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Regional scale estimates of baseflow and factors influencing baseflow in the Upper Colorado River Basin

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ABSTRACT

Study region: The study region encompasses the Upper Colorado River Basin (UCRB), which provides water for 40 million people and is a vital part of the water supply in the western U.S.
Study focus: Groundwater and surface water can be considered a single water resource and thus it is important to understand groundwater contributions to streamflow, or baseflow, within a region. Previously, quantification of baseflow using chemical mass balance at large numbers of sites was not possible because of data limitations. A new method using regression-derived daily specific conductance values with conductivity mass balance hydrograph separation allows for baseflow estimation at sites across large regions. This method was applied to estimate baseflow discharge at 229 sites across the UCRB. Subsequently, climate, soil, topography, and land cover characteristics were statistically evaluated using principal component analysis (PCA) to determine their influence on baseflow discharge.
New hydrological insights for the region: Results suggest that approximately half of the streamflow in the UCRB is baseflow derived from groundwater discharge to streams. Higher baseflow yields typically occur in upper elevation areas of the UCRB. PCA identified precipitation, snow, sand content of soils, elevation, land surface slope, percent grasslands, and percent natural barren lands as being positively correlated with baseflow yield; whereas temperature, potential evapotranspiration, silt and clay content of soils, percent agriculture, and percent shrublands were negatively correlated with baseflow yield.

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1. Introduction

The Colorado River and its tributaries are an important source of water in the western United States, supplying water across seven states and Mexico. The river sustains communities and economies by providing municipal water for 40 million people, irrigating 20,000 km^2 of land, generating 4200 MW of hydroelectric power, and sustaining terrestrial and aquatic ecosystems (U.S. Bureau of Reclamation, 2012). Roughly 90% of the streamflow in the Colorado River originates from snowmelt from precipitation in the three upper basin states of Colorado, Utah, and Wyoming (Jacobs, 2011), making the Upper Colorado River Basin (UCRB) a vital part of water supply in the West.

To inform management of water resources in the UCRB, the hydrologic budgets of surface water and groundwater need to be quantified; however, the groundwater component of streamflow, or baseflow, in the UCRB has not been estimated extensively across the basin and is not well understood. Baseflow is groundwater that is discharged to streams, and it integrates groundwater from multiple flow paths of varying scales, from deep regional groundwater to shallow near-stream flow paths (Miller et al., 2014; Price, 2011). Declines in groundwater storage volumes documented in the UCRB during the past decade of drought (Castle et al., 2014) could affect the baseflow component of streamflow, potentially leading to decreases in streamflow volumes. To better assess and plan for this possibility, as well as the effects of groundwater development in the UCRB, it is necessary to quantify baseflow discharge to streams across the basin and to assess basin characteristics that influence its magnitude and distribution.

Many approaches have been developed to quantify baseflow, including graphical hydrograph separation approaches such as low-pass filters (Nathan and McMahon, 1990; Wolock, 2003) and recession curve analysis (Barnes, 1939; Tallaksen, 1995), as well as chemical mass balance hydrograph separation methods (Miller et al., 2014; Stewart et al., 2007). Chemical mass balance methods rely on conservative chemical constituents and streamflow to estimate baseflow, while graphical methods use only streamflow. Using readily available specific conductance (SC) data as the chemical constituent in chemical mass balance hydrograph separation allows for baseflow estimates to be made for larger basins over long periods of time (Stewart et al., 2007). Furthermore, the conductivity mass balance (CMB) method has been shown to work well for many types of watersheds, including snowmelt dominated systems like the UCRB (Miller et al., 2014).

In the past, application of the CMB method has been restricted either to locations that had continuous SC data or to small research watersheds that were intensively sampled for multiple chemical constituents (Stewart et al., 2007; Wels et al., 1991). Sanford et al. (2012) provides an example of using chemical mass balance hydrograph separation with continuous SC data to estimate baseflow at a large scale in Virginia. More recently, Miller et al. (2015) successfully estimated baseflow using regression derived estimates of daily SC from discrete SC measurements combined with a CMB approach. They show that for snowmelt dominated watersheds, baseflow can be estimated for the period of record using the CMB method with discrete SC data and daily stream discharge data. Additionally, they suggest that this new approach could be applied to a greater number of rivers and streams, allowing for investigation of watershed and climatic drivers that influence baseflow across large spatial scales.

Baseflow originates as precipitation that infiltrates to the subsurface and eventually discharges to streams. The amount of baseflow discharged to streams is influenced by many basin characteristics, including climate, soils, topography, and land cover. Conceptually, baseflow is greater in watersheds where there are high rates of infiltration, recharge, and groundwater storage, while high rates of evapotranspiration and runoff reduce baseflow (Brutsaert, 2005; Gardner et al., 2010; Price, 2011). Catchment geology dictates subsurface storage and drainage network structures (Farvolden, 1963; Price, 2011; Smith, 1981), while soil characteristics influence the rate of infiltration, hydraulic conductivity, and groundwater recharge (Pirastru and Niedda, 2013; Price et al., 2011; Wolock et al., 2004). Topographic characteristics such as land slope affect how water moves across the surface and in the subsurface, thereby influencing infiltration, flow processes, and rates of water transmission (McGuire et al., 2005; Price, 2011; Price et al., 2011). Land use alters vegetation which can decrease baseflow generation by increasing interception and evapotranspiration rates, or can increase baseflow by improving infiltration and recharge of subsurface storage (McCulloch and Robinson, 1993; Nie et al., 2011; Robinson et al., 1991). Lastly, climatic factors such as temperature and precipitation influence

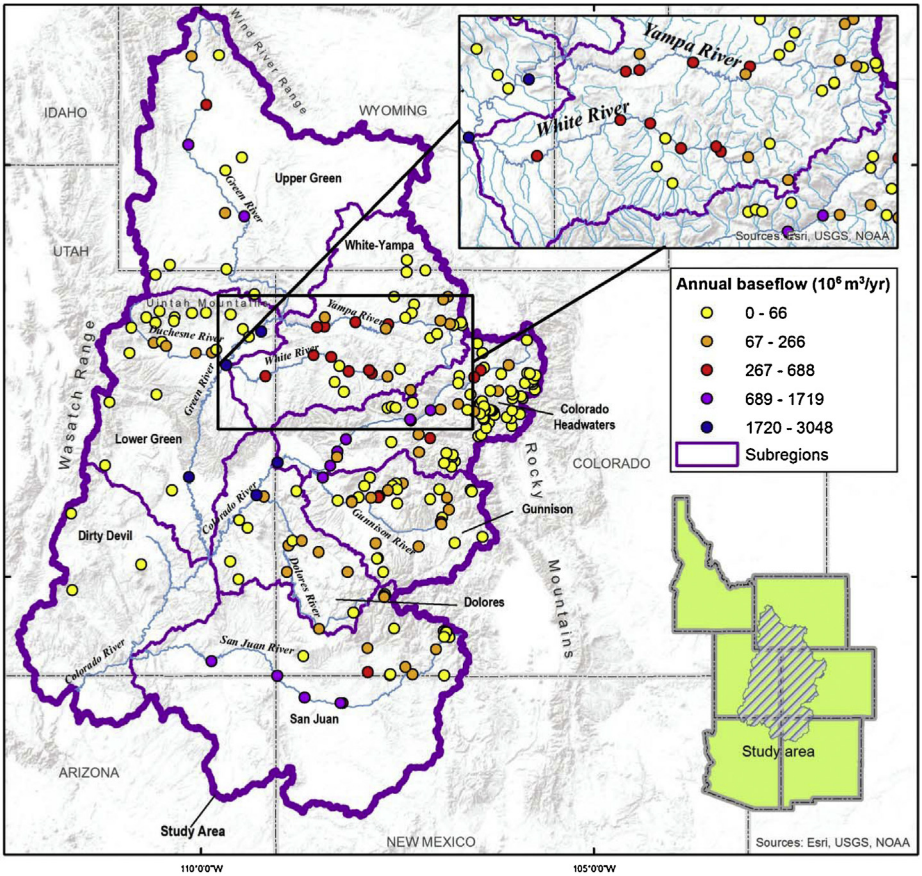

Fig. 1. Annual baseflow volumes for the UCRB and the White River watershed (subregions defined by HUC 4 boundaries).

baseflow by altering rates of evapotranspiration, infiltration and recharge, and timing of snowmelt runoff (Brutsaert, 2005; Tague and Grant, 2009; Winograd et al., 1998).

The objectives of this study are to quantify baseflow discharge in a large number of streams across the UCRB using estimated daily mean SC data and a chemical mass balance approach. Further, we identify relationships between area-normalized baseflow (hereafter referred to as baseflow yield) and basin characteristics, such as climate, soils, topography, and land cover, which are expected to influence baseflow. To our knowledge, this is the first study to estimate baseflow, and the basin characteristics that influence baseflow, using chemical mass balance hydrograph separation at a large number of sites in a multi-state region. Additionally, this study is the first regional assessment of baseflow in streams in the UCRB.

2. Methods

2.1. Study area, data sources, and data editing

The UCRB drains portions of Wyoming, Colorado, Utah, Arizona, and New Mexico and covers an area of roughly 294,000 km^2 (Fig. 1). The basin extends from the headwaters in the Rocky Mountains and Wasatch Range to Lees Ferry, Arizona, downstream of Lake Powell on the Colorado River. Major tributaries to the Colorado River include the Dolores, Duchesne, Green, Gunnison, San Juan, White, and Yampa Rivers. Climate, topography, and land cover characteristics vary throughout the UCRB (Table 1).

This study used daily streamflow (*Q*) and discrete SC data collected at U.S. Geological Survey (USGS) stream gages and obtained from Tillman and Anning (2014), who compiled data from the USGS National Water Information System (NWIS) database. Data between 1984 and 2012 were used, with periods of record varying from 2 to 28 years and with data that may span different time periods at different gages. Tillman and Anning (2014) estimated mean daily dissolved-solids concentrations at 323 stream gage sites in the UCRB using regression models. As part of this study, *Q* and SC were detrended to a base year of 2010 at sites with adequate data to allow for among-site comparisons where different sites may have data from different time periods. Precipitation in the UCRB during 2010 was slightly below the long term average (NOAA, 2015). Data were detrended at 155 of the 229 sites, while there were not adequate data for detrending at 74 sites. Detrending applies the environmental conditions of the base year to the entire period of record to provide estimates of *Q* and SC that are independent of changes in climate and management over time (Schwarz et al., 2006). Thus, detrending provides a time series of Q and SC that would be expected to have occurred if climate and management efforts were held constant in accordance with the conditions of the base year (2010). Detailed modeling information and results are provided in Tillman and Anning (2014).

The 323 sites for which daily SC was estimated by Tillman and Anning (2014) were evaluated further to retain only sites with data suitable for chemical hydrograph separation. Specifically, data at all sites were examined to ensure that low SC coincided with high discharge in the spring/summer (snowmelt runoff), and that high SC coincided with low discharge in the fall/winter (baseflow). This pattern is described by a power function where discharge is inversely related to SC. Miller et al. (2014) suggest that the lack of an inverse relationship between discharge and SC in snowmelt dominated systems is often an indication of direct effects from anthropogenic activities that alter natural hydrologic processes. Therefore, sites were eliminated if they did not have an inverse power function relationship between Q and SC. Sites without a snowmelt peak in the hydrograph were also removed, with the snowmelt peak defined as a peak in discharge due to melting snow during spring and early summer months that is approximately an order of magnitude greater than low-flow conditions (Miller et al., 2014). Additionally, sites with a narrow range of SC (<100 μS/cm) and with minimum SC values distant from the runoff end-member SC concentration (defined below) were eliminated. Model fit of the SC regression models was also evaluated, and sites were removed if the range of observed SC or *Q* values was substantially different than the range of modeled SC and *Q* values.

Finally, gage sites within 2 km downstream of reservoirs were not included in this study. 2 km was the approximate distance beyond which snowmelt peaks were observed and inverse SC vs. *Q* power relationships were upheld. Miller et al. (2014) suggest that CMB hydrograph separation conducted at sites located far enough downstream from reservoirs, such that the inverse SC vs. *Q* power function relationships are upheld, can be used to accurately estimate baseflow. Reservoirs, which are abundant in the UCRB, influence hydrologic and water quality conditions, including the timing of release of stored baseflow and runoff to downstream waters. While the timing of baseflow discharge from reservoirs to downstream waters is expected to be different than the timing of baseflow discharge under non-affected conditions, long-term representative baseflow discharge quantified using CMB (as reported here) is not expected to be strongly affected by the presence of reservoirs. Although a pulse of baseflow often occurs during snowmelt, and reservoirs retain this baseflow until it is released in times of low flow, the amount of baseflow estimated downstream of a reservoir using CMB over a long time period (greater than the reservoir residence time) is expected to be approximately equal to the amount of baseflow that would be estimated in the absence of the reservoir (Miller et al., 2014). Given that the influence of reservoirs on hydrologic and water quality conditions decreases with increased distance downstream from reservoirs, as shown by annual hydrographs and SC vs. *Q* relationships, only gage sites greater than 2 km downstream of reservoirs were included.

Following this editing procedure, 229 stream gage sites were retained for baseflow estimation (Fig. 1). All 229 sites drain snowmelt-dominated watersheds and have drainage areas ranging from 2 km^2 to 115,000 km^2. 27 of the 229 sites are part of the Hydro-Climatic Data Network (HCDN), which represents sites that are minimally affected by human activities and have a period of record greater than 20 years. Sites not included in the HCDN are located in basins where human activity has altered

Table 1
Summary of basin characteristics for each UCRB subregion (values represent averages of study sites in each subregion; subregions defined by HUC 4 watershed boundaries; data obtained from Gages-II dataset (Falcone, 2011)).

Subregion	Precip (mm/yr)	Snow % of total precip	Elevation (m)	Temp (°C)	Slope (%)	Wetlands (%)	Shrubland (%)	Agriculture (%)	Natural barren (%)	Grassland (%)	Forest (%)	Developed (%)	Number of sites
Colorado headwaters	740	59.5	3174	1.2	31.0	2.1	4.9	0.5	10.8	17.2	56.8	1.0	68
Gunnison	679	49.6	2877	2.9	23.8	1.8	9.5	3.0	6.0	14.5	64.1	0.8	27
Dolores	650	40.8	2624	5.3	23.0	0.6	15.1	1.2	3.6	8.6	70.4	0.4	12
Upper Green	573	52.1	2667	1.5	15.5	2.5	46.7	2.0	4.1	11.7	31.1	0.6	11
White-Yampa	710	49.2	2512	3.9	17.1	1.8	28.5	3.1	0.8	7.9	57.3	0.4	28
Lower Green	686	52.3	2798	2.6	23.0	0.6	21.8	1.6	8.7	5.6	60.7	0.6	20
Dirty Devil	728	52.8	2985	3.5	17.3	0.4	20.4	0.0	1.5	2.2	74.0	1.1	2
San Juan	795	46.9	2884	3.8	29.4	1.9	15.0	3.3	9.5	19.6	49.3	1.1	19

streamflow, have a period of record less than 20 years, or did not satisfy data quality criteria (Slack et al., 1994). Additional site information for all the stream gage sites, including which sites were detrended, is available in Tillman and Anning (2014).

2.2. Hydrograph separation

To estimate baseflow, the CMB method was used with mean daily regression model-derived SC and Q for all 229 sites. The CMB method uses a two component chemical hydrograph separation approach that has been shown to work well for estimating baseflow in snowmelt dominated watersheds, and that can be applied to estimate baseflow using discrete SC data and a regression modeling approach as described above (Miller et al., 2014, 2015). Daily baseflow was estimated using the following CMB equation (Pinder and Jones, 1969):

$$Q_{BF} = Q\frac{SC - SC_{RO}}{SC_{BF} - SC_{RO}}$$

where Q_{BF} is baseflow discharge (m^3/s), Q is total stream discharge (m^3/s), SC is the specific conductance (μS/cm) of the regression-derived daily SC, SC_{RO} is the SC of the runoff end-member (μS/cm), and SC_{BF} is the SC of the baseflow end-member (μS/cm). Mean daily hydrographs of Q and Q_{BF} were generated and annual Q_{BF} and baseflow index (BFI) values were calculated (Miller et al., 2014). BFI was calculated as mean annual baseflow divided by mean annual streamflow $\left(\mathrm{BFI} = \frac{\text{mean annual } Q_{BF}}{\text{mean annual } Q}\right)$.

End-members for runoff and baseflow (SC_{RO} and SC_{BF}, respectively) were estimated using the approach described by Miller et al. (2014). The SC_{RO} component of streamflow represents low SC water that discharges to the stream during snowmelt. SC_{BF} is the component of streamflow from all subsurface flow paths during low-flow conditions, and represents an integrated SC signature. Time-variable baseflow end-member SC concentrations were estimated for the period of record by linearly interpolating between the 99th percentile of daily SC values for each given year (Miller et al., 2014). The end-member for runoff was estimated as 33 μS/cm from in-stream SC measurements made during snowmelt at high-elevation watersheds in the headwaters of the UCRB. The SC_{RO} of 33 μS/cm was used at all but 29 sites, and although small temporal variation in SC_{RO} may occur, changes are expected to be small relative to measured in-stream SC, allowing for variation in SC_{RO} without significantly changing baseflow estimates (Miller et al., 2014). Twenty-nine sites had occurrences of daily estimated stream SC values less than 30 μS/cm, preventing reasonable hydrograph separation. SC_{RO} was changed to 10 μS/cm for these sites. Miller et al. (2014) showed that changing SC_{RO} to 10 μS/cm resulted in baseflow estimates that were statistically equivalent to using an SC_{RO} = 33 μS/cm at sites in the UCRB.

It is important to note that three assumptions are used when applying the CMB method: (1) no other end-members contribute to streamflow, (2) SC_{RO} does not change during the period of record, and (3) SC_{RO} and SC_{BF} are significantly different from each other. Miller et al. (2014) demonstrated that the CMB method provides reasonable estimates of baseflow within the constraints of these assumptions. They provide a more detailed discussion of model assumptions and the appropriateness of applying a CMB approach to estimate baseflow in snowmelt-dominated streams and rivers.

2.3. Statistical analyses

Comparisons of baseflow yield and BFI between subregions were evaluated using the nonparametric Wilcoxon-rank sum test (Wilcoxon, 1945) to spatially assess differences in baseflow and the BFI. UCRB subregions were defined using hydrologic unit code (HUC) 4 boundaries. Relationships between baseflow and basin characteristics (i.e. climate, soil, topography, and land cover variables) were evaluated using the Gages-II dataset (Falcone, 2011), which provides geospatial data of basin characteristics for gaged watersheds throughout the U.S. While sites in the Gages-II statistical analyses are not completely independent because sites integrate upstream characteristics, the relationships analyzed are still valuable for understanding the potential effects of watershed parameters on baseflow across large spatial scales. However, it is important to consider that different areas above a gaged site may have different influences on downstream chemistry (e.g. headwater basins having a large effect on stream chemistry at downstream gages). In the UCRB, Gages-II data were available for 187 of the 229 sites included in this study, therefore relationships between baseflow yield and basin characteristics were only investigated using data from this subset of sites. A principal component analysis (PCA) was run on select climate (mean annual precipitation, mean annual temperature, percent of precipitation as snow, and mean annual potential evapotranspiration), soil (% clay, sand, and silt content), topography (mean watershed elevation and slope) and land cover (watershed % urban, agriculture, forest, grassland, barren, shrubland, and wetland) variables to evaluate how baseflow varies across the landscape. Input data were fourth root transformed to down weight the importance of variables with high absolute values and were standardized to a mean of zero and standard deviation of one prior to running the PCA. PCA was run using the PRIMER package (Clarke and Gorley, 2006). A *t*-test was used to test for significant differences ($p < 0.001$) between average PCA axis 1 scores for groups based on baseflow yield. Finally, a t-test was also used to test for statistical differences ($p < 0.001$) in averages of the percent of precipitation that becomes baseflow at different elevations in the UCRB.

3. Results and discussion

3.1. Spatial variation in baseflow

Estimated annual baseflow volumes increased downstream within watersheds throughout the UCRB, as would be expected for increasing drainage areas (Price, 2011). As an example, Fig. 1 illustrates how estimated annual baseflow volumes in the UCRB and White River watershed accumulated downstream. Annual baseflow in the White River watershed increased from 9.37×10^6 m^3/yr at the highest elevation site (drainage area = 56 km^2) to 3.77×10^8 m^3/yr at the lowest elevation site (drainage area = 1030 km^2). Occasional deviations from expected longitudinal patterns in baseflow may be due to diversions, reservoirs, or irrigation return flows that occur in the watershed (Kenney et al., 2009; USGS, 2014).

To remove the influence of drainage area on baseflow, baseflow yield (i.e. area-normalized baseflow) was calculated and used in all subsequent analyses. Baseflow yield ranged from 4 to 590 mm/yr, with an average value of 120 mm/yr. Most (191 of 229) values were between 0 and 200 mm/yr. Distinct spatial patterns in baseflow yield are apparent across the UCRB (Fig. 2). Clusters of high baseflow yield occurred near the eastern edge of the UCRB in the Rocky Mountains, in the Uinta Mountains of northeastern Utah, and in the headwaters of the Green River in the Wind River Range. The Colorado headwaters, San Juan, and Gunnison subregions had the highest median baseflow yield (130, 130, and 110 mm/yr, respectively; Fig. 3). These regions are located along the eastern edge of the UCRB in the Rocky Mountains and have relatively high elevations, high precipitation, and low temperatures (Table 1). The lowest median baseflow yields occurred in the Dolores and Dirty Devil subregions (30 mm/yr in both watersheds; Fig. 3), which are found in the south-central and southwestern part of the UCRB and have relatively high temperatures, mid-range precipitation, and mid-range elevations (Table 1). Baseflow yield in the Colorado headwaters subregion was significantly greater than baseflow yield in the Dolores, the Upper Green, and the Lower Green subregions. Similarly, baseflow yield in the Gunnison subregion was significantly greater than baseflow yield in the Dolores subregion (Fig. 3).

The BFI for the 229 gage sites ranged from 0.12 to 0.92, with roughly 89% of sites having BFIs between 0.25 and 0.75 (Figs. 4 and 5). Recall that the BFI is the ratio of the mean annual baseflow divided by the mean annual streamflow and thus provides a measure of the importance of groundwater discharge in streamflow. The mean BFI in the UCRB was 0.48. Furthermore, about 40% of sites had a BFI greater than 0.5, indicating that a large fraction of streams obtain the majority of their streamflow from baseflow, and demonstrating the importance of the baseflow component of streamflow in the UCRB. Spatial patterns in BFI were not as clear as those for baseflow yield. Clusters of gage sites with high BFIs occurred along the western edge of the UCRB in the Wasatch Range and Uinta Mountains (Lower Green subregion), as well as in the White and upper Gunnison River watersheds (Fig. 4). Low BFI values were observed in the Yampa River watershed, in some areas of the Colorado headwaters subregion, in upper reaches of the San Juan River, and along the North Fork of the Gunnison River. There was no significant difference in BFI among subregions in the study area, with median BFI ranging from 0.44 to 0.61 (Fig. 5).

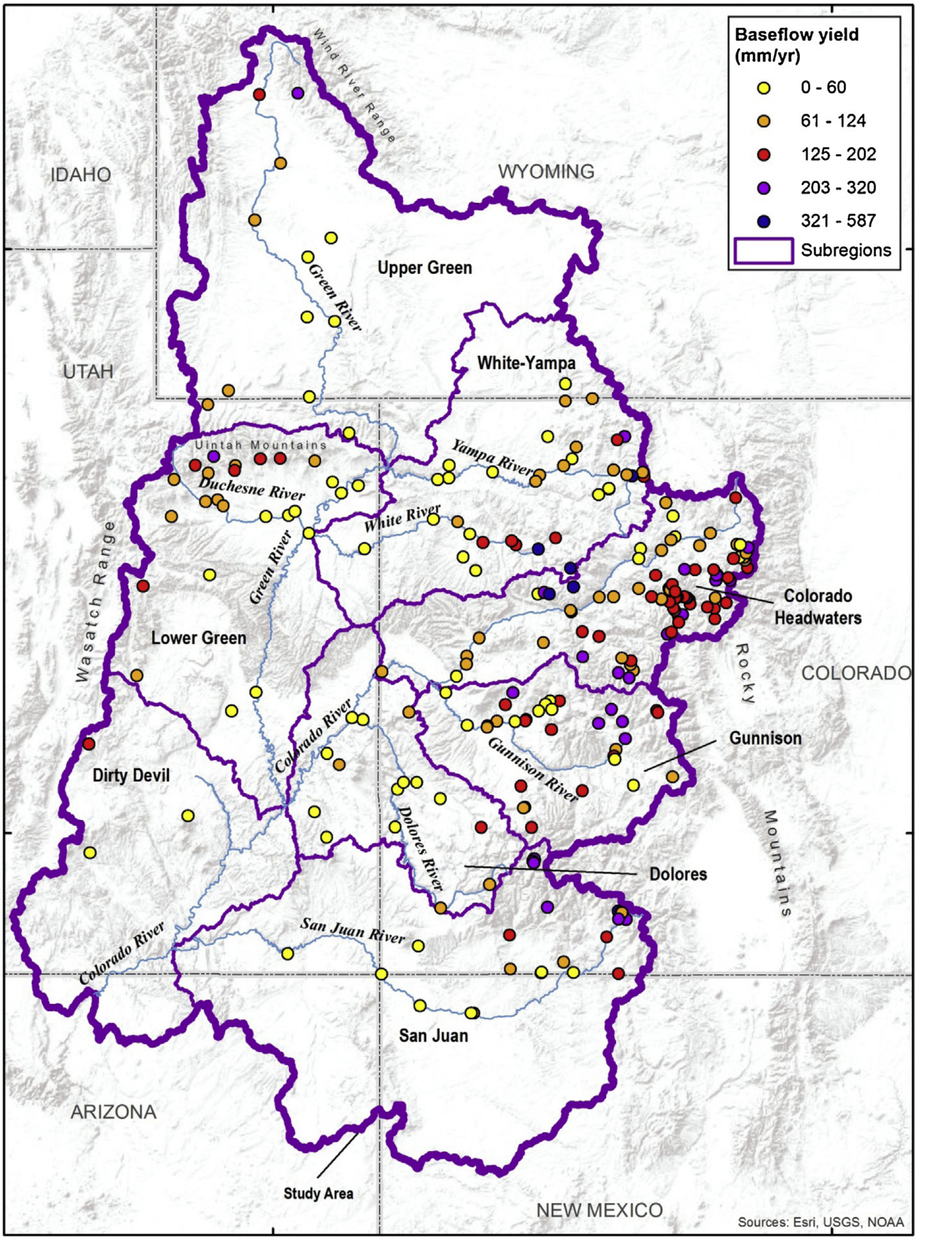

Fig. 2. Spatial distribution of baseflow yield in the UCRB (subregions defined by HUC 4 boundaries).

Studies by Wolock (2003) and Santhi et al. (2008), who estimated BFI values across the United States using the USGS smoothed minima BFI method and a recursive digital filter method, respectively, obtained estimates of BFI for the UCRB ranging from 0.1 to 0.8. Spatially, the USGS smoothed minima BFI method showed consistently high (0.6–0.8) BFIs for the Rocky Mountains, Wasatch Range, and Uinta Mountains, and did not include low BFIs throughout the UCRB as predicted with the CMB method

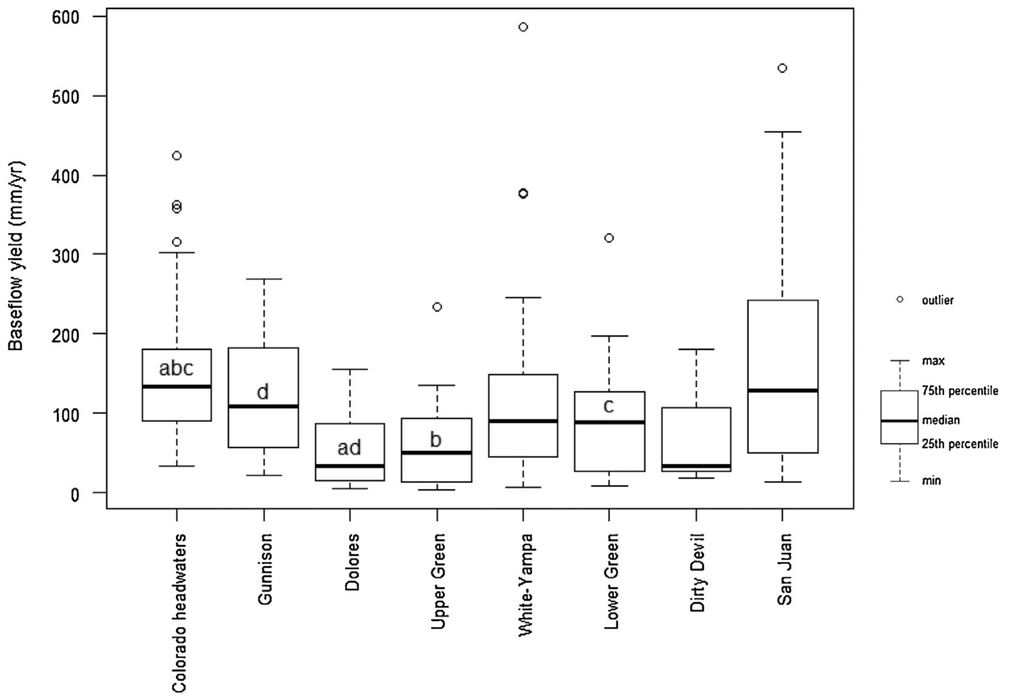

Fig. 3. Summary of baseflow yield by subregions (Letters indicate statistically significant differences between subregions ($\alpha = 0.05$, Wilcoxon-rank sum test); subregions defined by HUC 4 boundaries).

(Santhi et al., 2008; Wolock, 2003). The digital filter method predicted lower BFI values (0.3–0.7) for the Wasatch Range and much lower BFIs (0.1–0.5) in the south central and northeastern areas of the UCRB than estimates presented here (Santhi et al., 2008). Comparing BFIs from the CMB method and the USGS smoothed minima method (Wolock, 2003) shows that the smoothed minima method tends to estimate greater BFI than the CMB method (Fig. 6). Kronholm and Capel (2014) also found that using the smoothed minima method in a snowmelt-dominated watershed resulted in BFI estimates that were greater than those generated using a CMB approach.

Differences in BFI arise from the different hydrograph separation techniques used. Both the USGS BFI method and digital filter method are graphical hydrograph separation techniques that only require stream discharge data to estimate baseflow. Previous studies have suggested that these methods are more subjective than CMB because, unlike CMB, they are not related to physical and chemical processes and flow paths in the watersheds (Miller et al., 2014; Stewart et al., 2007). Additionally, these methods are not designed to estimate baseflow in snowmelt-dominated systems, making them less suitable for the UCRB (Santhi et al., 2008). The CMB method is inherently designed to deal with snowmelt processes, with the foundation of its application relying on changes in SC caused by snowmelt (Miller et al., 2014).

3.2. Relationships between baseflow and basin characteristics

PCA analysis was used to understand how topography, climate, soils, and land cover relate to baseflow yield distribution in the UCRB. PCA analysis for baseflow volume was not conducted due to the strong influence of drainage area on those values. Results of the PCA analysis are shown as gage sites plotted on the first and second principal component axes, which accounted for 52 and 12%, respectively, of the variance in the climate, soil, topography, and land cover variables (Fig. 7). Sites with low baseflow yield tended to have lower scores on axis 1 than sites with higher baseflow yield

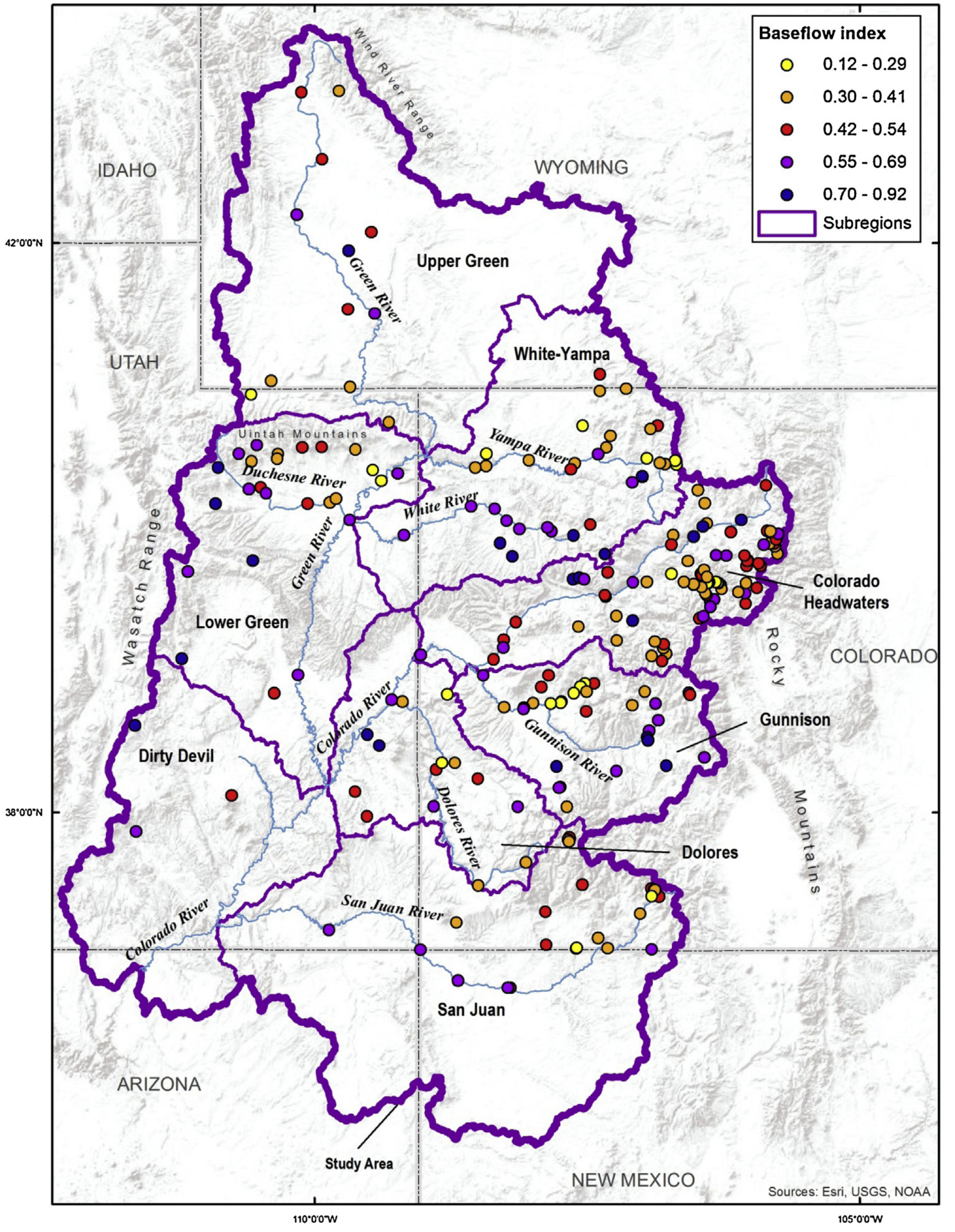

Fig. 4. Spatial distribution of baseflow index in the UCRB (subregions defined by HUC 4 boundaries).

(Fig. 8). The average axis 1 score for sites with baseflow yields <100 mm/yr was −1.95, which was significantly less ($p < 0.001$) than sites with baseflow yields between 100 and 200 mm/yr (average axis 1 score of 1.28) or >200 mm/yr (average axis 1 score of 3.12). There was also a statistically significant difference between the average axis 1 scores for sites with baseflow yield between 100 and 200 mm/yr and sites with baseflow yield >200 mm/yr ($p < 0.001$). There were no evident relationships between

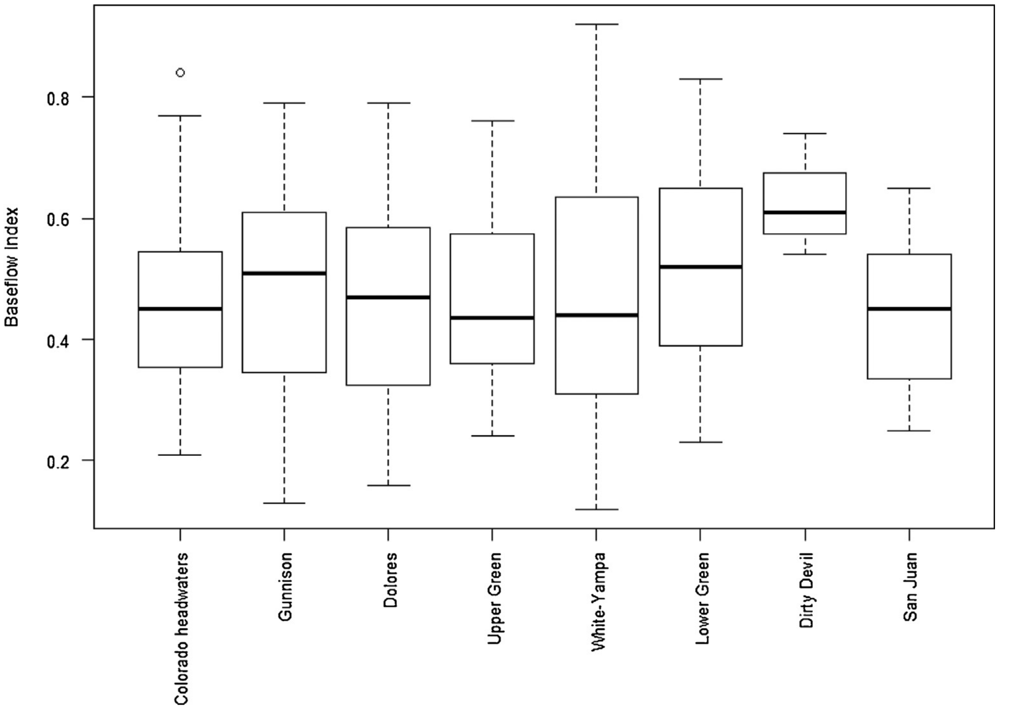

Fig. 5. Summary of BFI values by subregions (No significant differences between subregions (α = 0.05, Wilcoxon-rank sum test); subregions defined by HUC 4 boundaries).

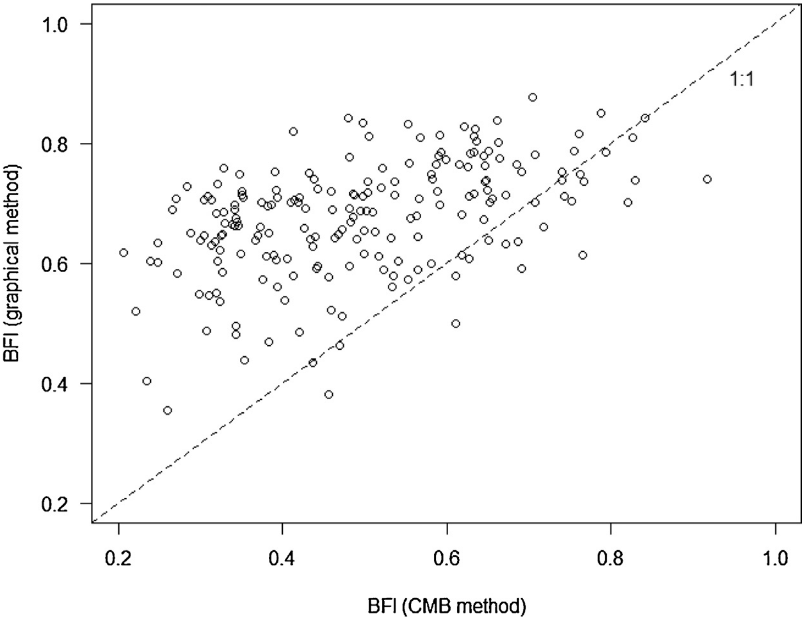

Fig. 6. Comparison of BFI estimates using graphical and CMB approaches (Wolock (2003) used the BFI smoothed minima graphical approach; the current paper uses the CMB method).

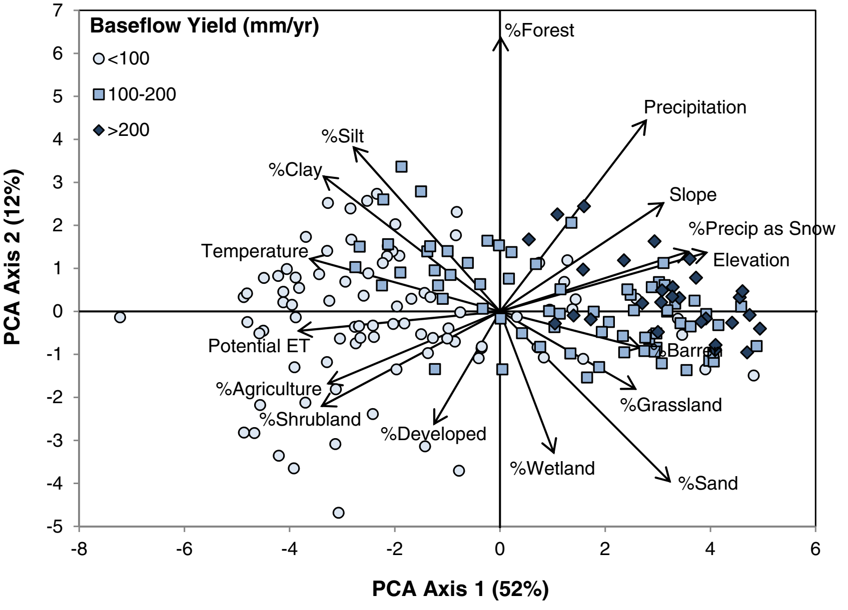

Fig. 7. Principal components analysis (PCA) scores and vectors for climate, soil, topography, and land cover variables. Sites are colored by estimated baseflow yield, and the percent of variance explained by each axis is indicated in the axis titles.

axis 2 scores and hydrologic characteristics (e.g. total stream discharge, baseflow discharge, baseflow yield or BFI).

Basin characteristics with strong positive weightings on axis 1, where sites with greater baseflow yield plot, include mean elevation, the percent of total precipitation that falls as snow, sand content of the soils, slope of the land surface, mean annual precipitation, and percent of the basin characterized as natural barren and grassland (Fig. 7; Table 2). Positive correlations between elevation and baseflow agree with spatial baseflow estimates (Fig. 2), which show that the highest baseflow yields are

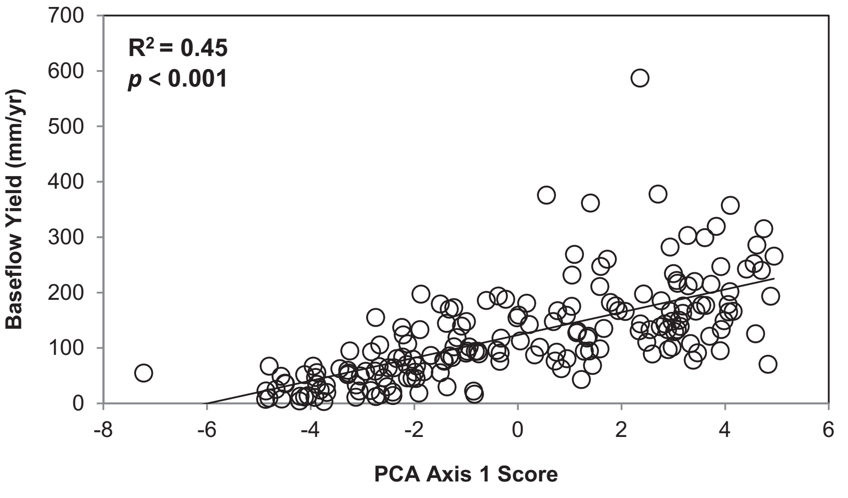

Fig. 8. Baseflow yield plotted as a function of PCA axis 1 score.

Table 2
PCA weightings for climate, soil, topography, and land cover variables.

Basin characteristics (Gages-II database)	Axis 1	Axis 2
Climate		
Air temperature, mean	−3.6	1.2
Annual precipitation, mean	2.8	4.5
Potential evapotranspiration	−3.9	−0.5
Snow % of total precipitation	3.6	1.4
Soils		
Clay content, %	−3.4	3.2
Sand content, %	3.3	−4.0
Silt content, %	−2.8	3.9
Topography		
Elevation, mean	4.0	1.4
Slope of land surface, %	3.1	2.5
Land cover characteristics		
Watershed percent developed	−1.3	−2.7
Watershed percent forest	0.0	6.4
Watershed percent herbaceous (grassland)	2.6	−1.8
Watershed percent natural barren	2.7	−0.9
Watershed percent agriculture	−3.3	−1.7
Watershed percent shrubland	−3.4	−2.2
Watershed percent wetlands	1.0	−3.3

generated in high elevation parts of the UCRB, such as the Rocky Mountains. Similarly, positive correlations between slope and baseflow are expected to be related to effects of elevation, although slope steepness is known to affect rates of groundwater transmission and determines whether groundwater will reach a channel network or be retained in the soil (Price, 2011). Increasing baseflow with precipitation is expected since precipitation is the major source of recharge to groundwater systems (Memon, 1995), and positive correlations between precipitation and baseflow have been shown in previous studies (Santhi et al., 2008; Stuckey, 2006). The importance of snow for generating baseflow may be explained by the fact that snowmelt is a major source of recharge (Winograd et al., 1998). Further, Huntington and Niswonger (2012) show that baseflow is influenced by snowmelt timing and hydraulic gradients, explaining that earlier snowmelt recession causes earlier peak groundwater discharge to streams, thus draining groundwater storage sooner and causing decreases in baseflow. Sandy soils are associated with higher rates of infiltration and recharge (Wolock, 2004), and have been shown to increase subsurface drainage (Yu et al., 2000). Lastly, increasing baseflow with percent grasslands and natural barren areas may be the result of their covariance with elevation (Table 1, supplemental information). Grasslands are also known to aid in infiltration and have relatively low rates of evapotranspiration, which may make them more favorable to baseflow generation than other land cover types (Nie et al., 2011).

Basin characteristics with strong negative weightings on axis 1, where sites with lower baseflow yield plot, include potential evapotranspiration, mean air temperature, clay content of the soils, and the percent of the basin characterized as shrubland and agriculture (Fig. 7; Table 2). Potential evapotranspiration decreases the amount of water available for recharge or runoff, and greater air temperatures increase potential evapotranspiration (Memon, 1995). Therefore, it is reasonable that both are associated with decreases in baseflow. Negative correlations between baseflow and soils with a high clay content may be due to the fact that clay-rich soils are associated with higher rates of evapotranspiration and runoff, resulting in lower recharge (O'Driscoll et al., 2005; Yu et al., 2000). Shrublands or agricultural lands may decrease baseflow depending on their infiltration, recharge, and evapotranspiration patterns, however without specific information about these land covers in the UCRB, it is impossible to infer direct processes. The negative correlation may be the result of covariance with elevation, since shrublands and agricultural lands are typically located in lower elevations of the UCRB (Table 1, supplemental information), where decreased baseflow yield occurs (Fig. 2).

PCA results indicate that baseflow yield is greater in high elevation areas where there is a greater percentage of precipitation that falls as snow, higher percentage of sandy soils, and steeper slopes;

whereas baseflow yield is lower in areas with higher air temperature, increased potential evapotranspiration, and clay-rich soils. While these correlations identify basin characteristics that may contribute to changes in baseflow yield, further investigation is warranted to determine the exact mechanisms by which these characteristics contribute to baseflow yield across the region. Further, it is important to note that these results only represent gaged, perennial streams and that a large number of streams

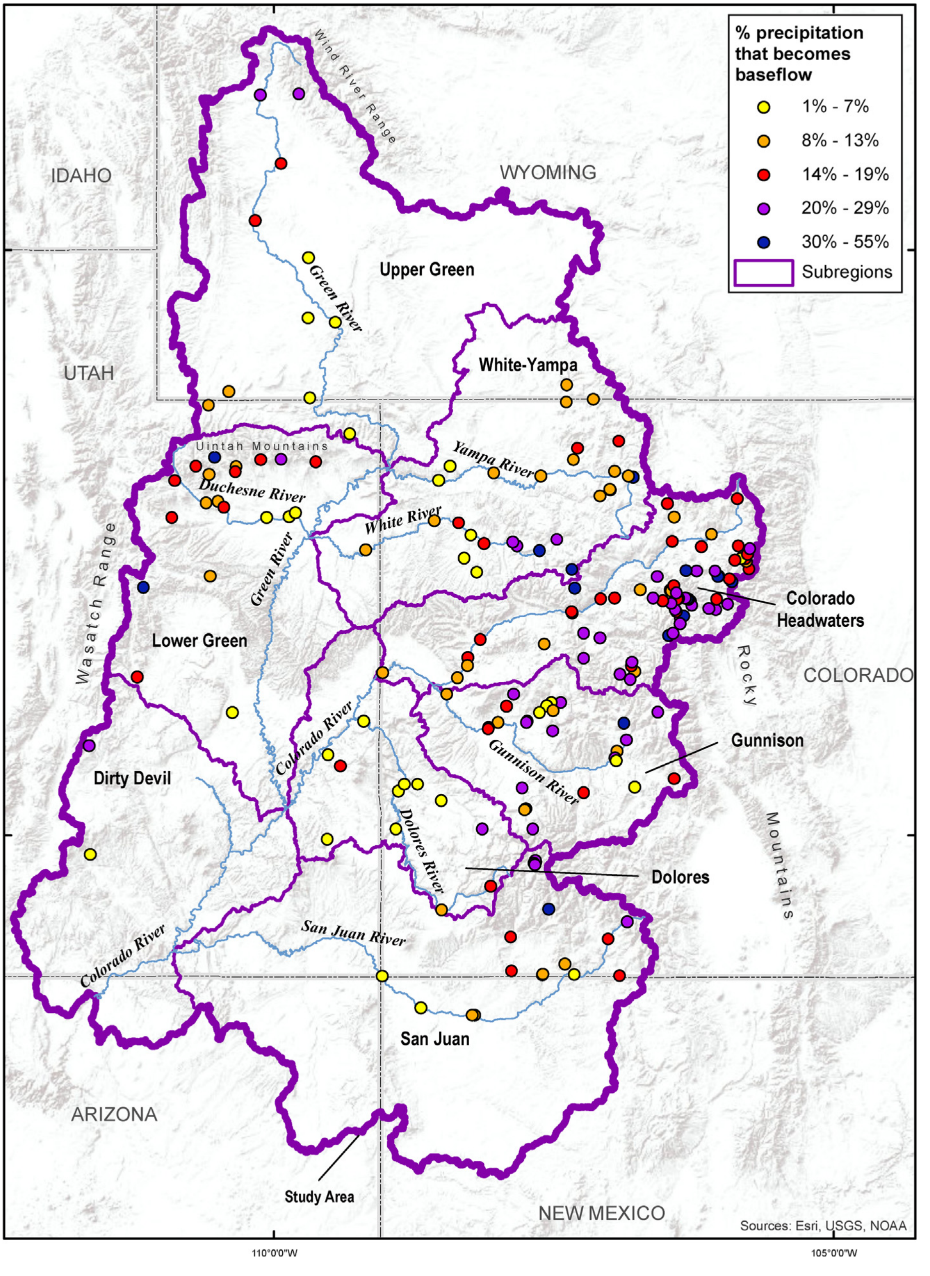

Fig. 9. Percent of precipitation that becomes baseflow (subregions defined by HUC 4 boundaries).

(e.g. ephemeral streams) are not included in these interpretations of the relationships between basin characteristics and baseflow yield.

As mentioned previously, many of the climate, soil, topography, and land cover variables covary with elevation, which is strongly correlated with air temperature, potential evapotranspiration, snow as a percent of total precipitation, slope, barren land, shrubland, grassland, and agricultural lands (Table 1, supplemental information). While elevation itself is unlikely to control baseflow yield, it is inherently related to watershed morphology and these results indicate that basin characteristics favorable to baseflow generally exist at higher elevations in the UCRB. This suggests that elevation acts as a surrogate for basin characteristics that may directly influence baseflow yield.

Another way to explore baseflow patterns is to consider the amount of baseflow that is generated from precipitation throughout the basin. The spatial distribution of the fraction of precipitation that becomes baseflow in the UCRB indicates that a larger percentage of baseflow is generated in upper elevation areas of the basin (Fig. 9). The average percent of precipitation that becomes baseflow at sites ranging in elevation from 3260 to 3600 m (highest 25%) is statistically greater than ($p < 0.001$) sites ranging in elevation from 2110 to 2580 m (lowest 25%). On average, $24 \pm 4\%$ of precipitation becomes baseflow at the high elevation sites, while an average of $8 \pm 3\%$ of precipitation becomes baseflow at the low elevation sites. This is consistent with the PCA results (Table 2; Table 1, supplemental information), and supports the idea that greater amounts of precipitation infiltrate and become baseflow in upper elevation areas of the UCRB (Memon, 1995; Price, 2011; Santhi et al., 2008; Winograd et al., 1998). Tague and Grant (2009) found that baseflow patterns in upper elevation areas may be adversely affected by climatic changes that alter precipitation, temperature, and timing of snowmelt, indicating that upper elevation baseflow in the UCRB may be vulnerable to similar changes. Further, Winograd et al. (1998) observed that snowmelt was the principal source of recharge for springs in a high elevation mountain range in Nevada, demonstrating that snow may play a critical role in baseflow generation in some areas.

Overall, results indicate that baseflow yield is greater in upper elevation watersheds where greater precipitation, snow, steeper slopes, and sandy soils are coupled with lower air temperatures and potential evapotranspiration. Greater precipitation at higher elevations contributes to higher baseflow volumes (Santhi et al., 2008), while lower temperatures allow a higher fraction of the total water input (precipitation) to become baseflow, runoff, and total streamflow (Memon, 1995). In addition, sandy soils with high infiltration rates increase permeability at upper elevations and transmit water more readily than finer soils at lower elevations (Price, 2011; Wolock et al., 2004). Higher air temperatures and potential evapotranspiration at lower elevations affect baseflow generation by decreasing the amount of precipitation that can infiltrate as a result of increased evapotranspiration (Brutsaert, 2005; Price, 2011).

Results of this study demonstrate that baseflow forms an important fraction (mean 48%, range of 12–92%) of total streamflow throughout the UCRB. Further, it identifies several important correlations between baseflow and basin characteristics that can be used to inform water management and planning. If temperatures continue increasing in the UCRB as they have been since the 1970s (Jacobs, 2011), our results suggest that baseflow may decrease as a result of increasing evapotranspiration rates and decreasing snow, which could affect groundwater recharge. Increases in groundwater withdrawals in the UCRB could also decrease baseflow, and ultimately streamflow volumes, as has been previously demonstrated in other studies (Garner et al., 2013; Weber and Perry, 2006).

4. Conclusions

Baseflow volume, baseflow yield, and BFI were determined at 229 sites throughout the UCRB using a chemical hydrograph separation approach. BFI values revealed that baseflow accounts for approximately half of the streamflow in the basin. Baseflow estimates suggest that there is typically greater baseflow yield in higher elevation watersheds, and that baseflow yield is positively correlated with precipitation, the percent of precipitation that is snow, sandy soils, land surface slope, and some land cover characteristics. Baseflow yield was generally lower at low elevation watersheds and at sites with high average temperatures and potential evapotranspiration. Quantification of baseflow discharge and identification of basin characteristics correlated with baseflow provides water managers with information that can be used to develop improved water management strategies. This will be important to consider as groundwater and surface water are considered a single water resource, and are managed jointly.

Conflict of interest statement

The authors require no conflicts of interest to disclose.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ejrh.2015.04.008.

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