THESIS

RIVERS AND BEAVER-RELATED RESTORATION IN COLORADO

Submitted by

Julianne Scamardo

Department of Geosciences

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Master's Committee:

Advisor: Ellen Wohl

Tim Covino
Ryan Morrison

ABSTRACT

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Interest in beaver-related restoration, such as reintroduction and dam analogs, for repairing incised and degraded streams is apparent across the American West. North American beaver (*Castor canadensis*) were historically abundant across their ecological range, and headwater streams across the U.S. likely held many beaver dams in the channel and on the floodplains. Beaver dams can effectively trap sediment, water, and solutes, and a thriving beaver meadow can have implications for biodiversity and carbon storage. After historical declines in populations throughout the 19th and 20th century, enthusiasm for reintroduction and dam analogs has grown for naturally restoring degraded streams that once housed beaver.

To guide enthusiasm in the State of Colorado, understanding (i) where reintroductions are viable and (ii) how beaver dam analogs change stream morphology and hydrology is critical. This study tackles those two objectives by modeling potential dam densities in 63 watersheds across Colorado as well as monitoring beaver dam analog restoration projects in two watersheds in the Colorado Front Range. While density models may not be accurate at small scales, regional patterns in dam density across Colorado suggest that many streams can still support beaver populations despite larger decreases from historic dam densities. Reintroductions could spur vegetation growth and create side channels through overbank flow, which would increase the capacity of a given stream to support beavers. On streams where densities are low or have been reduced to no beaver capacity, beaver dam analogs could be installed to aggrade channels and create ponds. Unlike natural beaver dams, the beaver dam analogs monitored here did not create

a groundwater response within the first year of restoration, which could be a limitation to restoration projects hoping to increase riparian vegetation. However, this study only covers the first year post-restoration and long-term restoration outcomes could differ from the short-term. In the future, smaller scale watershed modeling and site visits to watersheds or streams with high modeled dam densities are necessary to determine precise stream reaches that are prime for reintroductions. Additionally, post-restoration studies that extend over a longer time frame and include more watersheds are needed to fully understand the magnitude of change post-beaver-related restoration.

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1. Overview

Reintroducing North American beaver (*Castor canadensis*) to streams within their historic range can restore aquatic and riparian habitat where historic beaver loss has initiated degradation. Determining where beavers can and should be reintroduced is a first step in successful beaver-related stream restoration. This study uses the Beaver Restoration Assessment Tool (BRAT) developed at Utah State University to model potential beaver dam densities in 63 watersheds across Colorado. The objectives of this study are to model beaver dam densities over time and space and to compare modeled densities to dams recorded in the field.

Model results suggest that beaver dam densities are highest in high elevation hydrologic regions in Colorado, which include most of the ranges in the Southern Rocky Mountains. Dam capacities were historically higher than current predicted densities in all regions, and decreases could be explained by agriculture, urbanization, and natural vegetation regime changes. Changes in BRAT densities suggest that widespread habitat degradation has decreased density but not complete destroyed beaver reintroduction potentials. Beaver reintroductions could therefore be used to restore beaver habitat, thus creating a positive feedback loop of increasing beaver capacity. In places where BRAT predicts low densities, other beaver-related restoration such as beaver dam analogs could be used to improve degraded streams and set the scene for future reintroductions.

BRAT predicted densities did not strongly correlate with mapped dam densities in selected stream segments across Colorado, but disparities could be due to difficulties in comparing non-conflict capacity with actual densities. Regional scale patterns and historical magnitudes of change are likely still accurate for most of the mapped area. While BRAT highlights broad patterns and restoration potential, model output should be used as a first order approximation of suitable reintroduction locations, and future modeling and site visits should be conducted prior to restoration at any given site.

2. Introduction and Previous Studies

The restoration of North American beaver (*Castor canadensis*) can be a self-maintaining resource management tool for promoting spatial heterogeneity and connectivity of streams and rivers. Sediment and excess nutrient storage, attenuation of flood peaks, increased surface and subsurface water storage, and greater habitat diversity created by beaver activities are some of the reasons why beaver reintroduction is increasingly being used in restoration of river corridors (Pollock et al., 2015). River corridor here refers to the channel(s) and the adjacent floodplain, as well as the underlying hyporheic zone (Harvey and Gooseff, 2015).

Beaver are ideal ecosystem engineers and keystone species (Baker and Hill, 2003; Rosell et al., 2005). Beaver shape river corridors and create habitat by building dams and digging canals across the floodplain. While beaver primarily construct these features to provide protection from predators and access to food and dam building material by water (Muller-Schwarze and Sun, 2003), beaver activity can significantly alter fluxes of sediment, water, and solutes. Beaver will build dams not only on main channels of low order streams, but also on side channels and seeps (Olson and Hubert, 1994; Pollock et al., 2015). As increasingly more beaver dams are built on the main stem, floodplain, and side channels, the channel develops a stepped longitudinal profile with abundant standing water and wetlands. The resulting beaver meadow complex (Ruedemann and Schoonmaker, 1938; Ives, 1942; Polvi and Wohl, 2012) is a spatially heterogeneous valley bottom.

Beaver dams obstruct channels and floodplains, which reduces surface flow velocity, ponds water upstream, and enhances the magnitude and duration of overbank flow (Westbrook et al., 2006; Burchsted et al., 2010). In the channel, dams increase exchange with the hyporheic zone (Janzen and Westbrook, 2011). On the floodplain, increased overbank flow can create secondary channels and recharge groundwater in inundated areas (Westbrook et al., 2006). Storage of water on the surface, in the hyporheic zone, and in riparian aquifers can reduce flood peaks and potentially maintain or increase baseflow (Wegener et al., 2017).

Surface and subsurface water storage associated with beaver dams also influences downstream fluxes of nutrients and solutes. Soils saturated by beaver activity develop anaerobic conditions which alter biogeochemical pathways (Naiman et al., 1994). Increased hyporheic exchange reduces downstream solute transport due to microbial activity and nutrient storage in the hyporheic zone (Findlay, 1995). Previous studies document reductions in total N, total P, total organic carbon, and total suspended solids downstream of beaver meadows (Naiman and Melillo, 1984; Naiman et al., 1986; Correll et al., 2000; Wegener et al., 2017). Particulate organic matter can also be deposited in ponds and overbank areas caused by dams, where saturated, reducing conditions limit the decomposition of carbon. River corridors dammed by beaver can therefore store high concentrations of terrestrial carbon (Wohl, 2013; Johnston, 2014).

Beaver dams cause significant storage of fine-grained sediment in upstream ponds and in floodplains inundated by overbank flow (Naiman et al., 1986; Butler and Malanson, 1995; Westbrook et al., 2011). Sediment deposition behind beaver dams can aggrade the channel bed and reconnect incised streams with their floodplains. The effectiveness of beaver dams at reconnecting incised channels with floodplains is one of the reasons why beaver reintroductions are increasingly used in stream restoration (Pollock et al., 2014).

Storage of sediment, water, solutes, and organic carbon caused by beaver dams attenuates fluxes downstream. The magnitude of attenuation depends on factors such as size, number, and complexity of dams built by beaver. A single dam and pond may create limited attenuation during a peak flow (Burns and McDonnell, 1998), but numerous dams in a beaver meadow can effectively attenuate even the largest peak flows and serve as a sink for nitrates and organic carbon (Wegener et al., 2017). Ponded water and high riparian water tables associated with beaver dams can also reduce the effects of climatic extremes such as drought (Hood and Bayley, 2008) and make the river corridor more resistant to wildfire. Generally, beaver meadows are thought to increase the resilience of the river corridor to perturbation (Naiman et al., 1986).

In addition to physical benefits of attenuation and resilience, beaver meadows increase the biodiversity of river corridors by creating a diversity of riparian and aquatic habitat. Beaver meadows provide suitable habitat for vegetation (Westbrook et al., 2011), aquatic insects and their riparian predators (McDowell and Naiman, 1986; Fuller and Peckarsky, 2011; McCaffery and Eby, 2016), fish (Pollock et al., 2003), frogs and other amphibians (Anderson et al., 2015; Arkle and Pilliod, 2015), butterflies (Bartel et al., 2010), birds (Aznar and Desrochers, 2008), and other semi-aquatic mammals such as mink and otter (Rosell et al., 2005).

The apparent ecosystem and environmental benefits of beaver activity warrant increased interest in maintaining beaver on the landscape. However, reintroduction of beaver is necessary due to the continental scale decrease of beaver post-European settlement. Prior to European settlement, an estimated 60 to 400 million individual beaver populated North America (Seton, 1929). Trapping for the commercial fur trade caused the near extirpation of beaver by the late

19th century (Rutherford, 1964; Baker and Hill, 2003). In Colorado, increased State regulations regarding trapping allowed for some beaver colonies to recover in the early 20th century (Retzer et al., 1956). However, beaver populations have not recovered in many watersheds once housing colonies across Colorado. Reasons hindering recovery include habitat loss due to urbanization and agriculture, herbivory competition by elk, moose, and cows (Baker et al., 2005; Small et al., 2006), and removal of beaver due to property damage concerns (McKinstry and Anderson, 1999). Contemporary beaver populations are estimated at approximately 10 million individuals across their ecological range in North America (Naiman et al., 1988; Pollock et al., 2015).

Beaver were historically prevalent across all physiographic regions of Colorado (Fremont, 1844; Retzer et al., 1956). Simply, beaver need a reliable water source and food to survive. In lakes, ponds, and large perennial rivers where water depth is sufficient to provide beaver protection and access to vegetation, beaver will dig dens in the banks rather than pond water behind dams. Beaver prefer to build dams on smaller streams where dam building is possible at typical low flow (i.e., baseflow), but dams will not break during typical high flows (i.e., 2-year flood). Small to medium (<20 m wide) streams with low gradients (<3%) are ideal dam building habitat, but beaver can also build dams on steeper channels, on floodplains and side channels of wider rivers, and on hillside springs and seeps (Olson and Hubert, 1994; Townsend and Butler, 1996; Albert and Trimble, 2000; Pollock et al., 2015). Beaver will build dams on both perennial and intermittent streams as long as a woody riparian corridor is present (Gibson and Olden, 2014). Beaver diets are seasonal and diverse. In the summer, beaver prefer high nutrient, herbaceous vegetation such as sedges and rushes as well as leaves from deciduous trees. In the winter, beaver rely on the inner bark (cambium) of trees, preferably aspen, willows, and cottonwoods (Allen, 1983; Kimball and Perry, 2008). The maximum distance beaver will travel to harvest vegetation is 100 m, although beaver prefer to forage within 30 m of the stream (Allen, 1983).

Modeling potential and existing beaver habitat suitability based on known ecosystem preferences and requirements has been ongoing for decades (Slough and Sadleir, 1977; Allen 1983; Suzuki and McComb, 1998). As beaver gain appeal in river restoration (Pollock et al., 2007; Pilliod et al., 2017), understanding the location and distribution of suitable beaver habitat is a first step in the process of reintroduction. In this study, I use the Beaver Restoration Assessment Tool, or BRAT, developed at Utah State University (MacFarlane et al., 2017), to model and assess beaver habitat in the State of Colorado. BRAT uses nationally available spatial datasets for hydrology, vegetation, and topography to estimate beaver dam capacity on a stream network using fuzzy inference systems. BRAT incorporates maximum foraging distance, preferred foraging and building material, low and high flow requirements, and other known beaver habitat preferences when estimating the capacity of beaver and beaver dams that a landscape can sustain. Scientists at Utah State University and in the Riverscapes Consortium (https://www.riverscapes.xyz/) have implemented BRAT in watersheds in Utah, Idaho, Oregon, New York, and beyond, which suggests that the model is broadly applicable across North America. My objectives with the following study are to (i) examine how potentially suitable habitat abundance and distribution vary across biomes within Colorado and (ii) compare BRAT predictions of habitat to contemporary and historical beaver presence at a subset of representative sites within Colorado. By mapping dam density across the State and comparing it to field case studies, I aim to create a spatially complete and broadly useful resource for river managers in Colorado.

3. Methods

3.1. Description of Study Area

The state of Colorado is diverse in climate, terrain, and land use. Three major physiographic provinces trend from north to south across Colorado and describe physical variations in the State (Fenneman, 1931). Eastern Colorado lies within the rolling grasslands of the Great Plains, which are characterized by low relief, limited precipitation, shallow river valleys, and cultivated land. West of the Great Plains, most of central Colorado is within the Southern Rocky Mountains, which consist of high relief mountain ranges, intermountain valleys, and coniferous upland forests and mixed coniferous-deciduous riparian forests (Veblen and Donnegan, 2005). The western slope of the Rocky Mountains descends into the Colorado Plateau, which is dominated by steep, rugged canyons, low humidity, and high elevation. Previous works have detailed the climate, topography, and land use of each of these provinces and how they affect the stream network (Capesius and Stephens, 2009; Kohn et al., 2016). In general, variations in elevation across Colorado result in drastically different annual precipitation, which is significant to the streamflow and function of streams modeled in this study.

The state of Colorado contains headwaters of the Rio Grande, Arkansas, North and South Platte, and Colorado Rivers. To model dam density via BRAT for these basins, hydrologic unit code 8 (HUC 8 –Seaber et al., 1987) watersheds in Colorado were downloaded from the USGS Watershed Boundary Dataset. While the Watershed Boundary Dataset contains nested watersheds larger and smaller than the HUC8 level, HUC8 watersheds were chosen to reduce computation times associated with smaller watersheds but avoid skewing regional hydrologic regressions by using larger watersheds. Watersheds were selected for modeling based on (1) having a geographic centroid within the Colorado state line or (2) being tributary to downstream watersheds centered in Colorado. BRAT was run in 63 watersheds based on these selection criteria.

Selected watersheds were separated into the 6 hydrologic regions of Colorado: Plains, Foothills, Mountains, Rio Grande, Northwest, and Southwest (Figure 1.1). Separation by hydrologic unit is necessary to assign regional streamflow regressions to each watershed, but also provides useful units by which to assess the output and statistics of BRAT. Hydrologic units are based on physiographic provinces and major rivers basins and are defined and described by Kircher et al. (1985), Capesius and Stephens (2009), and Kohn et al. (2016). Originally, Colorado was divided into 5 regions which included the Foothills within the Plains. Kohn et al. (2016) recognized the climatic and physical basin differences which uniquely affect streamflow in the Foothills, and subsequently calculated regional regressions for the Foothills as a separate hydrologic region. Since hydrology is significant to accurately describing beaver habitat, I chose to include the Foothills as a separate hydrologic region in this study, as reflected in my statistics and output.

3.2 Model Inputs and Parameters

The Beaver Restoration Assessment Tool (BRAT) calculates capacity of dams for each stream based on 4 main lines of evidence: hydrology, topography, vegetation, and land use. Spatial layers to represent each element in the model were downloaded from nationally available datasets and combined into the BRAT model using ArcGIS 10.4.1 (Table 1.1).

Hydrology inputs to BRAT include both the stream network and discharge. Stream networks for each of the 63 HUC8 watersheds were downloaded from the USGS National Hydrography Dataset (NHD, https://www.usgs.gov/core-science-systems/ngp/national-hydrography). The NHD is mapped at the 1:24,000 scale or better and includes perennial, intermittent, and

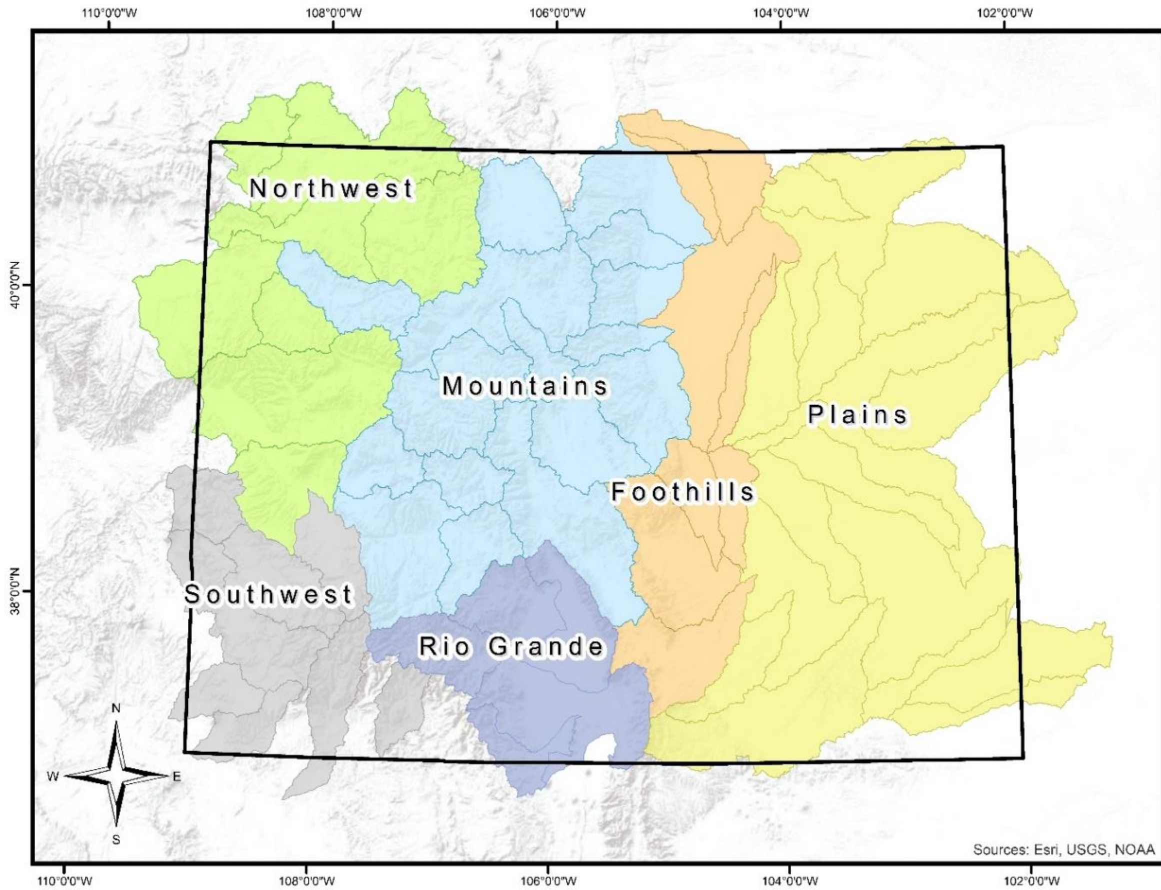

Figure 1.1. Map of all watersheds for which BRAT was run in Colorado separated into hydrologic region. Regions are based on Capesius and Stephens (2009) and Kohn et al., (2016).

ephemeral streams. Ephemeral streams were excluded from the BRAT analysis because they lack discharge necessary to support beaver colonies. Discharge was represented by regional regressions for the 2-year flood (Q_2) and baseflow (Q_{low}) for each of the 6 hydrologic regions in Colorado (Capesius and Stephens, 2009; Kohn et al., 2016). For 4 of the 6 regions, baseflow equations were given as regressions for the minimum 7-day, 2-year flow (${}_7Q_{10}^{MIN}$). Baseflow regressions were not available for the Foothills and Plains regions, likely due to the variability of flow in small, ungauged streams on the Great Plains. To estimate baseflow for the Foothills and Plains, the Q_2 discharge value was divided by 500, which was seen to be sufficiently small to represent low flow conditions on ungauged streams in the Great Plains. The assumption of baseflow for the Foothills and Plains is a possible source of error to the BRAT model.

Table 1.1. Watershed elements used as lines of evidence for beaver dam density in the Beaver Restoration Assessment Tool (BRAT). Elements are represented by model input sources from nationally available datasets.

Element	Model Input	Source
Hydrology	Stream Network	USGS National Hydrography Dataset
	Discharge equations (Q_2 and baseflow)	USGS Regional Regression Equations for Colorado
Topography	10-m Digital Elevation Models for Colorado	USGS National Elevation Dataset (NED)
Vegetation	Current vegetation	LANDFIRE Existing Vegetation Type
	Historic vegetation	LANDFIRE Biophysical Settings
Land Use	Land use raster	LANDFIRE Existing Vegetation Type

BRAT stores discharge for each modeled watershed by assigning a value based on drainage area at each point along the NHD line. Basin-averaged values for any regression input that was not drainage area were calculated for each watershed and included as a coefficient (Table 1.2). Equations in Table 1.2 essentially represent a template from which a regression including only drainage area raised to an exponent and multiplied by a coefficient was built for each of the 63 watersheds. Using HUC8 watersheds and not larger basins was meant to provide accuracy in basin-averaged values for inputs such as mean basin slope, mean annual precipitation, mean elevation, and others which would fluctuate with a changing drainage area. Basin-averaged inputs were calculated using USGS StreamStats (Ries et al., 2017). In watersheds where StreamStats was not available – including watersheds with outlets in Nebraska and Wyoming – basin-averaged hydrologic characteristics were recorded from nearby USGS stream gages, physical characteristics were recorded from the NRCS soil survey, and topographic characteristics were calculated from the DEM. Values for basin-averaged characteristics necessary to calculate the regional regression equation are given for each watershed in Appendix A. Choosing basin-averaged values instead of spatially modeling changing averages with changing drainage area is a source of error in BRAT recognized by this study.

Topography is represented in BRAT using 1/3 arc-second (approximately 10-m) digital elevation models (DEM) for Colorado downloaded from the USGS National Elevation Dataset. The DEM is then used to calculate stream gradient, drainage area, and valley bottom width in BRAT. Maximum drainage above which no dams would persist on a main channel can be programmed into BRAT. A maximum drainage area of 3500 km^2 was used for watersheds originating on the Plains and 400 km^2 for all other regions. Maximum drainage areas were arbitrarily chosen based on known locations of beaver dams in Colorado.

Table 1.2. Regional regressions for Colorado based on hydrologic region. Baseflow equations for the Foothills and Plains regions were estimated by dividing the 2-year flow equation by 500. Equations were taken from Capesius and Stephens (2009) and Kohn et al. (2016).

Region	Flow Type	Inputs	Equation
Mountains	2-year flow	Mean basin slope, mean annual precipitation	$Q_2 = 10^{-2.05} A^{0.78} S^{0.17} P^{2.10}$
	Baseflow	Mean annual Precipitation, mean elevation	${}_7Q_{10}^{MIN} = 10^{-33.76} A^{1.2} P^{2.25} E^{7.2}$
Northwest	2-year flow	Percent area above 7500 ft, mean annual precipitation	$Q_2 = 10^{-1.15} A^{0.75} A_{7500}^{-0.41} P^{2.15}$
	Baseflow	Mean elevation	${}_7Q_{10}^{MIN} = 10^{-38.52} A^{0.9} E^{9.42}$
Rio Grande	2-year flow	Mean annual precipitation	$Q_2 = 10^{-3.0} A^{1.0} P^{2.46}$
	Baseflow	Mean elevation	${}_7Q_{10}^{MIN} = 10^{-46.35} A^{1.06} E^{11.15}$
Southwest	2-year flow	Percent area above 7500ft	$Q_2 = 10^{1.67} A^{0.64} A_{7500}^{-0.1}$
	Baseflow	Mean annual precipitation, mean elevation	${}_7Q_{10}^{MIN} = 10^{-18.74} A^{0.97} P^{1.35} E^{3.88}$
Foothills	2-year flow	Percent clay, elevation of basin outlet, 6-hour 100-year precipitation	$Q_2 = 10^{9.952} A^{0.626}\ {}_6P_{100}^{1.401} C^{0.836} E_{out}^{-2.774}$
Plains	2-year flow	Mean basin slope, percent clay	$Q_2 = 10^{-1.033} A^{0.378} C^{1.742} S^{0.683}$

Current and historic vegetation can be used as inputs to BRAT in order to model current dam capacity compared to historic dam capacities. LANDFIRE vegetation rasters with a 30 m resolution were used to represent current and historic vegetation (https://www.landfire.gov/). Historic vegetation refers to vegetation that existed on the landscape prior to European settlement. LANDFIRE Biophysical Settings vegetation layers represent pre-European settlement vegetation based on current vegetation and estimated historical disturbance regimes, and therefore were used as a proxy for historic vegetation. LANDFIRE Existing Vegetation Type layers were used to represent current vegetation. LANDFIRE data are input to BRAT as a raster and used to determine vegetation assemblages within beaver foraging distance.

Since no complete land-use map was available for Colorado, land use was estimated from the LANDFIRE Existing Vegetation Type layers. Current vegetation was separated into 4 categories representing land-use: natural setting/no land use, low intensity agriculture, higher intensity agriculture, and urban/developed. For example, deciduous forest and riparian vegetation are considered a natural setting, pastures and hayland are considered lower intensity agriculture, cultivated row crops are higher intensity agriculture, and barren, urbanized land are developed.

3.3 Preprocessing

Before entering model inputs into BRAT in ArcGIS 10.4.1, most spatial layers needed to undergo some degree of pre-processing. Most simply, DEMs were clipped to the outline of each watershed. Without clipping the DEMs to the watershed size, excess area would cause errors in drainage area calculations which often caused the BRAT code to crash. LANDFIRE rasters for current and historic vegetation were also clipped to the outline of the watershed for easy processing. Additionally, LANDFIRE rasters were edited to include a vegetation code category that was called upon in the BRAT code. The vegetation code indicated suitability as beaver food and dam building material for each mapped vegetation type within Colorado. Vegetation code values ranging from 0 to 4 indicated unsuitable material, barely suitable material, moderately suitable material, suitable material, and preferred material, respectively.

NHD stream networks were clipped to each watershed to indicate the streams for which BRAT should be run. Perennial and intermittent streams were selected from the NHD flowline layer and dissolved into continuous networks before being clipped into 300 m or shorter segments. The goal is to have most stream segments be 300 m in length, but the ends of lines and tributary junctions commonly had 'leftover' stream segments shorter than 300 m. Streams were clipped to 300 m to provide a higher resolution to the BRAT network than the entire length of a stream. Additionally, 300 m was used rather than a smaller division due to the 30 m resolution of the LANDFIRE dataset. A 300 m stream reach would allow for approximately 20 cells to be sampled per reach for the 30 m vegetation buffer and approximately 60 cells per reach for the 100 m vegetation buffer in BRAT.

Additional information on pre-processing spatial BRAT inputs can be found online on the Riverscapes Consortium website, which details the original BRAT documentation and code assignments for vegetation suitability and land use (http://brat.riverscapes.xyz/).

3.4 Case Studies

Four case studies were used to compare BRAT to actual dam densities or habitat suitability on (i) headwater streams of the Cache la Poudre, St. Vrain, and Big Thompson Rivers in Rocky Mountain National Park, (ii) the Arikaree River in The Nature Conservancy Fox Ranch Preserve, (iii) headwaters of the Arkansas River in south-central Colorado, and (iv) Open Spaces and Natural Areas in Boulder County. The first 3 case studies directly compare BRAT to observed dam densities, while the Boulder County case study compares BRAT to site suitability assessments conducted in the field. The purpose of conducting case studies is to ground the BRAT model in reality and assess whether the model is accurately portraying natural conditions. However, conducting case studies relating real dam densities to BRAT dam densities can be difficult. Dam densities in the field might not represent the total capacity of dams that could be present, thus exhibiting field dam densities less than BRAT dam densities. Additionally, many dams mapped in the field were abandoned beaver berms, but it is assumed in this study that all dams could have been occupied at the same time. Assuming concurrent dam occupation might provide dam densities higher than actual dam density at any given time. Despite difficulties in mapping dams and determining occupation, the following case studies can still be used as a first-order evaluation of the accuracy of BRAT.

Rocky Mountain National Park was chosen for closer study because of its history of beaver abundance and decline as well as its designation as nationally protected land. The Rocky Mountain National Park case study included dams mapped by Ellen Wohl on the Cache la Poudre River immediately downstream of Poudre Lake, the Big Thompson in Moraine Park, Fern Creek, Mill Creek, Beaver Brook, Glacier Creek, Boulder Brook, North Fork Big Thompson, Cow Creek, Black Canyon Creek, Hunters Creek, Sandbeach Creek, North St. Vrain, and Ouzel Creek. Dams were mapped by walking stream reaches and recording GPS coordinates where active or abandoned dams were encountered on the channel. While many abandoned dams no longer span the channel or create ponds, they are still identifiable on the landscape by remnant berms that create topographic highs in the landscape (Figure 1.2). Remnant beaver dam berms typically have steep slopes on the downstream end of the berm with slightly shallower upstream slopes due to pond infilling. Additionally, abandoned berms commonly have

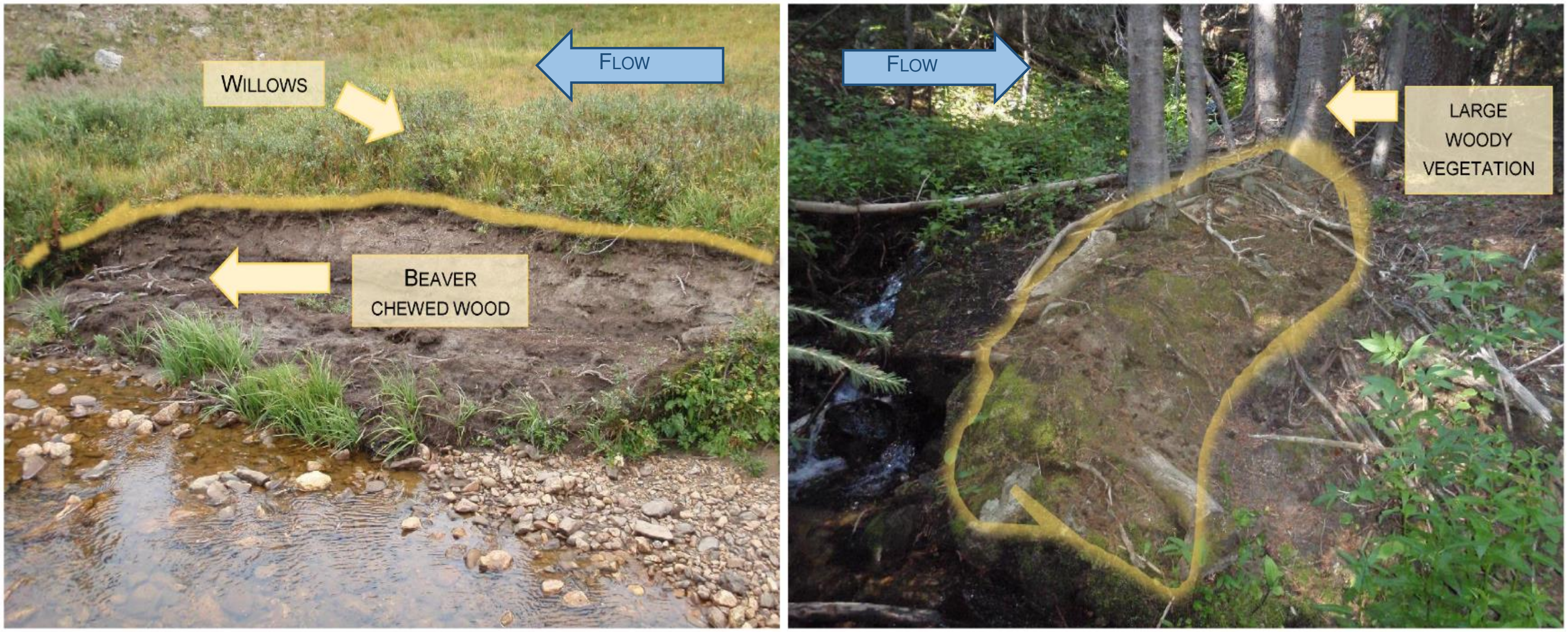

Figure 1.2. Examples of abandoned beaver berms mapped in Rocky Mountain National Park on the upper Cache la Poudre River (left) and Beaver Brook (right). Berms are identifiable as small topographic highs proximal to the channel (outlined in yellow). Additionally, berms typically encourage vegetation growth, as can be seen by the growth of willows (left) and coniferous forest (right), and can contain buried large wood.

vegetation such as willows spanning the old dam top. In a few cases, dams were identified by the presence of beaver-chewed wood sticking out of old berms.

The Arikaree River is located on the Fox Ranch Preserve, a 5700 ha ranch managed by The Nature Conservancy in northeastern Colorado near the border with Nebraska and Kansas. The Fox Ranch was chosen as a case study because of known pervasive beaver activity occurring on intermittent reaches of the Arikaree River. Therefore, the Arikaree offers a rare case of assessing BRAT performance on intermittent flows. Beaver dams on the Arikaree River were mapped using Google Earth. Remote mapping of beaver dams was possible due to the lack of large trees proximal to the channel and easily identifiable dams. Dams were identifiable by ponding, vegetation, and their linear nature (Figure 1.3). Dams on the Arikaree are typically made of mud, grasses, and some large wood. The abundance of mud causes vegetation to grow across even active dams, which helps make dams identifiable. Additionally, ponding followed by immediate constriction of the river is an indicator of an active dam on the Arikaree. However, when mapping dams remotely, assessing occupation of the dam is even more difficult. Dams can persist on the landscape and create ponds and constrictions even after being abandoned. To avoid mapping abandoned dams, dams that were obviously blown out or breached were not included.

Seven streams in the headwaters of the Arkansas River were also included as a BRAT case study: North Apishapa River, Jarosa Creek, North Hardscrabble Creek, St. Charles River, Beaver Creek, South Fork Upper Horn Creek, and Big Cottonwood Creek. Beaver dams were mapped on these reaches in 1939 by the Colorado Game and Fish Commission Beaver Survey (Carhart, 1940). The Colorado Game and Fish Commission Beaver Survey set out to assess the supply of beaver for commercial trapping, but in the process, mapped the relative location and density of dams. The benefit of using historic surveys as a case study is that dams were mapped before

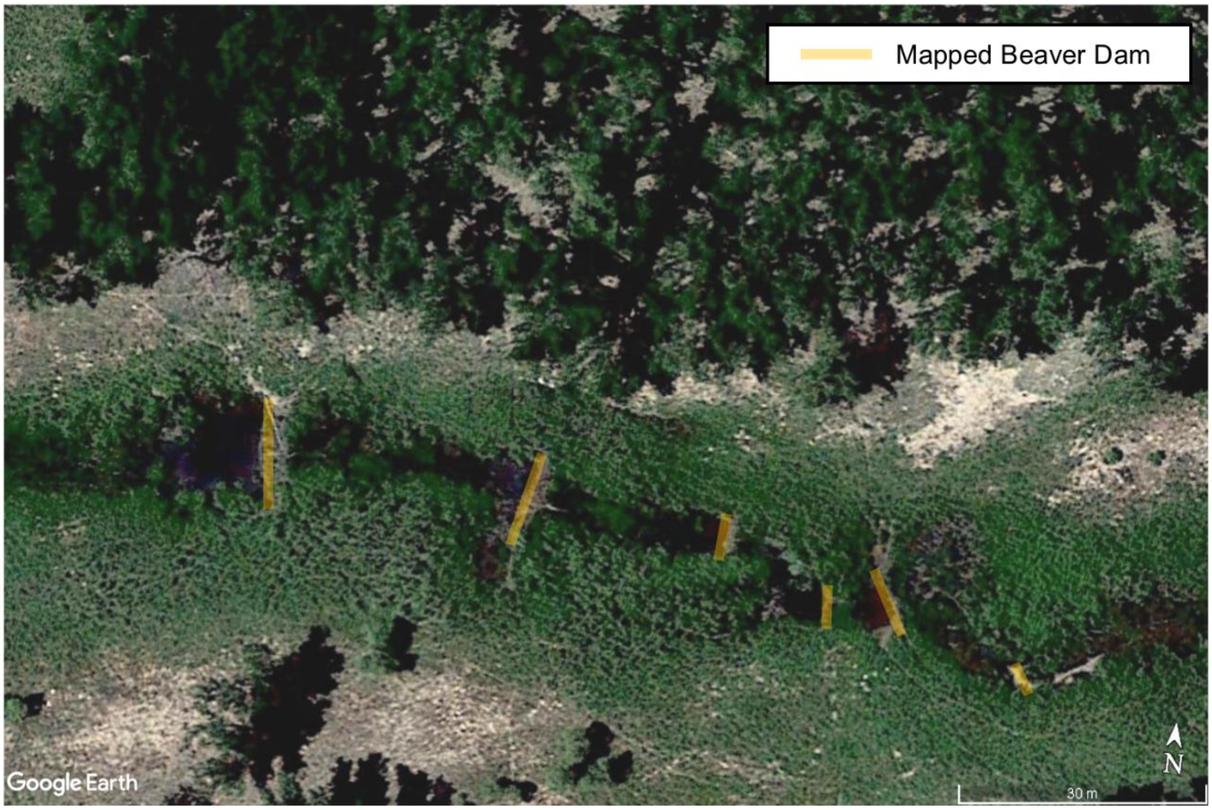

Figure 1.3. Mapped dams on a reach of the Arikaree River in east central Colorado. The reach is approximately 120 m in length. Photograph source: Google Earth.

additional commercial trapping occurred throughout the mid-20th century in Colorado. Therefore, dam densities were potentially closer to capacity than they are today. The problem with using historic surveys is that all surveys are relative to a non-marked starting point. Starting points were qualitatively described in the survey with all up and downstream points relatively measured from there. Historical photographs, Google Earth, and the USGS National Map were used together with qualitative starting point descriptions to determine survey starting coordinates and relative dam locations.

Eight streams in Boulder County and the City of Boulder were studied for geomorphic and ecologic potential for beaver reintroduction: Delonde Creek at Caribou Ranch Open Space, St. Vrain River near Lyons, Middle Boulder Creek in Boulder Canyon, Sherwood Creek at Mud

Lake Open Space, Coal Creek near Superior, Boulder and South Boulder Creeks in Boulder, and Left Hand Creek in Left Hand Canyon. All reaches of interest on streams listed above were on Boulder County or City of Boulder public lands. Points were randomly chosen along each creek to assign a geomorphic score based on a checklist adapted from Pollock et al. (2015). Checklists combined physical site characteristics such as channel gradient, valley bottom width, and vegetation type and abundance with potential conflicts at each site including human hazards and grazing by elk and moose (see Appendix B). While BRAT as it is currently run for Colorado does not specifically look at these additional conflicts, beaver will be deterred by these factors.

For 3 of the 4 case studies, the locations of dams were uploaded into ArcGIS to be compared with BRAT dam density. Field dam densities were calculated by counting the number of dams per 300 m reach of NHD flowline in ArcGIS. Field dam densities were then compared to the BRAT dam densities for the same reach of stream. For the Boulder County case study, geomorphic scores estimated from checklists were compared to BRAT dam densities for the same reach of stream.

3.5 Dam Statistics

BRAT outputs dam capacity by assigning a dam density in dams per kilometer of stream for each stream reach. Dam density can be none (0 dams/km), rare (0 to 1 dams/km), occasional (1 to 5 dams/km), frequent (5 to 15 dams/km), or pervasive (15 or more dams/km). These categories were initially described in MacFarlane et al. (2017). Statistics performed on BRAT output include the percentage of the stream network that falls within each category per hydrologic region. Current percentages are compared to historic percentages to see how dam capacity has changed over time.

Regional statistics were calculated for all streams for which BRAT was run (perennial and intermittent), but also for perennial streams separately. Perennial streams are often the focus of beaver restoration and relocation, so separate maps and statistics were created for perennial reaches to reduce noise introduced by intermittent streams which may not be of interest to managers (Appendix C).

4. Results

4.1 Current and historic dam densities

A total of 298,119 km of streams were modeled using BRAT across the 63 study watersheds. Intermittent streams account for 232,166 km of the modeled network (78%), and perennial streams account for 65,953 km (22%). According to dam density modeled across perennial and intermittent streams, streams in Colorado have the potential to support approximately 1.2 million dams currently. Historically, the same stream network could have supported approximately 2.3 million dams. On perennial streams alone, Colorado currently has a dam capacity of 370,000 dams and historically could have had up to 720,000 dams. The number of dams was calculated by multiplying dam density by reach length, and then adding together all reaches.

The distribution of dam density varies by hydrologic region. Generally, dam densities are highest on first through third order, headwater streams (Figure 1.4). Average dam densities in the Mountains, Rio Grande, and Southwest regions are approximately twice the average dam densities in the Plains, Foothills, and Northwest regions both currently and historically (Table 1.3, Figure 1.5). Patterns in dam density vary markedly between these two groups. Currently, the network distributions of the Plains, Foothills, and Northwest peak at streams with rare (0 – 1 dams/km) dam densities (Figure 1.6). The percentage of the stream network with no dams is much lower than the percentage of streams with rare dams in these regions. An increasingly smaller portion of the stream network has densities that are frequent (5 – 15 dams/km) or pervasive (15 + dams/km). Overall, the frequency of dam densities in the Plains, Foothills, and Northwest creates a skewed bell curve pattern with a peak in the lowest dam density range. In contrast, stream networks in the Mountains, Rio Grande, and Northwest regions are more evenly distributed between the BRAT dam density categories, with distributions peaking in the 1 – 5 dams/km range.

While the pattern of dam density is consistent between perennial and intermittent streams for the Plains, Foothills, and Northwest regions, the more mountainous regions (Mountains, Rio Grande, and Southwest) exhibit much more obvious distribution differences. Perennial stream networks in mountainous regions lack reaches with rare (0 – 1 dams/km) dam densities (Figure 1.6). A higher percentage of the stream network has no dam carrying capacity compared to a rare carrying capacity. Due to the lack of rarely suitable streams, the distribution of the perennial network across the 5 dam density categories appears to have two peaks – one around unsuitable reaches with no dams and another around occasionally suitable reaches with 1 – 5 dams/km. The dip in rarely suitable streams is not apparent in the intermittent stream networks for the mountainous regions. Instead, intermittent networks portray bell curves with peaks in the occasional dam density (1 – 5 dams/km) category. In the combined distribution of all streams, the perennial pattern dominates for the Rio Grande region, but not for Mountains or Southwest.

Contemporary dam density distributions in stream networks across the 6 hydrologic regions are consistent with historical density distributions. However, the historic distribution of dam densities in the Northwest looks more similar to the Mountains, Rio Grande, and Southwest regions than the Plains and Foothills regions. Historically, the distributions of dam densities for mountainous regions peaked at higher densities than currently (Figure 1.6). Stream networks in the Mountains, Rio Grande, and Southwest regions had the greatest percentage of reaches in the pervasive dam density (5 – 15 dams) category.

Table 1.3. Current and historic average dam densities calculated by BRAT for each hydrologic region.

Region	Current Average Dam Density (dams/km)	Historic Average Dam Density (dams/km)
Plains	1.4	3.2
Foothills	3.7	6.6
Mountains	5.9	10.8
Rio Grande	6.9	11.1
Northwest	3.9	7.7
Southwest	6.2	10.9

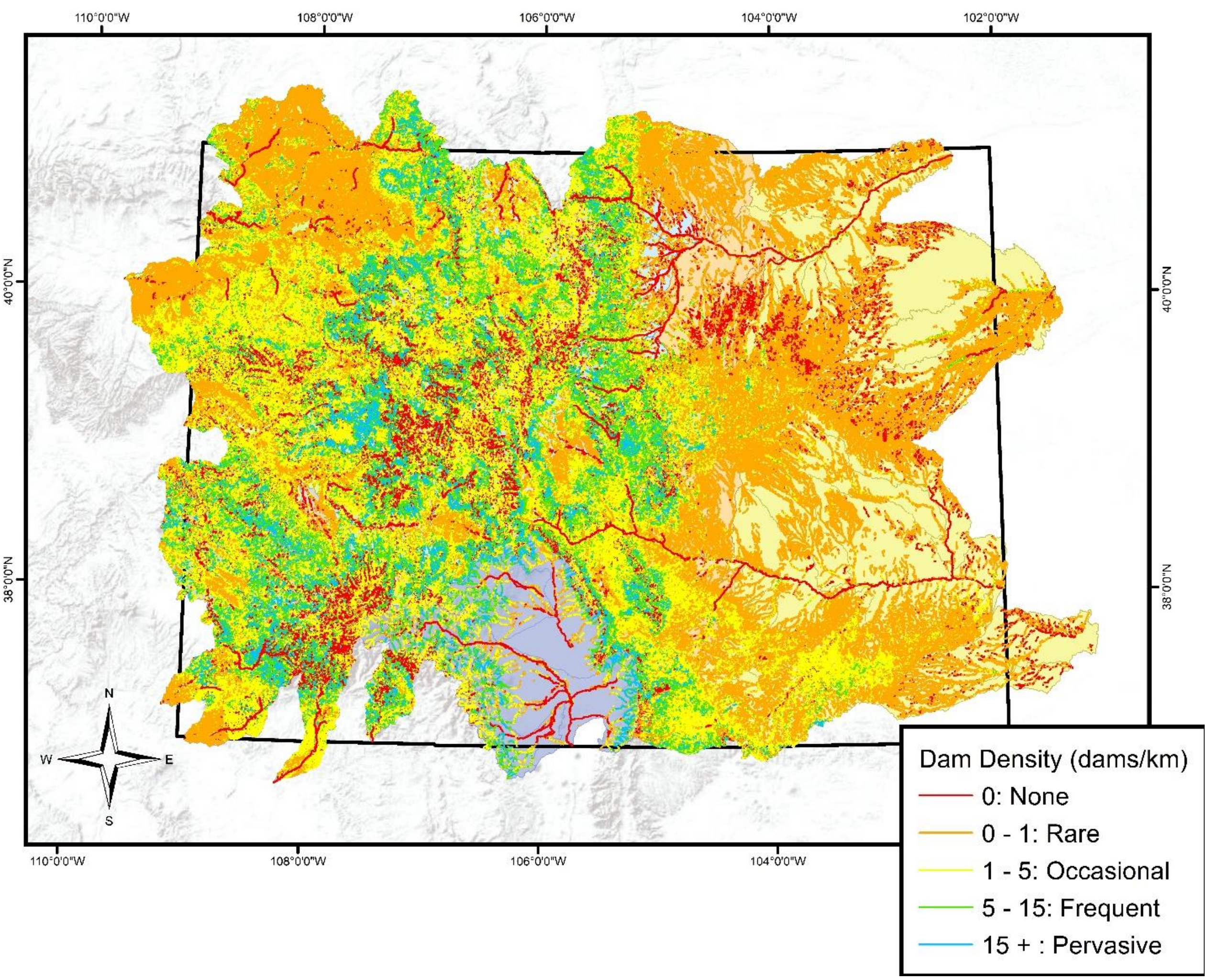

Figure 1.4. Current dam density for perennial and intermittent streams in Colorado based on the Beaver Restoration Assessment Tool (BRAT).

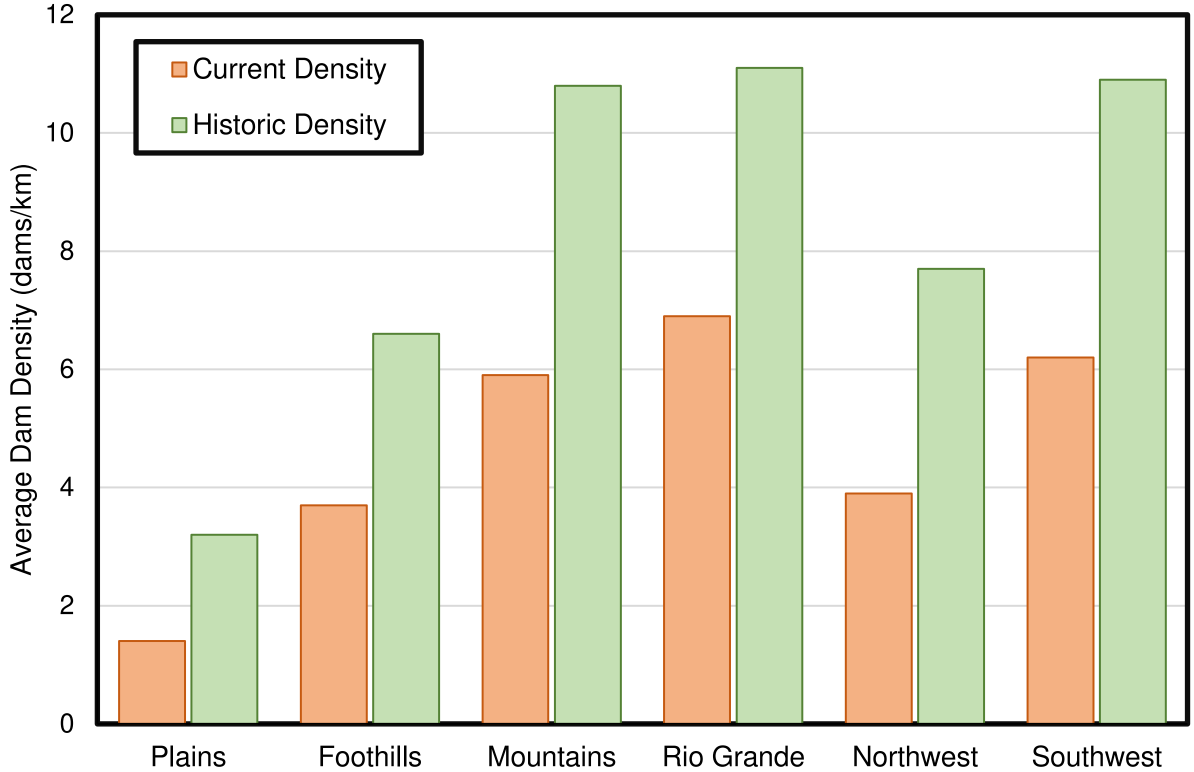

Figure 1.5. Average dam density for each hydrologic region from current and historic BRAT models. Average dam density is lower than historic densities for all regions.

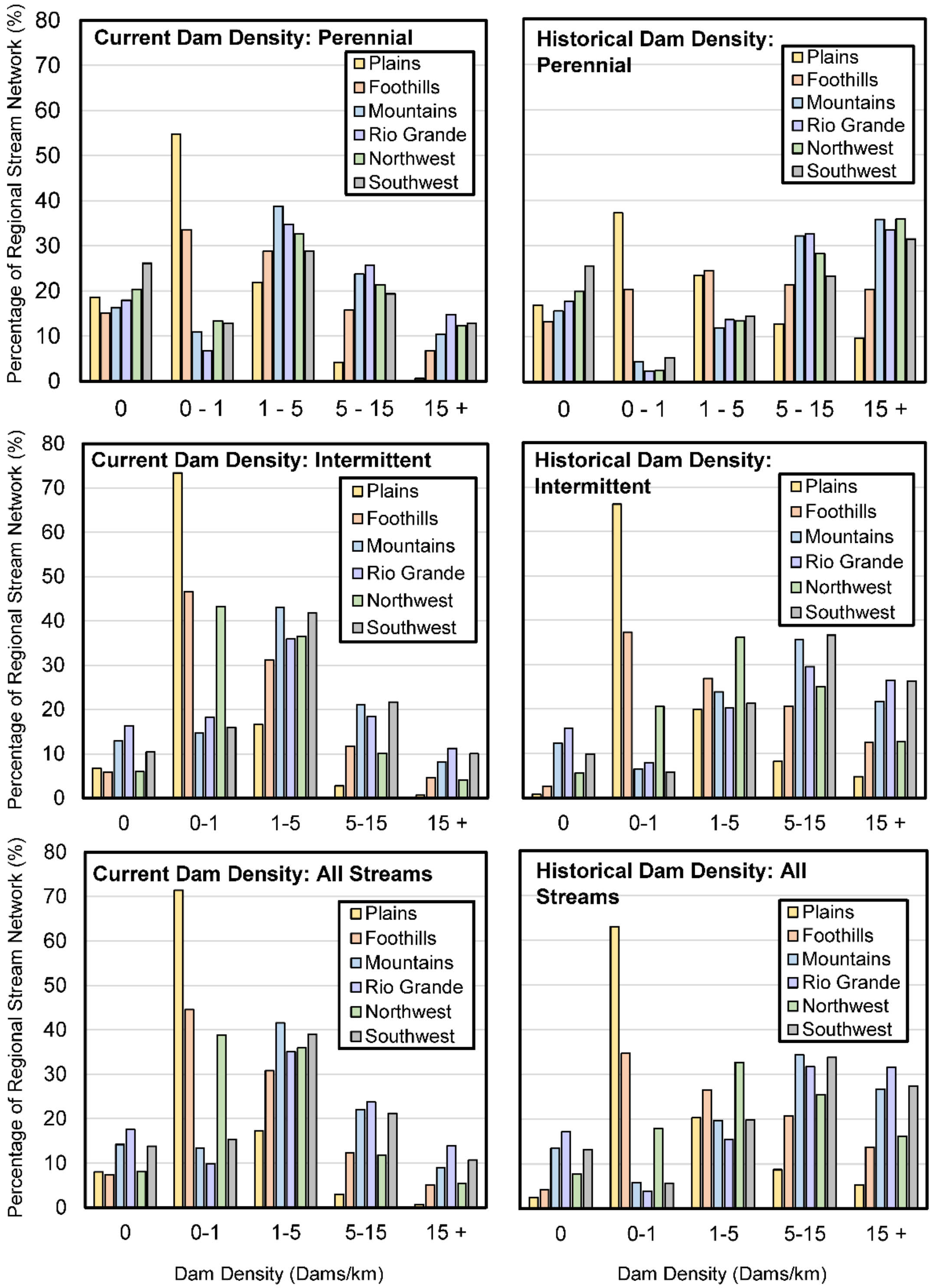

Figure 1.6. Length of stream (in km) occurring within each BRAT dam density category for each region presented as a percentage of the total stream network. Bar height represents the percent of the stream network for any given region that falls within the labeled category. Categories are as follow: None (0 dams/km), Rare (0 – 1 dam/km), Occasional (1 – 5 dams/km), Frequent (5 – 15 dams/km), and Pervasive (15 + dams/km).

4.2 Temporal changes to dam density

Current dam densities are typically lower than historic dam densities across the modeled watersheds. The average historic dam density for every region is approximately 50% to 100% higher than the current dam density (Table 1.3). However, changes from historic to current densities are not evenly distributed across the density categories. All regions experienced decreases in frequent and pervasive dam density reaches and an increase in rare dam density reaches from historic densities (Figure 1.7). Five of the 6 regions experienced an increase in occasional dam density reaches, except for the Plains, which experienced a decrease. The Plains region also experienced the greatest increase in no density reaches (Figure 1.7). Overall, the Plains experienced the greatest percent change from historic to current densities in the two most extreme categories: a negative percent change in pervasive dam reaches and a positive percent change in no dam reaches.

Despite the percent of stream networks in high dam density categories decreasing across all regions, not all streams experienced a decrease in dam density. Dam density increases from 0 to 5 dams per km occurred throughout the headwaters, the Northwest, and the Plains (Figure 1.8). In very few instances did dam density increase by more than 5 dams per km. In contrast, it was not uncommon for dam density to decrease by 15 dams or more per kilometer. To investigate extreme decreases in dam density across Colorado, areas that went from pervasive dam density (15 + dams/km) to rare dam density (0 to 1 dams/km) were identified (Figure 1.9). Extreme decreases occurred throughout Colorado, with clusters of streams undergoing extreme dam density decreases located in the South and North Platte headwaters, northwest of Grand Junction, and in a corridor between Denver and Colorado Springs in the Front Range.

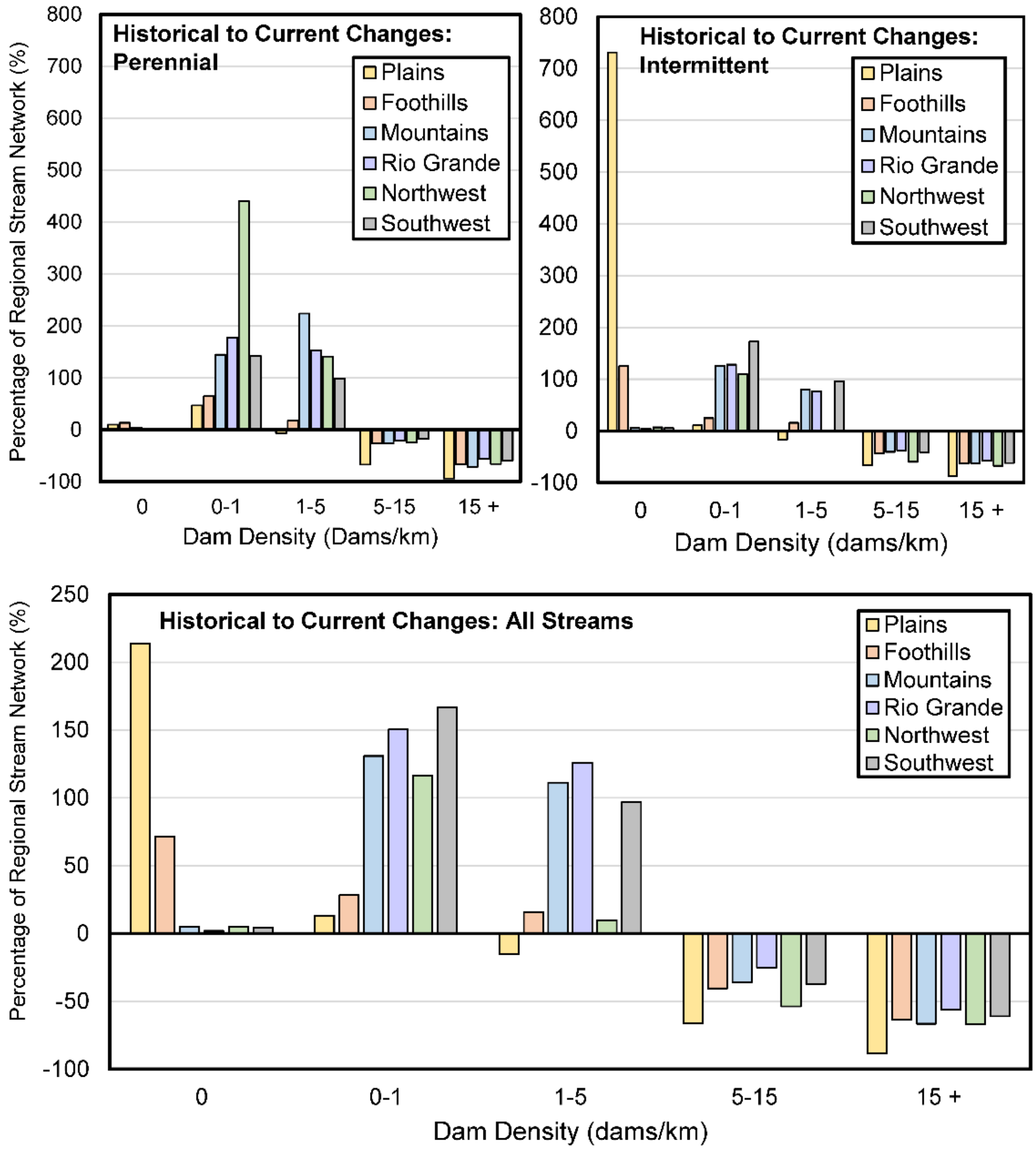

Figure 1.7. Percent change between the historic and current length of stream network (in km) falling within each category of BRAT dam density. A positive percent change indicates a temporal gain in stream length within a category whereas a negative percent change indicates a loss of stream length within the category since pre-European settlement. Note differences in vertical scale.

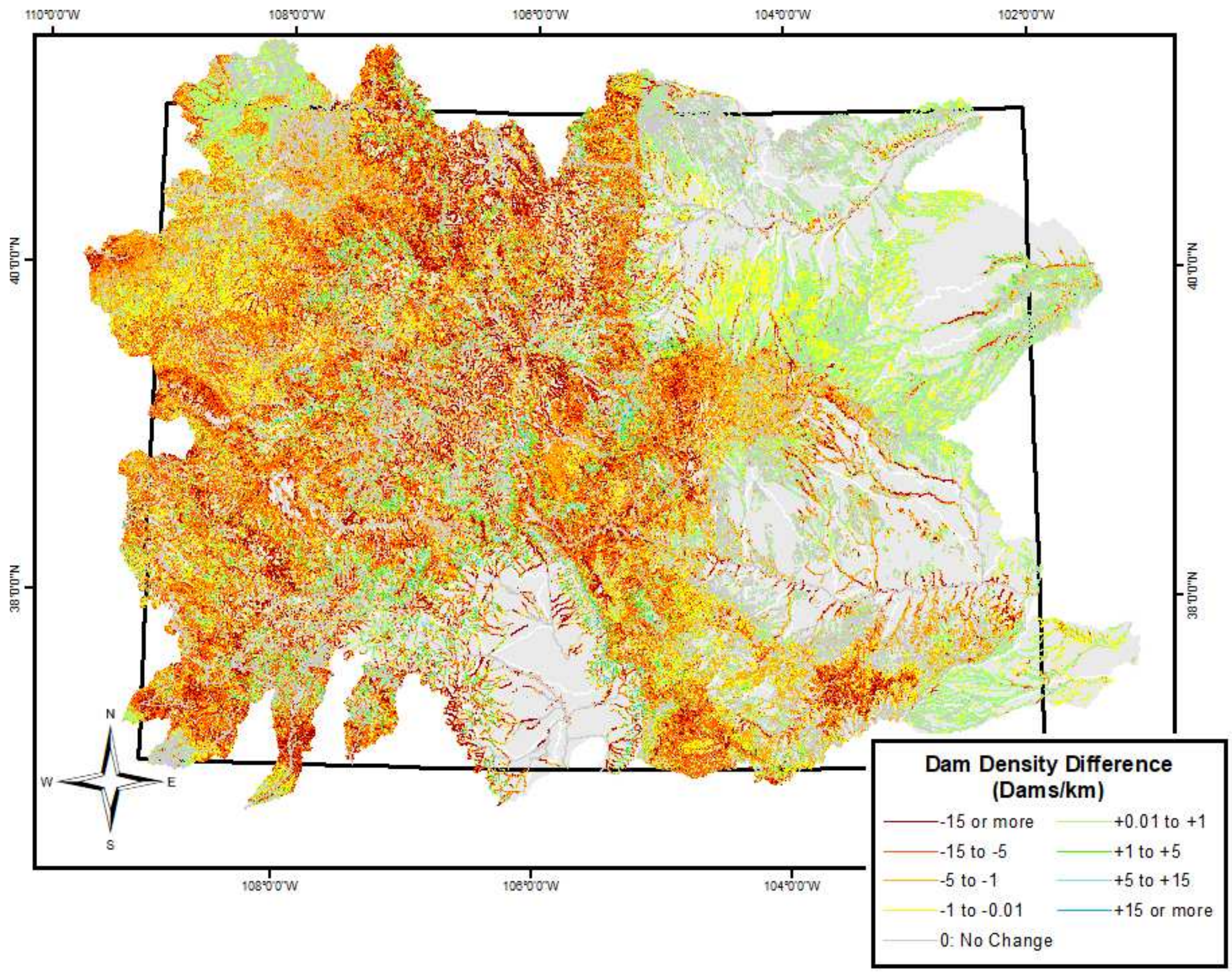

Figure 1.8. Magnitude of change in BRAT dam density from pre-European settlement to current time. Warm colors represent a loss of dam capacity whereas cool colors represent a gain in dam capacity. Gray represents no change.

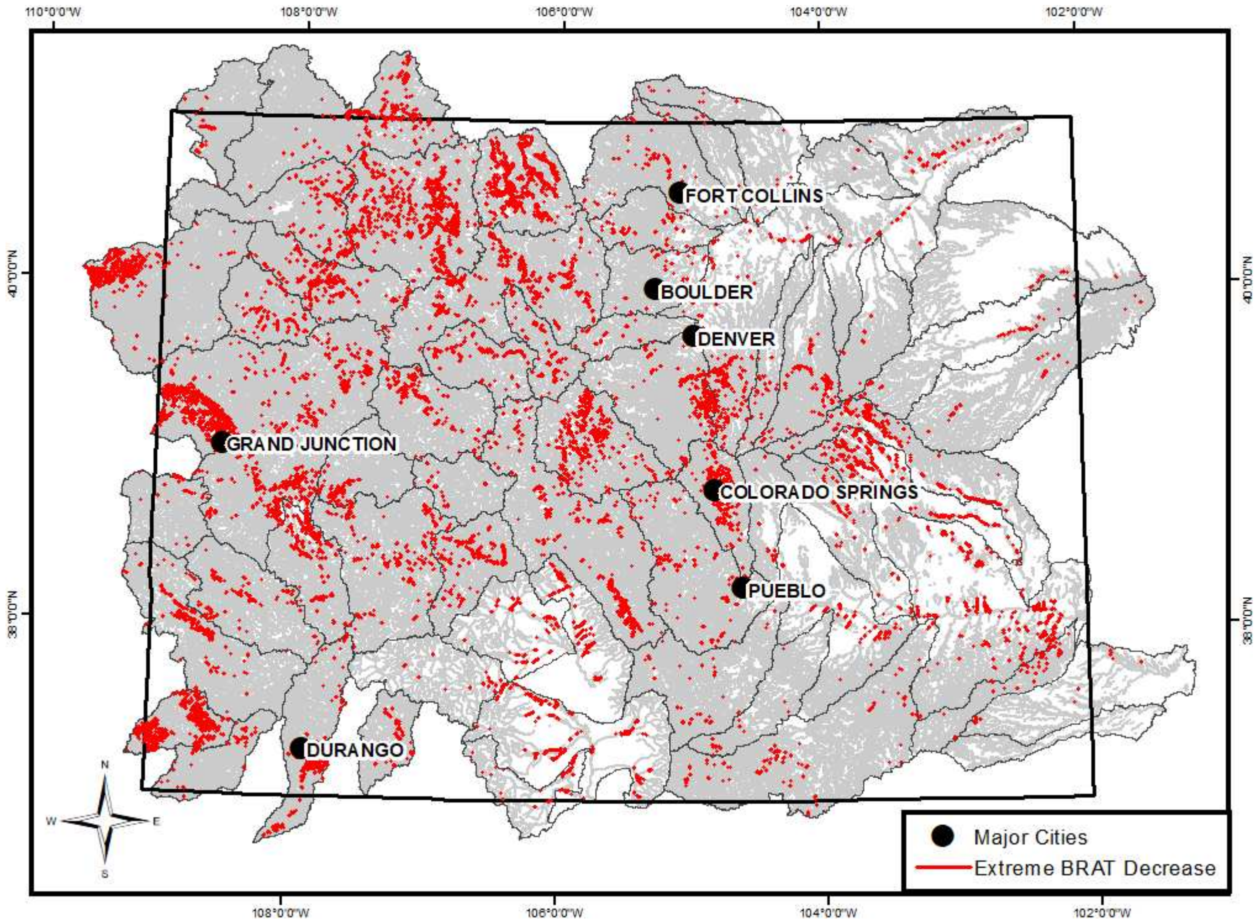

Figure 1.9. Location and density of streams that underwent extreme decreases in BRAT dam capacity from historic to current times. Extreme decreases indicate that historically, pervasive dams would have existed (15 or more dams/km) whereas currently, dam density is rare (0 to 1 dams/km).

4.3 Case Study Comparisons

A total of 792 dams along 62.6 km of stream and 45 checklists across 13.5 km of stream were used to compare field dam densities to BRAT models (Table 1.4; Appendix D). Field measured dam densities were compared to both current and historic dam densities calculated from BRAT (Figure 1.10). There was no correlation between field measured dam densities and BRAT output. The highest dam density assigned in BRAT was approximately 31 dams/km, but dam densities recorded in the field exceeded 40 dams/km at all three density case studies. Therefore, the limit to modeled dam densities could be a source of error on streams that have the capacity to hold more than 30 dams/km. Streams that have recorded dam densities lower than the modeled dam densities could represent streams that are not carrying their full beaver capacity. Despite these two recognized sources of error, there are still streams with high recorded dam densities from the field and low modeled dam densities.

Boulder County checklists also yielded no apparent correlation (Figure 1.11). Sites along Boulder and St. Vrain Creeks were ranked high in geomorphic suitability, but low for BRAT dam densities. Peak spring discharge is too high at these sites for beaver dams to persist, which was not readily apparent from field analysis based on mean visible grain size classification (e.g. sand, cobbles, boulders). Additionally, sites along Left Hand Canyon were ranked high by BRAT, but recent flooding has caused major changes to bed substrate and morphology.

Table 1.4. Number of dams or checklists and length of stream included in each case study.

Case Study	**Number of Dams**	**Length of Stream (km)**
Streams in Rocky Mountain National Park	339	26.7
Arikaree River	192	8.8
Streams in the Arkansas River headwaters	261	27.1
Case Study	**Number of Checklists**	**Length of Stream [km]**
Boulder County	45	13.5

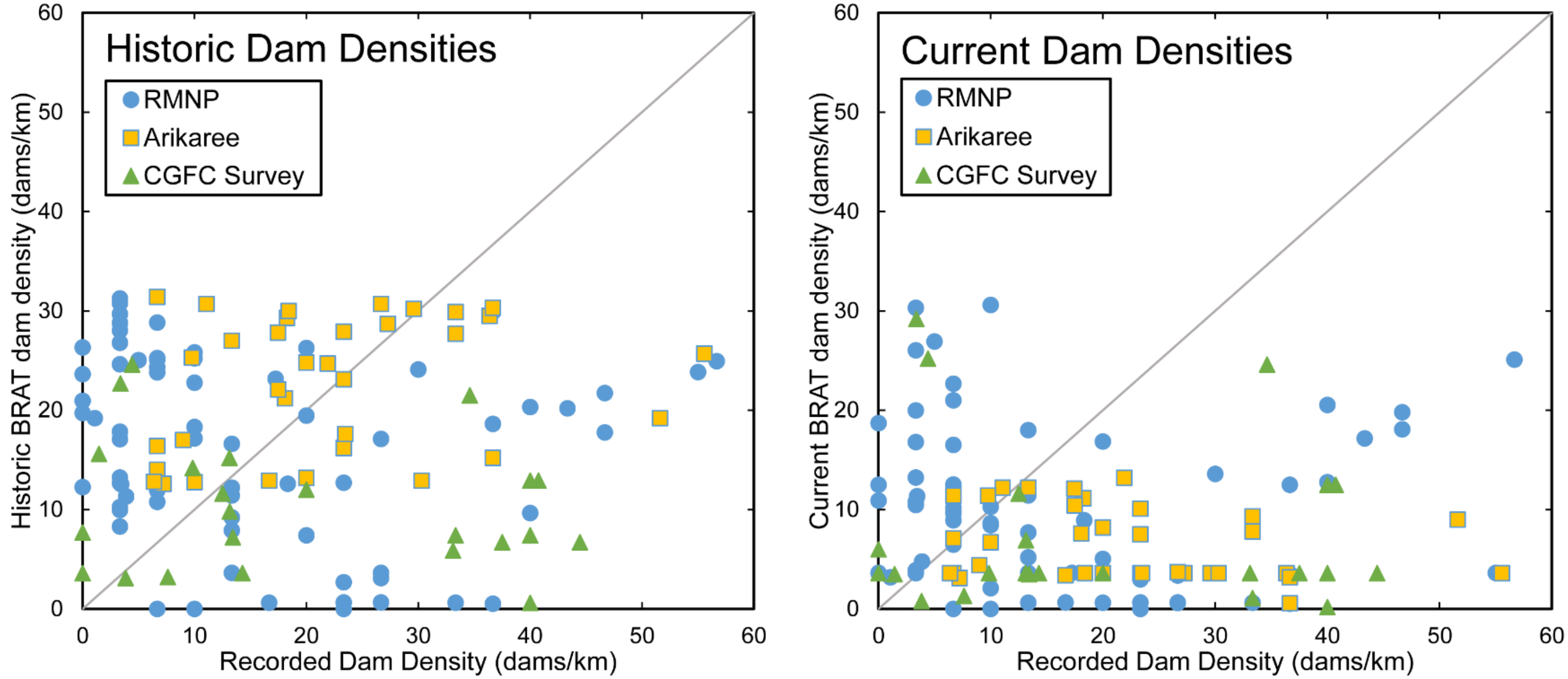

Figure 1.10. Comparison of recorded dam densities from Rocky Mountain National Park (RMNP), the Arikaree River, and headwater streams to the Arkansas River (Colorado Game and Fish Commission Survey) to historic and current BRAT dam densities. Points falling on the 1:1 line would represent a perfect model fit with dam surveys.

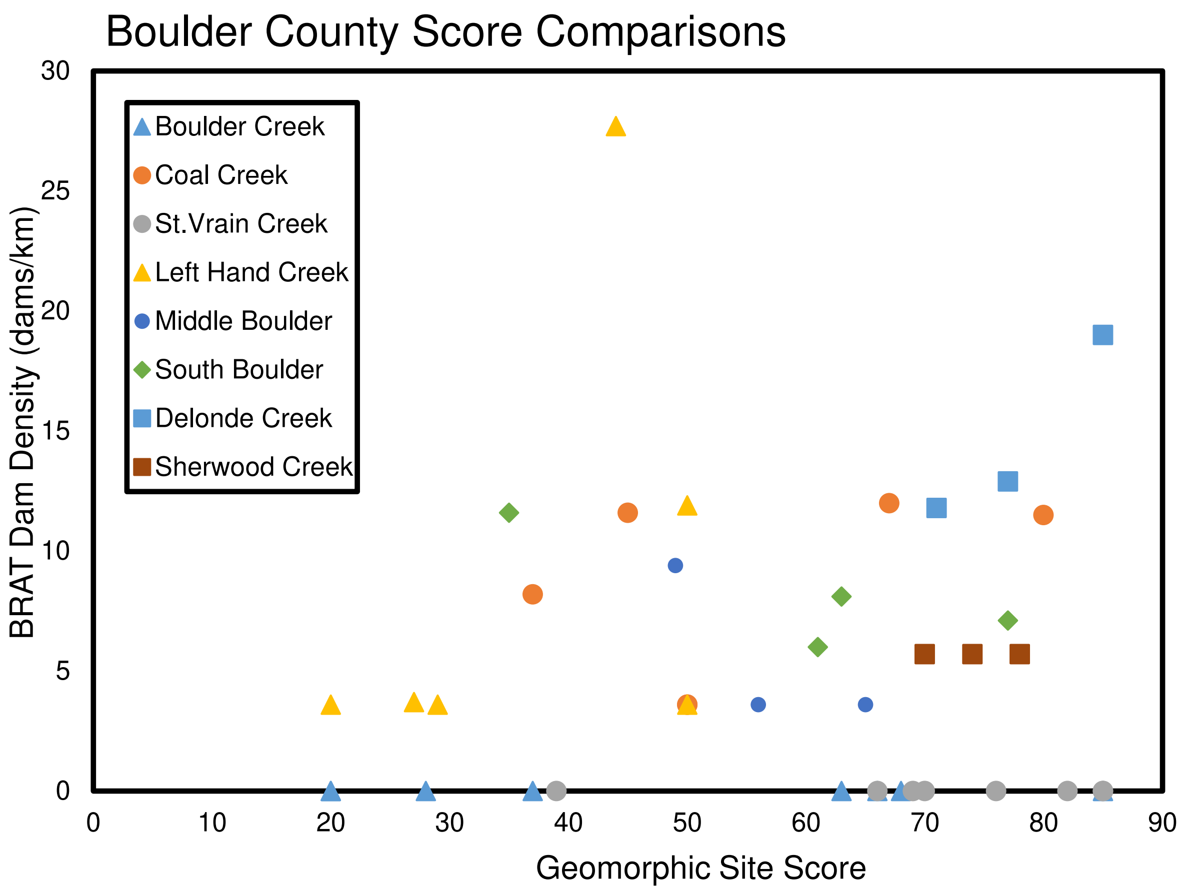

Figure 1.11. Scores assigned from site suitability checklist compared to BRAT on Boulder County streams. Streams with high geomorphic scores and low predicted BRAT dam densities are sites where typical yearly discharge is too large for beavers to establish.

5. Discussion

5.1 Spatial differences in BRAT

Mapping the BRAT network across Colorado reveals clear differences in the current distribution and magnitude of dam densities across the State (Figure 1.4). High densities prevail throughout the center of the state and dwindle towards the eastern and western borders. Overall, the Mountains, Southwest, and Rio Grande regions hold more dams than the Northwest, Foothills, and Plains. The two groups exhibit similar average densities and similar distribution of dam densities across their stream networks. Similarities in dam densities and distribution between the Foothills and Plains are intuitive because both are located in the Great Plains physiographic region. However, similarity between the Northwest region and the Foothills and Plains is not expected. Examining the model inputs could provide insight as to why the Northwest differs from surrounding regions and holds similarities with the Foothills and Plains, and overall, why the Mountains, Rio Grande, and Southwest hold the highest densities of dams.

Assigning explanation to spatial differences in mapped dam density are limited to the model inputs – topography, vegetation, hydrology, land use – and known effects those inputs have on beaver habitat. Model inputs, however, cannot be easily separated from one another. For example, precipitation changes with elevation in Colorado (Doesken et al., 2003). Differences in precipitation affect streamflow, soil moisture, and humidity, which all in turn affect vegetation across Colorado (e.g. Peet, 1978). Therefore, the influence of elevation cannot easily be untangled from the influences of hydrology and vegetation on the BRAT output. High dam densities at high elevations in Colorado are therefore due to interactions of topography, hydrology, and vegetation. High elevation streams in the Rocky Mountains are typically headwater streams with low drainage areas. Small drainages have low discharges which produce narrower streams that are ideal for building dams. Interactions between drainage area and discharge are not unique to the mountains, however. Headwater streams are also abundant across the Plains and Northwest, where dam densities are distinguishably lower. Despite the topographic and hydrologic qualities necessary to house beaver, low elevation headwater watersheds typically lack proper woody vegetation needed to support a beaver colony. Vegetation differences drive differences in dam density, but once again, vegetation differences occur due to disparities in precipitation across elevation in Colorado.

Exploring the relationship between elevation, hydrology, and vegetation may explain why the Mountains, Southwest, and Rio Grande regions hold higher dam densities than the Northwest, Foothills, and Plains. Overall, regions with higher densities have higher elevations (Figure 1.12). Maximum elevations in the Mountains, Southwest, and Rio Grande regions all peak above 4,270 m (14,000 ft). Suitable and preferred material for beaver throughout the Mountains, Southwest, and Rio Grande regions are abundant in the subalpine zone from 2,740 to 3,350 m (9,000 to 11,000 ft) (Figure 1.12). While maximum elevations approach approximately 3,660 m (12,000 ft) in the Northwest and 2,740 m (9,000 ft) in the Foothills region, the majority of watersheds in the Northwest and all watersheds in the Foothills and Plains regions fall below the subalpine zone. Elevation and subsequent suitable material in the subalpine zone may explain why the Mountains, Southwest, and Rio Grande all have similarly high dam densities. However, the suitability map of current vegetation does not suggest abundant similarities between the Northwest and the Foothills and Plains (Figure 1.13). High elevations and headwaters in the Northwest region display suitable and preferred material while the Foothills and Plains are dominated by unsuitable to moderately suitable material. Some frequency of suitable material is present in the southern Foothills in the upper Arkansas and Purgatoire watersheds, which may explain why the Foothills region has more similarities in magnitude and distribution of dam densities with the Northwest than the Plains. However, vegetation alone does not satisfactorily explain low dam densities in lower regions.

If elevation and vegetation alone do not explain regional differences in magnitude and distribution of dam density, perhaps land use does. Today, there are approximately 18.2 million hectares (45 million acres) of farmed and ranched land in Colorado (National Agricultural

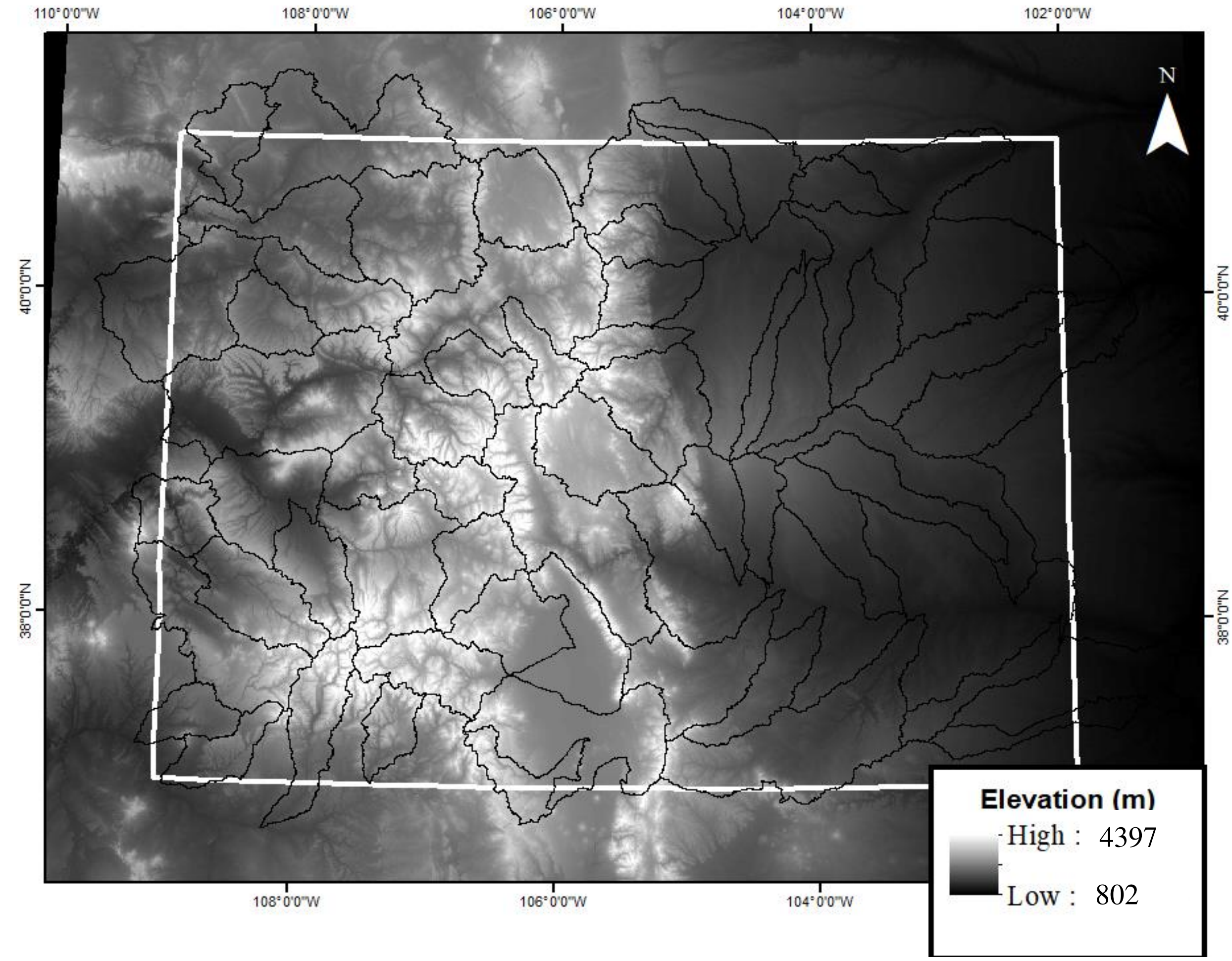

Figure 1.12. Elevation across the State of Colorado. The highest elevations are in the center of the State, and elevation decreases towards to the eastern and western borders.

Statistics Service, 2018). Cultivated farming across the state – particularly on the Plains and the Grand Valley of the Northwest – limits beaver habitat because cultivated crops are not suitable material for beaver foraging or dam building. However, cultivation of the San Luis Valley in the Rio Grande region proves that agriculture alone does not limit BRAT-predicted dam densities for an entire region. The Rio Grande region currently has the highest average dam densities of all regions (Table 1.3). Additionally, statewide population increases could be limiting dam densities by converting viable habitat to developed, urbanized land. Population has most drastically expanded in the Colorado Front Range – a corridor including cities in the Foothills from Colorado Springs to Fort Collins. However, the lowest dam densities do not occur in the

Foothills, which suggests that urbanization alone is also not a major suppressor of dam densities predicted by BRAT. The true cause of BRAT predictions of low beaver dam densities across the State cannot be determined from this study alone. Further analysis of climate, proximity to source, and relief could elucidate causation behind regional differences in BRAT.

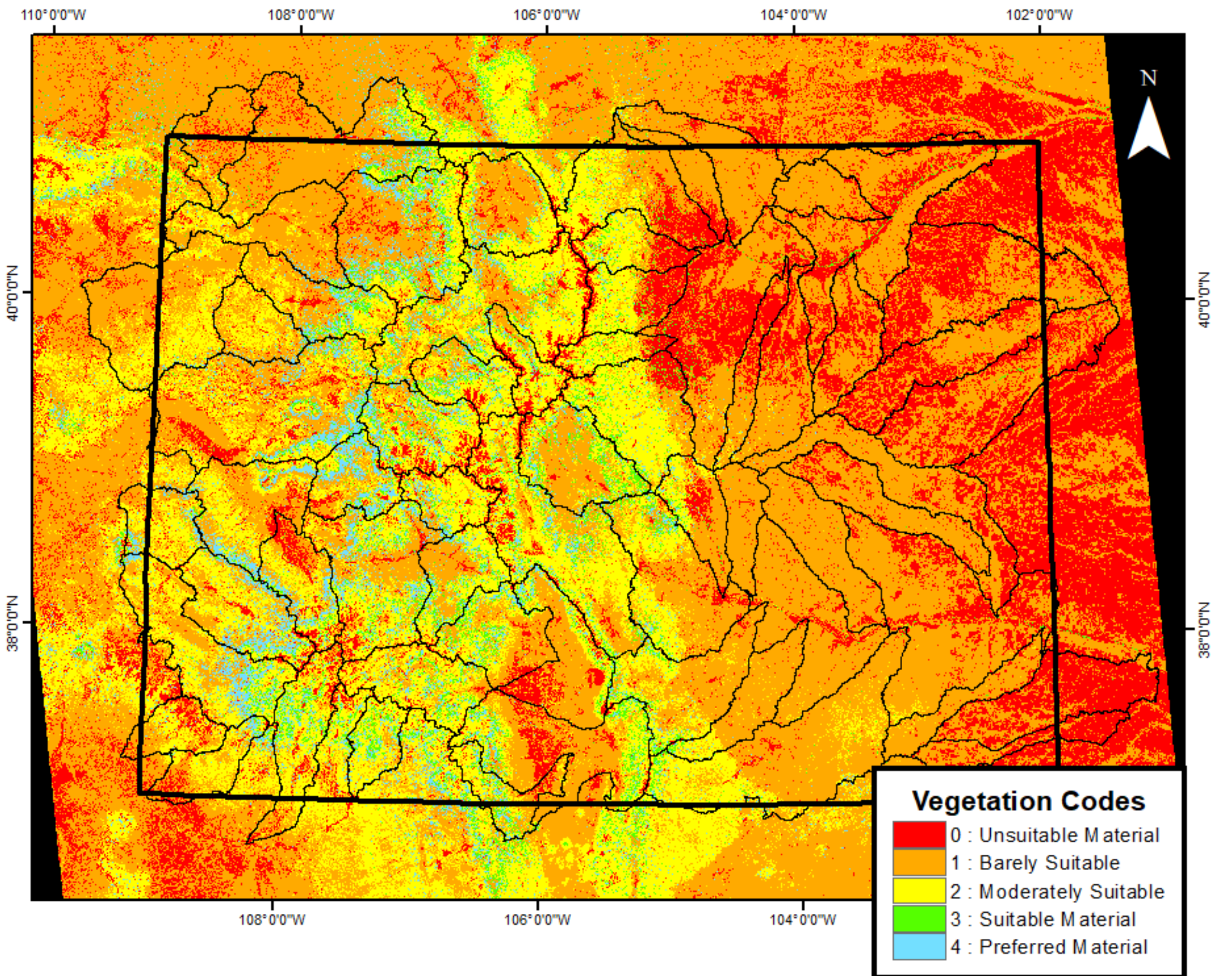

Figure 1.13. Current vegetation in Colorado coded by suitability for beaver foraging and dam building material. Unsuitable material represents developed, cultivated, or barren areas while preferred material would include aspen, cottonwoods, and willows.

5.2 Temporal differences in BRAT

All regions of Colorado have experienced decreases in beaver habitat suitability from historic to current times which are reflected in decreased dam densities. Considering that all variables are kept constant except vegetation across the temporal comparison of BRAT, changes in vegetation is the sole cause of changes in dam density. Changes that would not be represented by vegetation could have a significant influence on current dam densities compared to historical. Flow regulation resulting in a different discharge regime could influence dam building potential. While modeled dams were limited to channels with drainage areas less than 400 km^2 in 5 out of 6 regions, flow diversions can occur upstream in small, mountainous watersheds. Channel restoration design and projects meant to stabilize banks could limit beaver ability to access the stream or create ponds. Human-caused changes such as these could decrease dam densities across Colorado, but are not accounted for in BRAT. Despite not modeling conflicts related to river regulation and stabilization projects, BRAT is still a useful tool for mapping landscape changes recorded by vegetation changes.

Previous work and current environmental concerns point to three main causes of vegetation change in Colorado: vegetation encroachment and natural regime change, agriculture, and urbanization. Meadows and beaver habitat are threatened by a changing fire and land use regime which is causing conifers to replace aspen forests (Bartos, 2001) and forests to encroach into mountain meadows (Dunwiddie, 1977; Rochefort et al., 1994; Anderson and Baker, 2006). Comparing historic LANDFIRE vegetation (Figure 1.13) to current LANDFIRE vegetation (Figure 1.14) displays landscape scale changes in subalpine forest and meadow compositions (Figure 1.15). Abundant suitable material has converted to moderately suitable material throughout the Mountains, Southwest, and Rio Grande Regions, reflecting changes from mixed aspen-conifer forests to conifer forests. Vegetation has also changed on the Plains, in the Rio Grande Valley, and in the Grand Valley outside of Grand Junction due to agriculture (Steinel, 1926; MacDonnell, 1999). Cultivated crops and ranching replaced grasslands and riparian forests, which reduces vegetation suitability. Finally, urban development on floodplains, especially in the Front Range corridor around Denver, has resulted in the removal of vegetation preferred by beaver.

Reduction in suitable vegetation degrades highly suitable habitat, which explains decreases in high dam density stream reaches across all regions (Figure 1.6). However, 4 out of 6 regions saw only small (<10%) increases in stream reaches that no longer support beaver dams. Instead, all regions experienced an increase in stream reaches with rare (0 – 1 dams/km) and occasional (1 – 5 dams/km) dam densities. Percent decreases in stream reaches with high dam densities and increases in reaches with low dam densities suggest that suitable vegetation loss and human activities post-European settlement have not obliterated beaver habitat, but rather reduced capacity. Most streams that housed beaver historically can still house beaver today, but at lower densities.

The Plains and Foothills regions are an exception to the redistribution theory. Drastic increases in the proportion of the network that cannot support beaver were driven by changes occurring on intermittent streams. Loss of all dam density potential mainly occurred on intermittent streams in the South Platte watershed, where widespread agricultural production is highlighted by zones of unsuitable vegetation (Figures 1.4 and 1.13). Dam densities were historically low on intermittent streams in the South Platte watershed, and shifts to no dam capacity are indicative of small magnitudes of dam density loss on the order of a dam or less per kilometer (Figure 1.8).

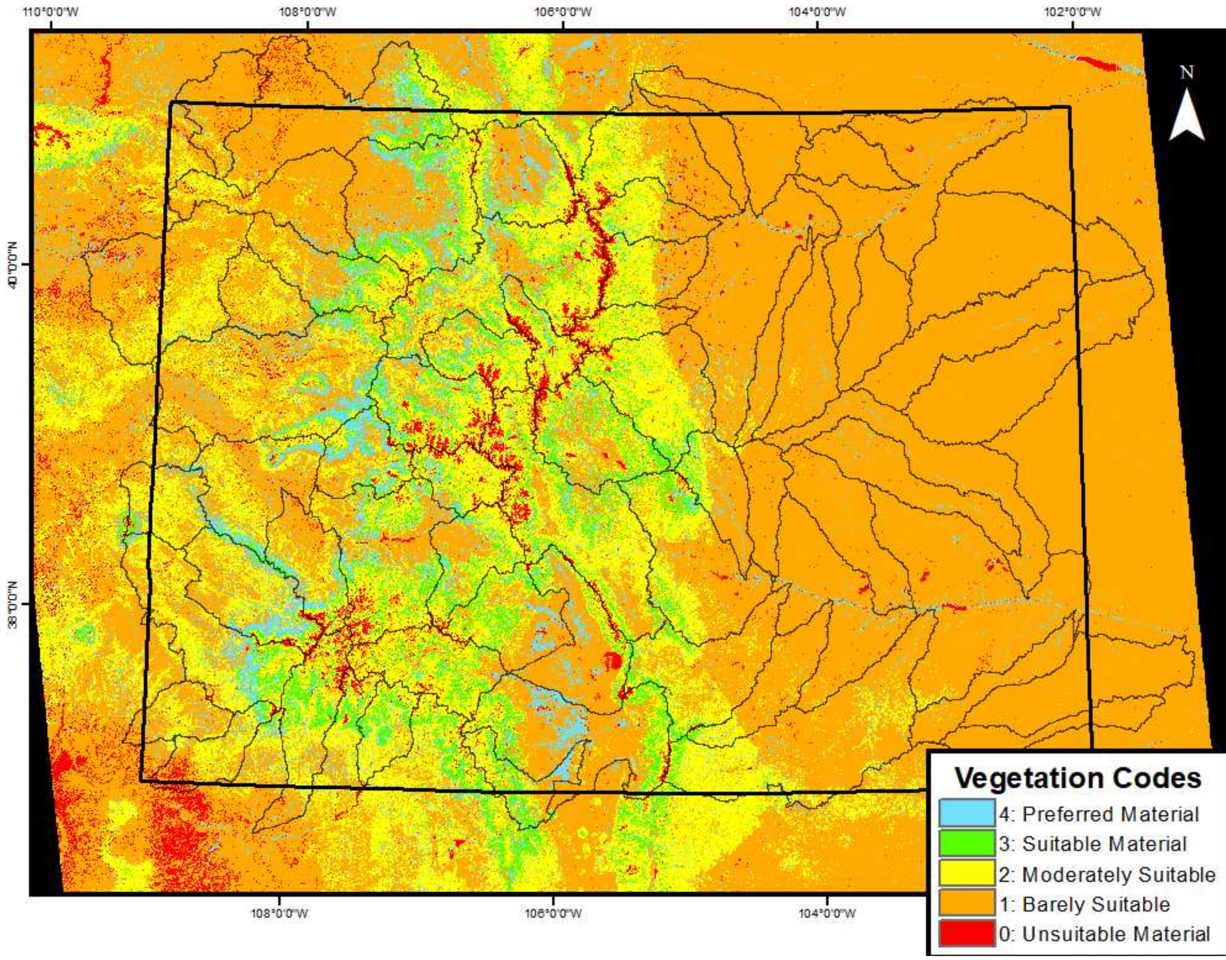

Figure 1.14. Historic vegetation across Colorado coded by beaver suitability for foraging and dam building material. Historic vegetation is estimated from LANDFIRE biophysical setting layers.

Small changes in the magnitude of dam density may appear insignificant initially. However, the structure of the BRAT dam density function creates disproportionately larger decreases in dam density at historically high capacity reaches compared to historically low capacity reaches for the same magnitude of habitat change. The six categories of dam density suggested by BRAT – none, rare, occasional, frequent, and pervasive – are not evenly weighted. Increasingly higher categories of dam density cover an increasingly larger range of dams per kilometer. Increasing stream suitability from one category to another results in a non-linear increase in dam density. Conversely, the same magnitude of habitat suitability loss at a historically high density reach would result in a much higher magnitude of density decrease compared to a historically low density reach (Figure 1.16). The non-linear relationship between habitat change and dam density change highlights the issue that significant habitat suitability loss could be occurring on arid, intermittent streams despite small magnitudes of dam density decrease. Additionally, non-linearity suggests that reach decreases in the highest dam density category – pervasive dams – are likely fueling increases in the lowest dam density – rare dams. Figure 1.8 highlights Colorado stream reaches that decreased from historically pervasive to currently rare dam densities.

Intermittent streams may appear to be more resilient to change due to non-linearity of dam density loss. However, small magnitudes of dam density loss could push intermittent or low capacity reaches past a threshold from limited beaver capacity to no beaver capacity. While streams with some remaining capacity could use beaver reintroduction as a tool to further improve beaver habitat, reintroduction is not an option on streams that can no longer support any beaver. Changes modeled in BRAT show that low capacity streams can lose capacity completely, and high capacity streams can be greatly diminished. In the future, streams that currently have low dam densities could be at a greater risk of being pushed past the threshold of beaver capacity. Additionally, streams are predicted to increase in intermittency as climate changes increase precipitation variability across the West in the future (Reynolds et al., 2014). Since intermittent streams currently account for up to 89% of stream networks in some regions of Colorado, complete loss of even low densities streams could have a significant impact on damming potential and subsequent geomorphic change across the State.

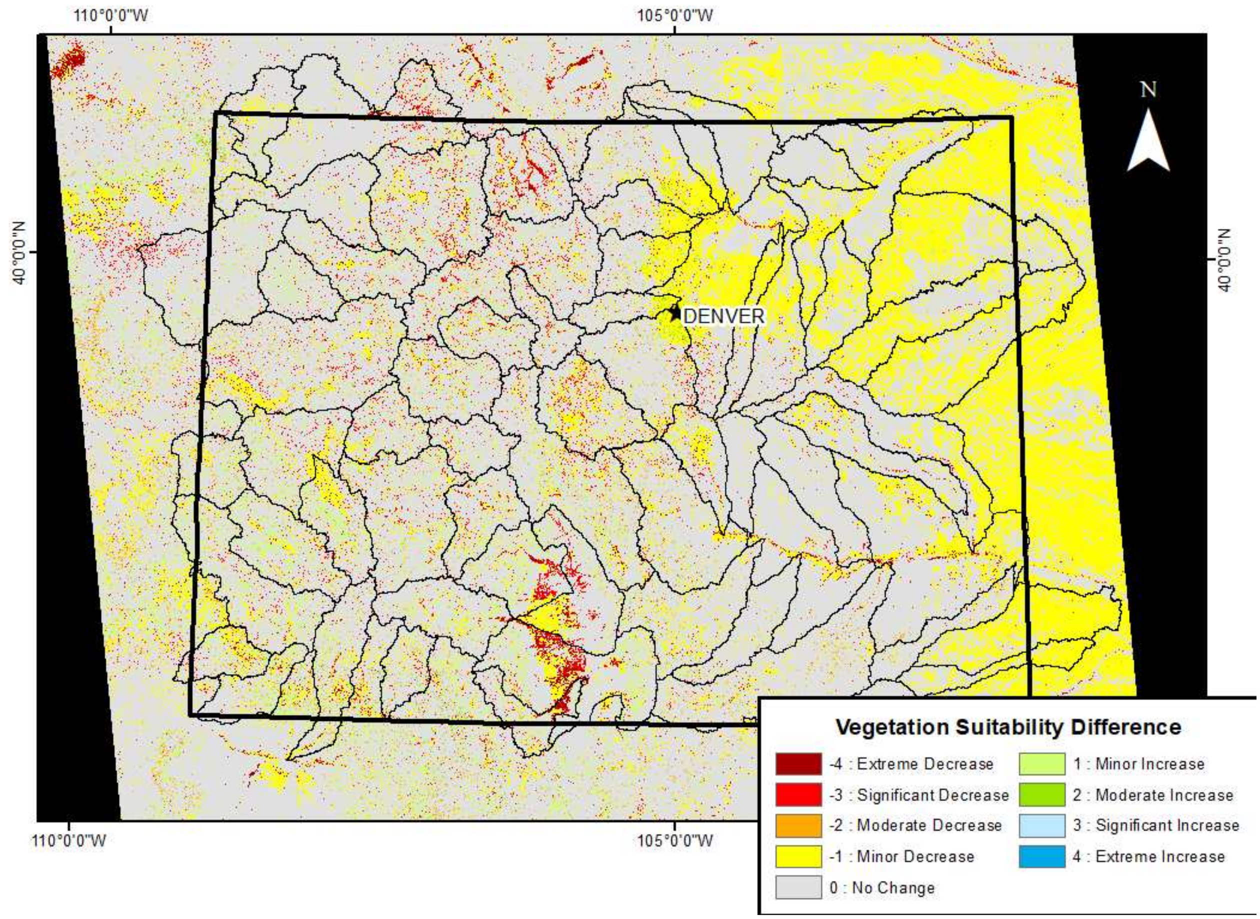

Figure 1.15. Changes in vegetation suitability from historical to current estimates. Warm colors indicate places where vegetation suitability has decreased from historical suitability, while cool colors indicate places where vegetation has improved. Across the state of Colorado, suitability decreases are more prevalent than the limited suitability increases. Suitability decreases could be due to agriculture, urbanization, or natural succession.

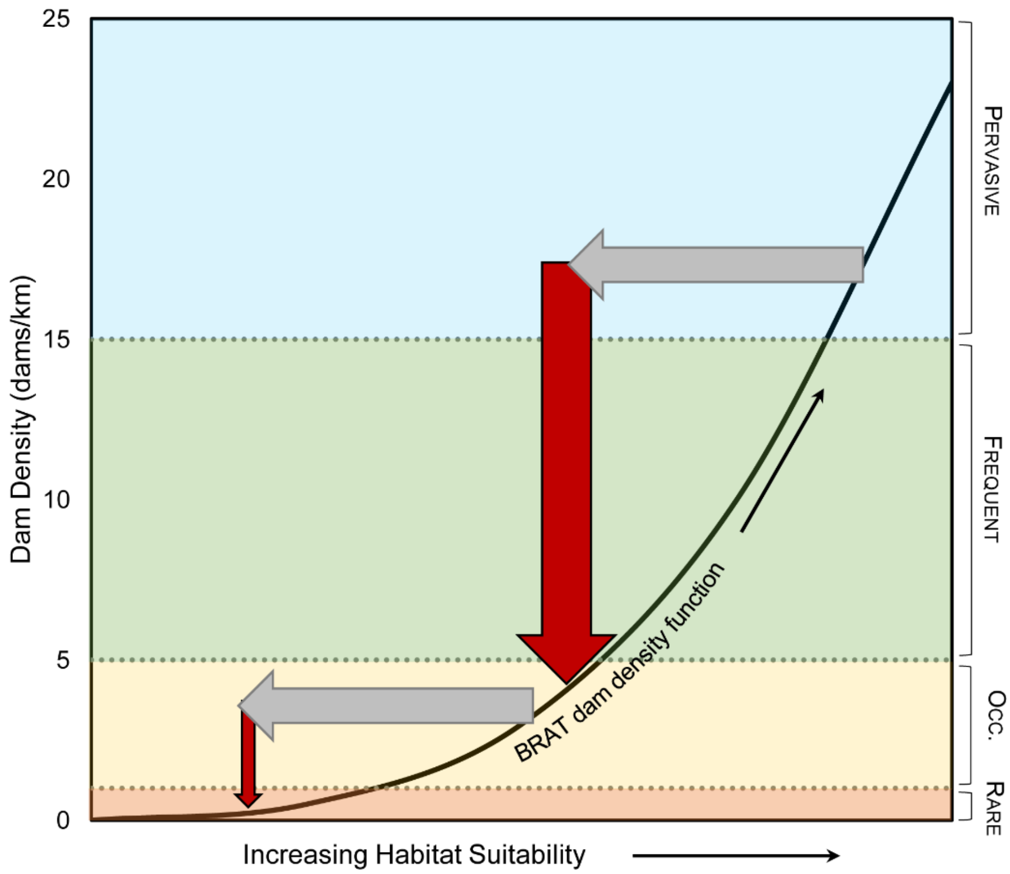

Figure 1.16. Conceptual model of predicted changes in dam density due to habitat suitability change. The BRAT dam density function is not linear, and higher categories of dam density (right axis) include an increasingly higher range of dams per kilometer (left axis). Therefore, a similar habitat suitability decrease (gray arrow) on a pervasive stream would result in a much larger magnitude of dam density loss (red arrow) than on a reach with a lower initial dam density.

5.3 Case Studies

Lack of correlation between field recorded dam densities, geomorphic site scores and BRAT could suggest that BRAT should not be used to predict precise dam densities at the reach scale. The disparity between actual dam density and BRAT could also highlight the difficulty in using field data to assess a capacity model. Assuming all dams were occupied at the same time during berm surveys overestimates the capacity of a stream and counting only active dams could underestimate densities on reaches not at capacity. Additionally, site suitability analysis might not capture hydrologic thresholds that are difficult to determine in the field while BRAT will over-predict suitability at reaches where hazards and conflicts limit beaver viability.

The point of a model such as BRAT is to determine where dam densities will be highest and lowest. Beaver dams were recorded on only a few streams where BRAT predicted no dam building activity. Seven dams on Beaver Brook, 3 dams on Cow Creek, and 2 dams on Sandbeach Creek in Rocky Mountain National Park existed where BRAT predicted the channel to be too steep to support beaver activity. Dams were recorded on channels with up to 25% slopes. On the other end of the spectrum, using case studies to evaluate BRAT on reaches with predicted high densities assumes that case study streams were at beaver capacity. Presuming beaver are at capacity is not a valid assumption on most Colorado streams.

Removing all reaches from the analysis where BRAT predicts higher densities than are currently mapped (Figure 1.10) begins to reveal a pattern in the Rocky Mountain National Park data. Without under-capacity streams, a positive relationship between recorded and modeled dam density emerges (Figure 1.17). The relationship is weak, which suggests that other factors beyond those modeled in BRAT have an influence on dam density. A relationship does not emerge if under-capacity streams are removed from the Arikaree or CGFW 1940 survey. All three case studies are located in separate hydrologic regions: RMNP is in the Mountains, the Arikaree is in the Plains, and the CGFW survey is in the Foothills regions. Patterns only emerge at Rocky Mountain National Park, suggesting that BRAT may perform better in mountainous headwaters than in lower relief regions.

While BRAT may not predict dam density well, field assessments for site suitability can also fall short. Estimating average high flow (Q_2) and whether a dam would be able to remain structurally intact is difficult to assess in the field. Two sites – Boulder and St. Vrain Creeks –

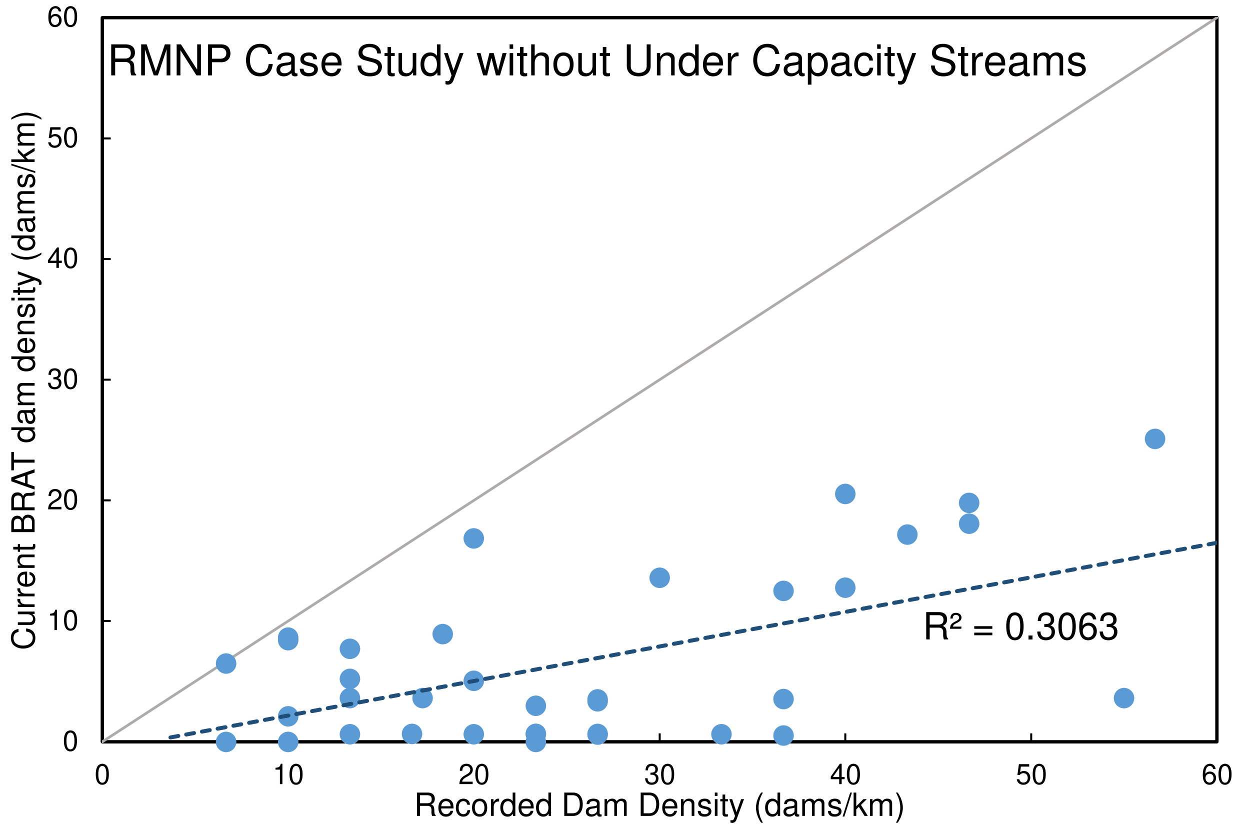

Figure 1.17. Relationship between recorded and modeled dam density for Rocky Mountain National Park case study reaches, excluding reaches where dams were below capacity (i.e. modeled dam densities were higher than recorded densities). A weak, positive relationship emerges between recorded and modeled dam densities, suggesting that BRAT densities could be indicative of suitability in mountainous headwater streams.

were predicted to have high suitability when discharge suggests otherwise. Additionally, parts of Left Hand Canyon were predicted to have low suitability because flood debris suggested much higher flows on the channel. Flood debris is likely from the 2013 Front Range Flood, which was not a regular high flow event. However, evidence such as recent flood debris could skew field assessments. Removing hydrologic outliers such as these reveals a weak pattern of increasing dam densities with increasing suitability (Figure 1.18). BRAT, as it is currently analyzed for Colorado, does not assess conflict for elk and moose herbivory or conflict due to human hazards such as roads and culverts. Further variation in field assessments compared to BRAT densities could be explained by conflicts not included in BRAT.

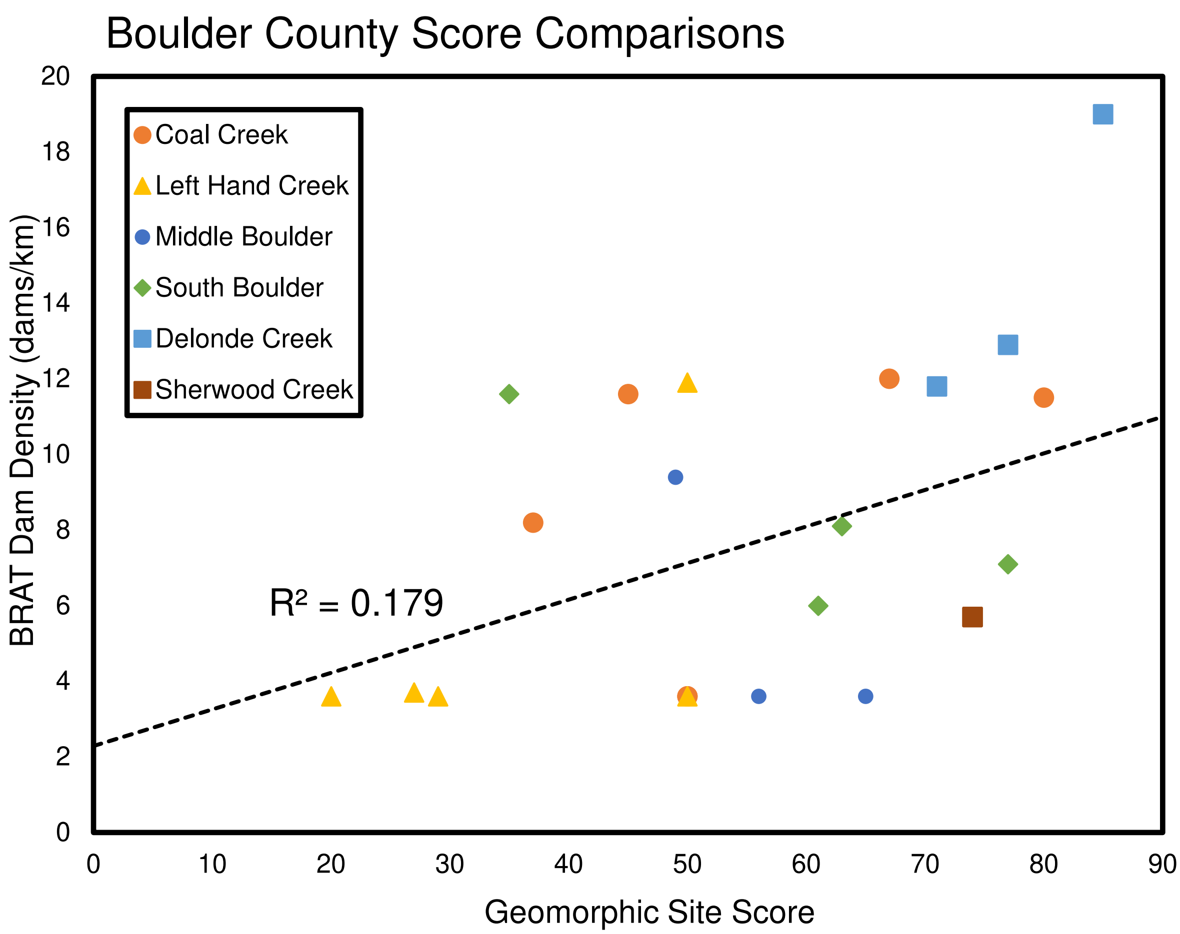

Figure 1.18. Relationship between geomorphic site scores and BRAT dam densities when hydrologic outliers are removed at Boulder County case study reaches. A weak, positive correlation suggests that BRAT may be consistent with visual site analyses.

Comparing BRAT to case study data can elucidate model shortcomings, particularly related to the inputs. The availability of national datasets such as NHD, LANDFIRE, or regional regressions make them alluring for broad scale spatial modeling. However, methods used to map and record the data comprising these datasets can result in error (Huang and Frimpong, 2016; LANDFIRE, 2011a), which perpetuate into the BRAT output. The upper Cache la Poudre River downstream of Poudre Lake in Rocky Mountain National Park serves as a prime example of spatial error resulting in incorrect density predictions. The river corridor downstream of Poudre

Lake is wide and filled with willow and evidence of historic beaver meadows. While no current beaver activity has been recorded, the river corridor is still prime beaver habitat. A comparison between mapped, historic berms and current BRAT output revealed large discrepancies between the model and the evidence of past beaver activity. Further investigation revealed that the majority of the river corridor proximal to the channel was coded as barren snow and ice in the LANDFIRE Existing Vegetation Layer (Figure 1.19). Surrounding peaks and hillsides are often covered by snow and ice, but the valley bottom is filled with preferred beaver foraging material. Discrepancies in spatial datasets cause suitable beaver habitat to appear unsuitable and vice versa in an inverse situation. Vegetation datasets that are mapped at a smaller scale are available for some wetland areas in Colorado, which could provide additional accuracy to BRAT. However, more accurate vegetation layers such as these do not cover the entire extent of Colorado, and small scale layers would likely need to be pieced together with larger datasets to provide a continuous layer. Instead, examples such as the Cache la Poudre River should emphasize the need to assess model reaches in the field before making restoration or reintroduction decisions.

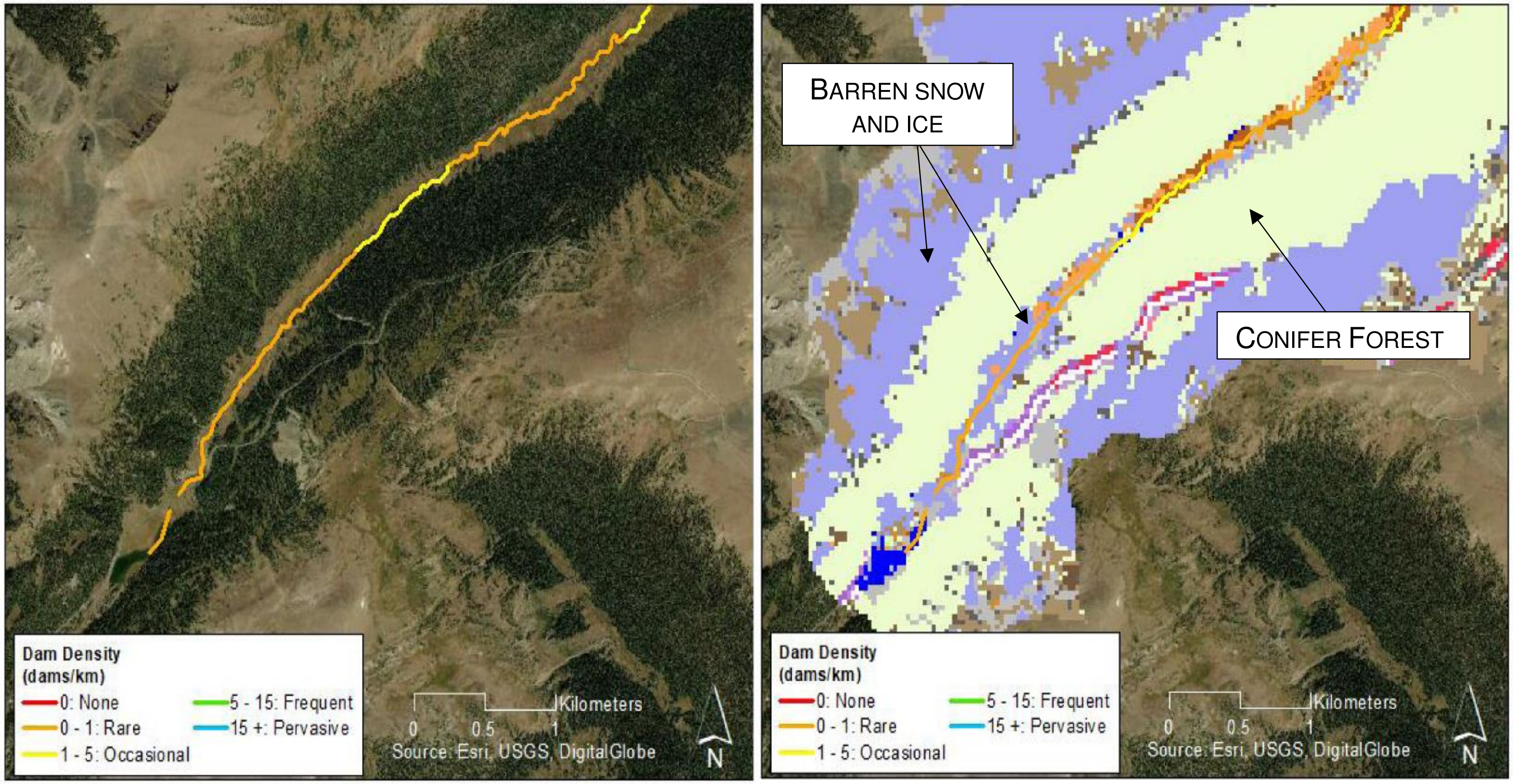

Figure 1.19. Incorrect coding in the LANDFIRE Existing Vegetation Layer resulted in inaccurately low beaver dam densities on the Cache la Poudre River below Poudre Lake.

6. Conclusions

The Beaver Restoration Assessment Tool (BRAT) can be a useful approach for first-order approximations of viable beaver reintroduction locations in Colorado. Disparities exist between the model and reality due to inaccuracies in spatial datasets, lack of beaver capacity in Colorado streams, exclusion of human conflicts from modeling, and a maximum model density that is lower than maximum field densities in Colorado. Differences between the model and case studies highlight the difficulty in assessing model performance more than actual model imprecision. Despite lack of agreement between modeled dam densities and field assessments of dams or suitability, regional density patterns are likely indicative of actual conditions. Beaver dam densities are high in mountainous regions and low in water-scarce dry regions, which is consistent with historic beaver activity and consistent with current understanding of suitable beaver habitat.

While the details of the BRAT model are not highly accurate, the spatial trends and magnitude of change from historic conditions suggest the enormous loss of riparian wetlands and aquatic and riparian habitat that Colorado has sustained as a result of loss of beaver populations. However, complete loss of beaver habitat is limited. Many regions and reaches still have the capacity for beaver reintroduction to restore streams and valley bottoms. Reaches where habitat and vegetation changes have extremely reduced habitat or resulted in complete habitat loss could be prime for other beaver-related restoration such as beaver dam analogs. Statewide BRAT models should be accepted with some scrutiny of specific densities, and further modeling on smaller scales with detailed, local spatial layers could highlight more accurate beaver dam capacity. BRAT should be used to identify broad locations where reintroduction would be viable, but field visits and site assessments should be conducted before restoration to determine local challenges or limitations to reintroduction.

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CHAPTER 2: THE GEOMORPHIC EFFECT OF BEAVER DAM ANALOGS IN THE COLORADO FRONT RANGE

1. Overview

Beaver dam analogs (BDAs) have been installed to help restore incised channels and riparian vegetation in the Colorado Front Range. BDAs are expected to create a similar channel response to natural beaver dams by causing channel bed aggradation and overbank flow, which subsequently raise water tables and support vegetation growth. Previously, natural beaver dams caused significant sedimentation partly as a function of stream gradient and pool surface area, as well as significant rise in the water table partly as a function of permeability. Lack of funding for monitoring projects post-restoration has limited research on whether BDAs actually cause channel change that mimics natural beaver dams in the Front Range and beyond.

To understand how BDAs change river corridors post-restoration, I studied hydrology and sedimentation in two BDA restoration projects in Front Range watersheds. BDAs are hypothesized to (i) behave like natural beaver dams by accumulating sediment and raising water tables, with (ii) aggradation correlating to pond surface area and stream gradient, and (iii) groundwater rise correlating to river corridor grain size. BDAs were studied in Fish Creek – a steep, mountainous catchment underlain by crystalline igneous rock – and Campbell Creek – a lower gradient, piedmont catchment underlain by sedimentary rocks. Restoration occurred in summer 2017 and river corridor response was studied from May to October 2018 at both sites. Residual pool surveys recorded sediment and pool volumes in four BDA ponds and one reference pool in both catchments. Hydrology was monitored using recording stream gauges and shallow groundwater wells proximal to two BDAs and a reference reach at Fish and Campbell Creeks. BDAs created upstream ponding and significantly increased sediment storage, but BDAs did not have a significant influence on shallow groundwater. Sediment storage correlated strongly to BDA height and surface area, but not channel gradient. The lack of groundwater response proximal to BDAs could indicate that local watershed factors have a stronger influence on groundwater response in the first year after restoration than restoration design. Systematic, long-term studies of channel and floodplain response to BDAs are needed to better understand how BDAs will influence geomorphology and hydrology.

2. Introduction and Previous Studies

Beaver dam analogs (BDAs) are increasingly being used as low-tech, low-cost solutions to restoring degraded streams across the American West (Pilliod et al., 2017; Pollock et al., 2017). Widespread stream incision and degradation in the mountain West was recorded post-European settlement concurrent with the trapping of beaver and anthropogenic removal of wood from streams (Naiman et al., 1988; Polvi and Wohl, 2012). To remedy streams once hosting North American beaver (*Castor canadensis*) across their historic range, BDAs are constructed to be permeable, instream structures made of wood, mud, and rock that are meant to mimic beaver dams and secondary effects associated with those dams (Pollock et al., 2017).

North American beaver populations in streams from northern Mexico to the Canadian tundra – the ecological range of beaver – have dwindled from 60 to 400 million individuals prior to European settlement to an estimated 9 to 12 million beaver today (Seton 1929; Jenkins and Busher, 1979; Naiman et al., 1988; Ringelman, 1991). In Colorado, widespread beaver trapping for fur between 1820 and 1840 led to a near-extirpation of beaver by the late 19th century (Rutherford, 1964; Baker and Hill, 2003). State regulations enacted in the early 20th century protected beaver from being harvested except in instances where beaver threatened property damage. By the 1950's, beaver were once again common in all major Colorado watersheds, with many beaver populations in suitable habitat reaching carrying capacity (Retzer et al., 1956; Rutherford, 1964). Colorado allowed beaver trapping for commercial harvesting again from 1956 to 1996, when a citizen referendum amended the state constitution to ban lethal trapping of beaver for any purpose. Today, beaver populations are not monitored by the State of Colorado, but beaver activity has been reported across the State (Colorado Parks and Wildlife, 2000). Still, the reestablishment of beaver in some Colorado watersheds is limited due to loss of habitat and grazing competition by elk, moose, and cows (Baker et al., 2005; Small et al., 2016).

When present, beaver can significantly alter river corridors of low-gradient, low-discharge streams. River corridor here refers to the channel(s) and the adjacent floodplain, as well as the underlying hyporheic zone (Harvey and Gooseff, 2015). Beaver are ecosystem engineers and a keystone species, meaning they have a disproportionately large ecologic, geomorphic, and hydrologic effect on their environment compared to their abundance (Baker and Hill, 2003; Rosell et al., 2005). In low order streams, beaver build channel-spanning dams that obstruct flow, cause backwater ponding, and decrease stream power and velocity (Naiman et al., 1986; Stout et al., 2016). Decreased velocities allow for the aggradation of sediment and organic matter behind dams, which raises the stream bed and reconnects incised channels with old floodplains (Butler and Malanson, 1995; Pollock et al., 2007). Channel-spanning dams also force a greater magnitude of overbank flow at a greater frequency and duration, causing stable, multi-threaded channel networks to form (Westbrook et al., 2006; Polvi and Wohl, 2012). Increased overbank flooding from dams increases the lateral extent of groundwater recharge and hyporheic exchange, thus raising local water tables (Westbrook et al., 2006; Janzen and Westbrook, 2011). Increased lateral connectivity and decreased stream power create a positive feedback, allowing for a higher density of beaver dams within a reach until the river corridor (channel(s) and floodplain) reaches a dynamic, wet equilibrium known as a beaver meadow complex (Ruedemann and Schoonmaker, 1938; Ives, 1942; Polvi and Wohl, 2012; Pollock et al., 2014).

Healthy beaver meadow complexes could have significant implications for climate, including fire mitigation, water retention, and carbon storage (Polvi and Wohl, 2012; Wohl, 2013). Meadows, including those occupied and not occupied by beaver, comprise approximately 5% of the landscape in watersheds on the eastern side of Rocky Mountain National Park, but account for up to 23% of terrestrial carbon storage (Wohl, 2013). Beaver dams in the Rocky Mountains also retain water, both behind dams and in the banks (Wegener et al., 2017), which could increase late summer discharges needed to support ecological communities in light of declining spring snow packs across the West (Pederson et al., 2011; Goode et al., 2013).

Removal of beaver results in loss of ecosystem function and habitat. Valley bottoms can transform from wet, multi-channel beaver meadows housing a diversity of plants and animals to a dry, single-threaded meandering channel after beaver are removed (e.g. Wolf et al., 2007). Abandonment and eventual failure of dams causes transport of trapped sediment and water downstream (Butler and Malanson, 2005), which causes ponds to drain, riparian water tables to decline, and streams to incise. Incision and lower water tables force geomorphic and ecologic systems into a drier stable state that is typically outside of the range of historical variability for valley bottoms with long histories of beaver habitation (Lewontin, 1969).

Beaver reintroductions are increasingly used as a tool to return valley bottoms back to a diverse, wet stable state (Pollock et al., 2015). The change from incised stream to heterogeneous beaver meadow complex can occur in as little as a decade after beaver introduction (Pollock et al., 2014; Bouwes et al., 2016). However, streams where vegetation loss and stream incision limit the reintroduction of beaver could be prime for beaver dam analog restoration (Pollock et al., 2014).

Beaver dam analogs (BDAs) can be installed in streams with limited current beaver habitat to accelerate stream recovery, reconnect streams with floodplains, and encourage beaver to build dams in the future (Pollock et al., 2012). BDAs are expected to cause the same complex channel response that natural beaver dams do by storing sediment and causing overbank flooding upstream of the analog (Pollock et al., 2012; Bouwes et al., 2016). Ideally, BDAs would be used to establish vegetation and habitat requirements to allow for the reintroduction of beaver, and BDAs can be used to encourage beaver to build more stable dams on top of the analog (Pollock et al., 2014; 2015).

The plethora of habitat, resource, and climate benefits associated with beaver dams explain enthusiasm for using beaver as a restoration tool through reintroductions and beaver dam analogs. However, lack of resources by watershed managers has limited systematic, scientific study of stream changes post-restoration. Particularly, there is a lack of studies identifying quantitative channel change post BDA or beaver dam structures, with existing post-BDA restoration studies primarily focusing on biological changes (Pollock et al., 2012; Bouwes et al., 2016; Silverman et al., 2019). During a study assessing steelhead response post-restoration, sediment aggradation and groundwater rise were documented after over 100 BDAs were installed in Bridge Creek, Oregon in 2010 (Bouwes et al., 2016).

Although restoration projects across the Colorado Front Range involve far fewer structures per individual stream than the Bridge Creek project, managers are interested in answering a similar question: are BDAs in the Colorado Front Range effective at causing stream bed aggradation and raising water tables? BDAs are typically installed by managers to address incision and riparian vegetation concerns in the Colorado Front Range (Walsh Environmental, 2015; Wildland Restoration Volunteers, pers. comm. May 2018). However, to guide expected outcomes and timelines for restoration projects, understanding how physical basin characteristics such as slope, valley width, and channel morphology can be used to predict channel change post-restoration is important.

3. Objectives and Hypotheses

In this study, I examine BDA efficacy in the Front Range and whether physical basin characteristics can explain channel change post-restoration by studying BDAs in two diverse watersheds. The main objective is to identify patterns and causes of channel change after BDA restoration. As suggested by previous studies (e.g. Pollock et al., 2014), I predict BDAs will result in statistically significant channel aggradation and rise in groundwater tables relative to an unrestored reference reach on the same channel (H1). Channel aggradation will correlate to the surface area of upstream pools formed by BDAs as well as valley gradient proximal to restoration (H2). Water tables should be higher upstream of BDAs compared to downstream (H3). Essentially, I hypothesize that pools with larger surface areas on steeper gradients will cause a greater magnitude of aggradation, whereas increased infiltration due to overbank flooding and ponding will create a greater magnitude of groundwater change upstream of BDAs (Figure 2.1).

Expected outcomes of BDA restoration are based on known changes that occur when natural beaver dams are built across channels. Previous studies have found pool surface area to be the strongest predictor of sedimentation in upstream ponds formed by dams (Naiman et al., 1986; Butler and Malanson, 1995). Basin characteristics such as slope and subsequent channel gradient could also have an impact on sedimentation. Steeper channels are capable of moving larger sediment discharges and grain sizes (Lane, 1955; Dust and Wohl, 2014). A channel-spanning dam or analog would slow channel velocity, thus causing some grain sizes to fall out of suspension. Since steeper channels have the capacity to carry larger grain sizes and greater volumes of sediment, there will be a greater capacity for sedimentation behind dams or analogs. Finally, overbank flooding and ponding is expected to occur upstream of BDAs similar to a natural dam, which will increase groundwater infiltration and raise water tables. Since larger grain sizes on the channel bed and the banks allow for quicker groundwater infiltration (Masch and Denny, 1966), river corridors with larger grain sizes and less clay will likely experience a greater magnitude of groundwater rise. This study comparing channel response post-BDA installation in two diverse watersheds along the Colorado Front Range will address whether hypothesized response matches real changes.

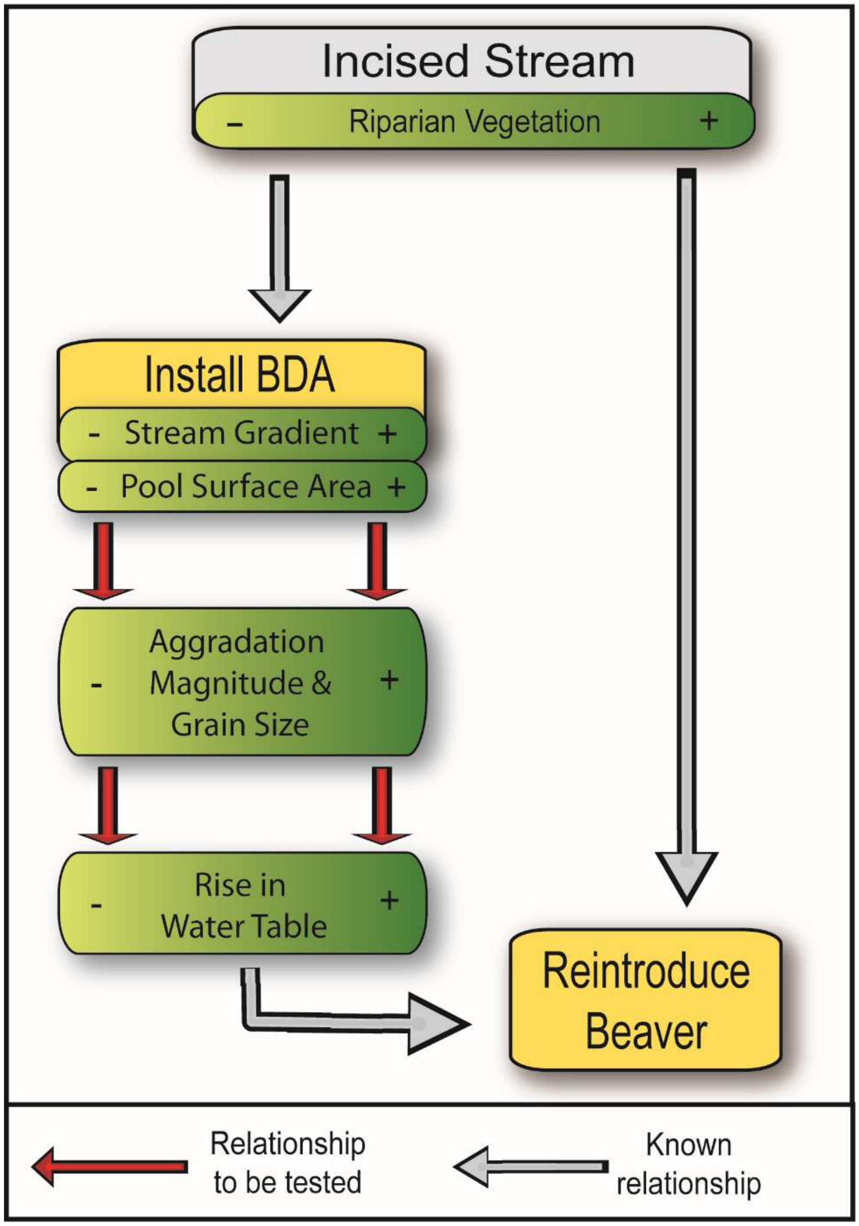


Figure 2.1. Conceptual diagram showing the proposed relationships to be tested using BDAs. The grey box represents the initial condition of an incised stream. Yellow boxes represent management options. Green gradient bars represent physical characteristics of the stream, where darker green represents a higher value. When abundant vegetation exists, beaver reintroduction can aggrade beds and influence water tables. If beaver reintroduction is not possible at a site, BDA installation can hypothetically initiate similar changes, which will eventually result in a suitable habitat for beavers.

4. Site Description

Beaver dam analogs (BDAs) were monitored at two restoration sites in separate watersheds along the Colorado Front Range in Larimer County: Fish Creek in Estes Park and Campbell Creek in Livermore (Figure 2.2). Fish Creek originates at Lily Lake in Rocky Mountain National Park and is a second order stream underlain by Proterozoic Silver Plume Granite at the restoration site (Braddock and Cole, 1990). Campbell Creek is a third order stream underlain by early Triassic, late Permian Lykins Siltstone and Quaternary alluvium that heads on the plains approximately 8.8 km north of Livermore, Colorado (Braddock et al., 1988).

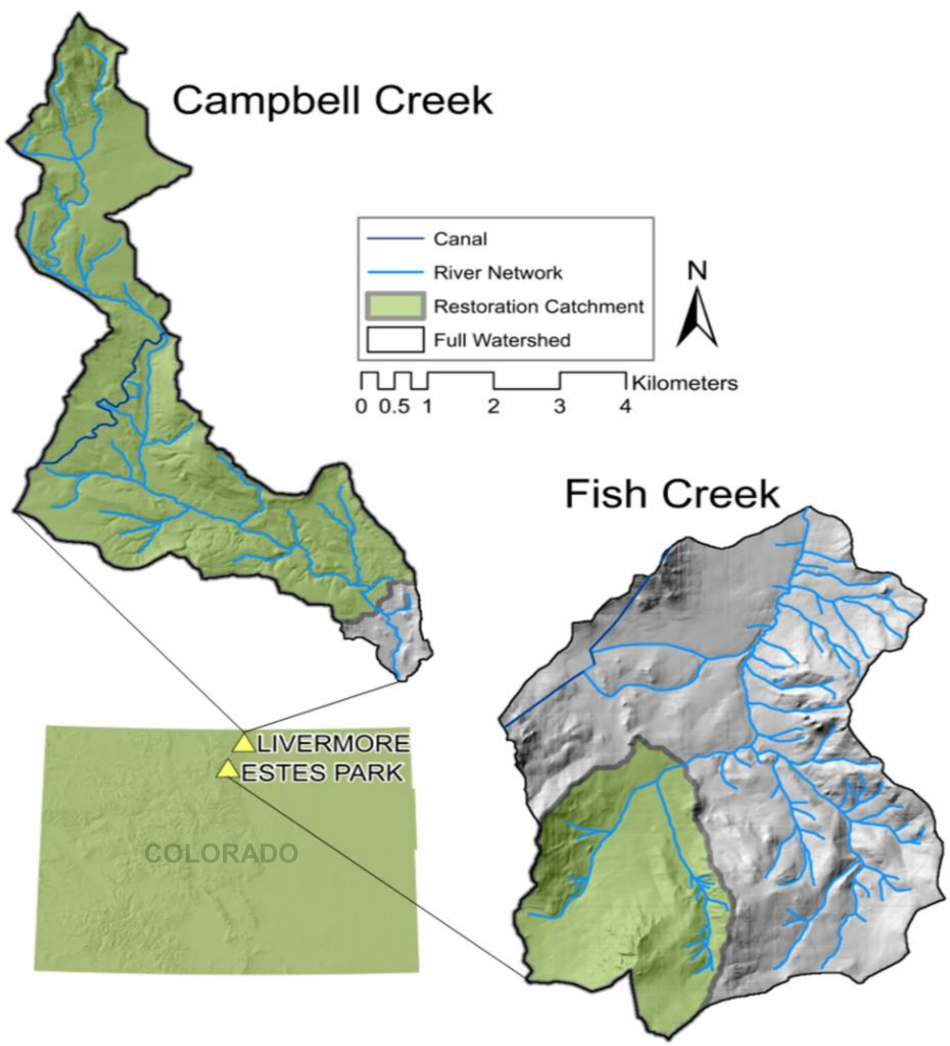


Figure 2.2. Map of study watersheds: Campbell Creek in Livermore, CO, and Fish Creek in Estes Park, CO. Watershed areas shaded in green lie upstream of the restoration site.

Both restoration sites in this study are located on private land; Campbell Creek is located on the Roberts Cattle Company Ranch and Fish Creek is located on the Cheley Ranch. While restoration on Fish Creek continues downstream of Cheley Ranch, only the BDAs on Cheley Ranch properties were considered in this study. The two restoration sites were chosen for study due to willing landowner collaboration and diversity of physical basin characteristics (Table 2.1). By studying restoration in two diverse watersheds, we can examine which geomorphic characteristics, if any, correlate with channel change post-restoration.

Table 2.1. Physical basin and geomorphic characteristics of BDA restoration sites on Campbell Creek (Roberts Ranch, Livermore, CO) and Fish Creek (Cheley Ranch, Estes Park, CO).

Site Name	Elevation[1] [m]	Restoration Length[1] [km]	Number of BDAs	Mean Valley Slope	Upstream Drainage Area[2] [km^2]
Campbell Creek	5555	0.68	7	0.008	8.1
Fish Creek	7989	0.30	7	0.046	4.1

[1] Elevation and reach length were measured using Google Earth.
[2] Upstream drainage area was calculated using USGS Stream Stats.

Incision is a driving factor influencing the geomorphology of the river corridor on Fish and Campbell Creeks. In 2013, a 200-year recurrence interval flood on Fish Creek caused severe incision and channel migration (Yochum et al., 2017). Today, the active channel of Fish Creek is incised up to 3 meters into the surrounding valley bottom (Figure 2.3). Beaver activity is present on the original floodplain perched above the channel. Campbell Creek in Campbell Valley has a much longer history of erosion and geomorphic change. In the early 1900s, water from the North Poudre Irrigation Canal was diverted through Campbell Valley, which significantly increased stream discharge and caused up to 12 m of erosion in some areas. Today, the active valley of perennial Campbell Creek is within a large, relatively stable arroyo incised into the adjacent uplands (Figure 2.4).

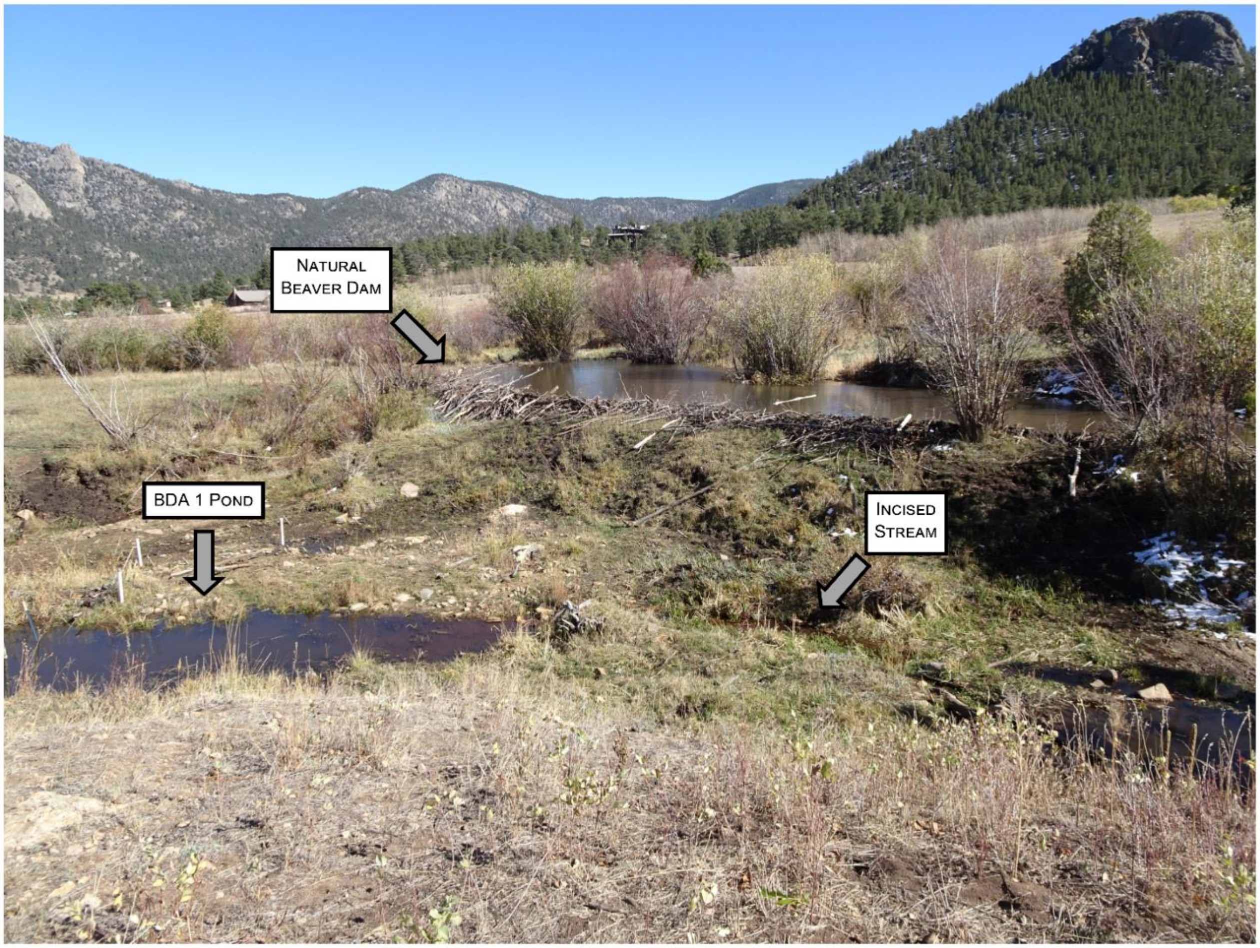


Figure 2.3. Looking from left to right bank of Fish Creek above BDA 1. The 2013 Colorado Front Range flood caused the creek to incise into the floodplain (up to 3 m in some places). Beaver activity has recovered on the old floodplain, with natural beaver dams perched above the stream off the right bank.

BDAs were installed at both sites in 2017 due to incision concerns and the desire to restore instream and riparian habitat. The 2013 Colorado Front Range flood caused severe incision and channel migration on Fish Creek as previously mentioned. Following flood damage, the Estes Valley Watershed Coalition spearheaded the restoration project on Fish Creek to restore the incised stream and rehabilitate beaver habitat. Chief objectives of the Fish Creek restoration include stabilizing channel incision and restoring riparian ecosystems (Welsh Environmental, 2015). Incision concerns have been ongoing on Campbell Creek, where previous attempts at stopping channel degradation included fortifying stream banks with old car tires. In 2004, nearly 5000 hectares of the Roberts Ranch including Campbell Valley was put under a conservation easement with The Nature Conservancy and Larimer County. Since 2010, the Wildland Restoration Volunteers (WRV) from Fort Collins, Colorado, have led a number of stream restoration projects with the goal of rehabilitating riparian habitat. In 2017, the WRV installed 7 BDAs on Campbell Creek to improve riparian vegetation and address ongoing incision concerns.

Figure 2.4. Looking upstream at the downstream end of restoration on Campbell Creek in Campbell Valley. Land use and discharge changes in the early 1900s resulted in up to 13 m of incision. Today, the active valley bottom of Campbell Creek is within a large, relatively stable arroyo indicated by the steep walls on either side of the floodplain.

The scale and timing of BDA restoration are similar at Fish and Campbell Creeks, but BDA design differs between the two sites (Figure 2.5). BDAs in Fish Creek were constructed as traditional post and willow structures, where a few large (diameter > 10 cm) wood posts were inserted in the stream bed and thinner branches were woven between posts and stacked on the downstream end of the analog. BDAs in Campbell Creek were constructed by pushing large logs (diameter > 10 cm) into the banks and across the bed in order to create a wood jam perpendicular to flow similar to a wooden dam. Managers at both sites consider the structures BDAs, which reflects the fact that there is no standard design for a BDA (Pollock et al., 2017).

5. Methods

5.1. Reach Selection

In each watershed, two beaver dam analogs (BDAs) and a reference reach were chosen for monitoring. Although closely monitoring more BDAs at each site would increase measurements of hydrologic and geomorphic changes, my choice of two BDAs per restoration reflected limitations in equipment and time. To capture potential variability in BDA response due to position in the sequence of BDAs, the upstream-most BDA and the downstream-most BDA were monitored at both sites. At Fish Creek, the downstream-most BDA on the Cheley Ranch showed signs of beaver alteration. To avoid changing beaver behavior, I monitored the next BDA immediately upstream of the downstream-most BDA. For organizational purposes, the upstream and downstream monitored BDAs are referred to as BDA 1 and 2, respectively, at both Fish Creek and Campbell Creek.

Because hydrologic and geomorphic data were not collected on Fish and Campbell Creeks prior to installing BDAs, a reference reach was monitored in each watershed. Reference reaches

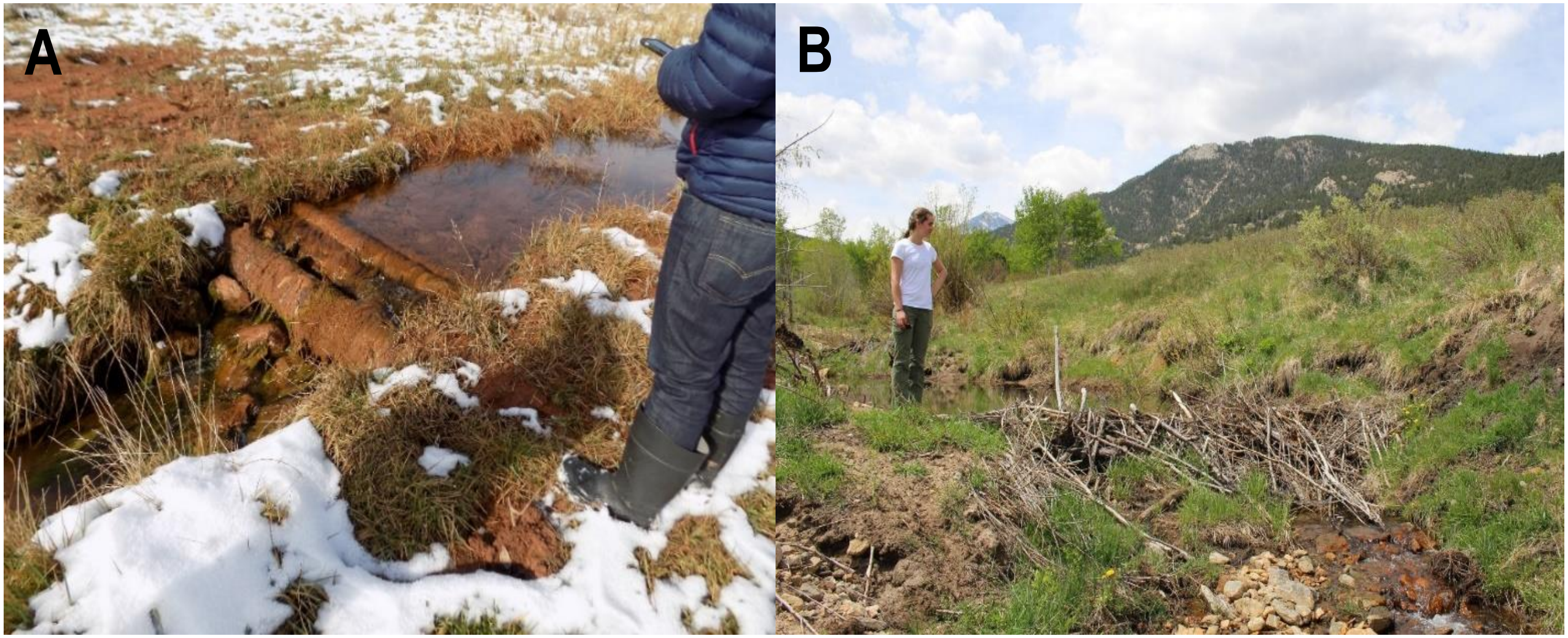


Figure 2.5. Examples of beaver dam analogs (BDAs) installed at (A) Campbell Creek in Livermore, CO and (B) Fish Creek in Estes Park, CO.

were chosen to represent the channel pre-restoration as well as record any natural changes that occurred throughout the field season. At both sites, no proximal tributaries adequately represented the pre-restored main channel, and upstream reaches had significant geomorphic differences in valley bottom confinement. Therefore, reference reaches were chosen downstream of restoration in Campbell and Fish Creeks. To avoid influence from the restoration, reference reaches were chosen at distances of at least 10 bankfull widths downstream of the last restoration structure. The type, location, and length of each monitored reach on Fish and Campbell Creeks are detailed in Table 2.2. The bulk of the field measurements were collected at BDA 1, BDA 2, and the reference reach on each creek, but some geomorphic assessments were conducted at additional BDAs for increased statistical power.

Table 2.2. Description and location of reaches at Campbell and Fish Creeks.

Site	Reach	Coordinates	Number of Wells	Length (m)[1]
Campbell Creek	Upstream - most BDA (BDA 1)	40.79284°, -105.15547°	4	3.8
	Downstream-most BDA (BDA 2)	40.78965°, -105.15314°	4	3.2
	Reference	40.78927°, -105.1528°	2	3
Fish Creek	Upstream-most BDA (BDA 1)	40.32886°, -105.51923°	4	3
	Second to downstream-most BDA (BDA 2)	40.32977°, -105.51734°	4	10.5
	Reference	40.33027°, -105.51588°	2	3

[1] Reach length is equal to twice the bankfull width (indicating one bankfull width distance up and downstream of BDA or reference site). Some analyses, such as channel longitudinal profiles, extended beyond reach lengths.

5.2. Surface Hydrology

Stream stage was monitored through a series of stream gages installed in May 2018 in Fish Creek and Campbell Creek. Stream gages were installed in the pools upstream of BDA 1 and 2 at each site as well as approximately one bankfull distance downstream of either BDA. An additional stream gage was installed in a pool at each reference reach. Gages were built by housing a TruTrack WT-HR 1000 capacitance rod within a PVC casing attached to a metal fence post inserted into the stream bed. Stream stage was recorded every 15 minutes from late-May to August. Although channel area surveys were conducted in early June (peak flow) and September (base flow), my ability to collect velocity measurements was severely hindered by low flows and significant instream storage. Consequently, I could not develop an accurate stage-discharge curve for 2018.

5.3. Shallow Groundwater Hydrology

To monitor groundwater dynamics, 20 shallow groundwater wells were installed at BDA 1, BDA 2, and the reference reach at each site in May 2018 using a grid design. Wells were constructed out of 1.5” Schedule 40 PVC pipe approximately 1.5 m in length where the bottom 0.75 m were slotted. Wells were installed to a depth of 1 m at both sites, or until the well reached a resisting layer and could no longer be inserted. If a resisting layer prohibited a well from being installed to a depth where no slots were exposed, the top of the well was sawed off using a hand saw and capped with a PVC connector and PVC stick up to ensure that surface runoff would not drain into the well. A total of 8 wells were installed at each BDA – four recording and four non-recording – and a total of four wells were installed at each reference reach – two recording and two non-recording. Wells were installed 1 m and 5 m from bankfull on the left and right bank directly upstream of each BDA and 1 m and 5 m from bankfull on the left and right bank approximately one bankfull distance downstream for a total of eight wells per BDA. At each reference reach, wells were installed 1 m and 5 m from bankfull on both stream banks for a total of four wells per reference reach. TruTrack WT-HR 1000 capacitance rods were installed in all 1 m wells to record water level at 15-minute intervals from June to August. The depth of water in all wells across all sites was measured using a Solinst Mini Water Level Meter (Model 102M) on approximately a weekly basis. These point measurements were the only data recorded at the 5 m wells, whereas point measurements were used to check continuously recorded water levels at the 1 m wells.

Time series data collected from recording wells were cleaned using R. Points that were more than 20% higher or lower than the previous 15-minute interval point were flagged as outliers and averaged out using surrounding time series points. Time series were also adjusted to match hand measurements collected in the field within the 50 mm range of error for TruTrack WT-HR 1000. Water height was converted to depth to groundwater for each well using detailed measurements of the length of the capacitance rod, height of the well cap, and length of the well exposed above ground (Figure 2.6). Depth to groundwater, D, refers to the distance between the ground surface and the water table adjacent to the stream.

$$D = F - (C + S + W)$$

Above, depth to groundwater (D) is measured by subtracting the depth of water recorded by the TruTrack WT-HR (W), the length of well stick-up (S), and the height of the cap (C), from the full length of the capacitance rod and hanging chain (F). All measurements were made in millimeters and recorded multiple times throughout the summer. Average values for C, S, and F were used to reduce the effect of human measurement error on the final value of D.

Groundwater well time series were fit to a linear mixed model to determine whether there was a statistically significant difference between groundwater levels up and downstream of the BDAs. To reduce noise in the model, 15-minute interval depth to groundwater measurements were averaged by date at Fish Creek and by 24-hour storm period at Campbell Creek. Storms were chosen by hand at Campbell Creek with the help of rainfall data collected in Livermore, CO by CoCoRaHS (ID: CO-LR-250). Storms chosen for analysis were those with sufficient rainfall for at least 5 of the 8 wells to respond. Wells were deemed 'responding' if depth to groundwater dropped below average within a 24-hour period post-rainfall. Depth to groundwater was averaged over a 24-hour period at each well starting at the average time of response. Because wells at Campbell Creek were typically dry except following significant rainfall, a 24-hour period was found to be sufficient in catching the rising limb, peak, and the falling limb of

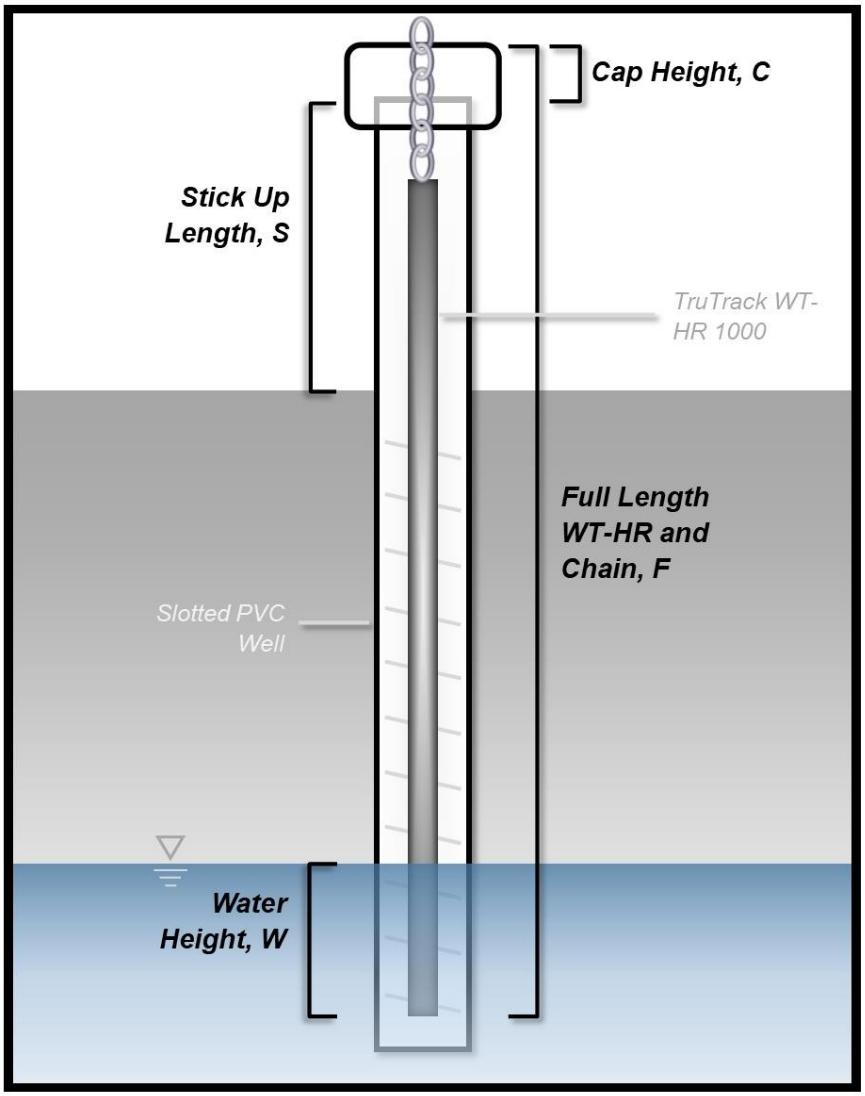


Figure 2.6. Schematic diagram (not to scale) of a TruTrack WT-HR 1000 housed within a recording groundwater well. TruTrack WT-HR measure the height of water above the capacitance sensor housed at the bottom of the instrument. Depth to groundwater was calculated by subtracting measured water depth from measurements of WT-HR length, cap height, and stick-up length.

the groundwater hydrograph for each storm. Separate mixed models were created for Campbell Creek and Fish Creek using the same model structure. Mixed models were fit in R using the lme4, lmerTest, and emmeans packages using average depth to groundwater as the response at both sites (Bates et al., 2015; Kuznetsova et al., 2017; Lenth, 2019). Fixed effects included the position of the well (up or downstream of BDA), the time period (storm or day), plus position*period interactions. To account for the variability that could be encountered at each BDA (1 or 2), stream bank (left or right), or each individual well, these variables were included as random effects in the model. Model assumptions were checked using residual diagnostic plots.

5.4. Channel Surveys

Channel cross-sections were surveyed at Campbell Creek and Fish Creek upstream and downstream of BDA 1 and 2 and across the reference reach in June and September 2018. Cross-sectional surveys were conducted in line with the groundwater wells and stream gage at each site. Channel long profiles were also surveyed along the thalweg at BDA 1, BDA 2, and the reference reach of Campbell and Fish Creeks in June and September 2018. All surveys were conducted using a TOPCON AT-B Series Auto Level and rod with a 0.5 cm accuracy. Local channel slope was extracted from long profiles and width-to-depth ratio was extracted from channel cross-sections for further analysis in statistical regressions.

5.5. Residual Pool Sediment Surveys

Residual pool volume surveys were conducted in 4 BDA pools and a reference pool at Campbell Creek and Fish Creek from July 2018 to October 2018 using an adapted V* method (Hilton and Lisle, 1993). During this time, each pool was sampled twice. Surveys are referred to by the watershed – F for Fish Creek and C for Campbell Creek – and the date of the survey for a total of 4 surveys: F1, F2, C1, and C2. Fish Creek surveys were conducted on July 24th, 2018

(F1) and October 12, 2018 (F2), and Campbell Creek surveys were conducted on July 23rd, 2018 (C1) and September 20, 2018 (C2).

The residual pool volume is the volume of water and fine-grained sediment that would remain in the pool if downstream flow was negligible, or essentially, the portion of a pool volume below the riffle crest forming the downstream lip of the pool. The residual pool was measured instead of the total pool in order to statistically compare fine-grained sediment and water volumes across individual pools, surveys, and sites. When adapting the V* method to be used on beaver dam analog pools, we considered the top of the BDA to be analogous with the top of the riffle crest.

Residual pool surveys consisted of systematic point measurements of water and fine-grained sediment depth along cross sections across the width of the BDA or reference pool, with zero-area cross sections assumed at either end of the pool (Hilton and Lisle, 1993). Residual pools beyond those instrumented at BDA 1 and 2 were included in these surveys for additional statistical and explanatory power regarding reach-wide aggradation. To measure a pool, a measuring tape was secured along the total length of one bank of the pool. The total length of the pool was determined by identifying the upstream riffle crest, or in some cases, the bed slope change leading up to the upstream BDA. Cross section intervals were chosen so that there would be 3 to 5 cross-sections along the length of the pool, depending on the pool size. Once the interval was chosen, the first cross-section was placed randomly within the first meter, or less if the interval was less than a meter, upstream of the BDA or riffle crest. Additional cross-sections were evenly spaced upstream of the initial cross-section at the calculated interval. Along each cross-section, water and sediment depth were systematically sampled at a consistent interval so that the widest cross-section of the pool would include 5 to 7 point measurements. Water depth was measured using a rigid tape while sediment depth was measured by pushing a piece of rebar into the fine bed sediment to the underlying coarse layer. Using this method to survey fine-grained sedimentation worked for Fish and Campbell Creeks because the pre-restoration bed material was significantly coarser than post-restoration aggraded material.

Residual pool survey points were used to interpolate water and sediment depth across entire ponds in MATLAB. Using the interpolated surface, total pool volume and total sediment volume were calculated for each pond using the quad2d() MATLAB function.

Multiple linear regressions were used to determine whether residual pool sediment volume could be predicted from physical reach characteristics (Ott and Longnecker, 2016). Independent (predictor) variables considered in the model were pool surface area, pool volume, channel slope, composite bank and bed soil clay percentage, BDA height, upstream catchment area, and width-to-depth ratio. All independent variables except for catchment area were measured in the field. Channel slope, width-to-depth ratio, pool volume, and pool surface area were natural log transformed and sediment volume was square root transformed in order to meet the model assumption of normality. Sediment surveys from Fish Creek and Campbell Creek were combined into the same multiple linear regression model for additional statistical power. A full multiple regression model was created for the response variable (sediment volume) that included all predictor variables using the *lm()* function in R. The significance of each predictor variable was tested at alpha = 0.05 to determine which predictor variables have explanatory power. AICc was used for selection of model variables, where the model with the lowest AICc was chosen as the final model (Hurvich and Tsai, 1989). Model selection was performed using the *dredge()* function in the MuMIn R package (Barton, 2018).

5.6. Sediment Cores

A hand auger was used to collect sediment cores to a depth of resistance from the bank and bed of Fish and Campbell Creeks. Cores were randomly sampled upstream and downstream of BDAs as well as proximal to the groundwater wells in order to assess dominant grain sizes at each BDA and the percent fines in surrounding soils, respectively. Cores taken in the stream were taken in areas of low velocity (i.e., pools) and shielded from flow by facing the auger downstream during removal from the stream. In total, 9 sediment cores ranging from 90 to 255 cm in depth were collected from Fish Creek – 5 from the bed and 4 from the banks. A total of 10 sediment cores ranging from 90 to 255 cm in depth were collected from Campbell Creek – 7 from the bed and 3 from the banks. Sediment cores were air dried, crushed, and sieved through sieves at 1 phi intervals from -2 to 4 phi using a Humboldt motorized sieve shaker for 15 minutes.

6. Results

6.1. Surface Hydrology

Comparisons of stage up and downstream of BDA 1 and BDA 2 at both sites indicate differences in pool dynamics between Campbell and Fish Creek (Figure 2.7). Gauges downstream of BDA 1 exhibited extreme variability from May to September 2018 in both watersheds, which suggests that there was equipment failure at these gauges (Figure 2.7a and 2.7c). Stage across BDA 2 on Fish Creek shows that the upstream pool was deeper than the downstream creek, whereas the upstream pool at BDA 2 on Campbell Creek is shallower than the downstream pool. Shallower pools upstream of Campbell Creek BDAs contradict expected outcomes. Typically, dams and BDAs form deeper upstream pools – such as at Fish Creek – due to backwater effects. Further discussion of pool differences between the two sites is provided in the Discussion section.

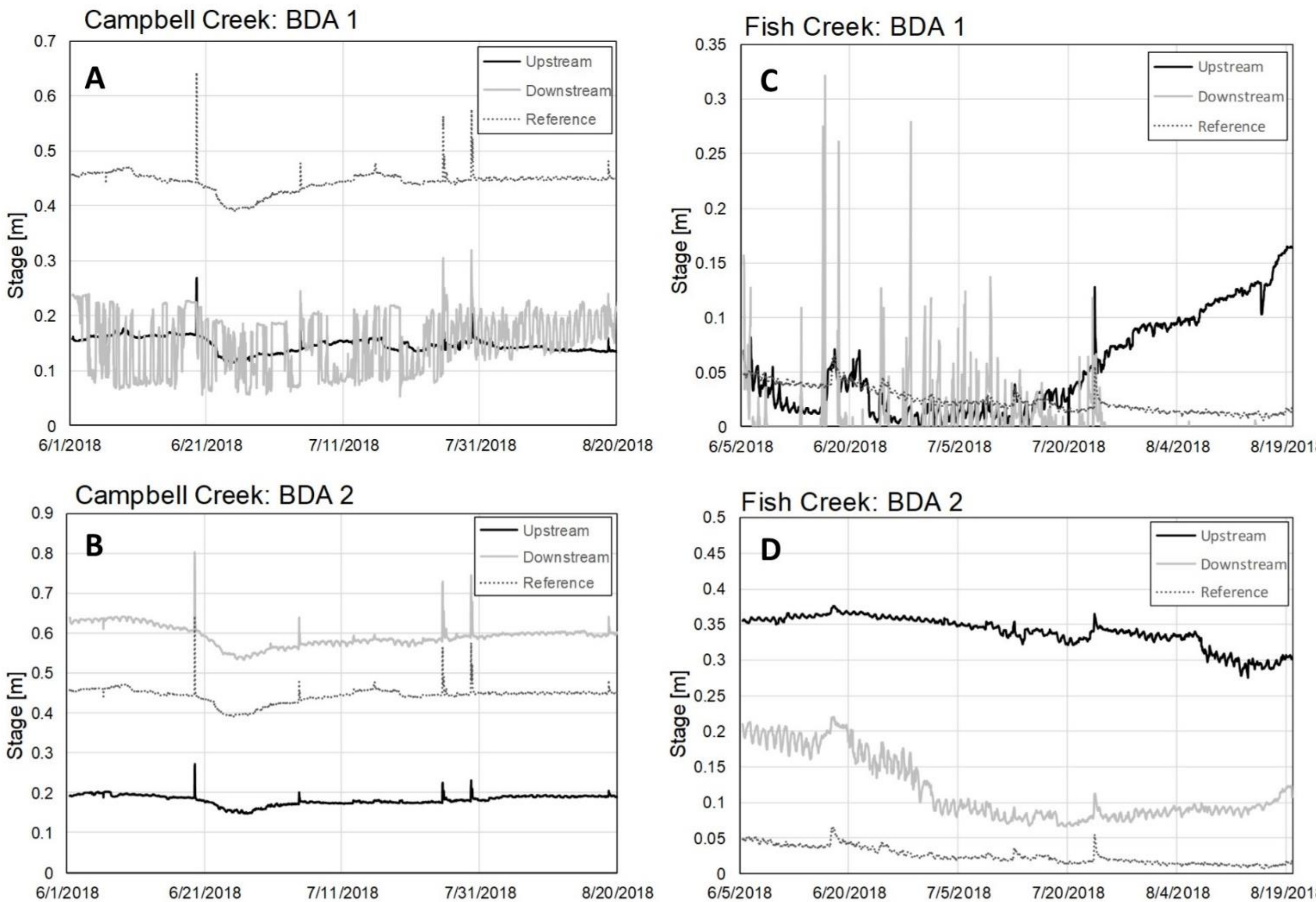


Figure 2.7. Stage comparisons across BDAs at Campbell Creek (A and B) and Fish Creek (C and D). Dashed, dark grey line represents stage at a reference pool at both sites. Variability in the downstream gage at BDA 1 for both sites (A and C) may suggest equipment failure.

6.2. Shallow Groundwater Hydrology

Recording wells at Fish Creek recorded water throughout the entire monitoring season, while wells at Campbell Creek went dry between periods of significant rainfall. Seasonal averages of depth to the groundwater table could be calculated for Fish Creek (Table 2.3), but not for Campbell where most of the monitoring period was recorded as greater than the depth of the well. The groundwater table is closer to the ground surface where the depth to groundwater is smaller. Differences in depth to groundwater between upstream and downstream well pairs is variable at Fish Creek (Table 2.3). Well pairs refer to wells on the same bank upstream and downstream of the same BDA. The groundwater table was up to 0.3 m lower upstream of a BDA compared to downstream at 3 out of 4 wells pairs on Fish Creek. However, one well pair at BDA 1 exhibited a higher water table upstream of the analog. Higher water tables are expected upstream of BDAs due to ponding and overbank flow increasing infiltration. Therefore, well response at Fish Creek conflicts with expected outcomes.

Beyond the seasonal averages, daily averages of depth to groundwater were calculated for 76 days from June 5, 2018 to August 19, 2019 at Fish Creek (Figure 2.8a and b). Depth to groundwater was averaged over 7 storms between June 1, 2018 and August 21, 2018 at Campbell Creek (Figure 2.8c and d). Storms large enough to cause at least 5 of the 8 recording wells to respond occurred on June 19, July 5, 12, 15, 25, 29, and August 18, 2018. Depth to groundwater averages per day or storm can be found for each well in Appendix E. Despite apparent differences in seasonal averages at Fish Creek, results from the linear mixed model comparing the difference in groundwater between well pairs for each day or storm at Fish and Campbell Creeks, respectively, found no significant difference in groundwater upstream of a

BDA compared to downstream (p = 0.27 and p = 0.86 for Fish and Campbell Creeks, respectively).

Table 2.3. Seasonal average of depth to groundwater for each recording well, and seasonal downstream to upstream differences for well pairs on the left and right banks at BDA 1 and 2 on Fish Creek. Seasonal averages could not be calculated for Campbell Creek due to wells being dry most of the season. Well-pair differences that are negative indicate the groundwater table was deeper upstream of the BDA compared to downstream. Well labels indicate location relative to BDA (U = upstream, D = downstream) and bank (L = left bank, R = right bank).

Site	BDA	Well	Average [m]	Downstream - Upstream Difference [m]
Fish Creek	BDA 1	UL	0.65	-0.29
		DL	0.36	
		UR	0.31	0.29
		DR	0.6	
	BDA 2	UL	0.65	-0.3
		DL	0.35	
		UR	0.51	-0.09
		DR	0.42	
	Reference	L	0.3	-
		R	0.32	

Statistically similar water table depths up and downstream of BDAs disprove the hypothesis that BDAs would cause a higher water table upstream of a BDA. However, a statistically similar water table surrounding a BDA might not indicate whether a BDA was influencing groundwater recharge. Water table depths and stream stage proximal to BDA 1 at Campbell and Fish Creeks on 7/19/2018 and 6/20/2018, respectively, were plotted to further elucidate groundwater dynamics. Groundwater will move into a stream if the stream surface is below the water table, while groundwater will move out of a stream if the stream surface is above the water table. Fish Creek is a clearly gaining stream downstream of BDA 1, meaning that water gradients suggest groundwater discharge into the creek (Figure 2.9). In contrast, Fish Creek is likely a losing stream upstream of BDA 1 because stage elevation is the same or slightly higher than surrounding groundwater. Therefore, BDA 1 at Fish Creek is likely causing groundwater recharge upstream of the structure compared to downstream or a non-restored reach. Campbell Creek was a losing stream both up and downstream of BDA 1, which suggests that the water table is consistently low enough that groundwater recharge would occur whether a BDA was installed or not (Figure 2.10). Since hyporheic recharge or discharge was not investigated at either site, comparisons between shallow groundwater tables and stream stage should only be viewed as a first order approximation of groundwater movement. For example, clay soils at Campbell Creek could be limiting all interaction between the stream and groundwater. While it is assumed that Campbell Creek is recharging shallow groundwater, the creek could be perched above the water table with no interaction.

Most non-recording, 5-m-distance wells were dry for a majority of the season at Fish and Campbell Creeks. Therefore, further analysis and discussion is not provided in this report. Raw data recorded for 5-m wells are included in Appendix F and in Figures 2.9 and 2.10.

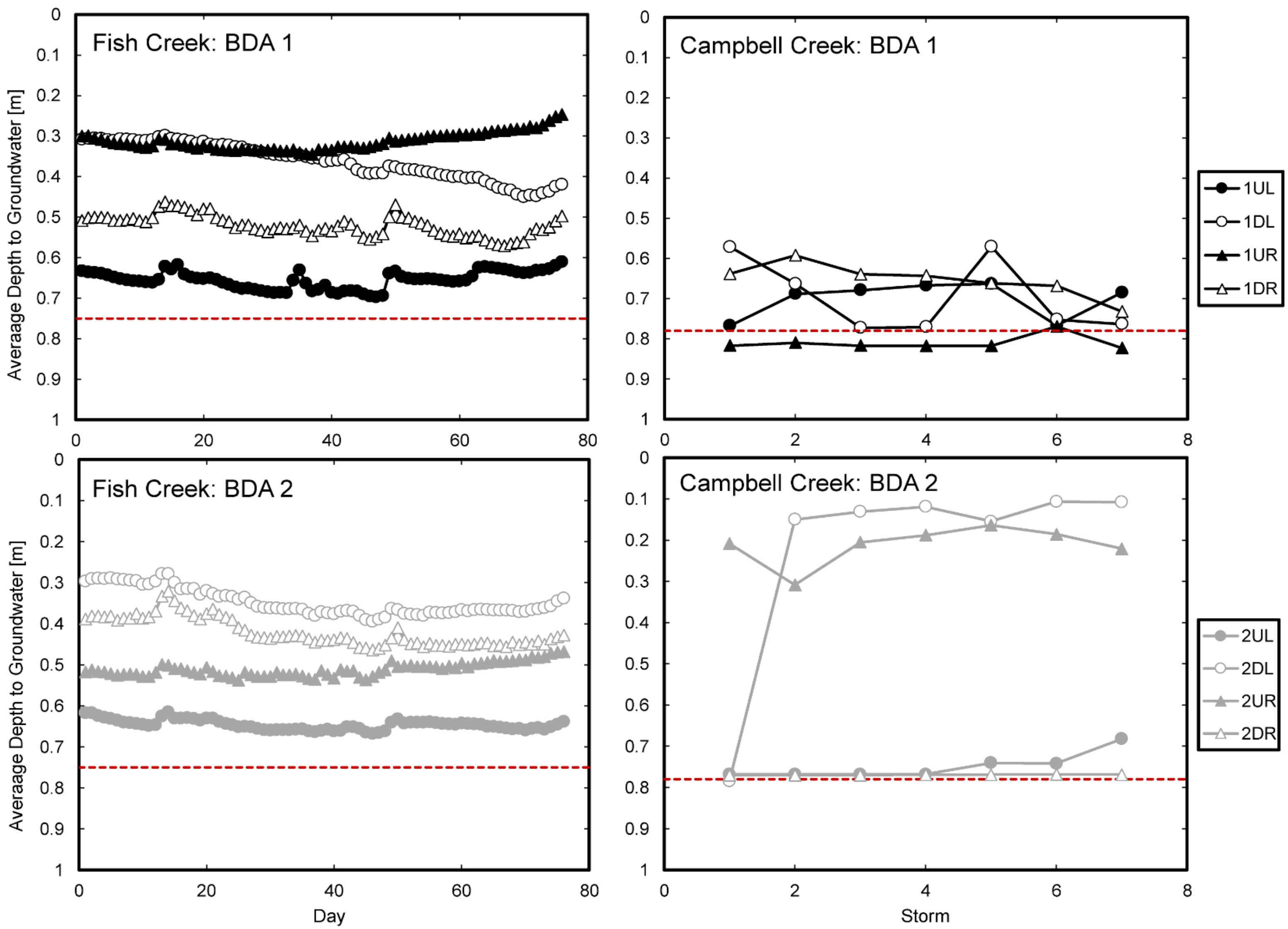


Figure 2.8. Average depth to groundwater by day at Fish Creek (A and B) and by 24-hour storm period at Campbell Creek (C and D). The dashed red line indicates that depth-to-groundwater was below the depth of the well. Solid symbols represent wells upstream of their respective BDAs, and open symbols represent downstream well.

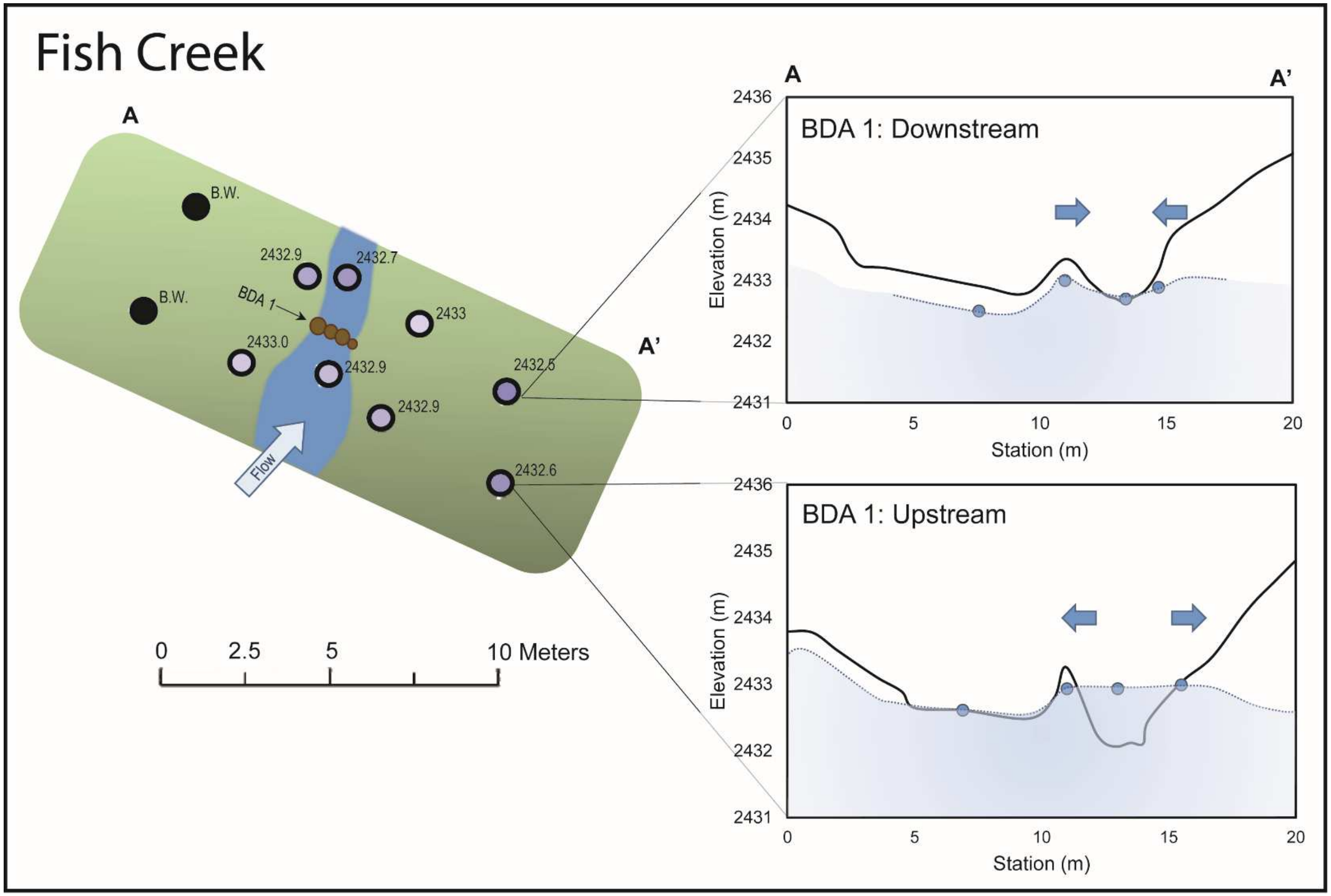


Figure 2.9. Absolute elevation of surface and groundwater surrounding BDA 1 on Fish Creek. Absolute elevations of the water table and stream stage are included in a planform map (left) where lighter colored points indicate a higher water surface elevation and elevations are labeled in meters. Cross-sectional views of stream stage and groundwater depth are superimposed over topographic cross-sections of the ground surface (right). In cross-sectional view, the location of groundwater is estimated from wells and gauges, and blue arrows indicate the expected direction of exchange between the channel and shallow groundwater. The elevations given are absolute elevation as measured by a real-time kinematic (RTK) GPS with centimeter accuracy.

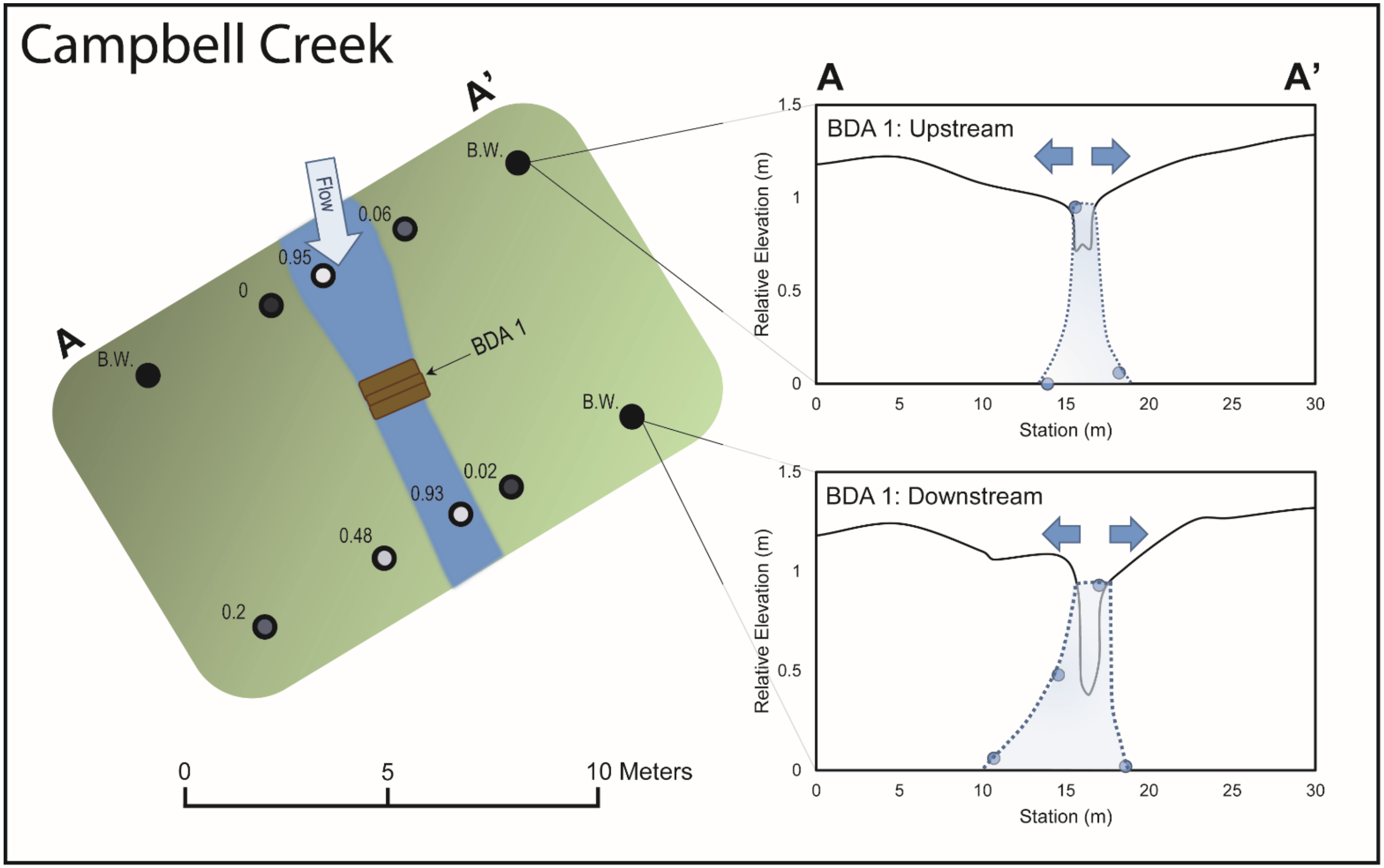


Figure 2.10. Relative elevation of surface and groundwater surrounding BDA 1 on Campbell Creek. Relative elevations of the water table and stream stage are included in a planform map (left) where lighter colored points indicate a higher water surface elevation and elevations are labeled in meters. All elevations are relative to the bottom of the deepest well, which is labeled as zero on the upstream right bank. Cross-sectional views of stream stage and groundwater depth are superimposed over topographic cross-sections of the ground surface (right). In cross-sectional view, the location of groundwater is estimated from wells and gauges, and blue arrows indicate the expected direction of exchange between the channel and shallow groundwater.

6.3. Residual Pool Surveys

Residual pool volume and sediment volume surveys were completed at 10 pools (8 BDA pools, 2 reference) across the Fish and Campbell watersheds twice from July to October 2018. One pool at Fish Creek was an exception and was only measured once due to time limitations. In total, 19 surveys were completed (see Appendix G). Pool names for each survey indicate the BDA where the pool survey was conducted. For both sites, BDA 1 and BDA 2 refer to the upstream and downstream-most BDAs, respectively, which were instrumented in other parts of the study. BDA A refers to the BDA directly downstream of BDA 1, and BDA B refers to the BDA directly upstream of BDA 2 for both sites (Figure 2.11). Reference refers to the reference pool at each site, which was a pool not created by a BDA but rather a natural pool in the reference reach.

Significant sediment aggradation occurred in pools created by BDAs compared to reference pools (Figure 2.12). BDAs at Campbell Creek store up to 3.2 m^3 of sediment, while BDAs at Fish Creek store up to 4.1 m^3. Despite drastically different stream gradients, BDAs at Campbell Creek and Fish Creek stored statistically similar volumes of sediment ($p = 0.946$, Figure 2.13). However, when normalized by pool volume, Fish Creek stores a lower ratio of sediment than Campbell Creek relative to pool size ($p = 0.001$). Therefore, BDAs at Fish Creek are storing a similar magnitude of sediment in larger ponds compared to BDAs on Campbell Creek. There is also a significant difference in the magnitude and ratio of sediment volume stored at BDAs versus reference reaches at both sites, which indicates that BDAs are significantly altering sediment storage on Fish and Campbell Creeks (Table 2.4).

Channel gradient was not a significant predictor of sediment deposition behind BDAs, which disproves part of H2 (Figure 2.14). Pool volume, pool surface area, and BDA height had the strongest correlations to sediment volume (Table 2.5). A dredged multiple linear regression analysis revealed that a combination of BDA height and pool volume created a model with the lowest AICc (AICc = 3.4, adjusted $R^2 = 0.86$).

Equation 1:

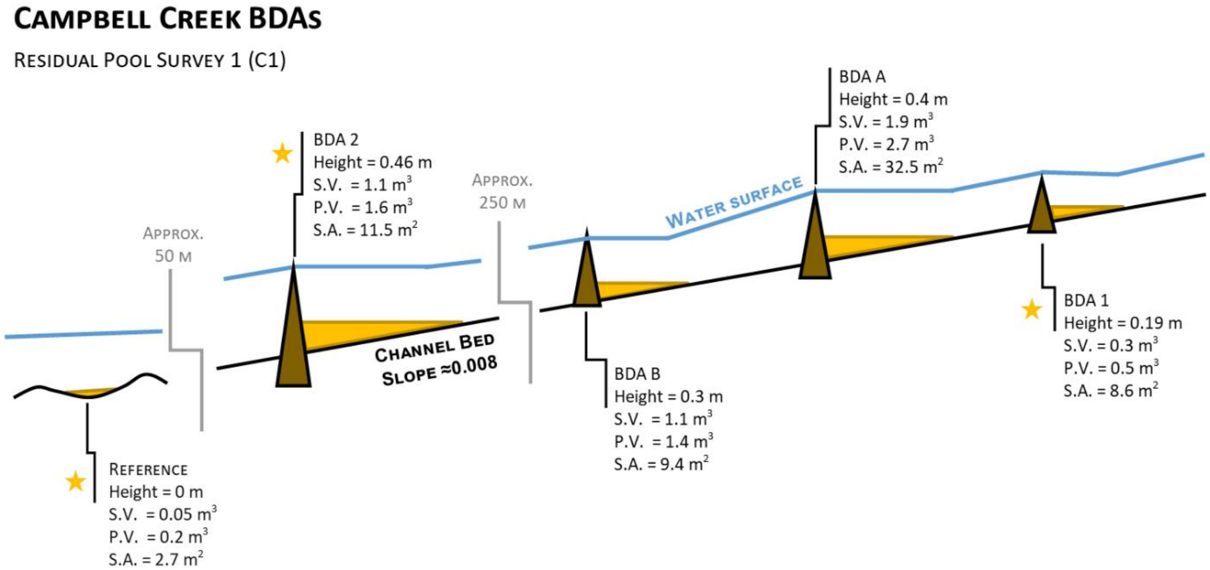
$$\sqrt{Sediment\ Volume} = 1.2 \cdot BDA\ Height + 0.17 \cdot \log(Pool\ Volume) + 0.68$$

Sediment volume was calculated in cubic meters along with pool volume, while BDA height was reported in meters. A second dredged linear regression model was created without transforming non-normal variables. The point of creating a second model was to determine whether significant relationships existed between sediment volume and predictor variables without transformation. Transformations typically have no physical basis in nature; for example, the log value of a pool volume does not have any additional meaning beyond meeting model assumptions of normality. The second linear regression model produced homoscedasticity of residuals, which is another assumption of linear regression models. By dredging the second model, sediment volume was revealed to be a function of BDA height and pool surface area (AICc = 35.9, adjusted $R^2 = 0.83$).

Equation 2:

$$Sediment\ Volume = 3.3 \cdot BDA\ Height + 0.04 \cdot Surface\ Area - 0.1$$

According to both multiple linear regressions, BDA height has the most explanatory power (Figure 2.15). BDA heights across the two restoration projects had a similar range, which explains why sediment volumes were not statistically different across watersheds. Since the models above were built with a small sample size (n = 19), equations should not be used as a predictive model, but rather as a means of showing correlation.



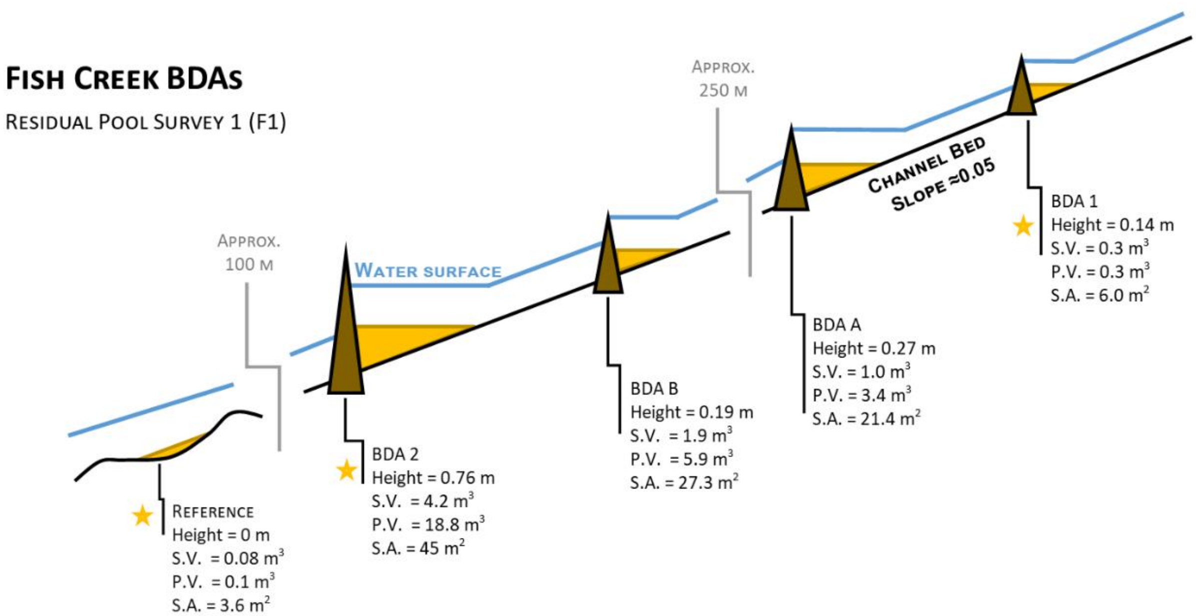


Figure 2.11. Schematic diagrams of BDAs on Campbell (top) and Fish (bottom) Creeks. Values for residual pool sediment volume (S.V.), residual pool volume (P.V.), and surface area (S.A.) are taken from C1 and F1 on Campbell and Fish Creeks, respectively. A star next to the pool description indicates that pool was monitored for surface and subsurface hydrology, as well. Vertical and horizontal lengths are not to scale.

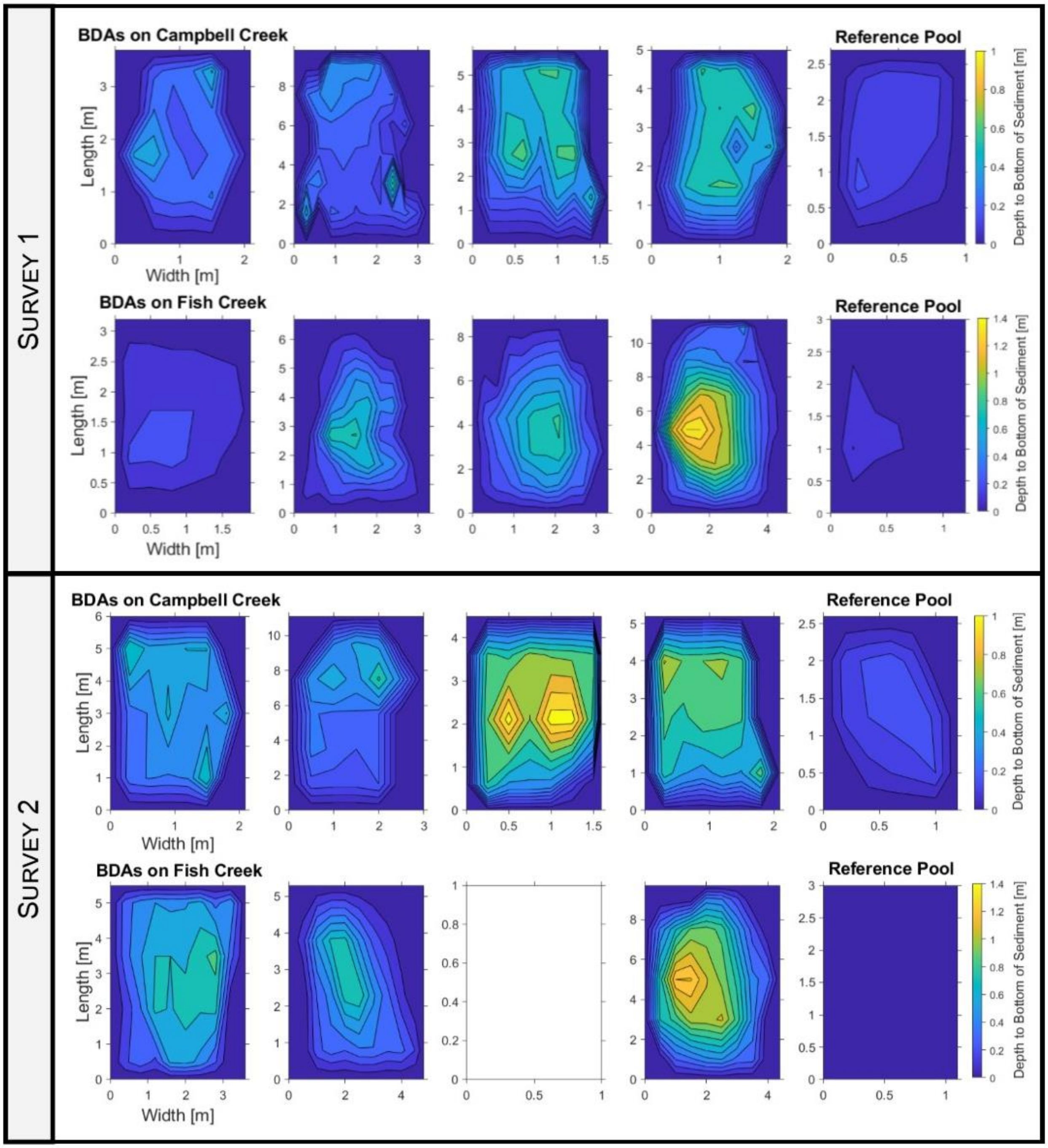


Figure 2.12. Extrapolated sediment + pool depth for all surveyed pools at Fish and Campbell Creek. For both surveys, the top line of pools are at Campbell Creek and the bottom are at Fish Creek. Pools are increasing in distance downstream from left to right. In order from left to right, the pools are behind BDA 1, BDA A, BDA B, BDA 2, and a reference pool at both sites for both surveys. The pool at Fish Creek BDA B was only measured in the first survey.

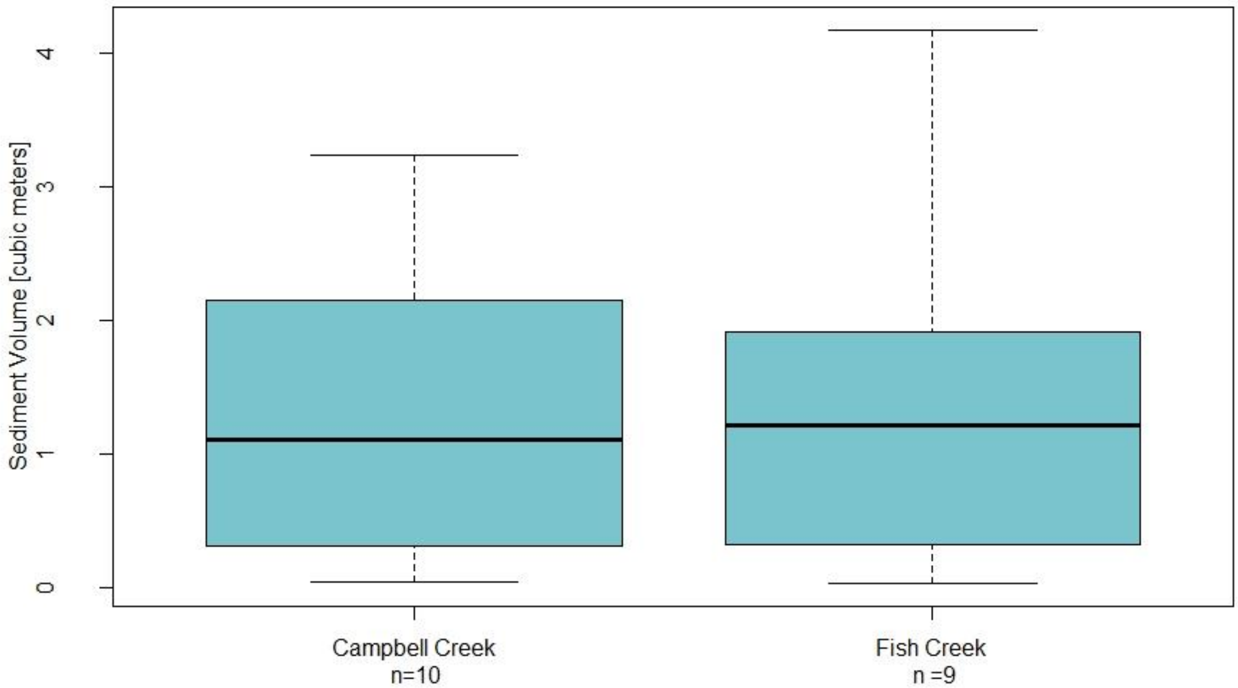


Figure 2.13. Average sediment volume stored in BDA and Reference pools at Campbell Creek (left) and Fish Creek (right). No significant difference in stored sediment volume was measured between the two watersheds.

Table 2.4. p-values comparing sediment volumes and sediment to water volume ratios at BDA pools and reference pools and Fish and Campbell Creeks. P-values < 0.01 indicate a significant difference between values for BDA pools and reference pools (bolded).

Site	Parameter	P Value
Campbell	**Sediment Volume**	**0.0008**
Campbell	**Ratio**	**0.002**
Fish	Sediment Volume	0.014
Fish	**Ratio**	**0.0019**

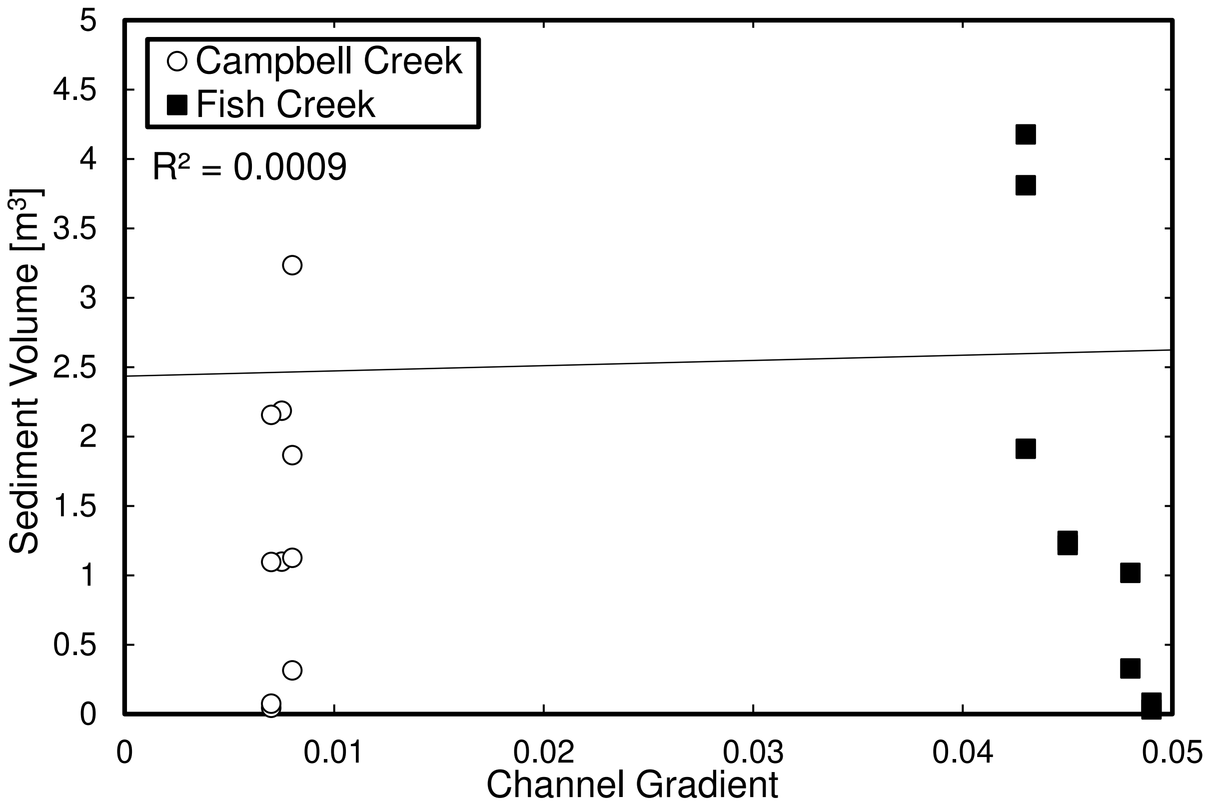


Figure 2.14. Linear relationship between sediment volume and channel gradient. Both BDA and reference pools are considered in the linear relationship. Stream gradient did not have a strong correlation to sedimentation behind BDAs.

Table 2.5. List of predictor variables of sediment volume, including units, range, transformations used in the model, and R values. Pool volume, BDA height, and pool surface area had the strongest correlations to sediment volume.

Predictor Variable	**Units**	**Range**	**Transformation**	**R value[1]**
Pool Volume	Cubic Meters	0.04 – 18.78	Natural Log	0.809
BDA Height	Meters	0 – 0.76	None	0.808
Pool Surface Area	Square Meters	2.7 - 45	Natural Log	0.805
Catchment Area	Square Kilometers	3.85 – 8.13	None	-0.163
Channel Slope	-	0.007 – 0.049	Natural Log	-0.102
Width-to-Depth Ratio	-	2.5 - 19	Natural Log	0.072
% Clay	Percent	21-25	None	0.038

[1] Spearman R values between predictor variable and sediment volume calculated in R using cor() function.

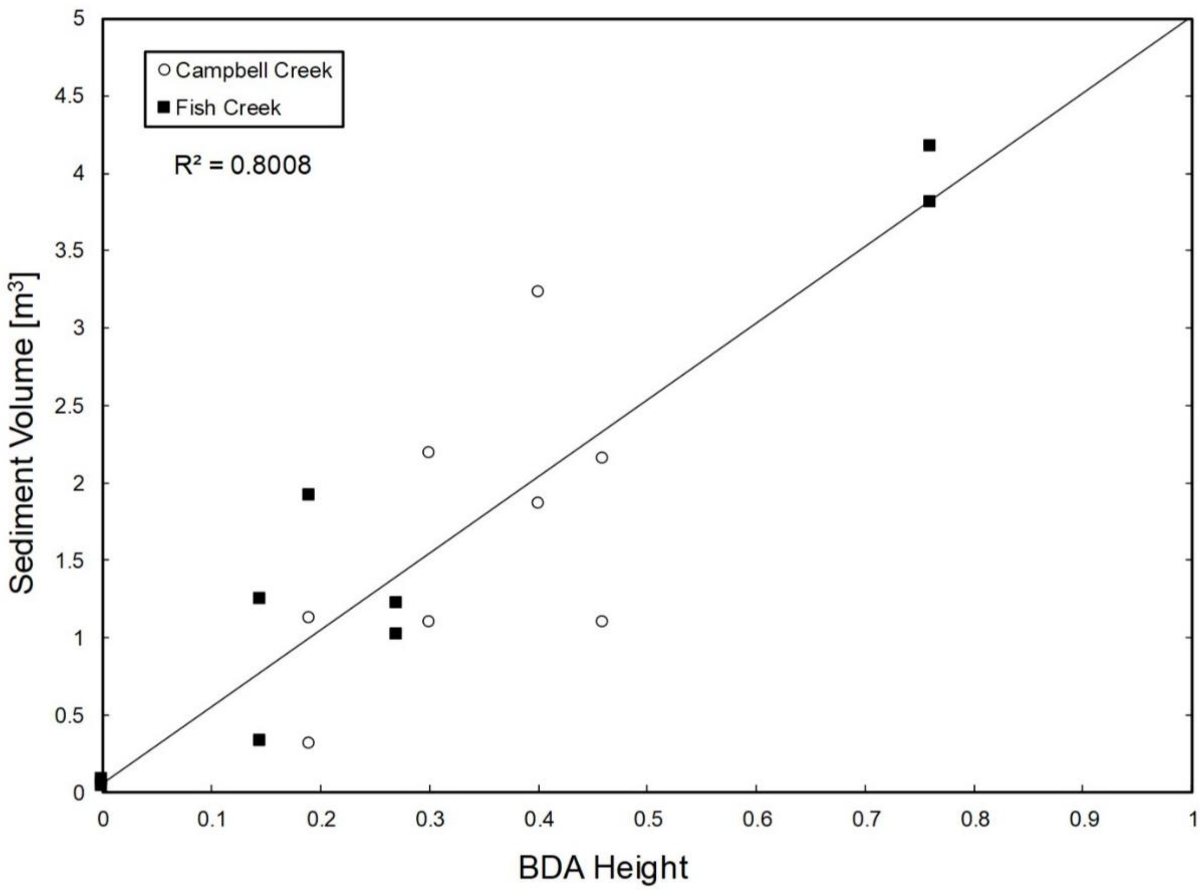


Figure 2.15. Linear relationship between sediment volume at reference and BDA pools and BDA height. BDA height at reference pools was recorded as zero. According to the multiple linear regression analysis, BDA height is the strongest predictor of sedimentation behind BDAs.

6.4. Grain Size Analysis

Sediment cores were analyzed to check for armoring in the pre-restoration channel bed and to estimate percent fines in bank material. It was assumed that the beds of Campbell and Fish Creek were armored based on observing coarser, less cohesive sediments downstream of the BDAs compared to the pond sediments. A pre-restoration armored bed is essential when using the modified V* method, because it is assumed that a coarse layer – the original bed surface – will be easily distinguishable from the accumulated fine sediments.

A grain size analysis from Campbell Creek shows that the reference reach core has nearly equal volumes of sediment for size classes between 0.06 and 4 mm, which suggests a well-graded sample and possible armoring (Figure 2.16). The bed core taken upstream of BDA 1 on Campbell Creek has a similar distribution, although the mean grain size is larger. While intuition would suggest that grain sizes would be finer behind a BDA, the depth of the soil core exceeded the depth of the fine sediment deposited behind the BDA. The gradation coefficient could not accurately be calculated for the Campbell Valley sediments because the d16 was finer than the sieve analysis recorded (<62.5 μm). However, the distribution of the analysis and field observations suggest that the pre-restored bed surface at Campbell Creek has a distinguishably larger grain size than finer material deposited upstream from the BDA.

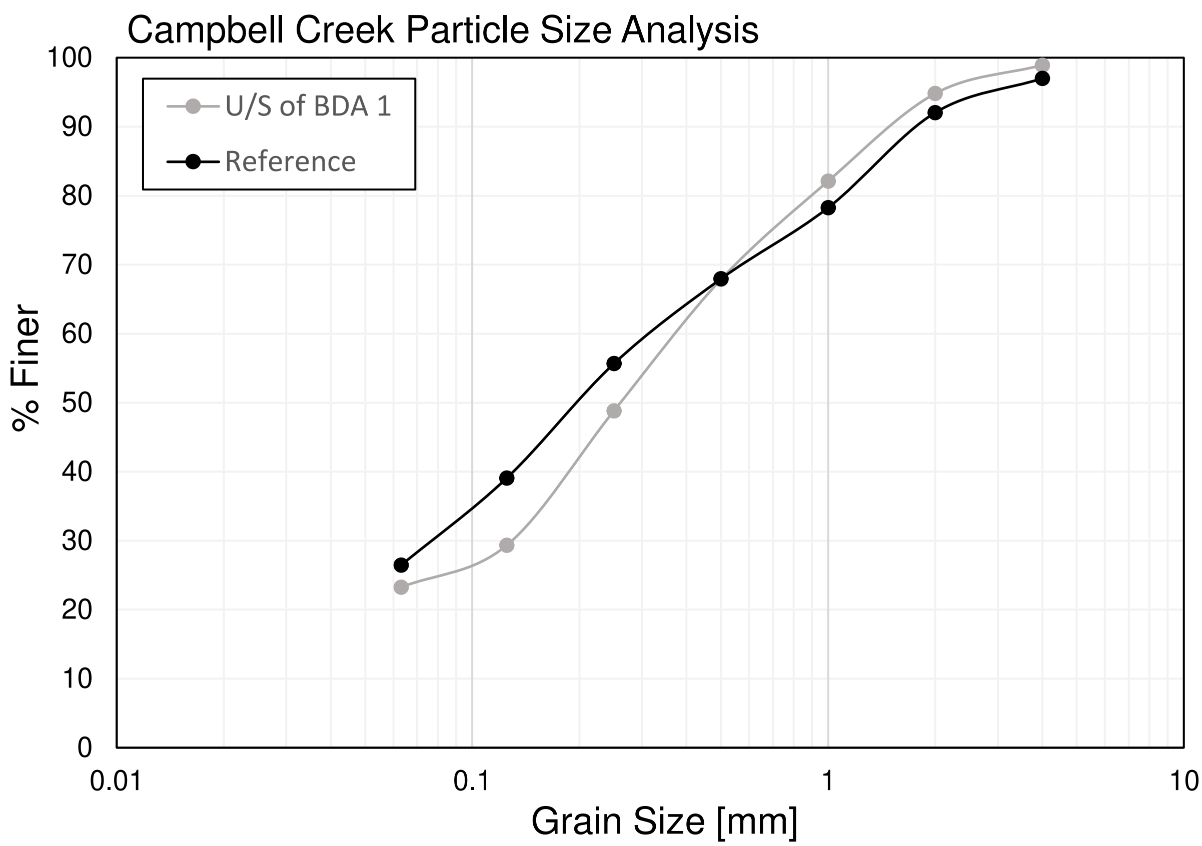


Figure 2.16. Grain size analysis of cores taken upstream of BDA 1 and at the reference pool on Campbell Creek. While surface sediment was not analyzed separately from subsurface material, the well-graded cores suggest that the creek contains an armor layer.

To further constrain armoring, a sample of Fish Creek bed sediments downstream of BDA 2 was separated into 0 – 50 mm depth and 50 – 225 mm depth categories in the field to determine the d50 of the surface compared to the subsurface (Figure 2.17). Separating surface from subsurface material was decided upon in the field after sampling at Campbell Creek, which is why a subsurface analysis was not done there. Average grain size of the surface material at Fish Creek was 5 times larger than the subsurface material, suggesting that the pre-restoration channel bed was armored.

Finally, the percent fines calculated from the sieve analysis were compared to the percent soil clay recorded in the Natural Resources Conservation Service (NRCS) Soil Survey for both valley bottoms. NRCS surveys recorded an average of 21% clay in soils proximal to restoration on Campbell Creek and an average of 25% clay in soils near the Fish Creek BDAs. All sediment finer than fine grained sand – the minimum grain size recorded in the sieve analysis – was considered part of the percent fines for the soils at both sites. The sieve analysis indicated approximately 23% fines in soils at Campbell Creek and 15% fines at Fish Creek. Therefore, the NRCS survey and the sieve analysis indicate similar percent fines for Campbell Creek, but not for Fish Creek.

Discrepancies between measured and mapped fines at Fish Creek could be due to scale issues on the soil survey map. A new soil survey map was completed in December 2013, after the 2013 Colorado Front Range flood where Fish Creek deeply incised into the finer surrounding valley bottom. However, the width of incision is small compared to the resolution of the soil survey map. Mapped units along the creek are the same as the mapped units on the un-incised floodplain. However, grain sizes visually appeared to be coarser near the incised channel compared to the old floodplain. No cores were taken on the old floodplain, so comparisons cannot be made from un-incised floodplain sediments to the NRCS soil survey.

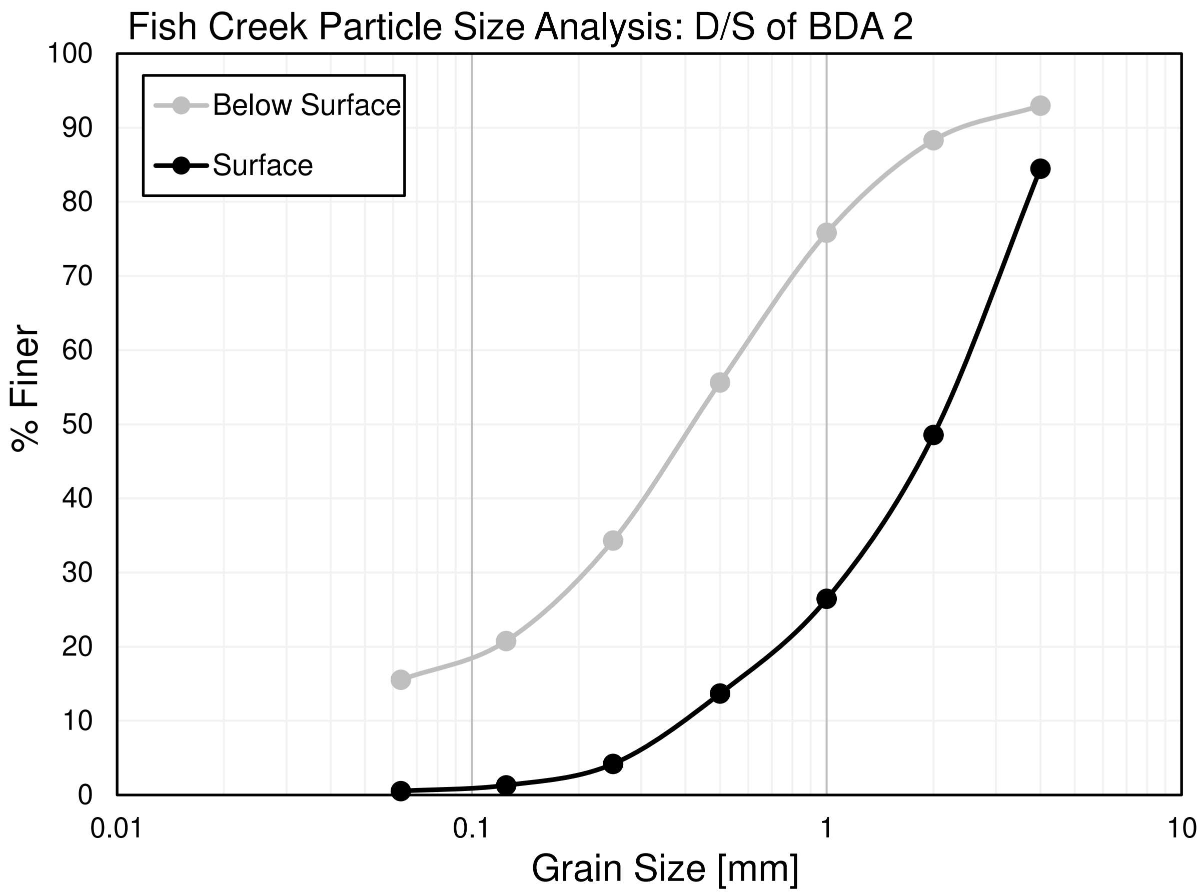


Figure 2.17. Grain size analysis of a sediment core taken downstream of BDA 2 on Fish Creek. Surface sediment (0 – 50 mm depth) was separated from the rest of the core in the field in order to compare the coarser bed material to the subsurface material. D50 for surface material was 2 mm while D50 for subsurface bed material was 0.4 mm.

7. Discussion

7.1. Determining palpable sediment relationships

Sedimentation models for BDAs are useful for managers to understand what variables are influencing bed aggradation, which was listed as a desired outcome at both restoration sites in this study. Due to low samples sizes, sediment models developed by this project should not be used predictively. Instead, variables included in the sediment equations represent general trends and correlations that could be useful for understanding future projects.

The three significant predictors of sediment volume – BDA height, pool volume, and pool surface area – all indicate that geometry specific to each analog and the near channel are influencing sedimentation more than watershed-scale characteristics. However, variables other than those included in the model could have an influence on sedimentation. For example, suspended sediment was not measured during monitoring, but likely has an influence on how much sediment could accumulate behind dams at either site. Campbell Creek should have a higher suspended sediment load based on lithology and climate. However, measured variables still provide insight into the correlation between restoration design and outcomes.

BDA height is the only variable to prove significant in both models, and analog height makes physical sense. If sedimentation behind a BDA is treated as a wedge forming approximately a triangular prism, the tallest part of the wedge would be buttressed against the BDA. Therefore, the maximum dimensions of the wedge would be controlled by the height of the BDA. Pollock et al. (2003) used physical dimensions of beaver ponds to estimate maximum sediment volume, and included BDA height as a significant predictor based on geometry of the pond alone:

$$V_m = 0.5H^2W/S$$

Where H is dam height (in meters), W is dam width (in meters), and S is stream slope. While only linear models were used to predict sedimentation in this study, BDA height has a significant correlation to sediment volume. Correlation between sediment and height, although geometrically intuitive, has not been recorded in previous field studies of beaver dam sedimentation. Naiman et al. (1986) found no significant correlation between dam geometry and sedimentation in ponds in boreal forests of Canada. Field studies such as this are what prompted the initial hypothesis that factors other than dam geometry would have the most significant correlation to BDA height.

The other two significant predictors – pool volume and pool surface area – are where the two sedimentation models diverge. Which model is better? While both models offer explanation of sedimentation behind BDAs, pure numbers would suggest that the pool volume is better than the pool surface area model, which have R^2 values of 0.86 and 0.83, respectively. However, pool volume is difficult to measure accurately in the field, and previous beaver dam sedimentation studies (e.g. Naiman et al., 1986) have not found pool volume to be a significant or simple predictor of sediment. Log transformation of the pool volume variable further decreases the physical usefulness of the pool volume model, because a log transformation holds no physical meaning in nature. Instead, a large change in pool volume would result in a small change in sediment volume. Conversely, surface area is easier to measure in the field or estimate from photographs, and since no transformation was necessary, the direct comparison makes more physical sense. Multiple studies have found pool surface area to be a significant predictor of sedimentation behind a beaver dam (Naiman et al., 1986; Butler and Malanson, 1995).

Despite pool surface area creating a slightly less significant model than pool volume, the model makes more physical sense. Additionally, the differentiation between the two models is likely small, because pools with larger volumes are likely to also have larger surface areas. Surface area is an easier variable to record in order to facilitate future comparisons and is cited as a significant predictor in previous dam sedimentation studies. Sediment volumes measured on Campbell and Fish Creeks were compared to maximum sediment volumes predicted by previously published models (Figure 2.18). Measured sediment data were compared to the geometric relationship in Pollock et al. (2003) and the surface-area-based equation from Naiman et al. (1986):

$$S = 47.3 + 0.39 \cdot SA$$

Where S is sediment volume in cubic meters and SA is surface area in square meters.

Sediment volumes calculated using Pollock et al. (2003) were higher than measured volumes except for a few pools at Fish Creek. Volumes calculated from Naiman et al. (1986) were all much higher than measured sediment volumes (note the logarithmic scale in Figure 2.18). Higher sediment volumes would be expected from these two equations. First, Pollock et al. (2003) estimates maximum sediment volume, which would likely not be reached within the first year after dam construction. Natural beaver dams and BDAs alike exhibit increasing sediment volumes with age (Butler and Malanson, 1995; Bouwes et al., 2016). Dams used to develop the Naiman et al. (1986) equation were a range of ages with many presumably over a year old, and all dams had higher surface areas (minimum surface area approx. 100 m^2) than measured BDA ponds, therefore the current comparison extends beyond the reach of the original equation.

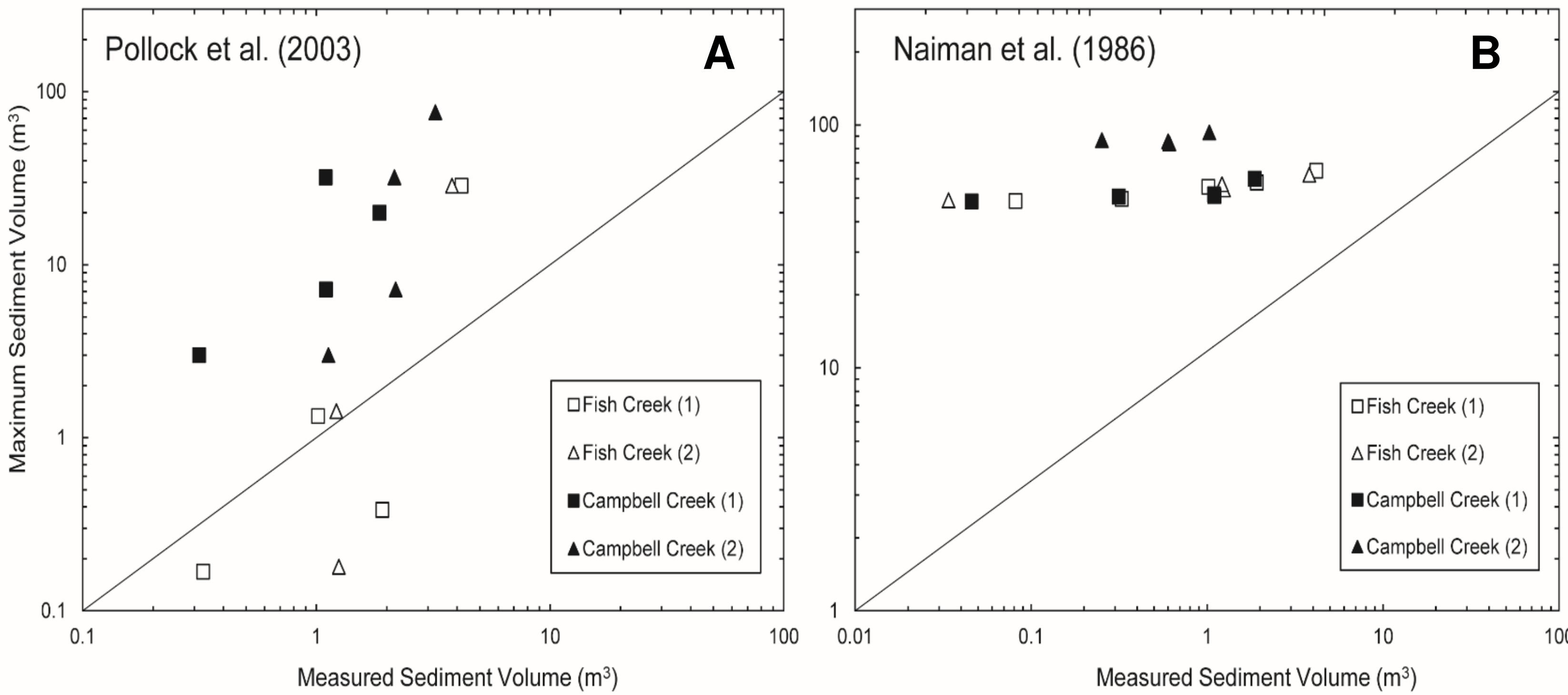


Figure 2.18. Comparison of measured sediment volumes to sediment volumes predicted by (A) Pollock et al. (2003) and (B) Naiman et al. (1986). Color and shape reflect the location and survey. Generally, sediment equations derived for beaver dams predict sediment volumes much higher than measured volumes on Fish and Campbell Creeks.

Differences between beaver dam sediment equations and measured BDA sediment could suggest that BDAs do not act like beaver dams. BDAs storing more sediment than predicted (Figure 2.18a) could indicate that the height of at least one BDA was measured incorrectly, or could indicate that the bed was not uniformly graded before BDA installation, which could have created more places for storage thus resulting in a higher stored sediment volume. High values predicted by Naiman et al. (1986) could either suggest that real beaver dams are more effective at trapping sediment, or that the studied BDAs are not sufficiently old to reflect a magnitude of sedimentation similar to the Canadian study. Natural beaver dams measured by Naiman et al. (1986) likely extended onto the floodplain and created pools that extended far beyond the channel banks, which is common for natural dams. Larger natural dams that extend onto the floodplain are less likely to pass suspended sediment than a BDA that could be overtopped or bypassed during high flow. Longer studies of BDA response could untangle whether discrepancies in sedimentation rates between beaver dams and the BDAs on Fish and Campbell Creeks are due to design, age, or some other factor.

7.2. Lack of groundwater response

The absence of a groundwater response was unexpected. Previous studies have monitored and described groundwater rise upstream of beaver dams in Colorado (Westbrook et al., 2006), and even proximal to BDAs at a study on Bridge Creek, Oregon (Bouwes et al., 2016). However, groundwater on Fish and Campbell Creeks appears to have been controlled more by local factors than by the installation of BDAs, thus disproving my third hypothesis (H3).

Variable response at wells located around the same BDA for the same rainfall event at Campbell Creek indicate that patches of clay in the soil could be the dominant control or limitation to the water table. Higher water tables on the right banks of Fish Creek could be driven by a series of natural beaver dams higher on the floodplain past the right bank. Both site-specific explanations describe groundwater dynamics better than the presence of BDAs, which have no statistically significant influence on the water table.

A lack of discernable groundwater difference around BDAs at Fish or Campbell Creek could be due to BDA construction compared to regular beaver dams. Beaver dams built on Fish Creek are much wider and pond more water, which suggests that real dams are less permeable. For example, a beaver dam built over a BDA on Fish Creek visually increased ponded water by double or more (Figure 2.3). Since ponded water and increased overbank flow are inferred to cause increased infiltration at beaver dams (Westbrook et al., 2006), BDAs might be too small and permeable to cause significant groundwater rise at Fish or Campbell Creeks. However, lack of groundwater response could also be due to time since installation. Monitoring of BDAs occurred one year after restoration at both sites and results may not be indicative of groundwater change that could occur over multiple years to decades post-restoration. Long-duration decline in riparian water tables following channel incision, for example, might take multiple years to reverse if water infiltrating into the bed and banks upstream from each BDA represents a small proportion of available riparian groundwater storage.

The indication that Fish Creek changes from a gaining to a losing stream around a BDA (Figure 2.9) could be evidence that larger groundwater changes will occur in future years after BDA restoration. While Fish Creek is normally fed by groundwater, water table gradients suggest recharge from the channel to shallow groundwater upstream of BDA 1. Therefore, BDAs could change a gaining stream to a losing stream. However, if the stream is already losing, as at Campbell Creek, potential recharge from BDAs in the first year is still not enough to significantly raise the water table. Expectations for groundwater response following BDA installation should not be immediate and further research is needed to understand the timeline of hydrologic response post-restoration.

7.3. Design influences BDA response

Construction differences between BDAs on Fish and Campbell Creek beg the question of whether BDA design influences channel response. Differences in BDA construction between Fish and Campbell Creeks affected pool morphology post-restoration. Deeper pools persisted upstream of Fish Creek BDAs compared to downstream, while Campbell Creek BDAs elicited an opposite response. Difference in pool depth are likely a function of how much water overtopped BDAs on Fish and Campbell Creek throughout the season. Campbell Creek BDAs were designed so that water would overtop the analog most of the season to avoid conflict with downstream water users. Constant overtopping likely created scour downstream of structures which accounts for the deeper downstream pools on Campbell Creek. Fish Creek BDAs were constructed to trap water and force ponding, which limited water downstream of the structure but increased water depths upstream. Pictures from the field indicate increased channel surface area upstream of BDAs at both sites, which means that ponds were created upstream of Campbell Creek BDAs despite the fact that BDAs did not increase depth upstream (Figure 2.19). Instead, upstream pools at Campbell Creek were shallow and filled with sediment. Theoretically, deeper ponds at Fish Creek should reduce velocities more effectively, thus causing more sediment to fall out of suspension. Campbell Creek dams likely store a similar amount of sediment to Fish Creek due to a high sediment load. Assessing whether one design is better than the other depends on the intent of the restoration project. Increased pool habitat for other species such as fish is commonly an outcome of BDA restoration (e.g. Pollock et al., 2004; Bouwes et al., 2016), but was not cited as a reason for restoration at Fish or Campbell Creeks.

Halting incision and promoting aggradation was cited as a restoration goal for projects on Campbell and Fish Creeks. BDAs at both projects successfully trapped sediment and caused aggradation, but design still had an effect on channel change post-restoration. As previously discussed, BDA height significantly correlates to and possibly influences sedimentation behind BDAs. Unlike pool morphology, sedimentation response was consistent across the two watersheds. The tallest BDAs stored the most sediment at both restoration sites, which means that the type of structure does not matter as much as the dimensions of the structure when it comes to addressing erosion concerns. Construction dominates over the watershed-scale variables examined in this analysis when explaining BDA-induced sedimentation.

This study can identify some channel changes post-BDA restoration, but initial channel change may not be indicative of long-term changes. This study suggests aggradation is dependent on construction features of BDAs, yet aggradation does not fuel increased infiltration as previously hypothesized (Figure 2.20). However, sedimentation will continue with age, which will likely continue to fill in gaps in the BDAs, thus reducing permeability further with time. As BDAs become less permeable, they become more efficient at trapping water and could subsequently create larger ponds and overbank flooding. Increased inundation could then cause a groundwater response. While design can be assessed within the first year, long term studies will determine whether pool, sedimentation, and groundwater patterns persist or whether watershed-scale factors will eventually have an effect on channel response.

Figure 2.19. Ponding behind BDAs at Campbell Creek (left) and Fish Creek (right). BDAs at both sites widen the channel upstream and cause overbank flow. BDAs on Fish Creek create upstream ponds that are much deeper than downstream flow, which is expected. However, BDAs on Campbell Creek have shallow upstream pond filled with sediment and deep downstream pools caused by scour.

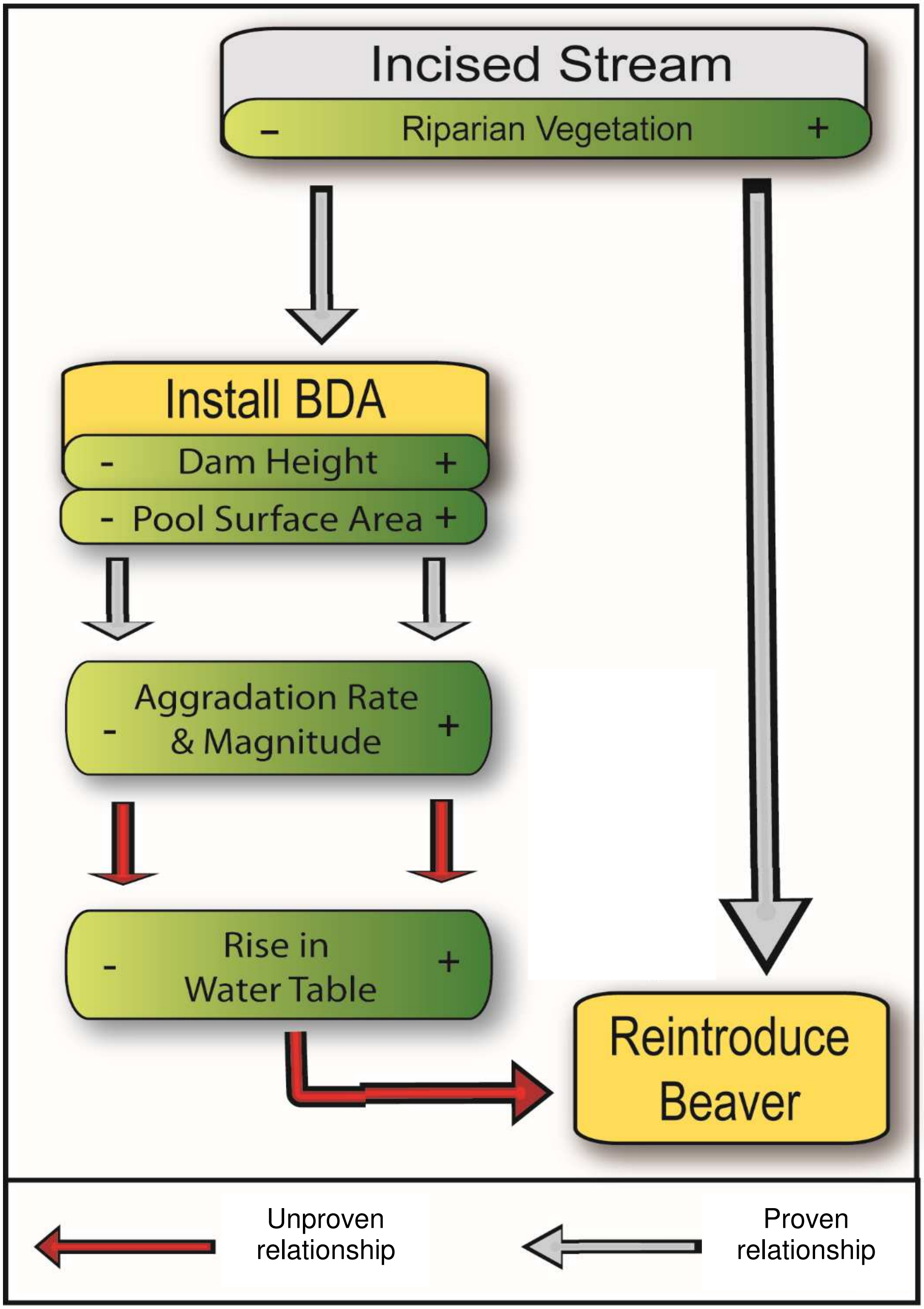


Figure 2.20. Edited conceptual diagram indicating known channel response to BDAs in the Colorado Front Range. BDA installation caused aggradation but not groundwater rise.

8. Conclusions

Increasing enthusiasm for using BDAs as a restoration tool in the Colorado Front Range elicited the current study on channel change post-installation. Research now shows that previous hypotheses equating channel response to BDAs with channel response to natural dams (H1) are not always true. Particularly, the idea that BDAs can be used to raise water tables and promote riparian vegetation (H3) in the Colorado Front Range is not demonstrated within the first year of installation. Local factors such as soil grain size and regional water table gradients have a larger effect on groundwater than BDAs. Systematic sampling across more watersheds and restoration sites could illuminate how local factors influence restoration outcome. Additionally, further studies where groundwater measurements can be made prior to restoration and over longer time periods would help elucidate how BDAs affect water tables in the Front Range.

BDAs can be used as an effective tool for causing aggradation and addressing incision concerns in Front Range channels (H2). Similar to natural dams, sedimentation behind BDAs can be predicted by surface area and BDA height. However, maximum sedimentation is likely not reached within the first year of BDA installation. Future studies should look at sedimentation in more ponds, across more restoration sites, for longer time periods. Future models of sedimentation should also investigate the influence of suspended sediment load on restoration outcomes. Long-term monitoring projects over years to decades will be needed to fully understand expected outcomes of BDA restoration projects.

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APPENDIX A: BRAT BASIN CHARACTERISTICS

Description

Regional regressions were used to model hydrology within the 6 major hydrologic regions of Colorado: Mountains, Northwest, Rio Grande, Southwest, Foothills, and Plains. Equations for high (2-year peak flow) and low (baseflow) are found in Capesius and Stephens (2009) and Kohn et al. (2015). Variables other than drainage area in all regional regressions were estimated for each basin. Necessary basin characteristics were estimated using USGS StreamStats. All estimated variables were then plugged into the Q_2 or Q_{low} regression equations to yield a coefficient. When plugging hydrologic regressions into BRAT, drainage area was multiplied by either the Q_2 or Q_{low} coefficient for high or low flow, respectively, and then raised to an exponent defined in the regression equation (see Table 1.2).

Regression Variables

S	Basin averaged slope given in percent gradient (%)
P	Mean annual precipitation in inches (IN.)
E	Mean basin elevation in feet (FT.)
A_{7500}	Percent area above 7500 ft. elevation (%)
${}_6P_{100}$	6-hour, 100-year precipitation in inches (IN.)
C	Percent clay in watershed soils (%)
E_{out}	Elevation of watershed outlet in feet (FT.)

Basin-averaged Estimates of Regression Variables

Table A1. Regression variable estimates for watersheds in the Foothills hydrologic region. Required variables for Q_2 and Q_{low} regressions are ${}_6P_{100}$, C, and E_{out}.

Watershed Name	Outlet Longitude	Outlet Latitude	6P100 (IN.)	C (%)	Eout (FT.)	Q_2 Coefficient	Q_{low} Coefficient
Lone Tree – Owl	-104.588	40.424	3.65	17.3	4591	41.366	0.083
Crow	-104.492	40.386	3.46	17.4	4557	39.313	0.078
Kiowa	-104.089	40.336	3.83	18.2	4383	52.457	0.105
Fountain	-104.589	38.254	3.89	22.4	4637	54.518	0.109
Chico	-104.365	38.242	3.92	15.2	4503	43.267	0.087
Upper Arkansas	-104.393	38.248	3.4	19.9	4517	44.026	0.088
Huerfano	-104.246	38.229	3.34	24.0	4442	52.704	0.105

Table A2. Regression variable estimates for watersheds in the Mountains hydrologic region. Required variables are S and P for Q2 regressions and E and P for Qlow regressions.

Watershed Name	Outlet Longitude	Outlet Latitude	S (%)	P (IN.)	E (FT.)	Q_2 Coefficient	Q_{low} Coefficient
Tomichi	-106.967	38.517	24	18.4	9697	6.907	0.006
Cache La Poudre	-104.600	40.422	16.9	18.7	7099	6.724	0.001
Big Thompson	-104.761	40.354	25.8	20.8	7298	9.104	0.001
Saint Vrain	-104.874	40.271	20.8	21.5	7234	9.352	0.001
Clear	-104.950	39.828	32.4	22.9	8912	11.494	0.005
Upper South Platte	-105.010	39.754	14.9	20.5	6787	8.019	0.001
South Platte Headwaters	-105.340	39.097	16.6	18.2	9641	6.340	0.006
Arkansas Headwaters	-105.257	38.434	29	18.0	9363	6.866	0.005
Blue	-106.398	40.042	31.3	24.9	10271	13.628	0.018
Eagle	-107.057	39.646	33.5	25.0	9418	13.961	0.010
East-Taylor	-106.847	38.664	32.1	26.9	10505	16.153	0.026
Roaring Fork	-107.330	39.549	38.3	29.3	9596	19.861	0.016
North Fork Gunnison	-107.836	38.783	28.1	25.0	8263	13.550	0.004
North Platte Headwaters	-106.345	40.930	14.6	22.9	8867	10.037	0.005
Upper Gunnison	-107.837	38.782	29.1	22.0	9712	10.422	0.009
Upper White	-108.404	40.173	25.5	22.7	7745	10.914	0.002
Colorado Headwaters	-107.330	39.549	22.6	24.2	7252	12.185	0.001

Table A3. Regression variable estimates for watersheds in the Northwest hydrologic region. Required variables are A_{7500} and P for Q_2 regressions and E for Q_{low} regressions.

Watershed Name	Outlet Longitude	Outlet Latitude	P (IN.)	E (FT.)	A_{7500} (%)	Q_2 Coefficient	Q_{low} Coefficient
Upper Yampa	-107.658	40.436	27.8	8010	57	17.171	0.018
Colorado Headwaters - Plateau	-109.100	39.093	16.0	8566	71	4.785	0.034
Lower Yampa	-108.984	40.527	20.1	7301	32	10.856	0.007
Little Snake	-108.455	40.453	16.6	7057	22	8.340	0.005
Lower White	-109.679	40.062	18.1	6913	26.6	9.328	0.004
Vermilion	-108.887	40.762	12.2	7060	17	4.783	0.005
Piceance-Yellow	-108.245	40.089	18.4	7296	39	8.213	0.007
Lower Gunnison	-108.578	39.062	18.0	8720	75	6.026	0.040

Table A4. Regression variable estimates for watersheds in the Plains hydrologic region. Required variables are S and C for Q_2 and Q_{low} regressions.

Watershed Name	Outlet Longitude	Outlet Latitude	S (%)	C (%)	Q_2 Coefficient	Q_{low} Coefficient
Arikaree	-101.938	40.020	2.9	18.8	31.725	0.063
Pawnee	-103.236	40.564	3.7	20.1	42.496	0.085
Beaver	-103.546	40.344	4.2	24.1	63.323	0.127
Bijou	-103.861	40.285	4.8	25.3	74.460	0.149
North Fork Republican	-101.938	40.019	3.0	19.0	33.148	0.066
South Fork Republican	-101.517	40.048	2.9	23.6	47.253	0.095
Middle South Platte - Sterling	-102.383	40.953	9.7	18.5	70.315	0.141
Upper Arkansas - Lake Meredith	-103.326	38.072	13.3	21.0	109.028	0.218
Upper Arkansas - John Martin Reservoir	-102.048	38.031	9.3	21.9	91.388	0.183
Sand Arroyo	-101.488	37.477	1.5	23.1	29.015	0.058
Bear	-101.338	37.856	1.6	18.1	19.772	0.040
Horse	-103.327	38.072	2.0	21.5	31.432	0.063
Rush	-102.528	38.367	2.2	18.2	24.902	0.050
Apishapa	-103.949	38.127	8.5	24.4	104.354	0.209
Purgatoire	-103.178	38.065	12.8	24.2	135.700	0.271
Two Butte	-102.126	38.042	3.6	21.6	46.854	0.094
Big Sandy	-102.484	38.112	2.6	21.2	36.185	0.072

Table A5. Regression estimates for watersheds in the Rio Grande hydrologic region. Required variables are P for Q_2 regressions and E for Q_{low} regressions.

Watershed Name	Outlet Longitude	Outlet Latitude	P (IN.)	E (FT.)	Q_2 Coefficient	Q_{low} Coefficient
San Luis	-105.744	37.474	14.28	8683	0.693	0.004
Saguache	-105.864	37.867	16.65	8979	1.011	0.005
Rio Grande Headwaters	-106.367	37.686	30.75	10511	4.572	0.031
Conejos	-105.737	37.304	26.2	9505	3.083	0.010
Alamosa - Trinchera	-105.719	37.000	19.07	9098	1.411	0.006

Table A6. Regression estimates for watersheds in the Southwest hydrologic region. Required variables are A_{7500} for Q_2 regressions and P and E for Q_{low} regressions.

Watershed Name	Outlet Longitude	Outlet Latitude	P (IN.)	E (FT.)	A_{7500} (%)	Q_2 Coefficient	Q_{low} Coefficient
Piedra	-107.402	37.008	27.0	8592	77	30.294	0.029
San Miguel	-108.803	38.380	21.8	7959	57	31.219	0.016
Uncompahgre	-108.090	38.756	19.0	7846	52	31.506	0.013
Animas	-108.221	36.714	29.0	9500	60	31.059	0.047
Lower Dolores	-109.279	38.821	20.3	7660	50	31.630	0.012
Upper Dolores	-108.803	38.380	21.5	7753	52	31.506	0.014
McElmo	-109.184	37.217	10.3	6200	2	43.641	0.002
Mancos	-108.980	36.983	15.4	6660	29	33.424	0.005

APPENDIX B: SITE SUITABILITY CHECKLIST AND SCORECARD

Boulder County/City Site Geomorphology Check List

Site Name/Location: ____

GPS Coordinates: ____

Physical Characteristics

Channel Gradient: ______________________

Valley Bottom Width: ________________________

Site Length: __________________

Flow Regime: Ephemeral Intermittent Perennial

Channel Width: __________ Channel Depth: ____________ Ratio: ___________

Channel incision depth: ___________________

Dominant stream substrate: Silt/Clay/Mud Sand Gravel Cobbles Boulders Bedrock

Ecological Characteristics

Dominant riparian vegetation: ____

____

Distance of viable vegetation from stream: ____________________________________

Presence of abundant 1-6" diameter woody vegetation? Yes No

Evidence of elk? (Ex: teeth marks on Aspen, evidence of grazed willows) Yes No

If yes, describe evidence: ____

Evidence of pre-existing berms? Yes No GPS coordinates of berms: _______

Human Hazards (Check if Present)

______ Ditches Coordinates: _______________

______ Culverts Coordinates: _______________

______ Intakes Coordinates: _______________

______ Bridges Coordinates: _______________ Height above water: ______

______ Roads or Trails Proximity to site: _____________________

______ Private Property LinesProximity to site: _____________________

______ Other (Specify :_____________________________) Location: ______________

Geomorphology Scorecard

Site Name/Location: ____

GPS Coordinates: ____

______**Channel Gradient**: ≤ 3% (**10 pts**) 4 – 6 % (**0 pts**) 7-9% (**-10 pts**) ≥ 9% (**-30 pts**)

______**Valley bottom width**: Wide, > 100 meters (**5 pts**) Narrow, <100 meters (**0 pts**)

______**Site Length**: > 1 km (**5 pts**) < 1 km (**1 pt**)

______**Flow Regime:** Ephemeral (**-10 pts**) Intermittent (**5 pts**) Perennial (**10 pts**)

Woody Food (Select the highest possible in each line – then multiply the lines)

a. Aspen/willow (**3 pts**) Alder (**2 pts**) Other hardwoods (**1 pt**)

b. Within 10 m (**3 pts**) Within 30 m (**2 pts**) Within 100 m (**1 pt**)

c. Abundant, >50 stems (**2 pts**) Moderately abundant (**1 pt**) Not abundant (**0 pts**)

______ **Woody food score = multiply a x b x c**

______**Herbaceous Food**: Grasses and forbs abundant (**10 pts**) No grasses/forbs (**5 pts**)

______**Dominant Stream Substrate:**

Silt/Clay/Mud (**5 pts**) Sand (**2 pts**) Gravel (**1 pt**) Cobbles (**0 pts**) Boulders (**-1 pt**) Bedrock (**-3 pts**)

______**Historical Beaver Use:** Old berms present (**15 pts**) No indication of berms (**0 pts**)

______**Presence of dam building materials:**

Abundance of 1-6” diameter woody vegetation (**5 pts**) No building material present (**-20 pts**)

______**Browsing/Grazing Impacts:** No browsing (**5 pts**) Heavy browsing (**-10 pts**)

______**Ease of Access:** Easy travel to deliver beavers and monitor (**2 pts**) Long hike (**-5 pts**)

______**Existing aquatic escape cover:** Multiple deep pools present (**10 pts**) No Pools (**-10 pts**)

______**Total Score** (100 points maximum)

APPENDIX C: PERENNIAL BRAT OUTPUT MAPS

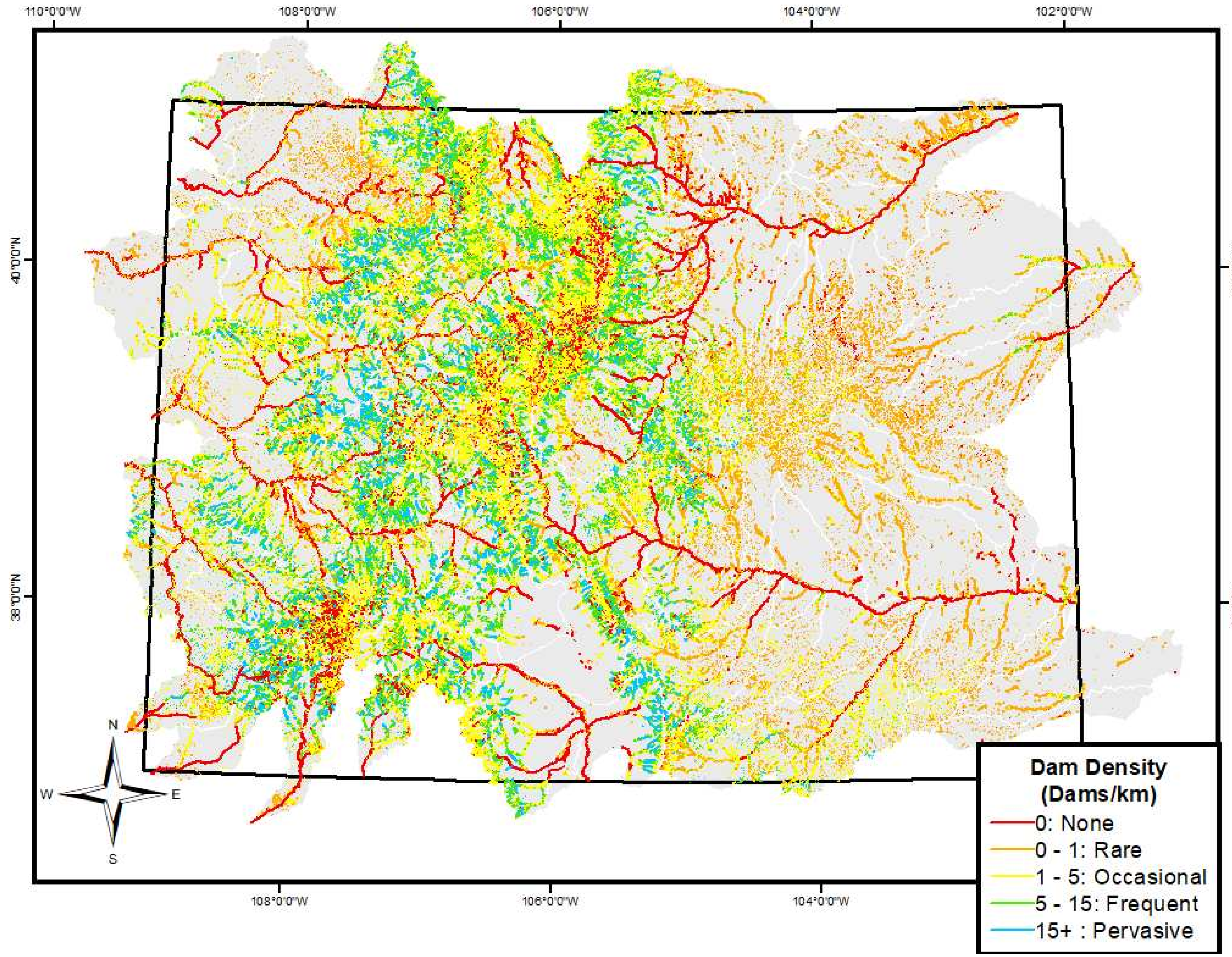

Figure C1. Current dam density predicted by BRAT for perennial streams in Colorado. Cool colors represent streams with high dam building potential while warm colors represent lower potential. Red streams indicate where dam building would not occur.

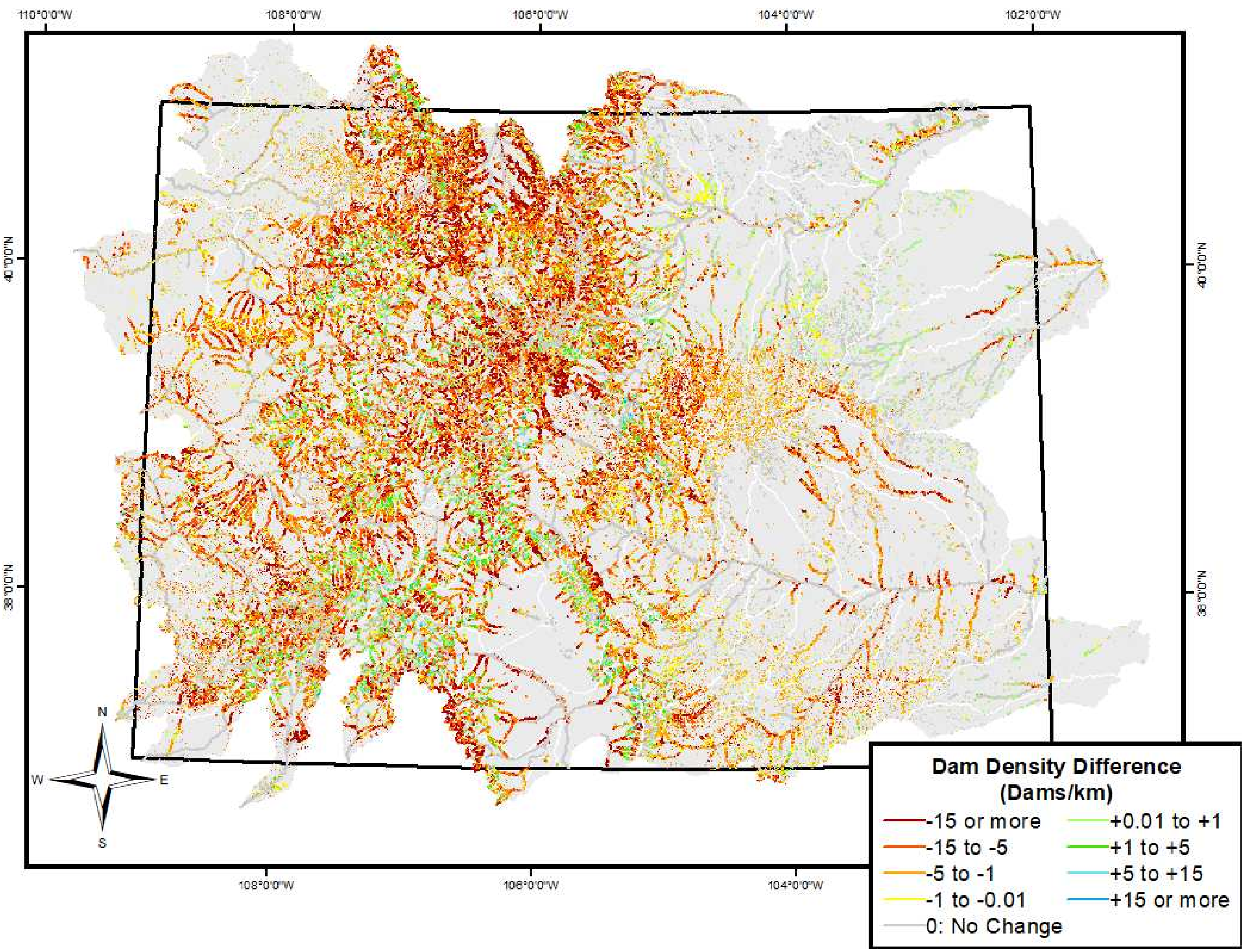

Figure C2. Magnitude of dam density decrease or increase from historic to current predicted dam densities for perennial streams in Colorado. Darker red colors indicate a greater decrease, while cool colors indicate an increase.

APPENDIX D: BRAT CASE STUDY DATA

This appendix contains raw data from Boulder County site suitability checklists as well as raw data for dam density case studies in Rocky Mountain National Park, the Arikaree River, and the Arkansas River headwaters. For site suitability analyses, channel gradient, valley bottom width, and site length were measured remotely either using Google Earth or ArcGIS.

Table D1. Location and site number of site suitability checklists conducted in Boulder County, CO.

Site Number	Creek Name	Date Visited	Coordinates
1	Boulder Creek	8/14/2017	40° 2.2850' N, 105° 12.6852' W
2			40° 2.3927' N, 105° 12.1618' W
3			40° 2.339' N, 105° 12.2392' W
4			40° 1.7567' N, 105° 13.4363' W
5			40° 1.9876' N, 105° 13.0364' W
6			40° 3.0894' N, 105° 10.6843' W
7			40° 3' 5" N, 105° 10' 6" W
8			40° 2' 58" N, 105° 8' 42" W
9			40° 2' 56" N, 105° 7' 53" W
10	Coal Creek	8/15/2017	39° 52.7082' N, 105° 16.1941' W
11			39° 53.0377' N, 105° 15.5053' W
12			39° 54.9659' N, 105° 14.3199' W
13			39° 55.5008' N, 105° 13.6280' W
14			39° 56.4500' N, 105° 11.6066' W
15			39° 56.4531' N, 105° 11.4818' W
16			39° 56.8980' N, 105° 10.4393' W
17	St. Vrain Creek	7/25/2017	40° 12'23.41" N, 105° 13' 29.79" W
18			40° 12.3394' N, 105° 13.3489' W
19			40° 12.4503' N, 105° 13.5984' W
20			40° 12.4935' N, 105° 13.6747' W
21		7/27/2017	40° 12.5015' N, 105° 13.7465' W
22			40° 12.1137' N, 105° 13.1122' W
23			40° 12.0430' N, 105° 13.1007' W
24			40° 11.9318' N, 105° 12.9645' W
25			40° 11.8867' N, 105° 12.8221' W
26	Left Hand Creek	8/18/2017	40° 6' 29" N, 105° 19' 60" W
27			40° 6' 18" N, 105° 19' 32" W
28			40° 6' 36.72" N, 105° 18' 26.21" W

Table D1 (Cont.)

Site Number	Creek Name	Date Visited	Coordinates
29	Left Hand Creek	8/18/2017	40° 6' 44.44" N, 105° 18' 25.73" W
30		8/8/2017	40° 6.0238' N, 105° 20.5822' W
31			40° 6.2683' N, 105° 20.2604' W
32			40° 6.2613' N, 105° 20.2420' W
33	Middle Boulder Creek	8/2/2017	39° 59' 22.339" N, 105° 25' 36.853" W
34			39° 58.3030' N, 105° 28.2129' W
35			39° 58' 53.45" N, 105° 27' 1.34" W
36	South Boulder Creek	8/18/2017	39° 57' 36.17" N, 105° 13' 56.60" W
37			39° 58' 9.65" N, 105° 13' 37.21" W
38			39° 59' 8.30" N, 105° 13' 16.19" W
39			39° 58' 49.76" N, 105° 13' 16.30" W
40	Delonde Creek	8/19/2017	39° 59.3183' N, 105° 32.4037' W
41			39° 59.3364' N, 105° 32.3502' W
42			39° 59' 22.08" N, 105° 31' 53.29" W
43	Sherwood Creek	9/2/2017	39° 58.7676' N, 105° 30.8381' W
44			39° 58.7713' N, 105° 30.8119' W
45			39° 58.7826' N, 105° 30.7668' W

Table D2. Physical factors included in site suitability analysis in Boulder County, CO by site.

Site	Channel Gradient	Valley Bottom Width	Flow Regime	Site Length [m]	Bankfull Width [m]	Bankfull Depth [m]	Incision [m]	Dominant Substrate	Largest Substrate
1	0.01	1326	Per	51	25.3	2.2	none	Fine sand	Boulders
2	0	1680	Per	78.5	39.2	2.2	0.1-0.3	sand	Cobbles
3	0.01	1680	Per				0.1-0.2		
4	0.01	250	Per	100	18.9	1.6	0.1	Fine sand	Cobbles
5	0.01	370	Per	100	14	1.3	1	Cobbles	Cobbles
6	0.01	4750	Per	650	38	2	1	Sand	Boulders
7	0	2890	Per	725	13	2.4	none	Sand	Cobbles
8	0.01	3680	Per	1700	18.9	0.5	1.1	Sand	Boulders
9	0	3800	Per	900	21.3	1.3	1.0	Sand/mud	Boulders
10	0.03	200	Per	1000	10.2	1.37	1.2	Sand	Boulders
11	0.03	200	Per	1000	16	2	1.4	Fine sand	Boulders
12	0.02	120	Int	1030	4.2	0.1	none	Sand	Cobbles
13	0.02	313	Int	1450	24	2.5	none	Fine sand	Boulders
14	0.01	370	NA			-	-	-	-
15	0.02	370	Per	2550	14.2	0.8	none	Sand	Boulders
16	0.01	1370	Per	1500	10	1.5	none	Sand	Cobbles

Table D2. (Cont.)

Site	Channel Gradient	Valley Bottom Width	Flow Regime	Site Length [m]	Bankfull Width [m]	Bankfull Depth [m]	Incision [m]	Dominant Substrate	Largest Substrate
17			Per		13.6	1.6	-	cobbles	boulders
18	0.01	4100	Per	400	12.9	1.3	1	cobbles	cobbles
19	0.01	5100	Per	145	5.9	1.16	0.9	sand	bedrock
20	0.02	5300	Per	100	10.9	2.04	-	gravel	bedrock
21	0.01	3600	Per	50	32	1.15	-	cobbles	boulders
22	0.01	5600	Per	200				silt	
23	0.01	6000	Per	200	17.5	1.78	0.2	silt	cobbles
24	0.01	4800	Per	280	12.5	1.15	0.2	sand	cobbles
25	0.01	3700	Per	125	21.2	1.23	-	sand	cobbles
26	0.05	50	Per	700	14	2.68	-	sand	boulders
27	0.02	75	Per	950	11	0.91	0.6	sand	boulders
28	0.03	55	Per	1000	14.5	0.92	0.6	cobbles	boulders
29	0.03	65	Per	250	10.3	1.03	0.75	Fine sand	boulders
30	0.03	50	Per	775	6.1	0.45	-	sand	boulders/ bedrock
31	0.03	60	Per	475	7.8	0.7	-	sand	cobbles
32	0.17	60	Per				1.3		
33	0.02	140	Per	400	21.3	1.75	-	cobbles	small boulders
34	0.02	70	Per	450	10	-	3	cobbles	boulders
35	0.01	50	Per	350	20	1	-	sand	boulders
36	0.01	1300	Per	1000	9.8	1.7	-	cobbles	Boulders (rip rap)
37	0.01	1120	Per	1500	12.5	1.6	0.23	sand	boulders
38	0.01	525	Per	150	16.8	0.81	-	cobbles	boulders
39	0.01	2245	Per	800	18	0.5	-	sand	boulders (rip rap)
40	0.08	270	Per	115	6	0.75	0.5	sand	Cobbles
41	0.03	230	Per	400	6	0.75	0.2	Gravel	Cobbles
42	0.04	300	Per	500	1.5	0.3	0.2	Silt/ Mud	Gravel
43	0.04	280	Per	233	3.45	0.86	-	sand	cobbles
44	0.03	280	Per	233	2.0	0.95	0.25	sand	cobbles
45	0.03	280	Per	233	2.2	1.15	1	cobbles	bedrock

Table D3. Vegetation and conflict characteristics included in site suitability analysis by site in Boulder County, CO

Site #	Dominant Vegetation	Abund.	Evidence of Elk?	Evidence of Berms?	Hazards
1	mature willow, cottonwood, sedges, tilled farmland	Low	No	No	Bridge, 2.7 m above water surface
2	willows, sedges, rushes, cottonwoods	Moderate	No	No	
3	willows, cottonwoods, abundant cattails, non-native olive	High	No	No	
4	cottonwoods, willows, invasive olive, sedges, lots of grasses	Low	No	No	Bridge and trail crossing, 3 m above water surface
5	mature willow, sedges, young cottonwood, perennial grasses, invasive olive	Low	No	No	Buried power line 3 m from stream on right
6	rushes, sedges, willows, cottonwood, aspen, poison ivy	Moderate	No	No	75th Street Bridge- 12.5 m upstream (3.2 m above water). Water intake on creek right, water outflow on creek left. Buried water line, 35 m u/s on right. Pedestrian path under bridge, on right.
7	invasive olive, willow, sedges, cottonwood	Low	No	No	Open grate metal bridge crosses stream at 2.4 m above the water
8	willows, invasive olive, cottonwood, rushes, sedges (mostly grasses, some mature trees)	Low	No	No	Bridge and Trail crossing, bridge is downed (in creek) -- trail closed
9	mostly grasses, sedges, rushes, small stand of cottonwood/willow by pond (50 m away), more willows 90 m u/s, russian olive	Low	No	No	95th Street Bridge, 2 m above the water. Dam d/s (past 95th street). Manhole for fiber optic cables 36 m from creek on left. Private property & fence on right bank.
10	willows, cottonwoods, rushes, aspen, pine	High	No	No	Plainview Rd. Bridge, 2.4 m above water. Water manholes, 25 m away from bank on the right
11	willows (young), rushes, pine, cottonwood, alder, aspen (sparse)	Moderate	No	No	N/A

Table D3 (Cont.

Site #	Dominant Vegetation	Abund.	Evidence of Elk?	Evidence of Berms?	Hazards
12	Alder, willow, cottonwood, pine, rushes, sedges (stand of young willows 30 m west)	Moderate	No	No	Highway 93 approx. 20 m away, considerable noise
13	Rushes, sedges, willow, aspen, other small trees	High	No	No	Height of trail bridge above water, 3 m. Large culvert and road, 42.8 m downstream, 2 m high opening.
14	-	-	-	-	-
15	Cottonwoods, willows (sparse), rushes	Low	No	No	N/A
16	Cottonwoods, willows, rushes, grasses	Moderate	No	No	Height of trail bridge above water, 3 m. Lots of downed woods, some spanning entire length of creek, creating ponding.
17	willows, cottonwoods, not many grasses	High	No	No	Mining ponds within 50 m on creek right
18	willows, aspen (young and mature)	Moderate	No	No	
19			No	No	Concrete in center of channel, rapid on river right. Exposed bedrock on right bank.
20			No	No	
21	sparse young willows, pea tree, sparse aspen	Low	No	No	Bridge with 5 culverts (width ~ 1 m), mining equipment spanning creek d/s. Old mining infrastr. on creek left ~ 50 m.
22	Willows and sedges	High	No	No	
23	Young willows (creek left), sedges, cottonwoods	High	No	No	
24	willows	High	No	No	
25	willows, cottonwoods (mature), grasses	Moderate	No	No	Lots of downed wood, remnants of old dam/bridge (concrete blocks), private property?
26	pines, willows, cottonwoods, aspen, limited grasses	Low	No	No	Left Hand Rd. is 28 m from creek left
27	pines, cottonwood and grasses downstream	Low	No	No	Left Hand Rd. is 15 m from creek left
28	pines (dominant), willows, cottonwoods, grasses (on left)	Moderate	No	No	
29	pines (dominant), cottonwoods, aspen, sedges, grasses	Moderate	No	No	

Site #	Dominant Vegetation	Abund.	Elk?	Berms?	Hazards
30	pines, cottonwoods, oak	Moderate	No	No	Road ~ 12 m from creek; anit-erosion manmade features along road
31	willows, pines, cottonwoods, no grasses	Low	No	No	Road ~ 30 m from creek on left
32					Culvert: 0.3 m diameter, left bank; 2.5 m drop (waterfall), approx. 10 m d/s - boulders and downed wood
33	young aspen and willow	High	Yes	No	Road 25 m on creek left
34	willows, pines, aspen, few grasses	Moderate	No	No	Hwy 119 ~20 m creek left
35	pine, willow, some sedges (sparse), aspen (sparse)	Moderate	Yes	No	Ditch (40 cm wide @ 39° 58' 45", 105° 27' 16"), Bridge (1.3 m above water @ 39° 58' 45", 105° 27' 16"), Hwy 119 ~ 10 m from bank
36	cottonwood, willow (sparse), grasses	Low	No	No	Height of Marshall Bridge: 1.6 m. Small wooden bridge 42.8 m d/s (private structure, about 2 m above water)
37	willows, cottonwood, aspen, rushes, grasses (abundant)	Moderate	No	No	Barbed wire fence 10.8 m from creek left
38	willows, cottonwood, grasses, algae in stream	Moderate	No	No	South Boulder Bridge: 1.5 m high; pedestrian bridge: 1.8 m high; fence in creek 55 m u/s of S. Boulder Rd.
39	willows, cottonwoods, grasses	High	No	No	HWY 36 bridge: 3.4 m high; Weir dam 25 m d/s of bridge, culvert/pipe on creek right; private property on creek right; 36 Denver/Boulder bikeway 10 m from creek left; erosion control d/s of bridge on left (tarp and hay bales); barbed wire fence 2 m from creek on left (new)
40	Aspen (large stand on creek left), pines (closer to stream), sedges and rushes	High	Yes	Yes	
41	Aspen, cottonwoods, pines	High	Yes	Yes	Culvert and trail/road at 39° 59.3719'N, 105° 32.0180'W. Trail crossing at 39° 59.3340'N, 105° 32.3682'W
42	Willows, Grasses, Aspen	High	Yes	Yes	
43	Aspen (large stand, 14 m on creek right), grasses, sedges	High	Yes	No	Caribou Ranch Trail Bridge = 0.76 m above water
44	Grasses, aspen, willow	High	No	Yes	
45	Grasses, thick stand of willows, sage	High	No	Yes	Dirt road adjacent to creek on left

Table D4. Comparison of site suitability scores and BRAT densities at sites in Boulder County, CO. Sites without scores did not have enough information to assign a suitability number.

Site #	Suitability Score	Current BRAT Density (dams/km)
1	20	0
2	20	0
3	-	-
4	63	0
5	66	0
6	85	0
7	28	0
8	37	0
9	68	0
10	50	3.6
11	50	3.6
12	45	11.6
13	80	11.5
14	-	-
15	37	8.2
16	67	12
17	-	-
18	66	0
19	70	0
20	69	0
21	39	0
22	85	0
23	85	0
24	82	0
25	76	0
26	20	3.6
27	29	3.6
28	50	11.9
29	44	27.7
30	50	3.6
31	27	3.7
32	-	3.7
33	65	3.6
34	49	9.4
35	56	3.6
36	35	11.6
37	63	8.1
38	61	6
39	77	7.1
40	85	19
41	77	12.9
42	71	11.8
43	78	5.7
44	70	5.7
45	74	5.7

Table D5. Comparisons between field data and BRAT output for Rocky Mountain National Park.

Name	Downstream Coordinates	Reach Length [m]	Measured Density (dams/km)	Current BRAT Density (dams/km)	Historic BRAT Density (dams/km)
Poudre River	40.427, -105.804	0.3	16.667	0.644789	0.622442
Poudre River	40.43, -105.802	0.3	33.333	0.6235	0.6263
Poudre River	40.432, -105.8	0.3	26.667	0.6466	0.6466
Poudre River	40.434, -105.798	0.3	36.667	0.523	0.523
Poudre River	40.436, -105.796	0.3	23.333	0.643	0.643
Poudre River	40.437, -105.793	0.3	26.667	0.598	3.104
Poudre River	40.439, -105.791	0.3	23.333	0.641	2.675
Poudre River	40.441, -105.788	0.3	26.667	3.354	3.625
Poudre River	40.442, -105.786	0.3	26.667	3.523	17.105
Poudre River	40.444, -105.786	0.3	23.333	2.977	12.696
Poudre River	40.445, -105.78	0.3	20.000	0.62	7.405
Poudre River	40.446, -105.778	0.3	13.333	0.633	3.625
Big Thompson	40.401, -105.741	2.8	1.071	3.173	19.198
Fern Creek	40.345, -105.669	0.3	6.667	6.475	12.41
Mill Creek	40.335, -105.629	0.3	3.333	19.99	29.68
Mill Creek	40.335, -105.626	0.3	0.000	18.691	20.953
Mill Creek	40.336, -105.622	0.3	3.333	30.321	31.24
Mill Creek	40.336, -105.619	0.3	6.667	22.675	28.834
Mill Creek	40.335, -105.616	0.3	3.333	26.031	26.799
Beaver Brook	40.378,-105.636	0.3	23.333	0	0
Beaver Brook	40.377,-105.633	0.3	40.000	12.76	9.648
Beaver Brook	40.376,-105.63	0.3	46.667	19.8	17.774
Beaver Brook	40.375,-105.627	0.3	43.333	17.167	20.1845
Beaver Brook	40.363,-105.578	0.3	20.000	16.855	19.445
Beaver Brook	40.364,-105.575	0.3	46.667	18.081	21.721
Beaver Brook	40.363,-105.571	0.3	56.667	25.103	24.925
Beaver Brook	40.363,-105.568	0.3	40.000	20.536	20.314
Beaver Brook	40.363,-105.564	0.3	36.667	12.503	18.636
Beaver Brook	40.363,-105.561	0.2	55.000	3.625	23.847
Beaver Brook	40.362,-105.559	0.3	36.667	3.532	29.9
Beaver Brook	40.361,-105.556	0.3	10.000	2.098	25.812
Glacier Creek	40.317,-105.628	0.3	3.333	10.468	28.03
Glacier Creek	40.319,-105.619	0.3	3.333	10.788	28.786
Boulder Brook	40.306,-105.617	0.3	10.000	8.639	17.167
NF Big Thompson	40.501,-105.56	0.3	3.333	3.625	30.772
NF Big Thompson	40.5,-105.558	0.165	0.000	3.606	26.318
NF Big Thompson	40.49,-105.555	0.3	0.000	3.625	23.624
NF Big Thompson	40.499,-105.552	0.3	13.333	3.625	7.898
NF Big Thompson	40.498,-105.548	0.3	13.333	5.2	9.218

Table D5. (Cont.)

Name	Downstream Coordinates	Reach Length [m]	Measured Density (dams/km)	Current BRAT Density (dams/km)	Historic BRAT Density (dams/km)
NF Big Thompson	40.498,-105.545	0.3	6.667	8.932	12.308
NF Big Thompson	40.498,-105.541	0.3	0.000	10.901	19.712
NF Big Thompson	40.497,-105.538	0.3	6.667	9.763	25.256
NF Big Thompson	40.497,-105.534	0.3	13.333	7.693	11.432
NF Big Thompson	40.498,-105.528	0.3	6.667	10.86	10.777
NF Big Thompson	40.498,-105.524	0.3	13.333	17.999	12.212
NF Big Thompson	40.498,-105.521	0.3	0.000	12.483	12.256
NF Big Thompson	40.497,-105.517	0.3	3.333	16.807	12.673
NF Big Thompson	40.496,-105.515	0.3	6.667	12.511	23.826
Cow Creek	40.438,-105.559	0.3	6.667	16.506	25.104
Cow Creek	40.438,-105.556	0.3	30.000	13.595	24.099
Cow Creek	40.438,-105.552	0.3	10.000	30.605	25.216
Cow Creek	40.435,-105.551	0.3	10.000	0	0
Cow Creek	40.434,-105.548	0.258	3.876	4.78	11.31
Cow Creek	40.432,-105.546	0.29	3.448	11.348	12.538
Cow Creek	40.427,-105.532	0.3	6.667	12.382	13
Black Canyon Creek	40.433,-105.598	0.3	3.333	3.625	8.288
Black Canyon Creek	40.423,-105.579	0.3	6.667	10.164	12.099
Black Canyon Creek	40.42,-105.566	0.3	6.667	21.007	11.92
Black Canyon Creek	40.417,-105.564	0.3	6.667	9.618	12.153
Hunters Creek	40.218,-105.585	0.3	3.333	3.625	24.632
Hunters Creek	40.216,-105.582	0.3	10.000	8.43	22.765
Hunters Creek	40.215,-105.579	0.3	20.000	5.04	26.263
Hunters Creek	40.214,-105.576	0.3	6.667	11.548	24.333
Sandbeach Creek	40.21,-105.596	1.2	3.333	3.887	17.829
Sandbeach Creek	40.209,-105.589	0.6	18.333	8.924	12.587
Sandbeach Creek	40.209,-105.586	0.232	17.241	3.625	23.158
Sandbeach Creek	40.207,-105.584	0.3	6.667	0	0
Sandbeach Creek	40.205,-105.574	0.6	5.000	26.921	25.044
Sandbeach Creek	40.205,-105.571	0.3	3.333	13.219	13.219
North St. Vrain	40.209,-105.62	0.9	3.333	3.625	17.09
North St. Vrain	40.203,-105.601	0.3	10.000	10.285	18.306
North St. Vrain	40.2,-105.596	0.3	13.333	11.421	16.623
Ouzel Creek	40.2,-105.596	0.3	3.333	3.673	10.262
North St. Vrain	40.208,-105.437	0.3	3.333	3.618	10.09
North St. Vrain	40.212,-105.434	0.3	3.333	3.6	9.967

Table D6. Comparison between field data and BRAT output for the Arikaree River. Starting coordinates are 39. 749, -102.532. All reaches are counted downstream from there.

Reach Length [km]	Measured Dam Density (dams/km)	Current BRAT Density (dams/km)	Historic BRAT Density (dams/km)
0.137	21.90	13.2	24.7
0.3	13.33	12.2	27.0
0.3	6.67	3.6	14.0
0.169	29.59	3.6	30.2
0.219	18.26	11.2	29.3
0.3	23.33	10.1	27.9
0.33	36.36	3.6	29.5
0.31	51.61	9.0	19.2
0.18	55.56	3.6	25.7
0.33	27.27	3.6	28.7
0.198	30.30	3.6	12.9
0.3	23.33	3.6	23.1
0.277	7.22	3.1	12.6
0.3	6.67	7.1	16.4
0.172	17.44	12.1	27.8
0.3	33.33	9.3	27.7
0.3	33.33	7.8	29.9
0.3	36.67	0.6	30.3
0.163	18.40	3.6	30.0
0.3	23.33	7.5	16.2
0.166	18.07	7.6	21.2
0.3	16.67	3.4	12.9
0.229	17.47	10.4	22.1
0.334	8.98	4.4	17.0
0.213	23.47	3.6	17.6
0.15	20.00	8.2	24.8
0.271	11.07	12.2	30.7
0.157	6.37	3.6	12.8
0.3	10.00	6.7	12.8
0.41	9.76	11.4	25.3
0.3	6.67	11.4	31.4
0.3	36.67	3.2	15.2
0.3	26.67	3.7	30.7
0.2	20.00	3.6	13.2

Table D7. Comparison between field data and BRAT output for the Colorado Game and Fish Commission Survey streams.

Name	Downstream Coordinates	Reach Length [km]	Measured Dam Density [dams/km]	Current BRAT Dam Density [dams/km]	Historical BRAT Dam Density [dams/km]
North Apishapa	37.388, -104.975	0.907	4.41	25.2	24.6
North Apishapa	Reach Average	2.96	3.38	29.2	22.7
Jarosa Creek	37.302, -104.786	2.77	1.44	3.5	15.6
N Hardscrabble Creek	38.177, -105.117	1.83	0.00		
N Hardscrabble Creek	38.177, -105.117	1.83	3.83	0.78	3.1
N Hardscrabble Creek	38.178, -105.121	0.3	40.00	0.17	0.6
N Hardscrabble Creek	Reach Average	2.1	7.62	1.3	3.2
N Hardscrabble Creek	38.162, -105.193	0.12	33.33	1.1	7.4
N Hardscrabble Creek	38.156, -105.203	1.22	9.84	3.6	14.2
N Hardscrabble Creek	Reach Average	1.22	13.11	3.6	15.2
St. Charles Creek	37.979, -105.131	0.09	44.44	3.6	6.7
St. Charles Creek	37.98, -105.132	0.16	37.50	3.6	6.7
St. Charles Creek	37.982, -105.135	0.32	0.00		
St. Charles Creek	37.985, -105.137	0.4	20.00	3.6	12
St. Charles Creek	Reach Average	3.35	13.13	6.9	9.8
Beaver Creek	38, -105.104	0.15	40.00	12.5	12.9
Beaver Creek	Reach Average	0.27	40.74	12.5	12.9
S. Fork Upper Horn Creek	38.014, -105.584	0.3	40.00	3.6	7.4
S. Fork Upper Horn Creek	38.011, -105.585	0.27	0.00	3.6	3.6
S. Fork Upper Horn Creek	38.007, -105.591	0.82	13.41	3.5	7.2
S. Fork Upper Horn Creek	Reach Average	1.39	33.09	3.6	5.88
Big Cottonwood Creek	38.296, -105.759	2.55	0.00	6	7.7
Big Cottonwood Creek	38.278, -105.76	0.21	14.29	3.6	3.6
Big Cottonwood Creek	38.275, -105.761	0.26	34.62	24.6	21.5
Big Cottonwood Creek	Reach Average	1.28	12.50	11.6	11.6

APPENDIX E: RAW DATA FOR FISH AND CAMPBELL CREEK LINEAR MIXED MODELS

Raw data for Fish Creek Linear Mixed Model separated by well and day. Averages indicate average depth to groundwater in meters. U = well upstream of BDA, D = well downstream of BDA.

BDA	Upstream or Downstream	Bank	Day	Average [m]	BDA	Upstream or Downstream	Bank	Day	Average [m]
1	U	L	1	0.63	1	U	L	39	0.67
1	U	L	2	0.64	1	U	L	40	0.69
1	U	L	3	0.64	1	U	L	41	0.69
1	U	L	4	0.64	1	U	L	42	0.68
1	U	L	5	0.64	1	U	L	43	0.68
1	U	L	6	0.65	1	U	L	44	0.68
1	U	L	7	0.65	1	U	L	45	0.69
1	U	L	8	0.66	1	U	L	46	0.70
1	U	L	9	0.66	1	U	L	47	0.70
1	U	L	10	0.66	1	U	L	48	0.69
1	U	L	11	0.66	1	U	L	49	0.64
1	U	L	12	0.66	1	U	L	50	0.63
1	U	L	13	0.65	1	U	L	51	0.65
1	U	L	14	0.62	1	U	L	52	0.65
1	U	L	15	0.63	1	U	L	53	0.65
1	U	L	16	0.62	1	U	L	54	0.65
1	U	L	17	0.64	1	U	L	55	0.65
1	U	L	18	0.65	1	U	L	56	0.65
1	U	L	19	0.65	1	U	L	57	0.66
1	U	L	20	0.65	1	U	L	58	0.66
1	U	L	21	0.65	1	U	L	59	0.66
1	U	L	22	0.65	1	U	L	60	0.66
1	U	L	23	0.66	1	U	L	61	0.66
1	U	L	24	0.67	1	U	L	62	0.65
1	U	L	25	0.67	1	U	L	63	0.63
1	U	L	26	0.68	1	U	L	64	0.62
1	U	L	27	0.68	1	U	L	65	0.63
1	U	L	28	0.68	1	U	L	66	0.63
1	U	L	29	0.68	1	U	L	67	0.63
1	U	L	30	0.69	1	U	L	68	0.63
1	U	L	31	0.69	1	U	L	69	0.64
1	U	L	32	0.69	1	U	L	70	0.64
1	U	L	33	0.69	1	U	L	71	0.64
1	U	L	34	0.66	1	U	L	72	0.63
1	U	L	35	0.63	1	U	L	73	0.63
1	U	L	36	0.66	1	U	L	74	0.63
1	U	L	37	0.68	1	U	L	75	0.62
1	U	L	38	0.68	1	U	L	76	0.61

BDA	Upstream or Downstream	Bank	Day	Average [m]	BDA	Upstream or Downstream	Bank	Day	Average [m]
1	U	R	1	0.30	1	U	R	40	0.33
1	U	R	2	0.30	1	U	R	41	0.33
1	U	R	3	0.30	1	U	R	42	0.33
1	U	R	4	0.31	1	U	R	43	0.33
1	U	R	5	0.31	1	U	R	44	0.33
1	U	R	6	0.32	1	U	R	45	0.33
1	U	R	7	0.32	1	U	R	46	0.33
1	U	R	8	0.32	1	U	R	47	0.32
1	U	R	9	0.32	1	U	R	48	0.32
1	U	R	10	0.33	1	U	R	49	0.31
1	U	R	11	0.33	1	U	R	50	0.31
1	U	R	12	0.33	1	U	R	51	0.31
1	U	R	13	0.31	1	U	R	52	0.31
1	U	R	14	0.31	1	U	R	53	0.31
1	U	R	15	0.32	1	U	R	54	0.31
1	U	R	16	0.32	1	U	R	55	0.30
1	U	R	17	0.32	1	U	R	56	0.30
1	U	R	18	0.33	1	U	R	57	0.30
1	U	R	19	0.33	1	U	R	58	0.30
1	U	R	20	0.32	1	U	R	59	0.30
1	U	R	21	0.33	1	U	R	60	0.30
1	U	R	22	0.33	1	U	R	61	0.30
1	U	R	23	0.33	1	U	R	62	0.30
1	U	R	24	0.33	1	U	R	63	0.30
1	U	R	25	0.34	1	U	R	64	0.29
1	U	R	26	0.33	1	U	R	65	0.29
1	U	R	27	0.33	1	U	R	66	0.29
1	U	R	28	0.33	1	U	R	67	0.29
1	U	R	29	0.33	1	U	R	68	0.28
1	U	R	30	0.33	1	U	R	69	0.28
1	U	R	31	0.33	1	U	R	70	0.28
1	U	R	32	0.34	1	U	R	71	0.28
1	U	R	33	0.34	1	U	R	72	0.28
1	U	R	34	0.33	1	U	R	73	0.27
1	U	R	35	0.34	1	U	R	74	0.26
1	U	R	36	0.34	1	U	R	75	0.25
1	U	R	37	0.35	1	U	R	76	0.25
1	U	R	38	0.33					
1	U	R	39	0.33					

BDA	Upstream or Downstream	Bank	Day	Average [m]	BDA	Upstream or Downstream	Bank	Day	Average [m]
1	D	L	1	0.31	1	D	L	40	0.36
1	D	L	2	0.31	1	D	L	41	0.36
1	D	L	3	0.31	1	D	L	42	0.36
1	D	L	4	0.31	1	D	L	43	0.37
1	D	L	5	0.31	1	D	L	44	0.38
1	D	L	6	0.31	1	D	L	45	0.39
1	D	L	7	0.31	1	D	L	46	0.39
1	D	L	8	0.31	1	D	L	47	0.39
1	D	L	9	0.31	1	D	L	48	0.39
1	D	L	10	0.31	1	D	L	49	0.37
1	D	L	11	0.31	1	D	L	50	0.38
1	D	L	12	0.31	1	D	L	51	0.38
1	D	L	13	0.30	1	D	L	52	0.38
1	D	L	14	0.30	1	D	L	53	0.38
1	D	L	15	0.31	1	D	L	54	0.39
1	D	L	16	0.31	1	D	L	55	0.39
1	D	L	17	0.31	1	D	L	56	0.39
1	D	L	18	0.31	1	D	L	57	0.40
1	D	L	19	0.32	1	D	L	58	0.40
1	D	L	20	0.31	1	D	L	59	0.40
1	D	L	21	0.32	1	D	L	60	0.40
1	D	L	22	0.32	1	D	L	61	0.40
1	D	L	23	0.32	1	D	L	62	0.40
1	D	L	24	0.32	1	D	L	63	0.40
1	D	L	25	0.33	1	D	L	64	0.41
1	D	L	26	0.33	1	D	L	65	0.42
1	D	L	27	0.33	1	D	L	66	0.43
1	D	L	28	0.34	1	D	L	67	0.43
1	D	L	29	0.34	1	D	L	68	0.43
1	D	L	30	0.34	1	D	L	69	0.44
1	D	L	31	0.35	1	D	L	70	0.45
1	D	L	32	0.35	1	D	L	71	0.45
1	D	L	33	0.35	1	D	L	72	0.45
1	D	L	34	0.35	1	D	L	73	0.44
1	D	L	35	0.35	1	D	L	74	0.44
1	D	L	36	0.35	1	D	L	75	0.43
1	D	L	37	0.36	1	D	L	76	0.42
1	D	L	38	0.36					
1	D	L	39	0.36					

BDA	Upstream or Downstream	Bank	Day	Average [m]	BDA	Upstream or Downstream	Bank	Day	Average [m]
1	D	R	1	0.51	1	D	R	40	0.53
1	D	R	2	0.50	1	D	R	41	0.52
1	D	R	3	0.50	1	D	R	42	0.51
1	D	R	4	0.50	1	D	R	43	0.52
1	D	R	5	0.50	1	D	R	44	0.53
1	D	R	6	0.51	1	D	R	45	0.55
1	D	R	7	0.51	1	D	R	46	0.55
1	D	R	8	0.51	1	D	R	47	0.55
1	D	R	9	0.50	1	D	R	48	0.54
1	D	R	10	0.51	1	D	R	49	0.50
1	D	R	11	0.51	1	D	R	50	0.47
1	D	R	12	0.50	1	D	R	51	0.50
1	D	R	13	0.47	1	D	R	52	0.50
1	D	R	14	0.46	1	D	R	53	0.51
1	D	R	15	0.47	1	D	R	54	0.51
1	D	R	16	0.47	1	D	R	55	0.52
1	D	R	17	0.48	1	D	R	56	0.53
1	D	R	18	0.48	1	D	R	57	0.54
1	D	R	19	0.49	1	D	R	58	0.54
1	D	R	20	0.48	1	D	R	59	0.55
1	D	R	21	0.48	1	D	R	60	0.54
1	D	R	22	0.50	1	D	R	61	0.55
1	D	R	23	0.51	1	D	R	62	0.55
1	D	R	24	0.51	1	D	R	63	0.55
1	D	R	25	0.53	1	D	R	64	0.56
1	D	R	26	0.52	1	D	R	65	0.56
1	D	R	27	0.52	1	D	R	66	0.57
1	D	R	28	0.53	1	D	R	67	0.57
1	D	R	29	0.53	1	D	R	68	0.57
1	D	R	30	0.54	1	D	R	69	0.56
1	D	R	31	0.53	1	D	R	70	0.56
1	D	R	32	0.53	1	D	R	71	0.54
1	D	R	33	0.53	1	D	R	72	0.53
1	D	R	34	0.53	1	D	R	73	0.53
1	D	R	35	0.52	1	D	R	74	0.53
1	D	R	36	0.54	1	D	R	75	0.51
1	D	R	37	0.55	1	D	R	76	0.50
1	D	R	38	0.53					
1	D	R	39	0.53					

BDA	Upstream or Downstream	Bank	Day	Average [m]	BDA	Upstream or Downstream	Bank	Day	Average [m]
2	U	L	1	0.62	2	U	L	40	0.66
2	U	L	2	0.62	2	U	L	41	0.66
2	U	L	3	0.62	2	U	L	42	0.65
2	U	L	4	0.63	2	U	L	43	0.65
2	U	L	5	0.63	2	U	L	44	0.66
2	U	L	6	0.64	2	U	L	45	0.67
2	U	L	7	0.64	2	U	L	46	0.67
2	U	L	8	0.64	2	U	L	47	0.67
2	U	L	9	0.64	2	U	L	48	0.66
2	U	L	10	0.65	2	U	L	49	0.64
2	U	L	11	0.65	2	U	L	50	0.63
2	U	L	12	0.65	2	U	L	51	0.64
2	U	L	13	0.63	2	U	L	52	0.64
2	U	L	14	0.62	2	U	L	53	0.64
2	U	L	15	0.63	2	U	L	54	0.64
2	U	L	16	0.63	2	U	L	55	0.64
2	U	L	17	0.63	2	U	L	56	0.64
2	U	L	18	0.63	2	U	L	57	0.64
2	U	L	19	0.64	2	U	L	58	0.64
2	U	L	20	0.63	2	U	L	59	0.65
2	U	L	21	0.63	2	U	L	60	0.64
2	U	L	22	0.64	2	U	L	61	0.64
2	U	L	23	0.64	2	U	L	62	0.64
2	U	L	24	0.65	2	U	L	63	0.65
2	U	L	25	0.65	2	U	L	64	0.65
2	U	L	26	0.65	2	U	L	65	0.65
2	U	L	27	0.65	2	U	L	66	0.65
2	U	L	28	0.66	2	U	L	67	0.66
2	U	L	29	0.66	2	U	L	68	0.66
2	U	L	30	0.66	2	U	L	69	0.66
2	U	L	31	0.66	2	U	L	70	0.66
2	U	L	32	0.66	2	U	L	71	0.66
2	U	L	33	0.66	2	U	L	72	0.65
2	U	L	34	0.66	2	U	L	73	0.66
2	U	L	35	0.66	2	U	L	74	0.65
2	U	L	36	0.66	2	U	L	75	0.65
2	U	L	37	0.66	2	U	L	76	0.64
2	U	L	38	0.66					
2	U	L	39	0.66					

BDA	Upstream or Downstream	Bank	Day	Average [m]	BDA	Upstream or Downstream	Bank	Day	Average [m]
2	U	R	1	0.52	2	U	R	40	0.53
2	U	R	2	0.51	2	U	R	41	0.51
2	U	R	3	0.52	2	U	R	42	0.52
2	U	R	4	0.52	2	U	R	43	0.52
2	U	R	5	0.52	2	U	R	44	0.53
2	U	R	6	0.53	2	U	R	45	0.54
2	U	R	7	0.52	2	U	R	46	0.53
2	U	R	8	0.52	2	U	R	47	0.52
2	U	R	9	0.52	2	U	R	48	0.51
2	U	R	10	0.53	2	U	R	49	0.49
2	U	R	11	0.53	2	U	R	50	0.50
2	U	R	12	0.52	2	U	R	51	0.50
2	U	R	13	0.50	2	U	R	52	0.50
2	U	R	14	0.50	2	U	R	53	0.50
2	U	R	15	0.51	2	U	R	54	0.50
2	U	R	16	0.51	2	U	R	55	0.51
2	U	R	17	0.51	2	U	R	56	0.51
2	U	R	18	0.52	2	U	R	57	0.51
2	U	R	19	0.52	2	U	R	58	0.50
2	U	R	20	0.51	2	U	R	59	0.51
2	U	R	21	0.52	2	U	R	60	0.50
2	U	R	22	0.53	2	U	R	61	0.51
2	U	R	23	0.53	2	U	R	62	0.50
2	U	R	24	0.53	2	U	R	63	0.50
2	U	R	25	0.54	2	U	R	64	0.49
2	U	R	26	0.52	2	U	R	65	0.49
2	U	R	27	0.52	2	U	R	66	0.49
2	U	R	28	0.53	2	U	R	67	0.49
2	U	R	29	0.53	2	U	R	68	0.49
2	U	R	30	0.53	2	U	R	69	0.49
2	U	R	31	0.52	2	U	R	70	0.49
2	U	R	32	0.53	2	U	R	71	0.48
2	U	R	33	0.53	2	U	R	72	0.48
2	U	R	34	0.52	2	U	R	73	0.48
2	U	R	35	0.53	2	U	R	74	0.47
2	U	R	36	0.53	2	U	R	75	0.47
2	U	R	37	0.54	2	U	R	76	0.47
2	U	R	38	0.51					
2	U	R	39	0.52					

BDA	Upstream or Downstream	Bank	Day	Average [m]	BDA	Upstream or Downstream	Bank	Day	Average [m]
2	D	L	1	0.30	2	D	L	40	0.38
2	D	L	2	0.29	2	D	L	41	0.37
2	D	L	3	0.29	2	D	L	42	0.37
2	D	L	4	0.29	2	D	L	43	0.37
2	D	L	5	0.29	2	D	L	44	0.38
2	D	L	6	0.29	2	D	L	45	0.39
2	D	L	7	0.29	2	D	L	46	0.40
2	D	L	8	0.29	2	D	L	47	0.39
2	D	L	9	0.30	2	D	L	48	0.38
2	D	L	10	0.31	2	D	L	49	0.36
2	D	L	11	0.30	2	D	L	50	0.37
2	D	L	12	0.30	2	D	L	51	0.38
2	D	L	13	0.28	2	D	L	52	0.38
2	D	L	14	0.28	2	D	L	53	0.38
2	D	L	15	0.30	2	D	L	54	0.38
2	D	L	16	0.32	2	D	L	55	0.37
2	D	L	17	0.31	2	D	L	56	0.37
2	D	L	18	0.32	2	D	L	57	0.37
2	D	L	19	0.33	2	D	L	58	0.37
2	D	L	20	0.32	2	D	L	59	0.37
2	D	L	21	0.33	2	D	L	60	0.37
2	D	L	22	0.33	2	D	L	61	0.37
2	D	L	23	0.33	2	D	L	62	0.37
2	D	L	24	0.33	2	D	L	63	0.37
2	D	L	25	0.34	2	D	L	64	0.37
2	D	L	26	0.34	2	D	L	65	0.37
2	D	L	27	0.35	2	D	L	66	0.37
2	D	L	28	0.36	2	D	L	67	0.37
2	D	L	29	0.36	2	D	L	68	0.37
2	D	L	30	0.36	2	D	L	69	0.37
2	D	L	31	0.36	2	D	L	70	0.37
2	D	L	32	0.37	2	D	L	71	0.37
2	D	L	33	0.37	2	D	L	72	0.36
2	D	L	34	0.36	2	D	L	73	0.36
2	D	L	35	0.37	2	D	L	74	0.36
2	D	L	36	0.38	2	D	L	75	0.35
2	D	L	37	0.38	2	D	L	76	0.34
2	D	L	38	0.37					
2	D	L	39	0.37					

BDA	Upstream or Downstream	Bank	Day	Average [m]	BDA	Upstream or Downstream	Bank	Day	Average [m]
2	D	R	1	0.39	2	D	R	40	0.44
2	D	R	2	0.38	2	D	R	41	0.43
2	D	R	3	0.38	2	D	R	42	0.44
2	D	R	4	0.38	2	D	R	43	0.45
2	D	R	5	0.38	2	D	R	44	0.46
2	D	R	6	0.39	2	D	R	45	0.46
2	D	R	7	0.39	2	D	R	46	0.46
2	D	R	8	0.39	2	D	R	47	0.46
2	D	R	9	0.38	2	D	R	48	0.45
2	D	R	10	0.39	2	D	R	49	0.44
2	D	R	11	0.38	2	D	R	50	0.41
2	D	R	12	0.37	2	D	R	51	0.44
2	D	R	13	0.33	2	D	R	52	0.45
2	D	R	14	0.32	2	D	R	53	0.45
2	D	R	15	0.34	2	D	R	54	0.46
2	D	R	16	0.36	2	D	R	55	0.45
2	D	R	17	0.37	2	D	R	56	0.45
2	D	R	18	0.38	2	D	R	57	0.45
2	D	R	19	0.39	2	D	R	58	0.46
2	D	R	20	0.38	2	D	R	59	0.45
2	D	R	21	0.36	2	D	R	60	0.45
2	D	R	22	0.38	2	D	R	61	0.45
2	D	R	23	0.39	2	D	R	62	0.45
2	D	R	24	0.39	2	D	R	63	0.45
2	D	R	25	0.41	2	D	R	64	0.45
2	D	R	26	0.42	2	D	R	65	0.45
2	D	R	27	0.43	2	D	R	66	0.45
2	D	R	28	0.43	2	D	R	67	0.46
2	D	R	29	0.43	2	D	R	68	0.44
2	D	R	30	0.44	2	D	R	69	0.45
2	D	R	31	0.43	2	D	R	70	0.45
2	D	R	32	0.43	2	D	R	71	0.45
2	D	R	33	0.43	2	D	R	72	0.44
2	D	R	34	0.43	2	D	R	73	0.45
2	D	R	35	0.43	2	D	R	74	0.44
2	D	R	36	0.44	2	D	R	75	0.43
2	D	R	37	0.45	2	D	R	76	0.43
2	D	R	38	0.44					
2	D	R	39	0.44					

Raw data for Campbell Creek Linear Mixed Model separated by well and storm. Averages indicate average depth to groundwater in meters. U = well upstream of BDA, D = well downstream of BDA.

BDA	Upstream or Downstream	Bank	Day	Average [m]	BDA	Upstream or Downstream	Bank	Day	Average [m]
1	U	L	1	0.77	2	D	R	1	0.77
1	U	L	2	0.69	2	D	R	2	0.77
1	U	L	3	0.68	2	D	R	3	0.77
1	U	L	4	0.67	2	D	R	4	0.77
1	U	L	5	0.66	2	D	R	5	0.77
1	U	L	6	0.77	2	D	R	6	0.77
1	U	L	7	0.68	2	D	R	7	0.77
1	U	R	1	0.82	2	U	L	1	0.77
1	U	R	2	0.81	2	U	L	2	0.77
1	U	R	3	0.82	2	U	L	3	0.77
1	U	R	4	0.82	2	U	L	4	0.77
1	U	R	5	0.82	2	U	L	5	0.74
1	U	R	6	0.77	2	U	L	6	0.74
1	U	R	7	0.82	2	U	L	7	0.68
1	D	L	1	0.57	2	D	L	1	0.78
1	D	L	2	0.66	2	D	L	2	0.15
1	D	L	3	0.77	2	D	L	3	0.13
1	D	L	4	0.77	2	D	L	4	0.12
1	D	L	5	0.57	2	D	L	5	0.15
1	D	L	6	0.75	2	D	L	6	0.11
1	D	L	7	0.76	2	D	L	7	0.11
1	D	R	1	0.64					
1	D	R	2	0.59					
1	D	R	3	0.64					
1	D	R	4	0.64					
1	D	R	5	0.66					
1	D	R	6	0.67					
1	D	R	7	0.73					
2	U	R	1	0.21					
2	U	R	2	0.31					
2	U	R	3	0.21					
2	U	R	4	0.19					
2	U	R	5	0.16					
2	U	R	6	0.19					
2	U	R	7	0.22					
2	D	R	1	0.77					

APPENDIX F: 5M GROUNDWATER WELL DATA

Table F1. Fish Creek 5 M wells. Depth to groundwater measured at 5m wells across BDAs at Fish Creek.

BDA	Bank	Up or Downstream	Date	Depth to Groundwater (m)
1	Left	Up	6/20/2018	>0.8
			6/27/2018	>0.8
			7/14/2018	>0.8
			7/24/2018	>0.8
		Down	6/20/2018	>1.0
			6/27/2018	>1.0
			7/14/2018	>1.0
			7/24/2018	>1.0
	Right	Up	6/20/2018	0.56
			6/27/2018	0.54
			7/14/2018	0.56
			7/24/2018	0.55
		Down	6/20/2018	0.41
			6/27/2018	0.43
			7/14/2018	0.32
			7/24/2018	0.37
2	Left	Up	6/20/2018	0.97
			6/27/2018	0.98
			7/17/2018	>1.0
			7/24/2018	>1.0
		Down	6/20/2018	0.88
			6/27/2018	0.96
			7/17/2018	>1.0
			7/24/2018	>1.0
	Right	Up	6/20/2018	0.65
			6/27/2018	0.70
			7/17/2018	0.72
			7/24/2018	0.68
		Down	6/20/2018	0.27
			6/27/2018	0.31
			7/17/2018	0.53
			7/24/2018	0.56
Reference	Left	-	6/20/2018	0.66
			6/27/2018	0.74
			7/17/2018	0.90
			7/24/2018	0.85
	Right	-	6/20/2018	0.68
			6/27/2018	0.69
			7/17/2018	0.75
			7/24/2018	0.69

Table F2. Campbell Creek 5 M wells. Depth to groundwater measured at 5m wells across BDAs at Campbell Creek.

BDA	Bank	Up or Downstream	Date	Depth to Groundwater (m)
1	Left	Up	6/22/2018	>1.0
			7/19/2018	>1.0
			7/23/2018	>1.0
			8/1/2018	>1.0
		Down	7/19/2018	>1.0
			7/23/2018	0.95
			8/1/2018	>1.0
	Right	Up	7/19/2018	>1.0
			7/23/2018	>1.0
			8/1/2018	>1.0
		Down	7/19/2018	>1.0
			7/23/2018	>1.0
			8/1/2018	>1.0
2	Left	Up	7/19/2018	>1.0
			7/23/2018	>1.0
			8/1/2018	>1.0
		Down	7/19/2018	>1.0
			7/23/2018	0.91
			8/1/2018	>1.0
	Right	Up	7/19/2018	>1.0
			7/23/2018	>1.0
			8/1/2018	0.1
		Down	7/19/2018	>1.0
			7/23/2018	>1.0
			8/1/2018	>1.0
Reference	Left	-	6/22/2018	0.58
			7/19/2018	0.98
			7/23/2018	>1.0
			8/1/2018	0.81
	Right	-	6/22/2018	>1.0
			7/19/2018	>1.0
			7/23/2018	>1.0
			8/1/2018	>1.0

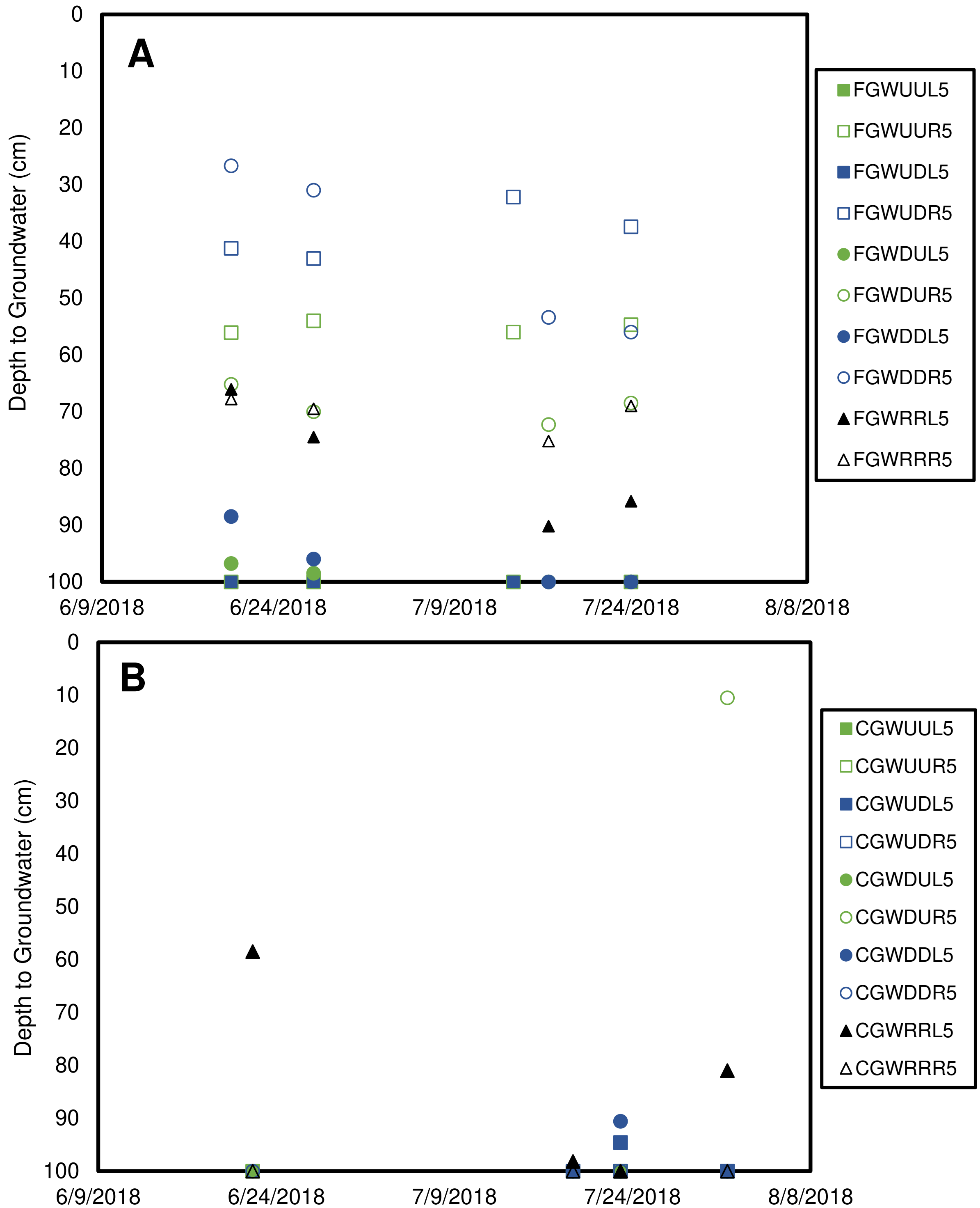

Figure F1. 5M Wells at Fish and Campbell Creeks. Graph of depth to groundwater at 5-m wells for Fish (A) and Campbell Creek (B). A depth of 100 cm indicates that the well was dry.

APPENDIX G: RESIDUAL POOL SURVEY DATA

Residual pool and sediment volumes recorded during residual pool surveys at Fish and Campbell Creek and values for predictor variables used in the multiple linear regression.

Survey[1]	**Pool**	**Pool Volume [m^3]**	**Sediment Volume [m^3]**	**Ratio[2]**	**Channel Slope**	**% Clay[3]**	**BDA Height [m]**	**Catchment Area[4] [km^2]**	**Width-to – Depth Ratio**	**Pool Surface Area [m^2]**
C1	BDA 1	0.458	0.315	0.688	0.008	21	0.19	7.91	7	8.6
C1	BDA A	2.711	1.866	0.689	0.008	21	0.4	7.91	19	32.5
C1	BDA B	1.408	1.099	0.781	0.0075	21	0.3	8.04	4	9.4
C1	BDA 2	1.588	1.096	0.69	0.007	21	0.46	8.13	4.6	11.5
C1	Reference	0.155	0.046	0.295	0.007	21	0	8.13	2.5	2.7
C2	BDA 1	0.735	1.126	1.533	0.008	21	0.19	7.91	7	13.2
C2	BDA A	2.316	3.234	1.397	0.008	21	0.4	7.91	19	27.8
C2	BDA B	1.263	2.187	1.731	0.0075	21	0.3	8.04	4	7.3
C2	BDA 2	1.766	2.157	1.221	0.007	21	0.46	8.13	4.6	11
C2	Reference	0.177	0.076	0.43	0.007	21	0	8.13	2.5	3.1
F1	BDA 1	0.347	0.328	0.944	0.048	25	0.145	3.85	5.3	6
F1	BDA A	3.362	1.018	0.303	0.048	25	0.27	3.85	6.5	21.4
F1	BDA B	5.955	1.913	0.321	0.043	25	0.19	3.91	4.8	27.3
F1	BDA 2	18.783	4.178	0.222	0.043	25	0.76	3.91	5.6	45
F1	Reference	0.096	0.0815	0.849	0.049	25	0	4.09	9	3.6
F2	BDA 1	4.674	1.248	0.267	0.045	25	0.145	3.85	5.3	18
F2	BDA A	5.028	1.218	0.242	0.045	25	0.27	3.85	6.5	25
F2	BDA 2	17.121	3.811	0.223	0.043	25	0.76	3.91	5.6	38.8
F2	Reference	0.036	0.034	0.95	0.049	25	0	4.09	9	4.2

[1] Survey labels indicate the site (F – Fish Creek, C – Campbell Creek) and the survey date (1st or 2nd survey of 2018)
[2] Ratio of residual sediment to pool volume
[3] Percent clay gathered from NRCS online soil survey
[4] Catchment area calculated using USGS StreamStats