Streamflow prediction in Colorado ungauged basins

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Abstract

This report tests three different methods for predicting streamflow at ungauged basins in Colorado: the USGS regional regression equations, new empirical regression equations, and the Variable Infiltration Capacity (VIC) hydrologic model. Streamflow data were compiled for 222 stations across the state, and these were converted to mean annual and mean monthly flows for two time periods: 1981-2018 and 2001-2018. The same streamflow metrics were extracted from daily simulations of streamflow in the VIC model. For the drainage area contributing to each watershed, variables related to topography, geology, and climate were computed. These were used as independent variables in new regression models that predict each of the streamflow metrics. For each streamflow metric, all three model results were compared to observed streamflow for 1981-2018, 2001-2018, and for each decade from 1930-2010. Results show that all models have comparable performance for predicting mean annual discharge, with the strongest performance from a new empirical model that incorporates mean annual snow persistence. For mean monthly discharge, new empirical models have the most consistent performance across months and usually stronger performance than the USGS regression models. When the regression models were tested against observed flow from earlier decades, the new models performed best for mean annual flow and for snowmelt runoff months of April-June. The USGS regression models performed best for winter flows, and both the new regressions and USGS models had comparable performance for fall flows. While the uncalibrated VIC model was not as accurate as the regression models for streamflow prediction, it still performed relatively well, especially for mean annual flow. Because this simulates physical processes, it is useful for exploring causes for differences in streamflow patterns across the state.

1. Introduction and Background

Colorado is a hydrologically diverse state, with climates ranging from arid to humid, vegetation ranging from grasslands to forests, and bedrock geology of all types. This diverse climate and landscape produces variable amounts and timing of streamflow, including snowmelt-dominated streamflow from the high elevations and rainfall-dominated streamflow at low elevations. While the existing stream gauging network in Colorado is extensive, water managers often need to know streamflow conditions in ungauged streams. The goal of this study is to test both existing and newly developed methods for streamflow prediction for ungauged Colorado streams.

The most widely used method for ungauged streamflow prediction is the regional regression approach in which attributes of watersheds such as area and slope are related to streamflow variables. For Colorado, the United States Geological Survey (USGS) developed regional regression equations for peak streamflow at eight different return intervals; 7-day minimum and maximum streamflow at 2-, 10-, and 50-year return intervals; mean annual and mean monthly streamflow, and five separate quantiles of the flow duration curve (Capesius and Stephens 2009). Equations were developed separately for five hydrologic regions: Northwest, Southwest, Rio Grande, Mountain, and Plains. The study used generalized least squares regression trained to observed streamflow with six independent variables related to watershed elevation, slope, and precipitation. Data for model development came from 422 USGS stations with at least ten years of streamflow data on stations identified as having "natural" streamflow conditions, meaning the streamflow had not been extensively modified by reservoirs or flow diversions. A few years following the release of the USGS regional regressions for Colorado, Kohn et al. (2015) conducted a validation study for the mean monthly streamflow regression equations. They selected 278 of the stations originally used in Capesius and Stephens (2009) and 154 additional stream gauges, using the same selection criteria of at least ten years of data and "natural" streamflow conditions. Tests of the regional regression equations on these stations gave adjusted R^2 values ranging from 0.44-0.89; the original Capesius and Stephens (2009) reported pseudo R^2 values from 0.39-0.95.

One potential approach for improving ungauged streamflow prediction in Colorado is adding additional independent variables to regression or other statistical models. Streamflow in Colorado is highly dependent on snow, and prior research has identified a high correlation between snow persistence and annual streamflow in arid and semiarid watersheds (Hammond et al. 2018). Snow persistence (SP) is defined as the fraction of time with snow cover present between January and June (Moore et al. 2015), and it can be derived for any watershed using snow cover data from the MODIS satellite sensor (Hammond et al. 2017). Snow persistence could therefore be a useful independent variable for regression equations predicting ungauged streamflow. Another independent variable that may relate to streamflow is potential evapotranspiration (PET), which is available from gridded datasets (gridMET; Abatzoglou, 2013). This indicates the potential loss of water to the atmosphere before becoming streamflow. Researchers have also used climate indices, temperature, pan evaporation, and soil moisture in streamflow predictions (Georgakakos et al. 1998; Sankarasubramanian and Lall 2003; Werner et al. 2004; Cherry et al. 2005; Woodhouse et al. 2016; Harpold et al. 2017). Bedrock geology, soils, and vegetation types can also influence streamflow and could be incorporated as additional independent variables for ungauged streamflow prediction.

Physically-based hydrologic models simulate how climate, land cover, and soils interact to affect streamflow generation. In contrast to regression equations, which each simulate a single streamflow metric such as mean annual flow, hydrologic models conduct continuous simulation of the water cycle at daily or finer time steps. These types of models are useful for exploring how changes in watersheds such as climate or land use change may affect streamflow. One hydrologic model that is commonly used to examine impacts of changing climate on streamflow is the Variable Infiltration Capacity (VIC) model (Liang et al. 1994). This is a fully distributed model that simulates streamflow at a daily time step as a function of dynamic meteorological inputs: precipitation, minimum and maximum temperature, windspeed, as well as static or seasonally varying inputs of vegetation, soil, and topography. Relatively recently, VIC was applied over the continental US to simulate streamflow and other hydrologic states and fluxes for the period 1950-2013 by Livneh et al. (2015). The model has also been widely used for both streamflow forecasting and to estimate impacts of changing climate on future streamflow (Christensen et al. 2004; McGuire et al. 2006, Shi et al. 2008; Tang and Lettenmaier 2010; Vano et al. 2012).

In this study, we compare three approaches for ungauged streamflow prediction in Colorado: (1) USGS regression equations, (2) new empirical models, and (3) VIC model simulations.

2. Methods

2.1. Data

Observed streamflow data used for evaluating the three methods were compiled from the USGS and Colorado Division of Water Resources (CDWR). Our goal was to focus on relatively small watersheds because larger watersheds tend to be more affected by dams and diversions, and large rivers in the state are already gauged. We therefore selected gauges with drainage areas <1500 km^2 (579 mi^2). Unlike the USGS studies that used any station with ten years or more of data (Capesius and Stephens 2009; Kohn et al. 2015), we chose to use fixed time periods for testing the models. Fixed time periods reduce bias in model evaluation that may be caused by climatic differences across records of different lengths. We focused on two fixed time periods: 1981-2018 and 2001-2018. The time period starting in 1981 represents a wide range of climate conditions in recent decades, and the time period from 2001-2018 corresponds with availability of snow cover data from MODIS (Hall and Riggs, 2016). We selected stations with >75% data availability during these time periods. These two criteria led to a dataset of 223 stream gauges (Table 1, 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 remaining 222 stream gauges in the dataset, we delineated the watershed using the Watershed tool in ArcGIS with the flow direction grids from NHDPlusV2 (USEPA and USGS, 2012). We then identified whether or not dams or diversions were present within each watershed boundary using a shapefile of water right locations from CDWR. We used National

Hydrography Dataset (NHD) flowlines to identify pipes or ditches that cross watershed boundaries; these represent transbasin diversions into or out of watersheds. Based on these analyses, we labeled each station as **natural** (n=38) indicating no water rights within the watershed or transbasin diversions; **within basin modifications** (n=115) indicating water rights within the watershed; **transbasin in** (n=24) indicating transbasin diversions into the watershed, or **transbasin out** (n=37), indicating transbasin diversions out of the watershed. Stations in the transbasin categories also typically have within basin modifications, ie water rights within the watershed. We also separately flagged basins with large fractions of urban land cover (11-56%, n=8), as urban surfaces can substantially change streamflow amounts. Urban land cover was identified using the 2011 National Land Cover Dataset.

Next we extracted attributes for each of the watersheds, as indicated in Table 2. For topography we used the 30m digital elevation model from the National Elevation Dataset to extract mean elevation, mean slope, and dominant aspect. For bedrock geology we used the National Geology Layer from the USGS Mineral Resources Program and determined dominant categories within each watershed. We also extracted watershed level information on soils from STATSGO2 but did not end up using these in any of the models. For climate we extracted mean annual precipitation (P) from PRISM (Daly, 2013; www.prismclimate.org), mean annual PET from GridMET (Abatzoglou 2013), and mean annual SP from Hammond et al. (2017). The Hydrologic Region from Capesius and Stephens (2009) was also identified.

The next step was to derive streamflow metrics for each of the selected stream gauges (Table 3) using observed data. Following Capesius and Stephens (2009), we extracted mean annual and mean monthly flow for each time period of analysis. The same set of streamflow metrics were also derived from daily streamflow simulations from the VIC model. For VIC we used only watersheds greater than 50 km^2 because the course resolution of VIC grid cells (6 km) makes the simulations best suited for larger watersheds.

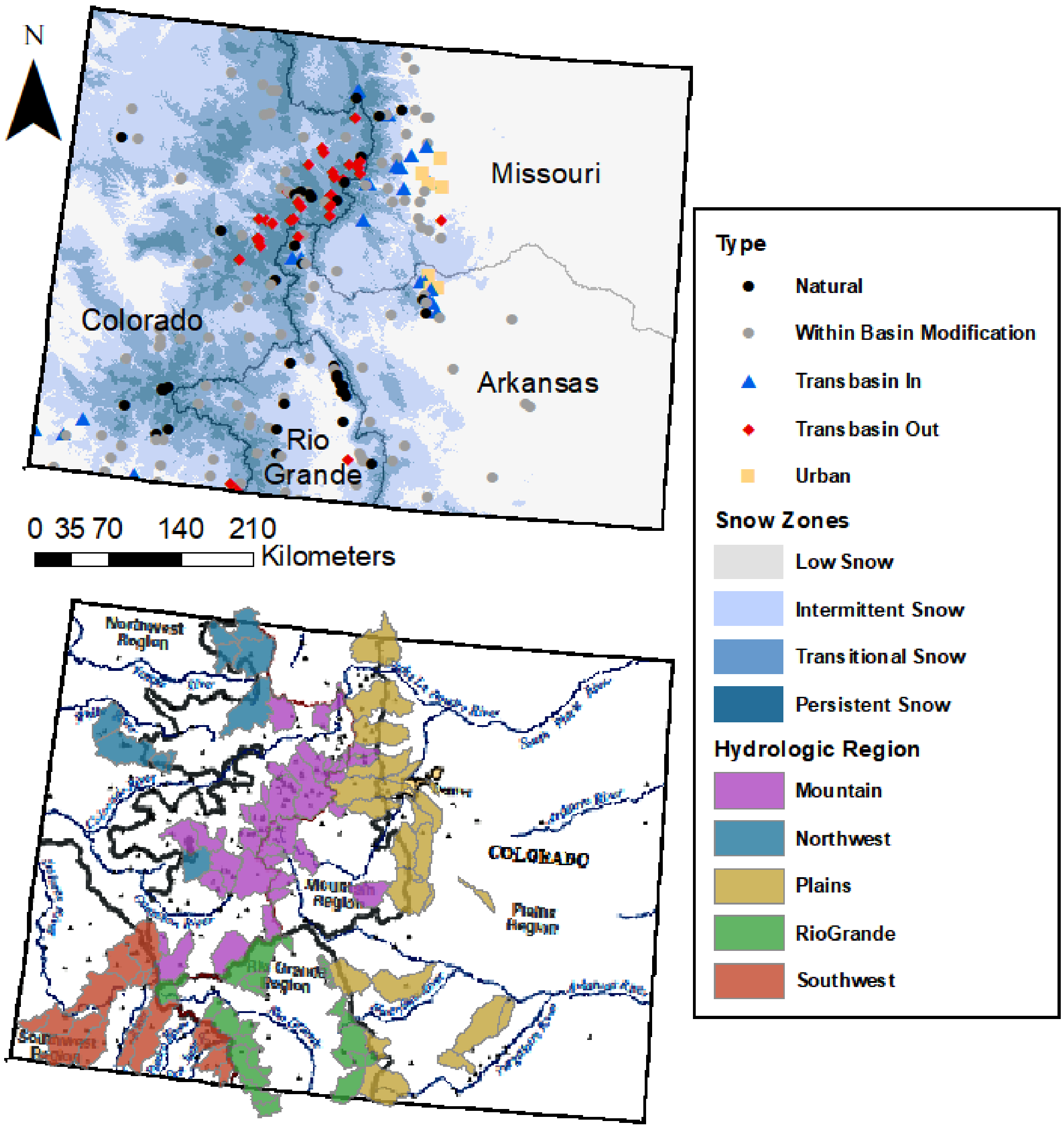


Figure 1. Streamflow gauging station locations (top) and contributing watersheds (bottom) for the dataset used in this study. Top stations are classified by type of flow modification; bottom watersheds are colored by USGS Hydrologic Region. Snow zones in top image are from Moore et al. (2015), where darker blue colors indicate longer time periods of snow cover.

2.2.Model applications

We used each of the existing models to predict values of the watershed variables (Table 3) for each of the two time periods: 1981-2018 and 2001-2018. The USGS regional regression models (Capesius and Stephens 2009) are separate equations for each streamflow metric and hydrologic region. The VIC model predictions are from the Livneh et al. (2015) daily simulations; unlike the regression models, these simulations were not calibrated to match the flow at the individual stream gauging stations.

Finally we developed new empirical models for each of the streamflow metrics and time periods above using multiple linear regression. Unlike the Capesius and Stephens (2009), who presented a separate equation for each hydrologic region, we developed a single empirical model for each streamflow metric using a combination of continuous and categorical predictor variables. The continuous predictors are:

1) Watershed Area (km^2)
2) Mean Annual Snow Persistence (%)
3) Mean Annual Precipitation (mm)
4) Mean Annual Potential Evapotranspiration (PET, mm)
5) Mean Slope (%)\

Elevation was considered as another continuous predictor variable, but it was not used in final models due to high correlation with other variables. The categorical predictors are:

1) Dominant Aspect (8 levels: cardinal directions)
2) Geology Group (8 levels)
3) Hydrologic Region (defined by USGS, 5 levels) (Table 2).

Because the streamflow variables were not-normally distributed, these were first square-root transformed before developing the models. Multiple linear regression models were then applied using the independent variables to predict the square-root transformed streamflow variables. The multiple linear regression model was selected using AIC criteria with the 'car' and 'MuMIN' packages in R (Fox and Weisberg, 2011; Bartón, 2019). 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 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. A k-value of 5 was chosen for the cross validation because this is a reasonable k value for n=77 observations. Cross validation was done using the 'caret' package in R (Kuhn, 2019).

For each comparison of model and observations, we computed the Nash-Sutcliffe Coefficient of Efficiency (NSE), the percent bias (PBIAS), and the adjusted coefficient of determination ($adjR^2$) using the hydroGOF package in R along with base R functions (Zambrano-Bigiarini 2017). Evaluation of each of these models excluded all stations with transbasin diversions and urban land cover because preliminary analysis showed that streamflow for these stations diverged substantially from the regional trends.

2.3. Model testing

Because the models were initially applied to only two recent time periods, we also evaluated whether they were applicable for predicting streamflow in other time periods. We computed mean annual and mean monthly streamflow for each of the gauging stations by decade, starting in the 1930's and continuing until the 2010's. Again we included only stations with >75% data for the time period. Then we compared the USGS regression and new empirical model predictions of mean annual and mean monthly streamflow to each decadal average.

Table 1. Streamflow gauging stations used in this study, including drainage areas, station type, and models that use the station data. Gauge ID's are USGS station numbers where available; ID's with letters are CDWR station IDs. Columns 1981-2018 and 2001-2018 indicates with "x" whether or not sufficient observation data were available for testing models during that time period; VIC column indicates with "x" all stations for which watersheds were large enough to extract VIC model simulations (>50 km^2); USGS columns indicate whether stations were included in Capesius and Stephens (2009) or Kohn et al. (2015).

Gauge ID	Station Name	Type	Area (km^2)	1981-2018	2001-2018	VIC	USGS 2009	USGS 2015
06614800	Michigan River near Cameron Pass	natural	4.0	x	x		x	x
06702500	North Fork South Platte River at Grant	transbasin in	328.3	x	x	x		
06708800	East Plum Creek abv Haskins Gulch nr Castle Rock	within basin modification	300.0		x	x		
06709000	Plum Creek near Sedalia	within basin modification	711.3	x	x	x		
06709530	Plum Creek at Titan Rd near Louviers	within basin modification	817.4	x	x	x		
06710385	Bear Creek above Evergreen	within basin modification	267.4	x	x	x	x	
06710500	Bear Creek at Morrison	within basin modification	426.0	x	x	x		
06711500	Bear Creek at Sheridan	within basin modification	676.0	x	x	x		
06712000	Cherry Creek near Franktown	within basin modification	436.3	x	x	x	x	
06713500	Cherry Creek at Denver	transbasin out	1057.0	x	x	x		
06715000	Clear Creek abv West Fork Clear Creek nr Empire	within basin modification	220.2		x	x		x
06716100	West Fork Clear Creek abv mouth nr Empire	transbasin in	149.1		x	x		x
06716500	Clear Creek near Lawson	transbasin in	379.8	x	x	x	x	x
06718500	North Clear Creek above mouth nr Black Hawk	within basin modification	155.9		x	x		
06719505	Clear Creek at Golden	transbasin in	1020.1	x	x	x		
06720000	Clear Creek at Derby	transbasin in	1475.0	x	x	x		
06720460	First Cr bel Buckley Rd at Rocky Mtn Arsenal	urban	73.3		x	x		
06720820	Big Dry Creek at Westminster	urban	120.9	x	x	x		
06720990	Big Dry Creek at mouth near Fort Lupton	urban	286.4		x	x		
06724000	St. Vrain Creek at Lyons	within basin modification	560.3	x	x	x		
06725450	St. Vrain Creek below Longmont	within basin modification	1089.2	x	x	x		
06725500	Middle Boulder Creek at Nederland	within basin modification	94.7	x	x	x	x	x
06727000	Boulder Creek near Orodell	within basin modification	265.7	x	x	x		
06729450	South Boulder Creek below Gross Reservoir	transbasin in	242.2	x	x	x		
06729500	South Boulder Creek near Eldorado Springs	transbasin in	287.7	x	x	x		
06730200	Boulder Creek at North 75th St near Boulder	transbasin in	799.6	x	x	x		
06730500	Boulder Creek at mouth near Longmont	transbasin in	1184.5	x	x	x		
06733000	Big Thompson River at Estes Park	within basin modification	355.4	x	x	x		x

Gauge ID	Station Name	Type	Area (km^2)	1981-2018	2001-2018	VIC	USGS 2009	USGS 2015
06735500	Big Thompson River near Estes Park	transbasin in	419.0	x	x	x		
06736000	North Fork Big Thompson River at Drake	natural	220.7	x		x		
06739500	Buckhorn Creek near Masonville	within basin modification	351.9		x	x	x	
06741510	Big Thompson River at Loveland	within basin modification	1386.0	x	x	x		
06746095	Joe Wright Creek above Joe Wright Reservoir	transbasin in	8.9	x	x			x
06746110	Joe Wright Creek below Joe Wright Reservoir	transbasin in	18.2	x	x			
06751150	N Fk Cache la Poudre R blw Halligan Res nr VA Dale	within basin modification	917.2		x	x		
06751490	North Fork Cache la Poudre River at Livermore	within basin modification	1399.3	x	x	x		
07079300	EF Arkansas R at US Highway 24, nr Leadville	within basin modification	129.3		x	x		
07081200	Arkansas River near Leadville	within basin modification	254.2	x	x	x		
07082500	Lake Fork Creek blw Sugar Loaf Dam nr Leadville	transbasin out	71.2	x	x	x		
07083000	Halfmoon Creek near Malta, CO	natural	60.8	x	x	x	x	x
07084500	Lake Creek above Twin Lakes Reservoir	transbasin in	189.7	x	x	x		
07085500	Lake Creek below Twin Lakes Reservoir	transbasin in	271.7	x	x	x		
07086000	Arkansas River at Granite	within basin modification	1116.6	x	x	x		
07086500	Clear Creek above Clear Creek Reservoir	natural	174.1	x	x	x		x
07087000	Clear Creek below Clear Creek Reservoir	within basin modification	178.2	x	x	x		
07089250	Cottonwood Creek near Buena Vista	within basin modification	304.7	x	x	x		
07091015	Chalk Creek at Nathrop	within basin modification	214.9	x	x	x		x
07095000	Grape Creek near Westcliffe	within basin modification	875.0	x	x	x	x	
07096250	Fourmile Creek below Cripple Creek near Victor	within basin modification	702.6		x	x		
07103700	Fountain Creek near Colorado Springs	within basin modification	264.2	x	x	x		
07103780	Monument C ab N. Gate Blvd at USAF Academy	urban	213.0	x	x	x		
07103797	West Monument Creek below Rampart Reservoir	transbasin in	18.8		x			
07103800	West Monument Creek at U.S. Air Force Academy	within basin modification	38.5	x	x			
07103970	Monument Cr abv Woodmen Rd nr Colo Springs	urban	466.0		x	x		
07103980	Cottonwood Creek at Woodmen Rd nr Colo Springs	urban	26.5		x			
07103990	Cottonwood Creek at mouth at Pikeview	urban	48.9	x	x			
07104000	Monument Creek at Pikeview	transbasin in	529.2	x	x	x		
07105000	Bear Creek near Colorado Springs	natural	18.1		x			
07105490	Cheyenne Creek at Evans Ave at Colorado Springs	within basin modification	56.4		x	x		
07105500	Fountain Creek at Colorado Springs	transbasin in	1017.9	x	x	x		
07105530	Fountain Cr blw Janitell Rd blw Colo Springs	transbasin in	1072.0	x	x	x		
07105800	Fountain Creek at Security	transbasin in	1316.8	x	x	x		
07105900	Jimmy Camp Creek at Fountain	within basin modification	169.4	x	x	x		
07105945	Rock Creek above Fort Carson Reservation	natural	17.5	x	x		x	
07108900	Saint Charles River at Vineland	within basin modification	1227.7	x	x	x		

Gauge ID	Station Name	Type	Area (km^2)	1981-2018	2001-2018	VIC	USGS 2009	USGS 2015
07111000	Huerfano R at Manzanares Xing nr Redwing	within basin modification	195.5	x	x	x		
07114000	Cucharas River at Boyd Ranch near La Veta	within basin modification	137.3	x	x	x	x	
07114500	Cucharas River at Harrison Bridge near La Veta	within basin modification	511.1		x	x		
07121500	Timpas Creek at mouth near Swink	within basin modification	1317.1	x	x	x	x	
07122400	Crooked Arroyo near Swink	within basin modification	267.9	x	x	x		
07124200	Purgatoire River at Madrid	within basin modification	1306.9	x	x	x		
07126200	Van Bremer Arroyo near Model	within basin modification	420.6	x		x	x	
08213500	Rio Grande at Thirtymile Bridge nr Creede	within basin modification	417.3	x	x	x		
08214500	North Clear Creek bl Contintental Reservoir	within basin modification	131.6	x	x	x		
08218500	Goose Creek at Wagonwheel Gap	within basin modification	235.9	x	x	x	x	x
08219500	South Fork Rio Grande at South Fork	within basin modification	545.9	x	x	x	x	x
08220500	Pinos Creek near Del Norte	within basin modification	178.9	x	x	x	x	x
08220900	San Francisco Creek at upper sta. nr Del Norte	natural	30.7		x			
08224500	Kerber Cr abv Little Kerber Cr nr Villa Grove	within basin modification	118.0		x	x	x	x
08226700	Cotton Creek near Mineral Hot Springs	within basin modification	35.5		x			x
08227000	Saguache Creek near Saguache	natural	1327.3	x	x	x	x	x
08227500	North Crestone Creek near Crestone	natural	33.3	x	x		x	x
08229500	Cottonwood Creek near Crestone	natural	17.5		x			x
08230500	Carnero Creek near La Garita	within basin modification	272.9	x	x	x	x	x
08231000	La Garita Creek near La Garita	natural	161.3	x	x	x	x	x
08236000	Alamosa River above Terrace Reservoir	natural	275.2	x	x	x	x	x
08236500	Alamosa River below Terrace Reservoir	within basin modification	296.5	x	x	x		
08238000	La Jara Creek at Gallegos Ranch nr Capulin	within basin modification	266.5	x	x	x		
08240500	Trinchera C ab Turners Ranch nr Ft Garland	natural	136.9	x	x	x	x	x
08241000	Trinchera C ab Mtn Home Re nr Fort Garland	within basin modification	165.2	x	x	x		
08241500	Sangre de Cristo Creek near Fort Garland	within basin modification	472.6	x	x	x	x	x
08242500	Ute Creek near Fort Garland	within basin modification	104.9	x	x	x	x	x
08243500	Trinchera Creek below Smith Res nr Blanca	transbasin out	1023.8	x	x	x		
08245000	Conejos River below Platoro Reservoir	within basin modification	105.8	x	x	x		
08246500	Conejos River near Mogote	within basin modification	729.7	x	x	x	x	x
08247500	San Antonio River at Ortiz	within basin modification	300.7	x	x	x	x	x
08248000	Los Pinos River near Ortiz	within basin modification	396.1	x	x	x	x	x
08250000	Culebra Creek at San Luis	within basin modification	649.8	x	x	x		
09010500	Colorado River below Baker Gulch nr Grand Lake	transbasin out	163.0	x	x	x		
09021000	Willow Creek below Willow Creek Reservoir	within basin modification	347.2	x	x	x		
09022000	Fraser River at Upper Sta, near Winter Park	transbasin out	27.3	x	x			x
09024000	Fraser River at Winter Park	transbasin out	71.6	x	x	x	x	x

Gauge ID	Station Name	Type	Area (km^2)	1981-2018	2001-2018	VIC	USGS 2009	USGS 2015
09025000	Vasquez Creek at Winter Park	transbasin out	73.8	x	x	x		
09026500	St. Louis Creek near Fraser	transbasin out	85.3	x	x	x	x	x
09032000	Ranch Creek near Fraser	transbasin out	51.8	x	x	x	x	x
09032100	Cabin Creek near Fraser	natural	12.4	x	x			
09034900	Bobtail Creek near Jones Pass	natural	15.6	x	x		x	x
09035500	Williams Fork below Steelman Creek	transbasin out	42.8	x	x		x	x
09035700	Williams Fork above Darling Creek, near Leal	transbasin out	91.5	x	x	x	x	x
09035900	South Fork of Williams Fork near Leal	transbasin out	72.8	x	x	x	x	x
09036000	Williams Fork near Leal	transbasin out	231.9	x	x	x		
09037500	Williams Fork near Parshall	transbasin out	479.5	x	x	x		
09038500	Williams Fork below Williams Fork Reservoir	transbasin out	595.2	x	x	x		
09041400	Muddy Crk blw Wolford Mtn Reser. nr Kremmling	within basin modification	700.9		x	x		
09046490	Blue River at Blue River	transbasin out	110.1	x	x	x		
09046600	Blue River near Dillon	transbasin out	319.6	x	x	x		
09047700	Keystone Gulch near Dillon	natural	23.6	x	x		x	x
09050100	Tenmile Creek bl North Tenmile C at Frisco	within basin modification	224.3	x	x	x	x	x
09050700	Blue River below Dillon	transbasin out	851.6	x	x	x		
09051050	Straight Cr blw Laskey Gulch nr Dillon	transbasin out	48.3	x	x			x
09057500	Blue River below Green Mountain Reservoir	transbasin out	1494.9	x	x	x		
09059500	Piney River near State Bridge	within basin modification	241.8	x	x	x	x	x
09063000	Eagle River at Red Cliff	transbasin out	195.3	x	x	x		
09063900	Missouri Creek near Gold Park	transbasin out	16.8	x	x			x
09064000	Homestake Creek at Gold Park	transbasin out	95.4	x	x	x		
09064600	Eagle River near Minturn	transbasin out	478.8	x	x	x		
09065100	Cross Creek near Minturn	within basin modification	88.7	x	x	x	x	x
09065500	Gore Creek at upper station near Minturn	natural	37.8	x	x		x	x
09066000	Black Gore Creek near Minturn	natural	32.4	x	x		x	x
09066200	Booth Creek near Minturn	within basin modification	16.1	x	x		x	x
09066300	Middle Creek near Minturn	within basin modification	15.5	x	x		x	x
09066325	Gore Creek abv Red Sandstone Creek at Vail	natural	199.2		x	x		x
09066510	Gore Creek at mouth near Minturn	natural	263.4		x	x		x
09067000	Beaver Creek at Avon	within basin modification	38.4	x	x			x
09067020	Eagle R blw wastewater treatment plant at Avon	transbasin out	1052.5		x	x		x
09067200	Lake Creek near Edwards	within basin modification	120.8		x	x		x
09073300	Roaring Fork River ab Difficult C nr Aspen	transbasin out	196.7	x	x	x		
09073400	Roaring Fork River near Aspen	transbasin out	276.9	x	x	x		
09073400	Roaring Fork River below Maroon Creek near Aspen	transbasin out	396.2		x	x		

Gauge ID	Station Name	Type	Area (km^2)	1981-2018	2001-2018	VIC	USGS 2009	USGS 2015
09074000	Hunter Creek near Aspen	transbasin out	109.6	x	x	x	x	x
09077000	Snowmass Creek	within basin modification	102.5		x	x		
09078500	North Fork Fryingpan River near Norrie	within basin modification	107.9	x	x	x	x	x
09078600	Fryingpan River near Thomasville	transbasin out	344.7	x	x	x		
09080100	Fryingpan River at Meredith	transbasin out	490.7	x	x	x		
09080400	Fryingpan River near Ruedi	transbasin out	612.9	x	x	x		
09081600	Crystal River abv Avalanche Crk near Redstone	natural	432.9	x	x	x	x	x
09107000	Taylor River at Taylor Park	natural	331.6	x	x	x	x	x
09109000	Taylor River below Taylor Park Reservoir	within basin modification	659.8	x	x	x		
09110000	Taylor River at Almont	within basin modification	1237.3	x	x	x	x	x
09112200	East River below Cement Creek nr Crested Butte	within basin modification	638.3		x	x		x
09112500	East River at Almont	within basin modification	749.0	x	x	x	x	x
09113980	Ohio Creek above mouth nr Gunnison	within basin modification	415.9		x	x		x
09115500	Tomichi Creek at Sargents	within basin modification	384.9		x	x	x	x
09118450	Cochetopa Creek below Rock Creek near Parlin	within basin modification	864.5	x	x	x		
09124500	Lake Fork at Gateview	within basin modification	879.2	x	x	x	x	x
09126000	Cimarron River near Cimarron	within basin modification	173.2	x	x	x	x	x
09131490	Muddy Creek above Paonia Reservoir	within basin modification	661.2	x	x	x		
09132500	North Fork Gunnison River near Somerset	within basin modification	1362.9	x	x	x	x	x
09146200	Uncompahgre River near Ridgway	within basin modification	384.3	x	x	x		x
09147000	Dallas Creek near Ridgeway	within basin modification	252.1	x	x	x	x	x
09147025	Uncompahgre River below Ridgway Reservoir	within basin modification	685.2	x	x	x		
09147500	Uncompahgre River at Colona	within basin modification	1159.2	x	x	x		x
09165000	Dolores River below Rico	natural	273.5	x	x	x	x	x
09166500	Dolores River at Dolores	transbasin in	1306.9	x	x	x	x	x
09172500	San Miguel River near Placerville	within basin modification	802.0	x	x	x	x	x
09237450	Yampa River above Stagecoach Reservoir	within basin modification	529.2	x	x	x		
09237500	Yampa River below Stagecoach Reservoir	within basin modification	583.0	x	x	x		
09238900	Fish Cr at Upper Sta nr Steamboat Springs	within basin modification	67.8	x	x	x		
09239500	Yampa River at Steamboat Springs	within basin modification	1460.0	x	x	x	x	x
09242500	Elk River near Milner	within basin modification	1161.8		x	x		x
09246200	Elkhead Creek above Long Gulch near Hayden	within basin modification	444.1		x	x		x
09253000	Little Snake River near Slater	within basin modification	649.6	x	x	x	x	x
09255000	Slater Fork near Slater	within basin modification	387.9	x	x	x	x	x
09306200	Piceance Creek bl Ryan Gulch nr Rio Blanco	within basin modification	1309.6	x	x	x	x	x
09306242	Corral Gulch near Rangely	natural	82.0	x	x	x	x	x
09306255	Yellow Creek near White River	within basin modification	678.6	x	x	x	x	x

Gauge ID	Station Name	Type	Area (km^2)	1981-2018	2001-2018	VIC	USGS 2009	USGS 2015
09342500	San Juan River at Pagosa Springs	within basin modification	726.9	x	x	x	x	x
09343600	Rio Blanco at the mouth near Trujillo	within basin modification	433.1	x	x	x		
09344000	Navajo R at Banded Peak Ranch near Chromo	within basin modification	178.4	x	x	x	x	x
09344400	Navajo River bl Oso Diversion Dam nr Chromo	transbasin out	252.2	x	x	x		
09352900	Vallecito Creek near Bayfield	natural	188.2	x	x	x	x	x
09353800	Los Pinos River near Ignacio	within basin modification	880.8		x	x		x
09354500	Los Pinos River at La Boca	within basin modification	1343.9	x	x	x		x
09357500	Animas River at Howardsville	natural	148.7	x	x	x	x	x
09358000	Animas River at Silverton	natural	182.5		x	x		x
09358550	Cement Creek at Silverton	natural	52.1		x	x	x	x
09359010	Mineral Creek at Silverton	natural	136.1		x	x		x
09362750	Florida River above Lemon Reservoir near Durango	natural	135.5	x	x	x		x
09362900	Florida River below Lemon Reservoir	within basin modification	177.3	x	x	x		
09363200	Florida River at Bondad	transbasin in	571.8		x	x		
09365500	La Plata River at Hesperus	within basin modification	84.1	x	x	x	x	x
09366500	La Plata River at Colorado-New Mexico state line	within basin modification	801.2	x	x	x	x	x
09370000	Mancos River near Mancos	within basin modification	187.3	x	x	x		
09371000	Mancos River near Towaoc	within basin modification	1355.9	x	x	x	x	x
09371492	Mud Creek at State Highway 32 near Cortez	within basin modification	89.1	x	x	x		x
09371520	McElmo Creek above Trail Canyon near Cortez	transbasin in	605.6		x	x		x
09372000	McElmo Creek near Colorado-Utah state line	transbasin in	893.9	x	x	x	x	x
385626107212000	Muddy Creek below Paonia Reservoir	within basin modification	665.3	x	x	x		
393109104464500	Cherry Creek near Parker	transbasin out	745.7		x	x		
393839107463801	West Rifle Creek above Rifle Gap Reservoir	transbasin out	13.6		x			
394839104570300	Sand Creek at mouth near Commerce City	urban	489.3		x	x		
402114105350101	Big Thompson bl Moraine Park nr Estes Park	natural	104.8		x	x		
BEVBEVCO	Beaver Creek below Beaver Creek Reservoir	within basin modification	125.0		x	x		
BIGHILCO	Big Thompson River at Hillsborough Diversion	within basin modification	1464.4		x	x		
BLUNINCO	Blue River at Highway 9 Bridge blw Breckenridge	transbasin out	209.1		x	x		
CHECRECO	Wild Cherry Creek near Crestone	natural	15.4		x			x
DOUOUTCO	Douglas Res at Smith Ranch nr Rush (outflow)	within basin modification	218.3		x	x		
ERIRGRCO	East Rifle Creek above Rifle Gap Reservoir	within basin modification	133.7		x	x		
GARVILCO	Garner Creek near Villa Grove	natural	13.6		x			
HAYREDCO	Hay Gulch above Red Mesa Ward Reservoir	within basin modification	73.1		x	x		
LITOSOCO	Little Navajo River below Little Oso Diversion Dam	transbasin out	35.1		x			
LITSPGCO	Little Spring Creek at Medano Ranch near Mosca	natural	180.3		x	x		
LONREDCO	Long Hollow at the mouth near Red Mesa	within basin modification	112.6		x	x		x

Gauge ID	Station Name	Type	Area (km^2)	1981-2018	2001-2018	VIC	USGS 2009	USGS 2015
MAJVILCO	Major Creek near Villa Grove	within basin modification	18.9		x			
MTNOUTCO	Mountain Home Reservoir (outflow)	within basin modification	182.3		x	x		
PINBVACO	Pine River below Vallecito Reservoir near Bayfield	within basin modification	659.0		x	x		
PLAANTCO	South Platte River below Antero Reservoir	within basin modification	481.2	x	x	x		
RIFRGRCO	Rifle Creek below Rifle Gap Reservoir	within basin modification	354.1	x	x	x		
RITCRECO	Rito Alto Creek near Crestone	natural	31.3		x			x
SANCRECO	San Isabel Creek near Crestone	natural	17.6		x			x
SPACRECO	Spanish Creek near Crestone	natural	9.0		x			x
WILCRECO	Willow Creek near Crestone	natural	18.6		x			x

Table 2. Watershed properties used as potential independent variables in developing new empirical streamflow prediction models. Final column indicates the variables that were used in Capesius and Stephens (2009) regression equations; the units and data source for the USGS equations may differ from those used in this study.

Category	Variable	Source	Used in USGS 2009
Topography	Mean elevation (m)	National Elevation	x
	Mean slope (m/m)	Dataset 30 m	x
	Dominant aspect: N, NE, E, SE, S, SW, W, NW		
	Area of watershed (km^2)		x
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)	PRISM	x
	Mean annual potential evapotranspiration PET (mm)	GridMET	
	Mean annual snow persistence (SP, %)	Hammond et al. 2017	
Hydrology	Hydrologic Region	USGS 2009	

Table 3. Streamflow metrics derived for each station.

Variable	Name	Time period
Q_{ann}	Mean annual streamflow (cfs or mm)	1981-2018, 2001-2018
Q_{month}	Mean monthly streamflow (cfs or mm), separate values for each month	1981-2018, 2001-2018

3. Results

3.1. Watershed characteristics

The watersheds analyzed have areas ranging from 4-1495 km^2, with a median area of 265 km^2. Their mean elevations range from 1367-3644 m.a.s.l., and most watersheds are at the higher end of that elevation range, with a median elevation of 3094 m (Figure 2). Mean watershed slopes range from 1-31%, with a median of 17%. Mean annual precipitation ranges from 344-1246 mm, with a median of 706 mm.

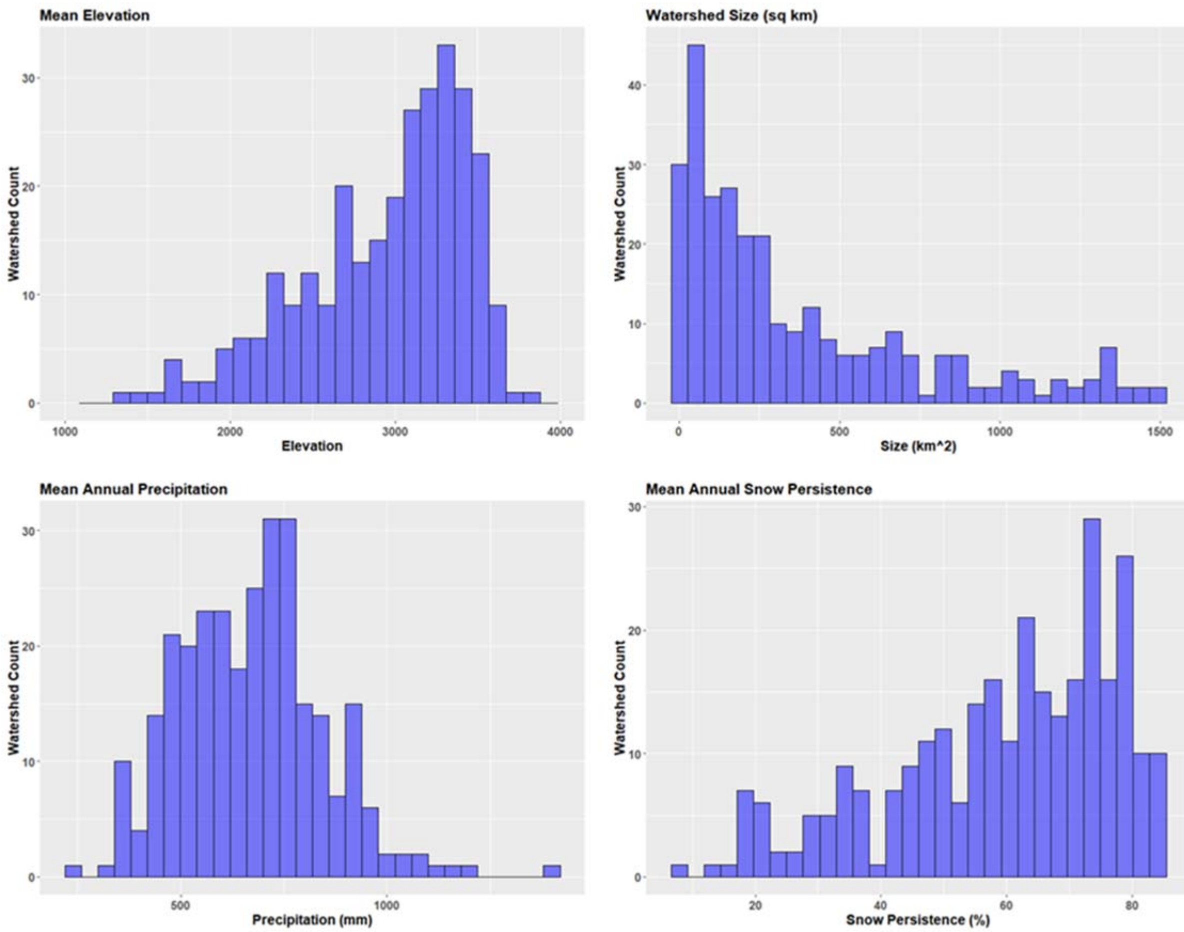


Figure 2. Histograms of watershed mean elevations (m), drainage areas (km^2), mean annual precipitation (mm), and mean annual January 1 – July 3 snow persistence (%). Data sources listed in Table 2.

Mean annual streamflow normalized by drainage area is negatively correlated with watershed area (r = -0.41) meaning that larger watersheds tend to produce less streamflow per unit area than small watersheds (Table 4, Figure 3). This is partly because the smaller watersheds tend to headwaters at higher elevations, which have higher precipitation and snowpack. Streamflow is positively correlated with elevation (r = 0.64), mean annual precipitation (r = 0.85), and mean annual snow persistence (r = 0.80). It is also positively correlated with mean watershed slope (r =

0.64) because the high elevation watersheds also tend to have steeper slopes. Finally, streamflow is negatively correlated with mean annual potential evapotranspiration (r = -0.62) meaning that streamflow declines with increasing PET, as would be expected. During most months, mean streamflows were similar to median streamflows, but during snowmelt runoff months, these distributions became more skewed, with median monthly values tending to be lower than mean monthly values (Figure 4).

Table 4. Pearson-rho correlation coefficients (r) between watershed attributes. All correlations are significant at $p<0.001$. P is precipitation (1981-2018); PET is potential evapotranspiration (1981-2018); SP is snow persistence (2001-2018), and Q is mean annual area-normalized streamflow (1981-2018). Area is drainage area in km^2.

Variable	Area	Elev	Slope	P	PET	SP
Mean elevation (m)	-0.44					
Mean slope (m/m)	-0.44	0.78				
Mean annual P (mm)	-0.37	0.65	0.60			
Mean annual PET (mm)	0.44	-0.92	-0.76	-0.67		
Mean annual SP (%)	-0.32	0.87	0.64	0.75	-0.85	
Mean annual Q (mm)	-0.41	0.64	0.64	0.85	-0.62	0.80

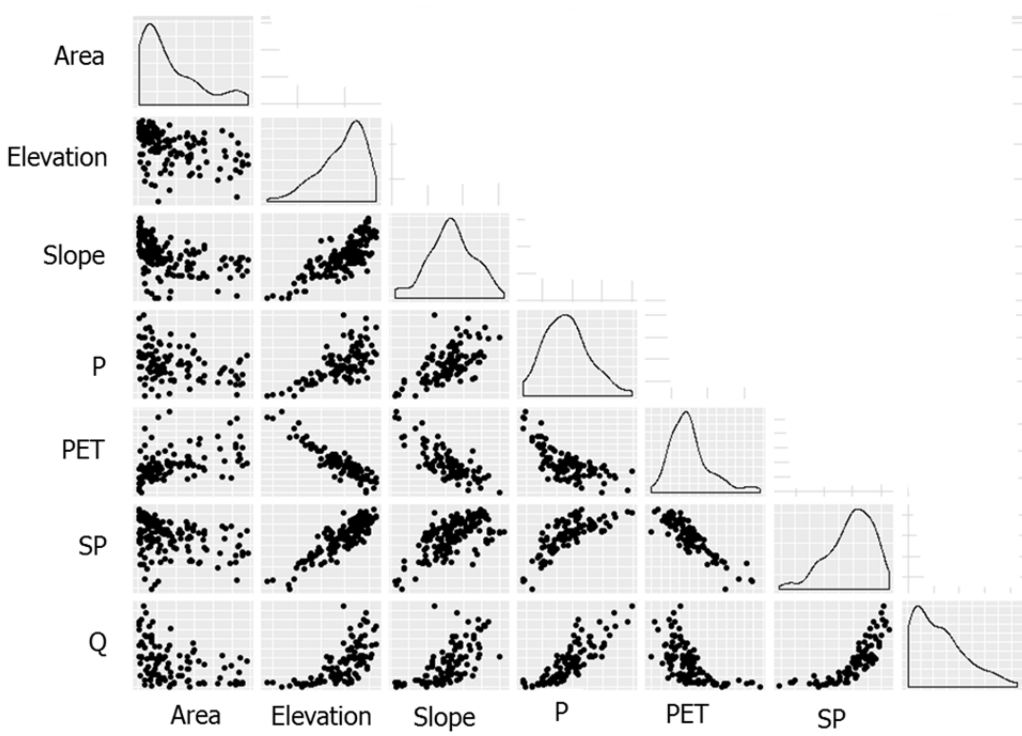


Figure 3. Cross correlation plot for the variables listed in Table 4.

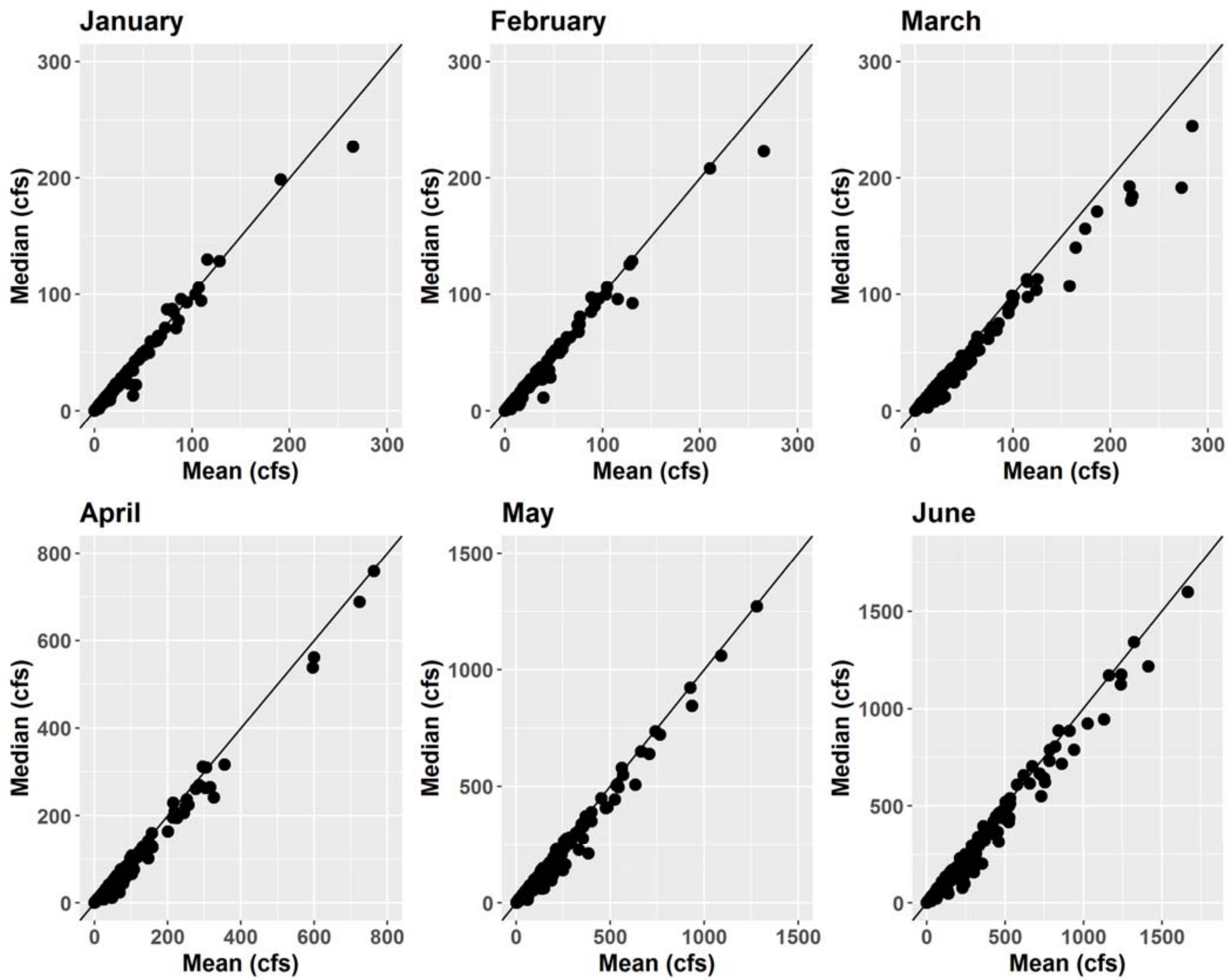


Figure 4. Mean vs. median monthly streamflow for the study stations, 1981-2018. Line is 1:1.

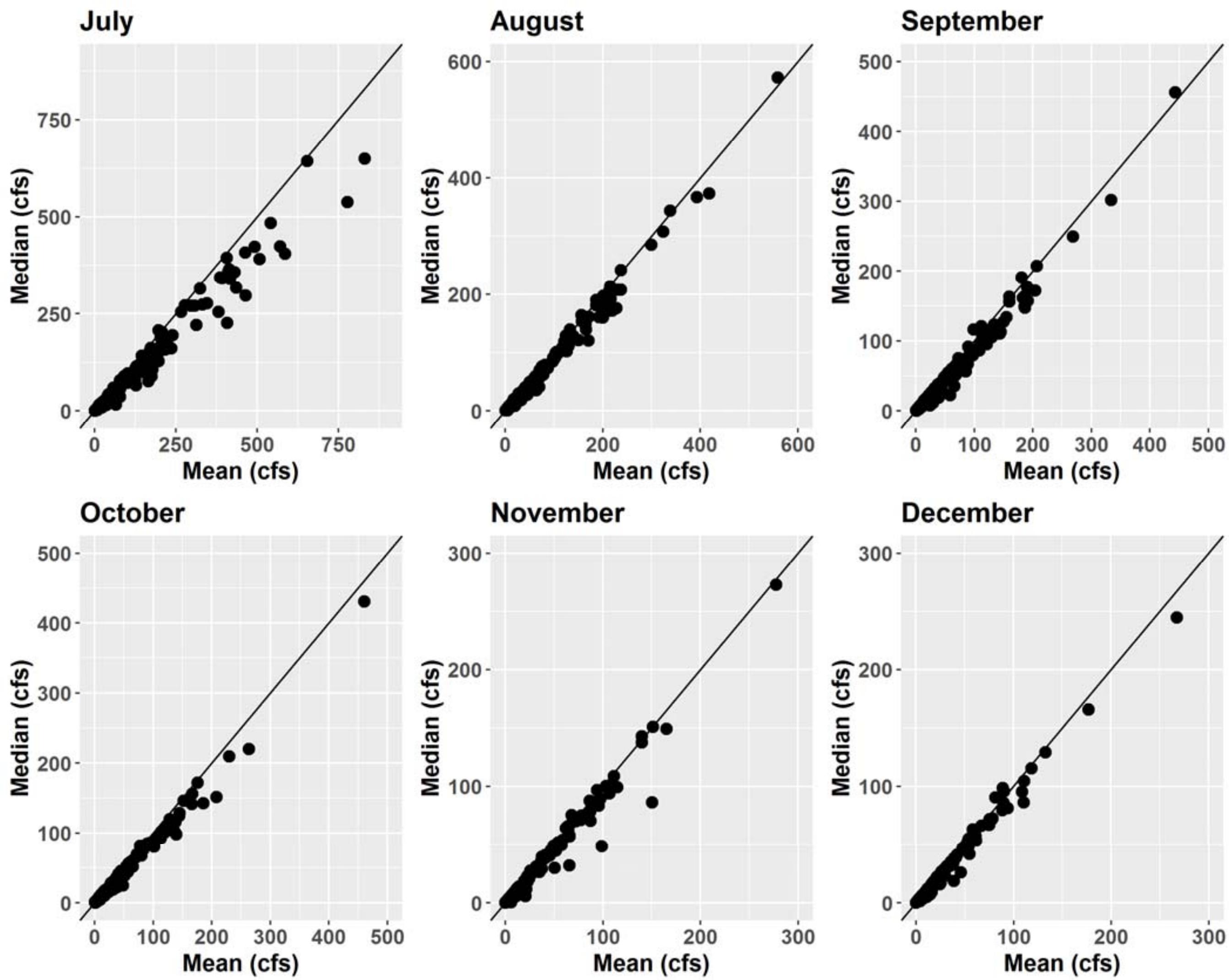


Figure 4. continued.

3.2.USGS regression models

The Capesius and Stephens (2009) regression equations performed well for mean annual discharge across the tested watersheds, with NSE 0.72 for 1981-2018 and 0.79 for 2001-2018. Percent bias was -7.5 for the longer time period (1981-2018) and higher (14.7) for the 2001-2018 time period, when regression equations had a greater tendency to over-predict mean annual flow (Figure 5). For reference, Figure 5 also shows predicted versus observed mean annual flow including the stations affected by transbasin diversions. The regression equations tend to over-predict mean annual flow for stations with transbasin diversions out of the watershed and under-predict for stations with transbasin diversions into the watershed. However, the flow predictions for stations affected by transbasin diversions mostly fall within the range of prediction variability for the natural and within basin diversion stations.

Regression equations for mean monthly discharge did not perform quite as well as annual equations, with NSE ranging from 0.32 in August to 0.65 in May for the 1981-2018 time period (Figure 6). Percent biases ranged from -39 in March to -1.6 in June for this time period, as regression equations tended to under-predict the early snowmelt hydrograph. This under-prediction in early spring was mainly evident for watersheds with within-basin modifications. For the 2001-2018 time period, regression equation NSE values ranged from 0.11 in June to 0.75 in April, with percent bias ranging from -51 in March to 43 in June (Figure 7).

3.3.VIC model

The Variable Infiltration Capacity (VIC) model is the only uncalibrated model considered here, yet it has similar performance to the USGS regression equations for mean annual discharge (Figure 8), with NSE of 0.68 for 1981-2018 and 0.73 for 2001-2018. Predicted values tended to be biased high for the Rio Grande region. Model values were biased slightly low for the longer time period (-6%) and high for the more recent time period (2%). VIC model performance was weaker for individual months (NSE -0.9 – 0.68 for 1981-2018 and -0.090.70 for 2001-2013), with low flow months tending to have a low bias and high flow months a high bias (Figures 9,10).

3.4.New empirical models

The new empirical models we developed are multiple linear regressions of the form:

$$y = (\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots \beta_n x_n)^2$$

where y is the streamflow variable predicted; β values are model coefficients, and x values are continuous independent variables. β_0 is the intercept and is also modified by coefficients for categorical variables. If the watershed of interest falls into one or more of the categories, the value of the categorical coefficient is added to β_0. The coefficients and independent variables for the resulting models are given in Table 5. Categorical variables are represented in Table 5 as "+" if they are included in the model, and the corresponding coefficient values are in sub-tables 5a, 5b, and 5c. Mean annual and monthly Q models for 2001-2018 all include snow persistence, for which the coefficient values are highest for Q_{ann}, Q_{may}, and Q_{jun}. For July-March, slope has the highest coefficient values. Mean annual and monthly Q models for 1981-2018 could not use SP, as those data were not available prior to 2001. For these models slope is the independent variable with the highest coefficient value in most months. Most of the monthly models include Hydrologic Region as a categorical variable, and some include slope aspect and geology.

Empirical regression models for mean annual flow were developed for the 1981-2018 and 2001-2018 time periods (Figure 11). For the latter time period, the models include mean annual snow persistence (SP), which is available starting in 2001. The annual model for 1981-2018 had NSE=0.81, with a -13% bias. The model for 2001-2018, which includes SP, has NSE = 0.89 and a -0.2% bias. The effects of transbasin diversions and urbanization are particularly evident for this model. Nearly all stations with transbasin diversions out of the watershed are over-predicted by the model, whereas nearly all stations with transbasin diversions into the watershed are under-predicted by the model. Stations for urban watersheds are also under-predicted. Empirical monthly models for 1981-2018 did not perform quite as well as the annual models, with NSE from 0.63-0.85 and percent bias ranging from -4 to 10 (Figure 12). For 2001-2018 the models improved for some months, with NSE ranging from 0.54-0.89 and percent bias from -7 to 1 (Figure 13).

Table 5. 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 2, 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 are in the sub-tables a,b,c that follow. Blank cells indicate the independent variable is not used in the empirical model.

y	Training years	β_0	$\beta_1 SP$	$\beta_2 Slope$	$\beta_3 PET$	$\beta_4 P$	$\beta_5 Area$	$\beta_6 Elev$	Aspect	Geology	Hydrologic Region	R^2
Q_{ann}	2001-2018	-41.537	0.274	0.181	0.023	0.017	-0.001				+	0.89
Q_{jan}	2001-2018	-0.107	0.026	0.033					+		+	0.61
Q_{feb}	2001-2018	-1.653	0.026	0.032	0.001				+		+	0.60
Q_{mar}	2001-2018	-3.219	0.026	0.032	0.001				+		+	0.60
Q_{apr}	2001-2018	-10.766	0.082	-0.036	0.006	0.005			+		+	0.74
Q_{may}	2001-2018	-23.646	0.146		0.013	0.011	-0.001					0.83
Q_{jun}	2001-2018	-30.702	0.182	0.140	0.017	0.011	-0.001				+	0.87
Q_{jul}	2001-2018	-15.869	0.096	0.126	0.009	0.005	-0.001				+	0.78
Q_{aug}	2001-2018	-3.997	0.044	0.115	0.003	0.002				+	+	0.67
Q_{sep}	2001-2018	-2.984	0.030	0.096	0.003	0.003				+	+	0.69
Q_{oct}	2001-2018	-6.915	0.042	0.060	0.004	0.003					+	0.77
Q_{nov}	2001-2018	-2.678	0.024	0.049	0.002	0.002					+	0.70
Q_{dec}	2001-2018	-2.216	0.025	0.047	0.001	0.001			+		+	0.66
Q_{ann}	1981-2018	-6.934		0.223		0.025			+		+	0.86
Q_{jan}	1981-2018	0.582		0.034		0.002			+		+	0.67
Q_{feb}	1981-2018	0.502		0.028		0.001	0.0002		+		+	0.65
Q_{mar}	1981-2018	0.341		0.028		0.001	0.0002		+		+	0.65
Q_{apr}	1981-2018	-1.336				0.006			+		+	0.73
Q_{may}	1981-2018	-4.937		0.068		0.013			+			0.80
Q_{jun}	1981-2018	-5.983		0.167		0.016			+		+	0.84
Q_{jul}	1981-2018	-17.702		0.135	0.008	0.008		0.002	+		+	0.79
Q_{aug}	1981-2018	-1.071		0.104		0.003		0.001	+	+	+	0.74
Q_{sep}	1981-2018	1.713		0.086		0.003				+	+	0.73
Q_{oct}	1981-2018	0.773		0.056		0.003			+	+	+	0.79
Q_{nov}	1981-2018	0.927		0.039		0.002			+	+	+	0.80
Q_{dec}	1981-2018	0.437		0.039		0.002			+		+	0.70

Table 5a. 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	Training years	NE	NW	S	SE	SW	W
Q_{ann}	2001-2018						
Q_{jan}	2001-2018	0.001	0.036	0.046	-0.534	0.097	0.061
Q_{feb}	2001-2018	0.051	0.060	0.128	-0.487	0.157	0.116
Q_{mar}	2001-2018	0.079	-0.183	0.129	-0.503	0.403	0.084
Q_{apr}	2001-2018	0.096	-0.634	0.016	-0.103	0.847	0.128
Q_{may}	2001-2018						
Q_{jun}	2001-2018						
Q_{jul}	2001-2018						
Q_{aug}	2001-2018						
Q_{sep}	2001-2018						
Q_{oct}	2001-2018						
Q_{nov}	2001-2018						
Q_{dec}	2001-2018	0.069	0.084	0.111	-0.485	0.077	0.097
Q_{ann}	1981-2018	0.579	2.104	2.895	1.417	1.196	1.895
Q_{jan}	1981-2018	0.190	0.084	-0.001	-0.546	0.124	0.204
Q_{feb}	1981-2018	0.181	0.138	0.072	-0.455	0.173	0.216
Q_{mar}	1981-2018	0.207	-0.056	0.092	-0.459	0.565	0.161
Q_{apr}	1981-2018	0.407	-0.449	0.502	-0.086	1.481	0.316
Q_{may}	1981-2018	0.207	0.528	1.183	0.862	1.961	1.161
Q_{jun}	1981-2018	-0.320	1.882	1.928	1.076	0.069	1.181
Q_{jul}	1981-2018	0.658	1.513	1.658	0.994	-0.039	0.745
Q_{aug}	1981-2018	0.304	0.668	1.178	0.636	0.130	0.708
Q_{sep}	1981-2018						
Q_{oct}	1981-2018	0.338	0.464	0.751	0.396	0.220	0.558
Q_{nov}	1981-2018	0.206	0.161	0.156	-0.254	0.048	0.273
Q_{dec}	1981-2018	0.195	0.122	0.073	-0.522	0.108	0.206

Table 5b. Coefficients (β_0) for Hydrologic Region. Reference group is *Mountain*. If a watershed falls in the mountain region, no Hydrologic Region adjustment is needed for β_0. If a watershed falls in any other region, add the coefficient value to β_0.

y	Training years	*Northwest*	*Plains*	*Rio Grande*	*Southwest*
Q_{ann}	2001-2018	-3.063	-2.066	-4.146	-2.059
Q_{jan}	2001-2018	-0.392	-0.469	-0.544	-0.202
Q_{feb}	2001-2018	-0.401	-0.475	-0.437	-0.066
Q_{mar}	2001-2018	-0.258	-0.469	-0.347	0.446
Q_{apr}	2001-2018	0.797	0.125	0.253	1.040
Q_{may}	2001-2018				
Q_{jun}	2001-2018	-2.078	-1.516	-3.630	-2.719
Q_{jul}	2001-2018	-2.101	-0.886	-2.845	-1.821
Q_{aug}	2001-2018	-0.630	0.052	-0.983	-0.071
Q_{sep}	2001-2018	-0.471	-0.258	-0.403	0.479
Q_{oct}	2001-2018	-0.560	-0.192	-0.486	0.038
Q_{nov}	2001-2018	-0.449	-0.407	-0.613	-0.077
Q_{dec}	2001-2018	-0.475	-0.474	-0.616	-0.188
Q_{ann}	1981-2018	-1.443	-0.359	-1.573	-0.212
Q_{jan}	1981-2018	-0.010	0.007	-0.308	0.335
Q_{feb}	1981-2018	-0.051	-0.024	-0.212	0.451
Q_{mar}	1981-2018	0.420	0.305	0.055	1.070
Q_{apr}	1981-2018	1.128	0.780	0.764	1.360
Q_{may}	1981-2018				
Q_{jun}	1981-2018	-1.854	-0.748	-1.963	-1.762
Q_{jul}	1981-2018	-1.877	-0.599	-1.412	-1.067
Q_{aug}	1981-2018	-0.963	-0.180	-0.306	0.108
Q_{sep}	1981-2018	-0.511	0.135	-0.085	0.448
Q_{oct}	1981-2018	-0.398	0.102	0.152	0.573
Q_{nov}	1981-2018	-0.285	-0.140	-0.329	0.208
Q_{dec}	1981-2018	-0.206	-0.130	-0.355	0.143

Table 5c. Coefficients (β_0) 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 category, add the coefficient value to β_0.

y	Training years	*Impermeable metamporphic*	*Impermeable sedimentary*	*Intrusive*	*Modern alluvium/ colluvium*	*Permeable metamorphic*	*Permeable sedimentary*	*Volcanic*
Q_{ann}	2001-2018							
Q_{jan}	2001-2018							
Q_{feb}	2001-2018							
Q_{mar}	2001-2018							
Q_{apr}	2001-2018							
Q_{may}	2001-2018							
Q_{jun}	2001-2018							
Q_{jul}	2001-2018							
Q_{aug}	2001-2018	-2.183	-2.045	-2.341	-1.864	-2.713	-2.659	-2.193
Q_{sep}	2001-2018	-1.721	-2.166	-2.176	-2.081	-2.592	-2.603	-2.199
Q_{oct}	2001-2018							
Q_{nov}	2001-2018							
Q_{dec}	2001-2018							
Q_{ann}	1981-2018							
Q_{jan}	1981-2018							
Q_{feb}	1981-2018							
Q_{mar}	1981-2018							
Q_{apr}	1981-2018							
Q_{may}	1981-2018							
Q_{jun}	1981-2018							
Q_{jul}	1981-2018							
Q_{aug}	1981-2018	-1.426	-1.547	-1.963	0.531	-2.513	-2.471	-1.597
Q_{sep}	1981-2018	-1.679	-2.356	-2.222	-0.666	-2.617	-2.875	-2.326
Q_{oct}	1981-2018	-0.473	-1.534	-1.597	-1.085	-1.867	-1.887	-1.346
Q_{nov}	1981-2018	-0.185	-0.810	-0.690	-0.474	-0.770	-0.941	-0.832
Q_{dec}	1981-2018							

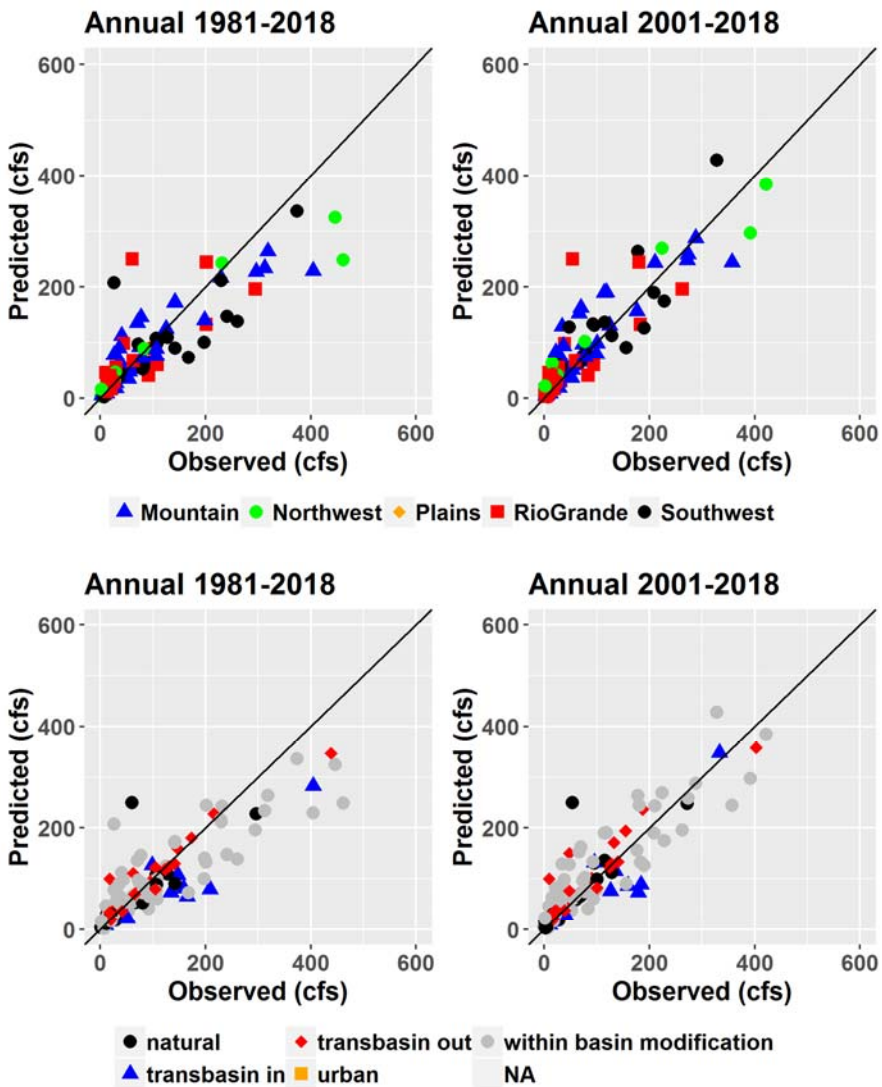


Figure 5. Predicted vs. observed mean annual discharge using Capesius and Stephens (2009) regression equations for two time periods colored by hydrologic region (top) and station type (bottom). Top plots exclude stations with transbasin diversions and urban land cover.

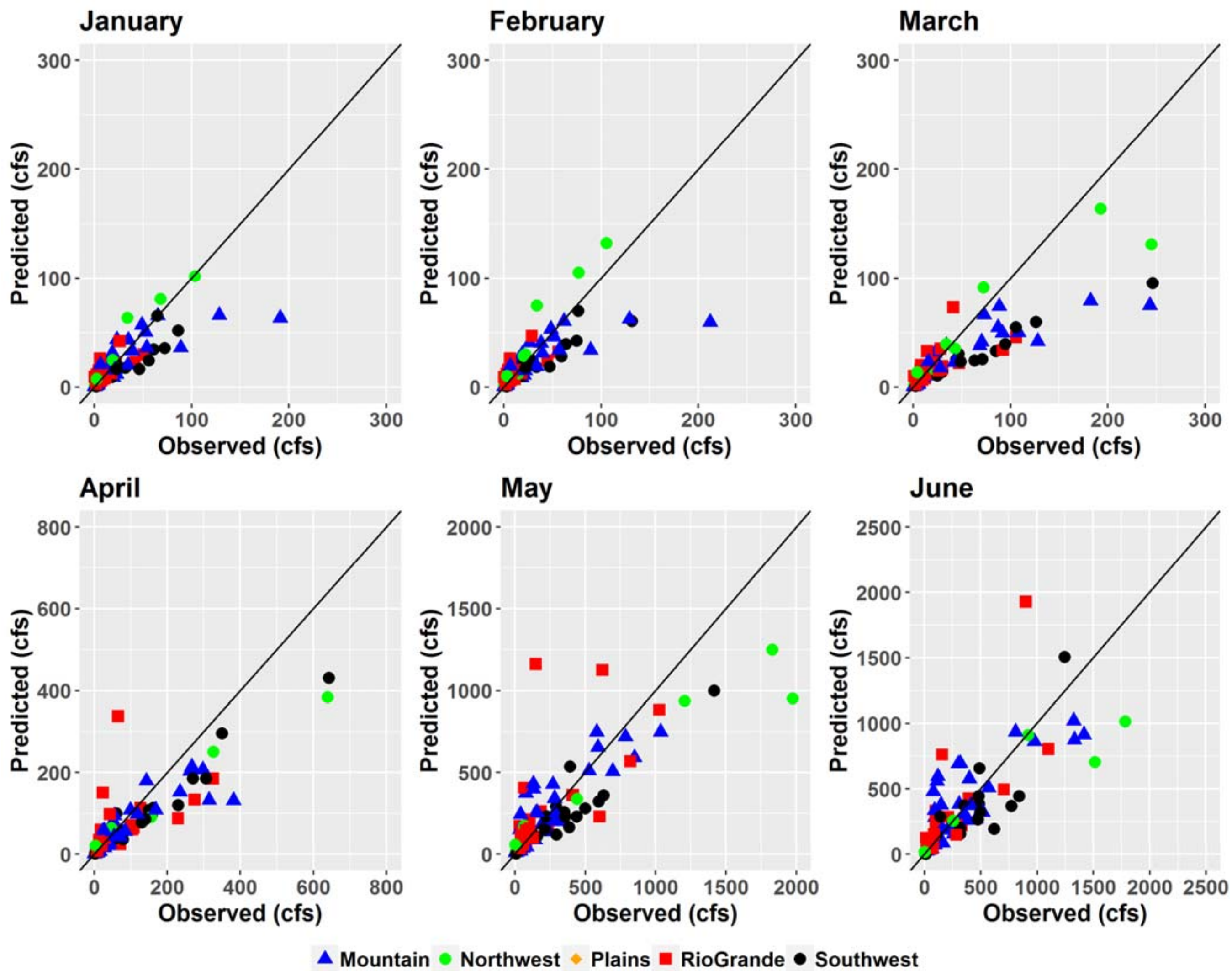


Figure 6. Predicted vs. observed mean monthly discharge using Capesius and Stephens (2009) regression equations for 1981-2018 colored by hydrologic region (first set) and by station type (second set). First set colored by hydrologic region excludes sites with transbasin diversions and urban land cover.

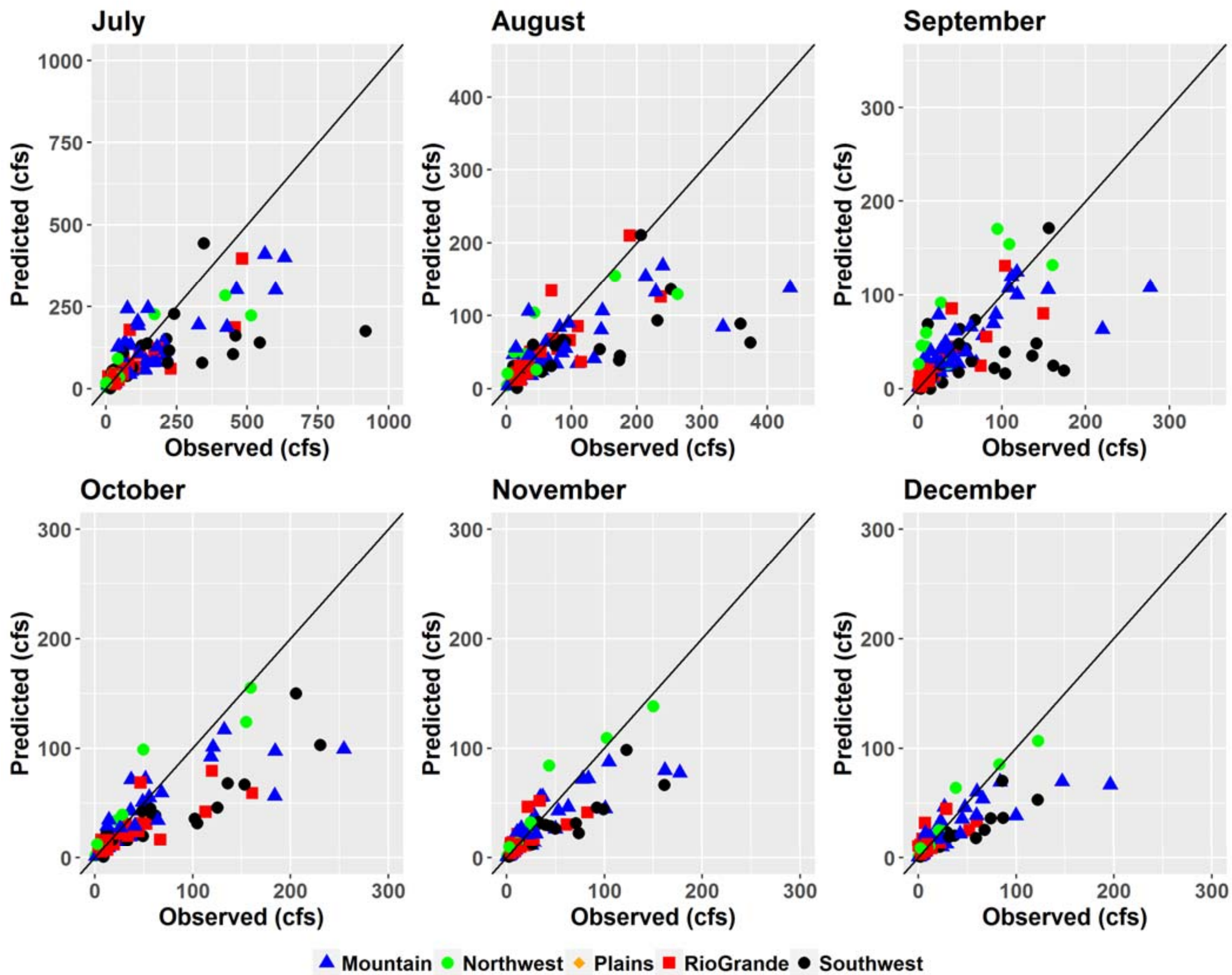
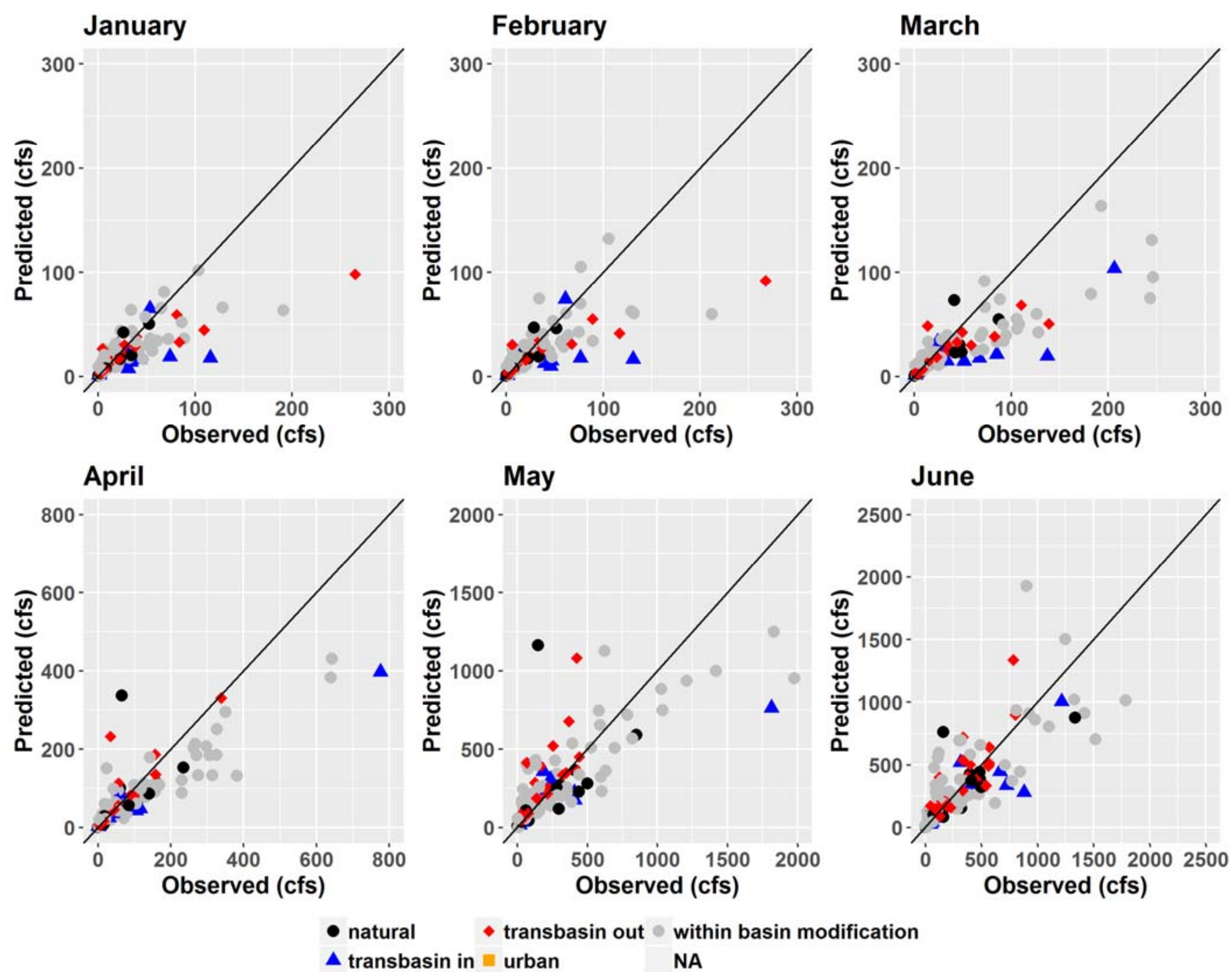


Figure 6, continued



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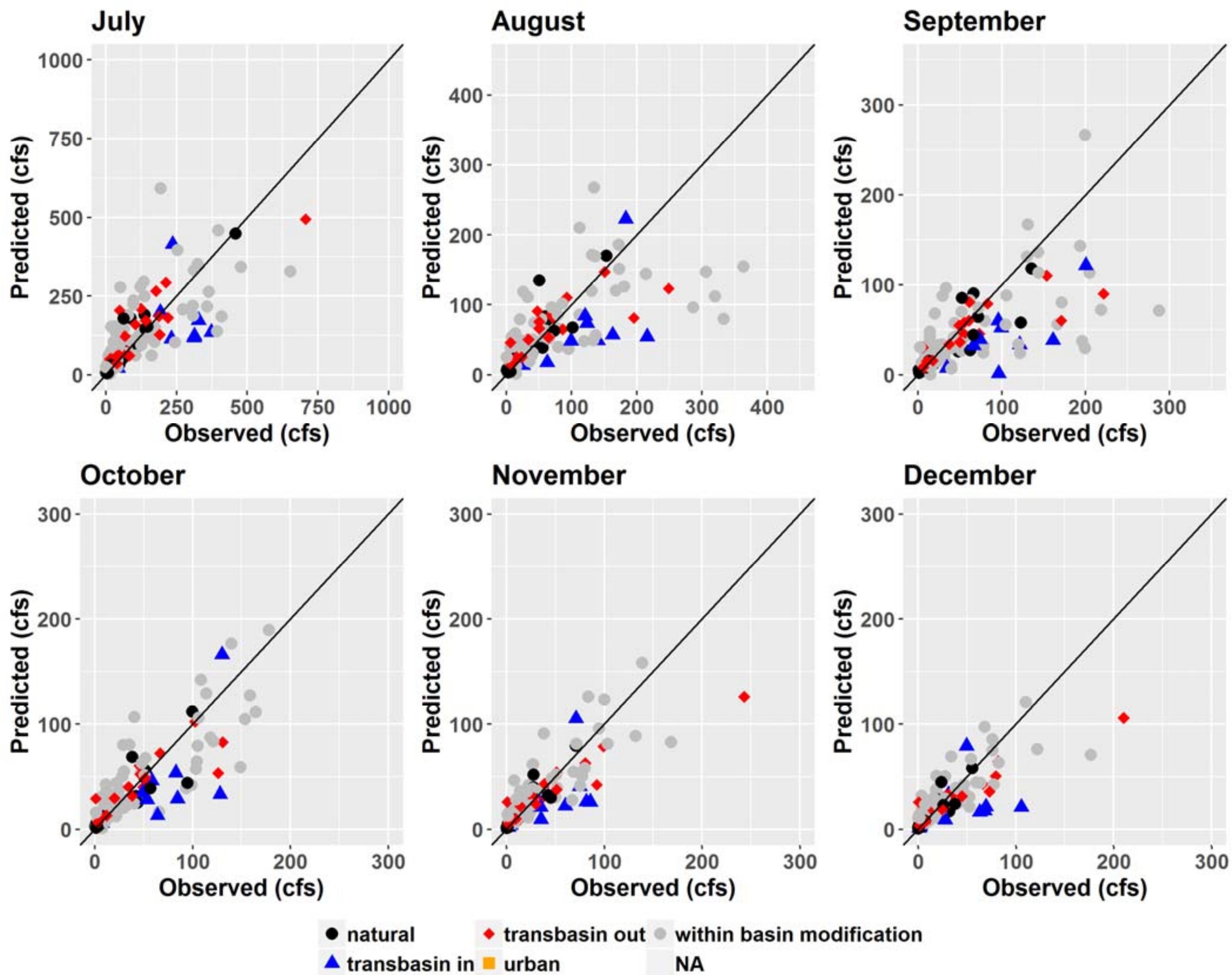


Figure 6, continued

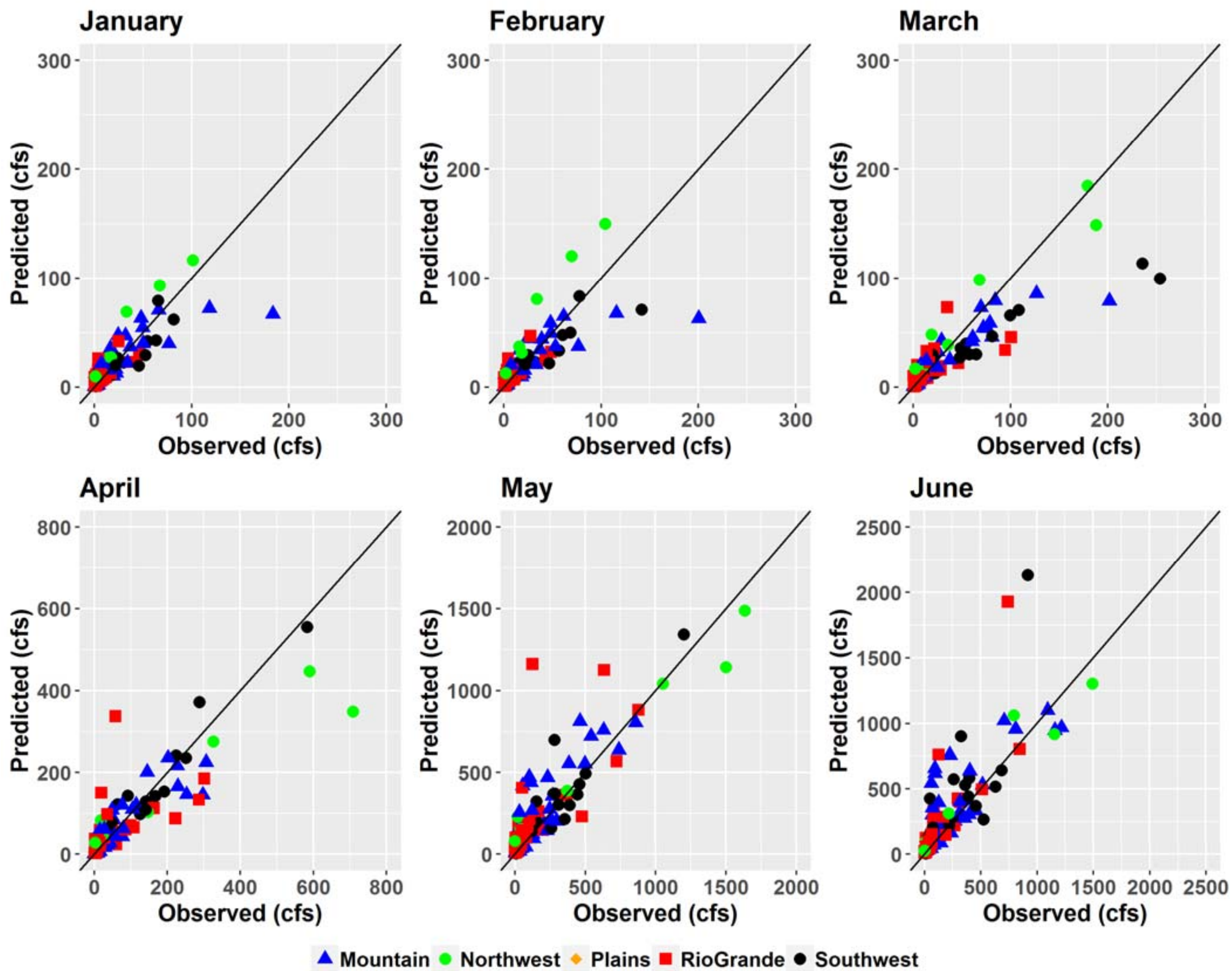
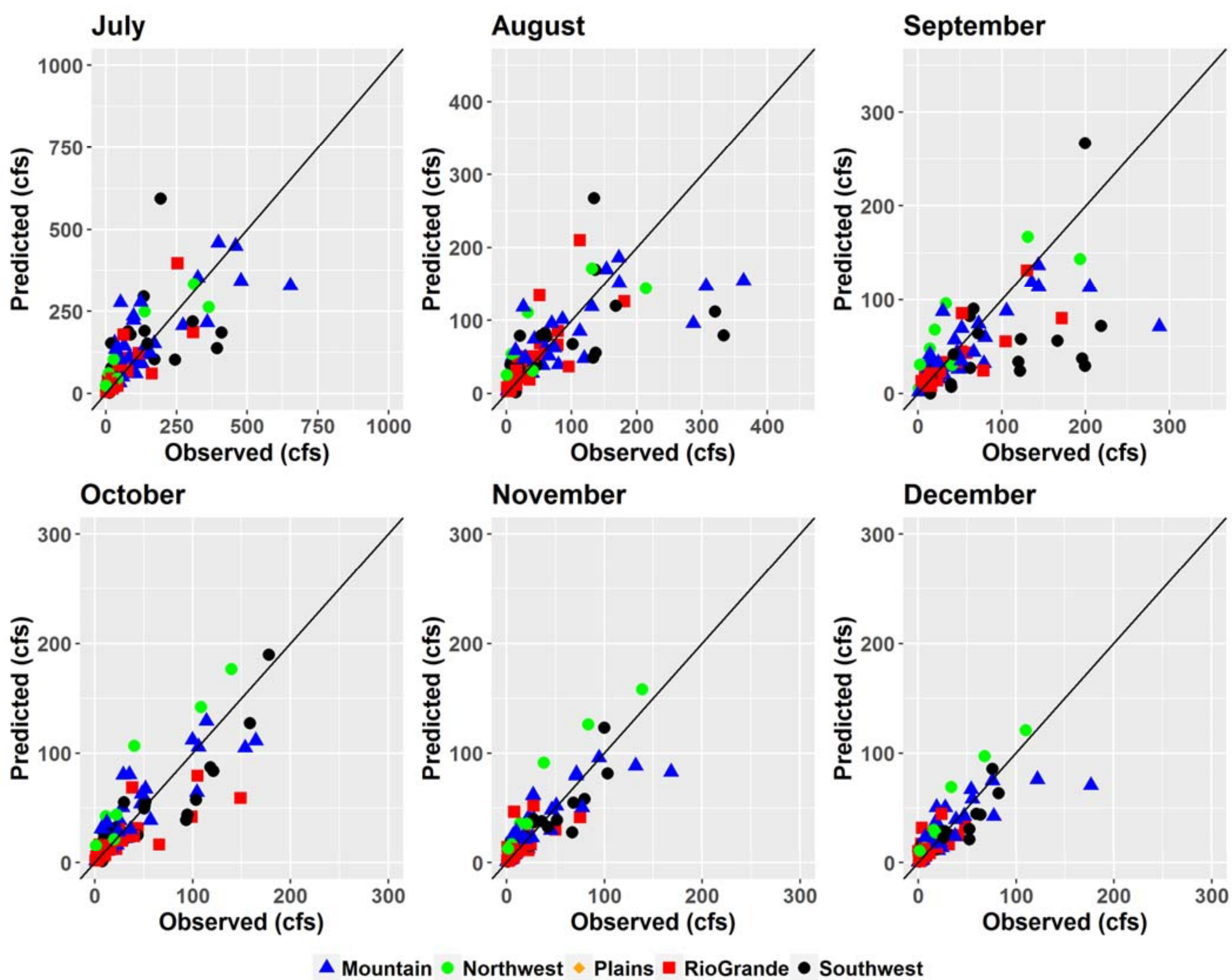


Figure 7. Predicted vs. observed mean monthly discharge using Capesius and Stephens (2009) regression equations for 2001-2018 colored by hydrologic region (first set) and by station type (second set). First set colored by hydrologic region excludes sites with transbasin diversions and urban land cover.



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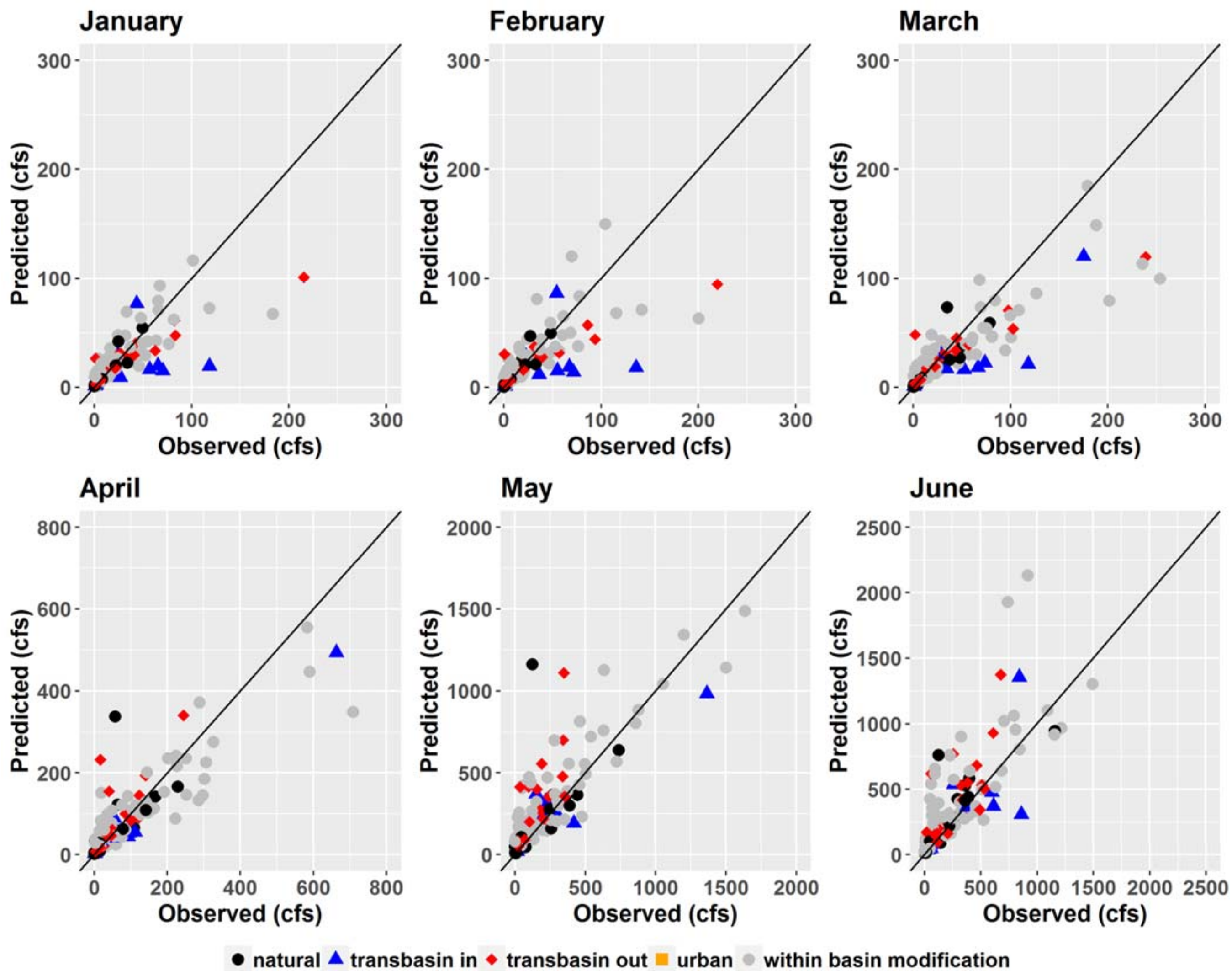
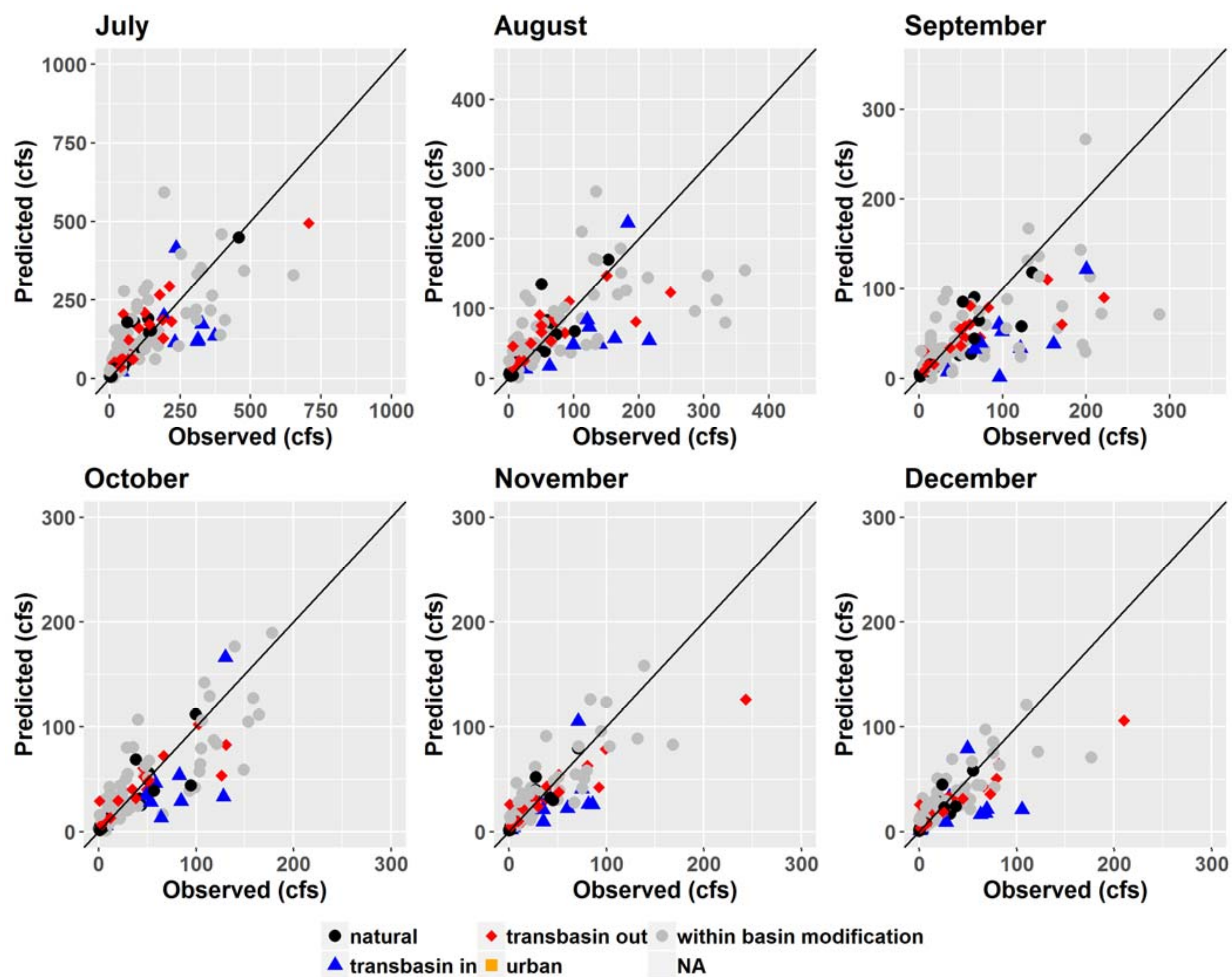


Figure 7, continued



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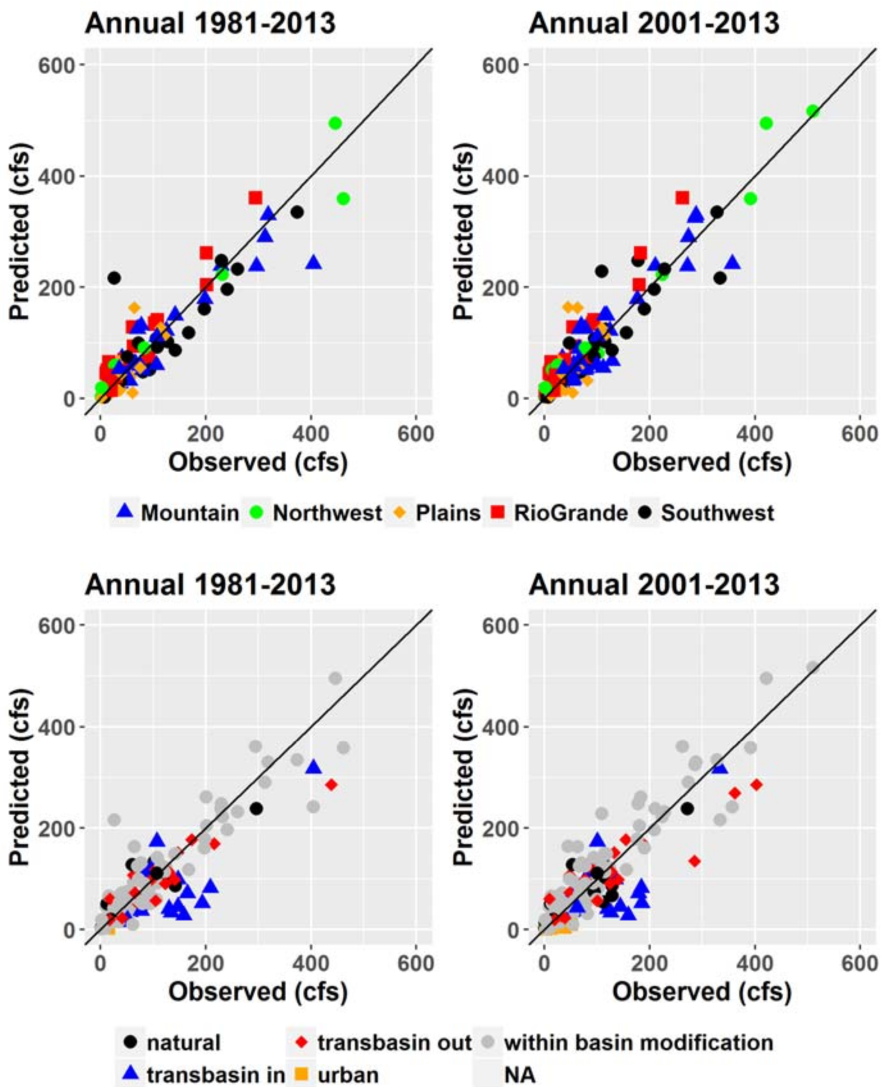

Figure 8. Predicted vs. observed mean annual discharge using the Variable Infiltration Capacity (VIC) model for two time periods colored by Hydrologic Region (top) and by station type (bottom). Top plots exclude stations with transbasin diversions or urban land cover.

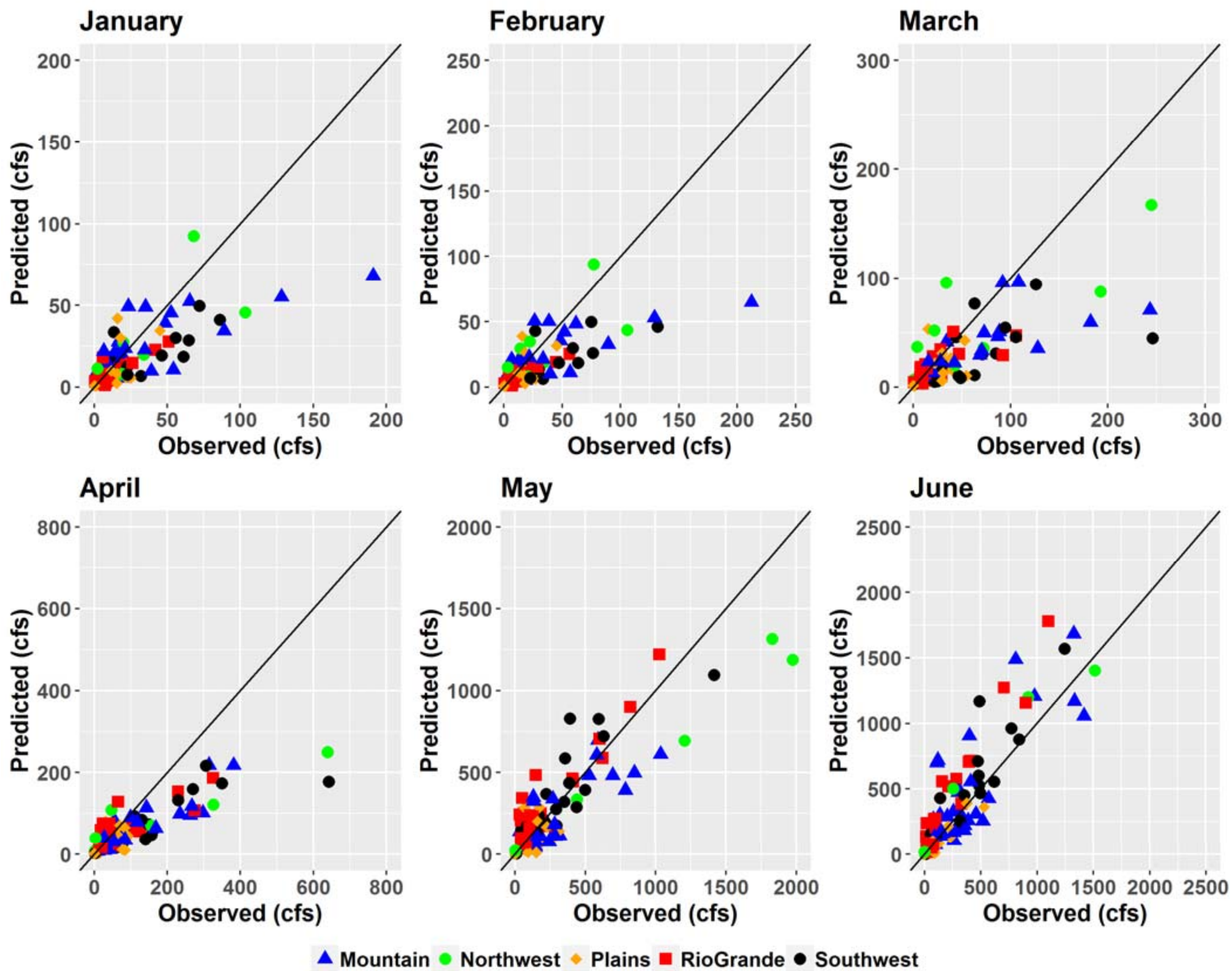

Figure 9. Predicted vs. observed mean monthly discharge using the VIC model for 1981-2018. Stations with transbasin diversions or urban land cover excluded.

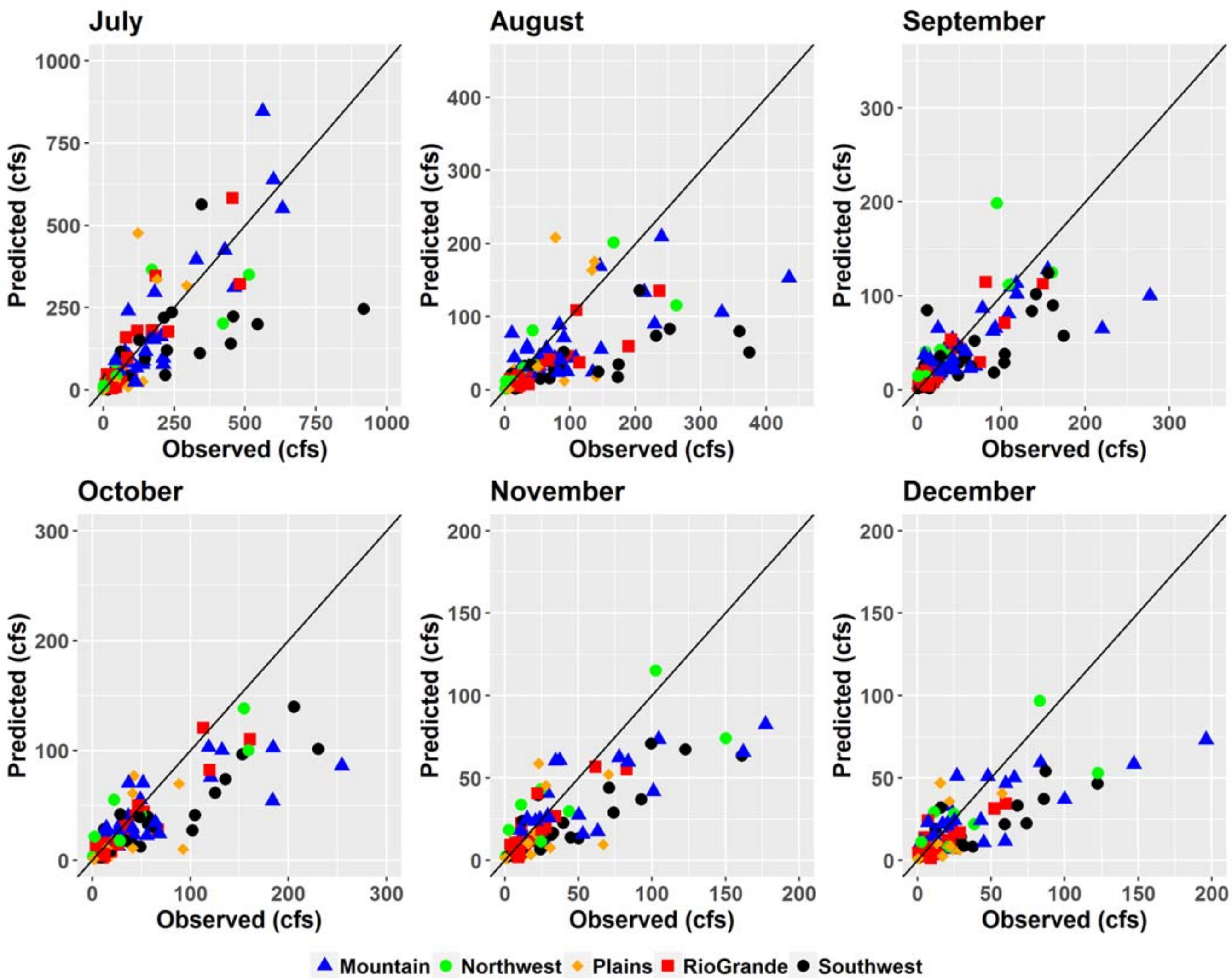

Figure 9, continued

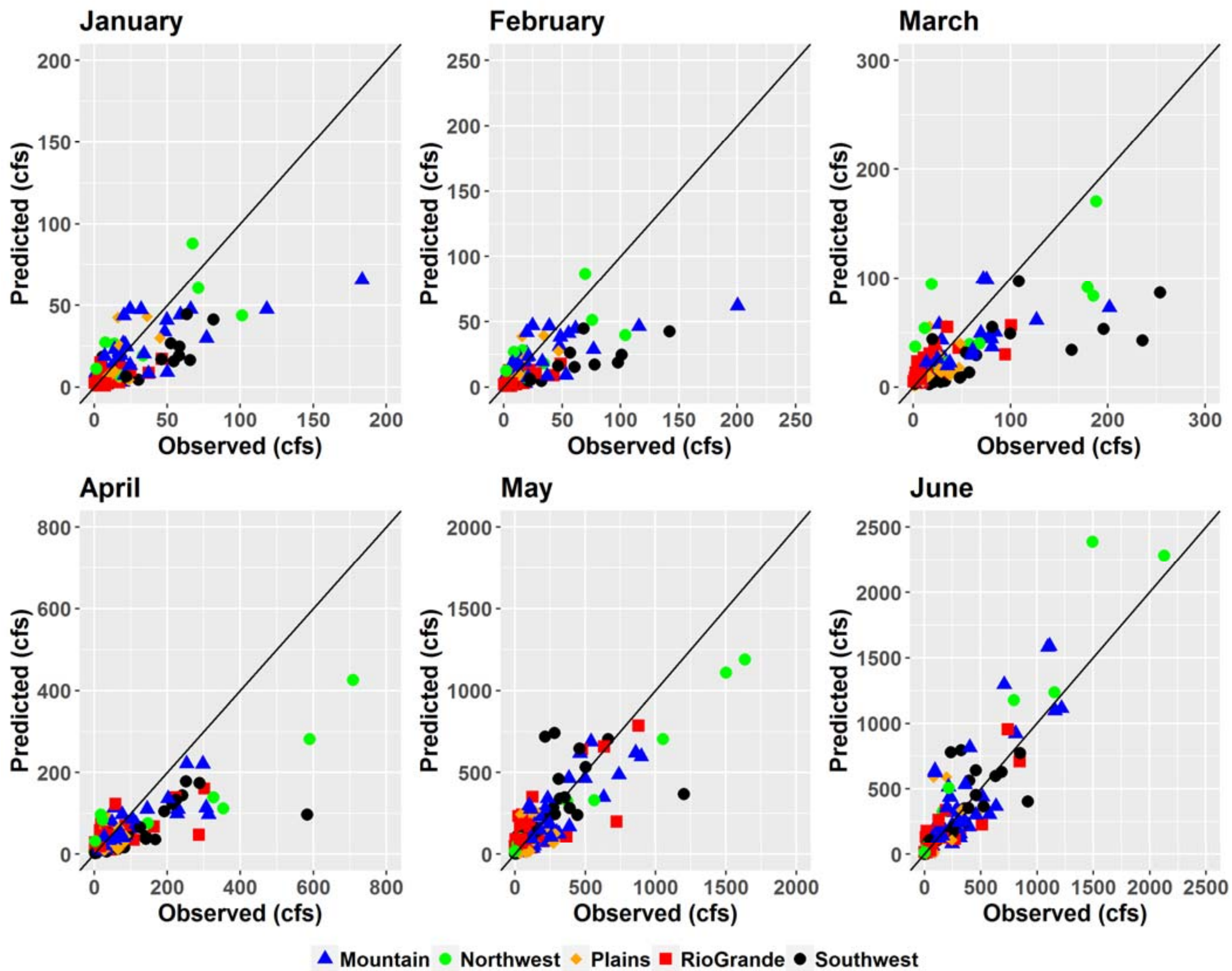

Figure 10. Predicted vs. observed mean monthly discharge using the VIC model for 2001-2018. Stations with transbasin diversions or urban land cover excluded.

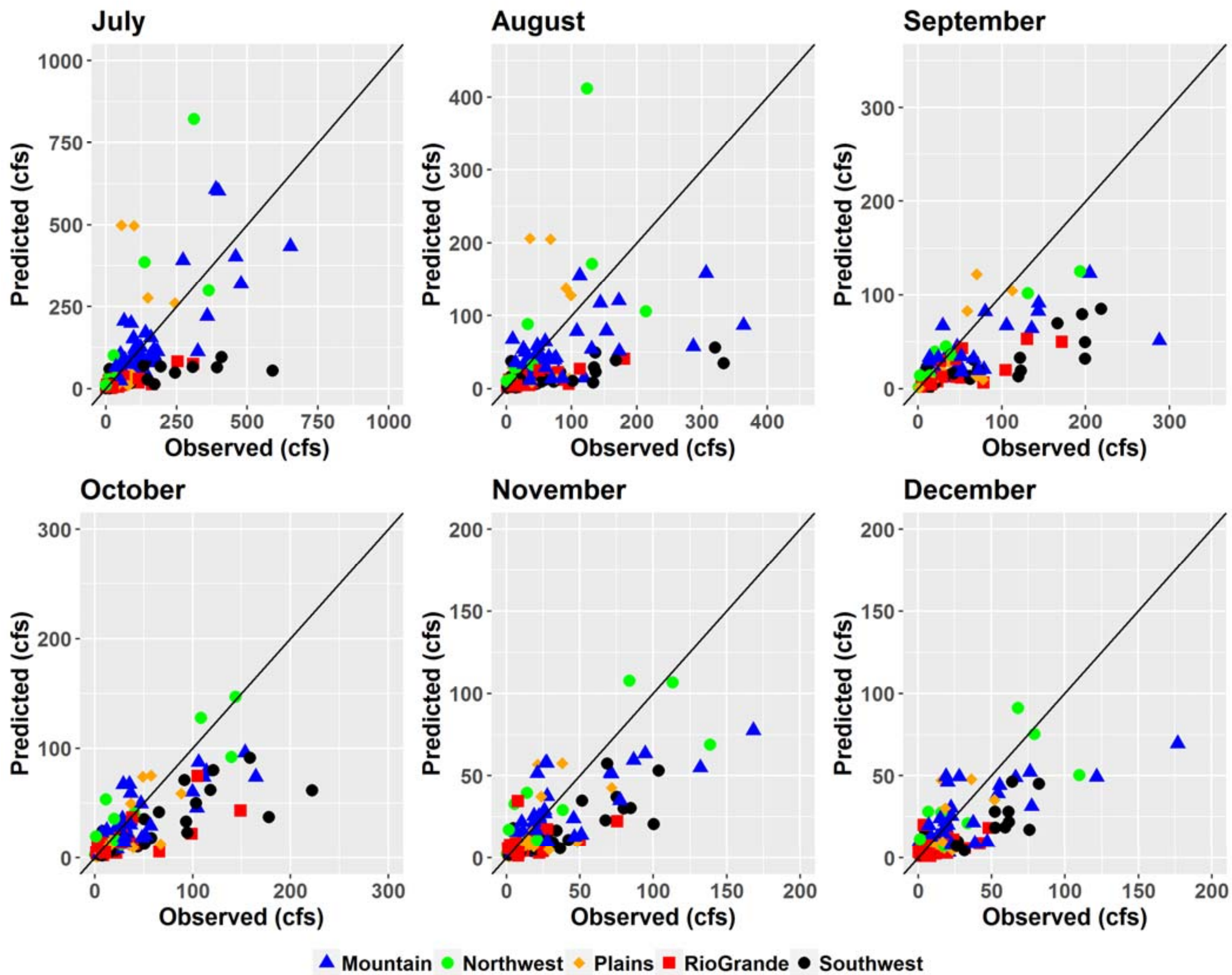

Figure 10, continued

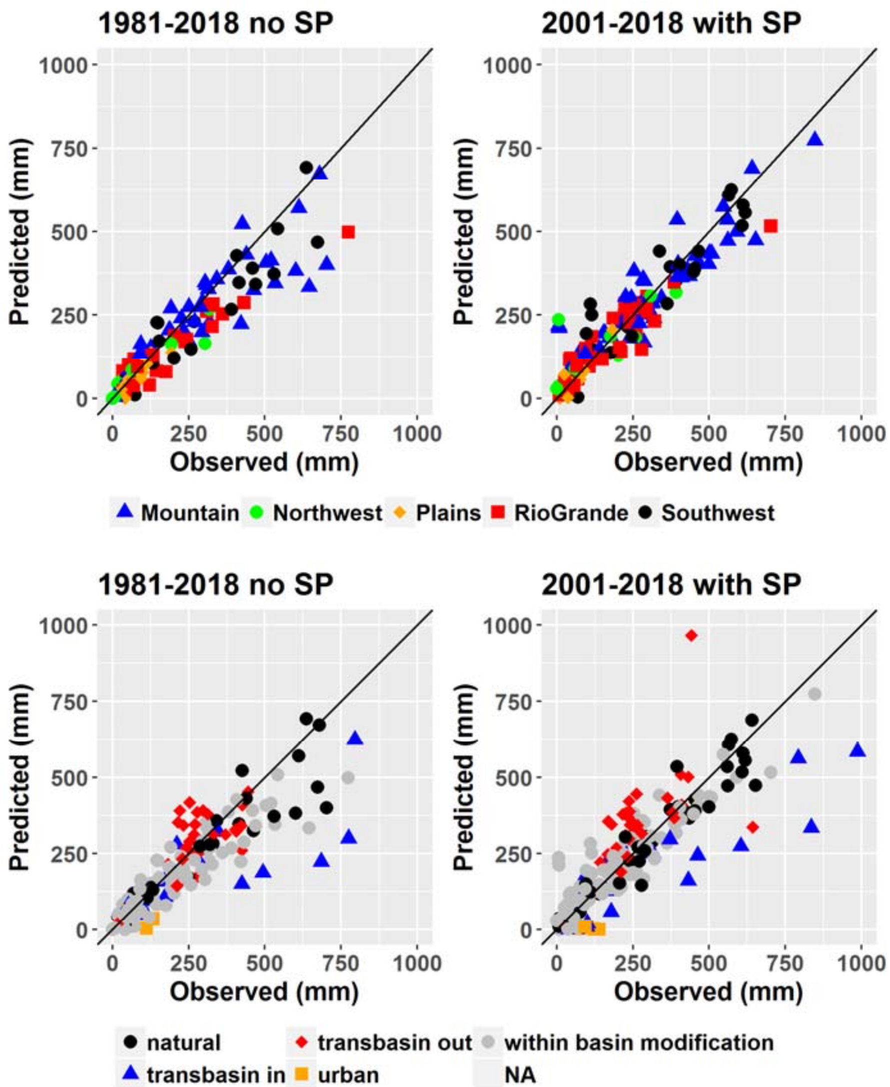

Figure 11. Predicted vs. observed mean annual discharge using the new empirical model for two time periods colored by hydrologic region (top) and by station type (bottom). Top plots exclude sites with transbasin diversions and urban landcover. SP is snow persistence.

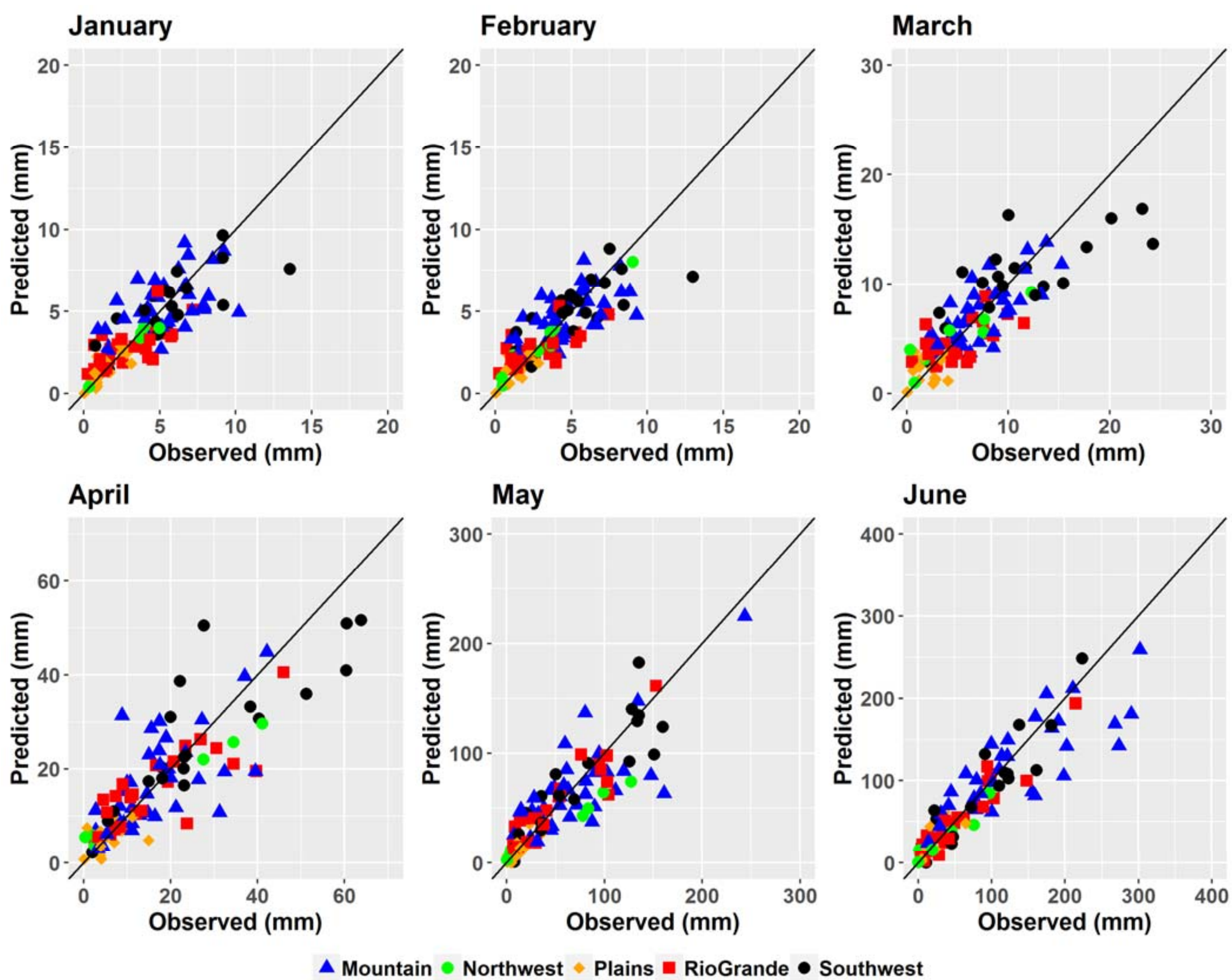

Figure 12. Predicted vs. observed mean monthly discharge using the new empirical model for 1981-2018. Stations with transbasin diversions and urban land cover excluded.

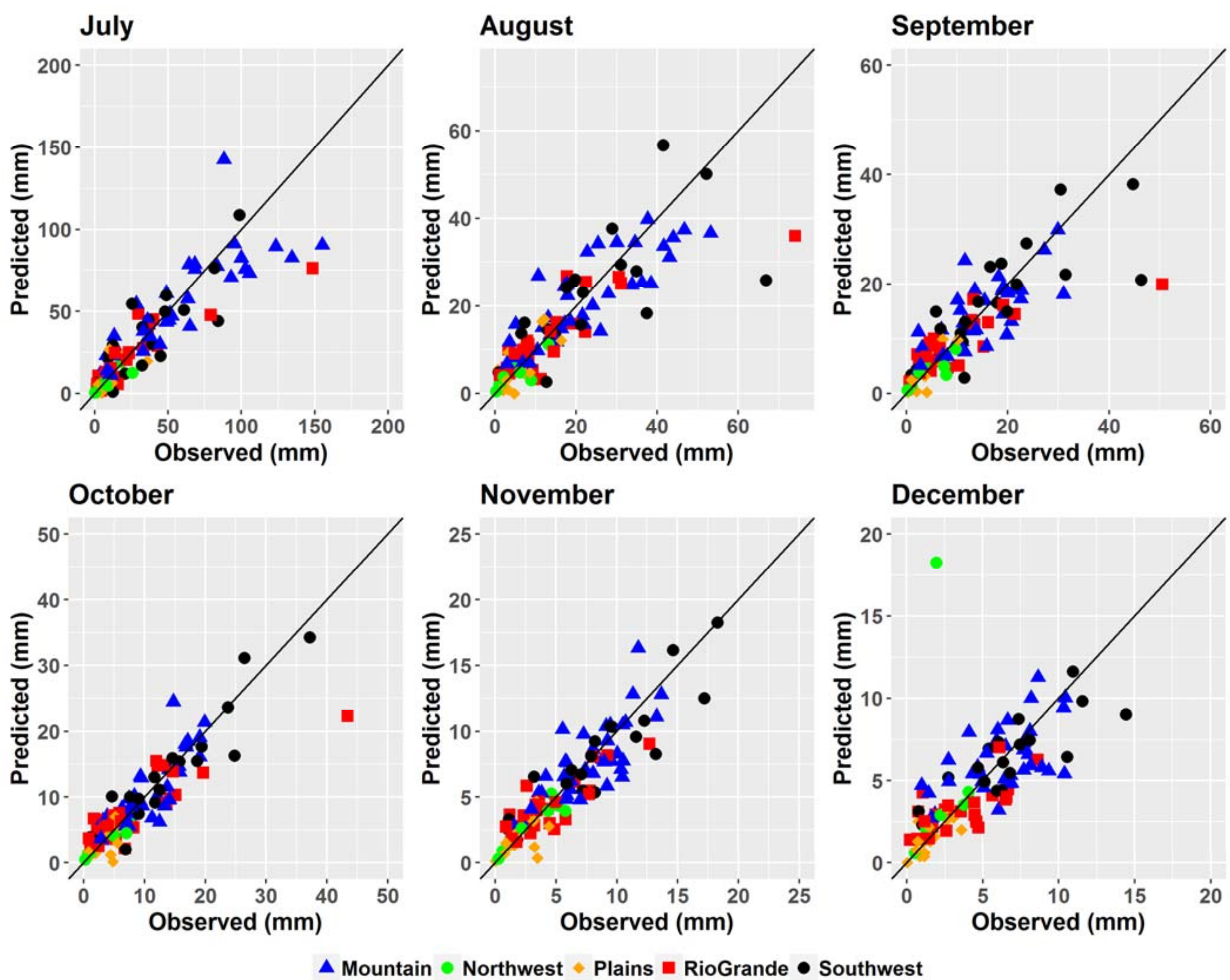

Figure 12, continued

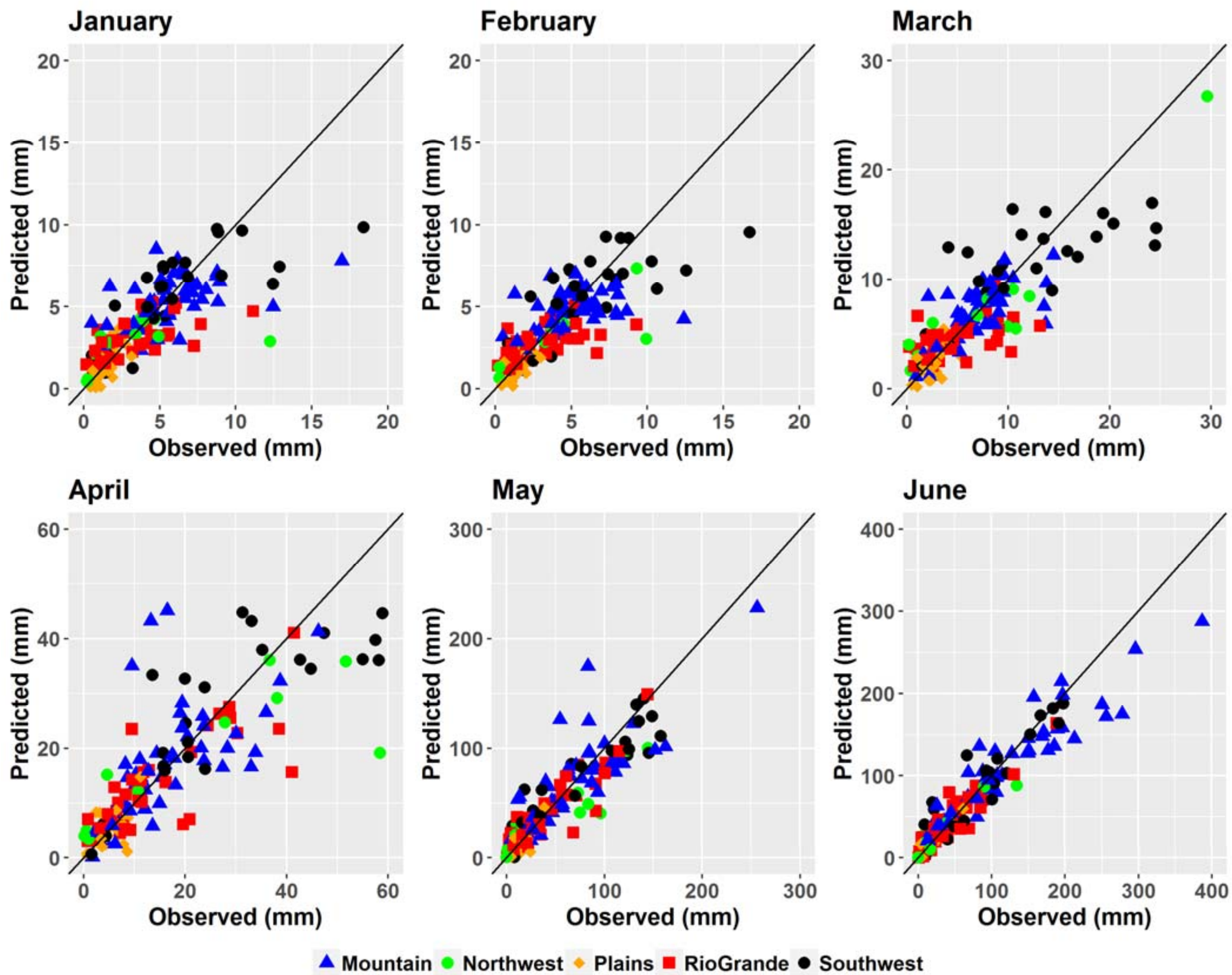

Figure 13. Predicted vs. observed mean monthly discharge using the new empirical model for 2001-2018. Stations with transbasin diversions and urban land cover excluded.

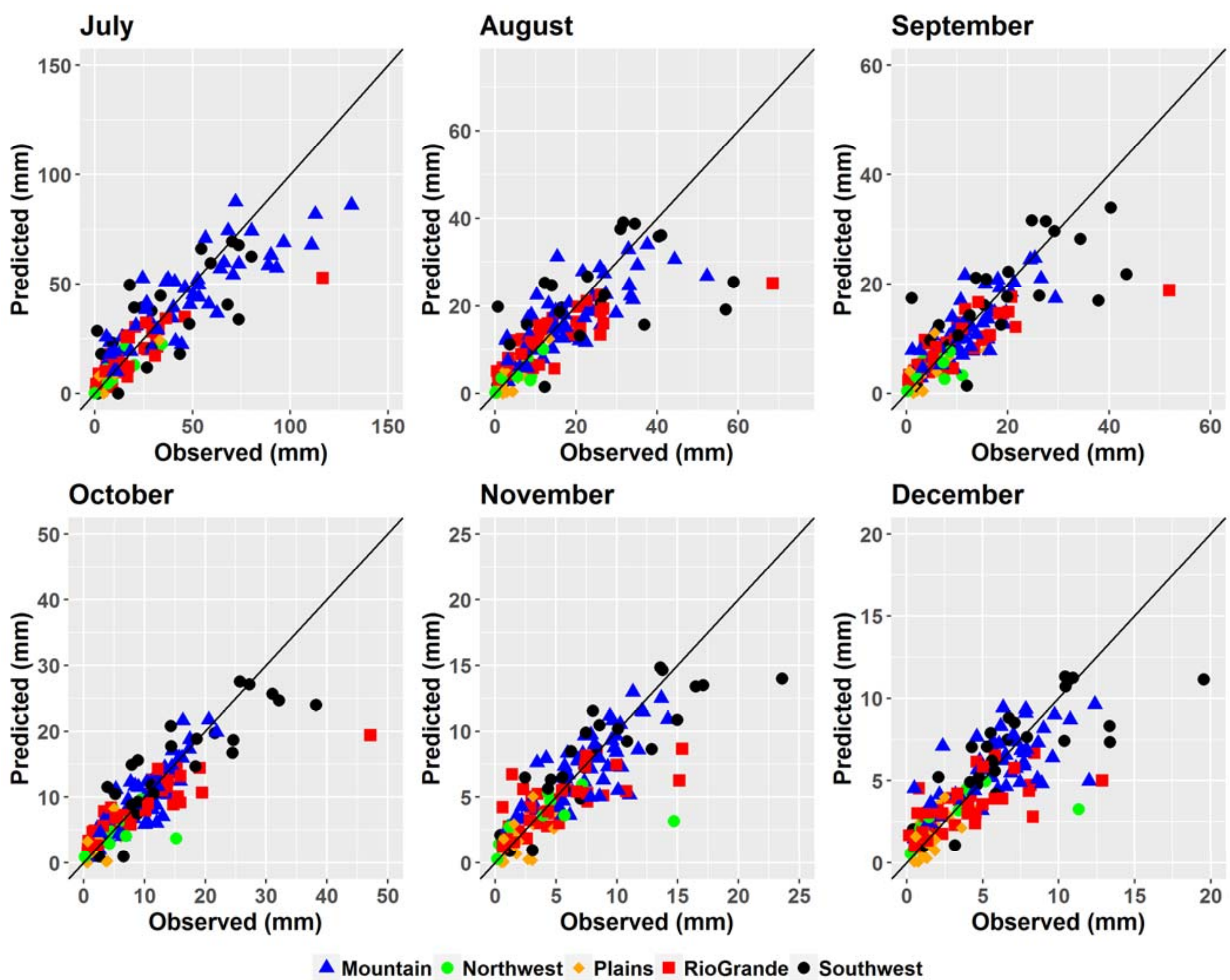

Figure 13, continued

3.5. Model comparison and evaluation

All of the models evaluated had good performance for mean annual discharge (Figure 14), with NSE 0.68-0.89; the highest NSE was for the new empirical model that uses SP. Percent bias ranged from -8 to 15. The model performance was more variable for mean monthly discharge. In most cases the new empirical models had the strongest performance. These models had NSE from 0.5-0.6 in winter months, increasing to 0.7-0.9 during late spring – early summer. Percent bias was relatively consistent at around -5 for most months.

The USGS regression equations had similar performance to the new empirical models in Oct-Apr, but they did not perform as well during June-September, when NSCE values were 0.4-0.5. Percent bias was also more variable between months, with high bias in May and June and low bias in August-October. The percent bias was higher for 2001-2018 than for 1981-2018 in USGS regression predictions. VIC model performance was seasonally variable, with strongest performance in May and June, when NSE was around 0.6 and percent bias near 0. Performance was substantially lower in other months, when the model had a large negative bias.

We compared our model evaluations to the performance statistics reported by Capesius and Stephens (2009) and Kohn et al. (2015) using the adjusted R^2 metric, as these previous studies did not report NSE or percent bias. Adjusted R^2 is similar to NSE for the relative performance and seasonal patterns of the models evaluated. For mean annual discharge, the adjR^2 values reported in the previous studies are similar to those we identified here. For mean monthly discharge, the previous studies reported higher adjR^2 for the same regression equations. This is likely because the previous studies used a larger number of stream gauges and did not include the restriction that gauges all be analyzed over the same time period.

Next we evaluated whether the new regression models and USGS regression equations would perform reliably for predicting streamflow during other time periods not used to develop the new model. For mean annual flow, the new empirical model has fairly consistent NSE ranging from 0.75-0.9 across decades, whereas the USGS model had good performance (NSE>0.75) in decades since 1980 but poorer performance for earlier decades (Figure 15). The USGS model tended to over-predict mean annual flow, whereas the new empirical model tended to under-predict, particularly in the 1940s and 1980s.

For mean monthly flow, the USGS regressions performed better than the new empirical models for winter months November- February (Figure 16), whereas the empirical models tended to perform better for the snowmelt runoff months April-June. In March, the USGS models performed better than the empirical models for early decades (1930-1970), after which the empirical model had better performance. Both models again tended to have positive biases up to the 1970s, after which the USGS model had large negative biases in March. In April-June, the USGS models tended to have positive biases, particular for earlier decades 1930-1970, whereas the empirical models tended to have negative biases. During summer months the two models had similar performance across decades. Both models tended to have negative biases in July and August, whereas in September and October, biases were positive in early decades (1930-1970) and negative in more recent decades.

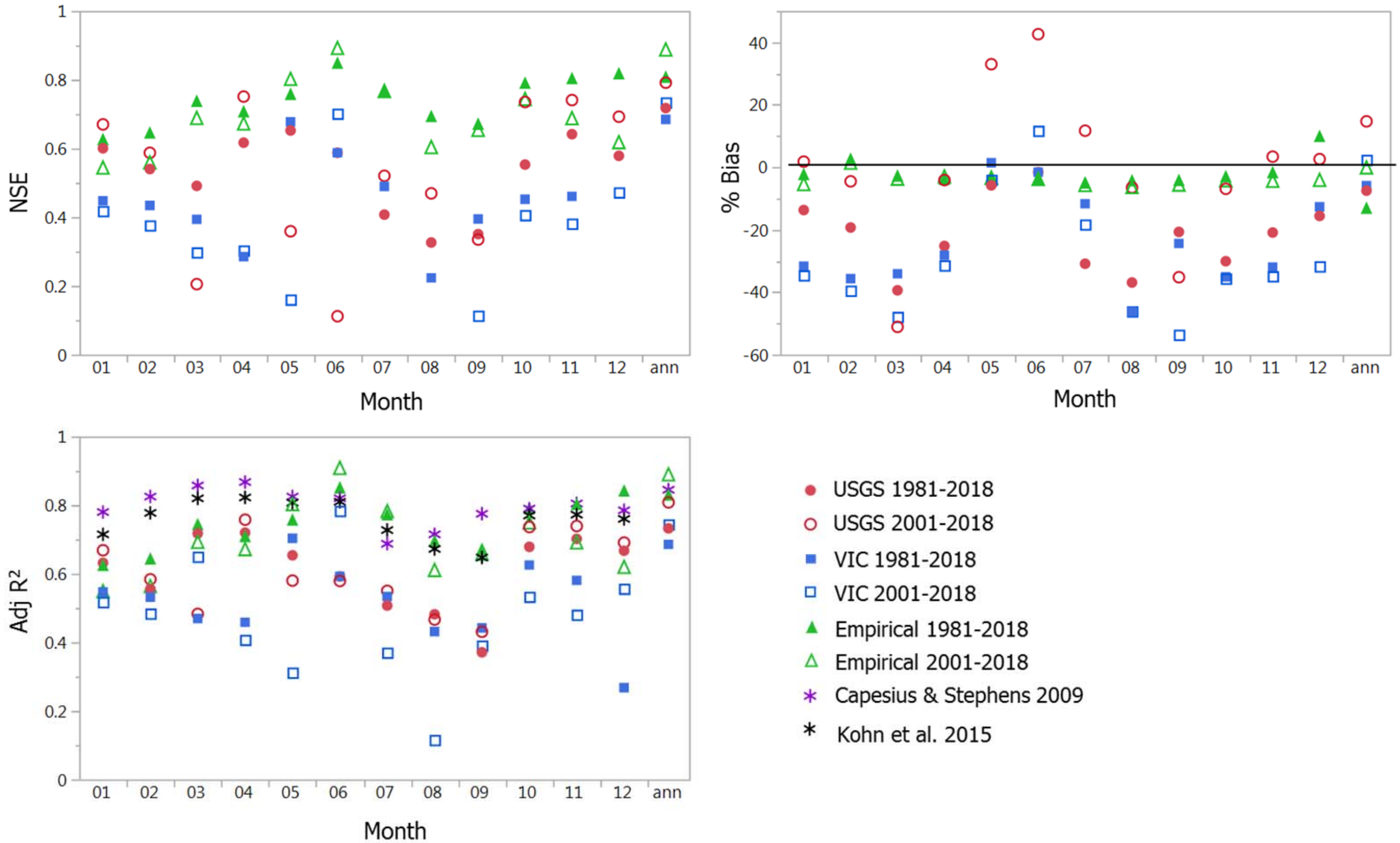

Figure 14. Performance comparison of mean monthly and mean annual (ann) discharge models. NSE is the Nash-Sutcliffe Efficiency Coefficient; Adj R^2 is the adjusted coefficient of determination. USGS refers to the Capesius and Stephens (2009) regression equations applied to the time period indicated, and empirical is the newly developed models. Values for Capesius and Stephens (2009) and Kohn et al. (2015) are the average values for all hydrologic regions.

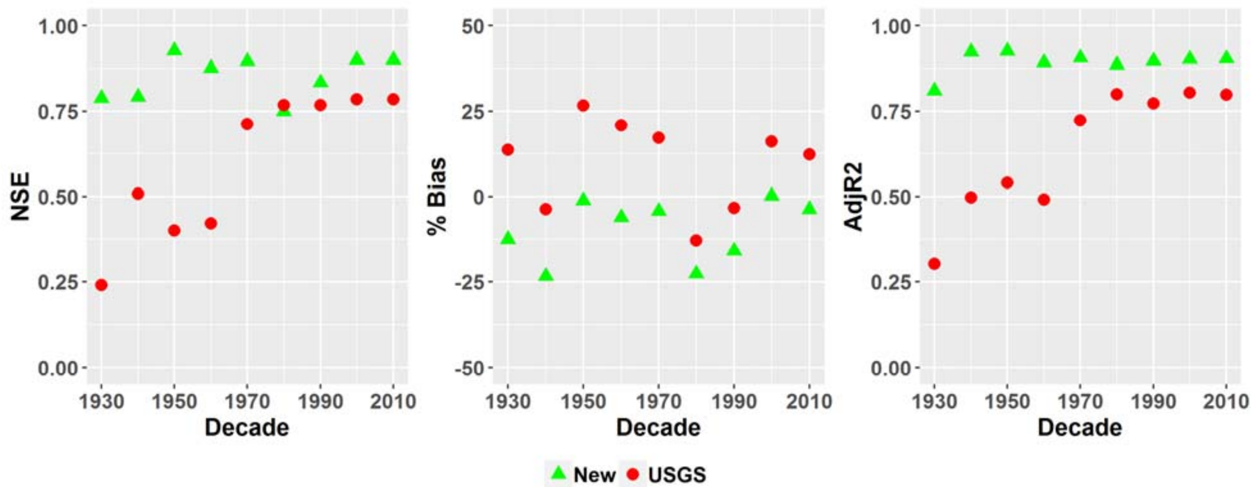

Figure 15. Performance comparison of mean annual discharge models by decade. NSE is the Nash-Sutcliffe Efficiency Coefficient; Adj R^2 is the adjusted coefficient of determination. USGS refers to the Capesius and Stephens (2009) regression equations applied to each decade, and New is the newly developed empirical models (Table 5, 2001-2018).

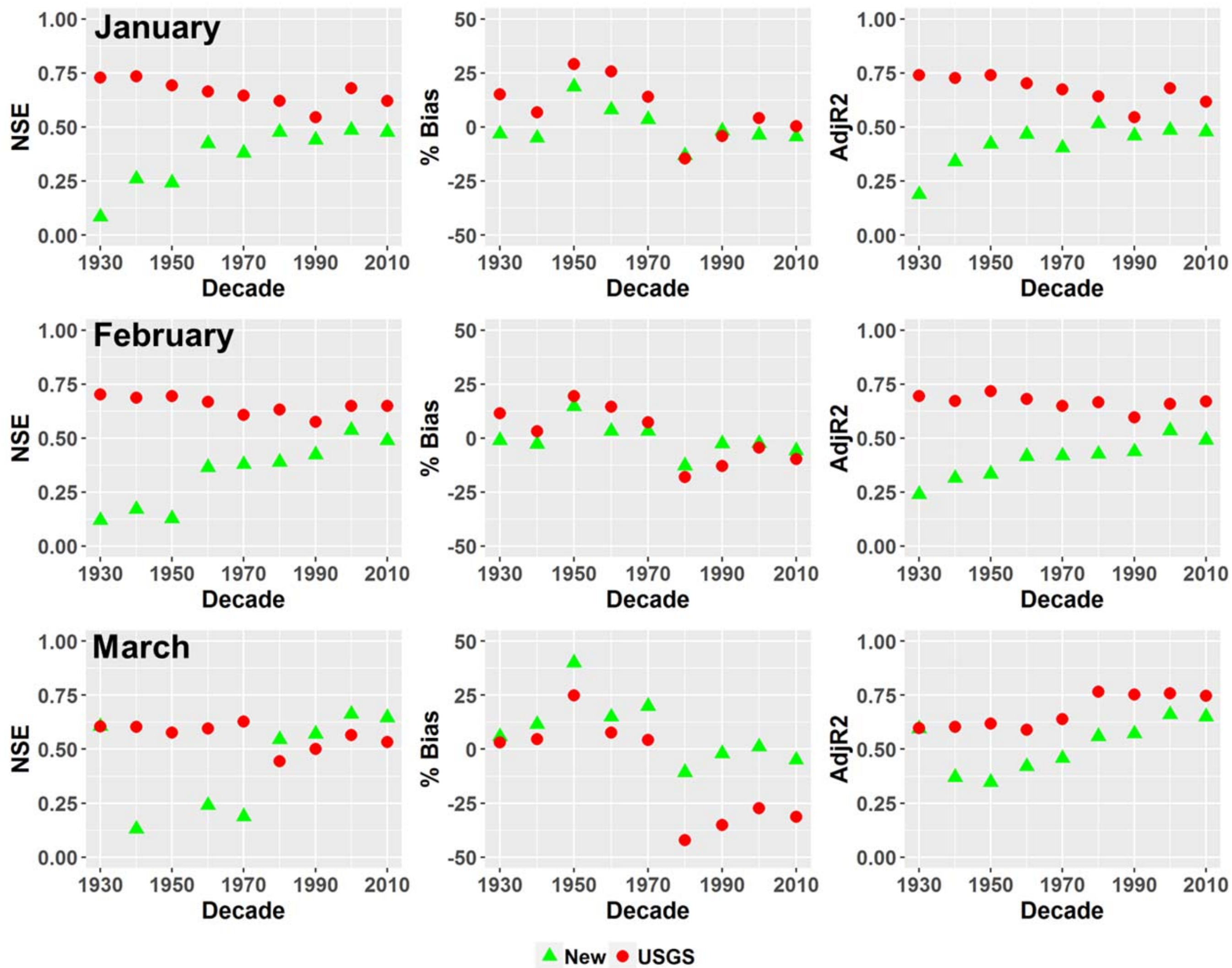

Figure 16. Performance comparison of mean monthly discharge models by decade. NSE is the Nash-Sutcliffe Efficiency Coefficient; Adj R^2 is the adjusted coefficient of determination. USGS refers to the Capesius and Stephens (2009) regression equations applied to each decade, and New is the newly developed empirical models (Table 5, 2001-2018).

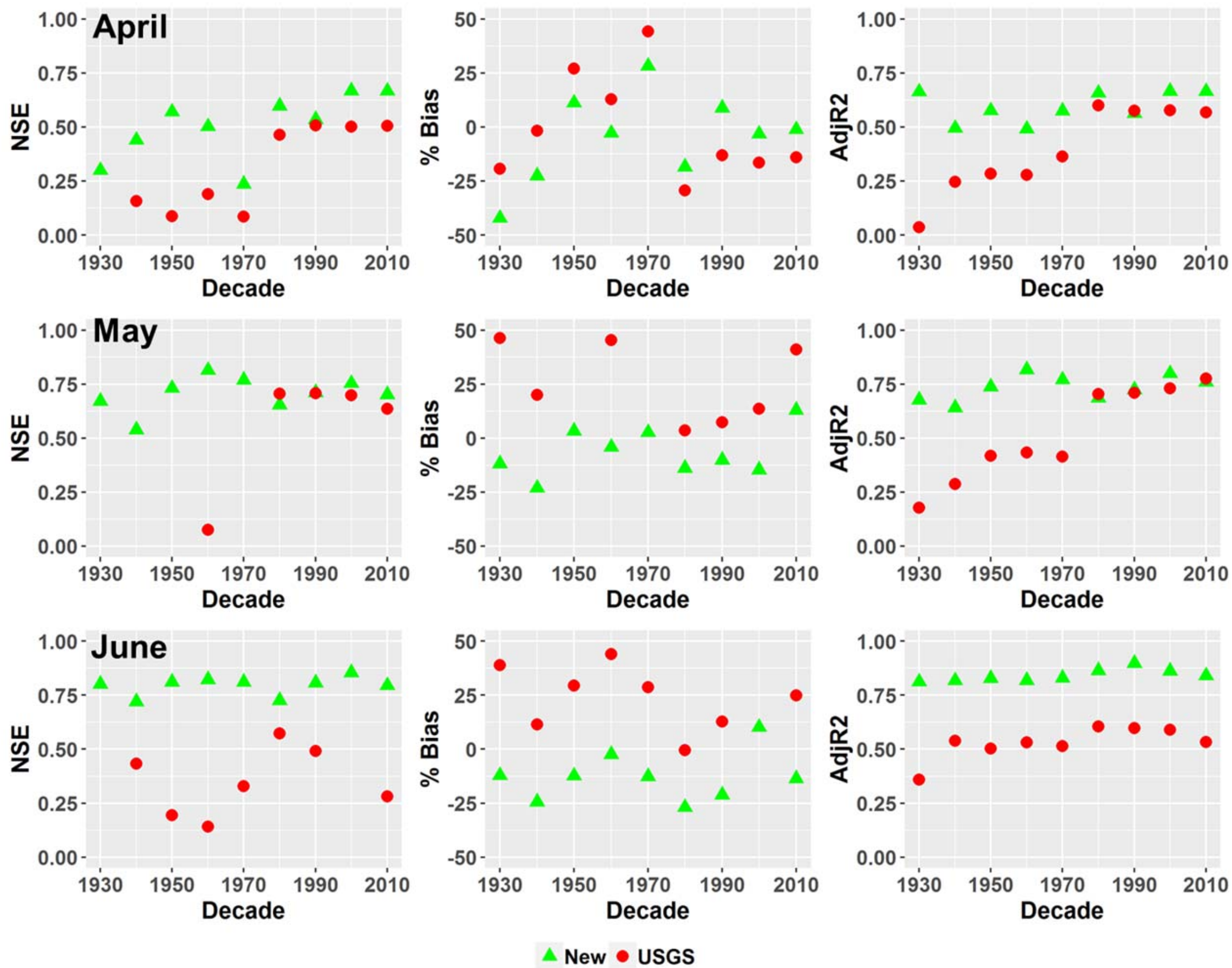

Figure 16. continued

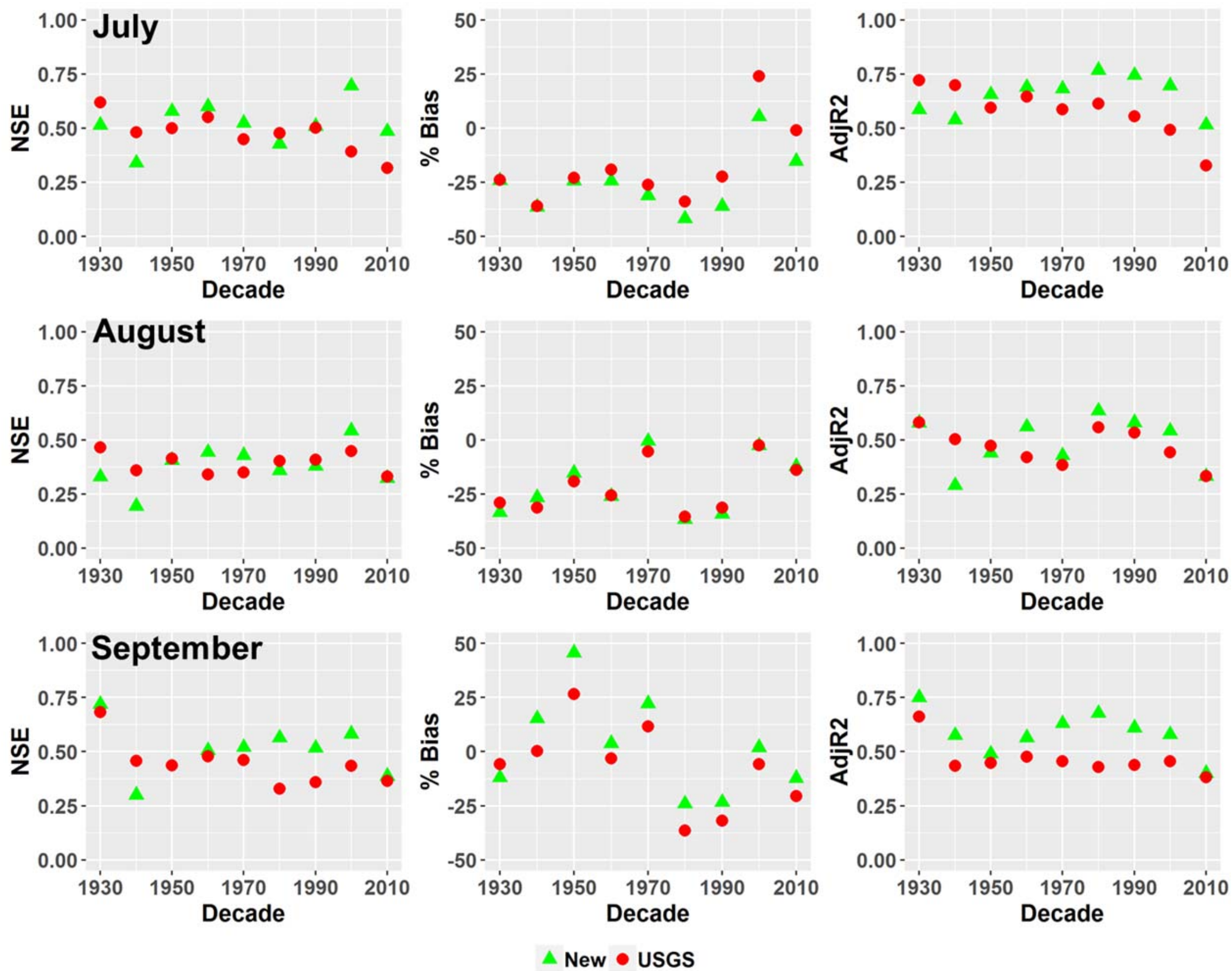

Figure 16. continued

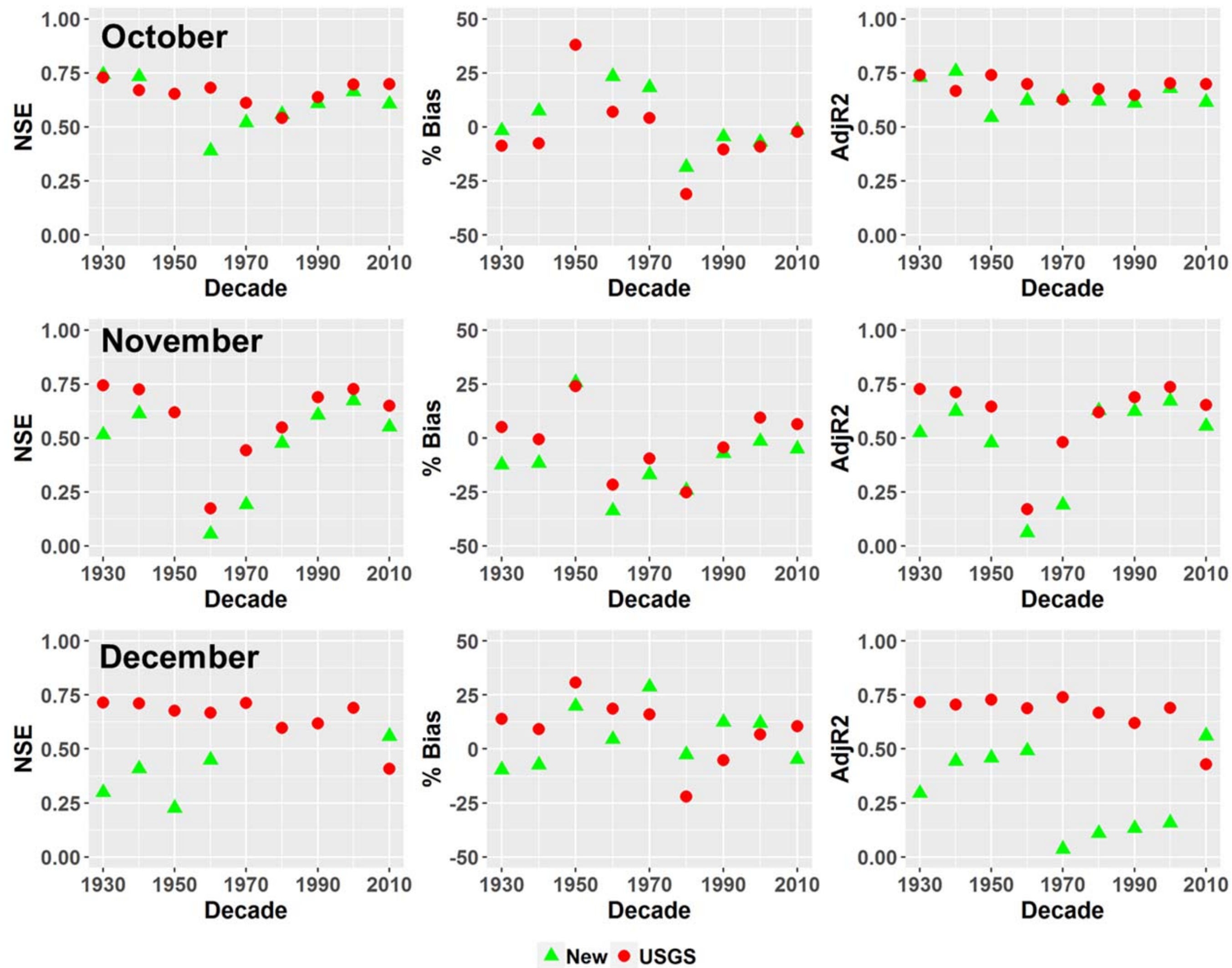

Figure 16. continued

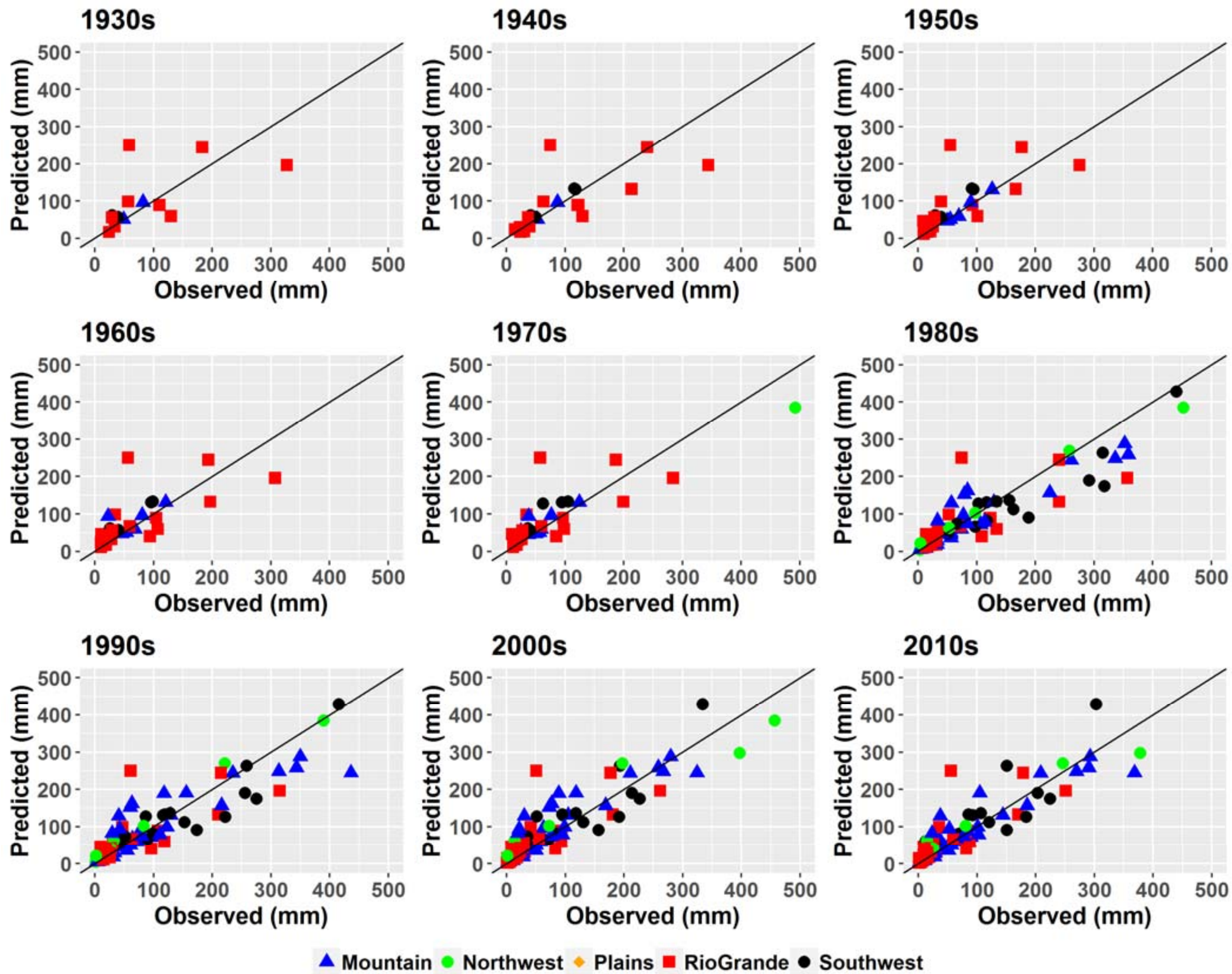

Figure 17. Predicted vs. observed mean annual flow by decade, with predicted values from the USGS regression equations.

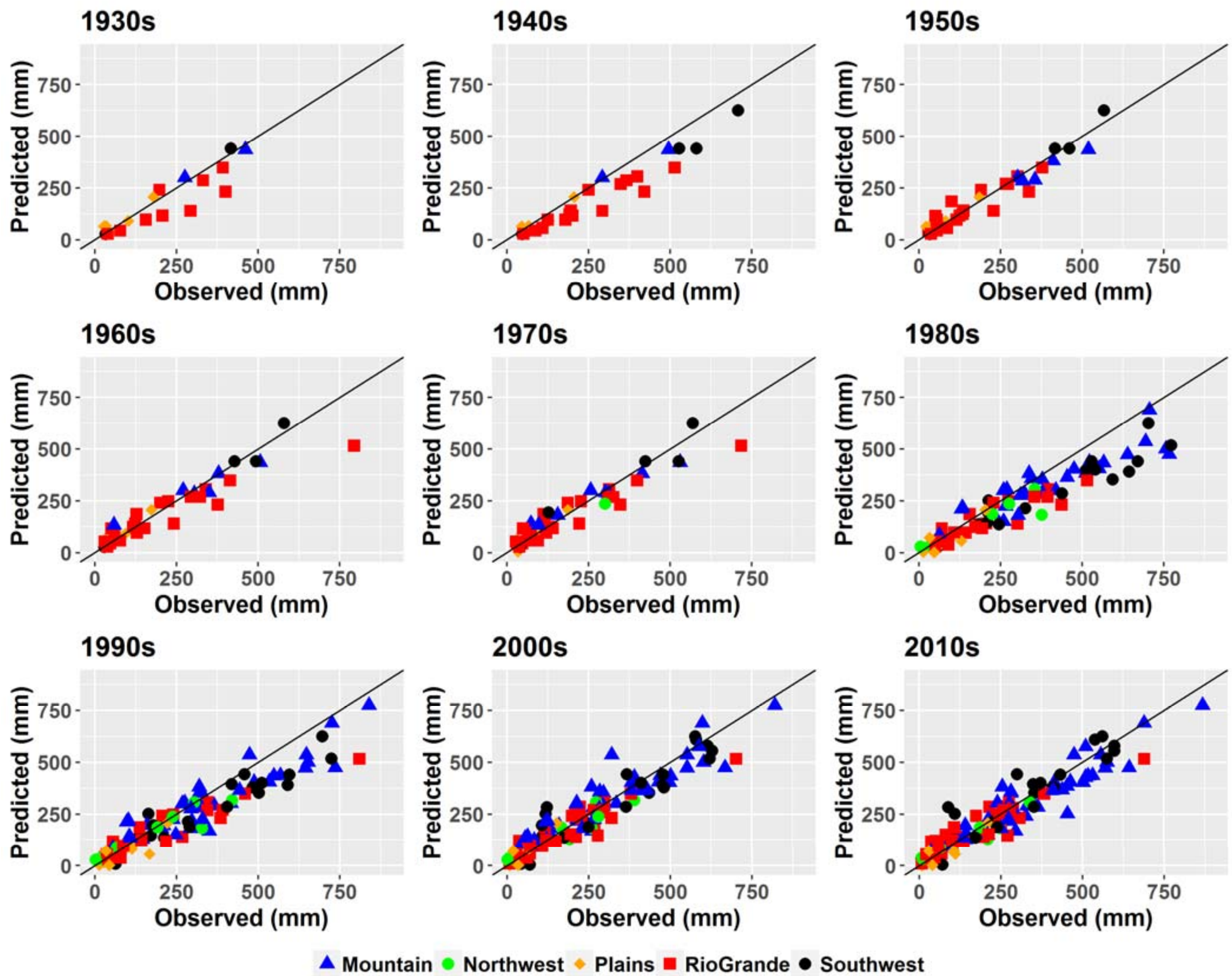

Figure 18. Predicted vs. observed mean annual flow by decade, with predicted values from the new regression equations (Table 5, 2001-2018).

4. Discussion

All of the models we tested had comparable and strong performance for predicting mean annual discharge. The best performing model was the new empirical model that incorporated snow persistence. This may be because the USGS regional regressions only account for precipitation and/or elevation, which may not fully capture patterns in snow accumulation. Snow accumulation and persistence is affected by additional factors such as temperature and slope aspect, and this may be why it provides added value for annual streamflow prediction. The new empirical models also differ from the USGS regressions in that they predict area-normalized discharge. Normalizing by area spreads out the range of annual streamflow values and reduces the need for area as an independent predictor.

The mean monthly discharge models diverged more in performance between models and months. The new models usually performed the best, followed by USGS regional regressions, then VIC. The new model performance was relatively consistent between months, compared to the USGS monthly models, which tended to under-predict low flows in Jan-Mar and Aug-Oct and over-predict high flows in May-Jun. Both the new models and the USGS regressions used mean annual precipitation as predictors, but the new models additionally used mean watershed slope. Coefficient values for the slope variable changed substantially between months, and it may be that addition of slope allowed for more consistent model performance across months. VIC simulations under-predicted flow in most months except May and June; this was the only uncalibrated model tested, so we would not expect the uncalibrated values to perform as well as the other models.

Regression models do not account for changing climate conditions, instead using mean annual variables such as precipitation and snow persistence to predict streamflow. Typically these types of models are developed using the longest time series of data possible for each station, so that the data record captures the full range of possible streamflow variability. While this approach is beneficial for maximizing the amount of data used to develop a regression model, it can also introduce biases because some locations or time periods can be over- or under-represented in the dataset. To avoid this type of bias introduced by varying data record lengths, we used a shorter but consistent period of record for all stations to develop our new regression models. Even with this reduced period for record, the resulting models performed as well as or better than the USGS regression models for predicting mean annual flow and most mean monthly flows during prior decades (Figure 16). The new regression models are only weaker than the USGS regression models for winter months in prior decades. This may be because the advantage the new models gain by adding the snow persistence variable is most evident during snowmelt runoff, whereas snow persistence provides little value for predicting streamflow during the winter snow accumulation season.

In addition to bias introduced by sample size, the regression models can also be biased by gaging station location. The gauging stations are most highly concentrated in high elevations, with few stations on small watersheds in the northwest and plains (Figure 1). This impacts the model performance, particularly in the northwest, which has several stations that diverge substantially from predicted values in the models. Expansion of the streamflow gauging network to include under-represented areas could help in developing improved ungauged streamflow predictions.

While both the USGS and new regression models are relatively reliable for predicting streamflow across a wide range of climate conditions (Figures 15,16), their performance was not always consistent between decades. Variability in regression model performance between decades likely relates to the sample size, which increased over the decades (Figures 17, 18), and this caused the systematic improvements in NSE and AdjR2 for the USGS regressions (Figure 15). A large increase in the number of stations in the 1980s may also have led to the shift in bias evident for many of the models between the 1970s and 1980s (Figure 16). Future work could expand the dataset to test the equations on additional stations during the earlier decades to evaluate the sample size effect. The relationships between precipitation, snow, and streamflow may also have been changing over the time period analyzed. These effects are challenging to disentangle from the effects of changing sample size over time, but future research evaluate the stationarity of relationships between precipitation and streamflow over the period of record.

5. Conclusions

This study evaluated three model types for predicting mean annual and mean monthly flow in Colorado streams. We found that all of the models have comparable performance for predicting mean annual flow, with the best-performing model incorporating mean annual snow persistence from the MODIS satellite sensor. For mean monthly flow, new empirical models tend to have the best and most consistent performance across months, whereas the USGS regressions have seasonal variability in bias, with under-predictions in low flows and over-predictions during peak snowmelt runoff. The new regression models out-perform the USGS regression equations for predicting mean annual flow prediction in prior decades, and they also perform better for predicting mean monthly flow in April-June. Both models have comparable performance during summer and fall months, and the USGS models perform better than the new regression models for winter months. While the VIC model does not perform as well as the other two models, that is because it is the only uncalibrated model. Future work could expand on the uncalibrated VIC model results presented here and examine what model changes would be needed to improve streamflow predictions throughout the state.

References

Abatzoglou, J. (2013). Development of gridded surface meteorological data for ecological applications and modelling. *International Journal of Climatology, 33*(1), 121-131.

Bartoń, Kamil. (2019). MuMIn: Multi-model inference. R package version 1.43.6. https://CRAN.R-project.org/package=MuMIn.

Capesius, J.P., and Stephens, V.C. (2009). Regional regression equations for estimation of natural streamflow statistics in Colorado: U.S. Geological Survey Scientific Investigations Report 2009–5136, 46 p.

Cherry, J., Cullen, H., Visbeck, M., Small, A., Uvo, C., 2005. Impacts of the North Atlantic Oscillation on Scandinavian Hydropower Production and Energy Markets. Water Resour. Manag. 19, 673–691. https://doi.org/10.1007/s11269-005-3279-z

Christensen, N. S., Wood, A. W., Voisin, N., Lettenmaier, D. P., & Palmer, R. N. (2004). The effects of climate change on the hydrology and water resources of the Colorado River basin. *Climatic change*, *62*(1-3), 337-363.

Daly, C. (2013). Descriptions of PRISM spatial climate datasets for the conterminous United States (PRISM Doc., 14 p.). Corvallis, OR: PRISM Climate Group, Oregon State University.

Fox, John and Sanford Weisberg (2011). An {R} Companion to Applied Regression, Second Edition. Thousand Oaks CA: Sage. URL: http://socserv.socsci.mcmaster.ca/jfox/.

Georgakakos, A.P., Yao, H., Mullusky, M.G., Georgakakos, K.P., 1998. Impacts of climate variability on the operational forecast and management of the Upper Des Moines River Basin. Water Resour. Res. 34, 799–821. https://doi.org/10.1029/97WR03135

Hall, D.K. and Riggs, G.A. (2016) MODIS/Terra Snow Cover 8-Day L3 Global 500m Grid, Version 6 [2000-01-01:2016-12-31]. Boulder, CO: NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi-org.ezproxy2.library.colostate.edu/10.5067/MODIS/MOD10A2.006.

Hammond, J. C., Saavedra, F. A., & Kampf, S. K. (2017). MODIS MOD10A2 derived snow persistence and no data index for the western U.S. Cambridge, MA: Hydroshare. https://doi-org.ezproxy2.library.colostate.edu/10.4211/hs.1c62269aa802467688d25540caf2467e

Hammond JC, Saavedra FA, Kampf SK, 2018. How does snow persistence relate to annual streamflow in mountain watersheds of the western U.S. with wet maritime and dry continental climates? Water Resources Research 54(4), 2605-2623, doi:10.1002/2017WR021899.

Harpold, A.A., Sutcliffe, K., Clayton, J., Goodbody, A., Vazquez, S., 2017. Does Including Soil Moisture Observations Improve Operational Streamflow Forecasts in Snow-Dominated Watersheds? JAWRA J. Am. Water Resour. Assoc. 53, 179–196. https://doi.org/10.1111/1752-1688.12490

Kohn, M.S., Stevens, M.R., Bock, A.R., and Char, S.J., 2015, Evaluation of mean-monthly streamflow-regression equations for Colorado, 2014: U.S. Geological Survey Scientific Investigations Report 2015–5016, 53 p., http://dx.doi.org/10.3133/sir20155016.

Kuhn, M, Wing, J., Weston, S., Williams, A., Keefer, C., Engelhardt,A., Cooper,T., Mayer,Z., Kenkel, B, & the R Core Team (2019). caret: Classification and Regression Training. R package version 6.0-84. https://CRAN.R-project.org/package=caret

Liang, X., Lettenmaier, D. P., Wood, E. F., & Burges, S. J. (1994). A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research: Atmospheres*, *99*(D7), 14415-14428.

Livneh, B., Bohn, T. J., Pierce, D. W., Munoz-Arriola, F., Nijssen, B., Vose, R., ... & Brekke, L. (2015). A spatially comprehensive, hydrometeorological data set for Mexico, the US, and Southern Canada 1950–2013. *Scientific data*, *2*, 150042.

McGuire Marketa, Wood Andrew W., Hamlet Alan F., Lettenmaier Dennis P., 2006. Use of Satellite Data for Streamflow and Reservoir Storage Forecasts in the Snake River Basin. J. Water Resour. Plan. Manag. 132, 97–110. https://doi.org/10.1061/(ASCE)0733-9496(2006)132:2(97)

Moore C, Kampf S, Stone B, Richer E. 2015. A GIS-based method for defining snow zones: application to the western United States. Geocarto International 30(1), 62-81, DOI 10.1080/10106049.2014.885089.

National Hydrography Dataset Plus – NHDPlusV2. (2012) U.S. Environmental Protection Agency (USEPA) and the U.S. Geological Survey (USGS). <http://www.epa.gov/waters>

PRISM Climate Group, Oregon State University, http://www.prismclimate.org, created 4 Feb 2004.

R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Sankarasubramanian, A., Lall, U., 2003. Flood quantiles in a changing climate: Seasonal forecasts and causal relations. Water Resour. Res. 39, 1134. https://doi.org/10.1029/2002WR001593

Shi, X., Wood, A. W., & Lettenmaier, D. P. (2008). How essential is hydrologic model calibration to seasonal streamflow forecasting?. *Journal of Hydrometeorology*, *9*(6), 1350-1363.

Tang, Q., Lettenmaier, D.P., 2010. Use of satellite snow-cover data for streamflow prediction in the Feather River Basin, California. Int. J. Remote Sens. 31, 3745–3762. https://doi.org/10.1080/01431161.2010.483493

USDA-USGS Mineral Resources. 2005. State geologic maps. <http://pubs.usgs.gov/of/2005/1351/>.

Vano, J. A., Das, T., & Lettenmaier, D. P. (2012). Hydrologic sensitivities of Colorado River runoff to changes in precipitation and temperature. *Journal of Hydrometeorology*, *13*(3), 932-949.

Werner, K., Brandon, D., Clark, M., Gangopadhyay, S., 2004. Climate Index Weighting Schemes for NWS ESP-Based Seasonal Volume Forecasts. J. Hydrometeorol. 5, 1076–1090. https://doi.org/10.1175/JHM-381.1

Woodhouse, C.A., Pederson, G.T., Morino, K., McAfee, S.A., McCabe, G.J., 2016. Increasing influence of air temperature on upper Colorado River streamflow. Geophys. Res. Lett. 43, 2015GL067613. https://doi.org/10.1002/2015GL067613

Zambrano-Bigiarini, Mauricio. (2017) hydroGOF: Goodness-of-fit functions for comparison of simulated and observed hydrological time series. R package version 0.3-10. URL http://hzambran.github.io/hydroGOF/. DOI:10.5281/zenodo.840087.

Addendum: Hydrologic Monitoring for Streamflow Prediction in Colorado Ungauged Basins

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Colorado State University

Gigi Richard

Fort Lewis College

Joel Sholtes

Colorado Mesa University

Part of the 2019 funding for the Streamflow Prediction in Colorado Ungauged Basins project supported a network of hydrologic monitoring sites across the state. These sites were described in our 2018 project report, and they will be integrated with the statewide analysis for next year's report. We maintain five sites across an elevation gradient in the Front Range, three sites near Grand Junction, and three sites in the Uncompahgre Basin. This addendum summarizes briefly the monitoring activities at each location.

Colorado Front Range: The CSU group continued to monitor snow depth, rain, air temperature, soil moisture, soil temperature, stream stage, and stream discharge at Andrews Meadow and Michigan River (high elevation, persistent snow); Dry Creek and Bighorn Creek (middle elevation, transitional snow); and Mill Creek (low elevation, intermittent snow). Abby Eurich (MS student) led the monitoring in collaboration with Kira Puntenney-Desmond (research associate) after John Hammond (PhD graduate) left for a new USGS job. Lenka Doskocil (undergraduate) assisted with field work and data processing.

Grand Junction: The CMU group monitored the same variables at Grand Mesa persistent (high elevation, persistent snow), Grand Mesa transitional (middle elevation, transitional snow), and Colorado National Monument intermittent (low elevation, intermittent snow) sites. The Grand Mesa transitional site has a poor stream stage-discharge rating curve, so the group is working on adding a flume to that site to improve streamflow measurements. The Colorado National Monument site rarely has flow, so developing a rating curve is not possible. The group plans to develop a synthetic rating curve with a hydraulic model. Joel Sholtes is now leading this monitoring effort working with undergraduate student Meghan Cline.

Uncompahgre: The Uncompahgre sites have been maintained by Gigi Richard at Fort Lewis College with help from undergraduate student Sierra Heimel. These sites include Senator Beck (high elevation, persistent snow), Uncompahgre transitional (middle elevation, transitional snow), and Ridgway (low elevation, intermittent snow). All of these sites have been challenging to maintain. The extremely deep snow at Senator Beck this winter broke the stream stage sensor.

Both ice and debris repeatedly buried the stream stage sensor at the transitional site, and the intermittent site was damaged by vandalism. Consequently we decided to take down the transitional and intermittent sites and plan to move them to new locations closer to Fort Lewis College next project year.