Prepared in cooperation with Colorado State University

Modeled Streamflow Metrics on Small, Ungaged Stream Reaches in the Upper Colorado River Basin

Data Series 974

U.S. Department of the Interior
U.S. Geological Survey

Cover. Left: Henrieville Creek near Henrieville, Utah, a perennial stream. Photograph taken by Joel Shute and Mark Paglierani (2012). Right: Coyote Creek, Utah, near Page, Arizona, an intermittent stream. Photograph taken by Joel Shute and Mark Paglierani (2012).

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Conversion Factors

[Inch/Pound to International System of Units]

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as
°F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as
°C = (°F – 32) / 1.8.

Horizontal coordinate information is referenced to the North American Datum of 1983 with an Albers projection (NAD 83 Albers).

Modeled Streamflow Metrics on Small, Ungaged Stream Reaches in the Upper Colorado River Basin

By Lindsay V. Reynolds[1,2] and Patrick B. Shafroth[2]

Abstract

Modeling streamflow is an important approach for understanding landscape-scale drivers of flow and estimating flows where there are no streamgage records. In this study conducted by the U.S. Geological Survey in cooperation with Colorado State University, the objectives were to model streamflow metrics on small, ungaged streams in the Upper Colorado River Basin and identify streams that are potentially threatened with becoming intermittent under drier climate conditions. The Upper Colorado River Basin is a region that is critical for water resources and also projected to experience large future climate shifts toward a drying climate. A random forest modeling approach was used to model the relationship between streamflow metrics and environmental variables. Flow metrics were then projected to ungaged reaches in the Upper Colorado River Basin using environmental variables for each stream, represented as raster cells, in the basin. Last, the projected random forest models of minimum flow coefficient of variation and specific mean daily flow were used to highlight streams that had greater than 61.84 percent minimum flow coefficient of variation and less than 0.096 specific mean daily flow and suggested that these streams will be most threatened to shift to intermittent flow regimes under drier climate conditions. Map projection products can help scientists, land managers, and policymakers understand current hydrology in the Upper Colorado River Basin and make informed decisions regarding water resources. With knowledge of which streams are likely to undergo significant drying in the future, managers and scientists can plan for stream-dependent ecosystems and human water users.

Introduction

Modeling streamflow is an important approach for understanding landscape-scale drivers of flow and estimating flows where there are no gaged records (Carlisle and others, 2010; Murphy and others, 2012). The number of streams instrumented to measure flow are decreasing because of funding limitations (http://streamstats09.cr.usgs.gov/ThreatenedGages/ThreatenedGages.html). In addition, with projected changes in future climate conditions, there is a need to estimate the effects of climate change on streamflow (Teng and others, 2012); therefore, modeled projections of streamflow are essential for scientists, managers, and policymakers to make informed decisions regarding water resources and stream-dependent ecosystems (Eng and others, 2013; Teng and others, 2012).

In the southwestern United States, mean annual streamflow is projected to decrease during the next century because of changing climate conditions (Seager and others, 2013). Some studies suggest strong seasonal signatures will result in increasing winter precipitation and streamflow (especially in northern latitudes) and decreasing late summer and fall precipitation and streamflow (especially in southern latitudes) because of climate change in western North America (Milly and others, 2005; Cayan and others, 2008; Colorado Water Conservation Board, 2010; Seager and others, 2013). In arid and semiarid regions of the western United States where intermittent streams are common, several studies predict that minimum flows will decrease, and the number of zero-flow days will increase in the future (Das and others, 2011; Leppi and others, 2011; Jaeger and others, 2014). Decreased minimum flows could lead some perennial streams to shift to intermittent streamflow regimes under climate-driven changes in timing and magnitude of precipitation and runoff and increases in temperature (Jaeger and others, 2014).

We focused the study on the Upper Colorado River Basin, which is a region that is not only critical for water resources but also projected to experience large future shifts towards a drier climate (Christensen and Lettenmaier, 2007; Clow, 2010; Seager and others, 2013). The Colorado River Basin is one of the most intensively managed river systems in the world and a vital water resource in the western United States supplying water for cities, agriculture, energy production, and natural ecosystems across seven states and two countries (Jerla and others 2012). This study was conducted by the U.S. Geological Survey in cooperation with Colorado State University with the objectives of producing maps of modeled streamflow metrics on small, ungaged streams in the Upper Colorado River Basin and identifying streams that

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are potentially threatened with becoming intermittent in the next century based on twentieth century hydrology and our understanding of modeled future climates. The datasets presented here build on analyses developed in a previous study by Reynolds and others (2015).

Study Area

The Upper Colorado River Basin extends from southwestern Wyoming to northern Arizona and New Mexico and includes the western one-half of Colorado and the eastern one-half of Utah (fig. 1). The headwater streams of the Upper Colorado River Basin form at high elevations in the Wind River, Uinta, Wasatch, and Colorado Rocky Mountains. Higher elevation and northern streams in the Upper Colorado River Basin are characterized by snowmelt peak runoff in the late spring that decreases to base flow in the late summer and early fall (Poff and Ward, 1989). Streams in the southern part of the Upper Colorado River Basin may experience a second streamflow peak in mid- to late summer associated with rainfall from the North American Monsoon, and this monsoon rainfall is often the primary driver of annual flow in smaller, southern Upper Colorado River Basin streams (Hereford and Webb, 1992; Ely, 1997; Gochis and others, 2006).

Methods

Streamflow Metrics

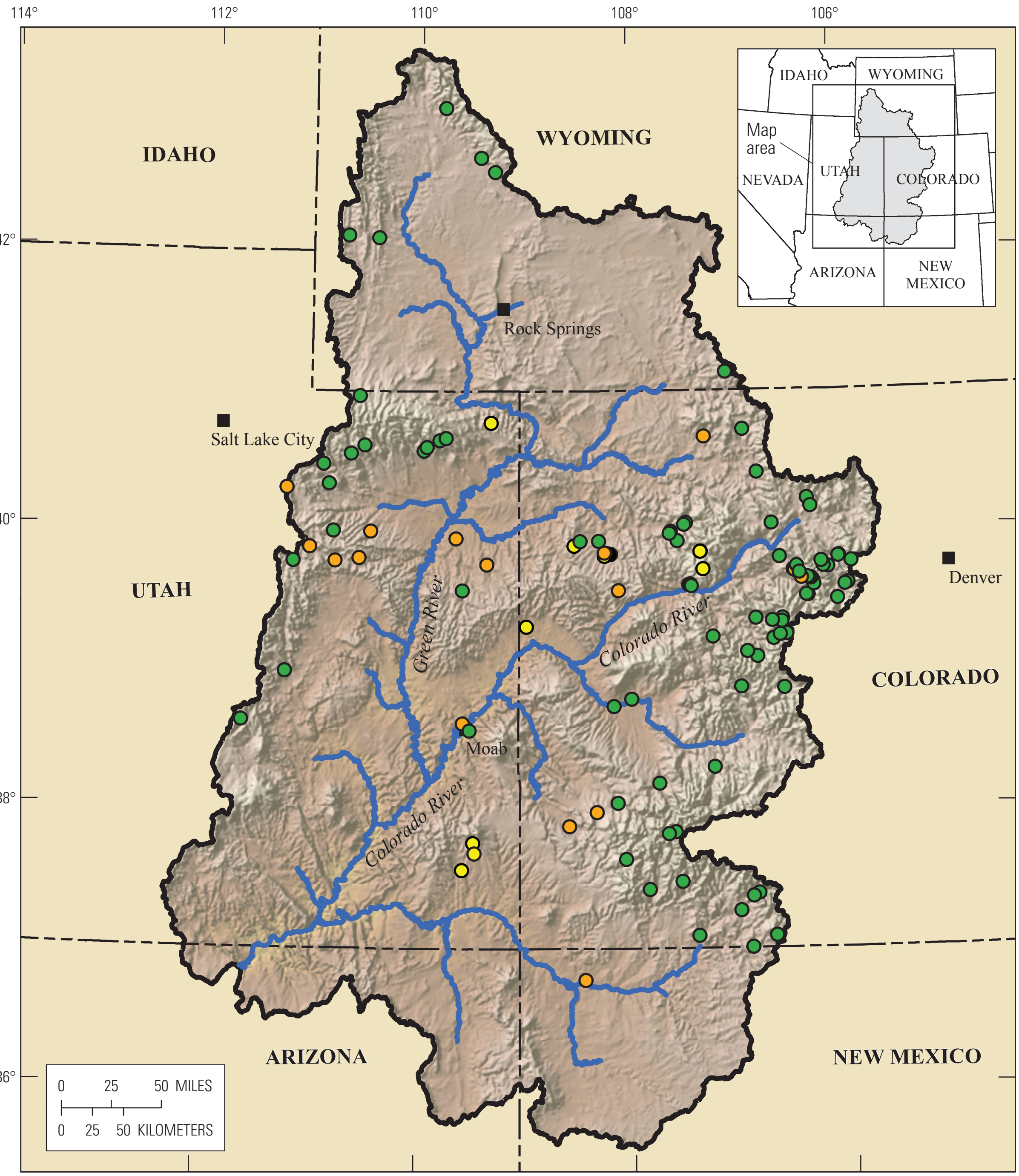
To train our models, we selected 115 streamgages with at least 8 years of data on small (1st–4th order), unaltered streams in the Upper Colorado River Basin (fig. 1; Reynolds and others, 2015). We selected nine flow metrics that are important to low-flow stream hydrology: minimum flow coefficient of variation (CV), baseflow, zero-flow days, zero-flow months, 7-day minimum, frequency of low-flow pulses, specific minimum flow, specific mean daily flow, and intermittency (table 1). All flow metrics except intermittency were calculated using the Hydrologic Index Tool (HIT) software on the historic daily streamflow data (Olden and Poff 2003; Heasley 2006; table 1). We defined intermittency based on zero-flow days and zero-flow months and placed the streams into three categories: strongly intermittent, weakly intermittent, or perennial. Stream reaches were strongly intermittent when greater than 5 percent of months during the period of record were zero-flow months and the number of zero-flow days averaged across years was greater than 20 per year; weakly intermittent when between 0 and 5 percent of months were zero-flow months and the number of zero-flow days averaged across years was between 0 and 20 years; and perennial when the percent of zero-flow months and the number of zero-flow days averaged across years were zero. If a stream, for example, had a 20-year period of record (240 months), at least 12 months of the record would have to have zero-flow days for the entire month, and an average across years of at least 20 zero-flow days per year, for the stream to qualify as strongly intermittent. The strongly intermittent stream category may also include ephemeral streams; however, we did not distinguish between strongly intermittent and ephemeral streams.

Environmental Covariates

Environmental covariates for our models were derived from Geographic Information System datasets of climate (17 datasets), soils (2 datasets), geology (13 datasets), and land cover (7 datasets) for each individual raster cell in the Upper Colorado River Basin stream network (Falcone, 2011; table 2). We used the National Hydrography Dataset Plus, version 1, flow accumulation raster (30-meter resolution) to represent stream cells in the Upper Colorado River Basin (NHDPlus, 2010). Temporal and spatial scale varied somewhat across the datasets depending on the nature of the data. Climate and soil rainfall runoff factor (R factor) data were mean values for 30-year periods (climate normals) in the latter one-half of the 20th century, which overlapped with the streamgage records that were used (table 2). Soil permeability, geology, and land-cover data did not have a temporal range and were associated with their publication dates (table 2). Since the spatial scales of environmental variables were different, we used the ArcGIS raster “resample” tool to resample each variable’s raster using the bilinear method to a 30-meter scale. Environmental variables were then accumulated for the upstream drainage area or a percentage of upstream drainage area was calculated for each cell as appropriate (table 2).

Model Development

We used a random forest approach to model the relationship between flow metrics and environmental variables (Cutler and others 2007). We rectified our gage site locations with the raster datasets of environmental variables for the random forests. To improve explanatory power and model fit, we implemented a model selection process where variables that fell below a calculated model improvement ratio were dropped from the model (Murphy and others 2010). We then selected the model that minimized mean square error (MSE) and maximized percentage of variation explained for each flow metric (Murphy and others 2010; Reynolds and others 2015). We assessed model fit with percentage of variation explained (pseudo-R^2), MSE, and a calculated P-value (a measure of the strength or statistical significance of a relation; smaller p-values indicate stronger relations) for the best model for each flow metric (Murphy and others 2010). To fit our models we used the “randomforest” function of R’s “RandomForest” package (R 3.0.0, R Development Core Team, 2013). The model for base flow was dropped from further analysis because of poor model performance and fit (less than



Base from U.S. Geological Survey
North America Shaded Relief, 2011

EXPLANATION

Upper Colorado River Basin

Study streamgages

- Strongly intermittent
- Weakly intermittent
- Perennial

Figure 1. The Upper Colorado River Basin study area elevation, major rivers, and study gage locations (strongly intermittent, weakly intermittent and perennial).

Table 1. Streamflow metrics modeled by environmental variables in the Upper Colorado River Basin.

[Adapted from Reynolds and others (2015). CV, coefficient of variation]

Streamflow metric	Definition (units)
Minimum flow CV	Standard deviation of annual minimum flows times 100 divided by the mean of annual minimum flows (percent).
Base flow	The mean of the ratios of the minimum annual flow to mean annual flow for each year times 100 (dimensionless).
Zero-flow days	Mean annual number of zero-flow days (days/year).
Zero-flow months on record	The number of months during which there was no flow during the entire record (months/record).
7-day minimum	Mean of the annual minimums of a 7-day moving average for each year (cubic foot per second).
Frequency of low-flow pulses	Mean of the annual average number of events below 5 percent of the mean flow for the entire record (number of events/year).
Specific minimum flow	Mean of the annual minimum flows divided by drainage area (cubic foot per second/square mile).
Specific mean daily flow	Mean for the entire flow record divided by drainage area (cubic foot per second/square mile).
Intermittency	Strongly intermittent, weakly intermittent, or perennial streams. See full definition of intermittency in the “Methods” section.

27 percent variance explained; Reynolds and others, 2015). More details of this modeling approach are included in Reynolds and others (2015).

Model Projection to Ungaged Streams

To project each flow metric to ungaged reaches in the Upper Colorado River Basin, we used the environmental variables for each stream raster cell in the basin to predict flow variables across the stream network. We used the “predict” function of R’s “raster” package (R Development Core Team, 2013) which uses the independent (environmental) variable data and the associated fitted model to predict a given flow metric at each stream raster cell. Because our random forest models were trained on streamgage data from small streams, we filtered out all stream cells in our projection maps with a drainage area greater than 4,000 square kilometers or approximately 5th order and greater streams. We repeated this process for each flow metric except base flow, which had poor model performance, and zero-flow months, which is not amenable to projection since its units are in months per record (table 1, Reynolds and others, 2015).

Predicting Streams Threatened with Intermittency

Last, we used the random forest models built in the “Model Development” section described above to predict which streams are currently perennial or only rarely intermittent and threatened to become intermittent under drier climate conditions. Reynolds and others (2015) used conditional inference tree models to show that stream intermittency was best predicted by the streamflow metrics minimum flow CV and specific mean daily flow with the thresholds of 230 percent minimum flow CV, 61.84 percent minimum flow CV, and 0.096 specific mean daily flow as particularly important thresholds for differentiating streams (Reynolds and others, 2015). Streams that had less than 61.84 percent minimum flow CV were perennial streams. Streams that had greater than 230 percent minimum flow CV were strongly intermittent streams. These first two groups of streams are unlikely to shift from their current hydrology of perennial or strongly intermittent despite a drier climate; however, our conditional inference tree indicated that streams between 61.84 and 230 percent minimum flow CV, and less than 0.096 specific mean daily flow were moderately dry streams, which included a mix of weakly intermittent and perennial streams (Reynolds and others, 2015). Because this set of streams includes perennial and weakly intermittent streams, we hypothesize that these streams are threatened to become intermittent under a drier climate. We used our projected raster datasets of minimum flow CV and specific mean daily flow to highlight streams that met this criteria (between 61.84 and 230 percent minimum flow CV and less than 0.096 specific mean daily flow) in the Upper Colorado River Basin and suggest that these streams will be most threatened to shift flow regimes under drier climate conditions.

Table 2. Environmental variables used to predict flow metrics on gaged streams in the Upper Colorado River Basin.

[Adapted from Falcon (2011). See Falcone (2011) for more explanation of the variables. sq. km, square kilometer; NHDPlus, National Hydrography Dataset Plus; m, meter; cm, centimeter; km, kilometer; mm/yr, millimeter per year; 100's ft-tonf-in/ac/hr/yr, hundreds of feet times ton-force times inches per acre per hour per year; n/a, not applicable; NLCD, National Land Cover Database]

Variable	Units	Accumulation or percent of upstream drainage area	Source	Scale/ resolution
Drainage area	sq. km	Accumulated	NHDPlus[1]	30 m
Mean annual precipitation	cm	Accumulated	PRISM[2]	800 m
Relative humidity	percent	Accumulated	PRISM[3]	2 km
Average days of measurable precipitation	days	Accumulated	PRISM[3]	2 km
Mean-annual potential evapotranspiration (PET)	mm/yr	Accumulated	PRISM[4]	1 km
Snow percent of total precipitation (percent snow)	percent	Accumulated	McCabe and Wolock (2009)[5]	1 km
Average soil permeability	inches/hour	Accumulated	Wolock (1997)	1 km
Soil Rainfall and Runoff factor (R factor)	100's ft-tonf-in/ac/hr/yr	Accumulated	PRISM[6]	4 km
Mean January precipitation	cm	Accumulated	PRISM[2]	800 m
Mean February precipitation	cm	Accumulated	PRISM[2]	800 m
Mean March precipitation	cm	Accumulated	PRISM[2]	800 m
Mean April precipitation	cm	Accumulated	PRISM[2]	800 m
Mean May precipitation	cm	Accumulated	PRISM[2]	800 m
Mean June precipitation	cm	Accumulated	PRISM[2]	800 m
Mean July precipitation	cm	Accumulated	PRISM[2]	800 m
Mean August precipitation	cm	Accumulated	PRISM[2]	800 m
Mean September precipitation	cm	Accumulated	PRISM[2]	800 m
Mean October precipitation	cm	Accumulated	PRISM[2]	800 m
Mean November precipitation	cm	Accumulated	PRISM[2]	800 m
Mean December precipitation	cm	Accumulated	PRISM[2]	800 m
Surficial geology	n/a	Percent of drainage area for each geologic type (11 types)	Hunt (1979)	30 m
Bedrock permeability	n/a	Percent of drainage area for each permeability type (2 types)	Wolock and others (2004)	1 km
Developed land cover	percent	Percent of drainage area	[7]NLCD classes 21–24	30 m
Forest land cover	percent	Percent of drainage area	[7]NLCD classes 41–43	30 m
Planted/cultivated land cover	percent	Percent of drainage area	[7]NLCD classes 81 and 82	30 m
Natural barren land cover	percent	Percent of drainage area	[7]NLCD class 31	30 m
Shrubland land cover	percent	Percent of drainage area	[7]NLCD classes 51 and 52	30 m
Herbaceous land cover	percent	Percent of drainage area	[7]NLCD classes 71–74	30 m
Wetland land cover	percent	Percent of drainage area	[7]NLCD classes 90 and 95	30 m

[1]National Hydrography Dataset Plus, NHD drainage area 14 (NHDPlus).

[2]Mean values for the 30-year period 1971–2000 (PRISM).

[3]Mean values for the 30-year period 1961–1990 (PRISM).

[4]Estimated using the Hamon (1961) equation on mean values for the 30-year period 1961–90 (PRISM).

[5]Mean for period 1901–2000 (McCabe and Wolock 2009).

[6]Rainfall and Runoff factor ("R factor" of Universal Soil Loss Equation); average annual value for period 1971–2000 (PRISM). Note that these data are no longer available through the PRISM website.

[7]National Land Cover Database 2006 (Fry and others, 2011).

Results and Data Products

The random forest models we used to project flow metrics to small, ungaged streams varied in model performance between 45.3- and 82.55-percent variance explained (table 3).

We successfully projected low flow metrics to small, ungaged reaches across the Upper Colorado River Basin using random forest models developed in Reynolds and others (2015) and described above in the “Methods” section. We produced seven flow metric datasets, one for each modeled flow metric (tables 3 and 4), for small stream reaches across the Upper Colorado River Basin. An example of the dataset products is shown in figure 2. We produced an eighth dataset showing modeled intermittency status for each stream reach, including streams that are potentially threatened with intermittency because of drier conditions (fig. 3). The eight geospatial datasets included in this Data Series are summarized in the “Accompanying Data Products” section below.

Table 3. Results of random forest models using environmental variables to predict streamflow metrics.

[Adapted from Reynolds and others (2015). See table 1 for definitions of streamflow metrics. See table 2 for definitions of predictor variables. P-value, [a measure of the strength or statistical significance of a relation; smaller p-values (<0.01) indicate stronger relations]; PET, potential evapotranspiration; <, less than; CV, coefficient of variation; R factor, Rainfall and Runoff factor; OOB, out-of-bag; n/a, not applicable]

Streamflow metric	Top five predictor variables	Variance explained	P-value
Specific mean daily flow	April precipitation, percent forest land cover, average days of measurable precipitation, average annual basin precipitation, and mean-annual PET	82.55 percent	<0.001
Frequency of low flow pulses	February precipitation, June precipitation, PET, May precipitation, and December precipitation	50.3 percent	<0.001
Minimum flow CV	Percent snow, November precipitation, PET, February precipitation, and R factor	49.8 percent	<0.001
7-day minimum	Drainage area, August precipitation, October precipitation, September precipitation, and January precipitation	49.4 percent	<0.001
Specific minimum flow	December precipitation, average annual basin precipitation, November precipitation, February precipitation, and April precipitation	47.6 percent	<0.001
Zero-flow days per year	Percent snow, December precipitation, February precipitation, R factor, and November precipitation	45.3 percent	<0.001
Intermittency	Percent barren land cover, drainage area, PET, June precipitation, and November precipitation	OOB[1] error rate—20 percent	n/a

[1]The OOB error rate is a cross-validation measure calculated by classification random forests. Better models have lower OOB error rates. See Cutler (2007) for details.

Table 4. Geospatial datasets of projected streamflow metrics and threatened intermittency status in the Upper Colorado River Basin

[Geospatial datasets are available at http://dx.doi.org/10.3133/ds974. See table 1 for streamflow metric definitions. See table 2 for predictor variable definitions. Flow metrics were predicted by random forest models built using 115 streamgage sites across the Upper Colorado River Basin as training data and climate, land cover, and geology variables as predictor variables. CV, coefficient of variation]

Mapped unit	File name	Data type	Description
Specific mean daily flow	SpMeanFlow.tif	Raster	Predicted specific mean annual flow for small streams in the Upper Colorado River Basin stream network under historic hydrologic conditions. Values shown on the map are specific mean flow multiplied by 1,000. Nonstream cells in the raster are represented by NoData cells.
Frequency of low-flow pulses	FreqLowPulse.tif	Raster	Predicted frequency of low pulse events for small streams in the Upper Colorado River Basin stream network under historic hydrologic conditions. Values shown on the map are low flow frequency (events/year) multiplied by 1,000. Nonstream cells in the raster are represented by NoData cells.
Minimum flow CV	MinFlowCV.tif	Raster	Predicted minimum flow CV for small streams in the Upper Colorado River Basin stream network under historic hydrologic conditions. Values shown on the map are minimum flow CV multiplied by 100. Nonstream cells in the raster are represented by NoData cells.
7-day minimum	SevenDayMin.tif	Raster	Predicted 7-day minimum flow for small streams in the Upper Colorado River Basin stream network under historic hydrologic conditions. Values shown on the map are 7-day minimum values multiplied by 1,000. Nonstream cells in the raster are represented by NoData cells.
Specific minimum flow	SpMinFlow.tif	Raster	Predicted specific mean annual minimum flow for small streams in the Upper Colorado River Basin stream network under historic hydrologic conditions. Values shown on the map are specific minimum flow multiplied by 10,000. Nonstream cells in the raster are represented by NoData cells.
Zero-flow days per year	ZeroFlowDays.tif	Raster	Predicted number of zero-flow days per year (days/year) for small streams in the Upper Colorado River Basin stream network under historic hydrologic conditions. Zero-flow day values shown on the map are not modified by any multiplier. Nonstream cells in the raster are represented by NoData cells.
Intermittency	Intermittency.tif	Raster	Predicted intermittency category (perennial [value=3], weakly intermittent [value=2] or strongly intermittent [value=1]) for small streams in the Upper Colorado River Basin under historic hydrologic conditions. Nonstream cells in the raster are represented by NoData cells.
Threatened with intermittency	ThreatenedIntermittency.shp	Vector (polyline shapefile)	Predicted hydrology of small stream reaches under drier climate conditions in the Upper Colorado River Basin: perennial, threatened with intermittency, intermittent, or strongly intermittent (Reynolds and others, 2015).

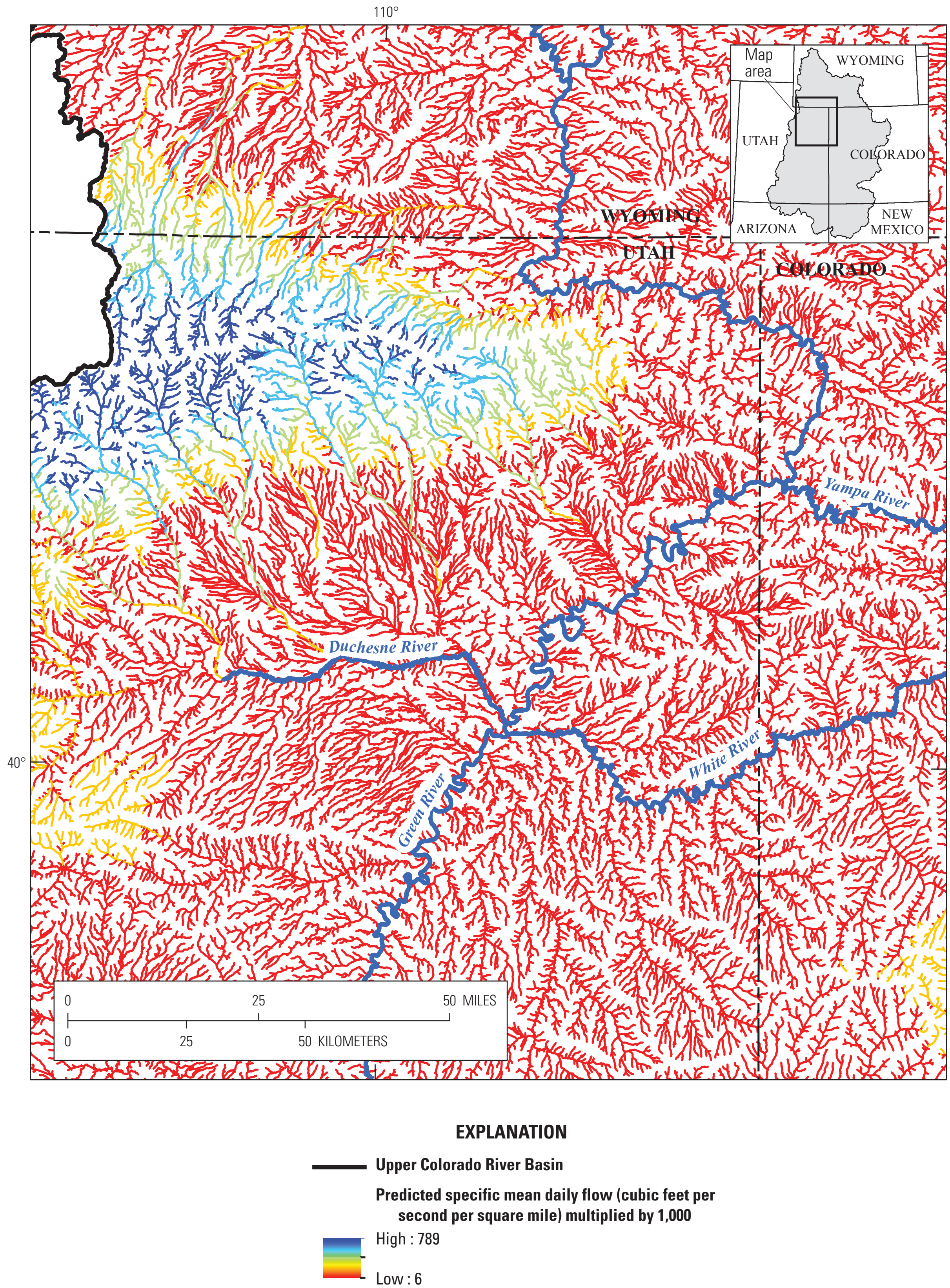
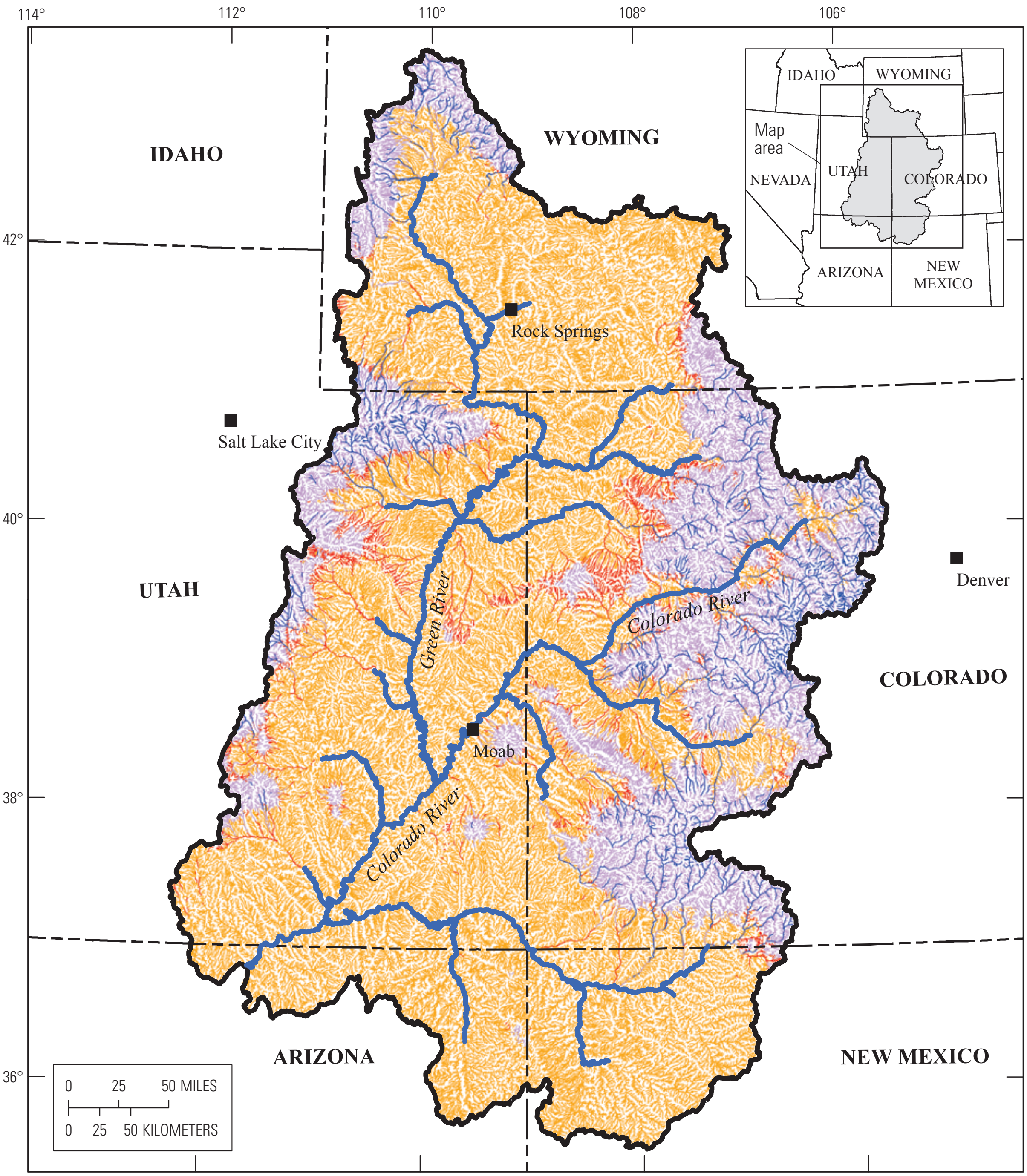


Figure 2. Predicted values of specific mean daily flow multiplied by 1,000 for small streams in a small area of the Upper Colorado River Basin.



EXPLANATION

Upper Colorado River Basin

Intermittency status

Perennial (minimum flow cofficient of variation [CV] less than 61.84 percent)

Threatened with intermittency (minimum flow CV between 61.84 percent and 230.32 percent and specific mean annual flow less than 0.096)

Intermittent (minimum flow CV between 61.84 percent and 230.32 percent and specific mean annual flow greater than 0.096)

Strongly intermittent (minimum flow CV greater than 230.32 percent)

Figure 3. Predicted intermittency status of small stream reaches based on current streamflow metrics in the Upper Colorado River Basin: perennial, threatened with intermittency, intermittent, or strongly intermittent.

Disclaimers

Although these data have been processed successfully on a computer system at the U.S. Geological Survey, no warranty expressed or implied is made regarding the display or utility of the data on any other system, or for general or scientific purposes, nor shall the act of distribution constitute any such warranty. The U.S. Geological Survey shall not be held liable for improper or incorrect use of the data described and (or) contained herein.

Summary

We developed geospatial datasets of projected mean and low streamflow metrics on small streams in the Upper Colorado River Basin using random forest statistical models. Our models varied in performance and explained about 45–85 percent of variance for each flow metric. These datasets can help scientists, land managers, and policymakers understand current hydrology in the Upper Colorado Basin and to make informed decisions regarding water resources. With knowledge of which streams are likely to undergo significant drying in the future, land managers and scientists can more effectively plan for drying conditions, human water uses, and the consequences for stream dependent ecosystems.

Accompanying Data Products

See table 4 in the “Results and Data Products” section for geospatial dataset file names and descriptions. Geospatial datasets are available at http://dx.doi.org/10.3133/ds974.

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