THESIS

DECREASING STREAM HABITAT FOR GREENBACK CUTTHROAT TROUT UNDER FUTURE CLIMATE PROJECTIONS IN HEADWATER STREAMS OF THE SOUTHERN ROCKY MOUNTAINS, COLORADO

Submitted by

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ABSTRACT

DECREASING STREAM HABITAT FOR GREENBACK CUTTHROAT TROUT UNDER FUTURE CLIMATE PROJECTIONS IN HEADWATER STREAMS OF THE SOUTHERN ROCKY MOUNTAINS, COLORADO

Headwaters are vital to the abundance and diversity of biota as they produce various temperatures, light, hydrologic regimes, water chemistry, substrate type, food resources, and species pools. Many studies have shown that headwater streams are especially vulnerable to changing climate, and coldwater fish are especially sensitive to the fluctuations in streamflow and water temperature during summertime low flows. Though previous studies have provided insights on how changes in climate and alterations in stream discharge may affect the habitat requirements for native cutthroat trout species, the suitable physical habitats have not been evaluated under future climate projections for the threatened Greenback Cutthroat Trout (GBCT) occupying the headwater regions in the Southern Rocky Mountains. Thus, this study used field data collected in the summers of 2019 and 2020 from selected headwater streams across the Front Range in the Southern Rocky Mountains to construct one-dimensional hydraulic models (HEC-RAS) to evaluate streamflow and physical habitat under four future climate projections. A principal component analysis (PCA) was then performed to demonstrate the importance of each morphological feature of these streams. Results illustrate high variations in both predicted streamflow reductions and physical habitat for all future climate projections. The projected mean summer streamflow shows much greater decline compared to the projected mean August flow.

Moreover, sites located at higher elevations with larger substrate (D50 and D84) and steeper slopes may experience greater reductions in physical habitat under mean summer future climate projections. Future climate change studies on cold-water fisheries need to take multiple influential factors into account instead of heavily focusing on the thermal characteristics. Reintroduction and management efforts for GBCT should be tailored to the individual headwater stream with adequate on-site monitoring that can be applied in a more holistic manner as well.

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1 Introduction

1.1 Importance of Headwater Streams

Headwater streams are defined as first- and second-order channels that account for 79% of river length in the Unites States (Wohl, 2017; Colvin et al., 2019). They typically have a relatively high gradient of greater than 0.002 m/m along most of the channel length due to the steep topography of mountainous regions (Jarret, 1992; Wohl, 2010). Large variabilities are expected for headwater streams for various characteristics including hydrologic regime, channel gradient, channel planform, grain size and bedform, sediment dynamics, and aquatic and riparian biota (Wohl, 2010). Headwater streams are critical to ecosystems as they directly affect the abundance and diversity of the biota through: 1) offering a refuge from extreme temperature or flows, predators, competitors, or introduced species; 2) providing a vital habitat for endemic and threatened fish species that are not available elsewhere, and 3) providing spawning and rearing areas, as well as food sources, for fish and other aquatic and riparian organisms (Schlosser, 1995; Meyer et al., 2007; Wohl, 2017; Colvin et al. 2018).

1.2 Climate Change in Mountainous Regions

Due to the unique environments of headwater streams, they are especially sensitive to changing climate (Beniston, 2003). Climate change in mountainous regions is of particular concern because seasonal snowpack, an important component for regional water supplies, is declining in the western United States (Pederson et al., 2013; Scalzitti et al., 2016). In addition, warmer temperatures in winter and spring are altering the precipitation patterns from snow-dominant to rain-dominant hydrologic regimes (Klos et al., 2014). Earlier snowmelt timing and the decline in annual streamflow are expected because of the loss of snow (Clow 2010; Jefferson, 2011; Furey et al., 2012; Berghuijs et al., 2014; Hammond and Kampf; 2020), which would result in lower flows later during summer months and a reduction of stream habitat to an extent that could significantly affect coldwater fish species of which some are already threatened or endangered (Bradford and Heinonen, 2013; Watts et al., 2016).

1.3 Native Cutthroat Trout in the Southern Rocky Mountains

The native cutthroat trout species in the Southern Rocky Mountains have been declining with habitat loss from land-use changes, non-native trout species invasion, and water abstraction from human activities over the last 150 years (Roberts et al., 2017). It is expected that the increase of temperature and diminishing streamflow in summer will amplify the already stressful environment for native cutthroat trout species (Mantua et al., 2010; Roberts et al., 2017).

One of the native cutthroat trout species in the Southern Rocky Mountains is the Greenback cutthroat trout (*Oncorhynchus clarkii stomias*), which has been listed as endangered species under the U.S. Endangered Species Act (ESA) in 1973 and upgraded to threatened in 1978 (Young et al., 2009). Since then, tremendous conservation and restoration efforts have been implemented to translocate and restore Greenback Cutthroat trout (GBCT) that face multiple stressors including habitat loss from land uses and water abstraction, environmental stochasticity, and invasion by nonnative species that have caused GBCT declines in many regions in the past decades (Young et al., 2009, Roberts et al., 2017). The habitat requirements of GBCT, similar to other trout species, include a variety of flows to provide suitable habitat for the GBCT populations during different phases of the life cycle including free passage for migration, clean and stable gravel beds for successful incubation of eggs, and desired velocity and volume of flow for summer rearing and overwintering (Sullivan et al., 1987). Though GBCT populations have been successfully restored in multiple sites at headwater streams and lakes, many of these populations are considered unstable owing to the small population size, lacking reproduction, or the presence of nonnative salmonids (McGrath and Lewis, 2007). More uncertainties to the GBCT populations are expected under the influence of the globally changing climate.

Harig and Fausch (2002) stated that the existing native cutthroat trout populations in the western United States are already restricted to short headwater stream fragments due to habitat loss and non-native trout invasions, and the appropriate scale of habitat measurements for predict cutthroat trout translocation success in a fragmented watershed (with a minimum area of 14.7km^2) is at the patch rather than landscape scale. Roberts et al. (2013) found that the interaction of short stream fragments <7 km long and stochastic disturbances are more detrimental to the survival of the native Colorado River cutthroat than the high temperatures during the warmest summer period. Roberts et al. (2017) later examined the rate of invasion of nonnative trout along with the direct and indirect effects of climate change and found that the combined outcome could extirpate 39% of the total Colorado River cutthroat trout populations and put another 37% of the populations at risk of extirpation in the Southern Rocky Mountains. Moreover, Uthe et al (2019) indicated that there is a positive relationship between stream discharge and growth rates in length and mass of the Yellowstone Cutthroat Trout, though temperature effects were not comparably significant.

For GBCT specifically, Cooney et al. (2005) modeled stream temperatures for 10 streams where GBCT has been translocated and found that high variability occurred in modeled results due to the significant differences between sites. They also found that modeled warmer temperature projections (+2°C and +4°C warming of average air temperatures) may improve the probability of translocation success, leading to a mixed effects on GBCT from climate change. Scarnecchia and Bergersen (1986) assessed the production and habitat of GBCT and Colorado River cutthroat trout in north-central Colorado and found that the stream-specific physical characteristics (e.g., maximum temperature, diversity of substrate, undercover banks, etc.) also exert strong influences on the biomass and production of cutthroat trout in addition to biological factors. These studies highlighted the importance of taking multiple factors (e.g., flow regimes) into account instead of only focusing on the thermal characteristics for future climate adaption strategies for cutthroat trout.

1.4 Research Objectives

Quantitative analysis for other native cutthroat trout species in the southern Rocky Mountain have occurred to evaluate the minimum habitat requirements under climate change. Furthermore, several studies on GBCT have demonstrated the importance of understanding the changes in physical characteristics and discharge as they can greatly affect the production and habitat of GBCT. However, the suitable streamflow conditions of the headwater regions in the Southern Rocky Mountains for the threatened GBCT under the influences of climate change have not been assessed.

Hence, the main objectives of this research are to understand and review the streamflow conditions of the headwater regions through collecting and evaluating field data from June 2019 to August 2020, and then evaluate the future suitable physical habitats for the survival of threatened GBCT. To meet the goal, two measurable objectives are introduced. These objectives are 1) to develop one dimensional (1-D) hydraulic model to evaluate the current stream physical habitats for GBCT using field data from potential GBCT reintroduction locations throughout the Southern Rocky Mountains of Colorado; and 2) to statistically compare the current physical habitat metrics to projected physical habitat metrics using flow predictions from previously published studies.

2 Methods

2.1 Study Sites and Morphological Field Data

A total of 12 study sites located in the headwater regions in the southern Rocky Mountain along the Front Range in Colorado were selected with elevation ranges from 2201 m to 3650 m (Figure 1 and Table 1). The climate in the Front Range varies with altitude from an annual average of 100 cm of precipitation and 2°C at the highest mountains, to 40 cm and 10°C at the mountain front (Wohl, 2001). High flows within the Front Range River corridors are either from convective summer storms occurring mainly in July and August, or from snowmelt during late May and June that may last for two to three weeks (Wohl, 2001). Soil formation and plant communities are controlled by the climate, and the distinctive bands of vegetations in the Front Range can be categorized into cushion plants, alpine tundra of ground hugging grasses and dwarf tress lie between 3480 m to 4300 m; subalpine forest of spruce and fir down to 2800 m; and montane forest of mixed aspen, conifers and other deciduous down to the transition to steppe vegetation about 1700 m (Wohl, 2001).

Channel surveys were conducted for each site throughout the summer of 2019 using a stadia rod and Leica automatic level. The surveyed reach length for each stream was between 27 m to 75 m depending on the specific morphology of the stream (Table 1). A total of ten cross sections for each reach were surveyed. The morphological data collected for each study site included elevation of the reach, average slope, aspect, average channel width, average bankfull depth, and particle size distribution (Table 2). The elevation of each reach was obtained using GPS data collected in the field, and the average slope for each reach was calculated through the difference between thalweg at upstream and the lowest elevation downstream over the total reach distance. The total reach length was obtained as the distance between the most upstream and downstream cross-sections surveyed in the field. The aspect for each site was derived using both Google Earth and CalTopo. Channel width was calculated through averaging differences between right bankfull and left bankfull elevation for the entire reach; average bankfull depth was obtained by averaging the weighted bankfull depth, which is calculated by subtracting elevation of each point from the averaged right and left bankfull elevation. The particle distribution for each site was calculated using R2Cross (https://r2cross.erams.com/) based on sediment samples collected using the Wolman pebble count method (Wolman, 1954). Finally, each channel is classified using the Montgomery and Buffington channel classification system (Montgomery and Buffington, 1998).

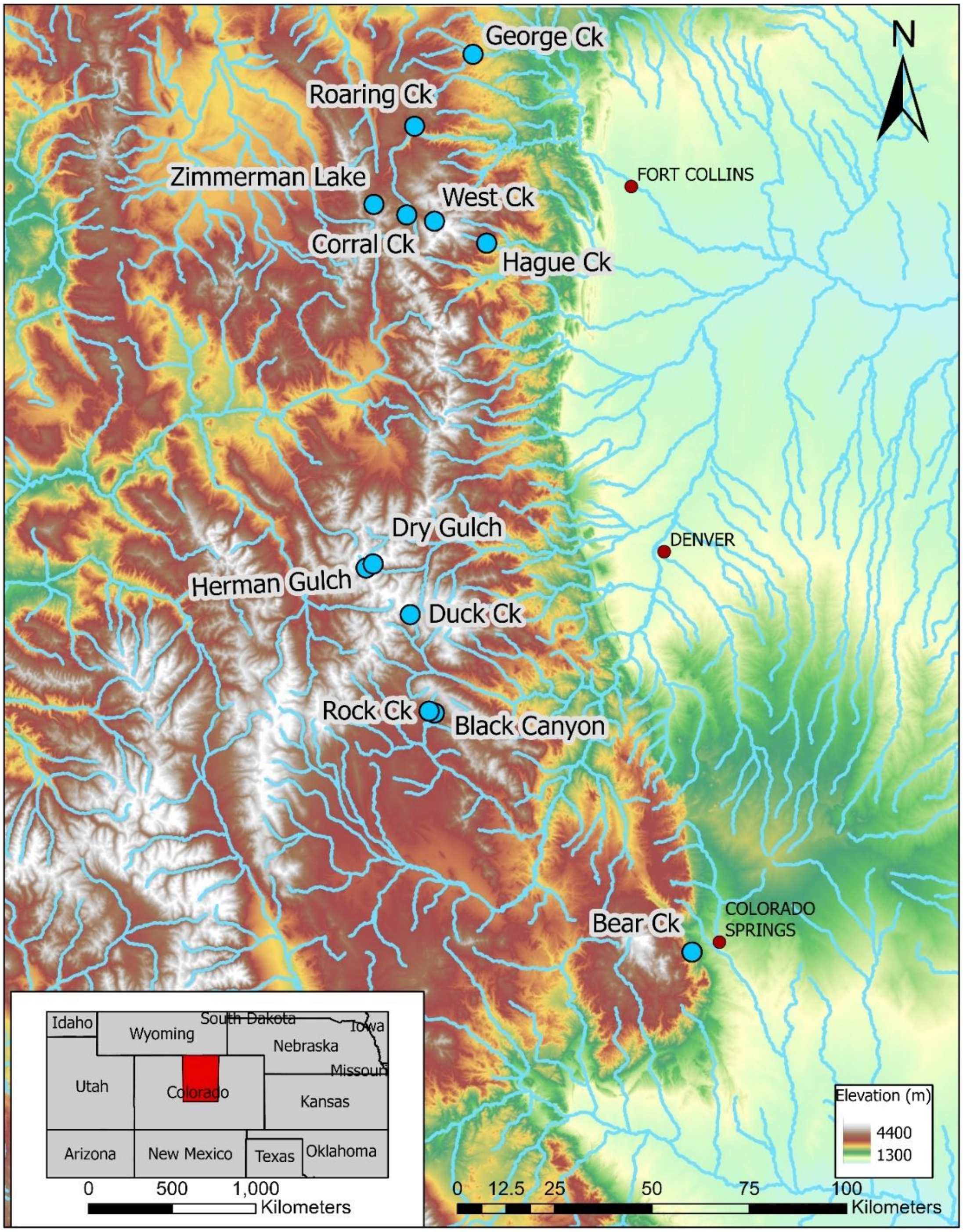

Figure 1. Map of study sites

Table 1. Summary table of morphological data

Site	Latitude	Longitude	Particle Size (mm)			Slope	Elevation	Aspect	Reach Length	Mean Bankfull Depth	Mean Channel Top Width	Montgomery and Buffington Classification	Drainage Area
	Degrees N	Degrees E	D25	D50	D84		(m)		(m)	(m)	(m)		(km^2)
Bear Creek	38.799	-104.949	2.3	3.8	10.8	0.07	2201	SW	27	0.23	2.8	Step Pool	11.7
Black Canyon Creek	39.363	-105.670	2.8	5.4	91.3	0.05	2933	SE	33	0.33	2.4	Step Pool	10.3
Corral Creek	40.520	-105.822	5.3	75.9	186.5	0.03	3036	NE	55	0.5	3.9	Step Pool	14.5
Dry Gulch	39.705	-105.895	56.1	104.7	173.1	0.04	3298	SE	44	0.36	3.8	Step Pool	8.0
Duck Creek	39.591	-105.745	24.0	42.5	119.3	0.11	3650	NW	29	0.3	2.5	Cascade	2.0
George Creek	40.889	-105.699	8.7	50.6	86.6	0.02	2367	SE	35	0.42	3.2	Pool Riffle	37.3
Hague Creek	40.498	-105.678	19.0	30.2	54.3	0.007	3008	NW	75	0.6	10.2	Pool Riffle	13.4
Herman Gulch	39.719	-105.898	47.0	84.1	157.1	0.05	3306	NE	30	0.37	3.8	Step Pool	8.1
Roaring Creek	40.770	-105.731	24.7	51.8	138.9	0.02	2677	SE	36	0.38	5.3	Pool Riffle	23.9
Rock Creek	39.368	-105.686	27.4	41.8	76.2	0.02	2925	SE	42	0.37	3.8	Pool Riffle	16.0
West Creek	40.458	-105.534	24.7	41.3	200.1	0.07	2502	SW	34	0.56	9.3	Step Pool	24.3
Zimmerman Creek	40.541	-105.865	3.4	4.5	8.7	0.006	3202	NE	27	0.25	1.8	Pool Riffle	1.1

2.2 Streamflow data

2.2.1 Discharge Time Series

Time series data of water levels and atmospheric pressure data were obtained using Onset HOBO (Honest Observer By Onset) U20L data loggers that were placed in stable stream location within each study site. Data from the study sites was collected every 30 minutes from June 2019 to August 2020. A time series of relative head was calculated using the pressure differences between the water level and atmosphere as follows:

$$h_{relative} = \frac{P_{water} - P_{air}}{\rho_w g}$$

Here the $h_{relative}$ is the relative head (m), the P_{water} is the recorded water level pressure (N/m^2), P_{air} is the recorded atmospheric pressure (N/m^2), ρ_w is the water density (1,000 kg/m^3), and g is the acceleration due to gravity (9.81 N/kg).

For each study site, a rating curve was constructed using measured discharge data and the calculated relative head at the time when the discharge was measured. Discharge was measured using a Sontek FlowTracker 2 Acoustic Doppler Velocimeter. The rating curve equation was generated through the power trendline between the relative head and stream discharge, and the derived equation for each site was then applied to calculate stream discharge using the computed relative head for each 30 min interval. Rating curves for Duck Creek and Zimmerman Creek could not be developed because accurate atmospheric data was not collected those two sites.

2.2.2 Mean 30-Day Minimum Discharge

A mean 30-day minimum discharge (M30MD) was computed between June 14 to September 30 using a 30-day rolling average for the years 2019 and 2020. This metric is particularly important for cold water fish habitat during summertime low flow since a certain level of water depth is required as the minimum habitat (Martin and Arihood, 2010). The mean value for M30MD was derived using the average of the 2 years of M30MD.

2.2.3 Percent Reductions from Projected Streamflow

Reductions in the projected streamflow for the years 2040 and 2080 were obtained from the Western U.S. Stream Flow Metrics database (https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml) that was developed by U.S. Forest Service Rocky Mountain Research Station. The forecasted changes to streamflow were based on daily simulations using a variable infiltration capacity (VIC) macroscale hydrologic model. A VIC model is physically based and fully distributed model that solves surface water balance, which has been widely adopted in the western United States to forecast the hydrologic changes (Wenger, et al., 2009). The historical (1977 – 2006), 2040 (mid central time period, centered around 2040s) and 2080 (end of century time period, centered around the 2080s) projected stream flows were downloaded directly from the Flow Metrics database based on the stream network IDs that aligned with GPS coordinates of each study site (Data Guide, 2022). The flow variables selected from the database that were relevant to this study include the mean summer flow (MS) which is the average of daily flow between June 1 and September 30, and the mean August flow (MAUG), which is the average of daily August flows and generally represents baseflows in headwater streams (USDA Forest Service Office of Sustainability and Climate, 2022). The projected MS and MAUG discharge estimates for 2040 and 2080 were downloaded for stream reaches that aligned with the locations of the study sites. To estimate hydrologic responses to future climate projection at each site, the 2040 and 2080 MS and MAUG percent reductions from the Flow Metrics database were applied to the current

M30MD discharge at each study site. The resulting discharges based on the four climate change projections were designated as 2040MS, 2080MS, 2040MAUG and 2080MAUG.

2.3 One-Dimensional Hydraulic Modeling

2.3.1 Model Development and Calibration

Surveyed channel geometry data for each site were used to develop one-dimensional (1-D) hydraulic models. The US Army Corps of Engineering Hydrologic Engineering Center's River Analysis System (HEC-RAS) version 6.1 model was chosen for the 1-D models because it is freely available and widely used (User's Manual, 2016). As previously stated, at least ten surveyed cross-sections were measured in the field, and these cross-sections formed the basis for the channel geometry in HEC-RAS. The models used a mixed flow regime to account for supercritical and subcritical hydraulic conditions. Depending on the specific characteristics of each site, the downstream boundary condition was chosen as either critical depth or normal depth based on the average downstream slope. Upstream boundary conditions were assigned normal depths based on the average upstream channel slope. Additional cross sections were interpolated in HEC-RAS for the most downstream cross-sections at some sites to improve the model reliability.

An accurate Manning's roughness coefficient plays a significant role in improving the simulation results for hydraulic modeling. To calibrate the Manning's roughness coefficient for each model, the root mean square error (RMSE) was calculated using differences in water surface elevation between simulated and observed conditions for a range of roughness values. The calibration process for each site used a single discharge that was collected during the channel geometry surveys. The equation used to calculate the RMSE is denoted as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Simulated_i - Observed_i)^2}{N}}$$

where *RMSE* is the root mean square error (m), *N* is the total number of observations and *I* is the number of observations. The Manning's roughness coefficient with the smallest RMSE value was selected as the calibrated value for modeling different discharges.

2.3.2 Simulated Flows

Discharges simulated in each HEC-RAS model include: 1) the calibrated discharge, which was measured during cross-sectional surveys; 2) M30MD, which is the mean 30-day minimum discharge from the rolling averages between June 14 and September 30; 3) 2040MS and 2040MAUG discharges (see Section 2.2.3); and 4) 2080MS and 2080MAUG discharges (see Section 2.2.3).

2.3.3 Modeled Habitat Characteristics

Data for the following five habitat characteristics were examined based on the modeling results: channel velocity (m/s), average flow area (m^2), channel top width (m), channel wetted perimeter (m), and maximum flow depth (m). These habitat characteristics were selected as indicators for the physical habitat for cold water fish based on previous studies on habitat reequipments of salmonids (e.g., Bjornn and Reiser, 1991). The reach-averaged and cross-sectional habitat values were examined for each site.

2.4 Reduction in Study Site Dimensionality

Principal components analysis (PCA; Pearson, 1901; Jolliffe, 2002) was used to summarize dominant morphological variables among sites. PCA is known for its ability to reduce the dimensionality of a dataset while preserving its variability as much as possible (Jolliffe, 2002; Jolliffe and Cadima, 2016). Variables used in the PCA include elevation, average slope, D50, D84, averaged top width and average channel depth (Table 1). Latitude was initially added to the PCA but was removed because the inclusion of latitude caused minor changes in the PCA results and was not helpful for interpretation. All 12 sites were included in the PCA, which was conducted using R Statistical Software (version 4.1, R Core Team 2021), the stats (v3.6.2; R Core Team, 2021) and ggplot (v3.3.6; Wickham, 2016) packages.

3 Results

3.1 Streamflow Under Future Climate Projections

Results indicate reductions for both mean summer discharges (-7% to -53% for 2040; -18% to -80% for 2080) and mean August discharges (-7% to -37% 2040; -3% to -46% for 2080), as shown in Table 2. Mean summer discharges are projected to decrease more than mean August discharges. Sites with large reductions in streamflow under mean summer projections may have smaller percent reductions under mean August projection (Table 2). Additionally, reductions from 2080 scenarios for both mean summer and August illustrate greater decreases in streamflow compared to the 2040 future climate projection scenario. It is worth noting that the percent reductions in streamflow show large variations among different sites under both climate projection scenarios (e.g., Dry Gulch and George Creek).

Table 2. Summary table for calibrated, mean 30day minimum, and projected mean summer and mean August flows for 2040 and 2080

		Mean 30-Day Min Discharge (m^3/s)			Year 2040		Year 2080	
					Mean Summer Discharge	Mean August Discharge	Mean Summer Discharge	Mean August Discharge
Sites	Calibrated Discharge (m^3/s)	2019	2020	Average	% change	% change	% change	% change
Dry Gulch	0.44	0.042	0.084	0.063	-53%	-10%	-80%	-15%
Corral Creek	0.74	0.005	0.001	0.003	-45%	-11%	-79%	-16%
Herman Gulch	0.19	0.027	0.047	0.037	-52%	-12%	-77%	-18%
West Creek	0.21	0.143	0.159	0.151	-36%	-32%	-69%	-44%
Hague Creek	0.91	0.013	0.018	0.016	-33%	-37%	-64%	-46%
Roaring Creek	0.13	0.047	0.048	0.047	-32%	-6%	-48%	-10%
Bear Creek	0.018	0.01	0.007	0.009	-21%	-21%	-38%	-36%
Black Canyon	0.068	0.021	0.004	0.012	-19%	-7%	-28%	-10%
Rock Creek	0.15	0.019	0.008	0.014	-15%	-3%	-23%	-3%
George Creek	0.08	0.023	0.011	0.017	-7%	-7%	-18%	-10%

3.2 Simulated physical habitats

The calibrated Mannin''s roughness coefficients have a range of 0.055 to 0.45 for all sites with a RMSE ranging from 0.017 to 0.10 (Table 3).

Table 3. Results for RMSE after Manning's n calibration

Site	Calibrated Manning Roughness Coefficient	RMSE (m)
Bear Creek	0.45	0.086
Black Canyon Ck	0.09	0.044
Corral Creek	0.08	0.085
Dry Gulch	0.11	0.069
Duck Creek	0.15	0.063
George Creek	0.31	0.062
Hague Creek	0.055	0.075
Herman Gulch	0.25	0.033
Roaring Creek	0.1	0.028
Rock Creek	0.08	0.044
West Creek	0.35	0.10
Zimmerman Creek	0.095	0.017

The simulated velocity, wetted perimeter, and max channel depth values show the responses to future climate projections as these physical habitats can sufficiently represent the suitability of required habitat for GBCT. As shown in Figure 2 and 3, physical habitat reduced with the decreasing of flows, and mean summer projections show greater reduction in simulated habitats than mean August projection for both 2040 and 2080 future climate projections. The greatest decreases in all three simulated physical habitats are found under the 2080 mean summer future climate projection (Figure 3), which is expected since the streamflow is reduced the most. Some sites have greater variabilities in the simulated physical habitat (e.g., West creek and Roaring creek) than others. Furthermore, variation is observed among sites as shown in each boxplot (Figure 2 and 3), indicating the loss of physical habitats is site-specific under future climate projections.

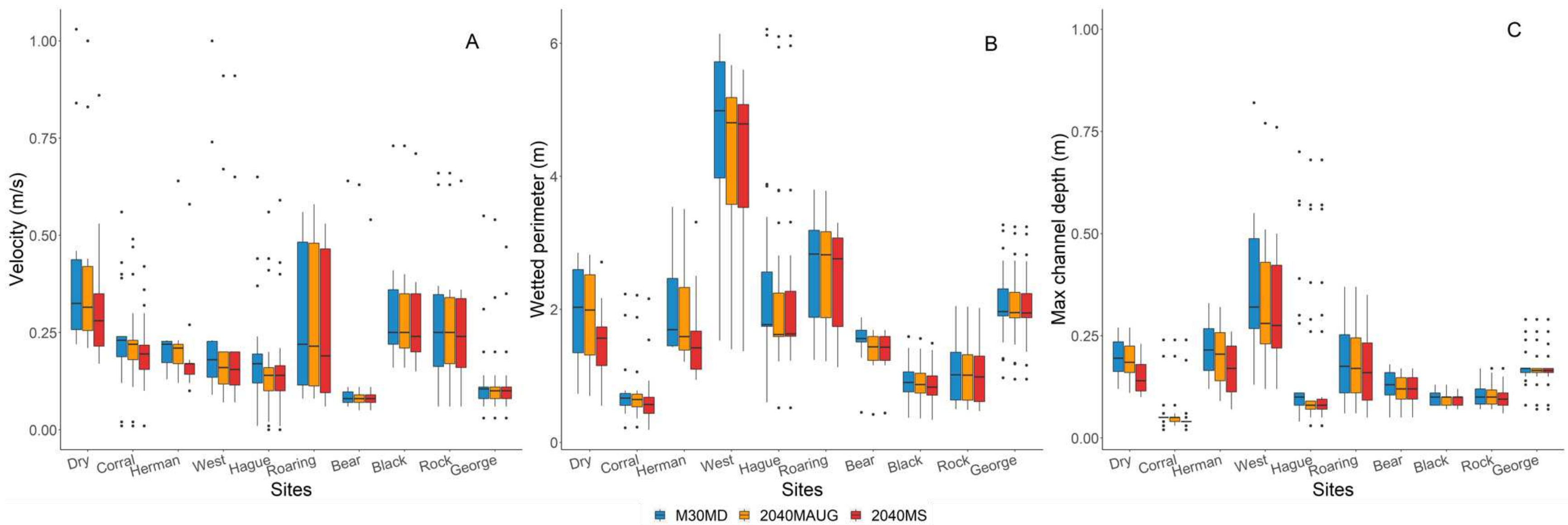

Figure 2. Boxplot results for simulated physical habitat under 2040 mean summer and mean August climate change projection. (a): velocity; (b): wetted perimeter; and (c): max channel depth

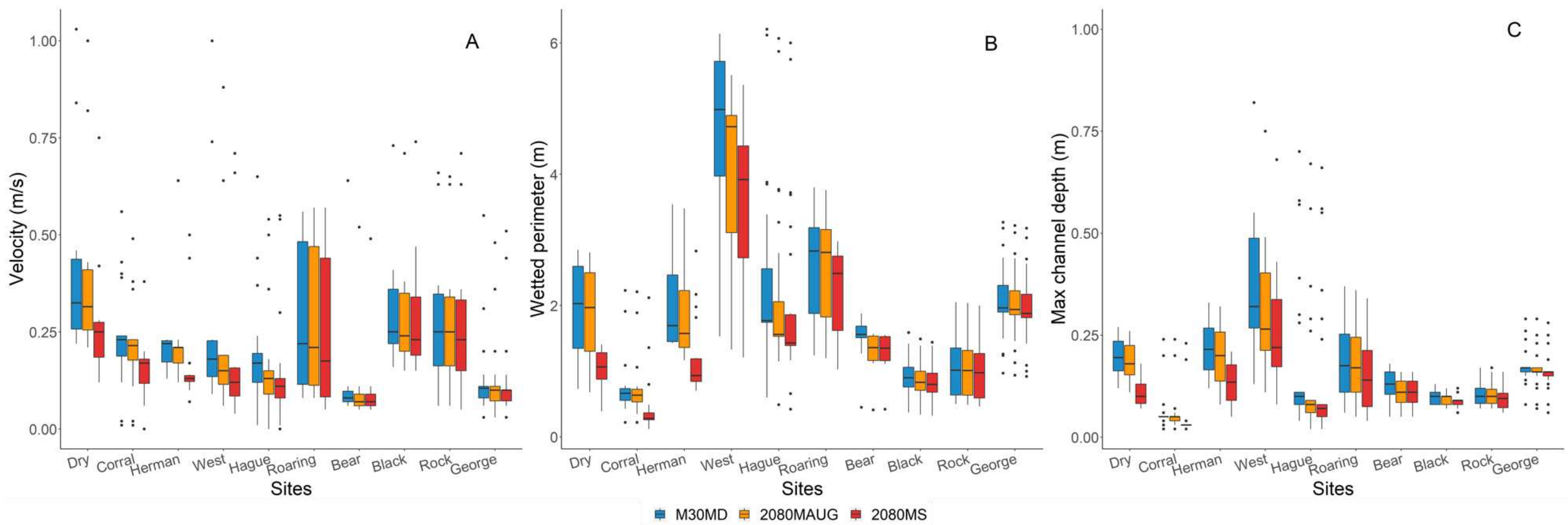

Figure 3. Boxplot results for simulated physical habitat under 2080 mean summer and mean August climate change projection. (a): velocity; (b): wetted perimeter; and (c): max channel depth.

3.3 PCA results

Results from the PCA show that approximately 68% of the variability among sites can be explained with two principal components, with the first component (PC1) explaining 38.7% and the second component (PC2) explaining 29.2% of the total variability in the dataset (Figure 4). Acute angles in Figure 4 (e.g., angle between average channel width and average bankfull depth; between average slope and elevation) indicate the variables are in the same direction or are collinear; while two variables that have obtuse angle illustrate negative correlation (e.g., angle between average slope and drainage area). The results differentiate the study sites according to two main combinations of morphological attributes: PC1 captures sites with larger channels and larger contributing drainage areas, and PC2 captures sites with steeper gradients, larger bed material (e.g., cobble beds), and higher elevations. In other words, sites with larger drainage areas, wider average channel widths and deeper average bankfull depths (e.g., Hague Creek and West Creek) are positively correlated with PC1, and sites located at higher elevations with larger substrate (D50 and D84) and steeper slopes (e.g., Herman Gulch and Dry Gulch) are negatively correlated with PC2.

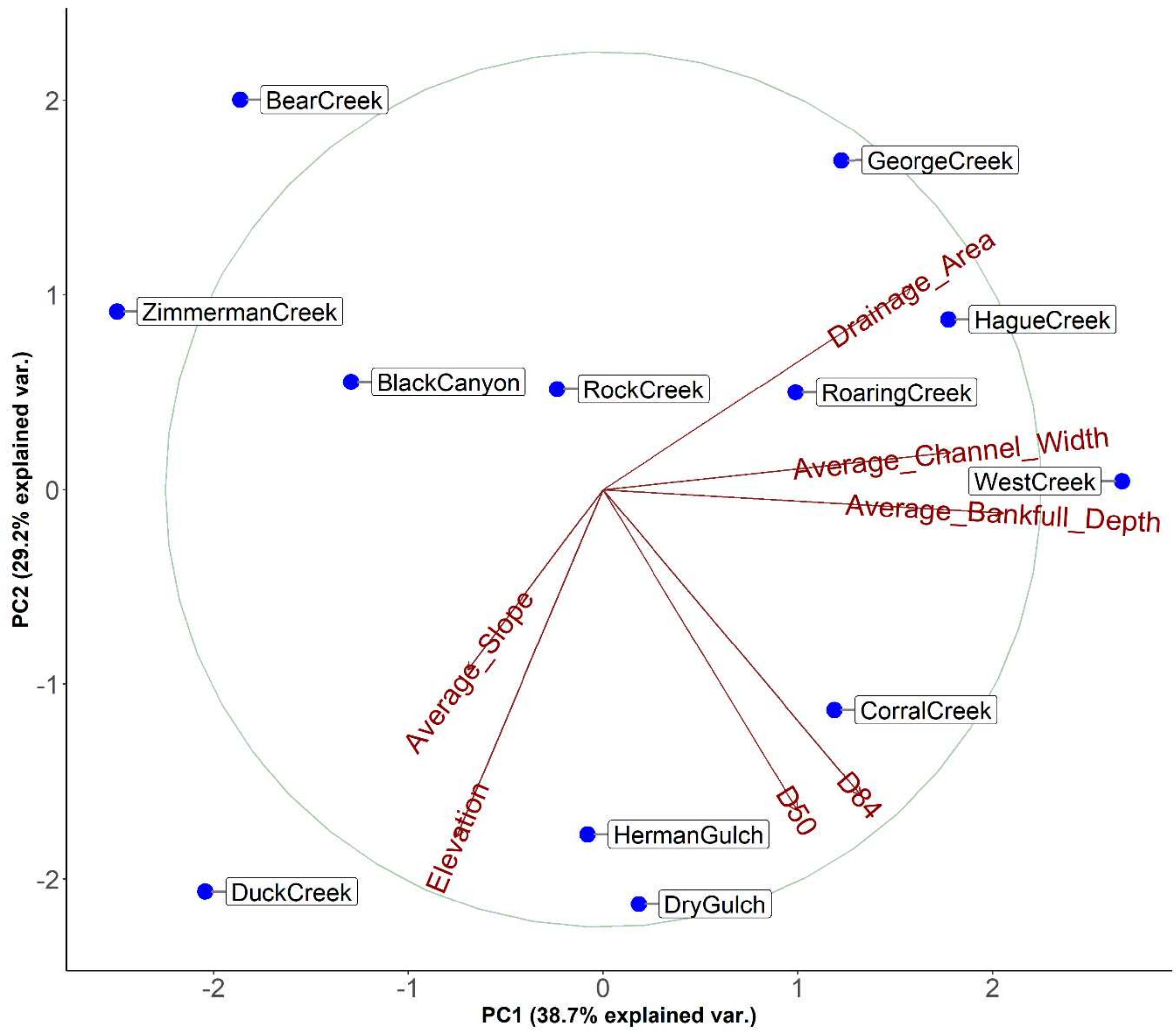

Figure 4. Results of PCA

3.4 Responses of Physical Habitat to Projected Flow Reductions

To better understand the effects of future climate projections on different physical habitats across sites, relationships between PCs and the percent change in simulated physical habitats under different future climate projections were analyzed. The results highlight linear correlations between the PC2 and percent change in simulated physical habitats for both 2040 (R^2 values range from 0.64 to 0.79) and 2080 (R^2 values range from 0.38 to 0.78) mean summer future climate projections (Figures 5 and 6). Since PC2 is negatively correlated with average slope, elevation, and substrate sizes, these results indicated that sites that are located at higher elevations with steeper slopes and larger substrates may experience greater reductions in simulated physical habitat for both 2040 and 2080 mean summer future climate projection. Furthermore, step-pool morphology streams may experience greater loss in physical habitats compared to streams with pool-riffle morphology (Figures 5 and 6).

No clear relationships were found between PC1 and reductions in physical habitats for 2040 or 2080 climate projections (R^2 between 0 and 0.31) (Figures 5 and 6).

Results for mean August future climate projections were not included in the main manuscript because the R^2 values are small enough to be neglected, indicating no correlations (Appendix A3).

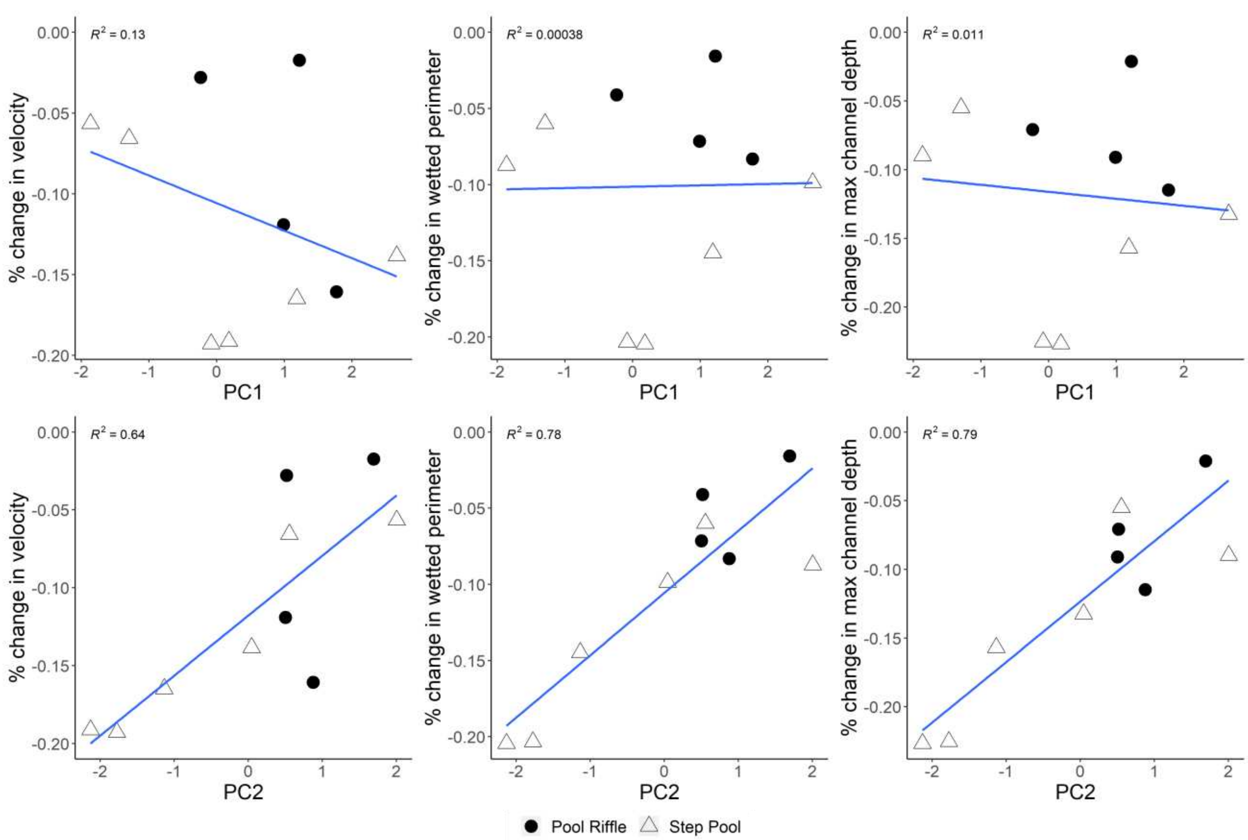

Figure 5. Relationships between PC and simulated reductions in physical habitats under 2040 mean summer projections.

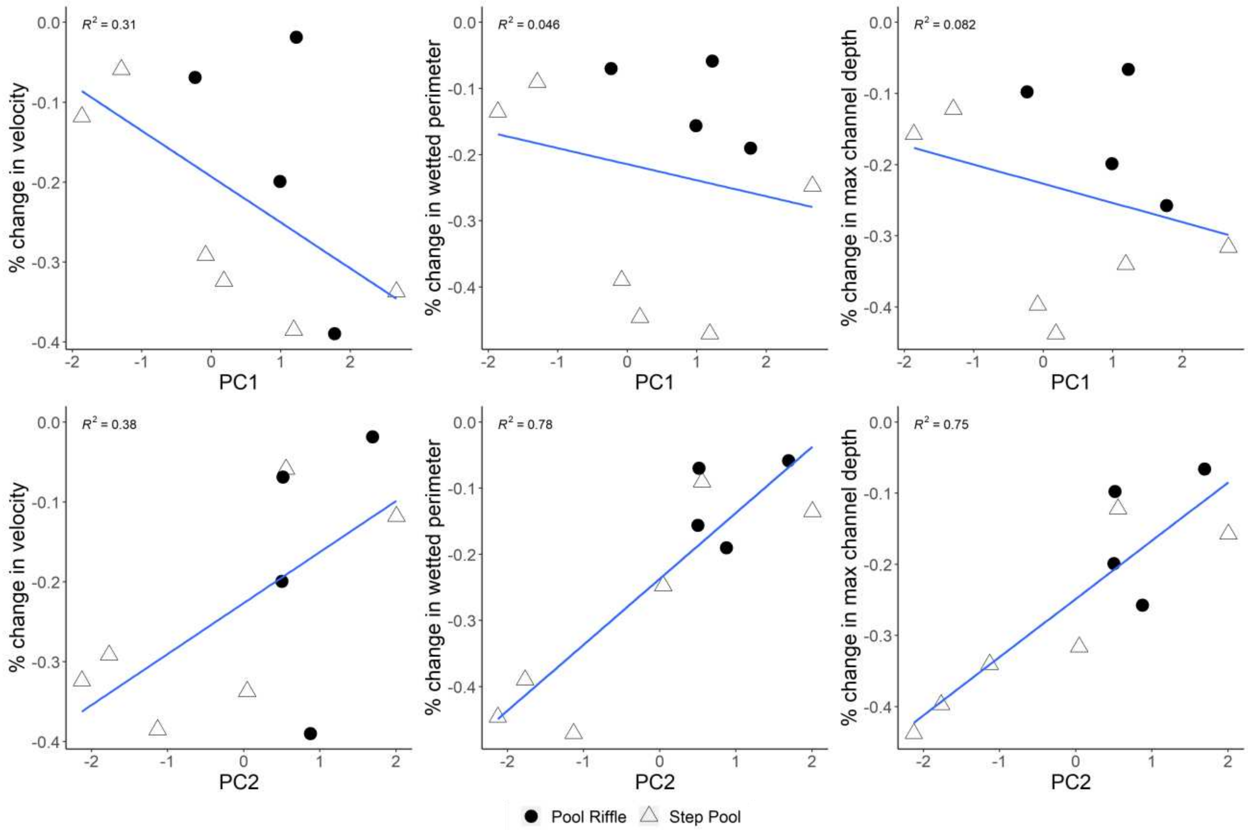

Figure 6. Relationships between PC and simulated reductions in physical habitats under 2080 mean summer projections.

4 Discussion

4.1 Implications for GBCT reintroduction and management

The results from the projected streamflow reductions (Table 2) demonstrate that substantial reductions occur in the mean summer projections but not in the mean August projections. This is likely because the mean summer flow represents the overall changing of summer streamflow that is reduced significantly by the declined snowpack and earlier snowmelt in the southern Rocky Mountain (Clow, 2010; Harpold et al., 2012; Pederson et al., 2013), whereas the August flow characterizes only baseflow which the model does not project will decrease to the same extent. Declining summer streamflow is also reported in the Central Rocky Mountains with different levels of reductions (Rood et al., 2007, Leppi et al., 2012). The milder decreases in mean August flow is likely due to the buffering effects of the groundwater storage and discharge in the mountain watersheds providing resilient to climate-driven hydrologic changes (Liu et al., 2004; Rumsey et al, 2015; Somers and McKenzie, 2020). However, it is worth noting that the decreases in mean August flows (baseflows) even with smaller percent reductions could be more stressful to GBCT especially coupled with higher stream temperature (Young, 2009).

Flow resistant coefficient for mountain streams is expected to be greater than streams at lower elevations due to the natural morphology of mountain streams (Aberle and Smart, 2003; Yochum et al., 2014). Though some calibrated Manning's roughness coefficients found in this study are much higher (e.g., Bear Creek and West Creek as shown in Table 3) compared to the suggested maximum value of 0.07 for mountain rivers indicated in the HEC-RAS Hydraulic Reference Manual (User’s Manual, 2016) based upon Chow (1959), these results are consistent with previous studies suggesting mountain streams with higher gradient have considerably high values of the Manning's coefficient (Reid and Hickin, 2008; Yochum and Bledsoe, 2010; Yochum et al., 2014).

Large variabilities in the modeled stream physical habitat among study sites can be found under all future climate projections (Figures 2 and 3), indicating physical habitat at each site responds to future climate projections differently. The maximum simulated cross-sectional average loss is almost 50% and the minimum reduction is 7% for wetted perimeter (Appendix A2). This is not surprising as characteristics of headwater streams can vary even within a single region due to different geology, slopes, aspect, contributing areas, surrounding vegetations and other factors (Cooney et al., 2005; Richardson, 2019; Birrell et al., 2020). Furthermore, stream-specific characteristics are found to be the primary controls on biomass and production of cutthroat trout (Scarnecchia and Bergersen, 1986), highlighting the importance of developing site-specific conservation plans while assessing the impacts of future climate change on GBCT. It needs to be noted that the accuracy of the simulated physical habitat in this study is affected directly by the HEC-RAS modeling. Detailed limitations are discussed in the next section.

The PCA results suggest that sites with higher elevations, steeper slopes and larger substrates tend to be more susceptible to future flow reductions (Figures 5 and 6). This aligns with the elevation dependent warming found in mountain regions of the world as high elevation regions appear to warm faster and experience more rapid climate-driven changes than elsewhere on Earth (Pepin et al., 2015; Birrell et al., 2020). Since GBCT has already been confined to higher elevations (Cook et al., 2010), the degradation in steep, high-elevation habitats will exert more stress on the GBCT population.

Based on the modeled reductions in physical habitat under future climate projections, some sites might be more suitable (e.g., George Creek, and Rock Creek) than others for the reintroduction of GBCT since they have relatively stable physical habitat. George Creek and Rock Creek may also have higher translocation success as they both exceed the 14.7 km^2 minimum watershed area requirements (Harig and Fausch, 2002). It is worth noting that lowered streamflow could amplify the habitat degradation (e.g., additional water temperature increases and decreasing of dissolved oxygen, Williams et al., 2015) that will stress the already threatened GBCT though some sites are showing smaller projected loss of streamflow and physical habitat.

4.2 Study Limitations and Future Work

The reliability of the percent reductions applied in this study is impacted by the accuracy of the VIC model results. Some limitations are expected associated with the usage of a VIC model including: 1) limitations in the VIC model meteorological forcing data that are extrapolated from stations located at low-mid elevations that do not represent the simulated regions; 2) existing land cover in real-world may change but the land cover is fixed in VIC model through time while simulating, and 3) failure to account for the heterogeneity in streamflow recession rates or snowmelt rates (Wenger et al., 2009; Mote et al., 2018).

HEC-RAS is traditionally designed for peak flow simulation as those are of the most concerns to the modelers (Sharkey, 2014). The one-dimensional HEC-RAS model assumes the flow to be steady and gradually varied, which are difficult assumptions to be met owing to the complicated geometry of a mountain stream bed (Chin, 2003). Besides the complex hydraulics of mountain streams, the HEC-RAS model is expected to be less reliable during some low flow conditions (Sharkey, 2014) as the channel bed roughness cannot be predicted accurately. Future efforts can consider using tools that incorporate dynamic roughness calculations that account for low relative depths, such as the implementation of the Ferguson Variable-Power Equation

(Ferguson, 2021) in the R2Cross tool used by the State of Colorado for instream flow allocations.

One potential limitation for PCA is the limited sample sizes that are used while conducting PCA. Previous studies have stated a sample size of 40 to 50 is considered sufficient in ecological and environmental studies (Forcino, 2012; Shaukat et al., 2016), whereas only a total of 12 sample sizes were used in this study. However, the grouping of the sites derived from PCA still make geomorphological sense.

Understanding the effects of climate change on GBCT is challenging due to the large variability among sites, various habitat requirements for different life-stage needs, and the complexity of forecasting mountainous environment interactions. Additionally, the increased frequency of stochastic environmental disturbances and the existing nonnative species invasions are also major threats to consider when evaluating the future suitable habitat for GBCT (Roberts et al., 2017). These climate and non-climate stressors are expected to interact with each other and are likely to aggravate the already shrunken habitat for GBCT. Hence, future conservation and management for the reintroduction of GBCT should adopt a more holistic approach to better understand the impacts of climate change on cold-water species (Kovach et al., 2016). Some recommended management strategies include restoring the habitat-forming processes to increase productivity and resilience at the potentially suitable stream, using site-specific stocking, and minimizing anthropogenic activities that might reduce baseflow. Placing large wood structure in the channel might also benefit GBCT as they create pools with overhead cover (Wohl et al., 2016) that can potentially alleviate the stress during summertime low flow. Different hydraulic models that can accurately capture the geomorphology of headwater streams better than a simple one-dimensional hydraulic model are recommended in future studies.

5 Conclusion

Headwater streams in mountainous regions are particularly sensitive to the changing of climate, and these climate-driven alterations in temperatures, precipitation and streamflow patterns are specifically problematic to the survival of native coldwater fisheries. Previous studies have primarily focus on the potential thermal consequence of climate change but not much on streamflow. This study evaluated the streamflow and physical habitat in various headwater streams under four future climate projections for GBCT reintroduction and management in the southern Rocky Mountains. The percent reductions for future climate projections (mean summer and mean August) derived from a pre-developed VIC model were applied to the summertime low flow for each study site across Front Range in the Southern Rocky Mountain. One-dimensional hydraulic model was then constructed for each site to simulate the physical habitat under different projected streamflows.

The results show high variations in both predicted streamflow reductions and physical habitat among sites. The projected mean summer streamflow indicates much greater decline compared to the projected mean August flow. Moreover, sites located at higher elevations with larger substrate (D50 and D84) and steeper slopes may experience greater reductions in physical habitat under mean summer future climate projections.

The effects of climate change on cold-water fisheries are difficult to evaluate due to the natural complexity of mountain environment and the interactions with other influential factors (e.g., non-native species invasions and stochastic events). Future research on cold-water fisheries needs adopt more holistic approaches while assessing the impacts of climate change rather than only focusing on one influential factor (e.g., thermal characteristics). Restoration efforts should address regional climate-driven change but work across entire watersheds to better withstand the rapidly changing climate (Williams et al., 2015). Adequate monitoring work would also be an important aid to ensure the success of restoration projects for cold-water fisheries in headwater streams.

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Appendix A: Extra analysis and results

A1. Flow duration curve

To derive flow duration curve, one averaged daily discharge was computed per day for each study site using the collected 30 mins-interval discharges for each day. We are only interested in the discharge from May to October because cold water fish is more sensitive to the changes in summer streamflow. Flow duration curves were then constructed for each site using the calculated averaged daily discharge values. The duration ranges from May to October 2019, and May to October 2020. All computations were done in R using the fdc() function built in the HydroTSM package. Detailed information about this function can be found at https://rdrr.io/cran/hydroTSM/man/fdc.html.

A2. Percent reductions in physical habitat

2040 MS			Percent change				
Site	PC1	PC2	Velocity	Flow Area	Top Width	Wetted Perimeter	Max depth
Bear ck	-1.865	2.004	-6%	-15%	-8%	-9%	-9%
Black canyon	-1.295	0.553	-7%	-14%	-6%	-6%	-5%
Corral ck	1.187	-1.132	-16%	-21%	-14%	-14%	-16%
Dry gulch	0.181	-2.129	-19%	-38%	-20%	-20%	-23%
George ck	1.223	1.691	-2%	-5%	-1%	-2%	-2%
Hague ck	1.774	0.874	-16%	-19%	-8%	-8%	-11%
Herman gulch	-0.081	-1.772	-19%	-38%	-21%	-20%	-23%
Roaring ck	0.989	0.501	-12%	-17%	-7%	-7%	-9%
Rock ck	-0.236	0.516	-3%	-10%	-4%	-4%	-7%
West ck	2.664	0.044	-14%	-24%	-9%	-10%	-13%

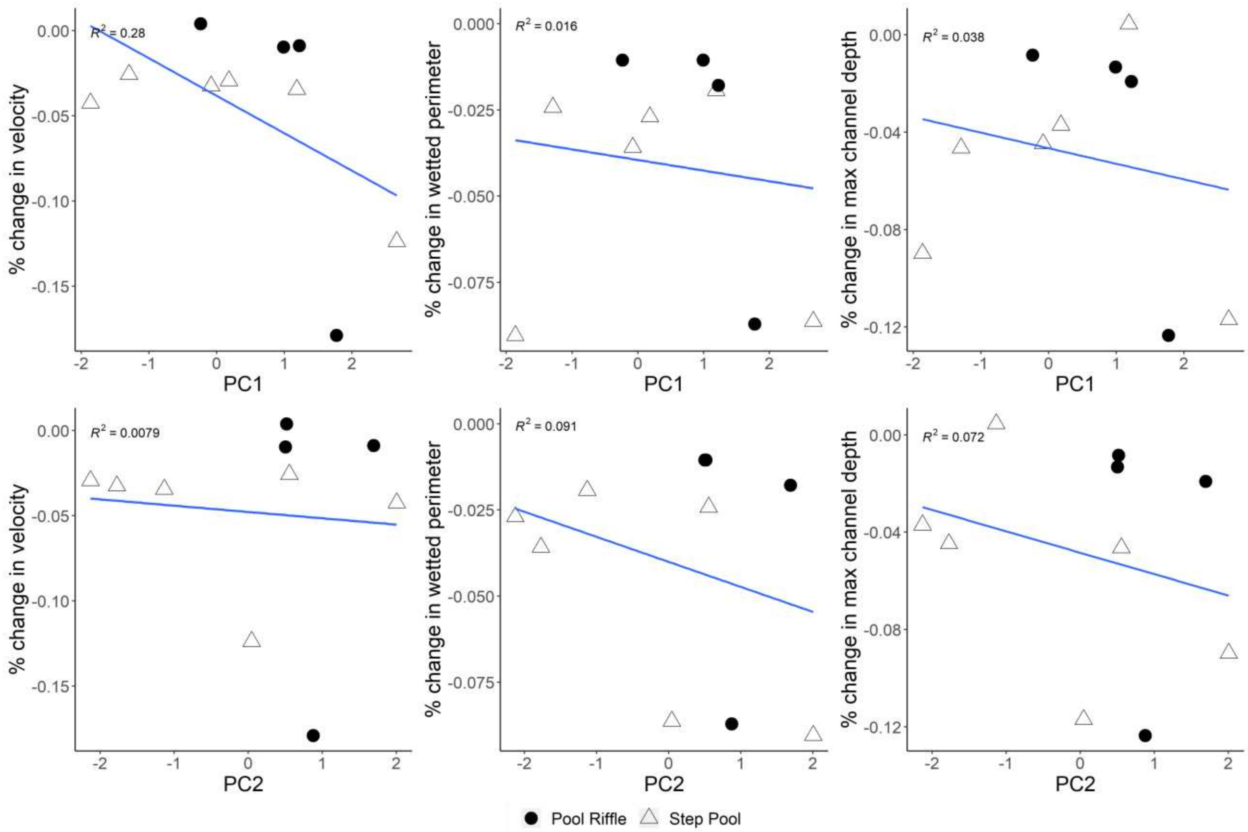
2080MS			Percent change				
Site	PC1	PC2	Velocity	Flow Area	Top Width	Wetted Perimeter	Max depth
Bear ck	-1.865	2.004	-12%	-25%	-14%	-14%	-16%
Black canyon	-1.295	0.553	-6%	-22%	-9%	-9%	-12%
Corral ck	1.187	-1.132	-39%	-81%	-47%	-47%	-34%
Dry gulch	0.181	-2.129	-32%	-68%	-44%	-45%	-44%

George ck	1.223	1.691	-2%	-12%	-6%	-6%	-7%
Hague ck	1.774	0.874	-39%	-40%	-19%	-19%	-26%
Herman gulch	-0.081	-1.772	-29%	-62%	-39%	-39%	-40%
Roaring ck	0.989	0.501	-20%	-32%	-15%	-16%	-20%
Rock ck	-0.236	0.516	-7%	-19%	-7%	-7%	-10%
West ck	2.664	0.044	-34%	-52%	-24%	-25%	-32%

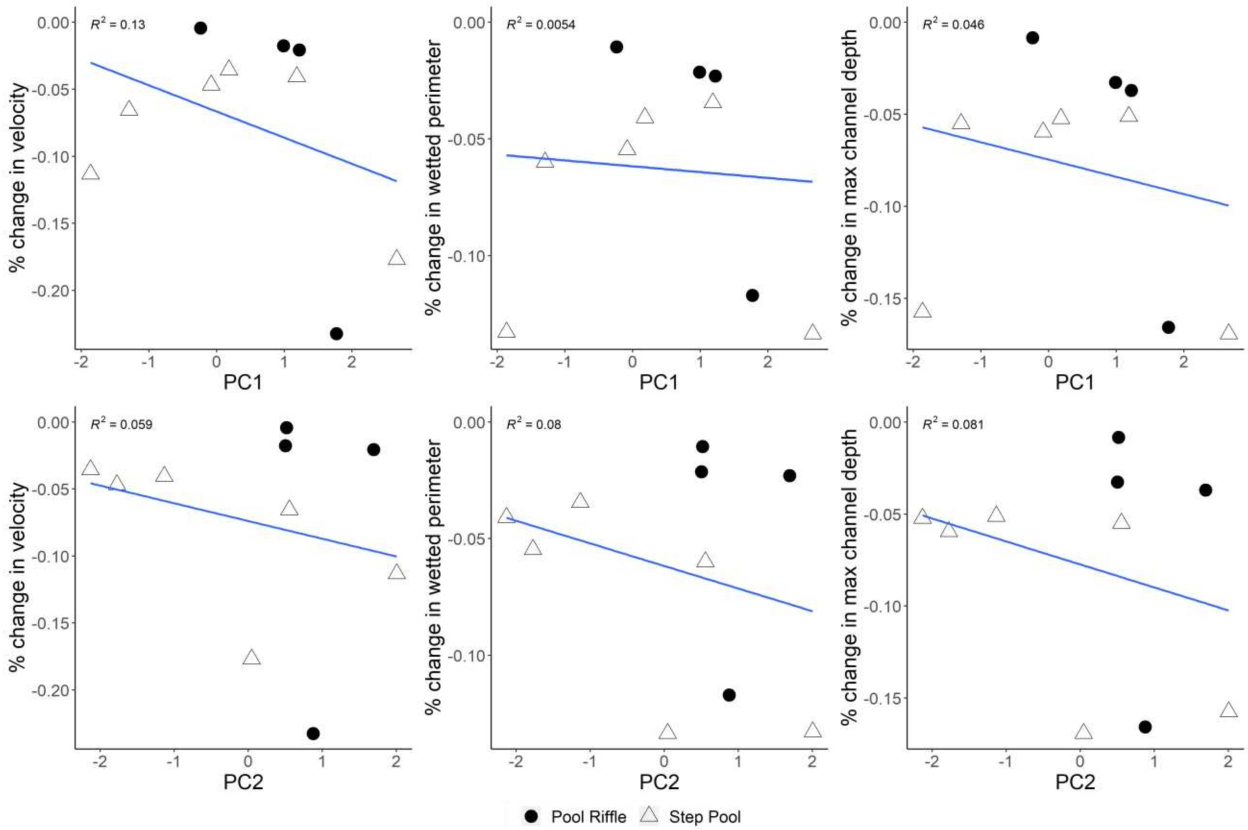
2040 MAUG			Percent change				
Site	PC1	PC2	Velocity	Flow Area	Top Width	Wetted Perimeter	Max depth
Bear ck	-1.865	2.004	-4%	-15%	-9%	-9%	-9%
Black canyon	-1.295	0.553	-3%	-5%	-2%	-2%	-5%
Corral ck	1.187	-1.132	-3%	-3%	-2%	-2%	0%
Dry gulch	0.181	-2.129	-3%	-6%	-3%	-3%	-4%
George ck	1.223	1.691	-1%	-4%	-2%	-2%	-2%
Hague ck	1.774	0.874	-18%	-21%	-9%	-9%	-12%
Herman gulch	-0.081	-1.772	-3%	-8%	-4%	-4%	-4%
Roaring ck	0.989	0.501	-1%	-1%	-1%	-1%	-1%
Rock ck	-0.236	0.516	0%	-2%	-1%	-1%	-1%
West ck	2.664	0.044	-12%	-22%	-8%	-9%	-12%

2080 MAUG			Percent change				
Site	PC1	PC2	Velocity	Flow Area	Top Width	Wetted Perimeter	Max depth
Bear ck	-1.865	2.004	-11%	-25%	-13%	-13%	-16%
Black canyon	-1.295	0.553	-7%	-14%	-6%	-6%	-5%
Corral ck	1.187	-1.132	-4%	-12%	-3%	-3%	-5%
Dry gulch	0.181	-2.129	-4%	-11%	-4%	-4%	-5%
George ck	1.223	1.691	-2%	-7%	-2%	-2%	-4%
Hague ck	1.774	0.874	-23%	-26%	-11%	-12%	-17%
Herman gulch	-0.081	-1.772	-5%	-12%	-5%	-5%	-6%
Roaring ck	0.989	0.501	-2%	-6%	-2%	-2%	-3%
Rock ck	-0.236	0.516	0%	-5%	-1%	-1%	-1%
West ck	2.664	0.044	-18%	-30%	-13%	-13%	-17%

A3. Mean August future climate projections



2040 mean August



2080 mean August

Appendix B: R codes

```
library(devtools)

#PCA with ggbiplot

data <- read.csv("D:/MS-Environmental Engineering/GreenBackCT-project/PCA
analysis/morphological_data.csv", header = TRUE)

require(stats)

data_subset<- subset(data,select=-c(ï..Site,Montgomery_and_Buffington))

pc_subset <- prcomp(data_subset,

        center = TRUE,

        scale. = TRUE)

library(ggplot2)

library(ggrepel)

ggbiplot(pc_subset, labels=(data$ï..Site), labels.size = 8,circle = TRUE, obs.scale = 1, var.scale =1,
varname.size=6)+

  theme(panel.grid.major = element_blank(), panel.grid.minor = element_blank(),panel.background =
element_blank(), axis.line = element_line(colour = "black"),axis.title.x = element_text(size = 20,
face="bold"),axis.title.y = element_text(size = 20, face="bold"))+

  theme(axis.text = element_text(size = 20))+ scale_color_manual(name="Montgomery_and_Buffington",
values=c("orange", "purple", "green"))+

  scale_shape_manual(name="Montgomery_and_Buffington", values=c(17:19)) +

  geom_point(aes(colour=data$Montgomery_and_Buffington,
shape=data$Montgomery_and_Buffington), size = 4) +

  theme(legend.direction ="horizontal", legend.position = "top")


bplot = ggbiplot(pcobj=pc_subset,

          choices = c(1,2),

          obs.scale = 1, var.scale = 1,

          varname.size=7,

          varname.abbrev=FALSE,

          varname.adjust = 0,

          circle=TRUE,

          ellipse=FALSE)
```

```
bplot + theme(panel.grid.major = element_blank(),
              panel.grid.minor = element_blank(),
              panel.background = element_blank(),
              axis.line = element_line(colour = "black"),
              axis.title.x = element_text(size = 15, face="bold"),
              axis.title.y = element_text(size = 15, face="bold")) +
  geom_point(color="blue", size=5)+geom_label_repel(aes(label = data$ï..Site),
                                                    box.padding   = 0.9,
                                                    point.padding = 0.5,
                                                    segment.color = 'grey50',
                                                    segment.size = 0.8,
                                                    size=6,
                                                    nudge_x=0.1)+
  theme(axis.text = element_text(size = 18))
```