THESIS

EXAMINING GEOMORPHIC EFFECTS OF FLOW DIVERSIONS ON LOW-GRADIENT MOUNTAIN STREAMS IN THE ROUTT NATIONAL FOREST, COLORADO

Submitted by

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ABSTRACT

EXAMINING GEOMORPHIC EFFECTS OF FLOW DIVERSIONS ON LOW-GRADIENT MOUNTAIN STREAMS IN THE ROUTT NATIONAL FOREST, COLORADO

The western United States is faced with an increasing human demand for water, coupled with a decreasing supply. Resource managers are looking for ways to meet the demands of both anthropogenic use and the needs of instream flows to maintain channel characteristics for water quality as well as riparian and aquatic ecosystems. In the Routt National Forest in northern Colorado, ditches typically divert flows from headwater streams to supply the land below the mountains for agricultural purposes. Many studies have focused on the biotic response to streamflow diversions, but relatively little research has been done to quantify the physical effects of ditch diversions. The purpose of this study was to contribute to the understanding of geomorphic effects of flow diversions in the Routt National Forest, and to inform management decisions related to water on the Routt by supplying localized data.

Thirteen streams were surveyed during the summer of 2011, yielding 11 control reaches, located upstream of a diversion point, and 11 diverted reaches, which were downstream of a diversion point. Reach lengths were spaced approximately 20 times bankfull width. Four cross sections per reach were surveyed to collect width and depth information using reference discharge indicators approximating bankfull flow. Pebble counts of 100 clasts per reach were evenly spaced between riffles, and pools were avoided. Riparian vegetation, lithology, and valley characteristics were qualitatively and quantitatively assessed at the reach sites and using US Forest Service geospatial data.

Statistical analyses conducted using the collected data included both t-tests and non-parametric Wilcoxon tests, as the small sample size limited the ability to reject assumptions of normality and conduct multivariate analyses. Univariate mixed-effects models were developed to compare reach response variables between diverted and control reaches while including the effects of unevenly-paired reaches, valley characteristics, lithology, and riparian vegetation. T-tests and Wilcoxon tests found only sinuosity to be significant, with the possibility of riparian vegetation types (willow or grass/sedge) having an effect on variables related to bank stability (width, depth). The mixed effects models found width, width-to-depth ratio, sinuosity, and cross-sectional area to be significant. Because the mixed models included the effects of valley characteristics, riparian vegetation types, lithology, and drainage basin size, these are considered to be more representative of the downstream response to flow diversions than the t-tests and Wilcoxon tests.

This study provides some evidence for the downstream alteration of channels due to diversions. Two channels were noted to have been completely dewatered at the time of surveying in late July-to-August, and several variables were significantly different in statistical tests. For management purposes, it is recommended that high flows periodically enter diverted reaches to help offset the morphology and water quality effects of diversions during dry years. This study stresses the importance of further research to more accurately constrain and quantify physical effects of diversions.

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Finally, I thank my family for instilling in me a love of the natural world and desire to understand it, and my husband Michael for encouraging me to continue my academic studies and finish my master’s degree.

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1. Introduction and Hypotheses

Introduction

In the arid-to-semiarid western United States, water resources are finite. Human populations in this region largely do not live near water resources needed for municipal and agricultural uses. In the state of Colorado, for example, 80% of the water is located west of the Continental Divide, while the vast majority of the state's population resides east of the Rocky Mountains (Jones and Cech, 2009). The natural flowing water available in the western U.S. is frequently extracted for human consumption and agriculture, sometimes over significant distances and commonly in the form of ditch diversions (Parker et al., 2003), to the detriment of stream flows. Most Colorado watersheds have been over-appropriated for water rights since the 1890s. In some cases where diversions are severe, channels are completely dewatered for weeks to months at a time. Channel diversions alter the natural flow regime of streams, including the timing, magnitude, frequency, rate of change, and duration of flows (Poff et al., 1997). Because of hydrologic alterations caused by diverting water, geomorphology of channels can be sensitive to flow diversions (Ryan, 1997). This in turn affects the ecological integrity of flowing rivers, including macroinvertebrate communities, fish populations, and related riparian ecosystems that depend on regular flooding and nutrient cycling that unimpeded rivers naturally provide (Rader and Belish, 1999; McCarthy, 2008).

The Routt National Forest is located within Colorado, and is jointly managed with the Medicine Bow National Forest. Together, these forests encompass over 11,700 square kilometers of largely mountainous terrain in northern Colorado and southern Wyoming, ranging between 1700 and 3900 meters above sea level. The Routt has over 850 known and recorded diversion points on streams, and almost none of the streams on the forest have gage records. The

Routt National Forest desires to protect instream flows for maintaining healthy aquatic and riparian ecosystems. The forest regularly receives proposals for extraction of water resources, but does not yet have a consistent method for evaluating whether these proposals are appropriate for given streams. This project addresses this problem by studying whether streams with flow diversions in the Routt National Forest have significant morphological differences from naturally flowing, non-diverted streams; examining the magnitude and direction of alteration within the affected streams; and providing data for the development of guidelines to analyze prospective water use projects.

Instream and Environmental Flows

Channel flows that are necessary to the maintenance of a certain quality of stream for natural ecosystems are known as environmental flows (Poff et al., 2010). Environmental flows have not been historically well studied, and most research on this topic has occurred only over the past three decades, while water extraction by European settlers has occurred since the late 18th to 19th centuries in the western US (Gillilan and Brown, 1997) and widespread use of diversions for irrigation and mining has occurred since at least the mid-19th century in Colorado (Jones and Cech, 2009). A growing scientific and social awareness of environmental sensitivity of channels and the benefits of rivers has led to an increase in the investigation of environmental flows, the effects of diversions on the stream, and the kinds of flows necessary to maintain a healthy stream (Rathburn et al., 2009). Recent studies have shown that diversions have the potential to change stream geomorphology, habitat, ecology, and water quality.

The management and maintenance of flowing water have been a part of the activities of the Forest Service since its founding when the Sundry Civil Appropriations Act of 1897, commonly known as the Organic Act, was signed into law, allowing for the creation of federally operated forest reserves and managing for “favorable conditions of water flows” (Schmidt and Potyondy, 2004). Maintaining those flows has increasingly become a concern for the U.S. Forest Service, as such flows are critical to the maintenance of habitat-creating channel morphology, riparian ecosystem function, and for non-consumptive uses and economic benefits such as recreation. The jurisdiction of water, however, is largely left up to the states, which can create significant conflict when it comes to the federal directives that the U.S. Forest Service must comply with to conserve and maintain ecosystems that depend on protecting instream flows (Almy and Shellhorn, 2007). Water rights in the western U.S. are typically governed by the prior appropriation doctrine, which gives the water rights that were claimed first priority over all other rights filed at a later date (Jones and Cech, 2009). This generally means that water rights held for non-consumptive, instream flow purposes, which have only been developed in the last two decades, are junior to most other consumptive use-based water rights. The acceptance of using water rights for instream flows varies by state; in Colorado, only the Colorado Water Conservation Board (CWCB) is allowed to apply for and hold a water right for this purpose. The CWCB is required to receive recommendations for instream flows from the state and federal agencies, including the Departments of Interior and Agriculture, but neither federal departments, nor their agencies, such as the Forest Service, have the legal ability to acquire a water right for instream flow purposes (Gillilan and Brown, 1997). Instream flows in the western U.S. and particularly Colorado are primarily managed for water rights for “beneficial use” purposes; typically, these are economically-based and not ecologically-based, and most extract water for consumptive use. Beneficial uses currently recognized by the state of Colorado include: industrial, municipal, snowmaking, aquaculture, washing of gravel and equipment, suppressing dust, fish and wildlife, and recreation (Jones and Cech, 2009). The limited definition of beneficial use reflects the history of Colorado water laws and the difficulties of changing these laws to respond better to ecological and recreational needs for water.

Previous Work on the Effects of Flow Alteration

Much of the published, peer-reviewed literature concerning flow alterations on low-order mountain streams has focused on changes in riparian vegetation and habitat, and to an extent hydrology, rather than channel morphology. Where morphological studies have been done, they were typically on larger rivers with dams, such as the study done by Williams and Wolman in 1984 on 20 rivers in the midwestern and southwestern U.S., and Andrews' (1986) study of the effects of Flaming Gorge Reservoir on the Green River. Other research on comparatively smaller streams has also focused on downstream flow alteration by dams (Stamp, 2000).

Large diversions of water have known biological effects. Rader and Belish (1999) found that large extractions of water from streams, drying the channel for 10-11 months of the year, significantly reduce aquatic invertebrate populations downstream by decreasing density and diversity of species. McCarthy (2008) studied the ecological impacts on invertebrate communities downstream of diversions in the Fraser River watershed, Colorado, and quantified recovery gradients for insect populations in the streams. Some recent studies have begun to connect the biotic and abiotic processes involved in environmental flows. Reductions of peak flows have been observed to reduce channel width through encroachment of vegetation. Ryan (1994) found that wider, less confined, lower gradient alluvial channels were more susceptible to vegetation encroachment, that widths could be reduced up to 50%, and that riparian vegetation invaded and established locations that were formerly in the channel below cut banks. Rathburn and others (2009) linked sediment transport and flood processes to the healthy functioning of an ecological system in a study to assess the specific needs for environmental flows on the North

Fork of the Cache la Poudre River downstream of a proposed reservoir expansion. Some studies have sought to create a general approach for assessing the physical and biological properties of a stream in order to more effectively manage sensitive sites. In a study by Wohl and others (2007) in the Bighorn National Forest in north-central Wyoming, several parameters that included stream gradient, lithology (calcareous or non-calcareous), and flow-regime (snowmelt or rainfall-dominated) were used to determine and classify stream and related ecosystem sensitivity at a sixth-level watershed unit scale.

Some analysis of changes in channel morphology due to flow diversion has occurred, primarily in the form of thesis projects. A Ph.D. thesis by Ryan (1994) on transbasin diversions in the Colorado River basin above Glenwood Springs, CO found that geomorphic sensitivity to diversions is dependent on the type of stream, size, precipitation conditions, and amount of water extraction. Comparison of morphologic response and bedload transport between step-pool and pool-riffle channel types indicated that wider, lower gradient channels were more responsive to reduced flows than steeper, step-pool channels. Montgomery and Buffington's (1997) channel type classification predicts that lower gradient, pool-riffle channels, described as "response reaches," should be more sensitive to water and sediment input changes than higher gradient, step-pool channels. Flow alteration can stabilize channel morphology by decreasing bedload transport and allowing vegetation to encroach and mature, as the vegetation is not subject to regular flooding. A thesis by Stamp (2000) focused on the effects of dams and diversions on the hydrology and geomorphology of two streams in the Uinta Mountains, a sub-range of the Rocky Mountains in Utah. One of the studied streams was altered by a transbasin diversion that perennially reduced flow, and the other stream by a dam that reduced flows in winter, while raising summer flows. Geomorphology was studied using historical photographs, gage record data, vegetation surveys, and characteristics of island morphology. Stamp found that the dammed channel showed limited signs of narrowing, but significant evidence of stabilization, and the diverted channel became simpler and narrower. Stamp and Schmidt (2006) characterized diversions into eight different types. These types were based on whether there were dams at or upstream of a diversion, whether diversions were multi-use or for irrigation only, and whether there was downstream storage for diversions. These different diversion types can alter hydrology and sediment downstream in varying ways, including the levels of flows at certain times, for example high spring floods and winter low flows, and also potentially decrease sediment supply.

Bohn and King (2000) found that on streams in Idaho with small diversions, vegetation stem diameters decreased downstream of diversions, and flow conveyance was reduced. Decreased flows below diversions were evidenced by width between vegetation lines on banks, and flow indicators approximating bankfull. Bankfull refers to the flow just below flood stage that maintains the features of a channel, and over time is thought to carry most of the sediment (Leopold, 1994, p. 141). In the Bohn and King study, sediment size, vegetation stem density, and channel roughness did not appear to be affected, but they noted that some types of diversions could trap sediment from being transported downstream. From their observations, Bohn and King found that diversions did not appear to significantly reduce flows during higher spring runoff levels, and therefore flows that were able to maintain channel form were relatively unimpeded.

Previous research has shown that reducing magnitude and/or duration of higher flows is likely to result in decreased sediment transport, reduction in cross-sectional area by deposition of sediment on the bed and banks of channels, and/or riparian vegetation encroachment. Lower gradient, pool-riffle reaches are expected to have a greater response to reduction in flows caused by diversions than higher gradient step-pool and cascade channels (Montgomery and Buffington 1997, Ryan 1997). This study will build on the existing body of research on the geomorphic effects of flow diversions by specifically studying lower gradient response reaches with flow diversions that are not regulated by dams, for physical changes in cross sectional dimensions, channel slope, sinuosity, and bedload transport via median grain size.

Hypotheses

This study focuses on the response of channel morphology to flow diversion, and the relative significance of specific parameter changes for channel structure in streams on the Routt National Forest (see Figure 1). The objective for acquiring this information is to inform U.S. Forest Service (USFS) managers on the Routt about the potential effects of future water extraction proposals. Two null hypotheses (H_0), along with two alternatives (H_A), were formulated to address these issues:

Hypothesis 1 (H1)

$H_0$1: Study reaches of channels with flow diversions will not have significant differences in physical parameters from similar streams without diversions.

H_A1: Channel form will be affected by flow diversions, reflected in the following ways for study reaches: decreased cross-sectional area, stable meanders in sinuous channels, and decrease in bedload transport. Reduced bedload transport will be inferred based on finer grain size and/or lower pool-riffle amplitude.

The assumption underlying ***H_A1*** is that diversion of flow will reduce peak flow magnitude and duration, and thus the energy exerted in transporting sediment and wood and eroding the channel boundaries. Encroachment of riparian vegetation and sediment deposition will result in channels growing narrower, and in meanders becoming less mobile. Accumulation of finer sediment in the bed will reduce grain size and partially fill pools, causing reduced amplitude of bedforms.

Hypothesis 2 (H2)

$H_0$2: If channel form parameters change as a result of flow diversion, there will be no significant difference in the magnitude or style of change in relation to underlying lithology, valley geometry, or type of riparian vegetation.

H_A2: If channel form parameters change as a result of flow diversion, channel segments with lithologies that produce silt and clay, valley geometries of greater bottom width and lower gradient, and dense willow communities along the valley bottom will show greater change than channel segments with lithologies that weather to sand and coarser sediment, valley geometries with lesser bottom width and gradient, and conifers in the riparian zone.

The assumption underlying ***H_A2*** is that channel segments of lower gradient and wider valleys are likely to be response reaches (Montgomery and Buffington, 1997) that preferentially accumulate sediment, again resulting in more rapid and pronounced response to reduced flow.

I am aware that other factors such as length of time a diversion has been in place, percentage of total flow diverted, and timing of flow diversion will also likely influence channel morphology. These potential influences are not addressed in this thesis, however, because I was not able to constrain the history and magnitude of flow diversion accurately enough at many of the study sites in the absence of consistently kept and publicly available records. Most daily diversion records are typically interpreted from 1-to-5 actual observations made per year by the Colorado Division of Water Resources, and none of the streams were gaged near study reach locations.

Chapter 1 Figures

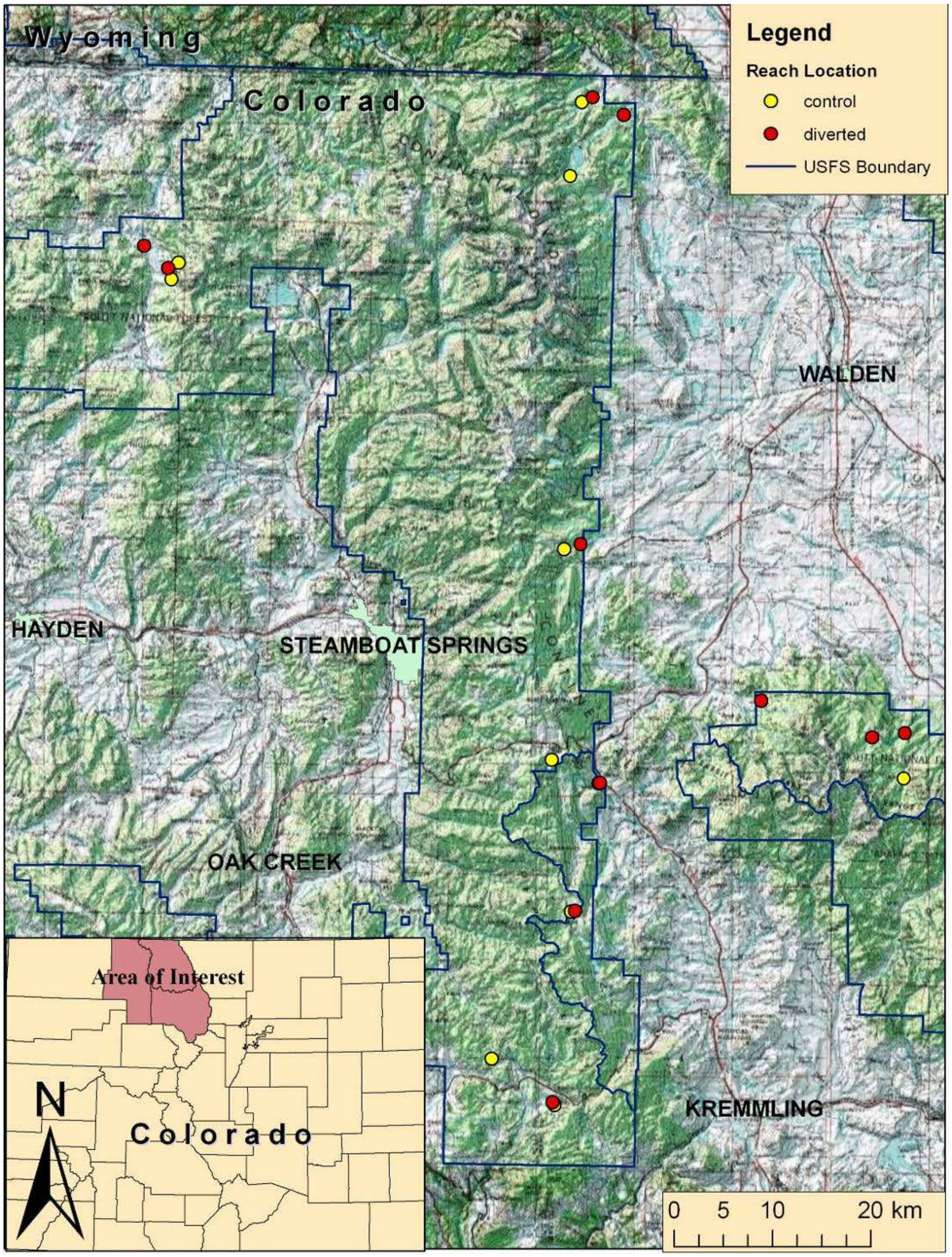

Figure 1. Map of study sites within Routt National Forest (blue line). Yellow circles are control reach locations, and red circles are diverted reach locations. Inset on lower left shows counties within Colorado where the Routt National Forest is located. Names in bold indicate nearby communities. Approximate latitude and longitude of the Routt National Forest are 40°33' N, 106°41' W.

2. Study Areas

Study Areas

The Routt National Forest is bisected by the Continental Divide and encompasses the primarily forested, mountainous terrain of the north-central Colorado Rocky Mountains (Figure 1). This includes the Park Range and northern Gore Range, which trend north-south through the main portion of the Routt, the Elkhead Mountains in the northwest, and the Rabbit Ears Range in the southeastern part of the forest. Major river basins include the Yampa, Little Snake, North Platte, and Colorado River headwaters. National Forest land is administered for multiple uses, including designated wilderness area, fish and wildlife habitat, motorized and non-motorized recreation, livestock grazing, timber, and mineral extraction. Topography varies widely from rugged, steep canyons and mountain peaks to lower-gradient glacial and alluvial valleys. The Medicine Bow-Routt has been affected by the bark beetle outbreak in the Rocky Mountains that began in the mid-to-late 1990s and has continued through the early 21st century. The outbreak has resulted from a number of factors that are believed to include changing climate that creates milder winter conditions, prolonged drought, past land use, and management practices in the forests. According to estimates conducted using aerial detection surveys by the USFS in 2010, over 1.6 million hectares have been affected by bark beetles in the Medicine Bow-Routt and the two adjacent forests, the White River and the Arapaho-Roosevelt (USDA Forest Service, 2011). Areas most affected by bark beetle outbreak on the forest are primarily lodgepole pine-dominated conifer forests. In addition to the beetle-affected lodgepole forest, other upland vegetation communities include spruce-fir conifer forests, aspen, and alpine tundra at moderate to high elevations, as well as oak-brush and sagebrush and grass in the lower elevations (Routt

National Forest Land and Resource Management Plan, November 1983). Riparian vegetation types are designated by the Routt National Forest using dominant vegetation type. These include herbaceous types such as grass and grass-like (including sedge and rush species of genera ***Carex*** and ***Juncus***), shrub types such as willow (genus ***Salix***), sagebrush (genus ***Artemisia***), other undesignated shrubs, and tree-dominant types including Engelmann spruce (***Picea engelmannii***)/subalpine fir (***Abies lasiocarpa***), lodgepole pine (***Pinus contorta***), aspen (***Populus tremuloides***), and cottonwood (***Populus angustifolia***).

All of the study sites are within montane and subalpine zones. Precipitation on the Routt NF typically occurs as snowfall in the winter months, with some rainfall from convective storms during the summer. Precipitation also increases with elevation, from 55 cm at the lower forest elevations around 2500 m, up to 100 cm to less than 200 cm of precipitation at the higher elevations of around 3000 m and above (Figure 2) (Elliot et al., 1999). Storms bring somewhat more moisture to the west slopes of the Park and Gore Ranges than the eastern side. Hydrology is snowmelt-dominated, with some increased runoff from summer convective storms (Figure 3). Flows normally peak between mid-May and mid-June from snowmelt runoff, with the falling limb of hydrographs occurring during summer, and base flows occur during the fall and winter months with minimum flows in late April and early September. The Yampa River headwaters originate within the western portions of the Routt National Forest; a portion of the Colorado River headwaters drain the southern part of the forest; and the North Platte River drains the parts of the forest bordering North Park. Figures 4a and 4b show recorded diversions and study sites on the Routt National Forest within major watershed boundaries designated by 8-digit hydrologic unit codes (HUC), and study reach locations within smaller watersheds delineated by 12-digit

HUC boundaries as designated by the U.S. Geological Survey's National Hydrography Dataset (USGS, 2012a).

The Routt National Forest is located in a geologically complex region of north-central Colorado (Figure 5). The Park and Gore Ranges were elevated during both the Laramide Orogeny and a regional uplift event in the mid-Tertiary Period, and consist of Precambrian metamorphic and granitic basement rocks. The Rabbit Ears Volcanics formed concurrently with the regional uplift, and extend from the Park Range across to the Rabbit Ears Range (Hail, 1968). Sedimentary units including interbedded sandstone, shale, and conglomerate deposited during the Jurassic and Cretaceous, flank the lower elevations of the Park and Rabbit Ears Ranges. An unconformity separates the sedimentary units, as the older Mesozoic sediments are overlain by later Tertiary sediments (Hail, 1968). Glaciers left deposits during the Pleistocene Epoch, including moraines composed of glacial till and terrace gravels from outwash (Hail, 1968). The Park Range experienced glaciation during the Wisconsin (Atwood, 1937), which has been correlated with the Bull Lake and Pinedale glaciations in the Rocky Mountains (Pierce, 2003). The Park Range also has some geomorphic evidence for pre-Wisconsin events earlier in the Pleistocene (Atwood, 1937). Madole (1980) found through stratigraphy and ^{14}C dating in the Buffalo Pass area, about 15 km northeast of Steamboat Springs, that the age of Pinedale deglaciation in the southern Park Range was about 11,000 years B.P. Glaciers were found at the crest of the Park Range, approximately 3000-3600 m, terminating at bottom of slopes around 2000-2500 m where outwash deposits are located (Atwood, 1937) (Figure 6).

A total of 22 reaches were surveyed. Channels are separated into two groups: the control streams, which have no previous or current flow diversions, and the diverted streams, which have current flow diversions. Data were collected from an equal number of control and diverted streams, with 11 stream segments in each group. The study reaches selected are located on mid-to-low-gradient, single-thread alluvial mountain streams within the Routt National Forest. Most are located within unglaciated alluvial valleys, with two reaches in unconfined glacial valleys. Stream reaches are distributed across a wide area of the Routt, ranging from 2500 to 2850 meters elevation, and all are located within Divisions 5 and 6 of the Colorado Division of Water Resources' designated management areas (Figure 7), which are further subdivided into water districts. Six of the reaches are located Division 5, which is designated as the Colorado River Basin. Within Division 5, the reaches are found in smaller sub-basins: three in the Muddy/Troublesome Creeks basin and three in the water district denoted as "tributaries north of Colorado River." Sixteen of the reaches are within Division 6, which is composed of the Yampa/White and North Platte River watersheds. This division is further subdivided into smaller basins: 10 reaches are located within the North Platte basin, four within the Slater/Timberlake Creeks basin, and two in the Upper Yampa.

All reaches are alluvial, unconfined channels, most of which are underlain by sedimentary units or glacial deposits. Most reaches are located within alluvial valleys. Reach sites for three streams are in valleys dominated by past glacial activity, including Beaver Creek, Chedsey Creek, and South Fork Big Creek. Reach lengths vary by over 20 times, from 5.3 m up to 122 m. The broad range of reach lengths is due to the diversity in active stream widths and watershed areas for studied streams, and the scaling of reaches to the width of the channel. Drainage area of the streams ranges from 0.6 to 30 km^2. Of the diverted reaches, six are downstream of multiple diversion points, while four are diverted by single ditches. All streams are typically diverted during the late spring and summer months (May through July), with one diversion taking water out of Ninegar Creek almost year-round. These diversions use water to flood-irrigate grass pasture for cattle grazing. Appropriation dates are the recorded times at which water began to be appropriated for diversions along the study streams. These range from the 1880s to 1930s (Table 1). Diversion decreed amounts are reported in cfs by Colorado's Decision Support Systems, the online record database for Colorado Division of Water Resources and the Colorado Water Conservation Board. Decreed amounts of diversions for study streams vary from 1.8 ft^3/s (cfs) (0.051 m^3/s (cms)) for one of the smallest streams, Jolley Creek, up to 115 cfs (3.26 cms) for South Fork Big Creek, one of the largest streams (Colorado's Decision Support Systems, 2011). Almost all of the study streams can be considered over-appropriated. Decreed water rights amounts for the diverted group of reaches are estimated to be 85 to1600 percent of mean annual flow, and 30 to 250 percent of the seven-day mean maximum flow that occurs on average once in 2 years (Table 2) using the USGS StreamStats program, which calculates flow estimates using regression equations for the State of Colorado (USGS, 2012b). The regression equations used are evaluated using climatic attributes, drainage basin characteristics, and USGS streamflow gage data for sites in Colorado (Capesius and Stephens, 2009).

Diversion Types

Diversion types on the Routt National Forest are highly varied with respect to both the amount of flow they are capable of diverting and the style of diversion points and headgates. These diversion types were documented where possible (Figure 8). In several cases, such as Slater Creek, observation of some of the diversion headgates was not possible due to private land boundaries. Some of the surveys were conducted during periods of active diversion on the reaches. For two diverted reaches—Service Creek[1] in early August and Little Muddy Creek in mid-July—100 percent of the water was being diverted, and complete dewatering of the channel was observed. The Sarvis Ditch and Martin No. 1 Ditch diversion points at Service Creek and Little Muddy Creek, respectively, were able to completely block and re-route flow into irrigation ditches using levees and headgates. Most other active diversions allowed a certain amount of flow to bypass diversion. Some, such as Rhea and Willford Ditches at Beaver Creek, used rock weirs to channel some flow into ditches with rudimentary headgates composed of timbers that limit inflow and instream wood in the ditch, but still allow smaller amounts of flow into the ditch at all times during high-to-moderate streamflows. Other ditches, such as Hans Clauson No. 1 Ditch at Beaver Creek, had no headgates and would only take water at the highest flows.

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[1] Service Creek is also known as Sarvis Creek on some maps (including U.S. Forest Service) but not others (U.S. Geological Survey quadrangles). For consistency with the CDSS online water rights database, I use the name "Service" for the stream and "Sarvis" for the diversion ditch that is connected to the water right.

Chapter 2 Figures

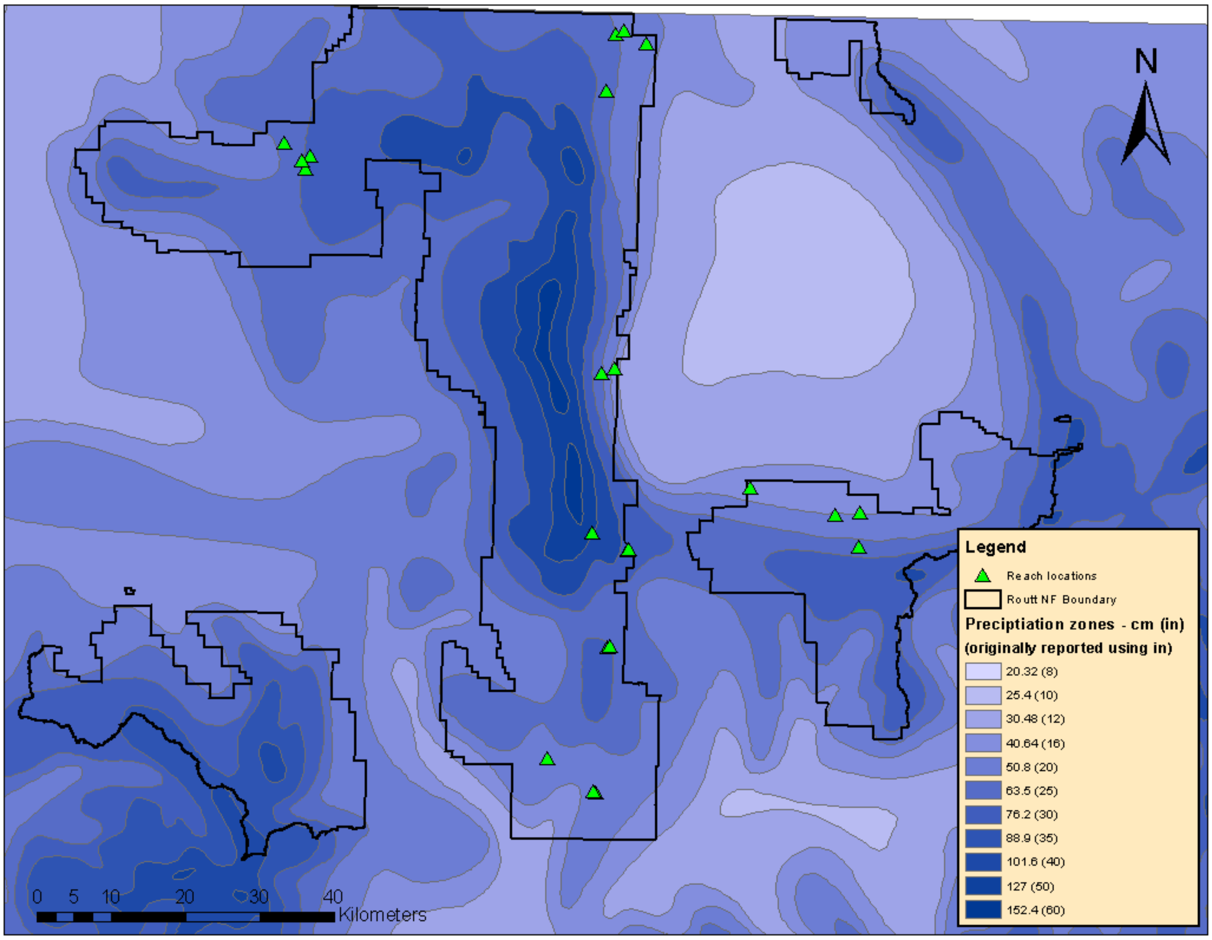
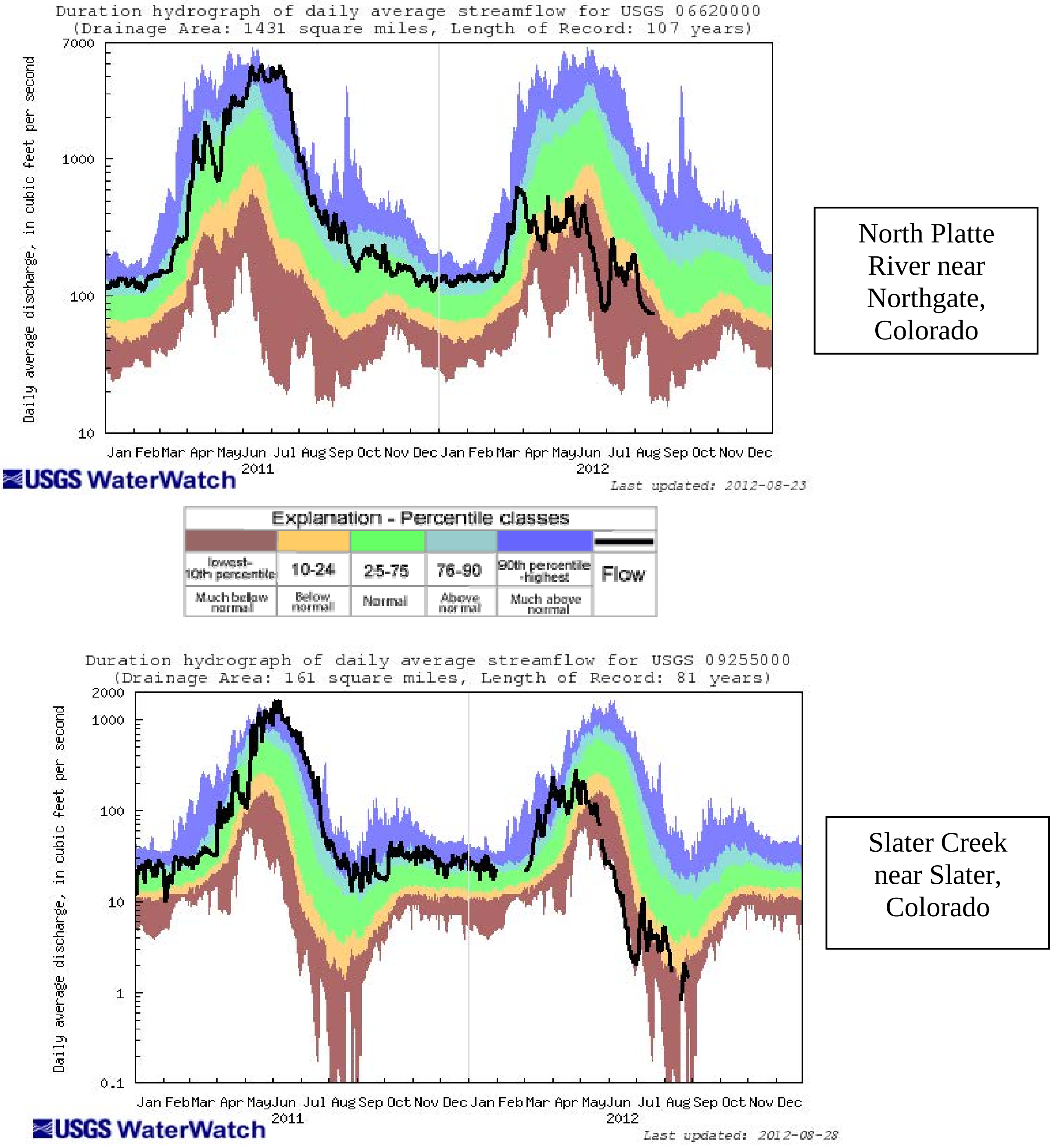


Figure 2. Precipitation zone map for the Routt National Forest, using geospatial data from the Medicine Bow Routt National Forest based on PRISM data. Green triangles are locations of study reaches.



Duration hydrograph of daily average streamflow for USGS 06620000
(Drainage Area: 1431 square miles, Length of Record: 107 years)

Last updated: 2012-08-23

North Platte River near Northgate, Colorado

Explanation - Percentile classes

🟫	🟧	🟩	🟦	🟪	▬
lowest-10th percentile	10-24	25-75	76-90	90th percentile -highest	Flow
Much below normal	Below normal	Normal	Above normal	Much above normal	

Duration hydrograph of daily average streamflow for USGS 09255000
(Drainage Area: 161 square miles, Length of Record: 81 years)

Last updated: 2012-08-28

Slater Creek near Slater, Colorado

Figure 3. Examples of annual hydrographs for 2011 through August 2012 from streams near Routt NF with daily streamflow data provided by the U.S. Geological Survey's Water Watch program using the USGS Streamflow Duration Hydrograph Builder (USGS, 2012). The upper hydrograph is for the North Platte River near Northgate, CO (USGS, 2012), and the lower is for Slater Creek near Slater, CO (USGS, 2012c, 2012. At the center is an explanation of the color bands representing percentile classes of flow calculated from data collected at the stations for the length of record. Black lines are data from daily streamflow records. Water year 2011 had exceptionally high peak flows and delayed timing, whereas in 2012 the peak was much lower and approximately 2 weeks to 1 month earlier than the normal peak, shown by the green band.

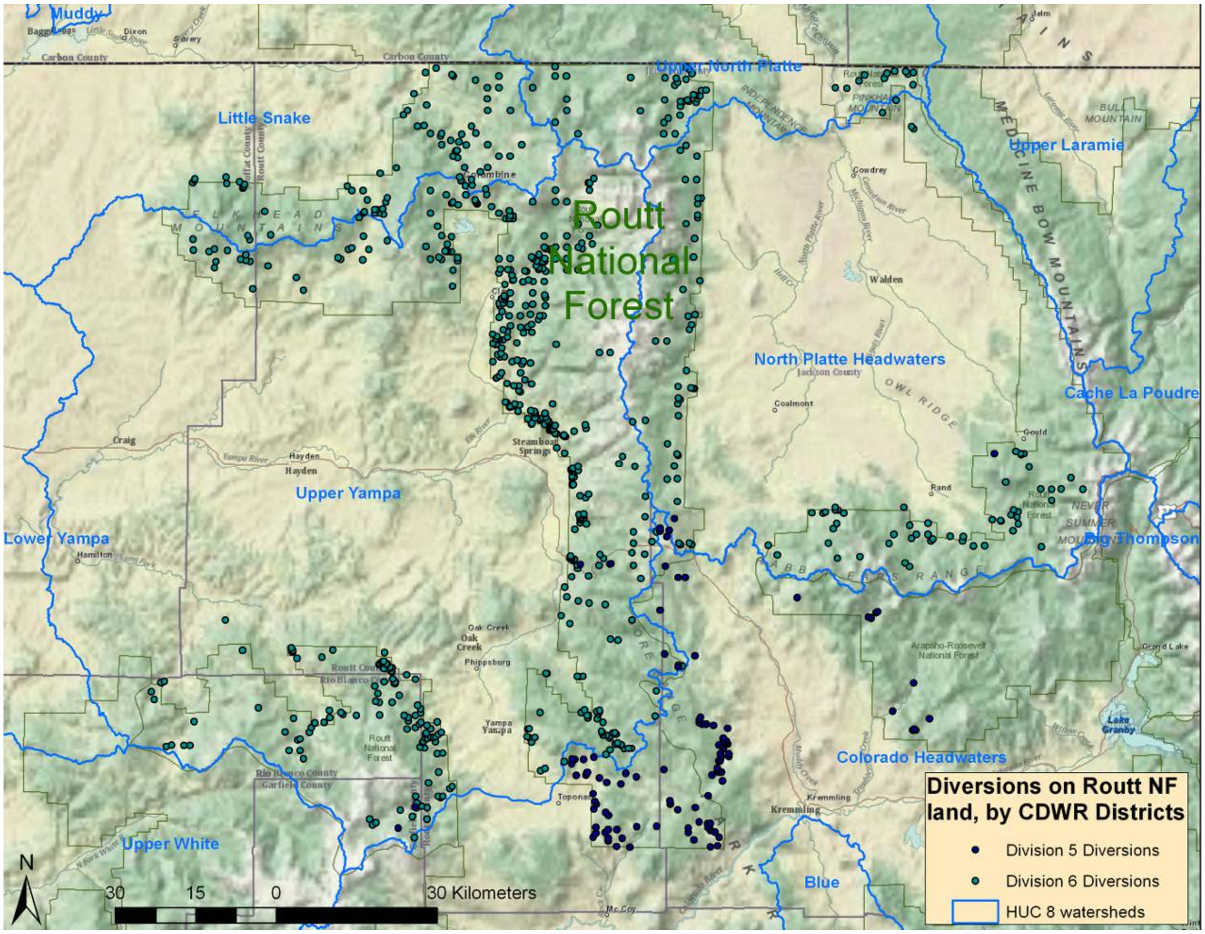


Figure 4a. Diversion locations on the Routt National Forest within HUC 8 watersheds. These include the Upper North Platte, Little Snake, North Platte Headwaters, Upper North Platte, Upper Yampa, and Colorado Headwaters.

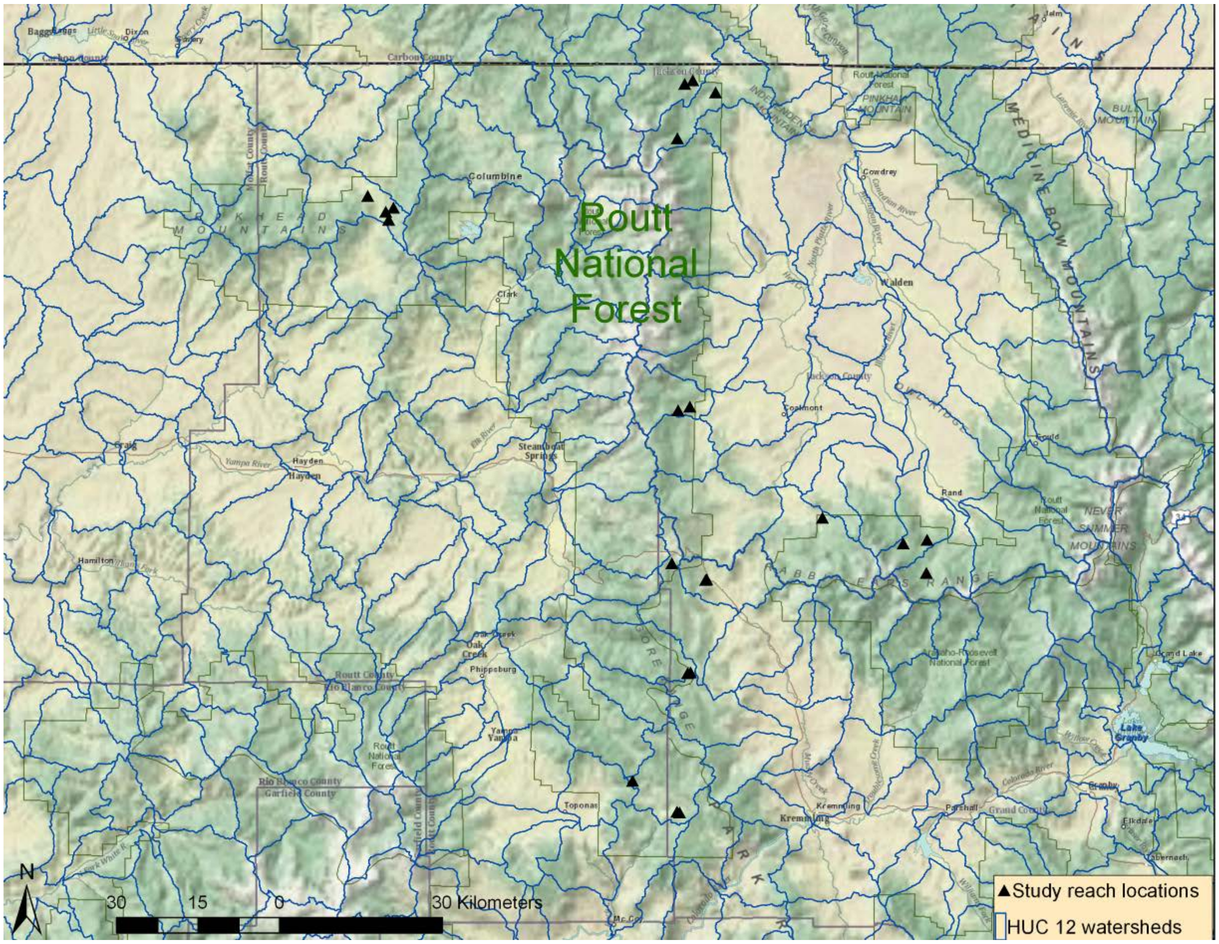


Figure 4b. Study reach locations within HUC-12 watersheds.

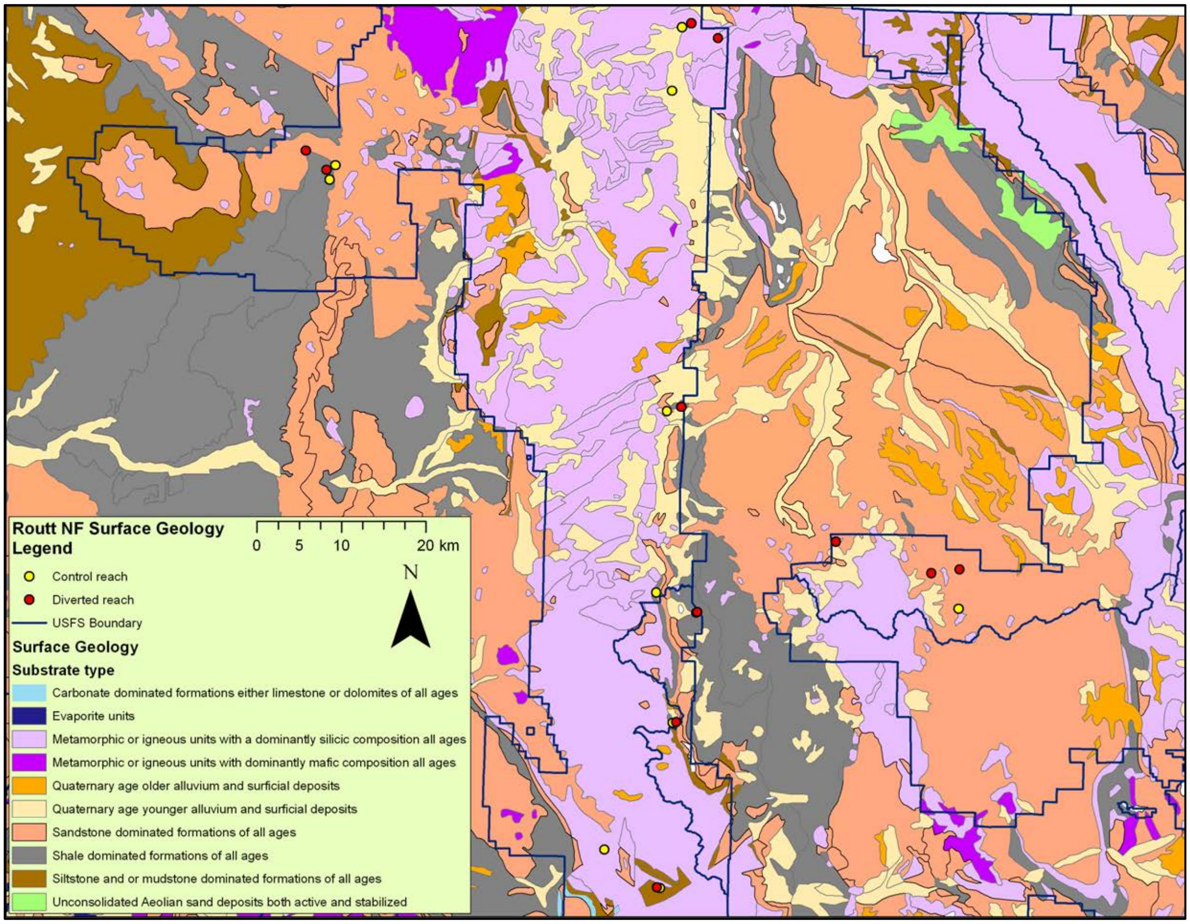


Figure 5. Geologic map of the Routt National Forest, using geospatial data available from the U.S. Forest Service. Reach study sites are primarily found in sedimentary-dominated units including sandstone, siltstone, and shale. Six reach sites are located on crystalline units and/or Pleistocene glacial deposits.

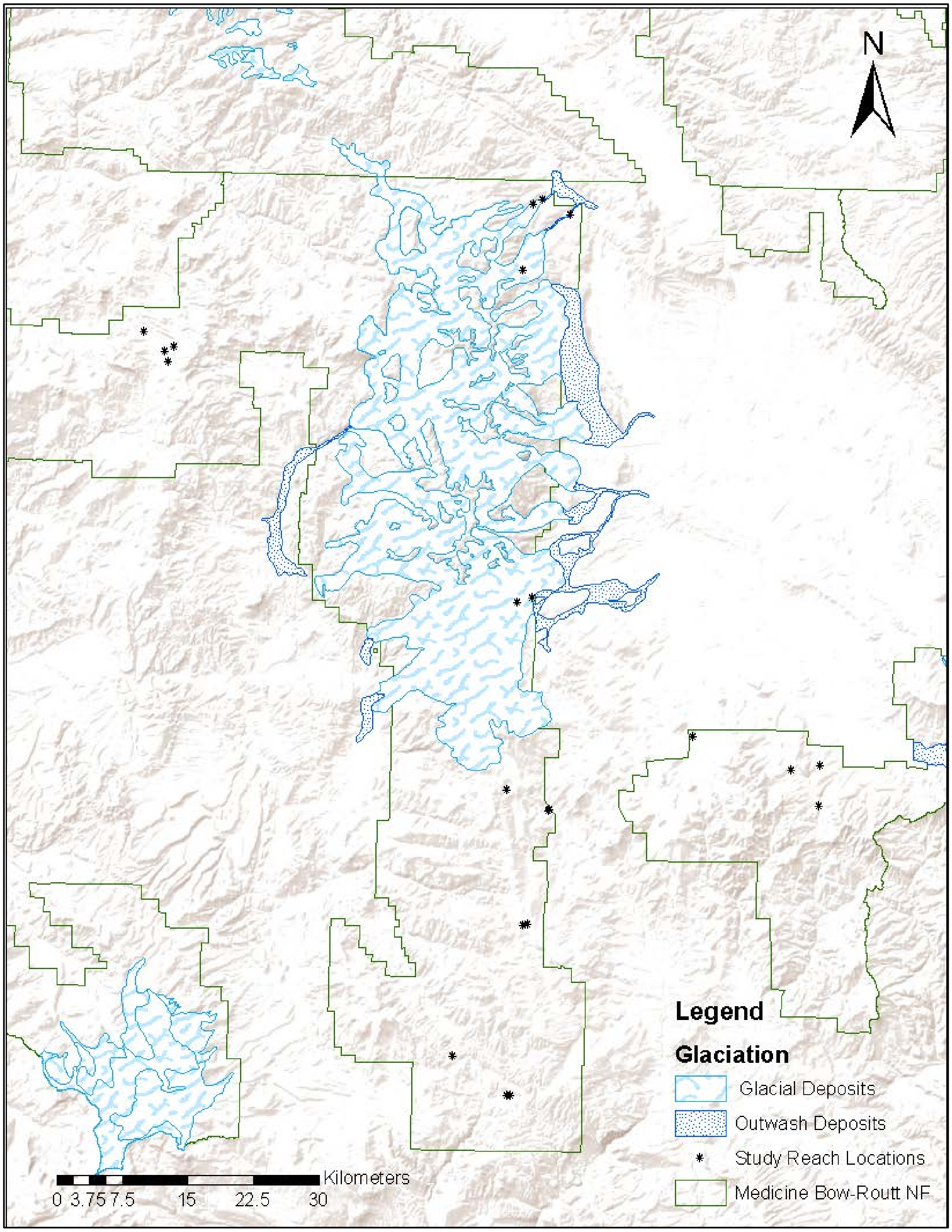


Figure 6. Map of glacial deposits from the Pleistocene, compiled by the U.S. Forest Service, and based primarily on research by Atwood, 1937, and Mears, 2001.

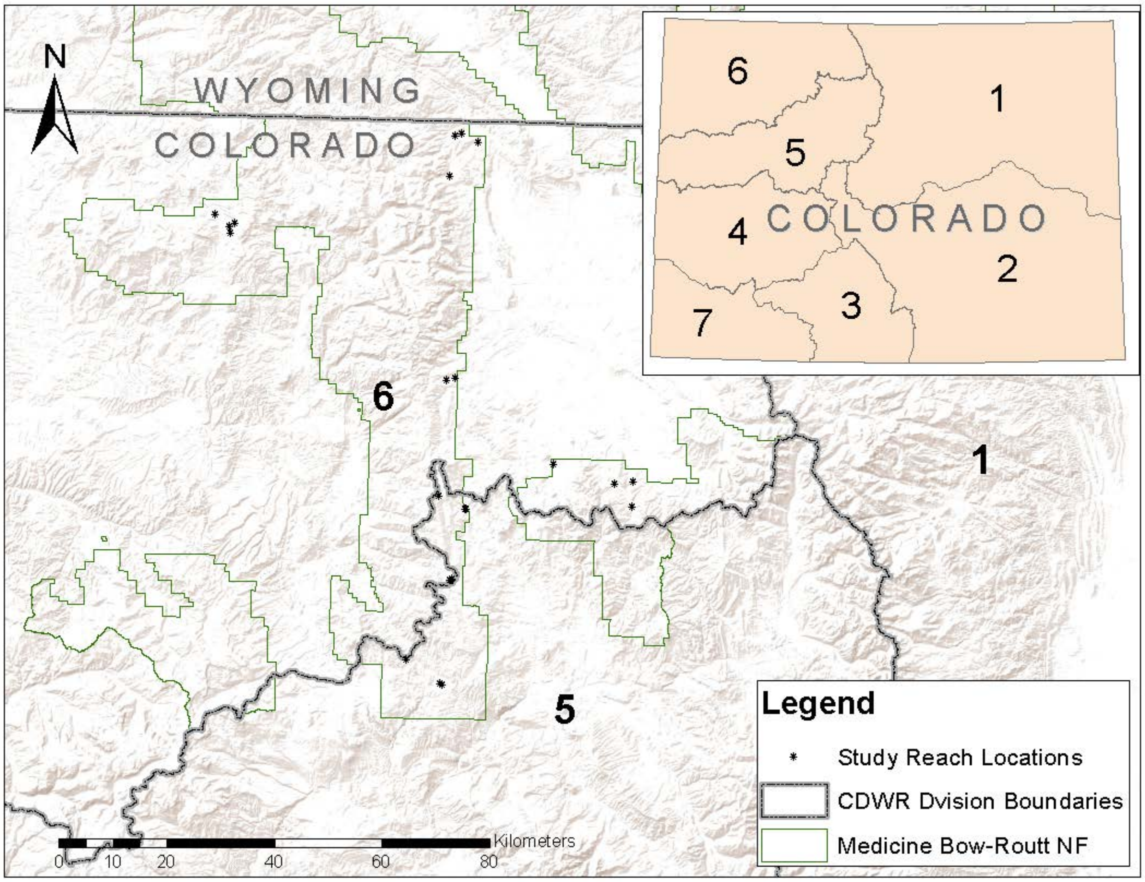


Figure 7. Management districts for the Colorado Division of Water Resources. Study sites are located in Division 5, the Colorado River Basin, and Division 6, the Yampa/White River Basin. Geospatial data from the Colorado Division of Water Resources at http://water.state.co.us/DataMaps/GISandMaps/Pages/GISDownloads.aspx

Table 1. Names of ditches, appropriation and adjudication dates of water rights, and timing of diversions for the diverted study sites, as reported by Colorado's Decision Support Systems, the online water rights database for Colorado Division of Water Resources and Colorado Water Conservation Board (http://cdss.state.co.us/Pages/CDSSHome.aspx).

Name	Diversion ditch name(s)	Appropriation Date(s)	Adjudication Date(s)	Timing of Diversions	Typical timing of largest diversions
Beaver Creek (of Big Cr.)	Hans Clauson #1, Willford, Rhea	1898	1923	Apr-Aug	May-Jul
Chedsey Creek	West, Burns	1910	1939	Mar-Oct	May-Aug
Jolley Creek	Jolly Homestead #1, #2	1902-1903	1907	Apr-Aug	May-Jun
Little Muddy Creek	Martin #1	1886-1935	1906-1938	May-Oct	Jun-Jul
Ninegar Creek	Slack Weiss, Cochrane	1890	1932	year-round	Apr-Oct
Rock Creek (Darcy Ditch)	Darcy	1919-1936	1932-1989	Apr-Oct	May-Aug
Rock Creek (Westfield Ditch)	Westfield, Darcy	1898-1937	1913-1993	Apr-Oct	May-Jul
Service Creek	Sarvis	1911	1964	year-round	Apr-Jul
Slater Creek	Slater Park #1 - #5, HGD 2	1899	1964	May-Oct	Jun-Jul
Slater Creek (tributary, #2 ditch)	Slater Park #2	1934	1964	May-Oct	Jun-Jul
South Fork Big Creek	Independence, East Lynne	1887-1955	1939-1958	Apr-Oct	May-Jul

Table 2. Total decreed water rights amounts (from Colorado Division of Water Resources) on diverted reaches as a percentage of mean annual flow (%MAF) and 7-day, 2-year maximum flow estimates (%7D2Yr Max) from USGS StreamStats (http://streamstats.usgs.gov/colorado) regression equations for the diverted study sites. Water rights decreed amounts, mean annual flow estimates, and maximum flow estimates are reported in cubic feet per second (cfs) by Colorado Decision Support Systems -- the online water rights database for Colorado's water management agencies -- and U.S. Geological Survey.

Diverted Reach	Total Decreed Amount (cfs)	Mean Annual Flow (MAF) (cfs)	% MAF	7 Day 2 Year Maximum Flow (7D2Yr Max) (cfs)	% 7D2Yr Max
Beaver Creek (of Big Cr.)	46	21.2	216.981	146	31.51
Chedsey Creek	42.67	21.5	198.465	164	26.02
Jolley Creek	1.8	2.1	85.7143	14	12.86
Little Muddy Creek	31	4.77	649.895	32.6	95.09
Ninegar Creek	44.03	2.76	1595.29	17.5	251.6
Rock Creek (Darcy Ditch)	43.38	8.58	505.594	61.4	70.65
Rock Creek (Westfield Ditch)	79.88	12.1	660.165	79.3	100.73
Service Creek	43	3.16	1360.76	23.3	184.55
Slater Creek	40.5	15.3	264.706	100	40.5
Slater Creek (tributary, #2 ditch)	5.1	2.35	217.021	17.3	29.48
South Fork Big Creek	115	29.4	391.16	146	78.77

Figure 8. Examples of diversion and headgate types for study sites. (A). Diversion of Service Creek at Sarvis Ditch headgate. Berm blocks and collects flow from Service Creek and wetland, diverting it into ditch on right side of berm in image.

(B). Diversion of Beaver Creek at Rhea Ditch. Headgate composed of wooden logs with rock weir directing flow. Some water leaks through to ditch when headgate is closed.

(C). Diversion of Little Muddy Creek at Martin No. 1 Ditch. Example includes two headgates; one in middle foreground blocks downstream flow to creek, one in middle background releases flow into ditch.

(D). Diversion of East Fork Williams Fork at Egry Mesa Ditch. Example of a rock weir with metal headgate. Williams Fork was not surveyed in this study, due to flows exceeding those safe for wading at the potential control reach site.

3. Methods and Data Analysis

Site Selection

Stream surveys were conducted to test the hypotheses and determine the direction of physical change in channels with flow diversions in the Routt National Forest. Channels appropriate for study were selected using records provided by Routt National Forest and geospatial data on streams. Information obtained from geospatial data included location, gradient, underlying lithology, landform type, records of known flow diversions, past history of flow diversions, and accessibility on public lands within the area of interest. Stream reaches classified on the presence of plane-bed or pool-riffle morphology (Montgomery and Buffington, 1997) and gradient lower than 4-5%, were selected for study (Figure 9a). These channels can be considered roughly equivalent to Rosgen types B, C, and E (Rosgen, 1994). The Rosgen classification method was not used to select reaches, but rather is used here as a reference for those familiar with the Rosgen stream types. Prior work done by Ryan (1997) found that unconfined, alluvial streams were more susceptible to change than more confined, steeper bedrock streams, and thus step-pool and cascade stream types, generally corresponding to Rosgen types A and Aa+, were omitted from this study (Figure 9b). Similar to site selection for a diversion study by Bohn and King (2000), sites with different stream types upstream and downstream of diversion points were avoided where possible. Many diversions are located at changes in slope to allow for easy conveyance of water, and some potential sites had to be omitted because the control reach upstream of the diversion was too steep to meet the criteria used for site selection in this study.

Field reconnaissance of potential survey locations was used to determine feasibility of reach selection and surveying, due to factors such as beaver dams that may not be visible in aerial imagery and the exceptionally high flows during the late spring through midsummer of 2011. Using management information available from the U.S. Forest Service, sites with impacts such as logging, tie-drives, large dams that regulate flow, recent fire, and significant amounts of beetle-kill trees were avoided. Selected sites also excluded the following: major tributaries, multiple-thread channels, abundant instream wood, and active beaver dams. Tributaries increase discharge downstream and might mitigate or hide effects of diversions. Surveying single-thread channels, as opposed to surveying both single and multiple-thread, made for simpler, more comparable stream surveys, and multiple-thread channels were rarely encountered. Time constraints also prevented the survey of large instream wood jams. Active beaver dams, particularly those with significant lengths of standing water, would have also added an extra complication to surveys, although some reaches were included that did have evidence of past beaver activity. Reaches were also placed far enough away from diversion points to avoid backwater effects. Approximately 10 sites were visited but rejected, due to high flows creating hazardous wading conditions, extensive beaver dam complexes, and/or diversions that were found to be inactive because water rights had not been developed.

Diversion records and geospatial information were obtained from Colorado’s Decision Support Systems, an online database of water resources information that is jointly managed by the Colorado Water Conservation Board and Colorado Division of Water Resources (CDWR), the state agency that administers and monitors water rights. Diversion records include structure summaries that list the locations, structure names, water sources, water rights owners, appropriation and adjudication dates of water rights, decreed amounts of water in cubic feet per second (cfs), acres irrigated (derived from GIS data), summary of timing by year and month, and amount of water diverted at those times in acre-feet. Detailed diversion records are also available, showing monthly amounts diverted, use, source, and diversion type. These records can be useful, as the amounts actually diverted by water rights holders are not always equal to the decreed amounts of the right. Some of the listed diversion amounts are measured by the CDWR or from user-supplied data; the rest of the records are interpreted from those observed values. For all of the diversion records in this study, actual measured values can be as few as one to five days out of each year, and as frequently as once a month; all other daily recorded diversion records are based on those amounts, and are not actual observations. Because of uncertainties concerning the accuracy of the diversion data at a site, and the consistency in record keeping between sites, these data were not used to test a hypothesis regarding potential correlations between the duration or magnitude of diversion and channel morphologic alteration. Diversion data were, however, used in statistical analyses evaluating channel responses to diversion. There were a range of years that diversions were developed (1996-1955), but these were not separated into groups, as there was not enough of a separation in dates to justify binning diversions by age, and many diversions had water rights developed over a series of years. For example, Little Muddy Creek has water rights that range from 1906 to 1938, and Rock Creek's water rights date between 1932 and 1989 (Table 1).

Field Data Collection

After site selection, data collection consisted of field surveys of stream segments conducted in summer 2011. In the field, reaches of length ~ 20 times the active channel width were selected and measured with a 100-meter tape. Diverted and control reaches were placed downstream and upstream, respectively, as close to the diversion as possible. A Topcon GTS-

212 total station with Carlson data logger attached, and rod and prism, were used to measure longitudinal profiles and cross sections. On two field days when there were technical issues with the total station setup, two diverted stream segments — Rock Creek downstream of Darcy Ditch, and Chedsey Creek — were surveyed with a Topcon RL-H3C auto-leveling laser and 100-meter tape.

Longitudinal profiles were measured with intervals of 1-2 m between points, and closer if necessary to capture significant channel features that were located within the 1-2 m intervals. Four cross sections per reach were measured, and were located to proportionally represent channel unit types. For example, where appropriate, two riffle and two pool cross sections per reach were measured at maximum pool depths and at crests of riffles. Where riffles and pools were not present, cross sections were spaced evenly apart within the reach. Elevations at a reference discharge approximating bankfull were also measured within cross sections on either side of the channel, and determined using morphological indicators described by Harrelson and others (1994), such as slope breaks and particle size change along banks, undercuts, changes in vegetation, and depositional features such as the tops of point bars and debris from high water marks.

Pebble counts were collected within the active channel and sorted by size classes with a gravelometer. One hundred clasts were measured per reach. Where pool-riffle morphology was present on a stream, pebble counts were evenly distributed between riffles; for example, 50% of the count would be conducted in riffle 1, and 50% in riffle 2 for a reach. Due to high water levels during summer 2011, pebble counts excluded pools. Where pools and riffles were not present, such as in plane-bed channels, pebble count sites were evenly spaced within the active channel of the reach.

Photos of the channels were taken from the upstream and downstream ends of the reaches, and visual estimates of Manning's n value were made when feasible using USGS calibrated photography (Barnes, 1967) (Table 3). Photos of diversions at head gates were taken where possible. General vegetation types were recorded and categorized as willow, grass/sedge, or conifer-willow (Table 4). Planform sketches of the reaches were drawn in the field, and coordinates were recorded of the field sites, typically at the location of the total station, using a handheld GPS device.

The data were processed after field collection, including obtaining median substrate size, $D_{50,}$ from pebble counts, and deriving channel slope from longitudinal profiles. Bankfull width, average depth, width-to-depth ratio, cross sectional area, and entrenchment, a measure of flood-prone width to bankfull width described by Rosgen (1994), were extracted from the cross section data for each reach. Flood-prone width is an area perpendicular to the channel that is derived from an elevation that is twice the bankfull depth (Rosgen, 1994). Length of the reach and straight line valley distance between the starting and ending points of the reach were used to calculate sinuosity.

Data Analysis

To test the hypotheses, the data were analyzed using the statistical software packages SAS and R. Boxplots were created to visually compare means and medians for diverted and control data, and corresponding summary statistics, including mean, median, standard deviation, and variance were calculated. The response variables tested included $\boldsymbol{D_{50}}$, sinuosity, bankfull width, channel slope, average depth at bankfull, width-to-depth ratio, and entrenchment (Table 5). For the above variables, sample sizes were n=11 for diverted reaches and n=11 for control streams. Pool and riffle depths and widths were also compared between diverted and control groups, with sample sizes n=12 for control and n=10 for diverted groups (Table 6). Small sample sizes typically do not allow enough evidence to base a firm decision on whether to reject normality assumptions; therefore, both parametric and non-parametric tests were applied to account for the small sample sizes (M. Meyer[2], pers. comm., April 26, 2012). A rejection level of $\alpha=0.10$ was used for statistical tests.

Of the 22 reaches, 16 were grouped into eight pairs, where one diverted reach was surveyed downstream of a diversion, and one control reach was surveyed upstream of a diversion on the same stream. These eight pairs include Beaver, Chedsey, Little Muddy, Service, Slater, Slater tributary, Jolley, and South Fork Big Creeks. Statistical analyses of the paired streams were conducted using paired t-tests and Wilcoxon signed-rank tests. Paired t-tests assume normality and independence of observations. Non-parametric Wilcoxon signed-rank tests provide an alternative to t-tests that does not assume normality and assigns ranks to absolute values of differences in ***n*** pairs of observations. Exact Wilcoxon p-values were used from these tests, as they more accurately represent small sample sizes than using the Wilcoxon normal approximation (Ott and Longnecker, 2010). These tests were two-sided, where $\boldsymbol{H_0}$ was rejected if $t \neq t_\alpha$, where t has an associated p value that is less than $\alpha=0.10$. Paired t-tests provide differences in paired measurements, including mean and standard deviation (Ott and Longnecker, 2010).

Because the remaining number of "unpaired" stream reaches was very small, where n=3 for the unpaired control group, and n=3 for the unpaired diverted group, pairing was ignored when testing the entire data set using non-parametric Wilcoxon rank-sum and unpaired t-tests. In unpaired t-tests, normality, independent sampling, and equality of variances are assumed. Wilcoxon rank-sum is an alternative to the t-test that calculates the differences in sample means

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[2] Colorado State University's Franklin A. Graybill Statistical Consulting Laboratory

of two populations by ordering data and assigning ranks to the data to reduce the effect of extreme values that can skew distributions. This test does not assume normality, allowing it to be used where normality assumptions may be in question, which is particularly useful for small sample sizes. A “semi-paired” t-test was created using the software package R, which included both paired and unpaired reach data in the same set. This test calculated the estimate of differences between average measurements for the diverted and control streams, where the difference under the null hypothesis is zero difference. A non-parametric version of the semi-pair test was not developed (Ott and Longnecker, 2010).

Two sets of mixed models were developed, with the reach response variables tested separately in each model. One set accounted for both the control reaches that were split into two groups: those with paired diverted reaches downstream of irrigation ditches, and those that did not have a diverted paired reach on the same stream. The set of models were used to look at the interaction between position of the streams (control or diverted), and whether the stream had a surveyed reach downstream of a diversion to account for unpaired control reaches. The second mixed model[3] took the uneven pairings into account as the mixed effect, as well as using valley type factors, lithology/weathering, and vegetation as different treatments. Radius of curvature of meanders was used as a potential influencing variable for sinuosity, and channel slope was also used as a predictor variable in an additional round of mixed models. Results from the mixed model analyses were obtained through the p-values and associated least-squared mean estimates, which compare the diverted and control groups by using the estimated difference between their means. Multivariate approaches were considered, but not taken, due to the limitations of the data set size (Scott Baggett, pers. comm., October 2012).

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[3] The second set of mixed effects models were developed largely with the help of Scott Baggett, statistician at the Rocky Mountain Research Station, US Forest Service, Fort Collins, CO.

Additional comparisons using t-tests, Wilcoxon rank-sum tests, and boxplots were created between specific reach response variables to see whether vegetation was an influencing factor. The two major vegetation types found in the surveys were willow-dominant and sedge/grass/rush-dominant. Numerous previous studies have shown that vegetation can be in influencing factor in bank stability (e.g., Micheli and Kirchner, 2002; David et al., 2009). Box plots, t-tests, and Wilcoxon rank-sum tests were conducted to compare channel depth, sinuosity, width, width-to-depth ratio, and cross-sectional area between the two major vegetation types that were surveyed.

Chapter 3 Figures

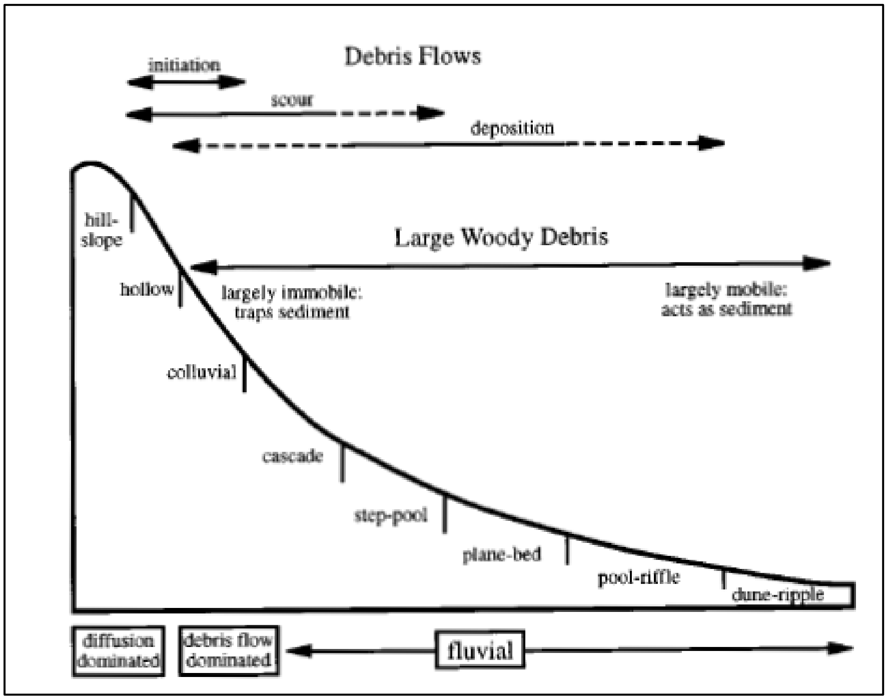
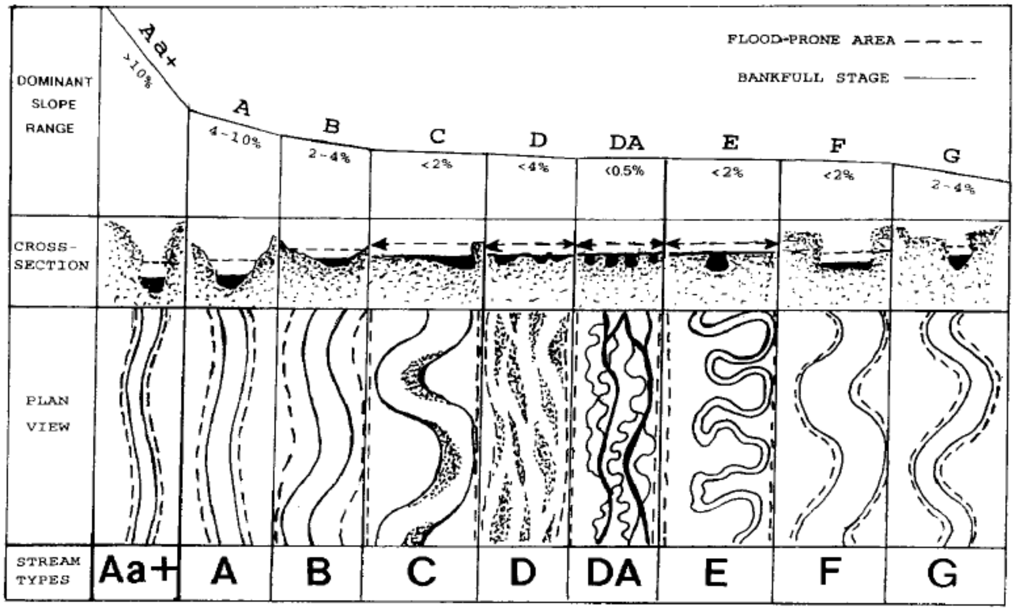


Figure 9(A). The Montgomery and Buffington classification system, based primarily on slope, used to define channel types for reaches in this study. Figure taken directly from Montgomery and Buffington (1997, Figure 4).



(B). The Rosgen classification system, directly from Rosgen (1994, Figure 1). Classification uses geomorphic characterizations largely based on visual estimates of bankfull elevation.

Table 3. Field estimates for channel roughness, using visual estimation based on calibrated photography from Barnes (1967).

Name	Group	Roughness estimate (n)
Beaver Creek (of Big Cr.)	control	0.043
Chedsey Creek	control	0.037
Jolley Creek (aka Rock Cr.)	control	n/a
Little Muddy Creek	control	0.045
Muddy Creek	control	0.027
Porcupine Creek (aka L.Rock Cr.)	control	0.043
Service Creek	control	0.0275
Slater Creek	control	0.043
Slater Creek (tributary, #2 ditch)	control	0.039
South Fork Big Creek	control	0.027
Willow Creek	control	0.028
Beaver Creek (of Big Cr.)	diverted	0.041
Chedsey Creek	diverted	0.038
Jolley Creek (aka Rock Cr.)	diverted	n/a
Little Muddy Creek	diverted	0.045
Ninegar Creek	diverted	0.043
Rock Creek (Darcy Ditch)	diverted	0.038
Rock Creek (Westfield Ditch)	diverted	0.036
Service Creek	diverted	0.027
Slater Creek	diverted	0.043
Slater Creek (tributary, #2 ditch)	diverted	0.037
South Fork Big Creek	diverted	0.043

Table 4. Generalized vegetation community types, stream order, lithology, weathering type, and landform type for study reaches. Landform type from Routt NF geospatial data.

Name	**group**	**vegetation**	**Stream Order (Strahler)**	**Lithology**	**Weathers to**	**Landform Type**
Beaver Creek (of Big Cr.)	control	conifer-willow	3	glacial deposits	gravel-cobble	terrace flats
Chedsey Creek	control	willow	2	glacial deposits	gravel-cobble	moiraine slopes
Jolley Creek (aka Rock Cr.)	control	grass-sedge	1	siltstone-mudstone	clay	flats and bottoms
Little Muddy Creek	control	willow	1	shale	clay	sideslopes
Muddy Creek	control	grass-sedge	2	shale	clay	floodplains and valley fill bottoms
Porcupine Creek (aka L.Rock Cr.	control	grass-sedge	1	metamorphic-granitic	gravel-cobble	streamcut slopes/flats and bottoms
Service Creek	control	grass-sedge	1	shale/siltstone/Qt alluvium	clay-sand-gravel	floodplains and valley fill bottoms
Slater Creek	control	willow	3	shale	clay	floodplains and valley fill bottoms
Slater Creek (tributary, #2 ditch)	control	willow	2	shale	clay	oversteepened and unstable slopes
South Fork Big Creek	control	willow	2	glacial deposits	gravel-cobble	moiraine flats
Willow Creek	control	willow	2	sandstone	sand-gravel	floodplains and valley fill bottoms
Beaver Creek (of Big Cr.)	diverted	willow	3	metamorphic-granitic	gravel-cobble	floodplains and valley fill bottoms
Chedsey Creek	diverted	willow	2	shale	clay	outwash flats
Jolley Creek (aka Rock Cr.)	diverted	grass-sedge	1	siltstone-mudstone	clay	flats and bottoms
Little Muddy Creek	diverted	willow	1	shale	clay	sideslopes
Ninegar Creek	diverted	grass-sedge	2	sandstone-Qt mass movement deposits	sand-gravel	flats and bottoms
Rock Creek (Darcy Ditch)	diverted	willow	1	sandstone	sand-gravel	floodplains and valley fill bottoms
Rock Creek (Westfield Ditch)	diverted	willow	2	sandstone	sand-gravel	floodplains and valley fill bottoms
Service Creek	diverted	grass-sedge	1	sandstone/Qt alluvium	sand-gravel	floodplains and valley fill bottoms
Slater Creek	diverted	willow	4	shale	clay	floodplains and valley fill bottoms
Slater Creek (tributary, #2 ditch)	diverted	willow	2	shale	clay	floodplains and valley fill bottoms
South Fork Big Creek	diverted	willow	2	metamorphic-granitic	gravel-cobble	floodplains and valley fill bottoms

Table 5. Channel variables, both measured and calculated, used in data analyses.

Reach name	**group**	**Drainage area (km^2)**	**Sinuosity (m/m)**	**D_{50} (mm)**	**width (m)**	**depth (m)**	**w/d (m/m)**	**XS Area (m^2)**	**Entrenchment (m/m)**	**Channel slope (m/m)**
Beaver	control	28.2	1.2	95	14.2	0.325	43.5	4.3	1.2	0.018
Chedsey	control	17.8	1.5	54	10.2	0.375	27.1	3.0	2.6	0.0046
Jolley	control	1.99	1.1	6.8	1.0	0.2	5.0	0.2	9.5	0.021
Little Muddy	control	7.95	1.3	62	5.2	0.2	26.1	0.7	5	0.019
Muddy	control	12.2	1.3	45	4.4	0.25	17.5	1.7	2.3	0.0016
Porcupine	control	0.62	2.7	0.18	1.0	0.1	10.0	0.1	6.7	0.0093
Service	control	3.86	1.3	23	1.3	0.175	7.3	0.3	3.5	0.031
Slater	control	6.03	1.5	81	2.8	0.275	10.3	0.5	1.8	0.027
Slater #2	control	3.4	1.4	40	1.6	0.325	4.9	0.5	3.5	0.02
South Fork Big	control	17	1.7	21	9.1	0.6	15.2	6.0	1.8	0.0053
Willow	control	16.4	1.9	61	5.6	0.35	15.9	1.0	2.4	0.0088
Beaver	diverted	30.6	1.1	66	9.2	0.4	22.9	3.5	2.6	0.0012
Chedsey	diverted	20.8	1.2	90	5.9	0.325	18.2	1.9	1.7	0.016
Jolley	diverted	4.84	1.1	0.18	1.6	0.15	10.7	0.2	5.9	0.015
Little Muddy	diverted	8.75	1.2	58	2.8	0.275	10.2	0.7	2.9	0.0195
Ninegar	diverted	1.14	1.1	47	1.0	0.1	9.5	0.1	3.2	0.036
Rock(Darcy)	diverted	12.07	1.0	67	2.7	0.35	7.6	1.0	2.3	0.0096
ock(Westfield)	diverted	22.9	1.1	45	4.8	0.25	19.0	1.2	2.7	0.0031
Service	diverted	4.38	1.2	8.3	2.1	0.15	14.0	0.3	6.1	0.0049
Slater	diverted	32.1	1.2	42	5.8	0.425	13.5	2.2	2.8	0.0064
Slater #2	diverted	3.5	1.3	44	2.1	0.25	8.3	0.5	2.5	0.028
South Fork Big	diverted	51.3	1.5	100	7.2	0.45	16.0	3.2	1.8	0.013

Table 6. Depths and widths for riffles (A) and pools (B), used for t-test and Wilcoxon analyses of diverted and control groups. These were recorded where surveying cross sections at pools and riffles in channels was possible. Cross section depths and widths for plane bed streams and small, Rosgen "E" type channels that did not have pool-riffle morphology were excluded from this analysis. Some reaches also did not have two surveyable pools and two riffles.

(A). Riffle width and depth

group	stream	riffle width (m)	riffle depth (m)
control	Chedsey	10.9	0.4
control	Chedsey	11.2	0.2
control	Little Muddy	2.7	0.1
control	Little Muddy	10.2	0.2
control	Muddy	7.2	0.2
control	Muddy	4.2	0.4
control	Slater	1.7	0.2
control	Slater	2	0.1
control	Slater #2	1.6	0.3
control	Slater #2	1.9	0.2
control	South Fork Big	9.6	0.6
control	Willow	7.8	0.4
control	Willow	5.1	0.2
diverted	Chedsey	6.7	0.3
diverted	Chedsey	6.9	0.2
diverted	Rock (Darcy)	2.6	0.3
diverted	Rock (Darcy)	2.3	0.2
diverted	Slater	4.3	0.3
diverted	Slater	8.2	0.3
diverted	Slater #2	2.2	0.2
diverted	Slater #2	2.3	0.2
diverted	South Fork Big	7.3	0.5
diverted	South Fork Big	7.4	0.5

(B). Riffle width and depth

group	stream	pool width (m)	pool depth (m)
control	Chedsey	7.3	0.3
control	Chedsey	11.3	0.6
control	Little Muddy	4.4	0.2
control	Little Muddy	3.6	0.3
control	Muddy	6.1	0.4
control	Slater	3.06	0.5
control	Slater	4.6	0.3
control	Slater #2	1.5	0.4
control	Slater #2	1.4	0.4
control	South Fork Big Creek	7.3	0.5
control	Willow	5.5	0.3
control	Willow	3.8	0.5
diverted	Chedsey	5.1	0.4
diverted	Chedsey	5	0.4
diverted	Rock (Darcy)	3.6	0.4
diverted	Rock (Darcy)	2.1	0.5
diverted	Rock (Westfield)	4.7	0.4
diverted	Slater	3.9	0.7
diverted	Slater	6.6	0.4
diverted	Slater #2	2.1	0.3
diverted	Slater #2	1.7	0.3
diverted	South Fork Big	7	0.4

4. Results

Comparing Group Variables

Boxplot comparisons and summary statistics show some differences between the means and medians of the control and diverted groups (Figure 10). Sinuosity, slope, width, width-to-depth ratio, entrenchment, and cross-sectional area all have slightly higher mean values for the control groups. Median grain size (***D_{50}***) has a slightly greater mean and median in the diverted group, while there is little difference between control and diverted means for depth. These values are not definitive due to small sample size (Table 7). Width, width-to-depth ratio, and sinuosity have wider variance in the control group than in the diverted group.

Except for sinuosity (Figure 10E), none of the physical parameters varied significantly between diverted and control reaches. Using paired t-tests and non-parametric Wilcoxon signed-rank for the 8 paired reaches, only sinuosity was found to be significant at $\alpha=0.10$, where $p=0.0054$ for the paired t-test and $p=0.0156$ for the signed rank test (Tables 8, 9). Sinuosity was also found to be significant in the unpaired t-test ($p=0.0205$) (Table 10). For the non-parametric Wilcoxon rank-sum, sinuosity was significant ($p=0.0056$) (Table 11). For the semi-paired t-test in R, sinuosity was again found to be significant (p=0. 000369), with no other variables significant at $\alpha=0.10$ (Table 12).

No significant differences between diverted and control groups were found when comparing pool depths and widths between diverted and control groups, and riffle depths and widths between groups using either t-tests or exact Wilcoxon rank-sum tests (Tables 13 and 14).

Mixed Models

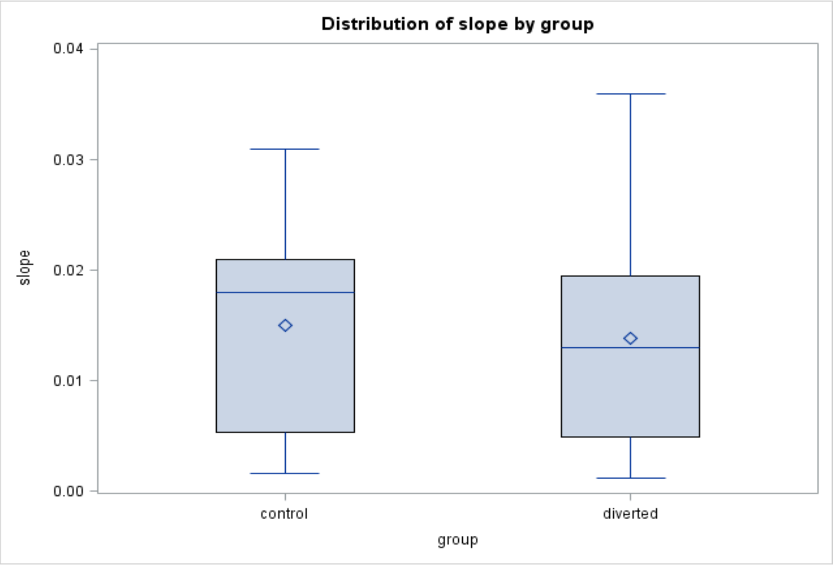
Using the first mixed models to compare reach response variables between the diverted and control groups, sinuosity was found to be significant ($p=0.0048$). No other variables were significant at α=0.10 (Table 15). The second round of mixed effects models, which took the effects of valley slope, valley width, vegetation type, drainage basin area, and lithology/weathering into account when looking at each reach response variable between the diverted and control groups, found several response variables to be significant. These included reduced width (p=0.0255) and width-to-depth ratio (p=0.0979), cross-sectional area (p=0.027), and decreased sinuosity (p=0.0608) (Table 16). The output of the mixed model includes the least-squared mean estimates of the response variables, which are calculated by subtracting the diverted group from the control group, after adjusting for all other effects in the model. Type III tests of fixed effects, which include F-values and corresponding p-values, were used to examine which predictor variables were influential on the response variables. The significant variables for channel slope included valley slope (F=7.1, p=0.0177) and lithology (F=4.12, p=0.0604). For depth, valley width (F=15.88, p=0.0014), vegetation (F=16.65, p=0.0011), and drainage area (F=9.27, p=0.0087) were significant. For D_{50}, channel slope (F=4.02, p=0.0646), vegetation (F=8.82, p=0.0101), and drainage area (F=5.73, p=0.0312) were influential. For entrenchment, vegetation (F=6.15, p=0.0265) was significant. For sinuosity, drainage area was influential (F=5.74, p=0.0917), as was radius of curvature (F=5.85, p=0.0298). Drainage area (F=9.92, p=0.0066) was a significant variable for width. For cross sectional area, valley width (F=28.38, p=0.0001) and drainage (F=23.84, p=0.0002) were significant, and for width-to-depth ratio, no variables were significant.

In one version of this mixed model, channel slope was included as a driver variable to analyze its possible effect on median grain size, width, depth, and the other cross sectional parameters; it was found to have a significant impact on D_{50} (F=4.02, p=0.0646). Width was normalized by drainage basin area using the transformation $w/A^{0.4}$ to account for potential nonlinear increase in stream width with larger drainage size. Using the transformed width variable in the mixed effects model, it was still significantly decreased downstream of diversions (L.S. means estimate=2.69, p=0.0229). No predictor variables had a significant effect on the drainage area-adjusted width.

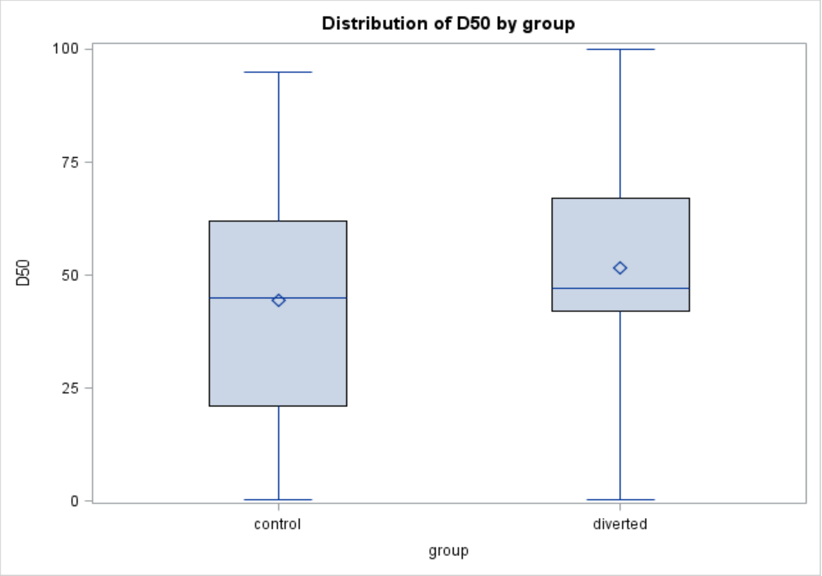
Riparian Vegetation

A summary of statistics for the variables tested in the riparian vegetation diverted and control groups can be found in Table 17, and boxplots in Figure 11. Riparian vegetation types were compared between control and diverted groups, as well as within the control and diverted groups. When comparing willow versus grass/sedge types within the control group, depth (t-test: p=0.0152, Wilcoxon: p=0.0152), width (t-test: p=0.0267, Wilcoxon: p=0.0242), width-to-depth ratio using the t-test (p=0.0948), and cross-sectional area (t-test: p=0.0971, Wilcoxon: p=0.0636) were significantly lower for the grasss-sedge types than willow (Table 18). When comparing the vegetation types within the diverted reaches, depth (t-test: p=0.0001, Wilcoxon: p=0.0121), width (t-test: p=0.0049, Wilcoxon: p=0.0182), and cross-sectional area (t-test: p=0.0054, Wilcoxon: p=0.0121) significantly less for the diverted grass/sedge group than for the diverted willow group (Table 19). Sinuosity (t-test: p=0.0169, Wilcoxon: p=0.0126) was the only variable that was found to be significantly less in the diverted group when comparing the diverted and control groups for the reaches with willow-dominant riparian vegetation (Table 20). No variables were significant at $\alpha=0.10$ for the grass/sedge riparian vegetation type when comparing the diverted and control groups (Table 21).

Chapter 4 Figures

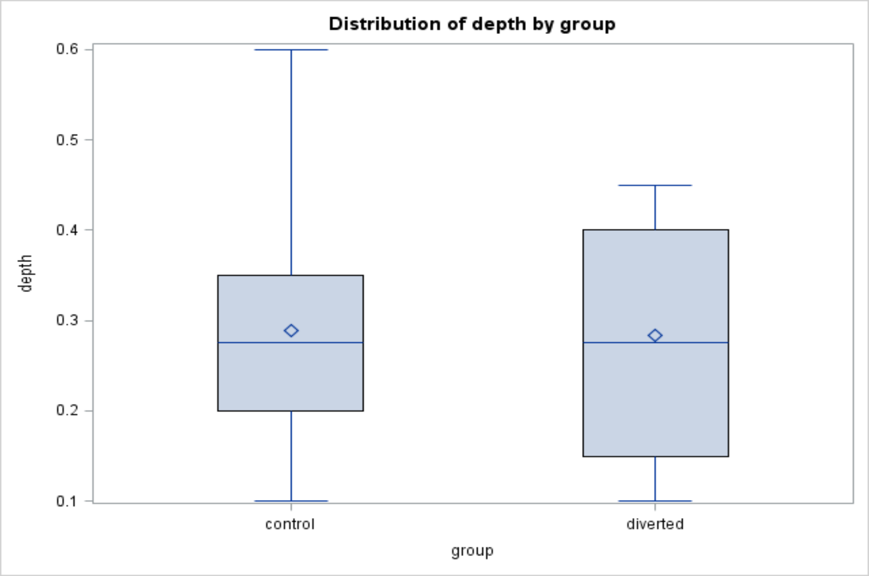


(A). Channel slope

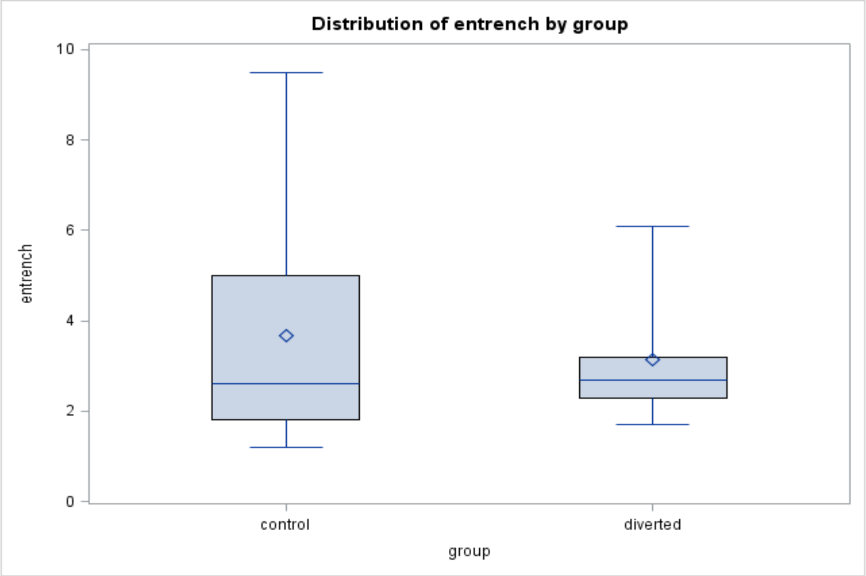


(B). Median grain size (D_{50})

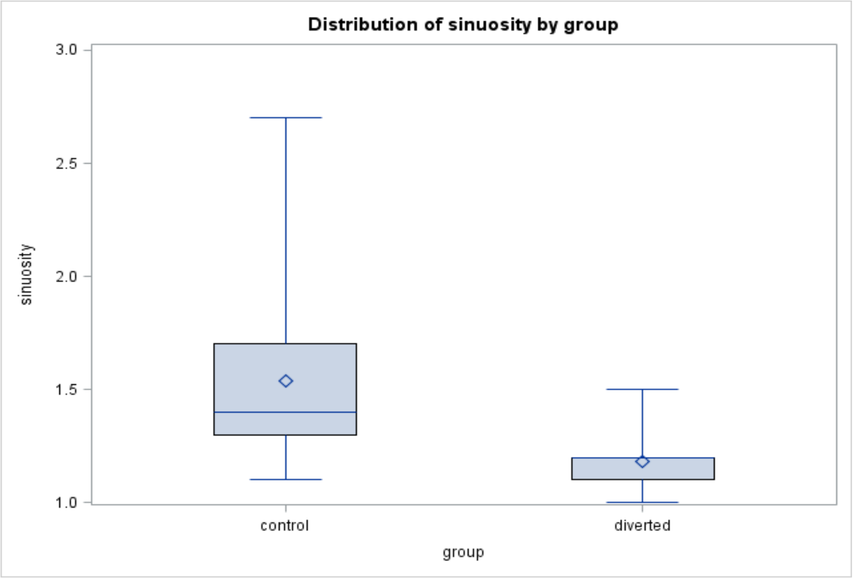
Figures 10 A-H. Boxplots comparing diverted and control groups for the following variables: channel slope (A), D_{50} (B), depth (C), entrenchment (D), sinuosity (E), width (E), width-to-depth ratio (G), and cross-sectional area (H). Sinuosity was found to differ significantly between the control and diverted groups. Diamonds indicate mean values, solid lines within boxes are median values, box ends are upper and lower quartiles and whiskers indicate 10th and 90th percentiles.



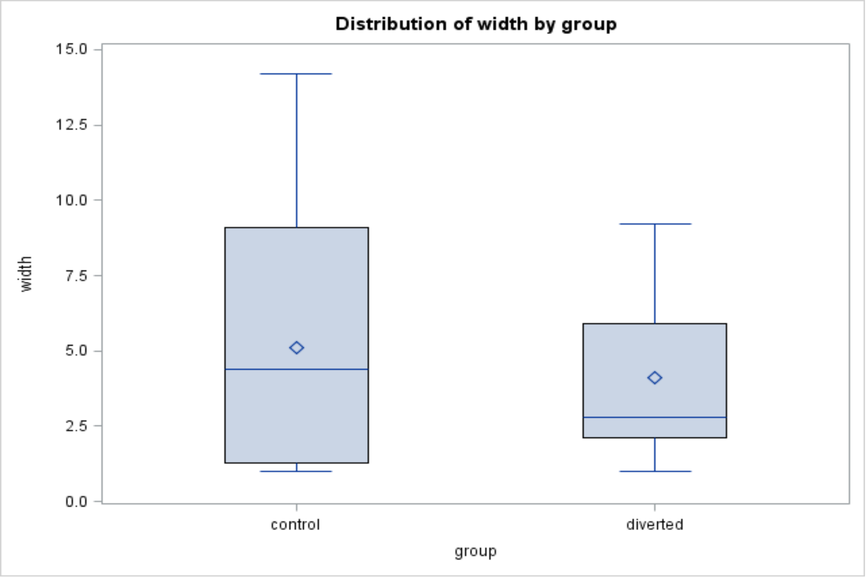
(C). Bankfull depth



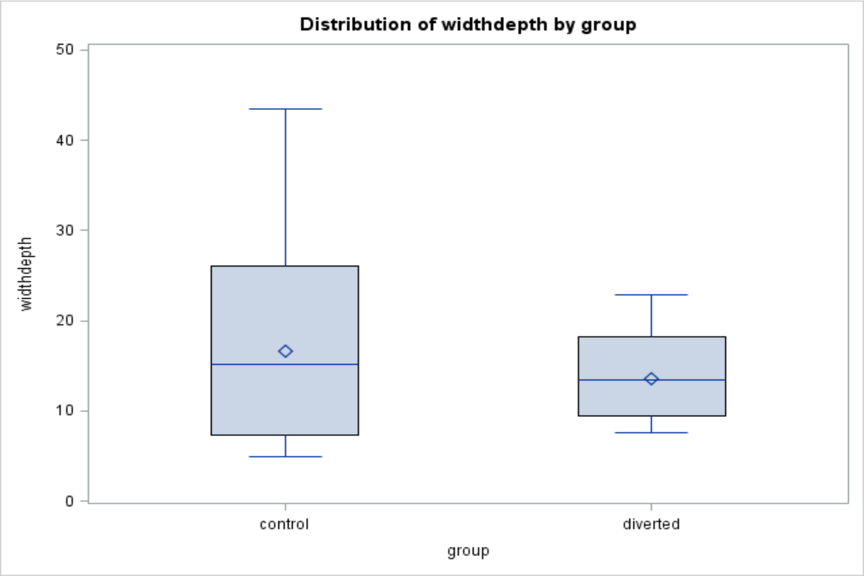
(D). Entrenchment ratio



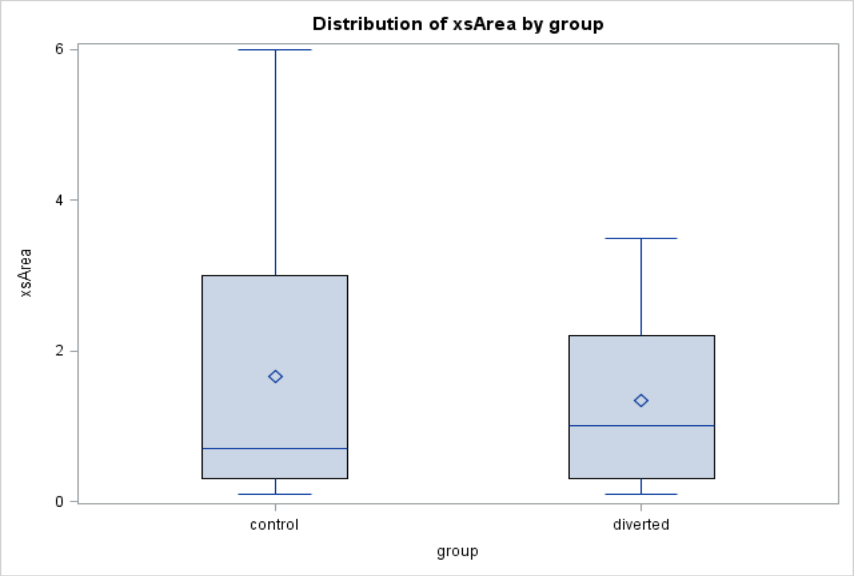
(E). Sinuosity



(F). Bankfull width



(G). Width-to-depth ratio



(H). Cross-sectional area

Table 7. Summary statistics for variables, including diverted and control groups, with parameters found to be significantly different using t-tests (sinuosity) highlighted.

Variable	Group	Mean	Median	Std Deviation	Variance
Channel Slope	control	0.015	0.018	0.01	0
Channel Slope	diverted	0.014	0.013	0.011	0
D_{50}	control	44.453	45	29.953	897.178
D_{50}	diverted	51.589	47	30.06	903.615
Depth	control	0.289	0.275	0.133	0.018
Depth	diverted	0.284	0.275	0.118	0.014
Entrenchment	control	3.664	2.6	2.505	6.273
Entrenchment	diverted	3.136	2.7	1.484	2.203
Sinuosity	**control**	**1.536**	**1.4**	**0.448**	**0.201**
Sinuosity	**diverted**	**1.182**	**1.2**	**0.133**	**0.018**
Width	control	5.127	4.4	4.372	19.116
Width	diverted	4.109	2.8	2.641	6.975
Width: Depth	control	16.618	15.2	11.699	136.856
Width: Depth	diverted	13.627	13.5	4.936	24.36
XS Area	control	1.664	0.7	1.951	3.807
XS Area	diverted	1.345	1	1.198	1.435

Table 8. Results from the non-parametric Wilcoxon Signed-Rank test for 8 paired reaches. Bold font indicates significant variables.

Wilcoxon Signed-Rank

Variable	S Statistic	$Pr \geq \lvert S \rvert$
Channel Slope	5	0.5469
D_{50}	**2.5**	**0.7656**
Depth	0.5	0.9844
Entrenchment	1.5	0.8438
Sinuosity	**14**	**0.0156**
Width	6	0.4609
Width: Depth	3	0.7422
XS area	2	0.625

Table 9. Results from the paired t-test for 8 paired reaches, including summary statistics for differences in pairs. Bold font indicates significant variables.

Variable	N	Mean	Std Dev	Std Err	Minimum	Maximum	DF	t Value	Pr > |t|
Channel slope	8	0.00524	0.0144	0.0051	-0.0114	0.0261	7	1.03	0.3388
D50	8	-3.21	38.0009	13.4353	-79	39	7	-0.24	0.818
Depth	8	0.00625	0.098	0.0346	-0.15	0.15	7	0.18	0.8619
Entrenchment	8	0.325	2.002	0.7078	-2.6	3.6	7	0.46	0.66
Sinuosity	**8**	**0.15**	**0.1069**	**0.0378**	**0**	**0.3**	**7**	**3.97**	**0.0054**
Width	8	1.0875	2.7684	0.9788	-3	5	7	1.11	0.3032
Width: Depth	8	3.2	10.5172	3.7184	-6.7	20.6	7	0.86	0.418
XS Area	8	0.375	1.2792	0.4523	-1.7	2.8	7	0.83	0.4344

Table 10. Results from the unpaired t-test in SAS. Tests assume unequal variances. Bold font indicates significant variables.

Unpaired t-test

Variable	t Value	Pr > |t|
Channel Slope	0.27	0.791
D_{50}	-0.56	0.5832
Depth	0.08	0.9332
Entrenchment	0.6	0.5563
Sinuosity	**2.52**	**0.0274**
Width	0.66	0.5177
Width: Depth	0.78	0.4482
XS Area	0.46	0.6508

Table 11. Results from the unpaired, non-parametric Wilcoxon Rank Sum test in SAS. Bold font indicates significant variables.

Wilcoxon Rank-Sum Test (exact test)

Variable	S statistic	Two-Sided Pr > |S|
Channel Slope	133.0	0.6994
D_{50}	117.0	0.5510
Depth	124.5	0.9101
Entrenchment	128.0	0.9359
Sinuosity	**168.5**	**0.0045**
Width	127.0	0.9870
Width: Depth	128.0	0.9487
XS Area	125.5	0.9619

Table 12. Results from the semi-paired t-test in R. Bold font indicates significant variables.

response variable	p-value	estimated difference
Channel Slope	0.790987	-0.00117
D50	0.582758	6.20061
Depth	0.86228	-0.00563
Entrenchment	0.498282	-0.43061
Sinuosity	**0.000369**	**-0.15934**
Width	0.243589	-1.06284
Width: Depth	0.330549	-3.06125
XS Area	0.392321	-0.35375

Table 13. Results from the unpaired t-test in SAS for pool and riffle widths and depths.

	DF	t Value	Pr > |t|
Pool depth	21	-0.56	0.5781
Pool width	21	0.54	0.5969
Riffle depth	21	-0.55	0.5862
Riffle width	21	0.6	0.5539

Table 14. Results from the unpaired, non-parametric Wilcoxon Rank-Sum Test in SAS for pool and riffle widths and depths. No variables were significant at α=0.10 level.

Wilcoxon Rank-Sum Test (exact test)		
Variable	S statistic	Two-Sided Pr ≥ |S|
Pool depth	121.5	0.6558
Pool width	128.5	0.8445
Riffle depth	133.0	0.4095
Riffle width	116.0	0.8190

Table 15. Results from the first set of mixed model tests in SAS, which does not take valley width, slope, vegetation, lithology or drainage basin size into account. Sinuosity was found to be significant at the α=0.10 level. Bold font indicates significant variables.

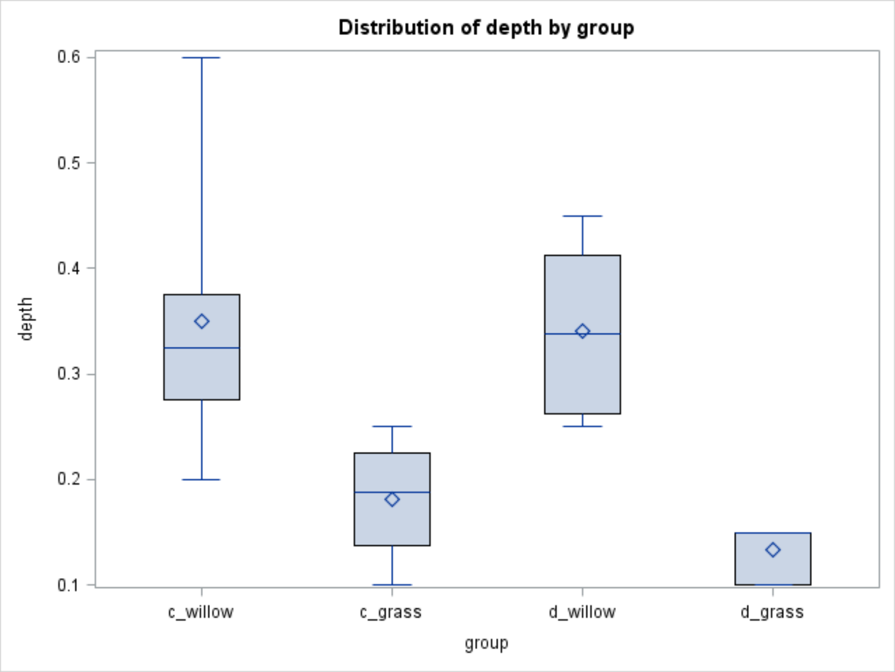
	Least Squares Means Estimates				
Variable	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**
Channel Slope	0.005125	0.0098	19	0.52	0.6071
D_{50}	31.7869	27.8107	18.57	1.14	0.2676
Depth	0.0974	0.1033	18.24	0.94	0.3581
Entrenchment	-1.7423	1.8177	18.93	-0.96	0.3499
Sinuosity	**-0.9293**	**0.2737**	**12.92**	**-3.4**	**0.0048**
Width	0.183	2.9356	18.13	0.06	0.951
Width: Depth	-3.6243	8.2683	18.91	-0.44	0.6661
XS Area	-0.00851	1.3368	18.22	-0.01	0.995

Table 16. Results from the second set of mixed effects models in SAS, which take valley width, slope, vegetation, lithology or drainage basin size into account and adjust for these effects, as well as the paired and unpaired reaches. Sinuosity, width, width-to-depth ratio, and cross sectional area were found to be significant at the α=0.10 level. Bold font indicates significant variables.

Differences of Group Least Squared Means, Adjustment for Multiple Comparisons: Tukey-Kramer								
Variable	Group	Group	Estimate	Standard Error	DF	t value	Pr>t	Adj P
D50	control	diverted	7.4536	9.6396	15	0.77	0.4514	0.4514
Entrenchment	control	diverted	0.06699	0.8302	15	0.08	0.9368	0.9368
depth	control	diverted	0.0239	0.02503	15	0.95	0.3549	0.3549
sinuosity	**control**	**diverted**	**0.08727**	**0.0313**	**3.334**	**2.79**	**0.0608**	**0.0608**
width	**control**	**diverted**	**2.3542**	**0.8912**	**9.572**	**2.64**	**0.0255**	**0.0255**
width:depth	**control**	**diverted**	**6.485**	**3.5469**	**9.839**	**1.83**	**0.0979**	**0.0979**
XS Area	**control**	**diverted**	**0.7819**	**0.3192**	**15**	**2.45**	**0.027**	**0.027**

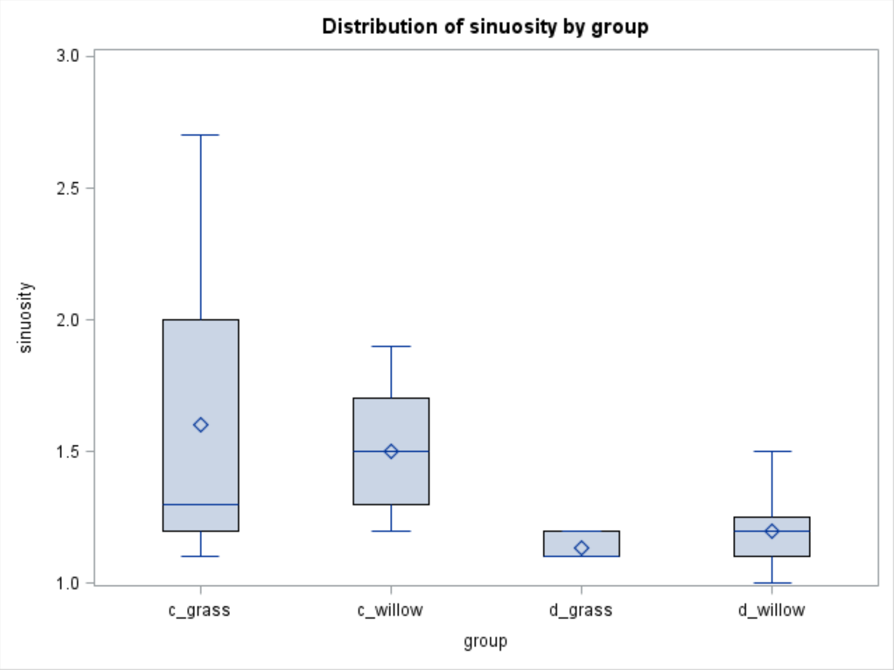
Table 17. Summary statistics for the vegetation group data. Vegetation types were divided and analyzed using the following categories: control willow, control grass/sedge, diverted willow, and diverted grass/sedge, with sample size n=7 for control willow, n=4 for control grass/sedge, n=8 for diverted willow, and n=3 for grass/sedge. Depth, sinuosity, width, width-to-depth ratio, and cross-sectional area were the variables tested using the vegetation categories, as these are influenced by bank stability, which in turn is affected by riparian vegetation.

Variable	**Group**	**N**	**Mean**	**Median**	**Std Deviation**	**Variance**
Depth	control willow	7	0.350	0.325	0.124	0.154
	control grass-sedge	4	0.181	0.188	0.063	0.004
	diverted willow	8	0.341	0.338	0.079	0.006
	diverted grass-sedge	3	0.133	0.150	0.029	0.001
Sinuosity	control willow	7	1.500	1.500	0.238	0.057
	control grass-sedge	4	1.600	1.300	0.739	0.547
	diverted willow	8	1.200	1.200	0.151	0.023
	diverted grass-sedge	3	1.133	1.100	0.058	0.003
Width	control willow	7	6.957	5.600	4.444	19.746
	control grass-sedge	4	1.925	1.150	1.626	2.743
	diverted willow	8	5.063	5.300	2.463	6.068
	diverted grass-sedge	3	1.567	1.600	0.551	0.303
Width: Depth	control willow	7	20.429	15.900	12.913	166.756
	control grass-sedge	4	9.950	8.650	5.432	29.510
	diverted willow	8	14.463	14.750	5.507	30.626
	diverted grass-sedge	3	11.400	10.700	2.330	5.430
XS Area	control willow	7	2.286	1.000	2.195	4.818
	control grass-sedge	4	0.575	0.250	0.754	0.569
	diverted willow	8	1.775	1.550	1.129	1.274
	diverted grass-sedge	3	0.200	0.200	0.100	0.010

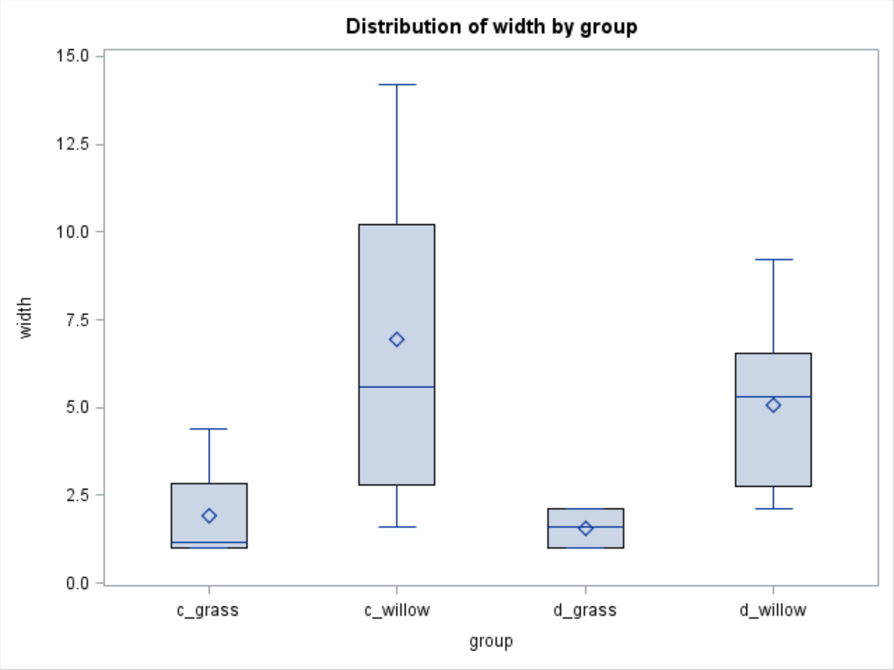


(A). Vegetation boxplots for depth.

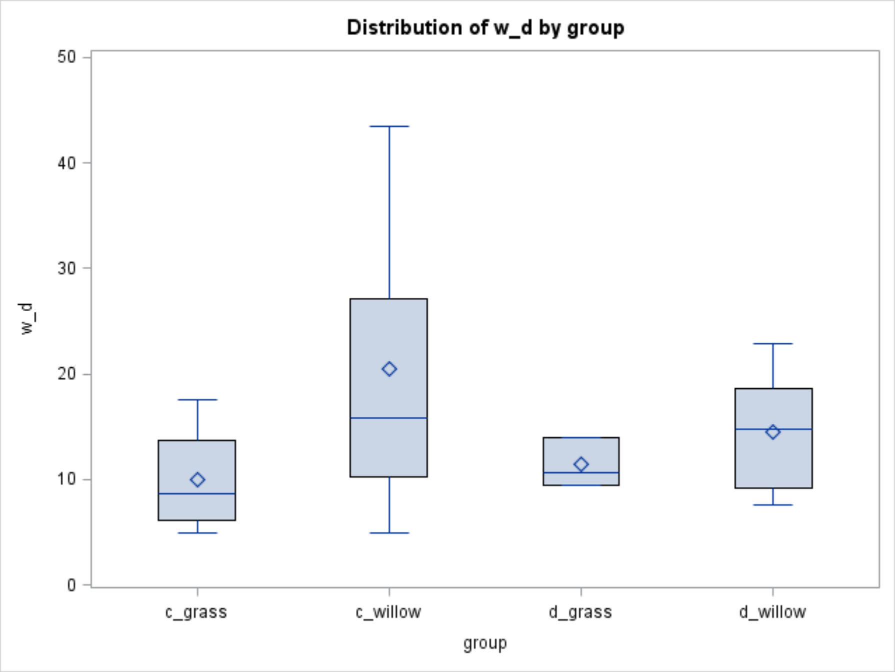
Figures 11 a-e. Boxplots comparing the vegetation groups control willow (“c_willow”), control grass/sedge (“c-grass”), diverted grass/sedge (“d_grass”), and diverted willow (“d_willow”) for the following variables: depth (A), sinuosity (B), width (C), width-to-depth ratio (D), and cross-sectional area (E). Diamonds indicate mean values, solid lines within boxes are median values, box ends are upper and lower quartiles and whiskers indicate 10th and 90th percentiles.



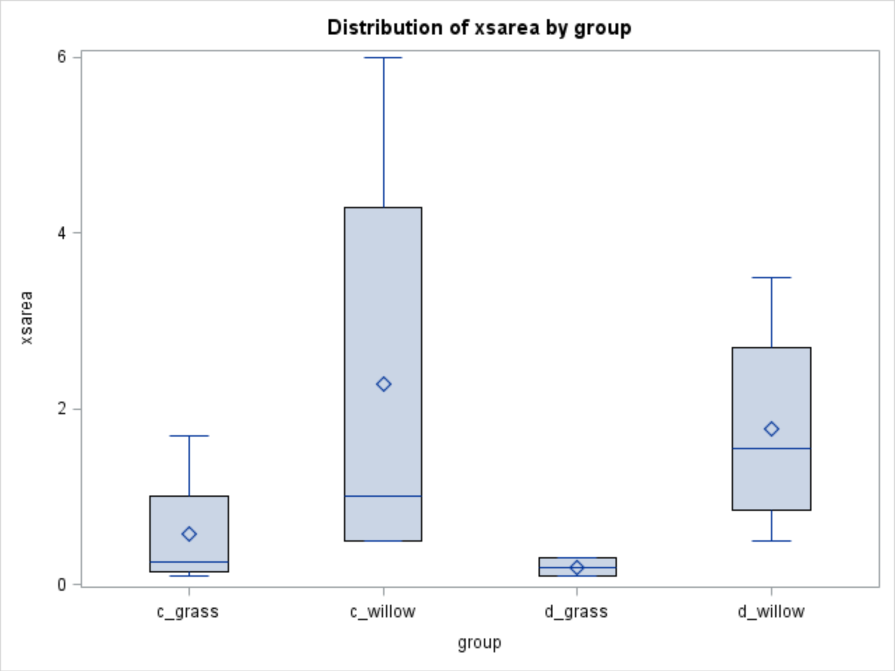
(B). Vegetation boxplots for sinuosity.



(C). Vegetation boxplots for width.



(D). Vegetation boxplots for width-to-depth ratio.



(-E). Vegetation boxplots for cross-sectional area.

Table 18. T-test and Wilcoxon rank-sum test results for comparisons of willow and grass/sedge dominant riparian vegetation types for control reaches. Channel variables influenced by bank stability were tested. Depth, width, width-to-depth ratio, and cross-sectional area were found to be significant at α=.10. Bold font indicates significant variables.

Control Willow vs. Control Grass/Sedge				
Variable	Unpaired t-test		Wilcoxon exact rank-sum test	
	t-value	Pr > |t|	S statistic	Two-Sided Pr > |S|
Depth	**-2.99**	**0.0152**	**11.5**	**0.0152**
Sinuosity	0.26	0.808	20	0.5061
Width	**-2.69**	**0.0267**	**12**	**0.0242**
Width:Depth	**-1.88**	**0.0948**	17	0.2303
XS Area	**-1.88**	**0.0971**	**14**	**0.0636**

Table 19. T-test and Wilcoxon rank-sum test results for comparisons of willow and grass/sedge dominant riparian vegetation types for diverted reaches. Channel variables influenced by bank stability were tested. Depth, width, and cross-sectional area were found to be significant at α=.10. Bold font indicates significant variables.

Diverted Willow vs. Diverted Grass/Sedge				
Variable	Unpaired t-test		Wilcoxon exact rank-sum test	
	t-value	Pr > |t|	S statistic	Two-Sided Pr > |S|
Depth	**-6.37**	**0.0001**	**6**	**0.0121**
Sinuosity	-1.06	0.318	14.5	0.5758
Width	**-3.77**	**0.0049**	**6.5**	**0.0182**
Width:Depth	-1.29	0.2297	15	0.6303
XS Area	**-3.91**	**0.0054**	**6**	**0.0121**

Table 20. T-test and Wilcoxon rank-sum test results for comparisons between diverted and control groups for willow dominant riparian vegetation type. Channel variables influenced by bank stability were tested, and of those, sinuosity was found to be significant at α=.10. Bold font indicates significant variables.

Control Willow vs. Diverted Willow				
Variable	Unpaired t-test		Wilcoxon exact rank-sum test	
	t-value	Pr > |t|	S statistic	Two-Sided Pr > |S|
Depth	0.17	0.8671	55	0.9302
Sinuosity	**2.87**	**0.0169**	**77**	**0.0126**
Width	1	0.3425	61.5	0.5565
Width:Depth	1.14	0.2895	63	0.4634
XS Area	0.55	0.593	55	0.9332

Table 21. T-test and Wilcoxon rank-sum test results for comparisons between diverted and control groups for grass/sedge dominant riparian vegetation type. Channel variables influenced by bank stability were tested, and of those, no variables were found to be significant at α=.10.

Control Grass/Sedge vs. Diverted Grass/Sedge				
Variable	Unpaired t-test		Wilcoxon exact rank-sum test	
	t-value	Pr > |t|	S statistic	Two-Sided Pr > |S|
Depth	1.35	0.2412	8.5	0.2857
Sinuosity	1.26	0.2964	8	0.2
Width	0.4	0.7078	13	0.9143
Width:Depth	-0.48	0.6559	14	0.6286
XS Area	0.98	0.3953	10.5	0.7714

5. Discussion

From the statistical analysis, it appears that diversions can potentially have a discernible effect on the geomorphic parameters measured for this study. In the second set of mixed effects models, sinuosity, width, width-to-depth ratio, and cross-sectional area were found to be significant, whereas only sinuosity was significant in the t-tests and non-parametric Wilcoxon tests. It is likely that these additional variables were found to be significant in the mixed effects models because the models took certain factors into account, such as drainage basin size and vegetation, and adjusted for these effects, whereas the t-tests were not sensitive enough to account for additional predictor variables. Drainage basin size was a significant driver for multiple variables, indicating that differences in drainage area were influencing observations. Differences between groups in width, width-to-depth ratio, and cross-sectional area suggest narrowing in diverted streams due to encroachment of riparian vegetation and some increased deposition. Wider variance in the control group versus the diverted group for width, width-to-depth ratio, and sinuosity suggest that homogenization of channels may be occurring downstream of diversions. One form of this simplification of channels is seen in reduction in sinuosity. Decreased sinuosity could be an indicator of reduced energy in streams downstream of diversions, but other parameters likely to reflect decreased energy, such as bed-material size, show no significant differences in relation to diversions. Changes in sinuosity downstream of diversions appear to be more pronounced in willow-dominated riparian zones than those with sedge and grass-type vegetation. Research from Hey and Thorne (1986) and Hession (2003) indicate that vegetation can be influential on sinuosity. The mixed model tests of predictor variables did not show vegetation as a significant driver, but did indicate that radius of curvature and drainage basin size were significantly influential on sinuosity. Differences in vegetation are also likely to be influential on channel dimensions, regardless of diversions. Streams with sedge and grass-type riparian areas appear to be more narrow and shallow than those with willows, as shown by the box plots and t-tests for width, depth, cross-sectional area and width-to-depth ratios (Table 16, Figure 11) While this seems counterintuitive, the t-tests and Wilcoxon tests, however, did not adjust for drainage area, as the reaches with grass/sedge dominant riparian vegetation tended to be headwater streams with much smaller watershed basins than reaches lined with primarily willows. Streams with larger drainage basin size and willow-dominated riparian areas appeared to be more responsive to diversions than those with sedge/grass vegetation. This may be due to sedge mat density increasing channel stability in these systems, and reducing response. Analysis of sinuosity by splitting streams into different groups by drainage basin area was considered, but was not completed, as justification for cutoffs in drainage size could not be made. Because the mixed effects models take multiple potential influences on channel response into consideration, I put more emphasis on the mixed models. The results from the mixed models are adjusted for differences in valley width and slope, drainage basin size, vegetation types, and lithology, and thus are considered to be a more accurate representation of channel response to diversions in this study than the t-tests and Wilcoxon tests, which do not take impacts such as differences in drainage basin size, riparian vegetation, or valley characteristics into account.

There is no question that diversions alter downstream channel segments. Diversion ditches completely dry out channels such as Little Muddy and Service Creeks. Channel dewatering has clear visual impacts to channels, and would very likely affect aquatic life such as macroinvertebrates, fish, and riparian vegetation adjacent to the channel. Channel dewatering was observed in two reaches—Little Muddy and Service Creeks—for the period of late July to early August. Because of a lack of streamflow records for these small channels, it is unclear whether 100% diversions were occurring during peak flows previous to the observations made later in the summer.

There were factors that limited the ability to detect geomorphic changes in channel morphology downstream from diversions. First, sample sizes were small, which limited the power of the statistical tests used in data analyses. Second, the data were collected during the summer 2011 season, which was a year of exceptionally high and in some cases record flows for many northern Colorado streams, as seen in the hydrographs in Figure 2. The U.S. Geological Survey (USGS) has records for gaged sites downstream of the study locations on Slater Creek (USGS, 2012c), Fish Creek near Steamboat Springs (USGS, 2012d), and Muddy Creek (USGS, 2012e), and the North Platte River (USGS, 2012f). The USGS records and estimates daily streamflow data for these sites, and provides information for each water year. This information is accessible through the USGS National Water Information System online database, which contains WaterWatch, an online streamflow monitoring service, and Annual Data Reports for water years of record through 2011 (USGS, 2012i). For the aforementioned gaged sites, peak flows were approximately two to four weeks earlier and lasted several weeks longer than normal peak flows. One of the hydrographs is from Slater Creek near Slater, CO, which is downstream of and approximately 25 kilometers northwest of the Slater Creek reaches and one of its tributaries in Slater Park. Slater Creek's peak flow recorded at the USGS gage site was 63.71 cms (reported as 2250 cfs) (USGS, 2012) for that year, the second highest flow since data have been consistently recorded at that stream gage site starting in 1932.

It is possible that these high flows, along with those occurring during the 2010 snowmelt runoff, could have re-worked some of the channel morphology that may have been altered by diversions during drier years. Previous research indicates that diverted streams may have more freely-flowing hydrographs during exceptionally high periods of runoff. Ryan (1997) noted that during years of higher flows that have a 5- to 10-year return interval, alterations to channel form from sustained diversions during years of lower flow may have been modified, with channels showing little-to-no evidence of physical change from diversions. In the high flow year of 2011, variables such as D_{50}, width, and width-to-depth ratio likely responded to the flooding and were not as reduced as they would be by diversions during extended drier periods. Additionally, diversions may be removing water near peak flows, and, depending on how they are designed, possibly not diverting enough water during that time to prevent flow levels necessary for channel maintenance. While this study did not find evidence of decreased grain size in diverted streams, other studies done previous to the high flow year of 2011 provide evidence for increased fine sediment deposition in streams below diversion structures. Dan Baker and others (2011) found accumulation of fine sediment in streams below diversion dams in a detailed study of diverted streams in northern Colorado and southern Wyoming, using multiple metrics to determine fine sediment buildup. This was particularly pronounced in streams of lower than 3% gradient, which showed decreasing drainage area, smaller D_{84}, and lesser bankfull depth. Pools may be more sensitive to increased fine sediment deposition and could have been altered by the high flow year, but were not surveyed in pebble counts, as they were inaccessible during high flows

Other confounding factors may include groundwater and the variety of diversion types and the amounts diverted in any given year. Groundwater may be playing a role in mediating the effects of diversions. In the case of Service Creek, for example, the stream and diversion point are located in a wetland meadow setting. The interaction between streams, groundwater, and diversions was not analyzed in this study, and it is suggested that future research possibly incorporate analyses regarding these relationships. Some diversions, such as Rhea and Willford Ditches off of Beaver Creek, were composed of wood logs that functioned as headgates, but still allowed some water to pass, even when the headgates were lowered and the ditches were not actively diverting water. Other ditches have the capability to completely block flows, like Sarvis Ditch off of Service Creek. The headgate is located in the middle of a large, linear berm that allows water from Service Creek to slowly collect into a wetland at the edge of the berm, then directs that water into a ditch that flows away from the stream and parallel to the berm. The Martin #1 Ditch of Little Muddy Creek is also capable of completely blocking flows by using two headgates: one that can cut off flow to the stream, and another that opens and directs flow into the ditch. Bohn and King (2000) interpreted their findings that differences in upstream and downstream measured parameters were not significant to potentially mean that sediment and water are able to pass through diversions. They thought that this ability to allow most of the sediment and water to flow through the channel downstream of diversions may make changes to channel form and substrate in diverted streams much less pronounced than those of streams below dams and large diversion structures. This may apply to streams in this study that are not being entirely diverted during peak flows.

Discharge measurements above and below diversions would have been useful in helping to determine how much water actually flowed past diversions and into streams below headgates. Surveying reaches that could only be paired, rather than surveying streams that could not be paired, would have likely made statistical analysis simpler. Several unpaired reaches created complications with analysis requiring mixed models that included both paired and unpaired streams. Survey and experimental design could have also been different, including surveying multiple diverted and control reaches on a single stream. This might have allowed for more detailed analyses of pool and riffle morphology, including an accurate estimation of pool-pool and riffle-riffle spacing, and how that may be changing due to diversions. Pebble count sampling was conducted in riffles only; this may have reduced the accuracy of surveying the percentage of fine sediment in the reach, as pools were avoided due to depth and difficulty of sampling. Bunte and others (2009) noted that selection of pebble count methodology can have an effect on particle size distribution sampled, depending on the protocol used.

6. Summary and Conclusions

Diversions to stream channels have been noted to impact a number of ecological and physical variables, including reduction of habitat quality and quantity, reduced flow, decreased width, and decreased bedload transport. The goal of this study was to examine whether the geomorphic variables of diverted sections of streams were significantly different from control sections of streams that did not have diversions. Twenty-two reaches were surveyed from 13 different streams. Each survey included four cross sections, one longitudinal profile, and a pebble count. Geomorphic variables included width and depth at field-estimated bankfull elevations, the cross-sectional areas and width-to-depth ratios from these measurements, sinuosity and bed slope measured from longitudinal profiles, and median grain size from pebble counts (D_{50}). Statistical tests were conducted on the data extracted from reach surveys to determine whether diverted reaches differed significantly from control reaches. These included paired and unpaired t-tests, nonparametric Wilcoxon tests, development of a mixed model, and multivariate regression in the form of stepwise selection. There were varied results from statistical tests. The t-tests and Wilcoxon tests overall did not provide enough support to reject the null hypotheses, with the exception of sinuosity. The mixed effects model that took valley characteristics, drainage basin size, lithology, and vegetation into account when comparing reach response variables, however, did support the first alternative hypotheses that channel form parameters would be affected by flow diversions, as sinuosity and channel dimension parameters including width, width-to-depth ratio, and cross-sectional area were significantly different at the $\alpha=0.10$ level. Because the mixed effects models take other potential influences into account and adjust for these affects, I emphasize these results over those from the t-test and nonparametric Wilcoxon tests. Most reaches were surveyed in locations that tended towards wider, unconfined valley types, and not enough reaches were surveyed that had conifers as the primary vegetation within the riparian zone in order to test the differences between streams with conifer-dominant versus willow-dominant riparian vegetation for the second alternative hypothesis. The two different vegetation types sampled were willow and grass/sedge, and these were used to test differences between width, depth, cross-sectional area, sinuosity, and width-to-depth ratio both between the diverted and control groups, as well as within the diverted and control groups for the two vegetation types. Within the diverted and control groups, several variables were found to be significantly different between the willow and grass/sedge vegetation types. The variables, including width, depth, width-to-depth ratio, and cross sectional area, appear to be potentially influenced by the type of vegetation lining the stream bank, with grass/sedge type streams being more narrow and shallower. Sinuosity was found to be significantly decreased downstream of diversions on streams with willow-type vegetation, while it was not significant in streams bordered by sedges and grass-type plants. The results of these tests are not emphasized, however, due to the small sample size in the riparian vegetation groups and lack of adjustment for watershed area. Sinuosity, width, and width-to-depth ratio appear to be more simplified in channels downstream of diversions, as these variables have lower variances in diverted channels.

Overall, $\boldsymbol{H_{01}}$ was rejected in favor of $\boldsymbol{H_{A1}}$, that diversions affect channels through decrease in channel form variables, as the mixed models showed some evidence of response to downstream diversions with the reduction of multiple variables after adjusting for the effects of other parameters, especially wide variations in drainage basin size; sinuosity was found to be significantly lower using the t-tests and Wilcoxon tests; and at least two reaches were observed to have been dewatered by diversion ditches during the time of this study. $\boldsymbol{H_{02}}$, which was concerned with the style and magnitude of change of diverted streams due to differences in valley type, riparian vegetation, and lithology, however, was not rejected in favor of the second alternative hypothesis. This was due to the very small sample size when breaking down the diverted and control groups into subunits by valley type, riparian vegetation, and lithology.

For management purposes, I suggest that high flows be periodically allowed to pass downstream of diversions to re-form and maintain morphology that is reduced during drier periods. This is a minimum recommendation, as channel morphology is likely to be affected more during prolonged periods of lower flows, and this study only observed and collected data for diverted streams during a year of exceptionally high runoff. Flushing flows offset some of the dry year-effects of diversions on channel dimensions (Ryan, 1997). Median grain size, width, and width-to-depth ratios are likely to be more responsive to a high runoff event like that in 2011. Allowing high flows to enter the diverted channel also helps maintain water quality and habitat for aquatic species such as fish, as high flows reduce fine sediment in spawning gravels, which increases fish embryo survival rates (Magee et al., 1996). Research conducted on diverted streams in years of lesser runoff found that fine sediment accumulated in streams downstream of diversions in lower-gradient response reaches (Baker et al., 2011) and that width can be reduced from 35-50% in pool-riffle, gravel channels (Ryan, 1997).

This project underscores the necessity of conducting further studies on the physical effects of streamflow diversions, as data collection for this study was limited due to the high flows of summer 2011. While there was some evidence of diversions affecting channel form parameters, additional studies conducted during long-term periods of low flows will likely represent the influences of diversions more accurately. Streams are complex systems, and more data are needed to better quantify the physical effects of stream diversion.

7. References

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