THESIS

EFFECTS OF FLOW MODIFICATION AND FOREST DISTURBANCE ON STREAMFLOW ACROSS COLORADO

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ABSTRACT

EFFECTS OF FLOW MODIFICATION AND FOREST DISTURBANCE ON STREAMFLOW ACROSS COLORADO

Human activities alter streamflow around the world. In Colorado, flow modifications, land use change, and forest disturbances all modify streamflow, but the relative magnitudes of these effects are not well-quantified. This study examined how streamflow quantity across Colorado has been affected by three classes of change: (1) flow modifications from reservoirs and diversions, (2) urbanization, and (3) forest disturbance. The goal of this work was to identify the magnitude of streamflow alterations from these different types of stressors to understand the sensitivity of the state's streams to future changes, both natural and anthropogenic. A total of 215 watersheds were used to analyze effects of flow modifications and urbanization, and 71 of these watersheds were analyzed for effects of forest disturbance. Flow modifications and land use change have altered 85% of the gaged streams in this study. Of the stressors studied, the largest effects are from transbasin diversions, which reduce flow by an average of 20% in watersheds with diversions out of the watershed and increase flow by an average of 221% in watersheds with diversions importing water from another basin. Across all types of watersheds, the gaged streams in the Plains and Southwest regions of the state are most altered, and those in the Rio Grande are the least altered. The lower elevation areas are experiencing the largest percent changes relative to their natural flow regime (average water imports = 38 mm, 875%); the reduction in flow from high elevation watersheds is large in magnitude as well, but it equates to a smaller percent of the expected flow (average water exports = -71 mm, -18%). Forest disturbance may increase or decrease streamflow depending on the characteristics of the watershed and the disturbance, but the magnitude of the impact remains within the natural variability of streamflow in similar watersheds. A significant change in streamflow was observed in 25% of watersheds affected by disturbance, mainly with increases in flow following beetle mortality and severe wildfire. Streamflow decreased following smaller wildfires and in watersheds with South- and West-facing dominant aspects. Overall, anthropogenic modifications to streamflow via diversions that move water between watersheds have the largest effect on mean annual streamflow, whereas streamflow changes from forest disturbance mostly remain within the range of natural variability.

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1. INTRODUCTION

Many rivers across the world have been altered by human activities. Humans modify streamflow timing and magnitude through diversions, reservoir operations, and increasing water use. Across the US, 86% of perennial gauged streams have altered streamflow magnitudes due to anthropogenic influences (Carlisle et al., 2011). The majority of water flowing through streams and rivers across Colorado originates as snow in the Rocky Mountains. Colorado is a headwaters state, and snowmelt water flows into seven other states and Mexico providing millions of people with water for drinking and other end uses, such as irrigation. Although some view the Colorado mountains as pristine headwaters, these watersheds have experienced anthropogenic influences from flow modifications and land use change as well as forest disturbances from wildfire and beetle mortality (Barnett et al., 2008; Littell et al., 2009; Stephens, 2005; Westerling, 2016). Forest disturbances are most common at higher elevations, whereas water uses and land use changes are greatest at lower elevations, so prior research has not directly compared the magnitude of these different stressors within the context of the overall system. However, Colorado's water system is so interconnected that a disturbance in one part of the state may impact the amount of water available downstream.

Colorado has a long history of diverting water from rivers for agricultural and municipal uses. Much of the water is diverted into reservoirs during snowmelt runoff in the spring and used for irrigation and municipal water supply later in the summer and fall when the demand for water is high. Each year, over one million acre-feet of water moves through transbasin diversions from the west side of the continental divide to the east side, where over 80% of the state's population resides (Coleman, 2014). The exact quantity of water diverted annually and the destination of that water can be difficult to trace because of incomplete gauging data.

Land use and land cover in a watershed also affect streamflow. Water diversions for irrigation can lead to both lower streamflow during the diversion time periods and higher streamflow from return flows during irrigation. Urbanization typically alters base flows, increases storm flows, and causes greater flow variability and flashiness (Leopold, 1968; Poff et al., 2006). Urban storm water systems channel runoff from the impervious land cover surfaces through gutters and pipes to the nearest stream channel. This decreases the time of concentration for storm runoff and increases the flashiness of hydrographs (Walsh et al., 2012). Sewer infiltration and inflow, lawn irrigation, and water supply imports can be significant alterations to streamflow in urban systems (Bhaskar & Welty, 2012).

Much of the state's streamflow originates in forests, which can be altered by wildfire or disease. Severe and widespread mountain pine beetle and spruce beetle outbreaks have caused tree mortality across five million forested acres in Colorado over the last two decades (Colorado State Forest Service, 2017). The state has also experienced an increase in the occurrence of large wildfires, a trend that is expected to continue in the future (Abatzoglou & Williams, 2016; Westerling, 2016). Wildfires and disease alter the structure of forests, causing patterns of snow accumulation and melt to change. Following tree mortality, large gaps in the canopy can reduce canopy interception and increase the amount of snow that reaches the ground, adding to the total snowpack. However, these large gaps also expose the snowpack to more incoming solar radiation, which increases evaporation, snowpack sublimation, and snowmelt rates (Barnhart et al., 2016; Biederman et al., 2014). Loss of vegetation from either fire or disease reduces evapotranspiration from the killed trees, but this extra water may then be used by remaining vegetation and understory growth (Buma & Livneh, 2017; Livneh et al., 2015), or it may contribute to increased streamflow (Bearup et al., 2014).

Because of the complex interactions between forest changes, snow, and evapotranspiration, the documented impacts of forest disturbance on streamflow have been inconsistent. These effects can differ based on topography, climate, severity of the impact, precipitation in a given year, and whether the precipitation falls as snow or rain (Biederman et al., 2015; Creeden et al., 2014). When precipitation is rain, lower transpiration after forest disturbance usually increases streamflow, unless that addition is balanced out by higher evaporation; when precipitation falls as snow, changes to accumulation and melt can lead to either increases or decreases in streamflow (Barnhart et al., 2016; Pugh & Small, 2012). Additionally, the percent of watershed disturbed, the severity and dispersion of the disturbance, the type of vegetation present, regeneration characteristics, and annual precipitation differences all affect the streamflow response (Bosch & Hewlett, 1982; Brown et al., 2005). Consequently, it is difficult to predict how streamflow will respond to forest disturbance, or whether it will respond at all.

Flow modifications, land use change, and forest disturbances all modify streamflow in Colorado, but the relative magnitudes of these effects are not well-quantified. Prior research has focused mainly on forest disturbance effects, with limited studies on land use and flow modification effects. This study examines how streamflow quantity across Colorado has been affected by three classes of change: (1) flow modifications from reservoirs and diversions, (2) urbanization, and (3) forest disturbance. The goal of this work is to identify the magnitude of streamflow alterations from these different types of stressors to better understand the sensitivity of the state’s streams to future changes, both natural and anthropogenic.

2. METHODS

2.1 Streamflow Data and Study Watersheds

To examine the changes of streamflow from these various stressors, we assembled a large streamflow dataset for gages throughout Colorado. Streamflow data were compiled from the United States Geological Survey (USGS) and Colorado Division of Water Resources (CDWR). Our goal was to focus on relatively small watersheds because larger watersheds tend to span large elevations and be affected by multiple disturbance types, dams, and diversions. We chose a drainage area with an upper limit of 1,500 km^2 (579 mi^2) because it allowed enough watersheds with stream gages that span the range of climate conditions in the state. We selected stations with >75% data availability from 2001-2018. This time period was selected because it corresponds with availability of snow cover data from MODIS (Hall & Riggs, 2016), which we use to calculate snow persistence (SP), an important streamflow predictor (Hammond et al., 2018).

These two criteria led to a dataset of 217 stream gauges (Figure 1). We excluded one of these gauges, Big Spring Creek at Medano Ranch, because it was a consistent outlier in all analyses, likely because the creek is spring-fed from groundwater originating outside the watershed boundaries. For each of the stream gauges in the dataset, we delineated the watershed using the Watershed tool in ArcGIS with the flow direction grids from NHDPlusV2 (McKay et al., 2012; Figure 1).

The steep elevation gradient that characterizes the headwaters of Colorado creates large snow and hydrologic regime changes among the watersheds studied. The watersheds analyzed have areas ranging from 4-1,464 km^2 with a median area of 236 km^2. Their mean elevations range from 1,367-3,644 m.a.s.l., and most watersheds are at the higher end of that elevation range, with a median elevation of 3,114 m. Mean watershed slopes range from 1-31%, with a median of 17%. Mean annual precipitation ranges from 330-1,332 mm, with a median of 671 mm.

Differences in elevation and precipitation lead to variable snow regimes. Therefore we differentiate streamflow changes by snow zone, which are delineated based on snow persistence (SP) (Moore et al. 2015), defined as the percent of time (Jan-Jun) that snow is on the ground. We used three snow zones: low-intermittent (SP<50%), transitional (50%<SP<75%), and persistent (SP>75%) (Figure 1). Mean annual snow persistence ranges from 9-86%, and most watersheds are at the high end of the range, with a median of 62% (Appendix A).

The USGS delineated five hydrologic regions in Colorado, which differ in terms of their overall hydrologic processes and the factors influencing streamflow in each region. These regions are: Mountain, Northwest, Plains, Rio Grande, and Southwest (Capesius & Stephens, 2009; Figure 1). Throughout this study, we refer to the hydrologic regions of Colorado and use them to both analyze and discuss the streamflow changes across the state.

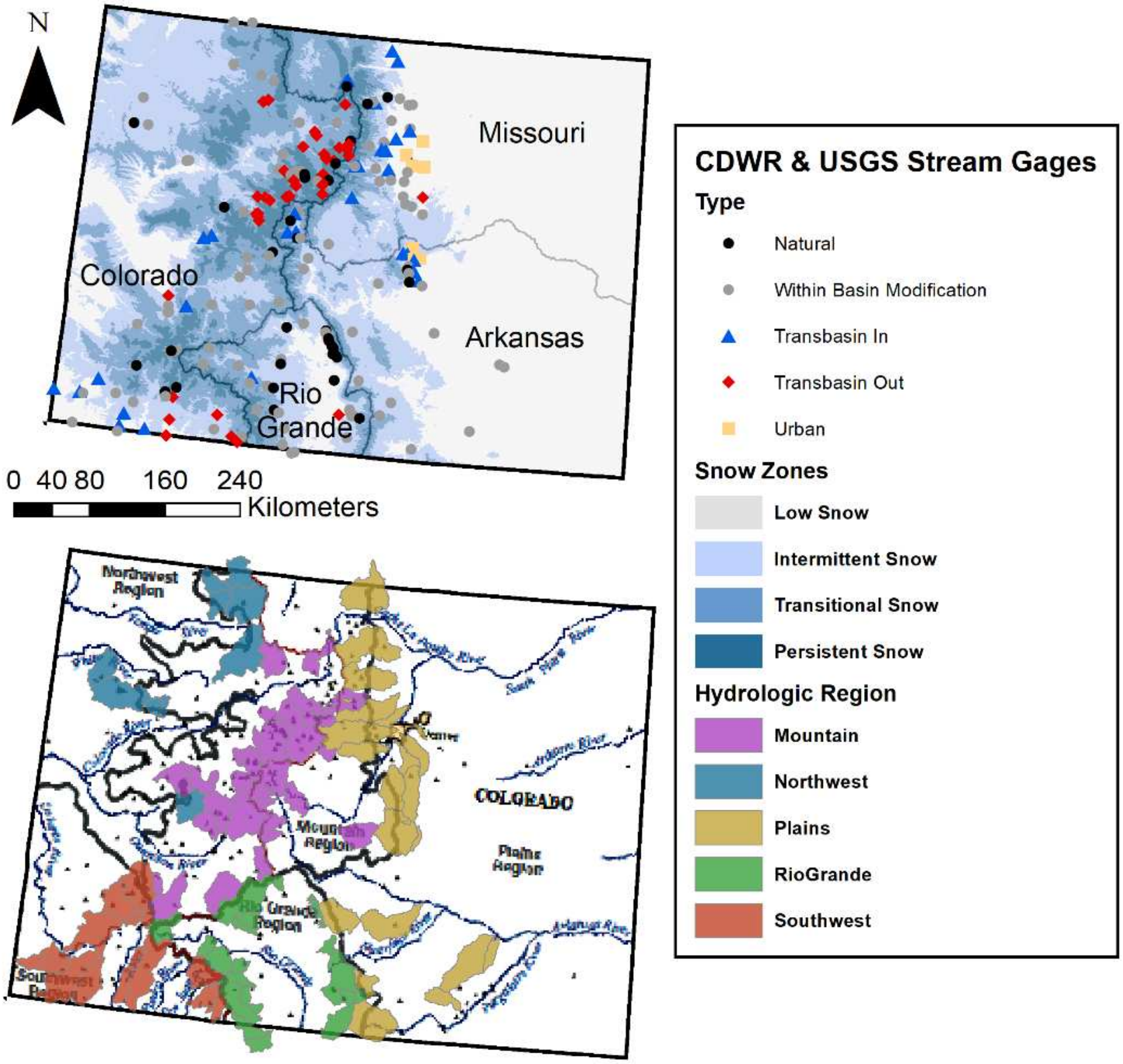

Figure 1. Streamflow gauging station locations (top) and contributing watersheds (bottom) examined in this study. Top stations are classified by type of flow modification overlaying snow zones (Moore et al. 2015), where darker blue colors indicate longer time periods of snow cover. Bottom watersheds are colored by USGS Hydrologic Region (Capesius & Stephens, 2009). Both snow zones and hydrologic regions are used in the natural streamflow model described in Section 2.3.

2.2 Flow Modification, Land Cover, and Forest Disturbance Data

To classify the diversion type of each watershed, we identified whether or not dams or diversions were present within each watershed boundary using a shapefile of water rights locations from CDWR. We used National Hydrography Dataset (NHD) flowlines and a shapefile provided by Colorado Water Conservation Board (CWCB) to identify pipes or ditches that cross watershed boundaries; these represent transbasin diversions into or out of watersheds. Based on these analyses, we categorized each station as **natural** (n=32) indicating no water rights within the watershed or transbasin diversions; **within basin modifications** (n=99) indicating water rights within the watershed; **transbasin-in** (n=34) indicating transbasin diversions into the watershed, or **transbasin-out** (n=42), indicating transbasin diversions out of the watershed. Stations in the transbasin categories also typically have within basin modifications, i.e., water rights within the watershed. There was one watershed with both transbasin-in and transbasin-out diversions, so this watershed was removed from the analysis, leaving a total of n=215 watersheds.

To identify watersheds affected by urbanization, we flagged basins with large fractions (>10%) of **urban** land cover (11-56%, n=8; 3-21% imperviousness), based on the 2011 National Land Cover Dataset (NLCD). The lower limit was chosen because 10-11% urban land cover within a watershed has been suggested as the threshold at which urbanization begins to affect streamflow (Eimers & Mcdonald, 2015). Three of the urban watersheds have no waste water treatment plants (WWTP's) and the other five have between 1-5 WWTP's. The urban basins are all affected by extensive flow modifications, as well as the urban land cover and WWTP's.

Forest disturbance data were compiled for both insect mortality and wildfire. The mountain pine beetle (*Dendroctonus ponderosae*) outbreak in Colorado peaked in 2008, impacting nearly 3.4 million acres in the state from 1996-2014. The spruce beetle (*Dendroctonus rufipennis*) outbreak in Colorado peaked in 2014 and it was Colorado's most widespread and damaging forest insect for the seventh consecutive year in 2018, impacting 1.84 million cumulative acres from 2000 to 2018 (Colorado State Forest Service, 2018). Lesser known pests such as roundheaded pine beetle (*Dendroctonus adjunctus*), Douglas-fir beetle (*Dendroctonus pseudotsugae*), western spruce budworm (*Choristoneura freemani*), fir engraver beetle (*Scolytus ventralis*), western balsam bark beetle (*Dryocoetes confusus*), and emerald ash borer (*Agrilus planipennis*) have also caused recent tree mortality across the state.

We quantified beetle mortality within each watershed annually for all years for which available streamflow data coincided with mortality data (1997-2018). We used maps from Meddens et al. (2012) to delineate severity and timing of bark beetle outbreaks, spanning all forest types, for years 1997-2010. Additional preliminary data from Hicke et al. (in prep) was used for years 2011-2018 to capture the more recent beetle mortality across the state, primarily caused by the spruce beetle in southwestern Colorado (Colorado State Forest Service, 2018; Meddens et al., 2012). These data products combine all species of beetle and all forest types. Values are given in number of hectares affected per 1km^2 pixel, effectively the percent of forest affected within each pixel. The 1 km^2 resolution dataset provides annual estimates for the year of mortality detection. These data were corroborated with beetle induced tree mortality data from Vorster et al. (in prep) which is a higher resolution (30m x 30m) dataset of tree mortality in lodgepole pine forests. Due to the difficult nature of detecting tree mortality from pine beetles in individual crowns using satellite imagery, it is useful to have multiple datasets to substantiate the results. Only watersheds with at least one year of >1% tree mortality were used in the analysis. The first year with tree mortality >1% was flagged as the start of the beetle outbreak or mortality event, and years before and after this year were classified into pre- and post-disturbance categories. Additionally, we only included watersheds with at least five years of streamflow data for both pre- and post-disturbance categories. This led to a dataset of 53 watersheds with beetle mortality and streamflow data across Colorado.

Annual wildfire disturbance was identified using data from the Monitoring Trends in Burn Severity (MTBS). This dataset was produced from 30m x 30m resolution Landsat imagery from 1984 to 2015 for all fires 1,000 acres or greater (Eidenshink et al., 2007). This dataset offers severity information based on a pre-determined classification with categories ranking fire severity from 1-4, with 4 indicating the highest severity. An area-weighted severity score was calculated for each fire event as the percent of the watershed burned at each severity multiplied by the severity rank (1-4). As with mortality, only fires with a total area burned >1% of the watershed total area and watersheds with at least five years of streamflow data for both pre- and post-disturbance were included in the final dataset. To maintain consistency in the sample size for pre- and post- disturbance categories, the total number in each category was limited to 10 years. This led to a dataset of 19 watersheds with fire and streamflow data since 1984 (Figure 2). One watershed had multiple fires with >1% area burned; these fires were just four years apart, so all years following the first fire were grouped as post-disturbance years. One watershed experienced both wildfire and beetle disturbance.

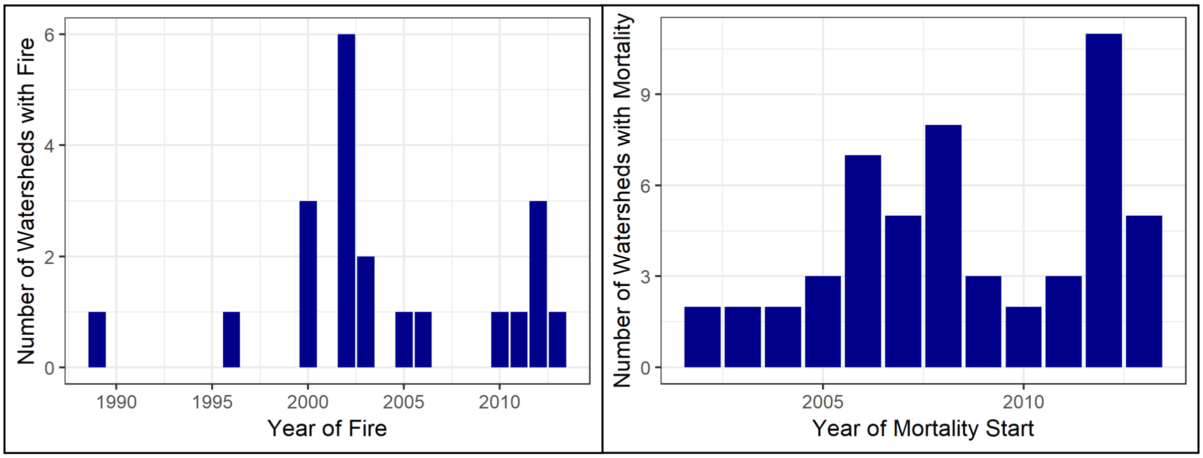

Figure 2: Number of watersheds with each type of forest disturbance included in the final dataset.

2.3 Natural Streamflow Model

To examine the effects of flow modifications, urbanization, and forest disturbance on streamflow, we first developed models of natural streamflow to represent the flow expected for a given watershed without disturbance. Regression models for mean annual and mean monthly streamflow were developed using multiple linear regression with watershed attributes used as potential independent variables (Table 1). These attributes include five continuous variables: area, snow persistence, precipitation, potential evapotranspiration, and slope. They also include three categorical variables: dominant aspect, geologic group, and hydrologic region. All watershed attributes were tested for collinearity; of pairs with $r \geq 0.85$, only one was kept as a possible predictor for the model. We chose to use the 2001-2018 fixed time period for developing the models to reduce bias in model evaluation that may be caused by climatic differences across records of different lengths.

For topographic variables we used the 30m digital elevation model (DEM) from the National Elevation Dataset to extract mean slope and dominant aspect. To determine dominant aspect, the aspect raster created from the DEM was classified into eight aspect bins (N, NE, E, SE, S, SW, W, NW; Table 1), and the aspect bin with the most pixels was labeled as the dominant aspect for the watershed. For bedrock geology, we used the National Geology Layer from the USGS Mineral Resources Program and determined dominant categories within each watershed (USDA-USGS Mineral Resources, 2005). The USGS regional streamflow regression equations were developed for five hydrologic regions in Colorado: Mountain, Northwest, Plains, Rio Grande, and Southwest (Capesius & Stephens, 2009; Figure 1). We used hydrologic region as a categorical predictor in the regression models. The hydrologic region categorical predictor is a proxy for the interactions between predictors that differ based on geographic location. In addition, it captures the indirect effects of regionally variable predictors that we were unable to include in the model. Future research may identify additional predictor variables by region that capture those differences more directly. Finally, for climate we extracted mean annual precipitation from PRISM (PRISM Climate Group, 2004), mean annual potential evapotranspiration from GridMET (Abatzoglou, 2013), and mean annual snow persistence from Hammond et al. (2017).

Table 1. Watershed properties used as potential independent variables in developing new empirical streamflow prediction models.

Category	**Variable**	**Source**
Topography	Mean elevation (m) Mean slope (m/m) Dominant aspect: N, NE, E, SE, S, SW, W, NW Area of watershed (km^2)	National Elevation Dataset 30 m
Geology	Dominant geologic group: Permeable sedimentary, impermeable sedimentary, volcanic, impermeable metamorphic, permeable metamorphic, intrusive, modern alluvium/colluvium, glacial/glacial drift	National Geology Layer, USGS Mineral Resources Program
Climate	Mean annual precipitation P (mm) Mean annual potential evapotranspiration PET (mm) Mean annual snow persistence (SP, %)	PRISM GridMET Hammond et al. 2017
Hydrology	Hydrologic Region	Capesius & Stephens 2009

Both mean annual and mean monthly streamflow values (Table 2) for each gauging station were normalized by drainage area to reduce the area influence on streamflow. These values were non-normally distributed, so they were square-root transformed before regression modeling. Both log-based and square-root transformations were tested using graphical checks for the assumptions of normality of residuals and equality of variance, and the square-root transformation was deemed most appropriate for this dataset. Multiple linear regression models were created to predict the square-root transformed streamflow variables using the predictor variables in Table 1. These models were applied for gages classified as **natural** or **within basin modification**, excluding stations with transbasin diversions or >10% urban land cover. We used within basin modification watersheds for model creation and evaluation because using only the natural stations substantially limited the sample size (n=32), and we found that regression model predictions that included within basin modification produced similar mean annual and mean monthly flow to values predicted for just natural stations.

Table 2. Streamflow metrics derived for each station.

Variable	Name	Time period
Q_{ann}	Mean annual streamflow (mm)	2001-2018
Q_{month}	Mean monthly streamflow (mm), separate values for each month	2001-2018

The multiple linear regression models were selected using AIC criteria with the ‘car’ and ‘MuMIN’ packages in R (Bartón, 2019; Fox & Weisberg, 2011). All possible subsets of the predictor variables were created and ranked by AIC value. Additionally, the r^2 values were reported. The model with the lowest overall AIC was selected as the final model. Following model selection, the *k*-fold cross-validation (CV) approach was used for model evaluation, rather than sub-setting a training and testing dataset. This approach was chosen because the data were not subset prior to any summarization or researcher evaluation of the dataset, and therefore a separate training and testing dataset would not have been valid (Hess, 2019). The goal of this model selection is estimation or prediction, for which the optimal number of *k*-folds is between 5 and 10; a *k*-value >10 has not been shown to lead to greater statistical performance (Arlot & Celisse, 2010; Hastie et al., 2009). A *k*-value of 10 was chosen for the cross validation with a sample size of n=131 to limit computation but retain robust statistical results (Arlot & Celisse, 2010; Sicotte, 2018). Cross validation was done using the ‘caret’ package in R (Kuhn et al., 2019).

For each comparison of model and observations, we computed the Nash-Sutcliffe Coefficient of Efficiency (NSE) and the percent bias (PBIAS) using the hydroGOF package in R along with base R functions (Zambrano-Bigiarini, 2017). Root Mean Squared Error (RMSE) and Mean Absolute Error (MAE) both provide average model prediction error as absolute values; lower values in these error estimates are better, indicating less error. The difference in the two is that the RMSE weights large errors with relatively higher weight than smaller errors, since the errors are squared before they are averaged. Estimates of both RMSE and MAE are related to the magnitude of the observations. To normalize these values, NRMSE and NMAE were calculated by dividing the RMSE or MAE by the inter-quartile range of observations, allowing for comparison of these values across models.

2.4 Effects of Stressors on Streamflow

Several statistical methods were used to assess the impacts of flow modifications, urbanization, and forest disturbance on streamflow.

2.4.1 Anthropogenic Modifications

Anomalies from Predicted Mean Annual and Mean Monthly Streamflow

For all watersheds across the study area, we used the predict() function from the ‘car’ package in R (Bartón, 2019) to compute the predicted mean annual and mean monthly streamflow for all watersheds with the multiple linear regression models described in section 2.3. These were plotted against the observed streamflow values. Anomalies from predicted are the observed minus predicted streamflow values. For each type of stream (natural, within basin modification, transbasin-in, transbasin-out, and urban), the mean annual and monthly anomalies were computed within the individual snow zones. A flow modification or land use effect can be identified if the anomalies from predicted streamflow are greater for modified streams than for natural streams. We conducted these analyses for all watersheds together and for groups of watersheds separated by snow zone (Figure 1): low-intermittent (SP<50%), transitional (50%<SP<75%), and persistent (SP>75%).

Flow Duration Curve Quantiles

Flow duration curves were then used to evaluate distributions of all daily flow rates and examine the effects of stressors on low, medium, and high flows. The quantile number (e.g. Q10) is the percent of the full daily streamflow distribution that lies below the streamflow rate indicated. For example, 50% of the daily streamflow values are lower than the streamflow rate indicated by Q50. Modified watersheds were compared to the natural watersheds for flow duration curve quantiles (Q10, 25, 50, 75, 90) using ANOVA pairwise comparisons with the Dunnett adjustment for comparing all groups to a control group (Lenth, 2019), where groups are separated into natural and modified (transbasin in, transbasin out, within basin diversion, urban) watersheds within each snow zone. All outliers were removed from this analysis. Any group with <5 watersheds was removed from the analysis to compare significance of differences from the natural watersheds; this was the case for transbasin-out in the low snow zone, urban in the transitional and persistent snow zones, and transbasin-in for the persistent snow zone.

2.4.2 Forest Disturbance

We examined whether forest disturbance caused departures from the mean annual streamflow in a similar manner, using the predict() function from the ‘car’ package in R (Bartón, 2019) to compute the predicted mean annual streamflow with the multiple linear regression models, described in section 2.3, for all watersheds that experienced disturbance. These were plotted against the observed streamflow values. The model was applied to the pre- and post-disturbance time periods for each watershed. Inputs for the model were the means of each continuous variable for the years pre- and post- disturbance along with the categorical predictors dominant aspect and hydrologic region. The years of analysis for beetle mortality were 1997-2018 and for fire were 1984-2018, coinciding with the available disturbance datasets. In order to expand the number of watersheds, we did not limit the time period to 2001-2018 for the disturbance analysis (Appendix B). One of the input variables, snow persistence, was not available for all years, so the mean of the years with SP data was used in the model. One watershed with a 1989 fire did not have SP data for pre- or post-disturbance, so it was excluded from this analysis. These predictions are therefore to be taken with an understanding that they are rough estimates of the streamflow in those watersheds, and mostly to be used as a visual assessment of the relative effects of forest disturbance on streamflow.

After this, to investigate the forest disturbance effect on each individual watershed, an analysis of covariance (ANCOVA) was conducted to compare streamflow pre- and post-disturbance using annual precipitation as a covariate. The results of the ANCOVA were then categorized as either streamflow increase, decrease, or no change post-disturbance.

2.4.3 Comparison of Stressors on Streamflow

Ultimately, we wanted to compare the anthropogenic modification effects on streamflow to the forest disturbance effects, in order to determine the relative magnitude of the disturbances on Colorado watersheds. To accomplish this we created three mixed effects models to include the repeated annual streamflow measurements with lmer() from the lme4 package in R (Bates et al., 2015). The first model was created using all types of watersheds (natural, within basin, transbasin-in, transbasin-out, urban) with complete annual data for 2001-2018. Then, two models were created for forest disturbance, one for watersheds that experienced fire disturbance and one for watersheds with beetle disturbance. Forest disturbance models were only applied to watersheds designated as either natural and within basin. In the first full dataset model, type was assigned as a random variable, whereas in the forest disturbance models, pre/post-disturbance was assigned as a random variable. In all three models, watershed was also assigned as a random variable to account for the within-site variability. The fixed effects in the models were chosen based on the variables used in the previous mean annual streamflow model (Table 1). The summary of a mixed effects model provides an estimate of the variance explained by each random variable in the model, translating to the relative importance of each random variable in explaining streamflow variability. An analysis of variance (ANOVA)-like table was created for each model using the ranova() function in the lmerTest package in r (Kuznetsova et al., 2017). This gives an estimated p-value for the test on the null hypothesis that the variance in streamflow explained by the random variable (type or pre/post-disturbance) is equal to zero. If this p-value is significant, we can reject the null hypothesis and conclude that disturbance or type explains some of the variance in streamflow.

3. RESULTS

3.1 Natural Streamflow Model

Multiple regression models to predict natural streamflow across the state had strong performance, and the mean annual model had the best fit (R^2=0.90; NSE = 0.93; -1.7% bias). Empirical mean monthly models did not perform quite as well as the annual model, with NSE ranging from 0.59 (Feb) to 0.91 (June) and percent bias from -5.3 (Aug) to -2.7 (June) (Table 3). The NRMSE and NMAE were lowest for the Q_{ann} and Q_{jun} models (Table 3). The models with the largest NRMSE and NMAE are the winter monthly models, Q_{jan}, Q_{feb}, Q_{mar}, and Q_{dec}. The similarities in NRMSE and NMAE values indicate that there are not any large errors or outliers in the data (Table 3). Statistical validation results for all mean annual and mean monthly streamflow regression models for the training years 2001-2018 are shown in Table 3.

Table 3. Performance of empirical mean monthly and mean annual (Ann) discharge models. NSE is the Nash-Sutcliffe Efficiency Coefficient; PBIAS is the percent bias; bold values are from the cross-validation result. The mean annual model has the highest NSE and lowest absolute PBIAS. NRMSE and NMAE are the Root Mean Squared Error and Mean Absolute Error normalized by the inter-quartile range of each dataset.

Month	Ann	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec
NSE	0.93	0.60	0.59	0.67	0.68	0.79	0.91	0.80	0.64	0.69	0.75	0.73	0.66
PBIAS	-1.7	-5.2	-4.9	-5.1	-5.1	-4.0	-2.7	-4.1	-5.3	-5.0	-4.1	-3.9	-4.7
NRMSE	0.01	0.12	0.12	0.10	0.06	0.02	0.02	0.04	0.06	0.07	0.06	0.08	0.09
R^2	0.90	0.63	0.56	0.58	0.68	0.82	0.89	0.81	0.62	0.65	0.76	0.72	0.65
NMAE	0.01	0.10	0.10	0.08	0.05	0.02	0.01	0.03	0.05	0.05	0.05	0.06	0.07

PET and P are included as continuous predictors in all models due to the role of climate in streamflow generation. All models include SP, highlighting the importance of snow storage in Colorado and the influence of the SP variable for streamflow prediction, especially during peak snowmelt runoff in May and June. Once the snowmelt hydrograph declines, SP becomes less important. Slope is a key variable for streamflow models in July-March, the times of year when streamflow declines or remains at baseflow. All of the models except May include hydrologic region as a categorical predictor, indicating some regional variability in the relationships between streamflow and predictor variables. All models except those for Q_{may}, Q_{aug}, Q_{sep}, and Q_{oct} include aspect as a categorical variable. This is likely because the May streamflow is dominated by the SP variable, so aspect does not add to the predictions of streamflow at these times of year. Models for Q_{aug} and Q_{sep} include geology, potentially because of the importance of bedrock type for baseflow. Lastly, area is included as a continuous predictor only for Q_{ann} and $Q_{may\text{-}jun}$. This likely relates to the clustering of small watersheds at high elevations, which have high SP and therefore higher streamflow relative to their size in the May, June, and Annual time periods. The coefficients for all mean annual and mean monthly streamflow regression models for the 2001-2018 training years are shown in Table 4.

Table 4. Coefficients (β) for empirical models of each y-variable, with performance indicated by R^2. Column headings indicate independent variables associated with each β. Independent variables defined in Table 1, and dependent (y) variables defined in Table 3, with annual and monthly Q in mm. Categorical variables included in the model are indicated with a "+", and the coefficient values for these variables can be found Appendix C. Blank cells indicate the independent variable is not used in the empirical model.

y	β_0	$\beta_1 SP$	$\beta_2 Slope$	$\beta_3 PET$	$\beta_4 P$	$\beta_5 Area$	Aspect	Geology	Hydrologic Region	R^2
Q_{ann}	-40.06	0.280	0.176	0.021	0.015	-0.001	+		+	0.91
Q_{jan}	-3.027	0.021	0.054	0.002	0.001		+		+	0.66
Q_{feb}	-2.382	0.019	0.041	0.002	0.001		+		+	0.63
Q_{mar}	-3.145	0.027	0.024	0.002	0.002		+		+	0.67
Q_{apr}	-9.030	0.079	-0.036	0.005	0.004		+		+	0.72
Q_{may}	-21.01	0.141		0.011	0.010	-0.001				0.82
Q_{jun}	-29.46	0.189	0.133	0.015	0.010	-0.001	+		+	0.90
Q_{jul}	-17.01	0.094	0.133	0.009	0.006		+		+	0.83
Q_{aug}	-4.753	0.039	0.113	0.004	0.003			+	+	0.72
Q_{sep}	-2.912	0.025	0.094	0.003	0.003			+	+	0.73
Q_{oct}	-7.190	0.042	0.068	0.004	0.003				+	0.77
Q_{nov}	-4.299	0.023	0.068	0.003	0.002		+		+	0.75
Q_{dec}	-3.265	0.022	0.058	0.002	0.001		+		+	0.69

3.2 Effects of Stressors on Streamflow

3.2.1 Anthropogenic Modifications

To evaluate and quantify the effects of transbasin diversions and urban development, streamflow values from modified watersheds were compared to predicted mean annual and mean monthly streamflow from the 2001-2018 regression models. Anomalies were computed as the difference between predicted and observed streamflow. Anomaly values for the natural and within basin watersheds reflect the natural variability that is not captured by the model. The mean annual flow anomalies in modified watersheds are much larger than the natural range of variability. The effects of transbasin diversions and urbanization are particularly evident for the annual model. The mean annual model over-predicts streamflow for transbasin-out watersheds and under-predicts streamflow for transbasin-in watersheds and urban watersheds (Figure 3). This indicates that the transbasin-out watersheds have lower streamflow than expected, whereas the transbasin-in and urban watersheds have higher streamflow than expected; this is the case across all snow zones, although the magnitude of the anomalies do vary by snow zone.

Monthly model predictions allow us to examine how these changes vary throughout the year. The streamflow in transbasin-out watersheds is most clearly over-predicted by the model during spring snowmelt runoff, April-July, when the high streamflow is diverted (Figure 5). The transbasin-in effects are most evident in late summer, fall, and into winter, when transbasin-in watersheds progressively diverge from the predicted values (Figure 5). This is the drier time of year when transbasin water is delivered from high elevation storage reservoirs to downstream areas using the water for agricultural and municipal irrigation. Urban watersheds show a similar seasonal pattern, in that they diverge more from the natural predictions in the later part of summer, fall and winter (Figure 5). These elevated flows in urban areas are most likely caused by added irrigation water and discharge from WWTP's. Not all stations are consistent with the pattern of over-prediction for transbasin-out watersheds or under-prediction for transbasin-in watersheds; this may be due to the size of the transbasin diversions relative to the basin streamflow.

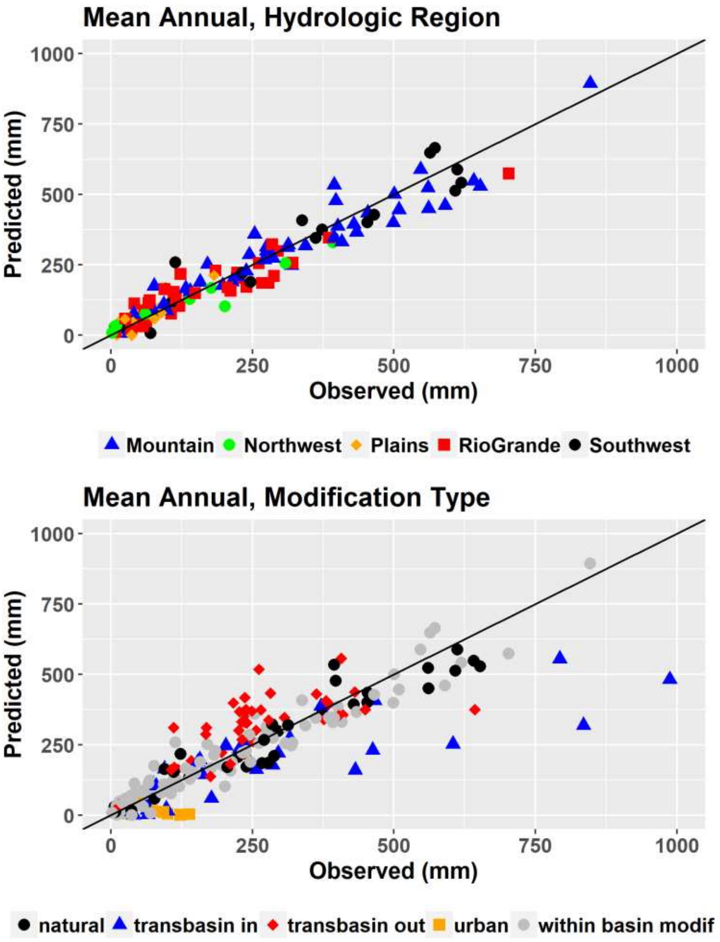

Figure 3. Predicted vs. observed mean annual discharge. Stations with transbasin diversions and urban land cover excluded from the top graph, colored by Hydrologic Region; these stations are added to the bottom graph, colored by modification type.

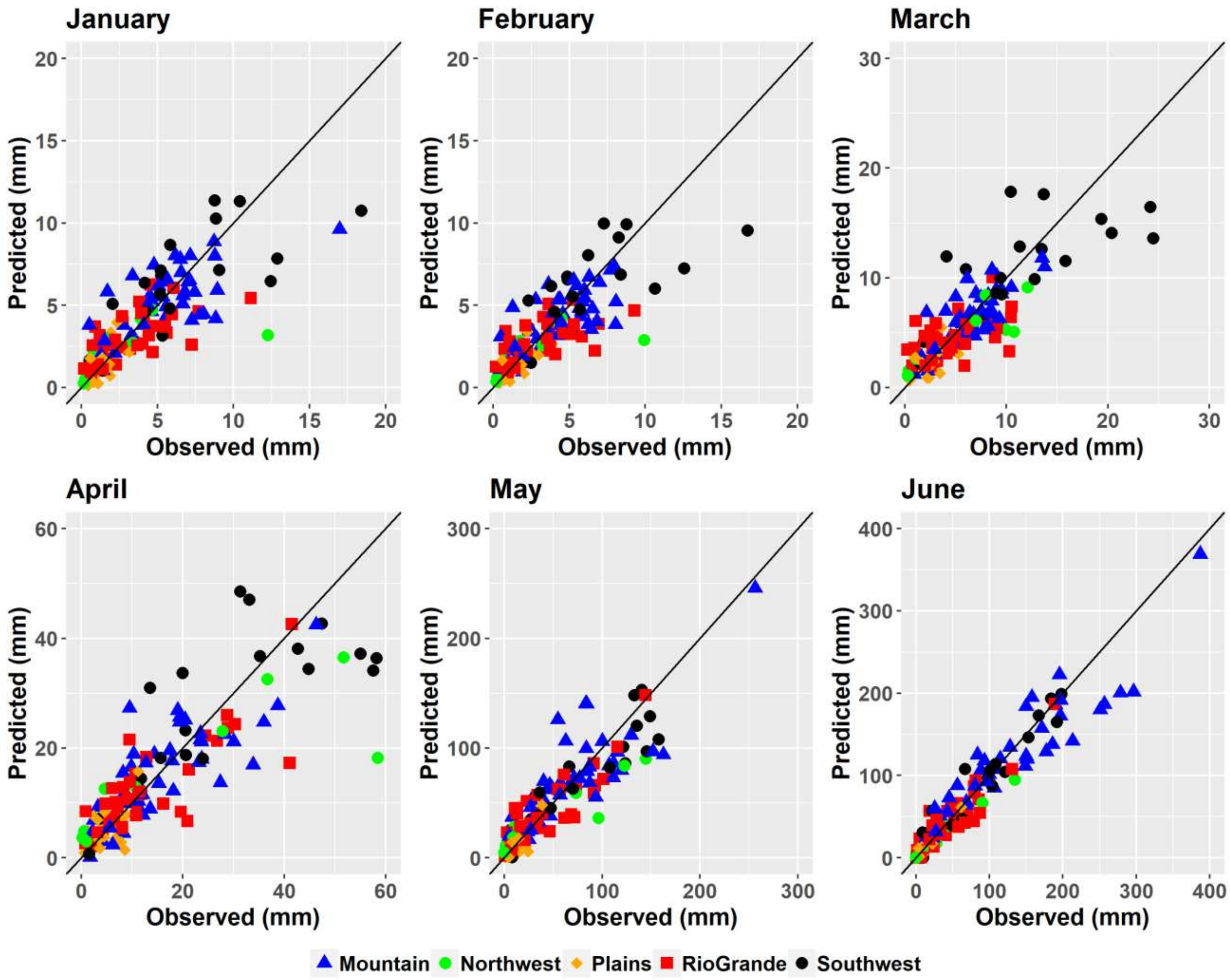

Figure 4. Predicted vs. observed mean monthly discharge. Stations with transbasin diversions and urban land cover excluded.

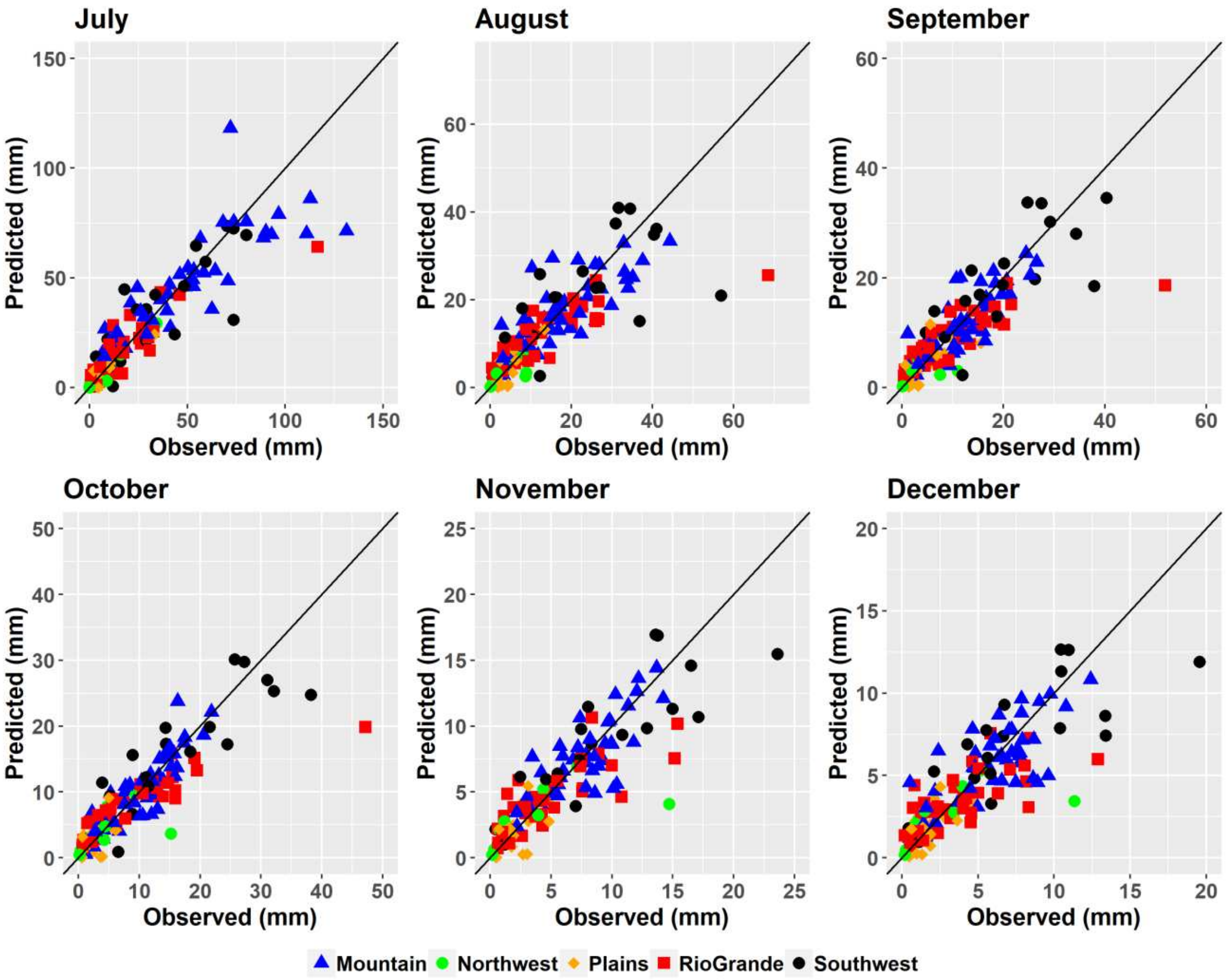

Figure 4, continued

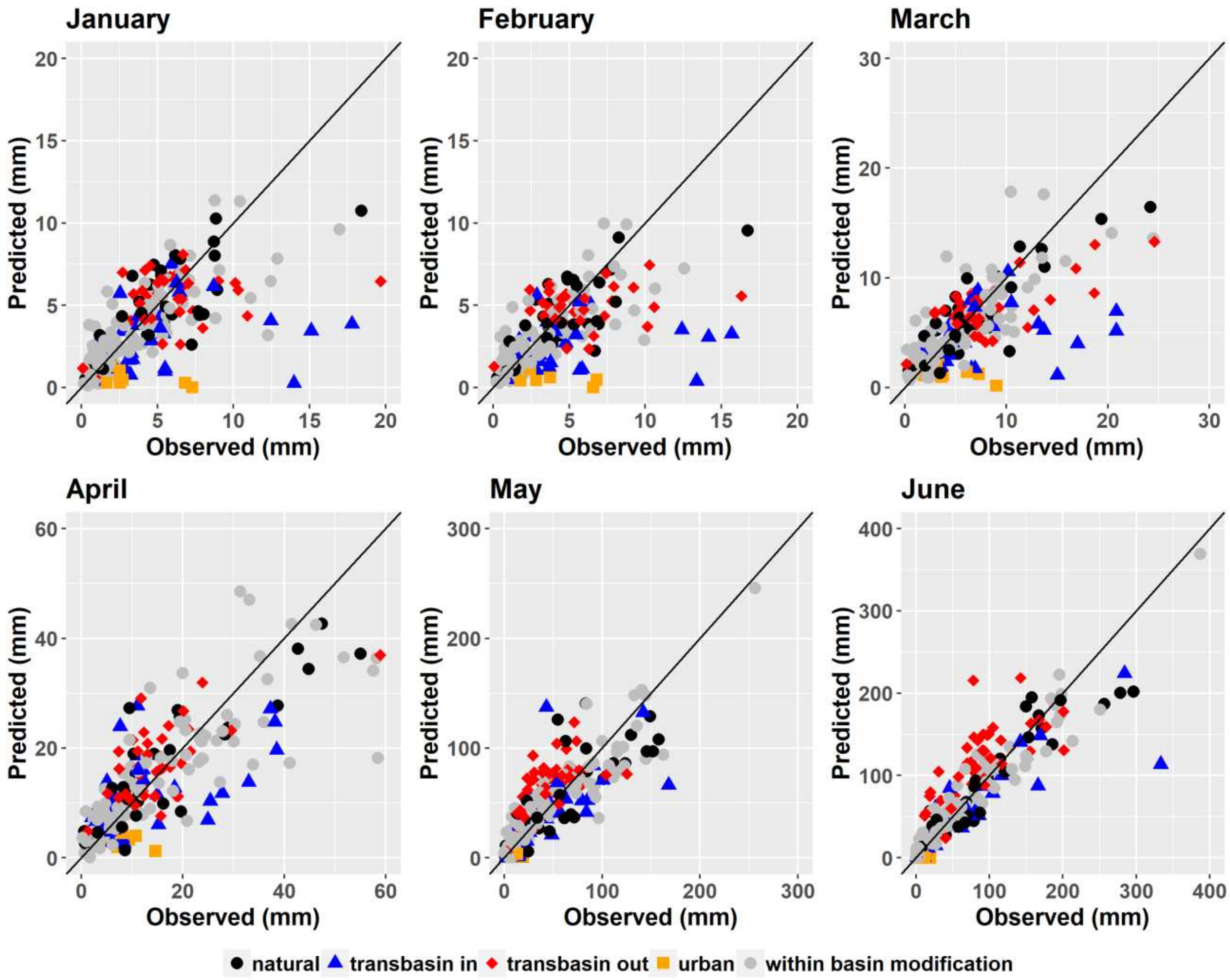

Figure 5. Predicted vs. observed mean monthly discharge showing all stations, colored by modification type.

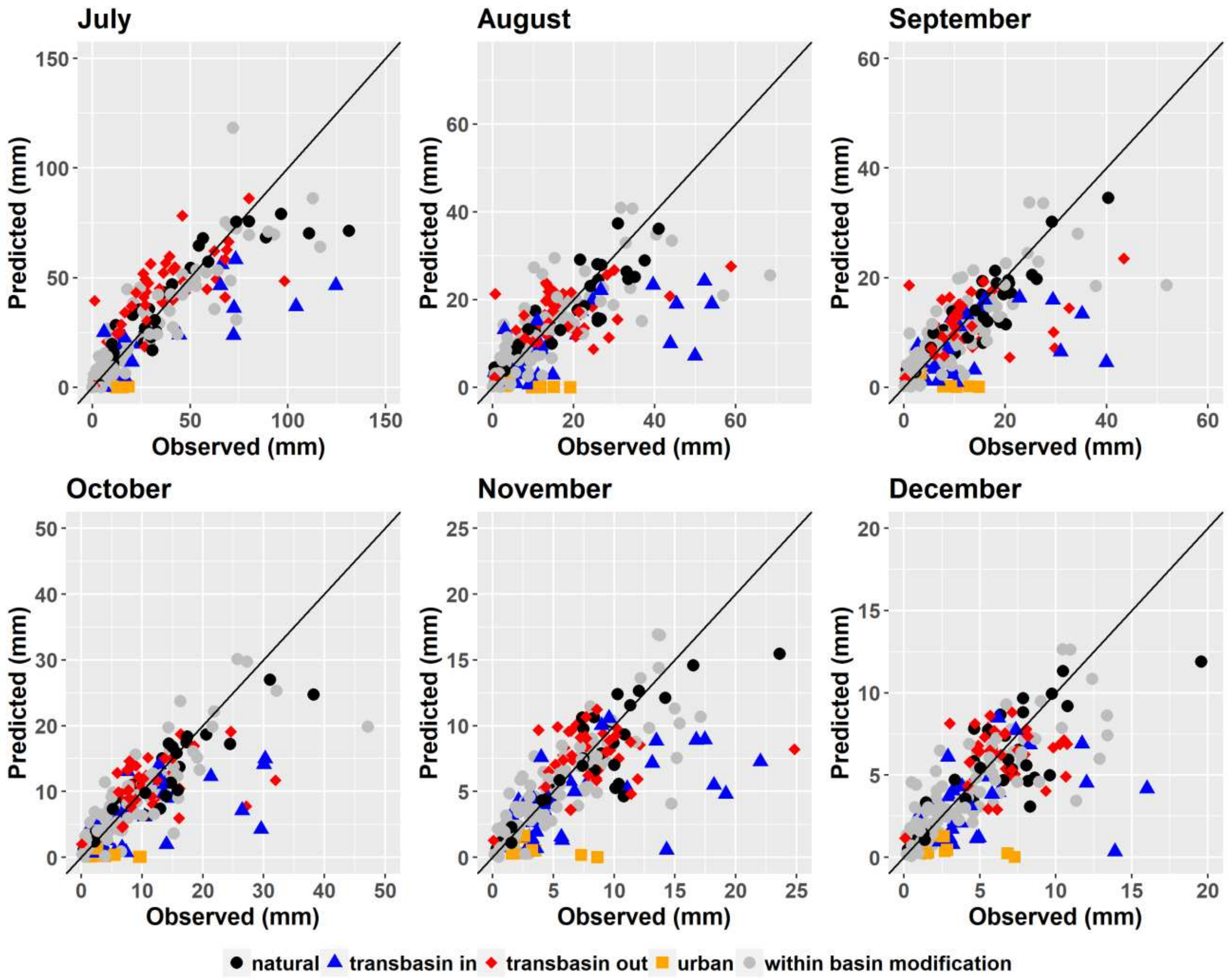

Figure 5, continued.

The effects of flow modifications also vary by snow zone (Figure 6). In the low snow zone, the dominant anthropogenic influence is urban land cover. The streamflow for all urban watersheds in this study is under-predicted by the regression models, and the monthly and annual anomalies fall outside the range of natural variability by 3-20 times (Figure 6). The mean annual anomaly in the low snow zone for urban watersheds is 65mm compared to an anomaly of just 4mm for natural watersheds (Figure 6). Anomalies for urban watersheds are over 4x the natural anomalies in May, July, and August, which is the time of year that rain storms are most likely to occur in Colorado. Urbanization has a particularly large influence on rainfall runoff because impermeable surfaces and installed drainage systems efficiently funnel runoff to the stream.

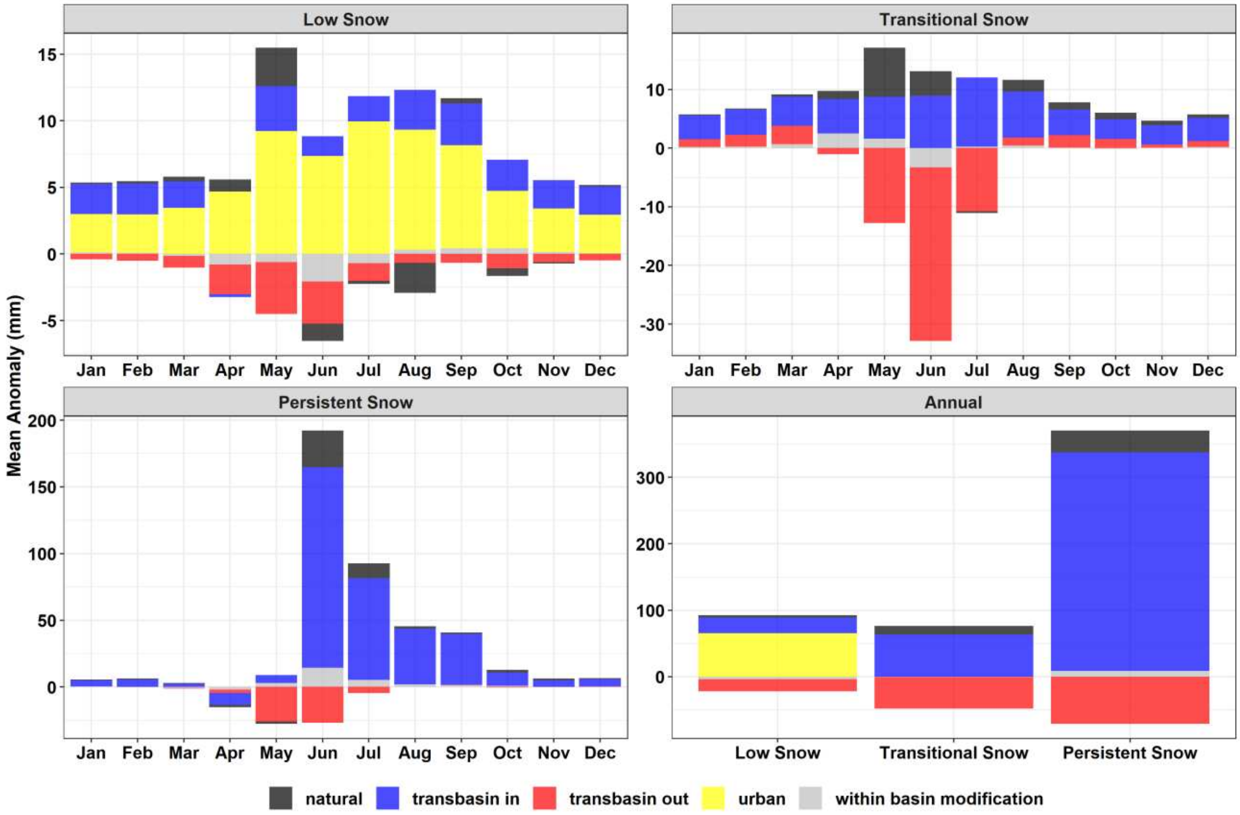

Figure 6. Mean anomaly from predicted mean monthly and mean annual streamflow for each watershed type, grouped by SP category. Positive anomalies indicate observed streamflow is greater than predicted by the models.

Some of the transbasin water enters watersheds in the low snow zone as well. The annual anomaly for transbasin-in watersheds is 24mm; this is 6x the annual anomaly for natural watersheds in this snow zone, indicating a large influence of transbasin-in diversions at the low snow zone (Figure 6). The largest monthly anomalies for transbasin-in watersheds are in May, August, and September. The mean annual anomaly for transbasin-out watersheds is -18mm and the monthly anomalies are largest in May and June (Figure 6). Positive anomalies during base flow months (Nov-March) in urban and transbasin-in watersheds are likely due to elevated water tables from irrigation during the previous year, as well as discharge from WWTP's. The same discharge year-round from these facilities has a more pronounced effect during months with lower natural flows.

Watersheds with within basin diversions in the low snow zone show a large negative anomaly in June when the water is likely being removed from the streams to be used for irrigation, but it is within the range of variability of the natural watersheds. Return flows take several weeks to make it back to the stream so in the late summer months this anomaly is washed out and even becomes slightly positive into the fall (Figure 6). The low snow zone is dominated by overall water imports and increased flow, relative to the expected flow under natural conditions.

The transitional snow zone is influenced by both imports and exports of water; the majority of the imports are on the east side of the divide, with exports usually on the west side of the divide. The largest influence on the transitional snow zone is from transbasin-in diversions, which have small positive anomalies throughout the year (Figure 6). The mean annual anomaly for transbasin-in diversions is 64mm, whereas the anomaly for natural watersheds is 13mm. The largest monthly anomalies are in June-August, and these are 2-4x the natural variability during those months. Timing of reservoir releases is reflected by the positive anomalies in the summer and fall. The mean annual anomaly for transbasin-out watersheds is -47mm, with the largest monthly anomaly in June, over 7x the range of natural variability (Figure 6). The transbasin-out watersheds show negative anomalies during the entire snowmelt season, May-July, when the water from high flows is diverted. These watersheds also show small positive anomalies during the rest of the year, which may be due to the high amount of natural flow in these watersheds which could be under-predicted by the model. Watersheds with within basin modifications have a negative anomaly in June and positive anomaly in April and May, but they are well within the range of natural variability.

The persistent snow zone also has both imports and exports of water. This snow zone appears to be dominated by transbasin-in diversions (Figure 6), but the large anomalies shown for transbasin-in diversions are averaged from just n=4 transbasin-in diversions in this snow zone. These give a mean annual anomaly of 329mm, and the largest positive anomaly in June, followed by July, August, and September. These are the months when streamflow is likely to be released from reservoirs to be used for irrigation in agricultural and urban areas downstream. The majority of watersheds in the persistent snow zone have transbasin-out diversions (n=24), making this is the dominant influence at these high elevations (Figure 1). Transbasin-out watersheds have 2-3 times less than the expected flow in May and June, when flow is diverted during snowmelt runoff. The mean annual anomaly for transbasin-out watersheds is -71mm, compared to a positive anomaly of 32mm for natural watersheds.

Overall, there are larger average positive anomalies than negative anomalies for the watersheds analyzed (Figure 6). This is in part because of incomplete gaging. In addition, the number of transbasin-out diversions is greater than the number of watersheds receiving transbasin imports. Transbasin out diversions tend to be spread between multiple small streams, with inputs are combined into pipelines that feed into single streams and reservoirs. This leads to a larger average anomaly for those transbasin-in watersheds. Lastly, WWTP's are difficult to account for but likely add a substantial amount of flow to many of the watersheds year-round, contributing to some of the positive annual anomalies.

Flow Duration Curve Quantiles

Flow duration curves illustrate how different parts of the hydrograph, such as the magnitude of base flows (Q10) and peak flows (Q90), are altered by streamflow stressors. The most dramatic changes to the hydrograph characteristics of watersheds in the low snow zone are in the urban watersheds, followed closely by the watersheds with transbasin-in diversions. Both of these watershed types have higher flow than natural for Q10-Q75 (Figure 7A-D). Although the differences are not significant, this may be due to low sample sizes in the low snow zone. Stream gauging is more limited in these lower flow areas, and the study watershed size limit of <1500 km^2 removed a number of larger watersheds in this zone.

The natural variability of flow in the transitional snow zone is large. Therefore, there are not significant differences between the natural watersheds and those with transbasin diversions in the transitional snow zone. Transbasin-out diversions reduce the highest flows (Q75, Q90), though this difference is not significant. Transbasin-in diversions tend to increase the high flows (Q75, Q90), though this difference is also not significant (Figure 7D, E) because stored transbasin water is often released for water users during times of year with low streamflow. In the transitional snow zone, watersheds with within basin modifications have significantly lower flow than natural watersheds for Q25 and Q50 (Figure 7A, B).

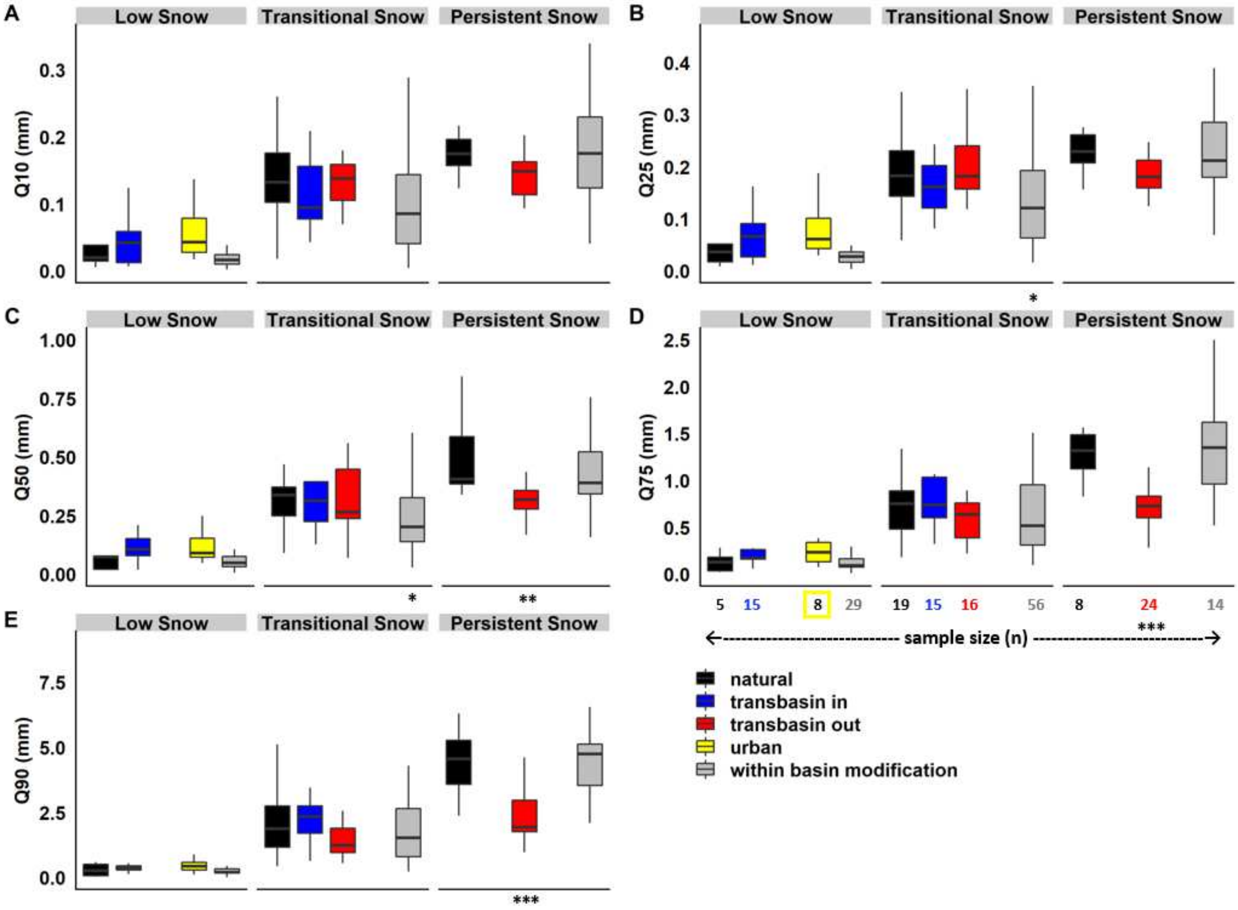

Figure 7. Daily flow quantiles (Q10, 25, 50, 75, 90), grouped by diversion type and by snow persistence (Low Snow=SP<50, Transitional Snow=50<SP<75, Persistent Snow=75<SP<100). Values of sample size for each group (n) are given in D. Removed outliers; removed groups with n<5. "*" indicates significance of the p-value for the ANOVA pairwise comparisons of natural vs. all other groups, using the Dunnett adjustment. (*p<0.1; **p<0.05, ***p<0.01).

Transbasin-out diversions are located primarily in the persistent snow zone and usually have lower high flows (Q90) than natural watersheds because water is removed from source streams when flows are high. In the persistent snow zone, flows are reduced at all quantiles for the transbasin-out watersheds, and this difference is significant for Q50, Q75, and Q90 (Figure 7C-E).

3.2.2 Forest Disturbance

When the predicted vs. observed streamflow values are plotted along with all mean annual streamflow data for natural and within basin modified watersheds, the post-disturbance streamflow values almost all fall within the range of natural streamflow variability (Figure 8). This is in stark contrast to the watersheds with anthropogenic diversions and urban land cover in Figure 5. Although forest disturbance can have a significant effect on streamflow, its effects are certainly much smaller than those of many anthropogenic streamflow modifications in similar watersheds across Colorado.

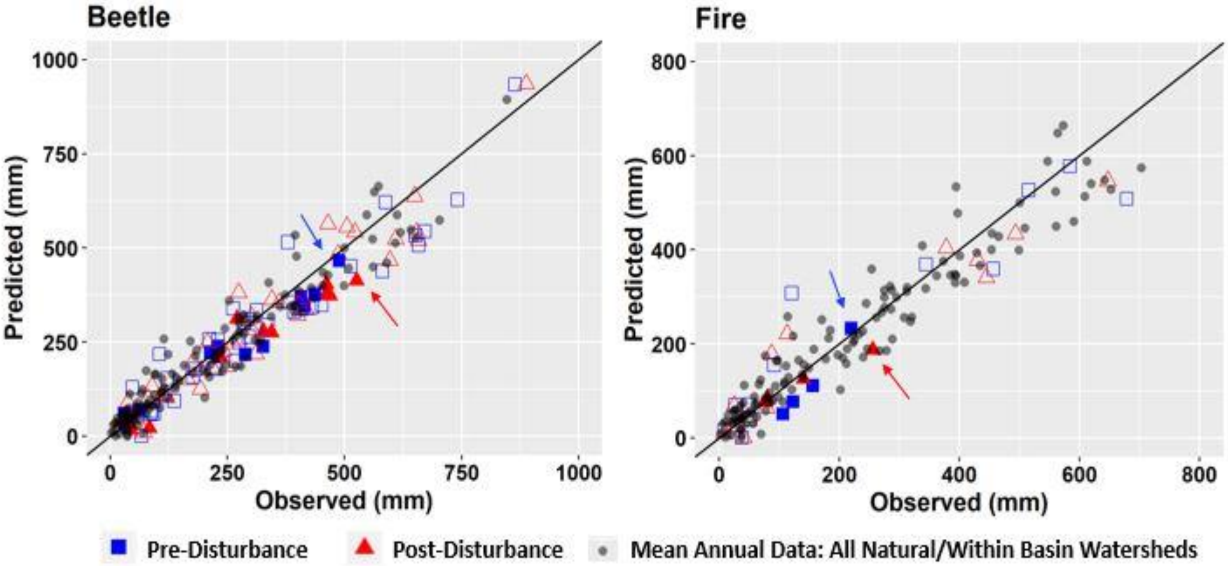

Figure 8. Predicted vs. observed values for mean annual streamflow in watersheds with forest disturbance compared to those for all natural and within basin modification watersheds (grey dots); pre- and post- disturbance values are shown as blue squares and red triangles, respectively. Values that have a significant change in streamflow after disturbance are filled symbols, and those with no significant change are unfilled symbols. Blue and red arrows identify the corresponding pre- and post- disturbance points for an example watershed for each type of disturbance.

We determined whether there was an increase or decrease in streamflow after each type of disturbance for each watershed using ANCOVA. The majority of watersheds with significant streamflow effects from beetle mortality have increased flow following the mortality; whereas three out of five watersheds with a significant streamflow effect from fire have decreased flow after fire (Figure 9). In both beetle and fire-affected watersheds, the mean P, SP, slope, and elevation are all higher for watersheds that show increased streamflow post-disturbance than for those with decreased streamflow. However, for both disturbance types, the watersheds with no change in flow span the same range of all of these variables.

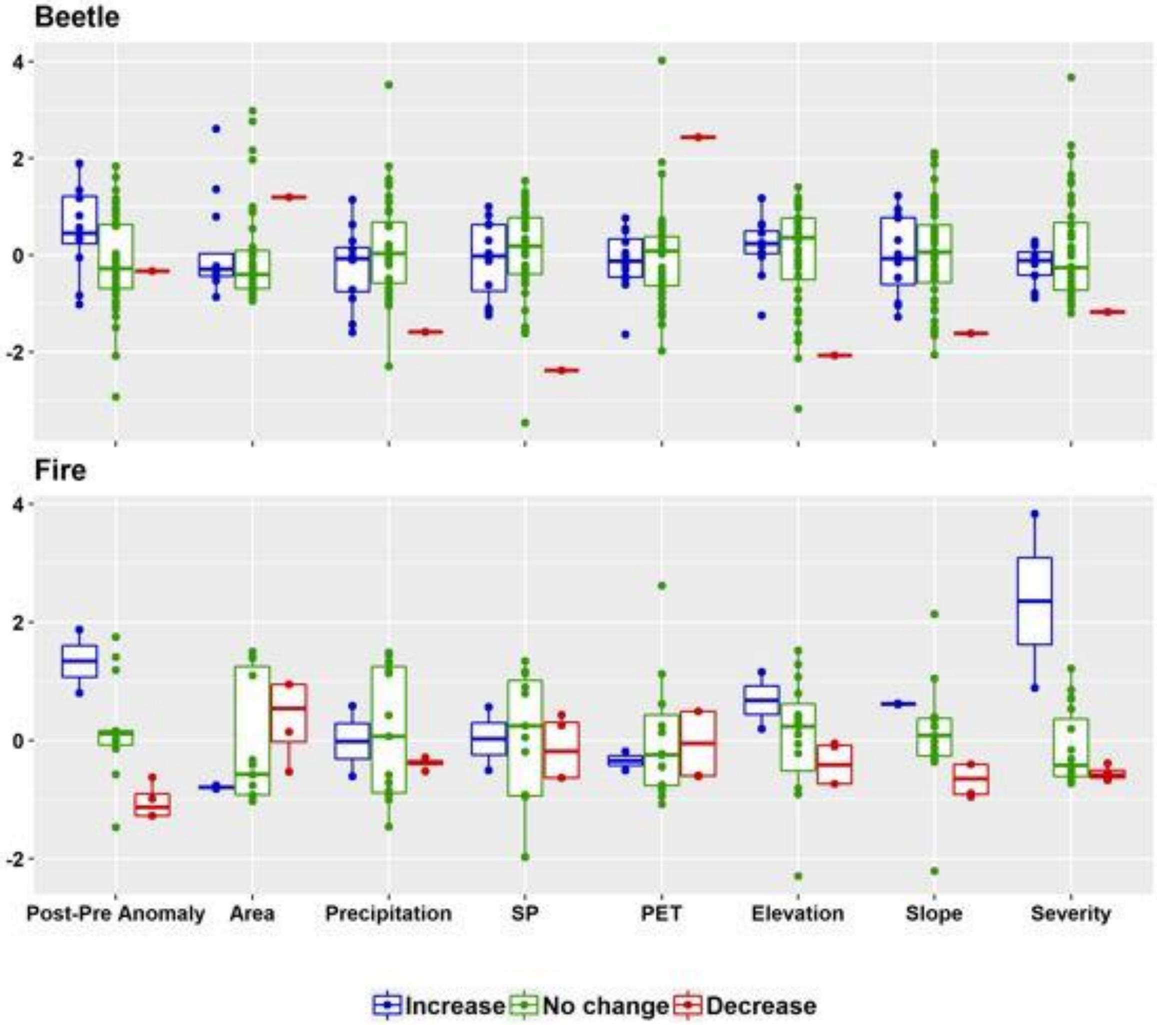

Figure 9. Watershed characteristics relevant to post-disturbance streamflow response. The y-axis shows standardized values for each variable range (subtracted the mean and divided by the standard deviation) and grouped by streamflow response, with significant ($p<0.1$) Increase/Decrease or No change.

The severity and extent of the disturbance plays a large role in how it affects streamflow; the percent mortality/severity is about 4x higher for watersheds that show a significant increase in streamflow post-disturbance than for those with a significant decrease in streamflow. In fire-affected watersheds, this difference is much more pronounced (Figure 9). The fire severity in the watersheds with increased streamflow post-fire is much higher than the fire severity for all watersheds with decreased streamflow as well as for all but two watersheds that show no change in streamflow. The watersheds with increased streamflow following fire both have East-facing dominant aspects, whereas the two watersheds within the same range of fire severity but no change in streamflow have South and West-facing dominant aspects. This may point to a potential role of aspect in modifying the streamflow response to wildfire. The fire severity effect may be more evident than the beetle severity effect because fire severity is weighted by both area burned and severity of the burn, whereas the beetle severity is simply the percent mortality area. The beetle mortality area is higher for all watersheds with increased streamflow than the one watershed with a decrease in streamflow; however, there are also many watersheds with high % mortality area in the No change category. There is no clear pattern of the dominant aspects in these watersheds, although the one watershed with a significant decrease in streamflow is South-facing.

3.2.3 Comparison of Stressors on Streamflow

The results of the three mixed effects models for mean annual streamflow show the variance explained by watershed diversion type (natural/within basin modification/transbasin-in/transbasin-out/urban), beetle mortality (pre/post), and fire (pre/post), respectively. This comparison illustrates the relatively small impact of forest disturbance on streamflow, when compared to anthropogenic effects such as flow diversions and urban land cover. In the first model, grouped by watershed type, the variance explained by type is 5.39, a larger amount than the residual variance (model error), which is 3.34 for the type model. The type factor p-value is highly significant ($p<<0.01$), indicating that the variance explained by that factor is not zero. In contrast, the model for mean annual streamflow grouped by pre- and post-disturbance shows the variance explained by beetle disturbance is 0.12 and by fire disturbance is 0.05, a smaller number than the residual variances of 0.35 and 0.54, respectively (Table 6). The beetle disturbance factor is only moderately significant ($p<0.1$). The fire disturbance factor is not significantly different from zero, indicating that it may not explain any variance in streamflow (Table 6). This could be due to the more varied results of both increasing and decreasing streamflow after fire (Figure 9).

Table 6. Variance explained by the random variables of Watershed and either Type or Pre/Post Disturbance, as well as the residual variance unexplained by the model. The p-value indicates the significance for a test of the null hypothesis that the variance explained by the corresponding factor is equal to zero.

	Watershed	Type/Dist	Residual	p-value
Type	7.90	5.39	3.34	$7.46*10^{-09}$
Beetle	6.94	0.12	0.35	0.075
Fire	14.05	0.05	0.54	0.6976

4. DISCUSSION

4.1 Anthropogenic Modifications

Flow modifications and land use change have altered 85% of the gaged streams <1,500 km^2 in Colorado. Of the stressors studied, the largest effects are from transbasin diversions, which reduce flow by an average of 20% in transbasin-out watersheds and increase flow by an average of 221% in transbasin-in watersheds. The percent of flow reduction for transbasin-out watersheds is lower than the percent increase for transbasin-in watersheds because the source watersheds are high elevation, high flow streams. Adding that flow to the transbasin-in watersheds translates to a much higher percent of the natural flow in those drier, low elevation areas. Most of the transbasin-in diversions in the state support large urban and agricultural areas on the Front Range. These remove water from multiple streams west of the continental divide and then concentrate the water input into fewer streams on the east side, translating to a larger percent of increased flow in the transbasin-in watersheds. Water is removed mostly in May-July from middle to high elevation watersheds and transferred to middle and lower elevation watersheds during the growing season and warmest months, May-September. Some of this water is also transferred for municipal use, and may be partially providing for the large positive anomaly in urban systems.

The overall pattern of these streamflow alterations is to move streamflow from the persistent snow zone to the low snow zone and also from the west side of the continental divide to the east side (Figure 1). Watersheds with transbasin-out diversions tend to have reduced high flows, relative to natural flow (Figure 7E); these watersheds are also generally located in high elevation headwaters and on the west side of the divide (Figure 1). These types of flow changes can affect channel morphology and riparian and aquatic ecosystems. Effects of losing peak and high flows include reduced lateral connectivity with the riparian zone and floodplain, which alters riparian vegetation communities and reduces access to backwater habitat for juvenile fishes (Junk et al., 1989). Also, peak-flow reduction can stimulate invasion by non-native species that would otherwise not survive the high flows (Horton, 1977; Roy et al., 2005), disrupt lifecycle cues for aquatic species (Nesler et al., 1988), and prevent downstream transport of water-borne seeds (Merritt & Wohl, 2006).

Watersheds with transbasin-in diversions and urbanized land cover have increased low flow magnitudes compared to natural watersheds and are generally located in the transitional and low snow zones, and on the east side of the divide (Figure 1). The addition of water at low flow impacts the stream ecosystem by augmenting water in the stream during the natural troughs in the hydrograph and causing these streams to experience increased flows throughout the year. These changes can cause streambed coarsening, loss of riffle habitat and changes in vegetation and aquatic species (Poff et al., 1997, 2006). Some of the low flow increases observed in this study are likely due to WWTP's within many of the urban watersheds, as these have been shown to have a large contribution to low flow increases in urban areas (Oudin et al., 2018).

The amount of impervious surface in urbanized watersheds also reduces infiltration and increases surface flow; these changes, in addition to installed drainage systems, lead to increased magnitude and frequency of high flows (Bhaskar & Welty, 2012; Eimers & Mcdonald, 2015; Hopkins et al., 2015; Leopold, 1968). The increased magnitude and frequency of high flows in urban systems can lead to channel incision and bank instability, disconnection from the floodplain, and alteration of sediment and nutrient cycling by the system (Leopold, 1968; Poff et al., 2006). Large increases in total annual flow in urban systems are likely a combination of increased high flows due to imperviousness and additions to base flows from WWTP discharges (Bhaskar et al., 2016; Oudin et al., 2018).

Watersheds with within basin modifications experience changes to the hydrograph caused by removing water during snowmelt runoff, but much of this water makes its way back to the stream as return flow, with different timing than a natural system. Reservoirs change the hydrograph characteristics by regulating flows and often reducing magnitude and frequency of high flows (Haddeland et al., 2007; Poff et al., 1997). This leads to similar total annual flow magnitudes as natural streams; however the timing of peaks and troughs may be altered, which can also impact riparian vegetation and aquatic species (Poff et al., 1997).

Across all of the watersheds analyzed, those in the Plains and Southwest regions are most altered. The Plains region receives on average over 500% more water than expected due to the many transbasin imports that supply water to the farms and cities in the Front Range and Plains (Figure 1, Figure 6). The Southwest region receives on average 194% more water than expected due to the transbasin movement of water from higher elevations to the lowland areas for agriculture in the Dolores River Basin (Figure 1, Figure 6). Of all the hydrologic regions, the watersheds in the Rio Grande have been the least altered by diversions as a whole, with a 2% mean anomaly from expected (Figure 1, Figure 6). This region has limited effects of transbasin diversions, and most of the gaged watersheds are in the mountains above the agricultural areas in the San Luis Valley.

The movement of these waters across the landscape can cause important disruptions to the natural characteristics and function of river ecosystems in Colorado. “The Natural Flow Regime,” a phrase coined by Poff et al. (1997), describes the natural dynamic character of a healthy river ecosystem. The magnitude, frequency, duration, timing, and rate of change of natural flow events maintain the ecological integrity of the system. This study indicates that the largest effects on the natural dynamic character of the river ecosystems in Colorado may be on the low elevation streams in the Plains and Southwest areas of the state. However, the transitional snow zone is also especially sensitive to annual variability in precipitation and temperatures. Therefore, with changing climate, the natural variability of streamflow in the transitional zone is likely to change (Kampf & Lefsky, 2016), which could lead to more significant effects of the transbasin diversions within this zone as well.

4.2 Forest Disturbance

Effects of forest disturbance on streamflow have been a hot topic in the recent literature (Bewley et al., 2010; Biederman et al., 2014; Boon, 2012; Bright et al., 2013; Buma & Livneh, 2017; Clark et al., 2014; Giles-Hansen et al., 2019; Gleason & Nolin, 2016; Harpold et al., 2014; Hubbard et al., 2013; Li et al., 2018; Livneh et al., 2015; Wehner & Stednick, 2017; Zhang et al., 2017; Zhang & Wei, 2012). Many previous studies identified streamflow effects of forest disturbance using a paired-catchment method, essentially a space-for-time approach (Bethlahmy, 1974; Bosch & Hewlett, 1982; Brown et al., 2005), or a modified double mass curve for a small number of watersheds (Biederman et al., 2015; Giles-Hansen et al., 2019; Zhang & Wei, 2012). This study is novel in that we examine a large number of watersheds across Colorado with long streamflow records and are therefore able to compare responses to disturbance across both space and time. Although the sample sizes here are still not ideal, this dataset reveals unique findings and raises interesting new questions regarding the controls on streamflow response to disturbance.

Analysis with this larger dataset indicates that the effects of forest disturbance are quite small relative to the anthropogenic movement and reallocation of water via diversions and flow modifications described previously. In addition, it is difficult to predict the direction of the forest disturbance effect on streamflow, or whether there will be a streamflow change at all. From the data presented, a fire disturbance area-weighted severity score greater than 29% is likely to experience a significant increase in streamflow, especially if the watershed has an East- or North-facing dominant aspect. All beetle-affected watersheds with a streamflow increase have higher percent mortality than those with a streamflow decrease; however, many beetle-affected watersheds with high percent mortality do not show a significant streamflow change.

Other recent research has also identified mixed results for the effects of beetle mortality on streamflow at the watershed scale (Bearup et al., 2014; Wehner & Stednick, 2017). In watersheds with snow influences, increases in streamflow following disturbance may be caused by greater snow accumulation due to decreases in forest interception; however increases in snow sublimation due to greater exposure to solar radiation after disturbance may also cause net loss of snowmelt input (Harpold et al., 2014). Possibly these two effects of increased accumulation and increased sublimation may balance each other and explain why many of the watersheds examined here showed no streamflow change after disturbance. Similarly Biederman et al. (2015) found no change in streamflow following beetle mortality in seven of eight study catchments in the Colorado River headwaters, while the eighth catchment experienced a decrease in streamflow. This watershed had a high watershed area affected (50%) and a SW-facing aspect, which may have led to greater snow ablation during the winter relative to more northerly-facing watersheds. Similarly the decreases in streamflow we identified were for low elevation watersheds that likely had relatively low snow accumulation (Figure 9). Higher elevations with more frequent cloud cover and colder temperatures may not experience net loss in snowmelt input; in these areas reduced transpiration due to mortality may be the dominant influence causing increased streamflow.

Two large-scale studies on the effects of both fire and beetle disturbance on streamflow across the US found varying effects of disturbance depending on watershed and climate characteristics. Hallema et al. (2018) studied 168 watersheds with >1% burned area from 1985-2008 and found increased streamflow post-fire when the burned area was >19% especially when the burn was moderate-to-high severity. A few watersheds in the western US did have decreased streamflow attributed to the fire disturbance; however, this study did not include any watersheds in the state of Colorado (Hallema et al., 2018: Figure 1). The other large-scale study found that for all types of disturbances, watersheds with >7% of the forested area disturbed had increases in streamflow, and watersheds with >20% affected area presented an even greater increase (Buma & Livneh, 2017). Similarly, in our data all watersheds with a significant increase in streamflow have >6% mortality/burned area; however, not all watersheds above this threshold experienced increased streamflow. Seven fire-affected watersheds with 8-15% burned area (15-35% severity score) show no change in streamflow. These watersheds are all South- or West-facing, so they may have experienced elevated snow ablation after fire. In the beetle data, there are 30 watersheds above 6% mortality area showing no streamflow change and of those, 10 watersheds have >20% mortality area. Interestingly, the majority of watersheds with high beetle mortality area and no change in streamflow are either South- or West-facing as well. This supports the idea that increased exposure to incoming solar radiation may balance out or override the reduction in transpiration following the disturbance (Biederman et al., 2014). Buma and Livneh (2017) found that watersheds with increased streamflow generally had lower precipitation than those with decreased streamflow, a finding opposite to ours. This difference could stem from their vastly different study area of the entire US and therefore much larger range of precipitation and climate signals. A review by Adams et al. (2012) suggests that streamflow is more likely to decrease, rather than increase, in drier forests or rain-dominated watersheds following tree die-off or harvest disturbances. Also, snow-dominated watersheds are more likely to experience streamflow increases (Adams et al., 2012); this is consistent with our finding of generally higher SP in watersheds with increased streamflow, especially in beetle-affected watersheds (Figure 9).

Soils, geology, and forest type, should all be considered in future work on this topic, as they may help to explain the variable streamflow response seen in our data. Buma and Livneh (2017) found average soil bulk density was significantly higher, and subsurface residence time was lower in watersheds with streamflow increases post-disturbance. These are two useful characteristics not included in our study. The complexity introduced by the beetle disturbance specifically is well-described in a review by Pugh & Gordon (2012), which concludes that more large-scale statistical analyses of changes to the relationships between streamflow, mortality area, and climate drivers are needed to understand the overall effects of beetle mortality on streamflow. This research is one in a number of current investigations into this complex, large-scale and yet site-specific, question.

4.3 Limitations

Here, my goal was to gather a large enough dataset to capture the differing watershed characteristics that contribute to these unique responses to disturbance. One nuance affecting each watershed is the time-varying effects of the stressors studied. Flow diversions are often not consistent over time, leading to varying effects on streamflow each year. We did not quantify these time-varying effects in this study. Similarly urbanization is time varying, but we did not quantify changes in urban area over time. Previous work has shown that forest disturbance effects can last anywhere from <5 years to decades post-disturbance (Pugh & Gordon, 2012). In a large-scale analysis, this makes it difficult to choose a time-period over which to study the disturbance effects and whether the time-period should be uniform across watersheds and disturbance types.

Spatial coverage of stream gaging networks also created some limitations in the streamflow dataset. Current stream gaging networks are focused on primarily perennial streams draining large watersheds that span elevations from mountains to plains. In large watersheds, quantifying the specific effects of an individual disturbance on streamflow is much more challenging. Headwater streams, particularly at transitional to low elevations, are most under-represented by the current streamflow monitoring networks. Within Colorado, streamflow monitoring was most limited in the Northwest region and in the eastern plains. Across the arid Southwestern US, stream gaging has the poorest spatial coverage of any region in the contiguous US, as well as short periods of record (Kiang et al., 2013). In order to further quantify the impacts of flow diversions and forest disturbance on streamflow across Colorado, streamflow gauging networks could be expanded to include more of these under-represented areas.

In addition, a more accurate identification scheme for where diversions remove water from and contribute water to streams would be helpful for quantifying streamflow modifications. This information is not straightforward to reconstruct from existing databases. More stream gaging networks placed in areas of known streamflow alterations, such as agricultural and urban areas, would also help in quantifying the effects of these stressors. Important future work includes a larger scale investigation using a longer period of record and greater spatial distribution of stream gages, with concurrent disturbance data spanning all forest types. It is difficult to maintain the depth of detailed investigation when the breadth of the study becomes large. Each watershed has unique characteristics that warrant future research on the detailed physical processes involved.

5. CONCLUSION

With this research, we quantified the overall changes to streamflow across the landscape in Colorado, due to flow modifications, urbanization, and forest disturbance. Transbasin diversions have the largest magnitude effect, with an average of 20% decreased flow in transbasin-out watersheds and an average of 221% increased flow in transbasin-in watersheds, across all snow zones. Urbanization increased streamflow by an average of 16x the expected natural flow. Within basin modifications tend to alter the timing of streamflow rather than changing the overall amount of flow in the system.

Forest disturbance effects on streamflow were less pronounced and fell within the range of natural variability across all natural and within basin modification watersheds (Figure 8). Streamflow increased significantly in 23% of beetle-affected watersheds and 11% of fire-affected watersheds, and it decreased in 2% of beetle-affected watersheds and 16% of fire-affected watersheds. No significant change in streamflow was seen in the remaining 75% of beetle-affected watersheds and 73% of fire-affected watersheds. Increases in streamflow were documented for watersheds with as little as 6% of the watershed disturbed, and these effects were most evident for high elevation North and East-facing watersheds with beetle disturbance. The highest severity fire disturbances generated streamflow increases; in lower elevation watersheds with low severity fires, streamflow decreased.

These findings have critical implications for the future of water planning in Colorado and other semiarid regions. As populations continue to rise and cities sprawl across the landscape, demands on limited water resources will also increase. Changes to streamflow quantity and timing from within basin and transbasin diversions as well as urbanization can impact important physical characteristics of the river including temperature, channel geomorphology (Ryan, 1997;

Baker et al., 2011; Bohn and King, 2000), habitat diversity (Poff et al., 1997), stream ecology (Coble & Kolb, 2012; Dietl & Smith, 2017; Paukert et al., 2011), and nutrient cycling (Smith et al., 2016). These are all vital components of a functioning river ecosystem, and important concepts to understand when managing rivers for water resources.

Addressing these and other similar questions requires representative and long-term monitoring networks. Although this study investigates more watersheds across the state of Colorado in this context than any previous study, an even larger dataset that pairs streamflow data with watershed characteristics and disturbance across the entire range of elevation, forest types, and geologies would allow for a better macro-scale understanding of the nuances involved in streamflow change after disturbance. In this new era of scientific research where processing and analyzing "big data" is quite feasible, we are limited only by the data that exist; therefore, it is of utmost importance that field research campaigns and long-term data collection remain a high priority.

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APPENDICES

Appendix A: Table of gages and watersheds used in flow modification analysis.

GAGE NAME	TYPE	AREA (km^2)	MEAN ELEVATION (m)	MEAN SLOPE (%)	DOMINANT ASPECT	GEOLOGY	HYDROLOGIC REGION	MA SP (%)	MA P (mm)	MA PET (mm)	MA Q (mm)
South Fork Of Williams Fork Near Leal, Co	transbasin out	73	3352	21	E	permeable metamorphic	Mountain	81	719	1028	410
Missouri Creek Near Gold Park, Co.	transbasin out	17	3470	24	SE	permeable metamorphic	Mountain	87	849	1034	407
Black Gore Creek Near Minturn, Co.	natural	32	3261	17	SW	permeable sedimentary	Mountain	79	748	1052	429
Middle Creek Near Minturn, Co.	within basin modification	16	3192	19	W	permeable sedimentary	Mountain	75	602	1110	288
Eagle R Blw Wastewater Treatment Plant At Avon, Co	transbasin out	1052	3187	19	NW	permeable sedimentary	Mountain	74	722	1085	307
Alamosa River Below Terrace Reservoir, Co.	within basin modification	296	3282	17	S	volcanic	Rio Grande	67	760	1110	275
Alamosa River Above Terrace Reservoir, Co.	natural	275	3316	17	S	volcanic	Rio Grande	68	781	1104	295
Animas River At Howardsville, Co	within basin modification	149	3637	26	W	volcanic	Southwest	78	1110	1030	573
Animas River At Silverton, Co.	within basin modification	182	3602	26	W	volcanic	Southwest	77	1100	1036	564
Ef Arkansas R At Us Highway 24, Nr Leadville, Co.	within basin modification	129	3498	17	W	permeable sedimentary	Mountain	76	743	1000	275
Arkansas River At Granite, Co.	transbasin in	1117	3358	16	W	intrusive	Mountain	70	623	1047	285
Arkansas River Near Leadville, Co	transbasin in	254	3391	15	W	permeable sedimentary	Mountain	74	693	1031	242
Bear Creek Above Evergreen, Co	within basin modification	267	2929	17	NE	intrusive	Mountain	56	603	1065	108
Bear Creek At Morrison	within basin modification	426	2713	16	NE	intrusive	Plains	51	573	1109	83
Bear Creek At Sheridan	within basin modification	676	2496	14	NE	intrusive	Plains	45	545	1173	59
Bear Creek Near Colorado Springs, Co	natural	18	2690	24	E	intrusive	Plains	40	576	1133	83
Beaver Creek At Avon, Co	transbasin out	38	3108	19	W	intrusive	Mountain	74	808	1123	282
Beaver Creek Below Beaver Creek Reservoir	within basin modification	125	3243	15	W	volcanic	Rio Grande	66	767	1097	223

GAGE NAME	TYPE	AREA (km^2)	MEAN ELEVATION (m)	MEAN SLOPE (%)	DOMINANT ASPECT	GEOLOGY	HYDROLOGIC REGION	MA SP (%)	MA P (mm)	MA PET (mm)	MA Q (mm)
Big Dry Creek At Mouth Near Fort Lupton	urban	286	1646	2	SE	permeable sedimentary	Plains	19	398	1373	122
Big Dry Creek At Westminster, Co	urban	121	1728	3	E	permeable sedimentary	Plains	20	429	1384	100
Big Thompson River At Hillsborough Diversion	within basin modification	1464	2418	16	E	permeable metamorphic	Plains	43	575	1130	26
Big Thompson River At Loveland, Co.	within basin modification	1386	2468	16	E	permeable metamorphic	Plains	44	587	1124	40
Blue River At Blue River, Co.	transbasin out	110	3547	19	E	permeable sedimentary	Mountain	80	756	1004	237
Blue River Below Dillon, Co.	transbasin out	852	3339	17	E	permeable metamorphic	Mountain	75	648	1037	196
Blue River Below Green Mountain Reservoir, Co	transbasin out	1495	3209	17	NE	permeable metamorphic	Mountain	72	635	1066	241
Blue River Near Dillon, Co	transbasin out	320	3351	17	NE	permeable metamorphic	Mountain	75	653	1036	252
Blue River At Highway 9 Bridge Below Breckenridge	transbasin out	209	3411	17	NE	permeable sedimentary	Mountain	77	697	1034	256
Bobtail Creek Near Jones Pass, Co	natural	16	3598	25	NW	intrusive	Mountain	86	704	966	561
South Boulder Creek Below Gross Reservoir	transbasin in	242	2848	15	NE	permeable metamorphic	Mountain	64	687	1126	463
South Boulder Creek Near Eldorado Springs, Co.	transbasin in	288	2753	15	E	permeable metamorphic	Plains	60	663	1144	157
Boulder Creek At Mouth Near Longmont, Co	transbasin in	1184	2283	11	E	permeable sedimentary	Plains	44	581	1271	63
Middle Boulder Creek At Nederland, Co.	within basin modification	95	3154	18	S	permeable metamorphic	Mountain	76	900	1059	500
Boulder Creek At North 75th St. Near Boulder, Co	transbasin in	800	2558	14	E	permeable metamorphic	Plains	53	657	1220	95
Boulder Creek Near Orodell, Co.	within basin modification	266	2895	16	SE	intrusive	Mountain	65	771	1144	245
Booth Creek Near Minturn, Co.	within basin modification	16	3308	26	SE	intrusive	Mountain	83	755	1038	590
Big Thompson River At Estes Park, Co.	within basin modification	355	3084	21	NE	intrusive	Mountain	66	846	1060	312
Big Thompson River Near Estes Park, Co.	transbasin in	419	3005	19	NE	intrusive	Mountain	62	783	1075	203
Big Thompson Bl Moraine Park Nr Estes Park, Co	natural	105	3236	22	NE	intrusive	Mountain	72	967	1012	454

GAGE NAME	TYPE	AREA (km^2)	MEAN ELEVATION (m)	MEAN SLOPE (%)	DOMINANT ASPECT	GEOLOGY	HYDROLOGIC REGION	MA SP (%)	MA P (mm)	MA PET (mm)	MA Q (mm)
Buckhorn Creek Near Masonville, Co	within basin modification	352	2254	15	NE	permeable metamorphic	Plains	37	510	1154	24
Cabin Creek Near Fraser, Co.	natural	12	3314	22	W	intrusive	Mountain	79	1002	1004	394
Crooked Arroyo Near Swink, Co.	within basin modification	268	1367	1	NE	modern alluvium/colluvium	Plains	15	357	1486	37
Carnero Creek Near La Garita, Co.	within basin modification	273	3064	14	NE	volcanic	Rio Grande	46	570	1104	29
Clear Creek Above Clear Creek Reservoir, Co.	natural	174	3552	24	SE	intrusive	Mountain	74	738	1016	313
Clear Creek Below Clear Creek Reservoir	within basin modification	178	3533	24	SE	intrusive	Mountain	73	738	1018	275
Cement Creek At Silverton, Co	natural	52	3487	26	W	volcanic	Southwest	78	975	1053	612
Chalk Creek At Nathrop	within basin modification	215	3467	23	E	intrusive	Mountain	69	709	1035	171
Wild Cherry Creek Near Crestone	natural	15	3378	26	SW	permeable sedimentary	Rio Grande	54	786	964	138
Cherry Creek At Denver, Co.	within basin modification	1057	1986	4	W	permeable sedimentary	Plains	29	484	1337	34
Cheyenne Creek At Evans Ave At Colorado Springs,Co	within basin modification	56	2706	23	E	intrusive	Plains	44	518	1156	81
Cherry Creek Near Franktown, Co.	within basin modification	436	2161	4	NW	permeable sedimentary	Plains	35	508	1271	15
Cherry Creek Near Parker, Co	transbasin out	746	2067	4	NW	permeable sedimentary	Plains	32	494	1306	14
Cochetopa Creek Below Rock Creek Near Parlin, Co	within basin modification	864	3108	11	E	volcanic	Mountain	56	452	1097	35
Cimarron River Near Cimarron, Co	transbasin in	173	3310	23	W	volcanic	Mountain	77	758	1074	466
North Fork Cache La Poudre River At Livermore, Co	transbasin in	1399	2385	10	SE	intrusive	Plains	41	470	1269	41
Clear Creek At Derby	transbasin in	1475	2717	17	E	permeable metamorphic	Plains	50	591	1131	61
Clear Creek At Golden, Co	transbasin in	1020	3033	20	SE	permeable metamorphic	Plains	59	639	1057	161
Clear Creek Near Lawson, Co	transbasin in	380	3408	23	SE	intrusive	Mountain	73	738	985	316

GAGE NAME	TYPE	AREA (km^2)	MEAN ELEVATION (m)	MEAN SLOPE (%)	DOMINANT ASPECT	GEOLOGY	HYDROLOGIC REGION	MA SP (%)	MA P (mm)	MA PET (mm)	MA Q (mm)
Clear Creek Abv West Fork Clear Creek Nr Empire Co	within basin modification	220	3460	23	E	permeable metamorphic	Mountain	74	699	980	318
Cottonwood Creek Near Buena Vista	within basin modification	305	3273	19	E	intrusive	Mountain	63	605	1112	77
Cottonwood Creek Near Crestone, Co.	natural	18	3481	31	S	permeable sedimentary	Rio Grande	63	985	915	285
Cotton Creek Near Mineral Hot Springs, Co.	within basin modification	35	3433	27	SW	permeable sedimentary	Rio Grande	62	931	954	261
Cottonwood Creek At Mouth At Pikeview, Co	urban	49	2107	3	SW	permeable sedimentary	Plains	19	468	1281	138
Cottonwood Creek At Woodmen Rd Nr Colo Springs, Co	urban	27	2170	3	S	permeable sedimentary	Plains	22	503	1267	73
Colorado River Below Baker Gulch Nr Grand Lake, Co	transbasin out	163	3211	19	E	permeable metamorphic	Mountain	78	813	999	376
Conejos River Near Mogote, Co.	within basin modification	730	3195	14	E	volcanic	Rio Grande	67	867	1142	321
Conejos River Below Platoro Reservoir, Co.	within basin modification	106	3432	18	S	volcanic	Rio Grande	80	1021	1059	703
Corral Gulch Near Rangely, Co	natural	82	2298	13	SE	permeable sedimentary	Northwest	40	449	1272	6
Cucharas River At Boyd Ranch, Near La Veta, Co.	within basin modification	137	3013	18	E	permeable sedimentary	Rio Grande	57	606	1127	121
Cucharas River At Harrison Bridge Near La Veta, Co	within basin modification	511	2654	14	E	permeable sedimentary	Plains	46	507	1199	36
Cross Creek Near Minturn, Co	within basin modification	89	3407	23	SE	permeable metamorphic	Mountain	81	791	1042	509
Crystal River Abv Avalanche Crk, Near Redstone, Co	natural	433	3098	24	SW	permeable sedimentary	Mountain	72	976	1079	560
Culebra Creek At San Luis, Co	within basin modification	650	2985	13	NW	impermeable sedimentary	Rio Grande	50	505	1128	53
Dallas Creek Near Ridgway, Co	within basin modification	252	2793	14	NE	impermeable sedimentary	Southwest	55	586	1125	108
Dolores River At Dolores, Co.	transbasin in	1307	2955	16	W	permeable sedimentary	Southwest	62	747	1158	228
Dolores River Below Rico, Co.	natural	274	3239	19	W	permeable sedimentary	Southwest	71	859	1070	373

GAGE NAME	TYPE	AREA (km^2)	MEAN ELEVATION (m)	MEAN SLOPE (%)	DOMINANT ASPECT	GEOLOGY	HYDROLOGIC REGION	MA SP (%)	MA P (mm)	MA PET (mm)	MA Q (mm)
Eagle River Near Minturn, Co	transbasin out	479	3258	18	NW	permeable metamorphic	Mountain	76	701	1074	237
Eagle River At Red Cliff, Co.	transbasin out	195	3290	16	W	permeable sedimentary	Mountain	75	675	1067	167
East River At Almont, Co	within basin modification	749	3130	18	SW	permeable sedimentary	Mountain	70	829	1051	343
East River Below Cement Creek Nr Crested Butte, Co	within basin modification	638	3197	19	SW	permeable sedimentary	Mountain	73	876	1044	401
Elkhead Creek Above Long Gulch, Near Hayden, Co	within basin modification	444	2421	10	W	impermeable sedimentary	Northwest	59	674	1103	202
Elk River Near Milner, Co.	within basin modification	1162	2641	13	S	permeable metamorphic	Northwest	66	926	1143	392
East Rifle Creek Above Rifle Gap Reservoir	within basin modification	134	2439	16	S	permeable sedimentary	Northwest	48	564	1250	139
First Cr Bel Buckley Rd, At Rocky Mtn Arsenal, Co	urban	73	1694	1	W	modern alluvium/colluvium	Plains	20	432	1366	28
Fish Cr At Upper Sta Nr Steamboat Springs, Co	within basin modification	68	2957	12	NW	permeable metamorphic	Mountain	83	1332	1074	847
Florida River Above Lemon Reservoir Near Durango	natural	136	3337	17	W	intrusive	Southwest	73	870	1079	453
Florida River Below Lemon Reservoir	within basin modification	177	3225	17	W	intrusive	Southwest	69	843	1090	392
Florida River At Bondad, Co.	transbasin in	572	2531	11	S	permeable sedimentary	Southwest	42	585	1253	75
Fountain Creek At Colorado Springs, Co	transbasin in	1018	2430	12	E	intrusive	Plains	33	504	1225	64
Fountain Cr Blw Janitell Rd Blw Colo. Springs, Co	transbasin in	1072	2402	12	E	intrusive	Plains	32	499	1231	100
Fountain Creek Near Colorado Springs, Co.	within basin modification	264	2773	18	E	intrusive	Plains	43	530	1139	53
Fountain Creek At Security, Co	transbasin in	1317	2320	10	S	intrusive	Plains	29	488	1247	97
Fourmile Creek Below Cripple Creek Near Victor, Co	within basin modification	703	2714	12	E	intrusive	Mountain	36	402	1189	19
Fraser River At Upper Sta, Near Winter Park, Co.	transbasin out	27	3424	21	E	intrusive	Mountain	81	891	990	431
Fraser River At Winter Park, Co.	transbasin out	72	3289	20	W	permeable metamorphic	Mountain	79	829	1015	237

GAGE NAME	TYPE	AREA (km^2)	MEAN ELEVATION (m)	MEAN SLOPE (%)	DOMINANT ASPECT	GEOLOGY	HYDROLOGIC REGION	MA SP (%)	MA P (mm)	MA PET (mm)	MA Q (mm)
Fryingpan River At Meredith, Co.	transbasin out	491	3220	20	W	permeable metamorphic	Mountain	75	733	1052	240
North Fork Fryingpan River Near Norrie, Co.	within basin modification	108	3211	19	SW	permeable metamorphic	Mountain	76	718	1049	254
Fryingpan River Near Ruedi, Co.	transbasin out	613	3166	20	W	permeable metamorphic	Mountain	73	715	1059	226
Fryingpan River Near Thomasville, Co.	transbasin out	345	3294	20	W	intrusive	Mountain	78	761	1045	239
Garner Creek Near Villa Grove	natural	14	3314	28	S	permeable sedimentary	Rio Grande	55	896	961	123
Goose Creek At Wagonwheel Gap, Co.	within basin modification	236	3272	18	E	impermeable metamorphic	Rio Grande	63	774	1121	223
Gore Creek At Mouth Near Minturn, Co	within basin modification	263	3136	20	SW	permeable sedimentary	Mountain	74	727	1083	434
Gore Creek Abv Red Sandstone Creek At Vail, Co	within basin modification	199	3205	21	SW	permeable sedimentary	Mountain	77	747	1062	499
Gore Creek At Upper Station, Near Minturn, Co.	natural	38	3387	24	S	intrusive	Mountain	82	789	1029	652
Grape Creek Near Westcliffe, Co.	within basin modification	875	2800	10	NE	impermeable sedimentary	Plains	47	502	1182	28
Halfmoon Creek Near Malta, Co	natural	61	3644	24	SE	permeable metamorphic	Mountain	79	908	1005	397
Hay Gulch Above Red Mesa Ward Reservoir	transbasin in	73	2321	10	S	permeable sedimentary	Southwest	31	431	1278	20
Homestake Creek At Gold Park, Co.	transbasin out	95	3437	21	NW	permeable metamorphic	Mountain	84	807	1027	262
Hunter Creek Near Aspen, Co	transbasin out	110	3303	18	SW	intrusive	Mountain	78	755	1029	265
Huerfano R At Manzanares Xing, Nr Redwing, Co.	within basin modification	196	3066	16	E	permeable metamorphic	Rio Grande	55	523	1161	106
Jimmy Camp Creek At Fountain, Co.	within basin modification	169	1845	3	SW	impermeable sedimentary	Plains	9	384	1336	11
Joe Wright Creek Below Joe Wright Reservoir, Co	transbasin in	18	3231	14	NW	permeable metamorphic	Mountain	83	1040	964	793
Joe Wright Creek Above Joe Wright Reservoir, Co	transbasin in	9	3289	16	E	permeable metamorphic	Mountain	83	1016	964	988
Kerber Cr Abv Little Kerber Cr Nr Villa Grove, Co	within basin modification	118	3170	18	S	volcanic	Rio Grande	55	560	1121	69

GAGE NAME	TYPE	AREA (km²)	MEAN ELEVATION (m)	MEAN SLOPE (%)	DOMINANT ASPECT	GEOLOGY	HYDROLOGIC REGION	MA SP (%)	MA P (mm)	MA PET (mm)	MA Q (mm)
Keystone Gulch Near Dillon, Co.	natural	24	3314	19	W	permeable metamorphic	Mountain	75	568	991	225
La Garita Creek Near La Garita, Co	natural	161	3129	14	E	volcanic	Rio Grande	50	622	1063	62
La Jara Creek At Gallegos Ranch, Nr Capulin, Co.	within basin modification	267	2989	9	E	volcanic	Rio Grande	55	655	1223	41
Lake Creek Above Twin Lakes Reservoir, Co.	transbasin in	190	3618	24	E	intrusive	Mountain	79	739	970	835
Lake Creek Below Twin Lakes Reservoir	transbasin in	272	3519	22	E	intrusive	Mountain	75	676	1004	604
Lake Fork At Gateview, Co.	within basin modification	879	3318	21	E	volcanic	Mountain	65	643	1090	213
Lake Creek Near Edwards, Co	within basin modification	121	3143	23	E	permeable metamorphic	Mountain	75	715	1068	408
La Plata River At Hesperus, Co	within basin modification	84	3127	25	SW	permeable sedimentary	Southwest	64	885	1106	338
La Plata River At Colorado-New Mexico State Line	within basin modification	801	2318	9	S	permeable sedimentary	Southwest	33	452	1278	20
Little Navajo River Below Little Oso Diversion Dam	transbasin out	35	2921	13	W	modern alluvium/colluvium	Southwest	59	735	1103	142
Little Spring Creek At Medano Ranch Near Mosca, Co	natural	180	2821	17	SW	modern alluvium/colluvium	Rio Grande	35	479	1140	8
Long Hollow At The Mouth Near Red Mesa	transbasin in	113	2143	4	S	modern alluvium/colluvium	Southwest	27	364	1321	37
Los Pinos River Near Ignacio, Co	transbasin out	881	3028	20	S	intrusive	Southwest	61	763	1151	111
Los Pinos River At La Boca, Co.	transbasin out	1344	2735	15	S	permeable sedimentary	Southwest	50	652	1207	118
Los Pinos River Near Ortiz	within basin modification	396	3005	11	E	volcanic	Rio Grande	60	785	1135	211
Little Snake River Near Slater, Co	within basin modification	650	2608	12	W	permeable sedimentary	Northwest	66	843	1153	308
Major Creek Near Villa Grove	within basin modification	19	3225	27	S	permeable sedimentary	Rio Grande	51	523	931	45
Mancos River Near Mancos	within basin modification	187	2866	14	SW	impermeable sedimentary	Southwest	57	751	1190	114
Mcelmo Creek Near Colorado-Utah State Line	transbasin in	894	1953	8	SW	permeable sedimentary	Southwest	20	337	1369	40

GAGE NAME	TYPE	AREA (km^2)	MEAN ELEVATION (m)	MEAN SLOPE (%)	DOMINANT ASPECT	GEOLOGY	HYDROLOGIC REGION	MA SP (%)	MA P (mm)	MA PET (mm)	MA Q (mm)
Mcelmo Creek Above Trail Canyon Near Cortez, Co	transbasin in	606	1988	6	SW	permeable sedimentary	Southwest	21	349	1364	65
Mineral Creek At Silverton, Co	within basin modification	136	3508	25	SE	volcanic	Southwest	79	929	1051	619
Michigan River Near Cameron Pass, Co	natural	4	3430	21	E	volcanic	Mountain	84	1057	949	641
West Monument Creek At U.S. Air Force Academy, Co	transbasin in	39	2753	14	E	intrusive	Plains	43	520	1154	59
Monument C Ab N.Gate Blvd At Usaf Academy, Co.	urban	213	2459	11	E	intrusive	Plains	37	534	1215	50
Monument Creek At Pikeview, Co.	transbasin in	529	2324	8	S	permeable sedimentary	Plains	31	504	1255	58
West Monument Creek Below Rampart Reservoir, Co	transbasin in	19	2797	9	SE	intrusive	Plains	46	545	1132	177
Monument Cr Abv Woodmen Rd At Colorado Springs, Co	urban	466	2352	9	S	intrusive	Plains	33	508	1248	50
Mountain Home Reservoir (Outflow)	within basin modification	182	3061	17	W	permeable metamorphic	Rio Grande	53	618	1103	58
Muddy Creek Above Paonia Reservoir	transbasin in	661	2639	13	SW	impermeable sedimentary	Mountain	57	661	1183	153
Muddy Creek Below Paonia Reservoir	within basin modification	665	2636	13	SW	impermeable sedimentary	Mountain	57	661	1183	158
Mud Creek At State Highway 32, Near Cortez, Co.	within basin modification	89	1929	7	NW	impermeable sedimentary	Southwest	19	330	1403	70
Muddy Crk Blw Wolford Mtn Reser. Nr Kremmling, Co	within basin modification	701	2622	9	E	impermeable sedimentary	Mountain	58	562	1131	98
Navajo R At Banded Peak Ranch, Near Chromo, Co.	within basin modification	178	3128	21	W	volcanic	Southwest	69	973	1062	465
Navajo River Bl Oso Diversion Dam Nr Chromo, Co.	transbasin out	252	3006	19	W	volcanic	Southwest	65	850	1083	169
North Clear Creek Above Mouth Nr Black Hawk, Co	within basin modification	156	2790	16	SE	permeable metamorphic	Mountain	50	582	1107	75
North Clear Creek Bl Continental Reservoir, Co.	within basin modification	132	3463	11	SE	volcanic	Rio Grande	70	775	1098	185

GAGE NAME	TYPE	AREA (km^2)	MEAN ELEVATION (m)	MEAN SLOPE (%)	DOMINANT ASPECT	GEOLOGY	HYDROLOGIC REGION	MA SP (%)	MA P (mm)	MA PET (mm)	MA Q (mm)
North Fork Gunnison River Near Somerset, Co.	transbasin in	1363	2709	17	SW	impermeable sedimentary	Northwest	60	687	1169	257
N Fk Cache La Poudre R Blw Halligan Res Nr Va Dale	transbasin in	917	2470	9	S	intrusive	Plains	46	489	1256	80
North Crestone Creek Near Crestone, Co.	natural	33	3443	30	W	permeable sedimentary	Rio Grande	63	804	917	267
Ohio Creek Above Mouth Nr Gunnison, Co	within basin modification	416	2916	13	SW	modern alluvium/colluvium	Mountain	62	609	1091	140
Piceance Creek Bl Ryan Gulch, Nr Rio Blanco, Co.	within basin modification	1310	2261	14	NW	permeable sedimentary	Northwest	41	430	1278	10
Pine River Below Vallecito Reservoir Near Bayfield	transbasin out	659	3229	22	W	intrusive	Southwest	69	839	1111	449
Pinos Creek Near Del Norte, Co.	within basin modification	179	3213	16	E	volcanic	Rio Grande	61	658	1103	115
Piney River Near State Bridge, Co	within basin modification	242	2962	17	SW	permeable sedimentary	Mountain	69	657	1101	286
South Platte River Below Antero Reservoir	within basin modification	481	3123	10	E	impermeable sedimentary	Mountain	55	522	1147	40
North Fork South Platte River At Grant	transbasin in	328	3355	18	S	permeable metamorphic	Mountain	68	524	988	431
East Plum Cr Abv Haskins Gulch Nr Castle Rock, Co	within basin modification	301	2157	8	E	permeable sedimentary	Plains	34	506	1303	37
Plum Creek Near Sedalia, Co.	within basin modification	711	2150	9	E	permeable sedimentary	Plains	36	512	1315	39
Plum Creek At Titan Road Near Louviers, Co	within basin modification	817	2117	9	E	permeable sedimentary	Plains	35	507	1322	35
Purgatoire River At Madrid, Co.	within basin modification	1307	2558	15	E	permeable sedimentary	Plains	33	517	1261	44
Ranch Creek Near Fraser, Co.	transbasin out	52	3182	16	W	intrusive	Mountain	77	768	1020	231
Rifle Creek Below Rifle Gap Reservoir	within basin modification	354	2431	16	SW	permeable sedimentary	Northwest	45	536	1232	61
Rio Grande At Thirtymile Bridge, Nr Creede, Co.	within basin modification	417	3541	18	SE	volcanic	Rio Grande	74	901	1078	385
Rio Blanco At The Mouth Near Trujillo	within basin modification	433	2725	17	W	permeable sedimentary	Southwest	54	687	1144	97
South Fork Rio Grande At South Fork, Co.	transbasin in	546	3169	16	E	volcanic	Rio Grande	65	818	1117	295

GAGE NAME	TYPE	AREA (km^2)	MEAN ELEVATION (m)	MEAN SLOPE (%)	DOMINANT ASPECT	GEOLOGY	HYDROLOGIC REGION	MA SP (%)	MA P (mm)	MA PET (mm)	MA Q (mm)
Rito Alto Creek Near Crestone	natural	31	3483	27	S	permeable sedimentary	Rio Grande	65	777	909	288
Roaring Fork River Near Aspen, Co.	transbasin out	277	3430	21	W	intrusive	Mountain	80	761	998	249
Roaring Fork River Below Maroon Creek Near Aspen	transbasin out	396	3375	20	SW	intrusive	Mountain	79	760	1012	643
Roaring Fork River Ab Difficult C Nr Aspen, Co.	transbasin out	197	3513	23	W	permeable metamorphic	Mountain	82	769	985	216
Rock Creek Above Fort Carson Reservation, Co.	natural	17	2497	23	SE	intrusive	Plains	32	526	1224	77
San Francisco Creek At Upper Sta. Nr Del Norte, Co	natural	31	3266	18	E	volcanic	Rio Grande	58	767	1108	95
Saguache Creek Near Saguache, Co	natural	1327	3034	12	E	volcanic	Rio Grande	49	481	1151	36
Sand Creek At Mouth Nr Commerce City,Co	urban	489	1760	2	W	permeable sedimentary	Plains	22	453	1382	93
San Isabel Creek Near Crestone	natural	18	3401	28	SE	permeable sedimentary	Rio Grande	63	725	1002	278
Sangre De Cristo Creek Near Fort Garland, Co.	within basin modification	473	2795	13	S	permeable metamorphic	Rio Grande	48	449	1206	25
San Antonio River At Ortiz	within basin modification	301	2849	8	E	modern alluvium/colluvium	Rio Grande	50	558	1121	56
San Juan River At Pagosa Springs, Co	transbasin out	727	2968	19	SW	volcanic	Southwest	64	878	1121	403
Slater Fork Near Slater, Co	within basin modification	388	2558	10	NE	permeable sedimentary	Northwest	62	771	1124	177
St. Louis Creek Near Fraser, Co.	transbasin out	85	3274	19	NW	permeable metamorphic	Mountain	79	706	1016	235
San Miguel River Near Placerville, Co	within basin modification	802	3031	19	W	impermeable sedimentary	Southwest	62	717	1106	233
Snowmass Creek	within basin modification	102	3420	26	E	permeable sedimentary	Mountain	80	1045	1012	547
Spanish Creek Near Crestone	natural	9	3475	30	S	permeable sedimentary	Rio Grande	62	671	938	240
Saint Charles River At Vineland	within basin modification	1228	2035	9	E	impermeable sedimentary	Plains	32	477	1453	24
Straight Cr Blw Laskey Gulch Nr Dillon, Co	transbasin out	48	3370	20	S	permeable metamorphic	Mountain	76	665	1014	279

GAGE NAME	TYPE	AREA (km²)	MEAN ELEVATION (m)	MEAN SLOPE (%)	DOMINANT ASPECT	GEOLOGY	HYDROLOGIC REGION	MA SP (%)	MA P (mm)	MA PET (mm)	MA Q (mm)
St. Vrain Creek Below Longmont, Co.	within basin modification	1089	2293	12	E	intrusive	Plains	43	595	1250	89
St. Vrain Creek At Lyons, Co.	within basin modification	560	2725	17	E	intrusive	Plains	57	748	1149	182
Taylor River At Almont, Co.	within basin modification	1237	3246	16	W	intrusive	Mountain	69	642	1040	197
Taylor River At Taylor Park, Co.	natural	332	3330	14	SW	intrusive	Mountain	74	698	1029	271
Taylor River Below Taylor Park Reservoir, Co.	within basin modification	660	3316	15	SW	glacial	Mountain	72	660	1034	239
Tenmile Creek Bl North Tenmile C, At Frisco, Co.	within basin modification	224	3416	18	E	permeable sedimentary	Mountain	80	744	1045	394
Timpas Creek At Mouth Near Swink, Co.	within basin modification	1317	1486	2	E	impermeable sedimentary	Plains	17	348	1480	36
Tomichi Creek At Sargents, Co	within basin modification	385	3121	16	W	intrusive	Mountain	65	597	1066	132
Trinchera C Ab Mtn Home Re, Nr Fort Garland, Co.	within basin modification	165	3114	19	W	permeable metamorphic	Rio Grande	55	649	1094	66
Trinchera Creek Below Smith Res, Nr Blanca, Co.	transbasin out	1024	2811	12	W	permeable metamorphic	Rio Grande	45	452	1185	8
Trinchera C Ab Turners Ranch, Nr Ft Garland, Co.	natural	137	3197	21	NW	permeable metamorphic	Rio Grande	58	649	1072	111
Uncompahgre River Below Ridgway Reservoir, Co	within basin modification	685	2893	18	NE	volcanic	Southwest	59	658	1142	247
Uncompahgre River At Colona, Co.	transbasin out	1159	2813	17	NE	volcanic	Southwest	56	622	1143	176
Uncompahgre River Near Ridgway, Co.	within basin modification	384	3048	22	NW	volcanic	Southwest	64	739	1143	362
Ute Creek Near Fort Garland, Co	within basin modification	105	3090	16	S	permeable metamorphic	Rio Grande	56	555	1180	149
Vallecito Creek Near Bayfield, Co.	natural	188	3458	27	W	impermeable metamorphic	Southwest	76	923	1050	609
Vasquez Creek At Winter Park, Co	transbasin out	74	3327	18	NW	intrusive	Mountain	79	710	1015	227
West Fork Clear Creek Abv Mouth Nr Empire, Co	transbasin in	149	3373	23	S	intrusive	Mountain	73	802	995	371
Willow Creek Near Crestone	natural	19	3336	26	SW	permeable sedimentary	Rio Grande	56	874	940	206

GAGE NAME	TYPE	AREA (km²)	MEAN ELEVATION (m)	MEAN SLOPE (%)	DOMINANT ASPECT	GEOLOGY	HYDROLOGIC REGION	MA SP (%)	MA P (mm)	MA PET (mm)	MA Q (mm)
Williams Fork Above Darling Creek, Near Leal, Co	transbasin out	92	3386	22	NW	intrusive	Mountain	81	712	1008	380
Williams Fork Below Williams Fork Reservoir, Co	transbasin out	595	2992	16	NE	permeable metamorphic	Mountain	68	590	1077	211
Williams Fork Near Leal, Co.	transbasin out	232	3319	21	NW	permeable metamorphic	Mountain	79	716	1032	385
Williams Fork Near Parshall, Co	transbasin out	479	3088	17	NW	permeable metamorphic	Mountain	71	632	1072	232
Williams Fork Below Steelman Creek, Co.	transbasin out	43	3523	23	NW	intrusive	Mountain	85	705	971	363
Willow Creek Below Willow Creek Reservoir, Co.	within basin modification	347	2900	15	E	permeable sedimentary	Mountain	62	615	1018	93
Yampa River Below Stagecoach Reservoir, Co	transbasin out	583	2708	10	NE	impermeable sedimentary	Mountain	62	647	1129	106
Yampa River Above Stagecoach Reservoir, Co	transbasin out	529	2739	10	NE	impermeable sedimentary	Mountain	62	659	1125	112
Yampa River At Steamboat Springs, Co	unclassified	1460	2675	11	NE	permeable sedimentary	Northwest	64	791	1130	258
Yellow Creek Near White River, Co.	within basin modification	679	2096	10	SE	permeable sedimentary	Northwest	36	381	1304	2

Appendix B: Table of gages and watersheds used in forest disturbance analysis.

DISTURB TYPE	GAGE NAME	TYPE	AREA (km^2)	MEAN ELEVATION (m)	MEAN SLOPE (%)	DOMINANT ASPECT	GEOLOGY	HYDROLOGIC REGION	YEAR OF DISTURBANCE	SEVERITY
FIRE	**Boulder Creek Near Orodell, Co.**	within basin modification	266	2895	16	SE	intrusive	Mountain	1989	2.5
	Big Thompson River At Estes Park, Co.	within basin modification	355	3084	21	NE	intrusive	Mountain	2012	7.6
	Buckhorn Creek Near Masonville, Co	within basin modification	352	2254	15	NE	permeable metamorphic	Plains	2000	10.2
	Elk River Near Milner, Co.	within basin modification	1162	2641	13	S	permeable metamorphic	Northwest	2002	26.1
	Florida River Above Lemon Reservoir Near Durango	natural	136	3337	17	W	intrusive	Southwest	2002	22.7
	Florida River Below Lemon Reservoir	within basin modification	177	3225	17	W	intrusive	Southwest	2002	35.1
	Fountain Creek Near Colorado Springs, Co.	within basin modification	264	2773	18	E	intrusive	Plains	2012	29.2
	Goose Creek At Wagonwheel Gap, Co.	within basin modification	236	3272	18	E	impermeable metamorphic	Rio Grande	2013	82.4
	Little Spring Creek At Medano Ranch Near Mosca, Co	natural	180	2821	17	SW	modern alluvium/colluvium	Rio Grande	2010	25.8
	Mancos River Near Mancos	within basin modification	187	2866	14	SW	impermeable sedimentary	Southwest	2012	4.4
	Mancos River Near Towaoc, Co.	within basin modification	1356	2202	13	W	permeable sedimentary	Southwest	1996	4.7
	Mancos River Near Towaoc, Co.	within basin modification	1356	2202	13	W	permeable sedimentary	Southwest	2000	27.1
	Muddy Creek Above Antelope Creek Nr. Kremmling, Co	natural	376	2647	10	E	impermeable sedimentary	Mountain	2002	6.0
	Muddy Crk Blw Wolford Mtn Reser. Nr Kremmling, Co	within basin modification	701	2622	9	E	impermeable sedimentary	Mountain	2002	3.2
	Purgatoire River At Madrid, Co.	within basin modification	1307	2558	15	E	permeable sedimentary	Plains	2002	16.6
	Rio Blanco At The Mouth Near Trujillo	within basin modification	433	2725	17	W	permeable sedimentary	Southwest	2005	1.9

DISTURB TYPE	GAGE NAME	TYPE	AREA (km^2)	MEAN ELEVATION (m)	MEAN SLOPE (%)	DOMINANT ASPECT	GEOLOGY	HYDROLOGIC REGION	YEAR OF DISTURBANCE	SEVERITY
FIRE	**Sangre De Cristo Creek Near Fort Garland, Co.**	within basin modification	473	2795	13	S	permeable metamorphic	Rio Grande	2006	28.6
	St. Vrain Creek Below Longmont, Co.	within basin modification	1089	2293	12	E	intrusive	Plains	2003	3.1
	Timpas Creek At Mouth Near Swink, Co.	within basin modification	1317	1486	2	E	impermeable sedimentary	Plains	2011	5.5
	Vallecito Creek Near Bayfield, Co.	natural	188	3458	27	W	impermeable metamorphic	Southwest	2003	7.5
BEETLE	**Black Gore Creek Near Minturn, Co.**	natural	32	3261	17	SW	permeable sedimentary	Mountain	2008	17.0
	Middle Creek Near Minturn, Co.	within basin modification	16	3192	19	W	permeable sedimentary	Mountain	2004	11.6
	Alamosa River Below Terrace Reservoir, Co.	within basin modification	296	3282	17	S	volcanic	Rio Grande	2012	27.4
	Alamosa River Above Terrace Reservoir, Co.	natural	275	3316	17	S	volcanic	Rio Grande	2011	30.0
	Beaver Creek Below Beaver Creek Reservoir	within basin modification	125	3243	15	W	volcanic	Rio Grande	2011	52.1
	Big Thompson River At Hillsborough Diversion	within basin modification	1464	2418	16	E	permeable metamorphic	Plains	2009	18.7
	Big Thompson River At Loveland, Co.	within basin modification	1386	2468	16	E	permeable metamorphic	Plains	2009	19.7
	Middle Boulder Creek At Nederland, Co.	within basin modification	95	3154	18	S	permeable metamorphic	Mountain	2006	25.7
	Boulder Creek Near Orodell, Co.	within basin modification	266	2895	16	SE	intrusive	Mountain	2007	17.9
	Booth Creek Near Minturn, Co.	within basin modification	16	3308	26	SE	intrusive	Mountain	2006	7.9
	Big Thompson River At Estes Park, Co.	within basin modification	355	3084	21	NE	intrusive	Mountain	2006	30.4
	Big Thompson Bl Moraine Park Nr Estes Park, Co	natural	105	3236	22	NE	intrusive	Mountain	2006	31.8
	Cabin Creek Near Fraser, Co.	natural	12	3314	22	W	intrusive	Mountain	2008	4.4

DISTURB TYPE	GAGE NAME	TYPE	AREA (km^2)	MEAN ELEVATION (m)	MEAN SLOPE (%)	DOMINANT ASPECT	GEOLOGY	HYDROLOGIC REGION	YEAR OF DISTURBANCE	SEVERITY
BEETLE	**Carnero Creek Near La Garita, Co.**	within basin modification	273	3064	14	NE	volcanic	Rio Grande	2012	6.1
	Cochetopa Creek Below Rock Creek Near Parlin, Co	within basin modification	864	3108	11	E	volcanic	Mountain	2012	7.1
	Clear Creek Abv West Fork Clear Creek Nr Empire Co	within basin modification	220	3460	23	E	permeable metamorphic	Mountain	2007	10.7
	Conejos River Near Mogote, Co.	within basin modification	730	3195	14	E	volcanic	Rio Grande	2012	26.1
	Conejos River Below Platoro Reservoir, Co.	within basin modification	106	3432	18	S	volcanic	Rio Grande	2012	37.9
	Elk River Near Milner, Co.	within basin modification	1162	2641	13	S	permeable metamorphic	Northwest	2002	12.6
	Fish Cr At Upper Sta Nr Steamboat Springs, Co	within basin modification	68	2957	12	NW	permeable metamorphic	Mountain	2002	15.8
	North Fork Fryingpan River Near Norrie, Co.	within basin modification	108	3211	19	SW	permeable metamorphic	Mountain	2007	5.2
	Goose Creek At Wagonwheel Gap, Co.	within basin modification	236	3272	18	E	impermeable metamorphic	Rio Grande	2005	13.2
	Gore Creek At Mouth Near Minturn, Co	within basin modification	263	3136	20	SW	permeable sedimentary	Mountain	2004	15.0
	Gore Creek Abv Red Sandstone Creek At Vail, Co	within basin modification	199	3205	21	SW	permeable sedimentary	Mountain	2006	14.4
	Gore Creek At Upper Station, Near Minturn, Co.	natural	38	3387	24	S	intrusive	Mountain	2008	8.7
	Keystone Gulch Near Dillon, Co.	natural	24	3314	19	W	permeable metamorphic	Mountain	2008	14.9
	La Garita Creek Near La Garita, Co	natural	161	3129	14	E	volcanic	Rio Grande	2012	13.3
	Lake Creek Near Edwards, Co	within basin modification	121	3143	23	E	permeable metamorphic	Mountain	2010	5.3
	La Plata River At Colorado-New Mexico State Line	within basin modification	801	2318	9	S	permeable sedimentary	Southwest	2003	3.2

DISTURB TYPE	GAGE NAME	TYPE	AREA (km^2)	MEAN ELEVATION (m)	MEAN SLOPE (%)	DOMINANT ASPECT	GEOLOGY	HYDROLOGIC REGION	YEAR OF DISTURBANCE	SEVERITY
BEETLE	**Los Pinos River Near Ortiz**	within basin modification	396	3005	11	E	volcanic	Rio Grande	2011	16.4
	Little Snake River Near Slater, Co	within basin modification	650	2608	12	W	permeable sedimentary	Northwest	2006	15.2
	Michigan River Near Cameron Pass, Co	natural	4	3430	21	E	volcanic	Mountain	2012	2.9
	Muddy Creek Above Antelope Creek Nr. Kremmling, Co	natural	376	2647	10	E	impermeable sedimentary	Mountain	2007	7.3
	Mud Creek At State Highway 32, Near Cortez, Co.	within basin modification	89	1929	7	NW	impermeable sedimentary	Southwest	2003	3.0
	Muddy Crk Blw Wolford Mtn Reser. Nr Kremmling, Co	within basin modification	701	2622	9	E	impermeable sedimentary	Mountain	2007	8.3
	Navajo R At Banded Peak Ranch, Near Chromo, Co.	within basin modification	178	3128	21	W	volcanic	Southwest	2013	17.2
	North Clear Creek Above Mouth Nr Black Hawk, Co	within basin modification	156	2790	16	SE	permeable metamorphic	Mountain	2008	12.2
	North Clear Creek Bl Continental Reservoir, Co.	within basin modification	132	3463	11	SE	volcanic	Rio Grande	2011	23.0
	Piney River Near State Bridge, Co	within basin modification	242	2962	17	SW	permeable sedimentary	Mountain	2006	10.6
	Rio Grande At Thirtymile Bridge, Nr Creede, Co.	within basin modification	417	3541	18	SE	volcanic	Rio Grande	2005	19.6
	San Francisco Creek At Upper Sta. Nr Del Norte, Co	natural	31	3266	18	E	volcanic	Rio Grande	2012	9.5
	Saguache Creek Near Saguache, Co	natural	1327	3034	12	E	volcanic	Rio Grande	2012	10.9
	Slater Fork Near Slater, Co	within basin modification	388	2558	10	NE	permeable sedimentary	Northwest	2008	6.6
	Snowmass Creek	within basin modification	102	3420	26	E	permeable sedimentary	Mountain	2010	5.8

DISTURB TYPE	GAGE NAME	TYPE	AREA (km^2)	MEAN ELEVATION (m)	MEAN SLOPE (%)	DOMINANT ASPECT	GEOLOGY	HYDROLOGIC REGION	YEAR OF DISTURBANCE	SEVERITY
BEETLE	**St. Vrain Creek Below Longmont, Co.**	within basin modification	1089	2293	12	E	intrusive	Plains	2008	8.7
	St. Vrain Creek At Lyons, Co.	within basin modification	560	2725	17	E	intrusive	Plains	2008	14.8
	Tenmile Creek Bl North Tenmile C, At Frisco, Co.	within basin modification	224	3416	18	E	permeable sedimentary	Mountain	2009	6.5
	Uncompahgre River Below Ridgway Reservoir, Co	within basin modification	685	2893	18	NE	volcanic	Southwest	2013	5.0
	Uncompahgre River Near Ridgway, Co.	within basin modification	384	3048	22	NW	volcanic	Southwest	2013	7.9
	Vallecito Creek Near Bayfield, Co.	natural	188	3458	27	W	impermeable metamorphic	Southwest	2013	16.8
	Willow Creek Below Willow Creek Reservoir, Co.	within basin modification	347	2900	15	E	permeable sedimentary	Mountain	2005	21.4
	La Jara Creek At Gallegos Ranch, Nr Capulin, Co.	within basin modification	267	2989	9	E	volcanic	Rio Grande	2013	8.5
	Pinos Creek Near Del Norte, Co.	within basin modification	179	3213	16	E	volcanic	Rio Grande	2012	35.9

Appendix C: Tables of coefficients for categorical variables used in streamflow prediction models.

Table C1: Coefficients for Dominant Aspect. Reference group is *E*. If a watershed falls in E, no aspect adjustment is needed for β_0. If a watershed falls in any other aspect category, add the coefficient value to β_0.

y-var	*NE*	*NW*	*S*	*SE*	*SW*	*W*
Q_{ann}	0.712	1.761	2.128	0.495	1.262	0.764
Q_{jan}	-0.027	0.041	0.041	-0.584	0.101	0.071
Q_{feb}	-0.018	0.093	0.071	-0.496	0.153	0.079
Q_{mar}	0.030	-0.128	0.111	-0.453	0.283	0.134
Q_{apr}	0.139	-0.529	0.453	-0.069	0.804	0.333
Q_{may}						
Q_{jun}	0.451	1.933	1.451	0.594	0.640	0.404
Q_{jul}	0.706	1.097	0.981	0.632	0.215	0.023
Q_{aug}						
Q_{sep}						
Q_{oct}						
Q_{nov}	0.068	0.135	0.252	-0.398	0.046	0.135
Q_{dec}	0.013	0.112	0.165	-0.526	0.114	0.110

Table C2: Coefficients for Hydrologic Region. Reference group is *Mountain*. If a watershed falls in the Mountain region, no adjustment is needed for β_0. If a watershed falls in any other hydrologic region, add the coefficient value to β_0.

y-var	*Northwest*	*Plains*	*Rio Grande*	*Southwest*
Q_{ann}	-1.865	0.579	-1.681	0.018
Q_{jan}	-0.113	-0.104	-0.311	0.150
Q_{feb}	-0.048	-0.032	-0.204	0.330
Q_{mar}	0.237	0.090	-0.083	0.733
Q_{apr}	1.095	1.004	0.665	1.467
Q_{may}				
Q_{jun}	-2.349	-0.280	-2.125	-1.709
Q_{jul}	-2.385	-0.604	-1.506	-1.041
Q_{aug}	-1.101	-0.256	-0.174	0.221
Q_{sep}	-0.575	0.088	-0.031	0.605
Q_{oct}	-0.317	0.217	0.180	0.629
Q_{nov}	-0.335	-0.121	-0.385	0.082
Q_{dec}	-0.212	-0.097	-0.357	0.102

Table C3: Coefficients for Dominant Geology. Reference group is *glacial*. If a watershed falls in the glacial category, no geology adjustment is needed for β_0. If a watershed falls in any other category, add the coefficient value to β_0.

y-var	*Impermeable metamorphic*	*Impermeable sedimentary*	*Intrusive*	*Modern alluvium/ colluvium*	*Permeable metamorphic*	*Permeable sedimentary*	*Volcanic*
Q_{ann}							
Q_{jan}							
Q_{feb}							
Q_{mar}							
Q_{apr}							
Q_{may}							
Q_{jun}							
Q_{jul}							
Q_{aug}	-2.281	-1.936	-2.255	-2.135	-2.704	-2.614	-2.366
Q_{sep}	-1.691	-2.053	-2.045	-2.141	-2.513	-2.491	-2.229
Q_{oct}							
Q_{nov}							
Q_{dec}							