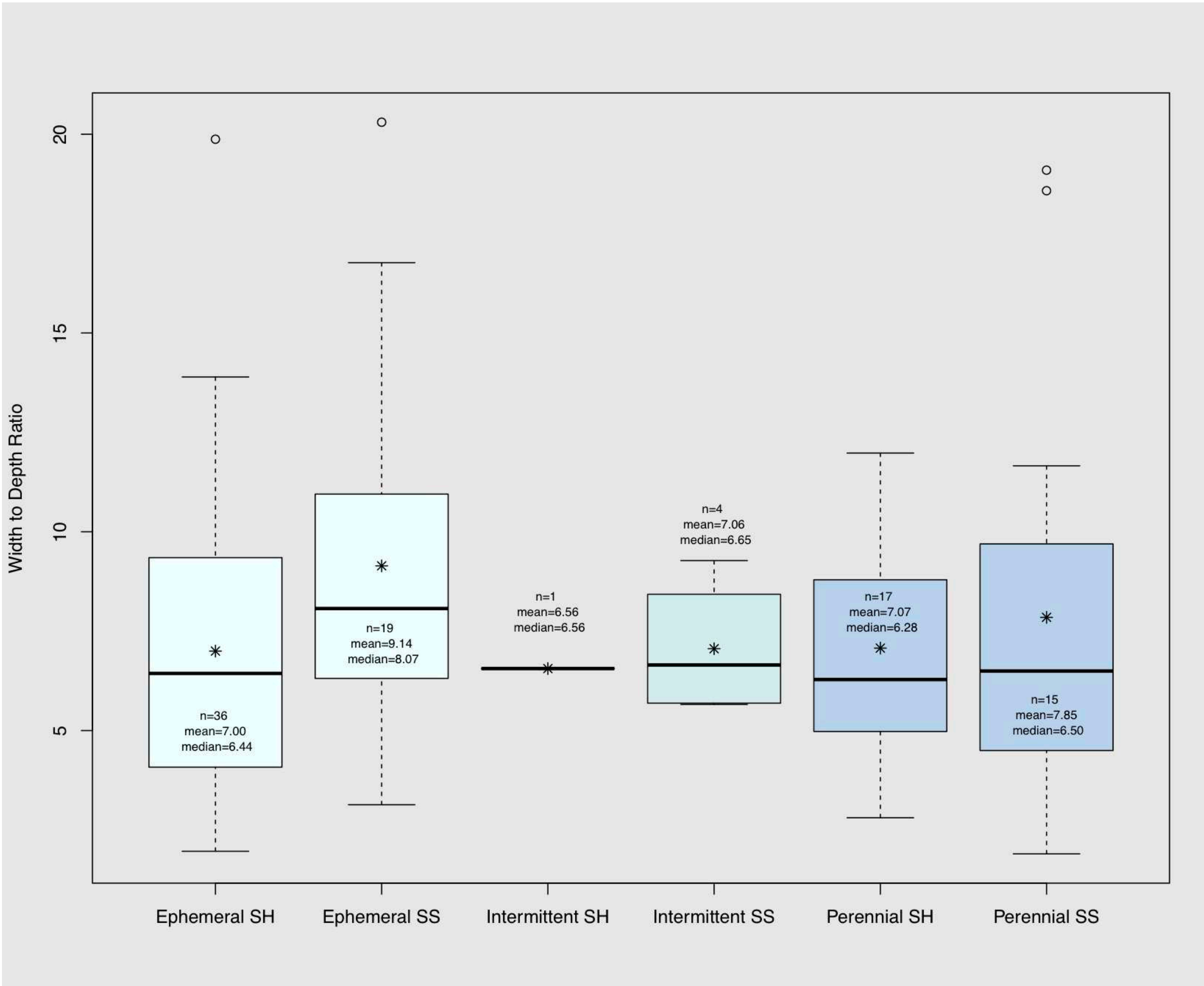


Figure 25: Comparison of width to depth ratios by flow regime and lithology. SH = shale; SS = sandstone. Boxplots are colored according to flow regime; i.e., the boxplots representing ephemeral streams are a different color than the boxplots representing perennial streams.

15.4. Principle Components Analysis

A Principle Components Analysis (PCA) was conducted to further explore the data. The dataset was plotted on the first two principal components by location and whether the reach was impacted (Figure 26). The reaches formed vague clusters on this plot, mostly according to location, but no significant groupings were observed. It is notable that there seems to be some distinction between the UNF reaches and the reaches from other study regions, but the reaches from the Chevron and PSWA regions overlap. This supports earlier conclusions about regional differences between the Chevron and PSWA study regions and the UNF study region.

The reaches were also plotted on the first two principal components by only location (Figure 27). Similarly, the data appeared to generally fall into groups according to location. In general, the UNF reaches varied along the axis representing the first principal component (PC1) and the Chevron and PSWA reaches varied along the axis representing the second principal component (PC2). The rotations of the principal components were examined; the variables percent vegetation cover, elevation, and width to depth ratio contributed the most to PC1 and the variables gradient, drainage area, and percent vegetation cover contributed the most to PC2.

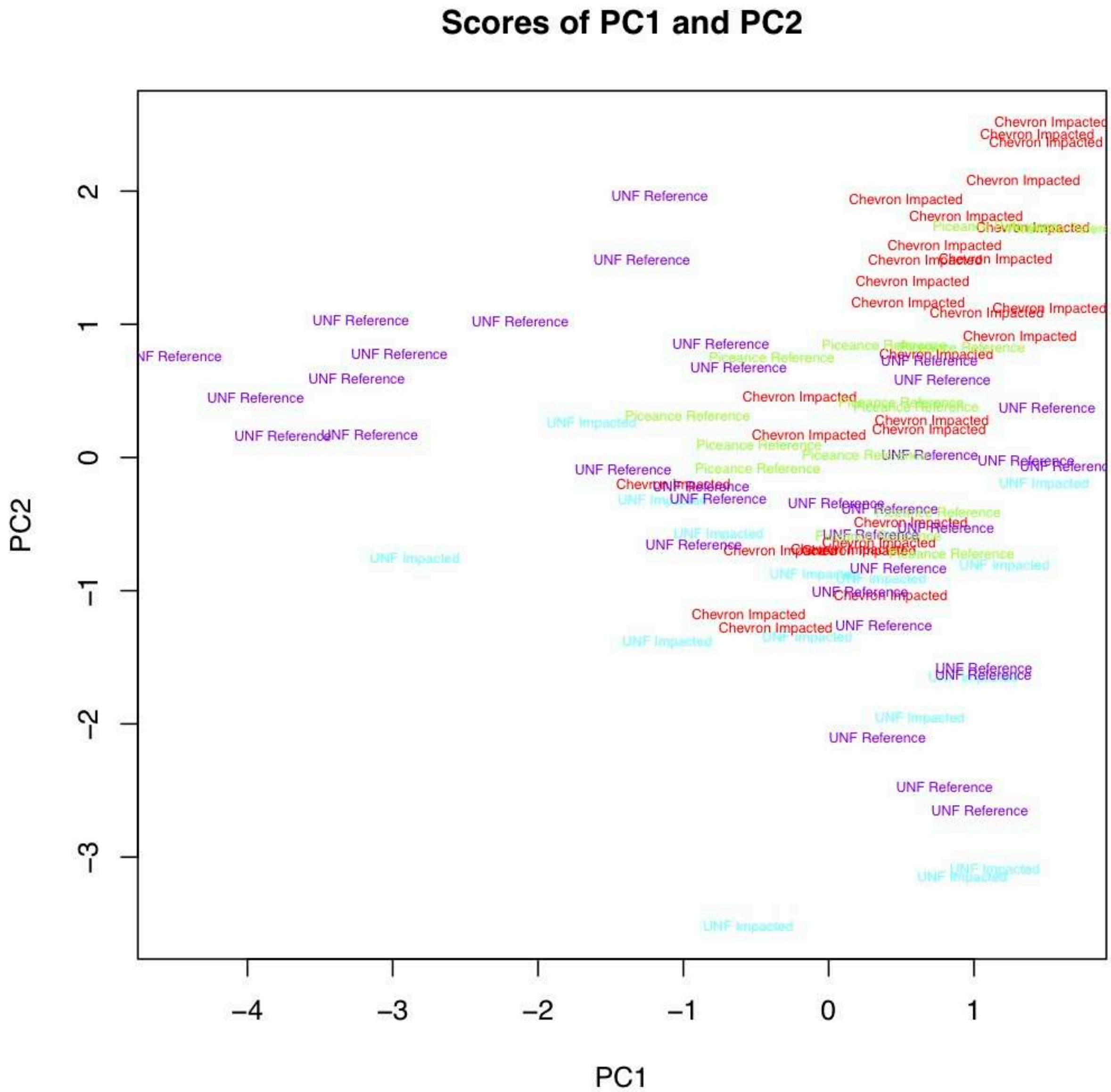


Figure 26: Principle Components Analysis. Data points are colored according to location and whether the study reach is impacted.

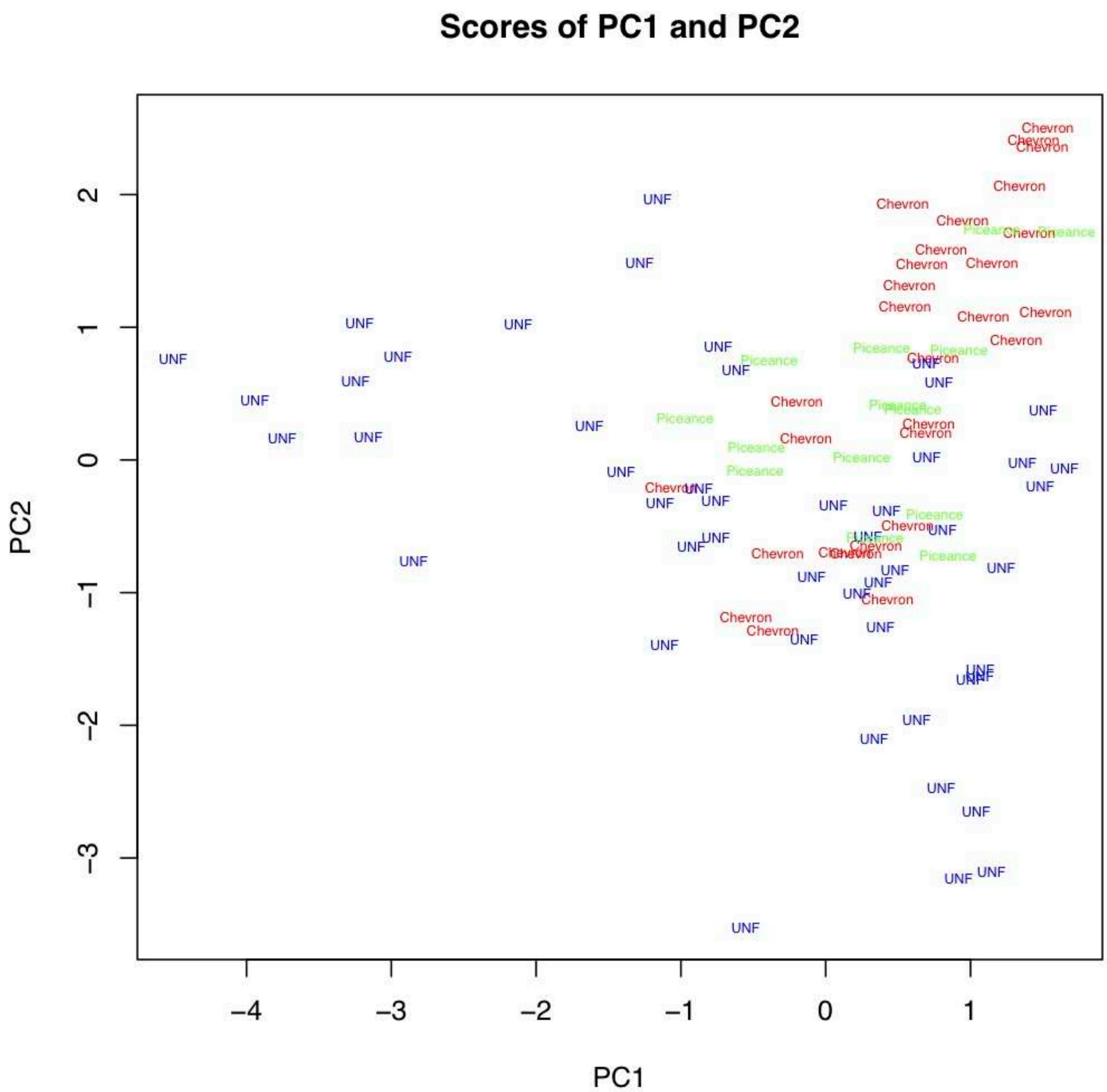


Figure 27: Principle Components Analysis. Data points are colored according to location.

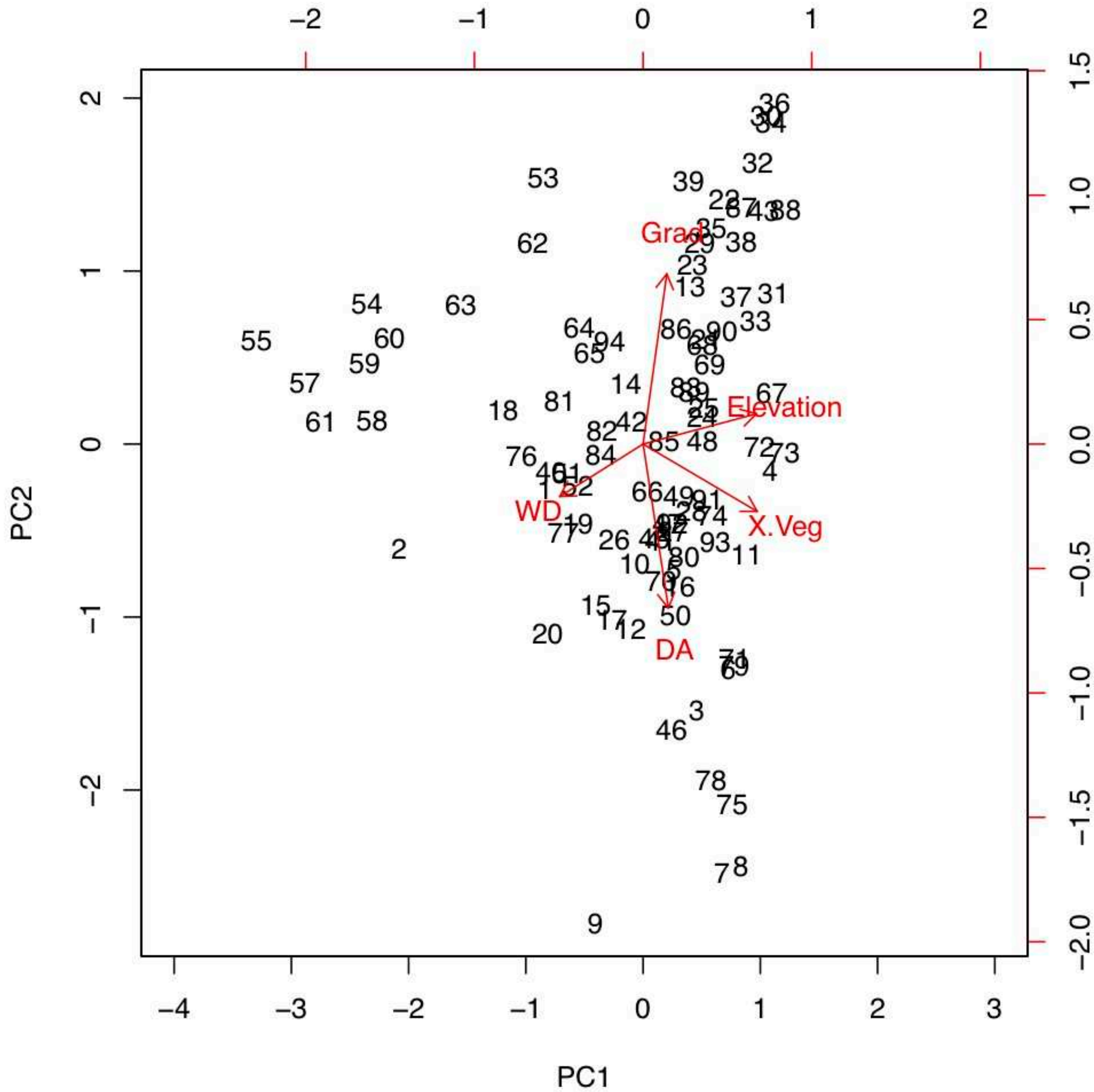


Figure 28: Loadings of the first two principal components, PC1 and PC2.

15.5. Scatterplots

Scatterplots of the data were created comparing drainage area, width to depth ratio, and gradient. The points were colored according to flow regime, lithology, whether they were impacted, or the location (Figure 29). The same plots were created on logarithmic axes (Figure 30). In the scatterplots with logarithm-scaled axes, there appears to be a relationship between drainage area and gradient (Figure 31). A linear regression equation was fitted to the log-transformed data (following the method used in Appendix B), yielding the equation $y=0.028*x^{-0.242}$, where x=drainage area and y=gradient. This relationship is statistically significant (p-value<0.05) and the R^2 value is 0.32.

The study reach data were also plotted with gradient on the x-axis and drainage area on the y-axis, in order to compare this relationship to the relationship established for the channel head data (Section 10.4.2). For this plot, drainage area was plotted as square meters. A regression equation was developed for the study reaches, yielding the equation $y=3113*x^{-1.323}$, where x=gradient and y=drainage area. For all channel heads, the corresponding equation is $y=1097*x^{-1.016}$. The equations for the headwater reaches and channel heads are not significantly different. This is intuitive, as most of the headwater study reaches are located within a short distance of the channel head.

In both sets of scatterplots, drainage area and gradient appear to have differences based on underlying lithology and flow regime. These trends were examined using boxplots (Figure 33-Figure 36) and the non-parametric Wilcoxon Rank Sum test, as the data are not normally distributed. While conducting comparisons based on flow regime, study reaches with intermittent flow regimes were ignored, as there are only five such reaches. Statistically significant (p-value < 0.05) differences were found for drainage area based on lithology, drainage area based on flow regime, gradient based on lithology, and gradient based on flow regime. Study reaches with shale lithology tend to have smaller drainage areas and steeper gradients. Similarly, study reaches with ephemeral flow regime have smaller drainage areas and steeper gradients.

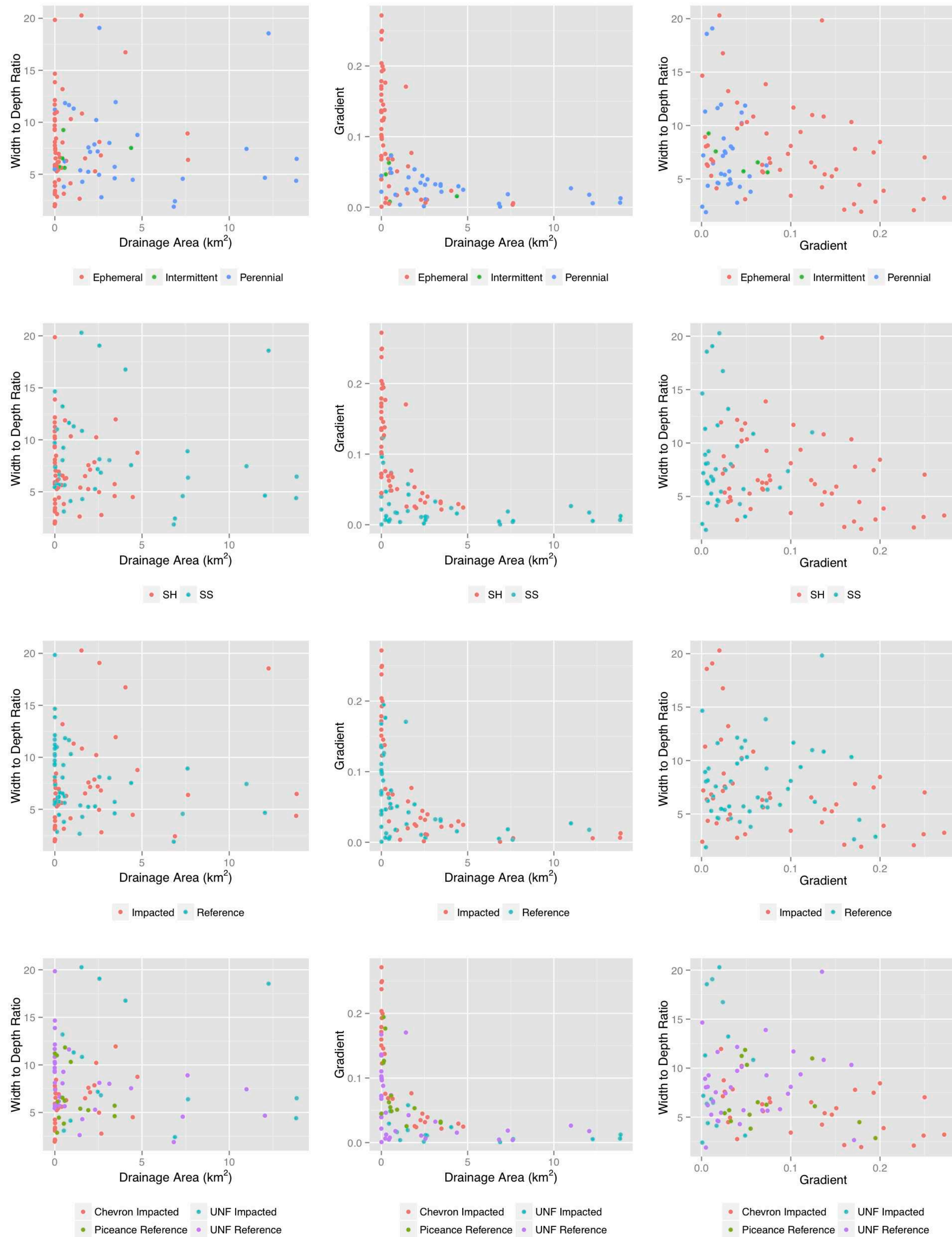


Figure 29: Scatterplots for data exploration.

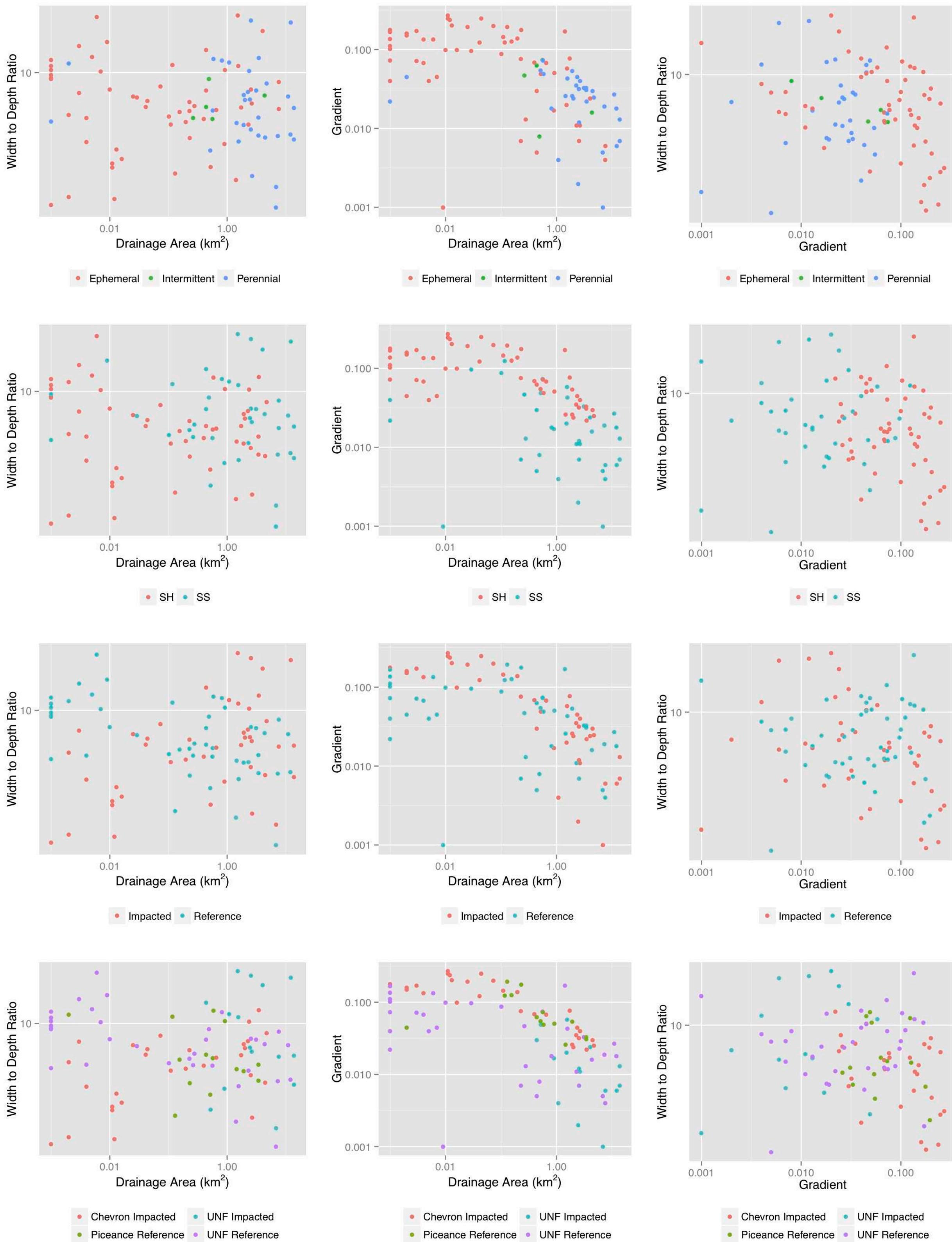


Figure 30: Scatterplots on logarithmic axes for data exploration.

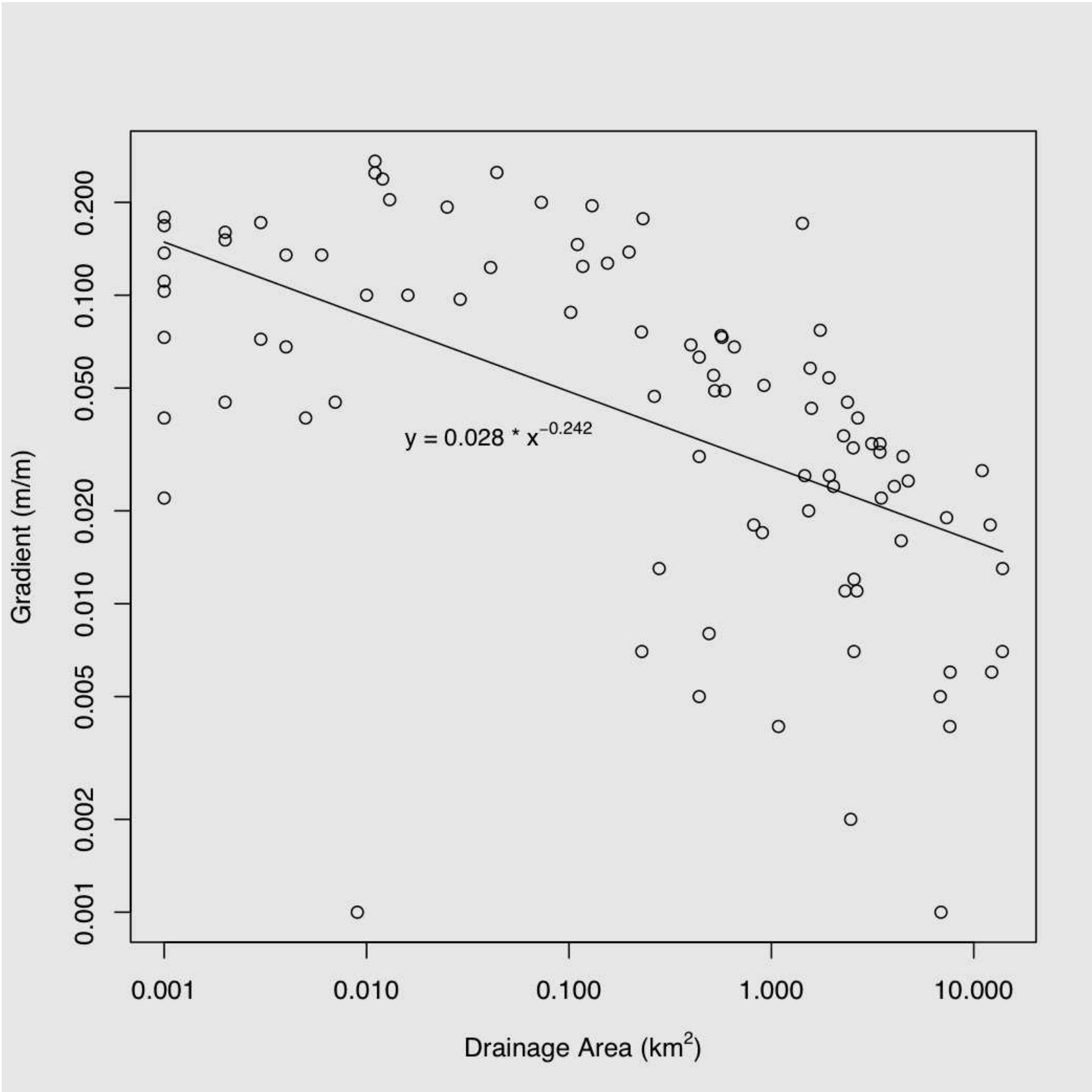


Figure 31: Drainage area versus gradient on logarithmic axes.

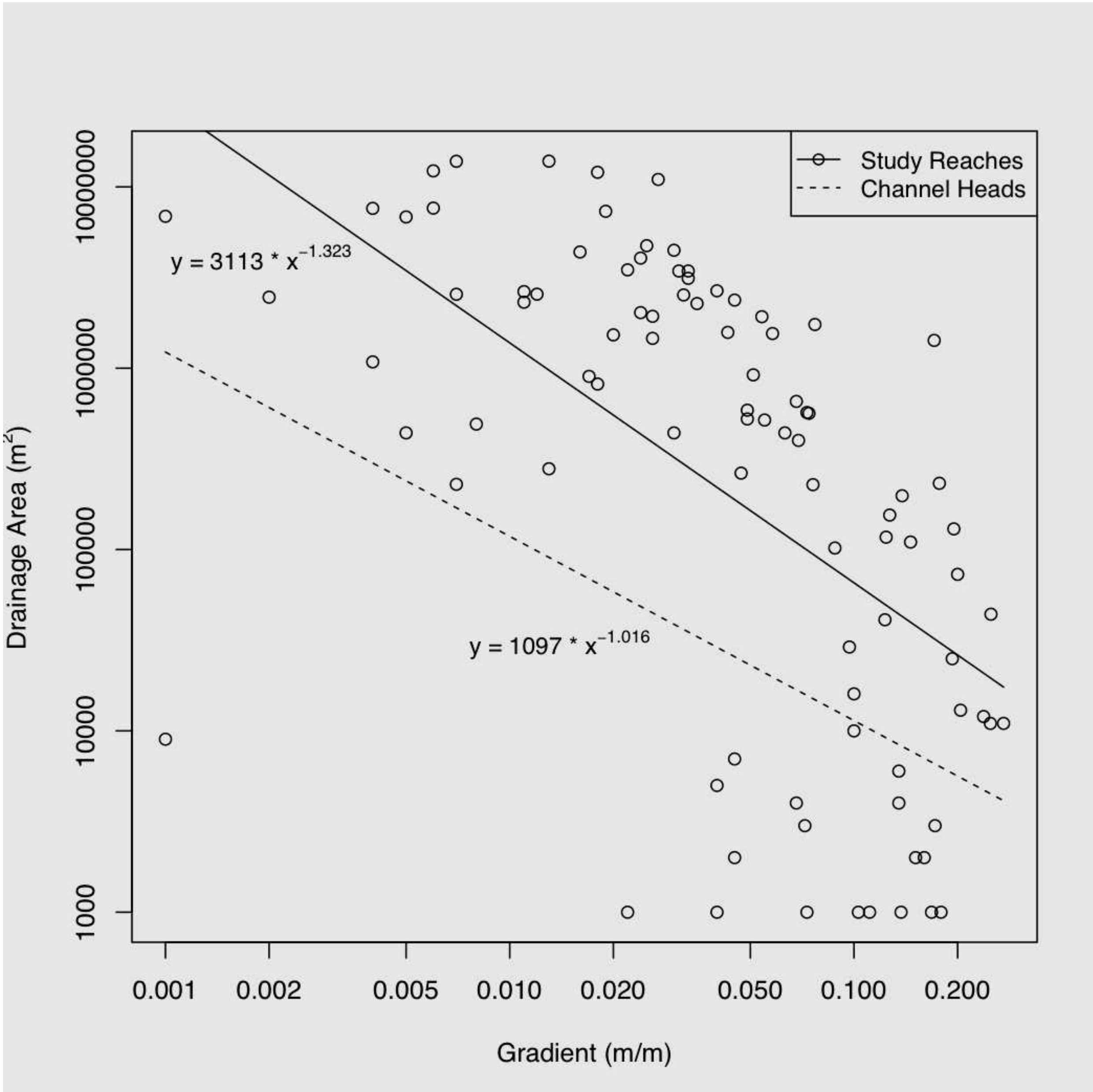


Figure 32: Gradient versus drainage area of study reaches. Drainage area is presented in square meters. The regression line for the gradient-drainage area relationship for channel heads is plotted as the dashed line. The regression equations are not significantly different.

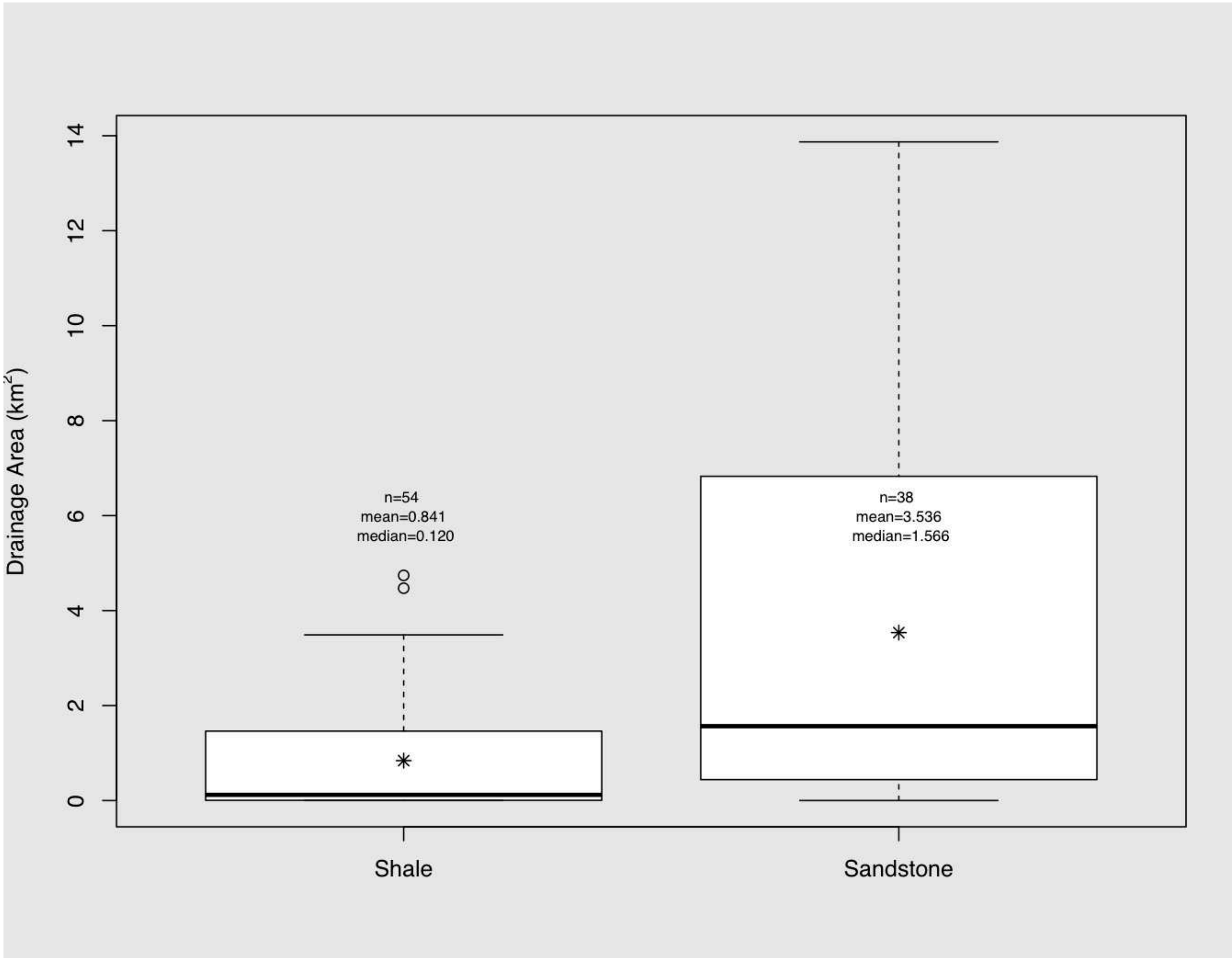


Figure 33: Comparison of drainage areas of study reaches with shale and sandstone lithologies. A statistically significant difference was found between the drainage areas of reaches underlain by shale versus sandstone.

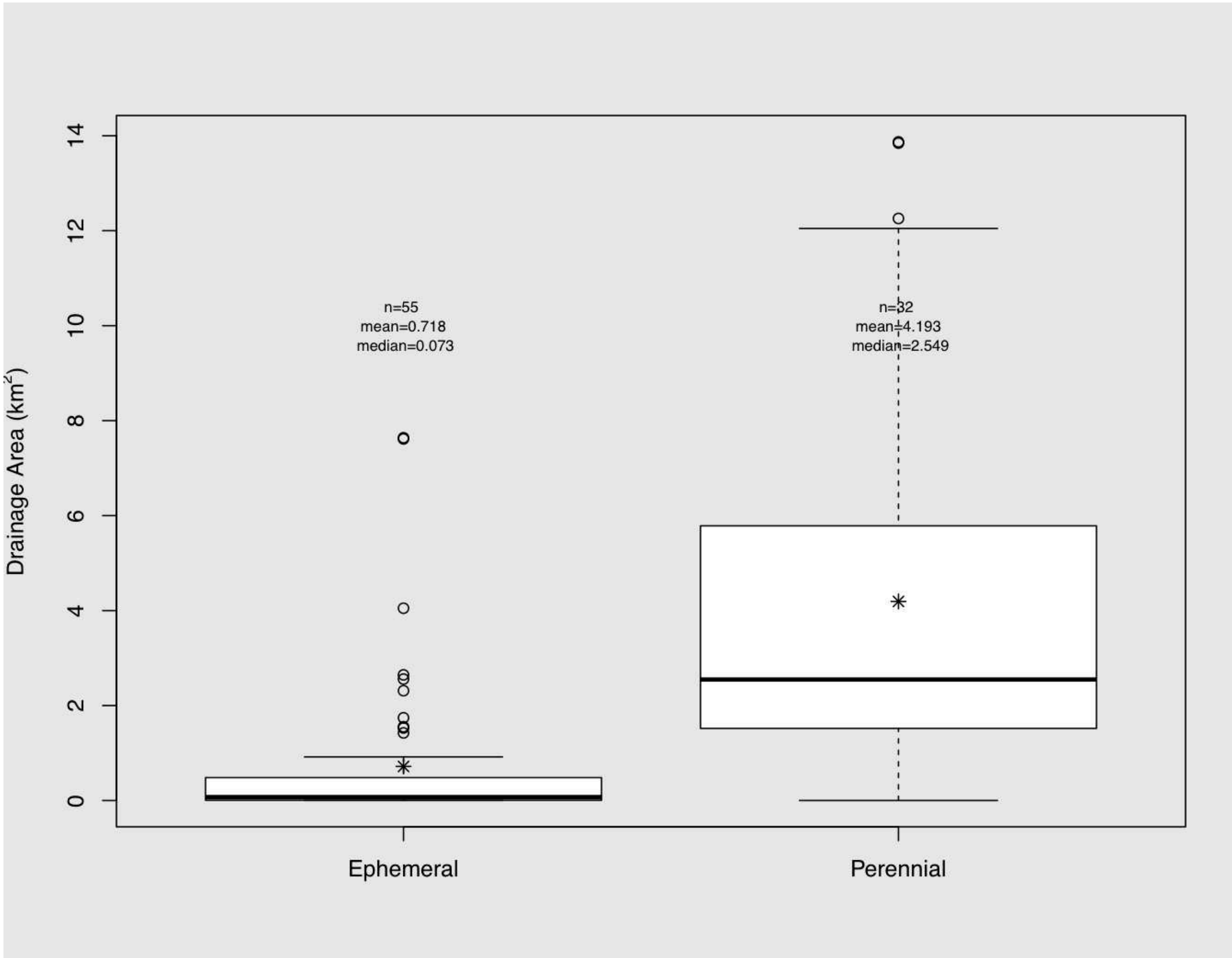


Figure 34: Comparison of drainage areas of ephemeral and perennial study reaches. A statistically significant difference was found between the drainage areas of ephemeral versus perennial study reaches.

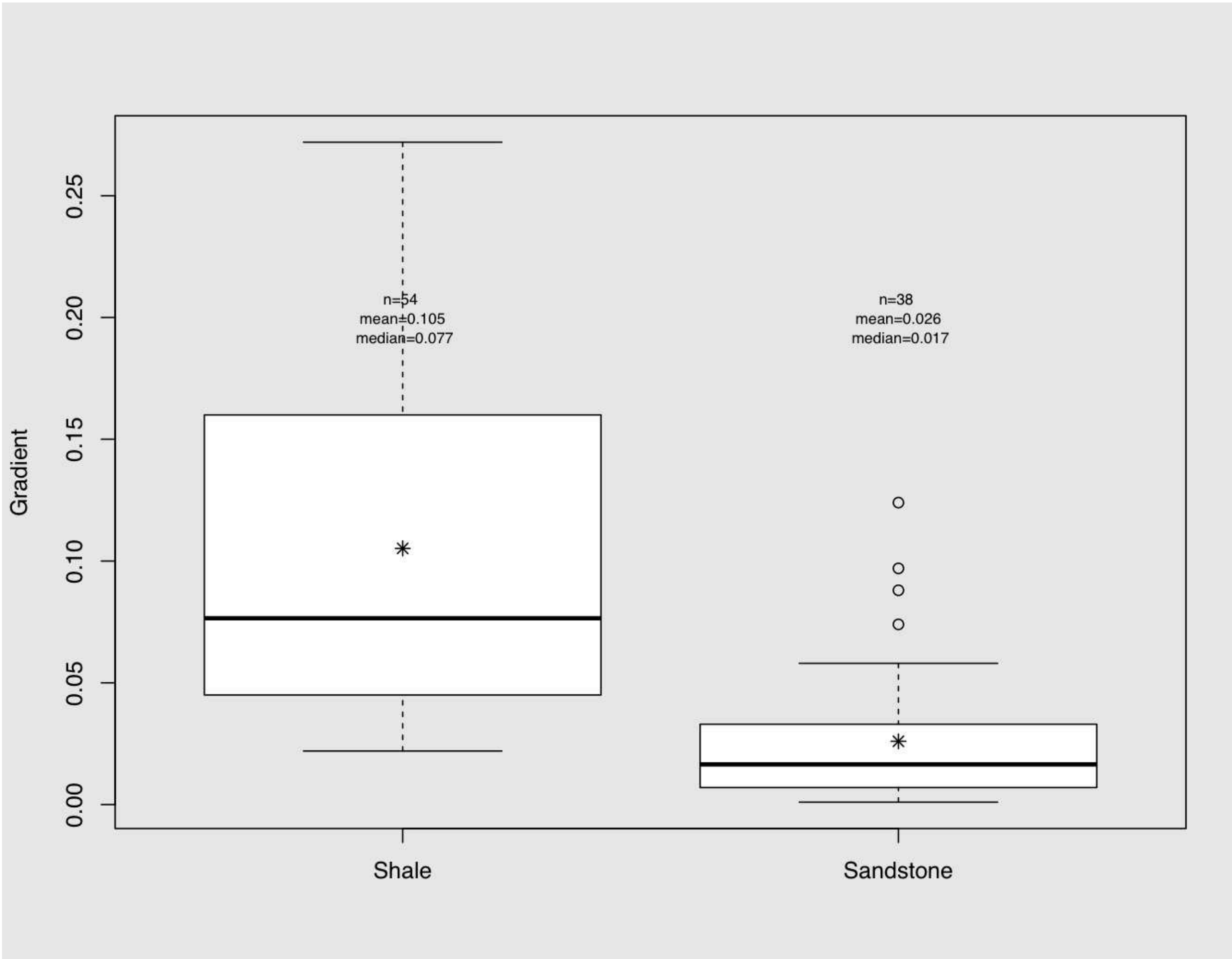


Figure 35: Comparison of gradients of study reaches with shale and sandstone lithologies. A statistically significant difference was found between the gradients of reaches underlain by shale versus sandstone.

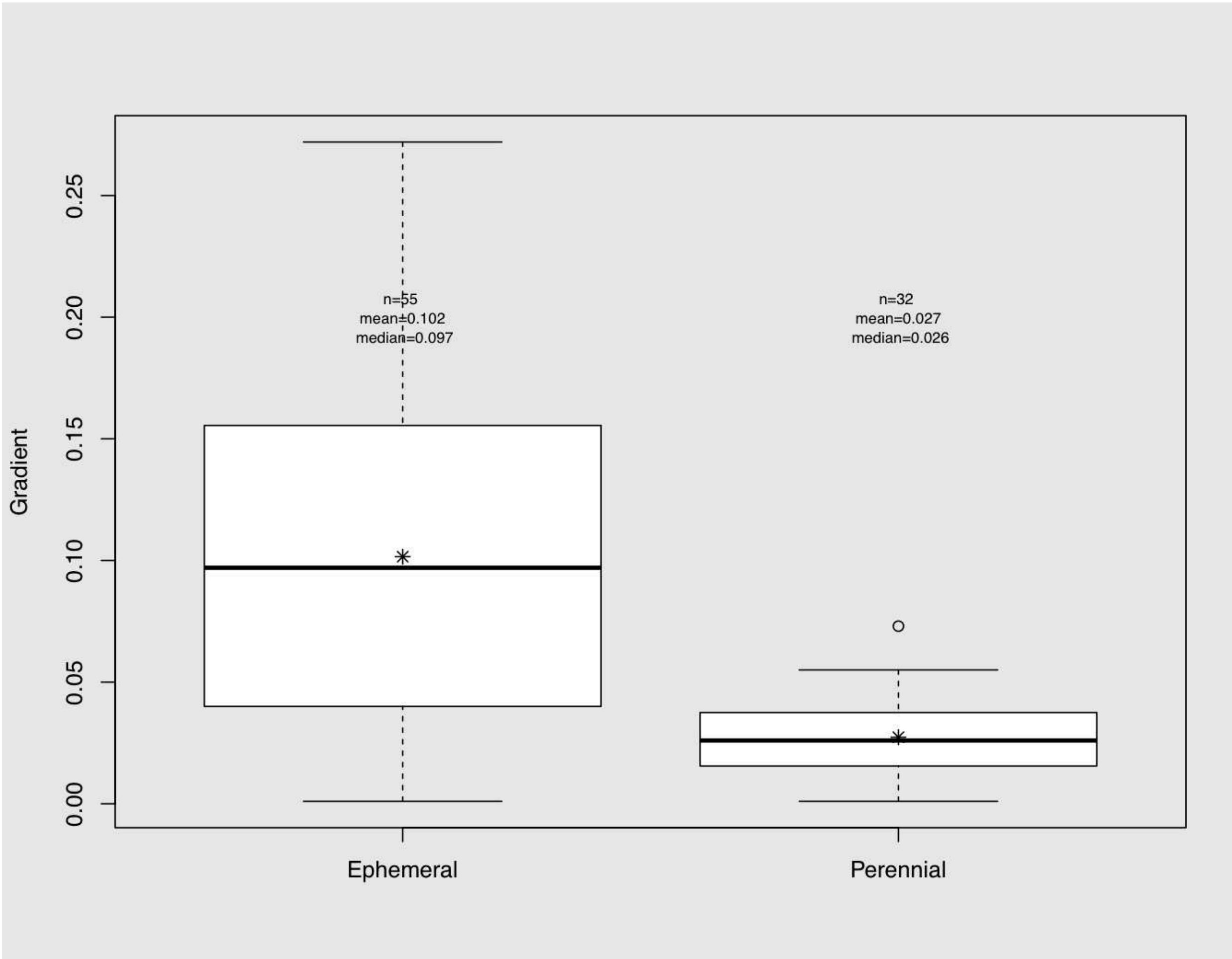


Figure 36: Comparison of gradients of ephemeral and perennial study reaches. A statistically significant difference was found between the gradients of ephemeral versus perennial study reaches.

16. APPENDIX B: DEVELOPING CHANNEL HEAD EQUATIONS

In order to develop relationship equations for channel head gradient and contributing area and for gradient and basin length, the following method was used:

1) Simple linear regression was conducted on log-transformed data to yield coefficients for the equation:

   $$log(contributing\ area) = \beta_1 + \beta_2 * log(gradient)$$

2) This equation was then back-transformed by taking the inverse of the logarithm:

   $$e^{(log(contributing\ area))} = e^{(\beta 1\ +\ \beta 2 * log(gradient))}$$

3) This yielded the final equation, in the form:

   $$contributing\ area = e^{\beta 1} * gradient^{\beta 2}$$

17. APPENDIX C: DATA TABLES FOR HEADWATER STREAMS

Table 6: Raw data for the headwater stream study reaches surveyed for this research. Reaches with an * are outliers that were excluded during data analysis. Lithology categories: SS=sandstone; SH=shale. Vegetation types: g=graminoid; f=forb; t=trees; s=shrubs. All vegetation categories are combinations of these four vegetation types.

Reach Number	Class	Location	Lithology	Flow Regime	Vegetation Type	Vegetation Cover (%)	Elevation (m)	Drainage Area (km^2)	Gradient (m/m)	Width/Depth Ratio
I1	Impacted	UNF	SS	Ephemeral	tsg	70	2464.06	0.440	0.030	13.230
I2	Impacted	UNF	SS	Ephemeral	tsg	40	2414.17	1.528	0.020	20.302
I3	Impacted	UNF	SS	Ephemeral	sg	100	2474.08	7.640	0.006	6.394
I4	Impacted	UNF	SS	Ephemeral	tsg	100	2649.26	0.902	0.017	4.156
I5	Impacted	UNF	SS	Ephemeral	sg	100	2472.58	2.646	0.011	6.857
I6	Impacted	UNF	SS	Perennial	g	100	2467.20	6.886	0.001	2.447
I7	Impacted	UNF	SS	Perennial	sgf	100	2478.41	13.871	0.013	6.497
I8	Impacted	UNF	SS	Perennial	sg	100	2478.61	13.845	0.007	4.401
I9	Impacted	UNF	SS	Perennial	g	100	2473.14	12.258	0.006	18.579
I10	Impacted	UNF	SS	Perennial	tsg	100	2497.89	1.084	0.004	11.333
I11	Impacted	UNF	SS	Perennial	tsg	100	2656.27	2.465	0.002	7.216
I12	Impacted	UNF	SS	Perennial	tsg	100	2648.07	2.561	0.012	19.096
I13	Impacted	Chevron	SH	Ephemeral	sg	80	2543.14	0.198	0.138	5.449
I14	Impacted	Chevron	SH	Ephemeral	sg	65	2504.42	0.656	0.068	6.336
I15	Impacted	Chevron	SH	Perennial	g	90	2439.74	3.489	0.022	11.980
I16	Impacted	Chevron	SH	Perennial	sg	100	2409.33	4.472	0.030	4.515
I17	Impacted	Chevron	SH	Perennial	sg	90	2392.89	4.742	0.025	8.792
I18	Impacted	UNF	SS	Ephemeral	tsg	55	2197.66	0.525	0.049	3.134
I19	Impacted	UNF	SS	Ephemeral	tsg	100	2330.35	1.554	0.058	10.884
I20	Impacted	UNF	SS	Ephemeral	tsg	80	2475.74	4.050	0.024	16.769
I21	Impacted	Chevron	SH	Ephemeral	tsg	100	2522.49	0.041	0.123	6.561
I22	Impacted	Chevron	SH	Ephemeral	sgf	90	2518.61	0.013	0.204	3.894
I23	Impacted	Chevron	SH	Ephemeral	sgf	90	2545.87	0.003	0.172	7.821

I24	Impacted	Chevron	SH	Ephemeral	sg	100	2508.94	0.400	0.069	5.652
I25	Impacted	Chevron	SH	Ephemeral	sgf	100	2541.64	0.228	0.076	6.964
I26	Impacted	Chevron	SH	Perennial	g	95	2422.54	2.377	0.045	10.253
I27	Impacted	Chevron	SH	Perennial	g	100	2419.92	2.536	0.032	4.977
I28	Impacted	Chevron	SH	Perennial	g	100	2410.48	2.673	0.040	2.807
I29	Impacted	Chevron	SH	Ephemeral	sgf	70	2620.37	0.002	0.151	5.934
I30	Impacted	Chevron	SH	Ephemeral	sgf	80	2609.69	0.012	0.238	2.106
I31	Impacted	Chevron	SH	Ephemeral	sgf	100	2622.77	0.004	0.135	4.265
I32	Impacted	Chevron	SH	Ephemeral	sgf	100	2606.04	0.044	0.250	7.062
I33	Impacted	Chevron	SH	Ephemeral	sgf	90	2622.24	0.016	0.100	3.451
I34	Impacted	Chevron	SH	Ephemeral	sgf	90	2594.64	0.011	0.249	3.117
I35	Impacted	Chevron	SH	Ephemeral	sgf	90	2593.88	0.073	0.200	8.474
I36	Impacted	Chevron	SH	Ephemeral	sgf	95	2573.93	0.011	0.272	3.263
I37	Impacted	Chevron	SH	Ephemeral	sg	100	2554.04	0.110	0.146	5.284
I38	Impacted	Chevron	SH	Ephemeral	sgf	100	2599.13	0.025	0.193	7.492
I39	Impacted	Chevron	SH	Ephemeral	sg	50	2596.85	0.002	0.160	2.167
I40	Impacted	Chevron	SH	Perennial	g	50	2431.83	2.274	0.035	7.875
I41	Impacted	Chevron	SH	Perennial	g	100	2449.10	2.027	0.024	7.157
I42	Impacted	Chevron	SH	Ephemeral	sg	75	2463.07	1.743	0.077	6.538
I43	Impacted	Chevron	SH	Ephemeral	sgf	90	2576.99	0.001	0.179	1.964
I44*	Impacted	Chevron	SH	Perennial	g	100	2431.11	2.230	0.020	29.363
I45	Impacted	Chevron	SH	Perennial	g	100	2443.41	1.934	0.026	7.597
R1	Reference	UNF	SS	Ephemeral	sg	100	2474.12	7.615	0.004	8.944
R2	Reference	UNF	SS	Intermittent	tsg	100	2532.89	0.492	0.008	9.276
R3	Reference	UNF	SS	Intermittent	tsg	100	2520.90	0.264	0.047	5.720
R4	Reference	UNF	SS	Ephemeral	tsg	100	2499.24	0.279	0.013	6.652
R5	Reference	UNF	SS	Intermittent	sg	100	2475.47	4.377	0.016	7.579
R6	Reference	UNF	SS	Ephemeral	tsg	60	2455.88	0.440	0.005	8.069
R7	Reference	UNF	SS	Ephemeral	tsg	50	2444.25	2.313	0.011	5.299
R8	Reference	UNF	SH	Ephemeral	ts	10	2434.69	1.424	0.171	2.667
R9	Reference	UNF	SH	Ephemeral	ts	10	2183.97	0.010	0.100	8.127

R10	Reference	UNF	SH	Ephemeral	ts	10	2178.22	0.006	0.135	19.874
R11*	Reference	UNF	SH	Ephemeral	ts	10	2178.05	0.006	0.089	38.462
R12	Reference	UNF	SH	Ephemeral	ts	10	2179.79	0.003	0.072	13.894
R13	Reference	UNF	SH	Ephemeral	ts	30	2171.30	0.007	0.045	10.172
R14	Reference	UNF	SH	Ephemeral	ts	20	2169.06	0.001	0.073	9.298
R15	Reference	UNF	SH	Ephemeral	ts	15	2172.13	0.004	0.068	5.743
R16	Reference	UNF	SH	Ephemeral	tsg	15	2167.59	0.005	0.040	12.170
R17	Reference	UNF	SH	Ephemeral	ts	45	2437.01	0.001	0.168	10.357
R18	Reference	UNF	SH	Ephemeral	tsg	20	2438.76	0.001	0.103	11.714
R19	Reference	UNF	SH	Ephemeral	tsg	75	2431.52	0.001	0.137	10.862
R20	Reference	UNF	SH	Ephemeral	tsg	75	2432.71	0.001	0.111	9.400
R21	Reference	UNF	SS	Ephemeral	tsg	90	2464.53	0.229	0.007	6.231
R22	Reference	UNF	SS	Intermittent	tsg	100	2668.91	0.564	0.074	5.657
R23	Reference	UNF	SS	Ephemeral	tsg	80	2601.25	0.102	0.088	5.852
R24	Reference	UNF	SS	Ephemeral	tsg	95	2582.19	0.029	0.097	7.387
R25	Reference	UNF	SS	Ephemeral	sg	100	2474.58	2.558	0.007	8.143
R26	Reference	UNF	SS	Perennial	gf	100	2468.00	6.828	0.005	1.898
R27	Reference	UNF	SS	Perennial	tsg	100	2660.66	0.001	0.022	5.490
R28	Reference	UNF	SS	Perennial	tsg	100	2670.39	1.577	0.043	4.301
R29	Reference	UNF	SS	Perennial	tsgf	100	2684.05	0.818	0.018	11.660
R30	Reference	UNF	SS	Perennial	sg	100	2475.42	12.048	0.018	4.681
R31	Reference	UNF	SS	Ephemeral	tsg	70	2330.19	0.001	0.040	9.728
R32	Reference	UNF	SS	Ephemeral	tsg	80	2509.11	0.009	0.001	14.679
R33	Reference	UNF	SS	Perennial	tsg	100	2495.48	10.998	0.027	7.464
R34	Reference	UNF	SS	Perennial	tsg	100	2519.00	7.339	0.019	4.597
R35	Reference	UNF	SS	Perennial	tsg	100	2510.75	3.133	0.033	8.055
R36	Reference	Piceance	SH	Ephemeral	gf	40	2559.42	0.919	0.051	10.357
R37	Reference	Piceance	SH	Perennial	gf	70	2551.36	0.002	0.045	11.258
R38	Reference	Piceance	SH	Perennial	g	75	2548.13	0.518	0.055	3.832
R39	Reference	Piceance	SH	Perennial	sgf	75	2534.11	0.587	0.049	11.879
R40	Reference	Piceance	SH	Perennial	sg	75	2518.74	1.924	0.054	5.272

R41	Reference	Piceance	SS	Ephemeral	sg	80	2642.79	0.117	0.124	11.010
R42	Reference	Piceance	SH	Ephemeral	sg	75	2650.11	0.232	0.177	4.490
R43	Reference	Piceance	SH	Ephemeral	sgf	100	2596.57	0.130	0.195	2.886
R44	Reference	Piceance	SH	Perennial	sgf	85	2571.35	0.570	0.073	6.284
R45	Reference	Piceance	SH	Ephemeral	sgf	100	2546.71	0.155	0.127	6.158
R46	Reference	Piceance	SH	Perennial	g	100	2522.88	1.461	0.026	5.403
R47	Reference	Piceance	SH	Perennial	tg	80	2521.02	3.438	0.031	5.756
R48	Reference	Piceance	SH	Perennial	tg	100	2503.73	3.438	0.033	4.616
R49	Reference	Piceance	SH	Intermittent	sgf	40	2589.71	0.440	0.063	6.559

18. APPENDIX D: DATA TABLES FOR CHANNEL HEADS

Table 7: Raw data for the channel heads used in this study. Eight channel heads with inaccurate GPS location information were removed.

Channel Head	Flow Type	Lithology	Elevation (m)	Contributing Area (m^2)	Gradient (m/m)	Basin Length (m)
Ch1	Subsurface	sandstone	2537.21	3900	0.220	177.96
Ch2	Subsurface	sandstone	2533.38	494400	0.119	1257.29
Ch4	Subsurface	sandstone	2534.58	201500	0.022	876.31
Ch5	Subsurface	sandstone	2524.68	20000	0.062	406.43
Ch6	Surface	sandstone	2499.38	265600	0.023	1264.36
Ch7	Subsurface	sandstone	2439.71	9000	0.020	369.77
Ch8	Subsurface	sandstone	2476.05	45800	0.035	732.09
Ch9	Surface	sandstone	2444.88	15500	0.018	577.05
Ch10	Surface	sandstone	2465.09	1400	0.241	99.44
Ch11	Surface	sandstone	2464.60	1900	0.278	80.78
Ch12	Surface	sandstone	2457.95	1500	0.357	71.45
Ch13	Surface	sandstone	2452.78	600	0.394	59.85
Ch14	Surface	sandstone	2460.41	600	0.304	39.59
Ch16	Surface	sandstone	2456.39	5600	0.533	202.09
Ch17	Surface	sandstone	2456.15	2800	0.399	152.23
Ch19	Surface	sandstone	2447.72	900	0.446	118.77
Ch21	Surface	sandstone	2447.90	1300	0.351	93.98
Ch24	Surface	shale	2182.43	800	0.543	74.65
Ch26	Surface	shale	2182.35	500	0.546	9.33
Ch28	Surface	shale	2187.47	800	0.617	83.98
Ch29	Surface	shale	2182.26	2500	0.381	119.71
Ch30	Surface	shale	2188.10	1600	0.510	110.37
Ch31	Surface	shale	2193.16	2500	0.719	138.37
Ch32	Surface	shale	2188.69	2000	0.395	97.18
Ch33	Surface	shale	2190.51	3400	0.697	125.17
Ch34	Surface	shale	2182.12	2300	0.262	166.36
Ch35	Surface	shale	2196.14	5900	0.848	254.21
Ch36	Surface	shale	2195.16	4400	0.723	125.17
Ch37	Surface	shale	2196.47	4500	0.661	134.50
Ch38	Surface	shale	2171.41	12200	0.137	248.74
Ch39	Surface	sandstone	2692.19	14300	0.013	475.62
Ch40	Surface	sandstone	2691.17	405700	0.036	1027.88
Ch41	Subsurface	sandstone	2627.82	4400	0.093	241.01
Ch42	Subsurface	sandstone	2611.22	83900	0.276	1003.08

Ch43	Surface	sandstone	2611.04	48300	0.042	831.53
Ch44	Subsurface	sandstone	2581.90	33100	0.058	587.98
Ch45	Subsurface	sandstone	2654.22	9600	0.060	595.60
Ch46	Surface	sandstone	2240.15	10600	0.071	221.41

19. APPENDIX E: HEADWATER STREAM FIELD PHOTOS

All photos are from the upstream end of the reach, looking downstream, unless otherwise noted.

19.1. Reference Reaches


Reference 1


Reference 2


Reference 3


Reference 4


Reference 5


Reference 6


Reference 7


Reference 8


Reference 9


Reference 10


Reference 11


Reference 12


Reference 13

Reference 14: Looking upstream.

Reference 15

Reference 16

Reference 17

Reference 18

Reference 19

Reference 20

Reference 21


Reference 22


Reference 23


Reference 24: Looking upstream.


Reference 25


Reference 26


Reference 27


Reference 28


Reference 29


Reference 30


Reference 31


Reference 32


Reference 33


Reference 34


Reference 35


Reference 36


Reference 37


Reference 38


Reference 39


Reference 40


Reference 41


Reference 42

Reference 43

Reference 44

Reference 45

Reference 46

Reference 47

Reference 48

Reference 49

19.2. Impacted Reaches


Impacted 1


Impacted 2


Impacted 3


Impacted 4


Impacted 5


Impacted 6

Impacted 7

Impacted 8

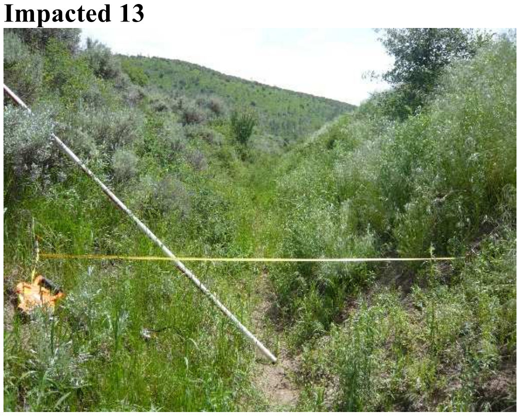
Impacted 9

Impacted 10

Impacted 11

Impacted 12

Impacted 13



Impacted 14

Impacted 15

Impacted 16

Impacted 17

Impacted 18

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Impacted 25


Impacted 26

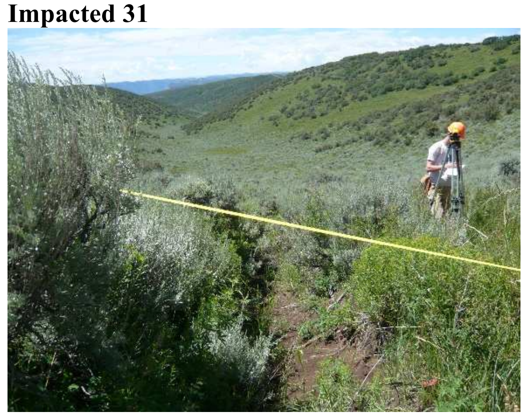

Impacted 27


Impacted 28


Impacted 29


Impacted 30


Impacted 31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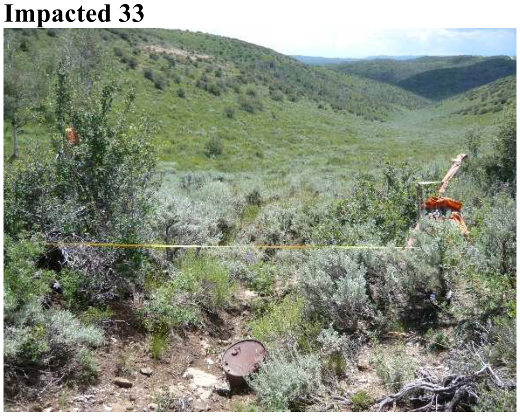
Impacted 33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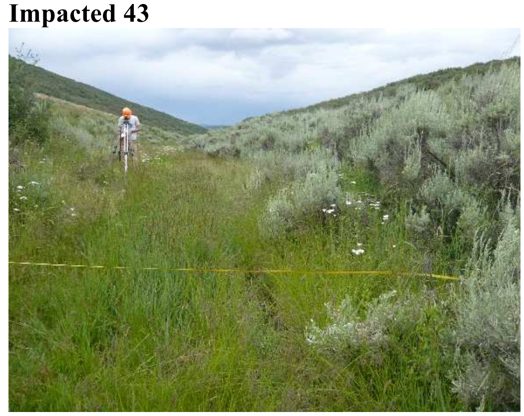
Impacted 43


Impacted 41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Impacted 45

20. APPENDIX F: CHANNEL HEAD FIELD PHOTOS

All photos are from the downstream end of the reach, looking upstream, unless otherwise noted.

Channel Head 1

Channel Head 2

Channel Head 4

Channel Head 5


Channel Head 6


Channel Head 7


Channel Head 8


Channel Head 9

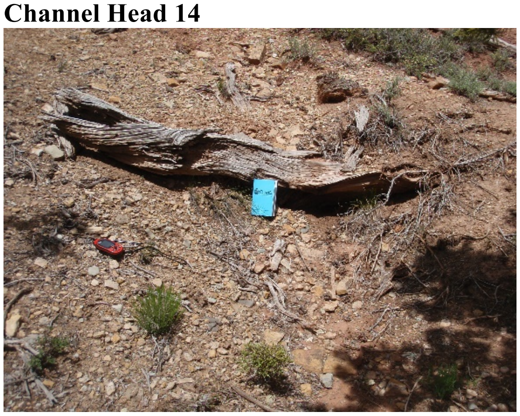

Channel Head 10


Channel Head 11


Channel Head 12


Channel Head 13


Channel Head 14


Channel Head 16


Channel Head 17


Channel Head 19


Channel Head 21


Channel Head 24

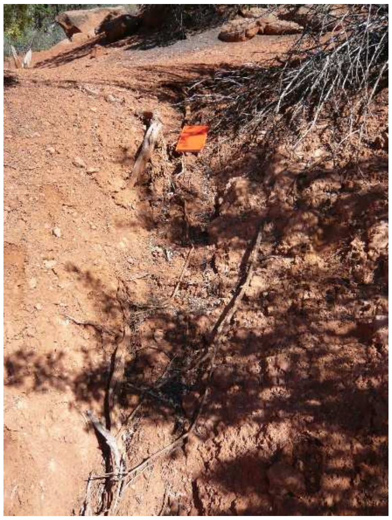

Channel Head 29

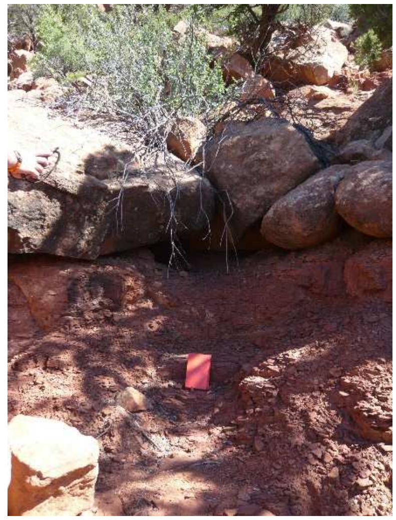

Channel Head 26

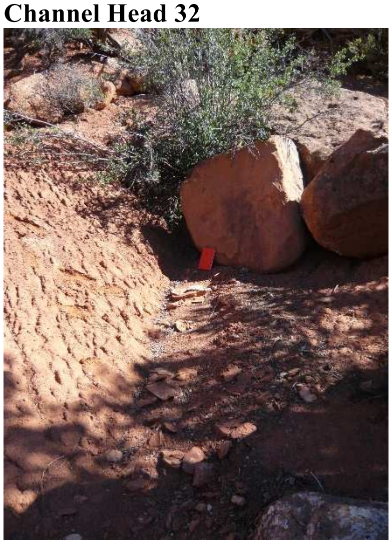

Channel Head 30


Channel Head 28


Channel Head 31


Channel Head 32


Channel Head 35


Channel Head 33


Channel Head 36


Channel Head 34


Channel Head 37


Channel Head 38


Channel Head 39


Channel Head 40


Channel Head 41


Channel Head 42


Channel Head 43


Channel Head 44

Channel Head 45

Channel Head 46