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PAPER

Quantifying the base flow of the Colorado River: its importance in sustaining perennial flow in northern Arizona and southern Utah (USA)

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Abstract

Water in the Colorado River, USA, is known to be a highly over-allocated resource, yet managers and decision makers rarely consider one of the most important contributions to the existing water in the river, i.e. groundwater. This oversight may result from the contrasting results of base-flow studies conducted on the amount of streamflow into the Colorado River sourced from groundwater. Some studies rule out the significance of groundwater contribution, while others show groundwater contributing the majority of flow to the river. This study uses new and extant instrumented data (not indirect methods) to quantify the groundwater base-flow contribution to surface flow. The precipitation, streamflow, and base flow of 10 remote subbasins of the Colorado Plateau in southern Utah and northern Arizona were examined in detail. These tributaries have an annual average base-flow discharge of 0.45 km^3/year (367,000 acre-feet per year) with an average base-flow fraction of 72% summing to more than 3% of the mean flow of the Colorado River at Phantom Ranch. The groundwater storage trend of the Colorado River Basin when measured with remote sensing is declining; however, when utilizing instrumented data, the average annual base-flow trend in the study area remains constant. This trend suggests that base-flow signatures in streams may have a delayed response from the decline observed in groundwater storage from remote sensing. The simple extant data measurement methods employed in this study can be applied to the entire drainage basin, revealing the quantity of base flow throughout the basin to better inform water resource management.

Keywords Base flow · Groundwater management · Water supply · USA

Introduction

Water flowing in the Colorado River supports 50 million people in the United States (more than one-seventh of the population), and by 2030, there is an expected increase of another 23 million people (Gleick 2010; Gober and Kirkwood 2010), all relying on this already over-allocated water source. By 2060, the demand for water is projected to be higher than the total annual discharge of the river (USBR 2012), making careful management and complete monitoring of all water sources to the river crucial. While surface-water supply of the Colorado River is closely monitored, the status of groundwater storage and discharge is generally not a concern of water managers (Rosenberg et al. 2013; Xiao et al. 2018). However, Miller (2016) revealed that groundwater contributions to the Upper Colorado River Basin (CRB) as base flow (the amount of stream flow sourced from groundwater) exceed 50% of the total river discharge. Studies ignoring the interactions of groundwater are still caught in the old paradigm that catchments function like "Teflon basins" where surface water is the most important factor and it receives no influence from geologic and biologic materials, soil processes, or groundwater flow (Clow et al. 2003; Williams et al. 1993). These kinds of discrepancies in existing literature show that the interaction

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between groundwater and surface water is highly understudied in the CRB. This issue surrounding the Colorado River lies in both the lack of recognition attributed to the importance of base flow in sustaining stream flow as well as the policies governing the river. Groundwater extraction and the policies governing it have a direct impact on the amount of groundwater contributed to surface-water supply.

Stored water resources in the CRB are declining. Groundwater and surface-water declines are most visible in reservoir surface-water levels of lakes Mead and Powell and ground subsidence and fissures from groundwater mining in the Lower Basin (Galloway et al. 1999; Castle et al. 2014; Annin 2019; Morelle 2016). This visible reduction in stored water resources, however, is not fully addressed in the basin's policies. GRACE satellite data from 2004 to 2013 were utilized to estimate that the CRB lost 50.1 km^3 of groundwater storage while only 14.7 km^3 was lost from surface-water storage (Castle et al. 2014). This declining trend is forecasted to continue (Rahaman et al. 2019). In response to surface-water declines, restrictions have been implemented on surface-water use, as seen with the Colorado River Drought Contingency Plan (DCP; USDOI 2019). This plan, however, does not address groundwater, which has sustained a greater loss in storage. With the heightened restrictions on surface-water use that currently comprise 78% of the Basin's withdrawals (Maupin et al. 2018), groundwater will likely be used to supplement demand (Brown et al. 2019; Hughes et al. 2012), as was recently the case in California before groundwater regulations were put into place (Milman et al. 2018). This increased reliance on groundwater will further decrease the amount of subsurface-water supply. A reduction in groundwater will lead to many adverse and cumulative effects for water resources, including aquifer compaction reducing storage, increased pumping costs, ground subsidence, and harm to groundwater dependent ecosystems (Leake et al. 2008; Leake and Pool 2010). Not least of all, reduced storage directly affects groundwater discharge to springs and rivers (Brutsaert 2008; de Graaf et al. 2019; Kreamer and Springer 2008). Additionally, groundwater recharge rates for the region are projected to decline by up to 10–20% due to climate change (Meixner et al. 2016; Tillman et al. 2016). Although groundwater studies and management are ongoing in the CRB, limited quantitative research has been conducted to relate groundwater contribution to surface flows.

The policies and laws surrounding the surface waters of the Colorado River are complex and interwoven, partially due to the expanse of the river basin which includes seven US and two Mexican states, a 630,000 km^2 area, making it a transboundary and transnational river basin (Fig. 1). The interjurisdictional management of the river is a matrix of international, federal, state, tribal, and private interests, through a series of compacts, acts, treaties, and other resource management policies (Davis 2001). The most central piece of legislature for the river is the 1922 Colorado River Compact, that allocates rights to the river's water supply to the basin states and Mexico. This interstate compact divides the river into the Upper and Lower Basins (Fig. 1) to "provide for the equitable division and apportionment of the use of the waters of the Colorado River System." The system is defined as "...all of the drainage area of the Colorado River System and all other territory within the United States of America to which waters of the Colorado River System shall be beneficially applied." (USBR 1922, page 1). The compact allocated 7.5 million acre-feet (maf) (9.25 km^3) per year to each half of the basin. The 1928 Boulder Canyon Project Act ratified the 1922 Compact and divided the Lower Basin's allocation to Arizona, California, and Nevada (Table 1; USBR 2008). It also approved Hoover Dam and irrigation diversions in the Lower Basin, as well as appointed the Secretary of the Interior to be the only contracting authority in the Lower Basin. It was not until the Mexican Water Treaty of 1944 that the US recognized water allocation to Mexico and allotted 1.5 maf (1.85 km^3) of the river's annual flow to Mexico. The Upper CRB Compact of 1948 distributed the Upper Basin's 7.5 maf (9.25 km^3) allocation to Colorado, New Mexico, Utah, Wyoming, and Arizona (Table 1) (USBR 2008). Additionally, Indigenous tribes and nations have recently secured the rights to an estimated 2.4 maf (2.96 km^3) of Colorado River water and continue to seek further allotments through ongoing adjudications (CRS 2019; Pitzer 2017).

The Colorado River is the seventh largest river in the US based on its 2,334-km length and 630,000 km^2 area (Kammerer 1990). At Lees Ferry, the division point between the Upper and Lower Basins (Fig. 1), discharge averages 13.5 maf (16.65 km^3) per year, a highly fluctuating average with annual totals ranging from 4.4 maf (5.43 km^3) to over 24 maf (29.6 km^3) from 1906 through 2018 (Best 2019; Christensen and Lettenmaier 2007; Gelt 1997). The Colorado River water supply was allocated in 1922, based on flow at Lees Ferry averaging 16.4 maf (20.23 km^3) annually. Thus, in many years, there are more water rights allocated than there is water flowing in the river. While historically this over-allocation has not been a point of contention, as states begin to use their full legal entitlement to meet growing demands, governance challenges are mounting. With shortages becoming more frequent and reservoir levels declining (Brown et al. 2019; Gober and Kirkwood 2010), improved surface-water management is critical, including the groundwater contribution.

To obtain a more inclusive and complete management system of Colorado River water, many additional ecological aspects need to be considered. For instance, with such diverse and increasing demand for water, environmental flows must be considered in Colorado River management, especially in the face of climate change. Water flows and quality need to remain at high enough standards so the water source can sustain freshwater and estuarine ecosystems, as well as humans

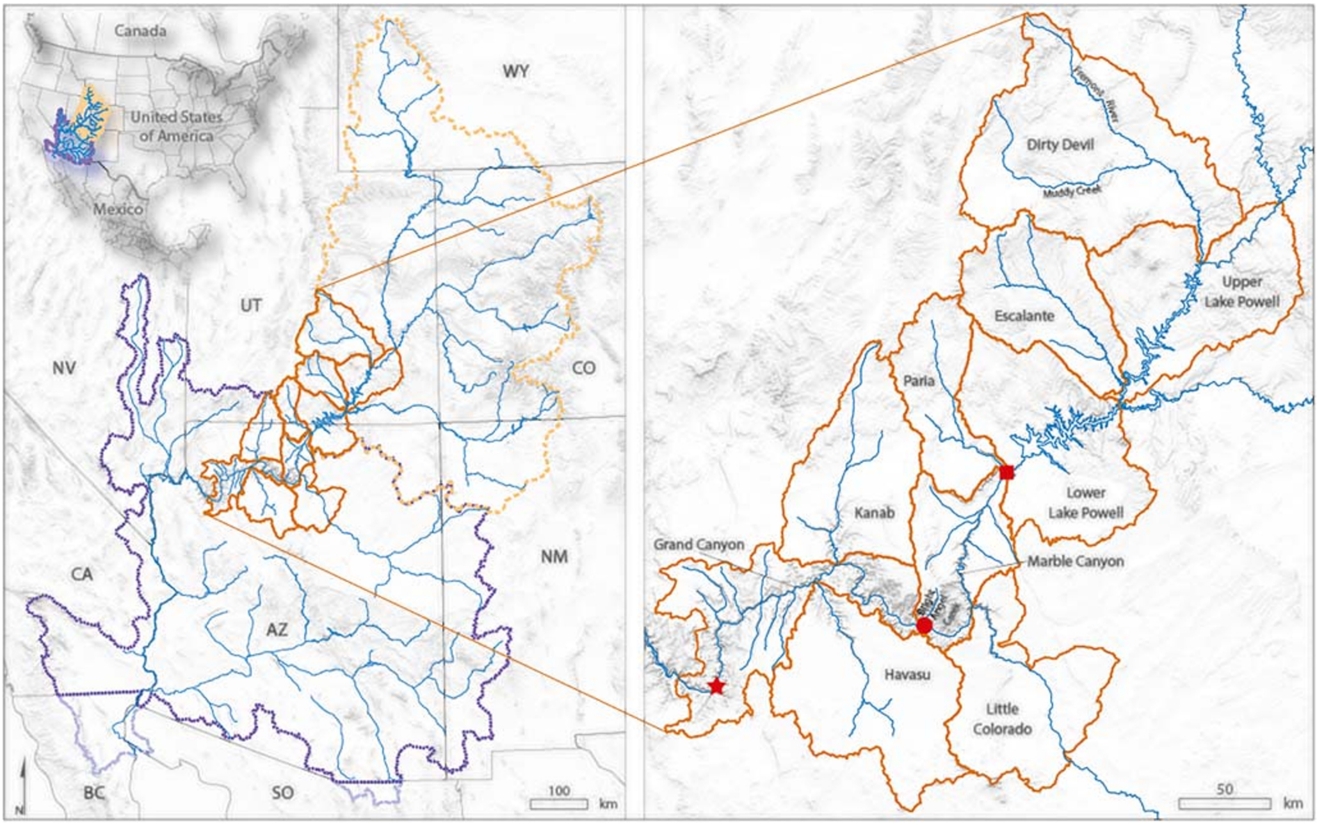

Fig. 1 The Colorado River Basin (CRB) with the Upper Basin outlined in dashed light orange, the Lower Basin in dashed purple, and Mexico's portion of the basin in dashed light purple. Solid blue lines indicate the Colorado River and its major tributaries. The 10 hydrologic unit code eight (HUC 8) subbasins are delineated in orange and red shapes represent Colorado River study gauges (red square shows Lees Ferry, red circle shows Phantom Ranch, and red star shows Diamond Creek). The basin states are abbreviated; USA: AZ Arizona, CA California, CO Colorado, NM New Mexico, NV Nevada, UT Utah, WY Wyoming, and Mexico: BC Baja California, SO Sonora

and their well-being (Acreman 2016; Bair et al. 2019; Mott LaCroix et al. 2016; Kreamer et al. 2015). Environmental flows have only recently been included in management plans on the Colorado River, with projects like Glen Canyon Dam that reduced its electricity generation potential by about one-third to help protect ecological resources in the Grand Canyon (Richter et al. 2010; GCDAMP 2019). These adaptive management strategies are important steps in the right direction, but groundwater has still been overlooked in these management alterations. This oversight is particularly glaring given that groundwater is a crucial fraction of the river's discharge that decision makers use to determine appropriate environmental flow regimes (de Graaf et al. 2019).

Table 1 Colorado River annual water allocation in millions of acre feet (maf) for the Upper and Lower US Basin divisions (USBR 2008)

States		Annual water allocation (maf)
Upper Basin states	Colorado	3.86 (4.76 km^3)
	Utah	1.71 (2.11 km^3)
	Wyoming	1.04 (1.28 km^3)
	New Mexico	0.84 (1.04 km^3)
	Arizona	0.05 (0.06 km^3)
	Subtotal	7.5 (9.25 km^3)
Lower Basin states	California	4.4 (5.43 km^3)
	Arizona	2.8 (3.45 km^3)
	Nevada	0.3 (0.37 km^3)
	Subtotal	7.5 (9.25 km^3)
Basin states	Total	15.0 (18.5 km^3)

Groundwater management is increasingly more difficult with prolonged drought trends curbing recharge rates while growing population's demands tap into the already scarce water resources (Gleick 2010; MacDonald 2010). The Fourth National Climate Assessment suggests the CRB is likely to become drier and experience more severe droughts than what is already observed (USGCRP 2018). Cayan et al. (2010) suggest these future drought conditions will be exacerbated by globally warmed temperatures that reduce spring snowpack and soil moisture content. These drying conditions have prompted the Colorado River DCP to stipulate increasing cuts to water supplied to the compact states based on predetermined surface-water level declines of Lake Mead (USDOI 2019). The DCP is focused on sustaining surface-water resources, but with future water sources predicted to be in higher demand, communities will likely turn to groundwater sources to supplement the supply cuts and growing demand (Brown et al. 2019; Hughes et al. 2012; Womble et al. 2018).

Of the few studies conducted to find groundwater's contribution to the Colorado River's flow various techniques have been utilized. Indirect chemical separation techniques used by Miller et al. (2014) utilized chemical hydrograph separation by applying chemical mass balance estimates from specific conductance to the entire Upper Basin. This technique found the annual base flow in the Upper Basin to be 21–58% of streamflow, with higher percentages during low-flow conditions. Other studies have used similar techniques in different locations at smaller scales (Caine 1989; Stewart et al. 2007; Frisbee et al. 2011; Sanford et al. 2011). Simpler filtering techniques have also been used to separate base flow that only utilizes stream discharge data (Nathan and McMahon 1990; Wahl and Wahl 1988; Eckhardt 2005). This technique has the advantage of only requiring stream discharge data, allowing for its application in a larger number of locations, making it especially ideal in locations with limited data and accessibility.

It is hypothesized that if base flow is the majority contribution to the Colorado River through the greater Grand Canyon region, then base flow separation techniques on the major tributaries will account for the majority of gain observed on the main stem of the Colorado River. This groundwater contribution is sustaining a substantial amount of perennial flow that is an overlooked source to surface-water supplies.

Study area

The Colorado River originates in high elevation areas of the drainage basin where alpine snowmelt predominantly infiltrates and recharges groundwater systems, which in turn supply base flow (Clow et al. 2003). Estimates indicated up to 90% of the streamflow in the Colorado River originated from snowmelt in the mountains of Colorado, Utah, and Wyoming (Jacobs 2011). Now, the majority of streamflow in the Upper CRB is shown to originate from groundwater (Miller et al. 2016). This contribution of base flow is due to large amounts of precipitation falling at the high elevations that infiltrate and recharge the local and regional groundwater systems. The groundwater then discharges into the basin's surface flows through short and long flow paths that accumulate to a large volume due to the scale of the Colorado River watershed (Frisbee et al. 2011).

The subbasin study area lies on the south western end of the Colorado Plateau, where the local stratigraphic units range from Mesozoic–Pre-Cambrian, with the main hydrostratigraphic units including the Navajo (N), Coconino (C), and Redwall-Muav (R) aquifers (Miller et al. 2016; Tobin et al. 2017). Infiltration occurs primarily through local faults, fractures, and karst features in the flat lying strata (Beisner et al. 2020; Jones et al. 2018). Recharge is dominantly from the higher elevations with a smaller fraction from lower elevation local areas, creating a variation of groundwater flow paths from these different recharge locations (Fig. 2; Ingraham et al. 2001; Meixner et al. 2016; Rice and Springer 2006). Groundwater extraction from these layers is for the small communities of the area; Valle and Tusayan (Fig. 2; Crossey et al. 2009).

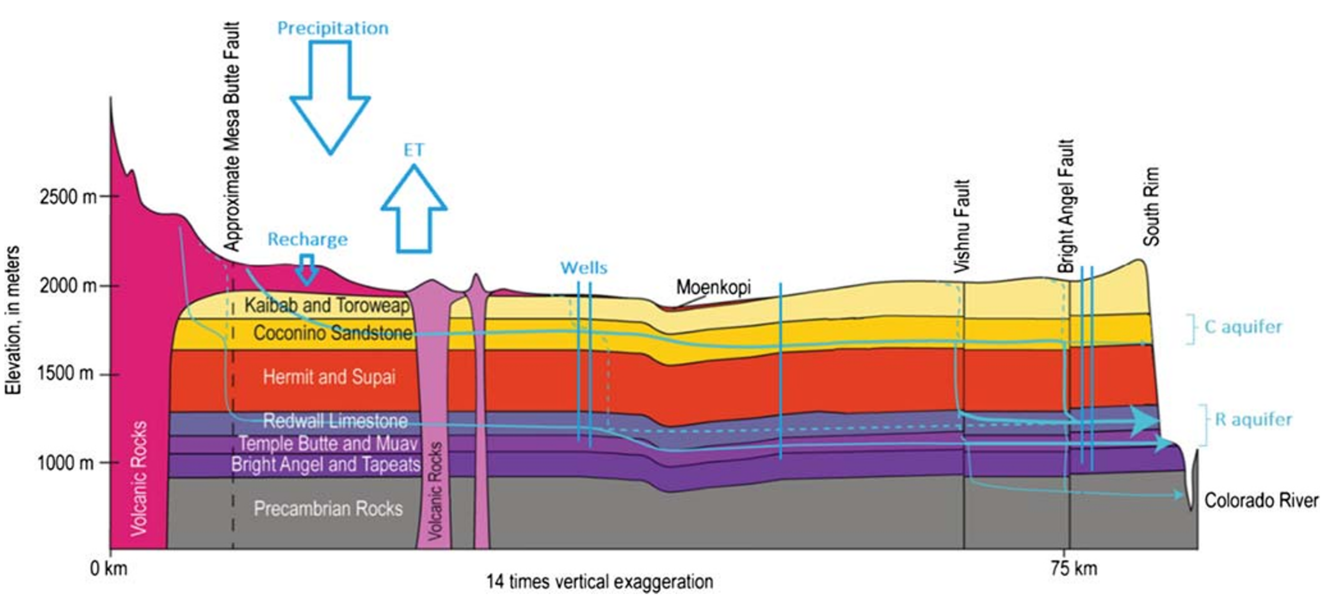

Fig. 2 Conceptual model of the study area showing the regional geology, generalized flow lines (light blue), groundwater extraction wells (blue); (modified from; Beisner et al. 2020; Crossey et al. 2009)

In this study, the CRB is subdivided into surface-water subbasins by the 8-digit tributary hydrologic unit codes (HUCs). Groundwater subbasins are included in the HUC 8 surface-water drainages that receive groundwater discharge from the local and regional aquifers. The study area was selected due to low anthropogenic disturbance to the hydrologic system and to help fill in knowledge gaps in the understudied groundwater aspects of the system. Ten HUC 8 tributaries to the Colorado River were studied covering almost 8% of the CRB, an area similar in size to Slovakia at nearly 50,000 km^2 (Fig. 1). Within these drainage basins are local plateau areas, where springs were monitored to better understand groundwater conditions of the local aquifers.

The southern drainages are fed by springs originating from the regional C and R aquifers (Fig. 2). The major tributaries in this reach are perennial, spring fed creeks that create keystone ecosystems that are the most diverse in the region (Stevens and Meretsky 2008; Sinclair 2018). The Little Colorado River and Havasu Creek are the major tributaries from the south rim of the Grand Canyon where they flow perennially from some of the largest springs in the region discharging from the Coconino Plateau. The Kanab Creek drainage, a HUC 8, and the largest drainage area tributary from the north rim of the canyon is sourced from the same regional C and R aquifers, but function as separate systems, as the Colorado River has bisected the aquifers (Tobin et al. 2017). Two HUC 8 drainages lie on the main stem of the Colorado River; Marble Canyon and Grand Canyon. These HUC 8 drainages are divided at Phantom Ranch, with Marble Canyon stretching 140 km long above and Grand Canyon extending 250 km below. At the northern end of the study area are the Escalante River, Dirty Devil River, and Paria River surface-water drainages (Fig. 1). The Dirty Devil River includes two additional HUC 8 tributaries, Muddy Creek and Fremont River. These tributary rivers derive the majority of their flow from groundwater discharged from springs primarily in the eolian Navajo Sandstone, stratigraphically higher in the layer cake structure of the region (Rice and Springer 2006). Upper and Lower Lake Powell HUC 8 tributaries were not included in this study due to the inundation of the reservoir.

Materials and methods

Base-flow separation

Due to flow regulation and other impacts from large dams on the main stem of the Colorado River disrupting base-flow signatures, major tributaries were analyzed instead. The tributaries in the study area do not have large dams or diversions, allowing for analysis with base-flow separation methods. Surface-water monitoring in this region is limited in scope and frequency, with gauges only in select tributaries that are typically HUC 8 or larger (USGS 2020). Gauges selected for this study are either the only gauge or the furthest downstream gauge on the tributary. Some gauges also contain large intervals of missing data where the site was not recording. Thus, the length of record analyzed was matched for all tributaries to the most recent continuous period (Table 2). The period of record for the Colorado River was chosen as the entire recorded record as well as pre-dam flows to eliminate the influence of flow regulation from Glen Canyon Dam. The differences in climate observed in this time period are negligible as pre-dam conditions show comparable annual discharges, precipitation, and runoff (Christensen and Lettenmaier 2007; USBR 2012).

To estimate the base flow of each tributary included in this study, a recursive digital filter was applied to the mean daily surface discharge for the entire period of record (Fuka et al. 2018; USGS 2020). The EcoHydRology package in Rstudio was utilized to separate base flow and surface flow by

Table 2 River gauges utilized for base-flow separation methods

Tributary	USGS gauge site number	Period of record	Years of record analyzed
Bright Angel Creek	09403000	2006–2017	12
Colorado River at Diamond Creek	09404200	1983–2019	36
Colorado River at Lees Ferry	09380000	1921–2019	99
Colorado River at Phantom Ranch	09402500	1922–2019	98
Colorado River at Phantom Ranch (Pre-dam)	09402500	1922–1955	34
Dirty Devil River	09333500	2001–2019	18
Escalante River	09337500	2001–2019	18
Havasu Creek	09404115	2001–2009, 2011–2019	17
Kanab Creek	09403850	2016–2019	4
Little Colorado River	09402300	2001–2019	18
Paria River	09382000	2001–2019	18

adjusting the filter parameter and number of times the filter was run over the data (Fuka et al. 2018). In the filtration process of the streamflow data, the best fit for the base-flow separation was obtained through a filter parameter of 0.9 and the filter being run three times (Fuka et al. 2018; Lyne and Hollick 1979; Nathan and McMahon 1990). Base-flow data were then averaged by each year to identify trends in the annual base flow for the period of record. To find the significance of these trends, base-flow discharge was treated as a response variable in two linear regression models: an intercept only model, representing no trend in the data, and a model with year as the predictor variable, to determine if there is a significant slope in the relationship between year and discharge. These data were then plotted with the slope of the year model and the associated 95% confidence interval. The average base flow was then compared to the mean flow of the Colorado River at Phantom Ranch. These base-flow analysis methods were conducted for the Dirty Devil River, Escalante River, Havasu Creek, Kanab Creek, Little Colorado River, and Paria River.

Extant data compilation

Quantifying the base-flow fraction for the Grand Canyon and Marble Canyon tributaries was achieved by compiling data from discrete monitoring trips to the different study sites. The majority of the tributaries in these drainages do not have continuous gauging and only have discrete measurement data. These sites were only measured at a very coarse scale of less than yearly measurements. Methods to estimate discharge of ungauged drainage basins exist and have varying degrees of accuracy, with arid regions and small drainage basins having the lowest accuracy (Parajka et al. 2013; Salinas et al. 2013). Due to this inconsistency, methods for discharge estimation from ungauged basins were not applied in this study and direct measurements were used, instead. The discrete monitoring was done by Grand Canyon National Park (GRCA) and Northern Arizona University (NAU) staff over 27 years. All measurements were taken by hand utilizing flumes, flow probes, or wading rods. These data are limited in the degree of certainty and were used to total the base flow for these areas, where other data are nonexistent. To convert these discrete measurements to base-flow values, extant measurement points were filtered based on the time of year and weather conditions to rule out surface flow contribution. All tributaries analyzed were void of any diversions, dams, or surface-water storage existing in the drainage. Individual measurements indicating the occurrence of any recent precipitation that was noted in the field were rejected from the analysis to ensure summer monsoon cycles were not adding surface flow to those measurements. To ensure that spring snow melt was not contributing surface flow, measurement points were compared to the snowmelt hydrograph response of Bright Angel Creek. This tributary has a representative annual cycle that shows the general timing of snowmelt for Marble and Grand Canyons. Snow melt occurred in March through early June and monsoons occurred from June through the end of August. Measurements falling within this time frame were removed from the calculations. After this comparison process, the entire flow that was measured was assumed to be the groundwater or base-flow contribution. All measurements with no signs of precipitation and with drainages void of human alterations were used and averaged to estimate the annual base flow. Each of these measurements was recorded as a representative base-flow value of their HUC 12 drainage basin. Discharge was then summed for HUC 12 drainages to give a minimum total for the larger HUC 8 drainage, Grand or Marble Canyon. Hand measured base-flow values were then compared, when available, to base-flow separated data to ensure accuracy of measurements.

Spring monitoring

Discharge measurements from springs throughout the study area provided data on the local and regional groundwater conditions and highlight the contributing aquifer sources for base flow. Springs were sampled to quantify the amount of direct contribution to base flow and identify and assess the key aquifers of interest in the study area. The spring sites were opportunistically sampled based on the magnitude of discharge, regional aquifer source, access, and spatial distribution, using Springs Stewardship Institute's level two inventory field protocols (Stevens et al. 2016). Springs were sampled from the Escalante River, Grand Canyon, Havasu Creek, Kanab Creek, Marble Canyon, and Paria River catchments. Spring discharge was measured with either a volumetric container, weir plate, flume, or wading rod, depending on the individual flow rate of the spring. The spring area was then assessed for maximum extent of spring runoff conditions to check for direct base-flow contribution to local tributaries.

Recharge estimations

The amount of base flow observed in each subbasin of the study area was converted to recharge to compare with other regional estimates of recharge (Meixner et al. 2016). The average annual base-flow volume of each tributary was divided by the area of the subbasin to give a recharge estimate (some areas were adjusted to larger HUCs to incorporate the larger groundwater basins). This amount was then divided by the average annual precipitation value for each subbasin. The average annual precipitation for each subbasin was from the 30-year mean precipitation data (PRISM Climate Group 2015). The result was the percentage of base flow from precipitation.

Study area reach of the Colorado River

The USGS gauges on the main stem of the Colorado River through the study area allows for percentages of base flow from total discharge gain to be made. To check base-flow quantities, results were compared to the total gains of the study reach. The total discharge gain was obtained utilizing the three USGS gauges in the study area on the Colorado River at Lees Ferry, Phantom Ranch, and Diamond Creek (Fig. 1). At these points, the total annual average discharge was calculated, then subtracted between each gauge to obtain how much water was gained in this reach of the river. The total gain was then divided by the base-flow separation value to give the percentage of total gain explained by groundwater contribution.

Results

Base-flow separation

The filter parameter selection process resulted in a large variety of base-flow values. Higher filter parameters for these tributaries tended to underestimate base-flow conditions resembling methods closer to smoothed minima techniques (Fig. 3a), while lower filter parameters showed more realistic base flow increases during discharge peaks (Fig. 3b). The filter parameter of 0.9 agrees most with the expected natural conditions that exist in the tributaries of the arid study area (Eckhardt 2005; Nathan and McMahon 1990). This filter choice shows a good separation of the flashy surface flows and matches the groundwater recharge from these events. The base-flow separations have inherent error included due to the USGS instrumentation commonly resulting in measurement being within 5–10% accuracy (Boning 1992).

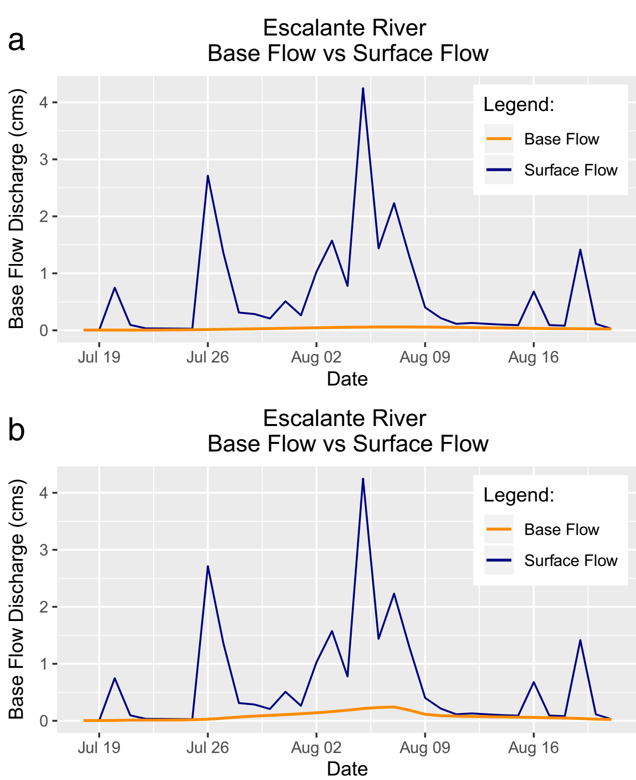

Fig. 3 Examples of base-flow separation using different filter parameters. **a** Filter parameter at 0.95 and **b** filter parameter at 0.9

Time-series trends in the average annual base flow for this period of record have varied results. Throughout the study area, the base flow showed similar visible temporal trends. Plotting these data with the linear regression model and a 95% confidence interval, visually shows the trends for the period of study (Fig. 4). The year models for all drainages did not have significant slopes, indicating that there was not a statistically significant trend; this was verified by the significance of the intercept in the intercept only models (Table 3). The slight visual changes seen in the Escalante River (Fig. 4b) and Paria River (Fig. 4f) do not have statistical significance. The change in the Escalante River (Fig. 4b) is attributed to the outlier year 2005; removing this year from the analysis resulted in a visually consistent base-flow trend. The second zero slope linear regression model confirmed that the tributaries do not have a statistically significant trend. The zero slope linear regression model showed that there is no significant variance of annual means from a zero slope or horizontal line (Table 3).

Utilizing USGS gauge data, base-flow separation techniques indicate a total annual base-flow contribution of 279,000 afy for all of the tributaries, accounting for an average of 66% of the discharge from these tributaries. Comparing this base flow to the mean flow of the Colorado River in pre-Glen Canyon Dam times, results in these tributaries contributing 3% of the total flow at Phantom Ranch (Table 4).

Grand and Marble Canyon manual measurements

The Colorado River reach through Grand and Marble Canyons has inaccessible tributaries and therefore, until recently, there were little available data on discharge gained from groundwater in this reach. Utilizing 100% of the flow as groundwater source for the discrete measurements, the base flow of the Grand Canyon tributaries totaled 81,000 afy (0.1 km^3/year) and the Marble Canyon tributaries totaled 7,000 afy (0.01 km^3/year)—Table 4; electronic supplementary material (ESM). Due to the lack of continuous discharge data in the region, it was not possible to obtain a base-flow percentage of the tributaries. Five tributaries in the study area contained both discrete and continuous measurements allowing for comparison of the data compilation to base-flow separation values and an estimate of the percent difference for each

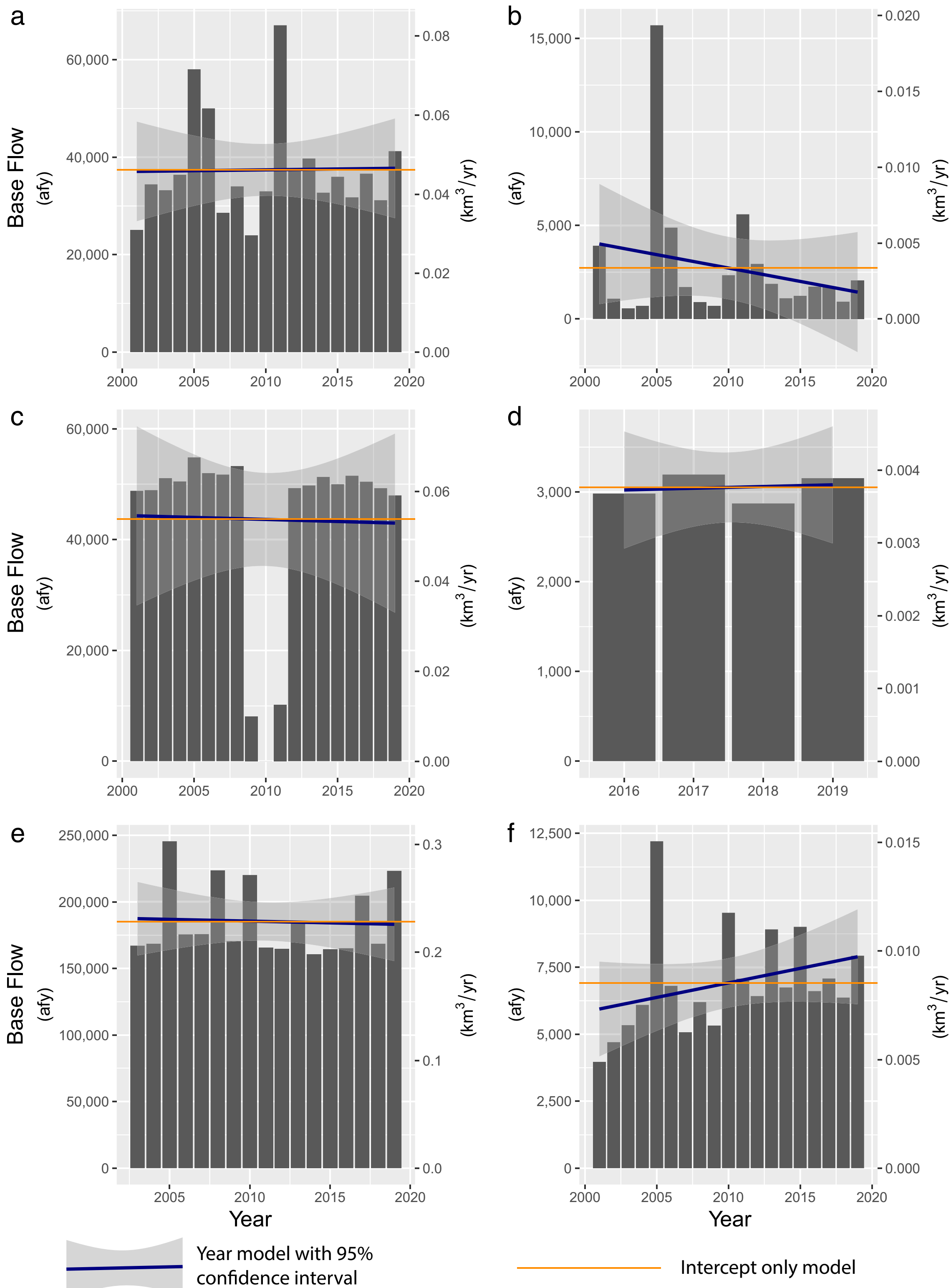

Fig. 4 Average annual base-flow totals with model trends for **a** Dirty Devil River, **b** Escalante River, **c** Havasu Creek, **d** Kanab Creek, **e** Little Colorado River, and **f** Paria rivers

tributary (Table 5). The majority of tributaries where data compilation was utilized underestimated the annual average base flow by up to 71% or had a close percent difference for discharge approximation.

Spring monitoring

Spring monitoring confirmed the aquifer sources of base-flow contribution from springs to the Colorado River and its

Table 3 Statistical significance of linear regression line models for total annual base flow

Tributary	Model	Intercept	Slope	Degrees of Freedom	*F*- statistic	R^2	*P*-value intercept	*P*-value slope
Dirty Devil River	Year	−34,269	35.66	17	0.006	−0.058	0.971	0.939
	Intercept only	37,412	–	18	–	–	9.52e-12	–
Escalante River	Year	290,118	−143	17	0.980	−0.001	0.332	0.336
	Intercept only	2,721	–	18	–	–	0.003	–
Havasu Creek	Year	190,379	−73	17	0.010	−0.058	0.898	0.921
	Intercept only	43,627	–	18	–	–	1.38e-09	–
Kanab Creek	Year	−35,548	19	2	0.056	−0.459	0.848	0.835
	Intercept only	3,051	–	3	–	–	3.27e-05	–
Little Colorado River	Year	715,352	−264	15	0.036	−0.064	0.800	0.851
	Intercept only	185,280	–	16	–	–	4.38e-15	–
Paria River	Year	−21,1046	108	17	1.854	0.045	0.205	0.191
	Intercept only	6,917	–	18	–	–	7.5e-12	–

tributaries. The majority of springs in the regional aquifers do not flow directly to the river as base flow. Only a few major springs from the R aquifer contribute direct continuous flow to the Colorado River. The C aquifer springs in this study area do not directly discharge to the Colorado River or its tributaries. The C aquifer may play a significant role in recharge and flow to the R aquifer (Wood et al. 2020). The majority of springs discharging from the N aquifer on the north side of the Colorado River do not reach the river, with the exceptions of springs in the corridor of major tributaries. On the south side of the Colorado River, there is no direct base-flow contribution from the N aquifer.

Recharge estimation

The amount of precipitation averaged for each subbasin ranged from 297 mm for the Dirty Devil to 415 mm for Havasu Creek (Table 6). The amount of recharge for the subbasins ranged from 0.6 mm for the Escalante River to 6.6 mm for Havasu Creek (Table 6). For each of the subbasins, the percentage of precipitation resulting in base flow fell in the range of 0.17–1.59%, with Kanab Creek at the low end and Havasu Creek at the high end (Table 6).

Colorado River reach

The total discharge gains of the Colorado River through the study area reach of the river average 786,300 afy (0.97 km^3/year; Table 7). This gain is divided into Marble Canyon and Grand Canyon gains, as Phantom Ranch is the divide between the HUCs. The discharge gain in Marble Canyon is 430,200 afy, and the gain in Grand Canyon is 356,000 afy (0.44 km^3/year). Dividing the base-flow separation values by total gains shows the percent of gain contributed by base flow for each reach. This makes the total reach 42% base flow and Marble and Grand Canyons 46 and 36% respectively (Table 7). The gains observed for the study area are relative gains due to the overall accuracy of the USGS gauges. The 5–10% accuracy for these gauges does not allow for confidence in the relatively small amount of gain observed in this reach.

Table 4 Summary of base-flow separation drainage basins and the percentage of total flow. Basin discharge based on the mean annual average for instrumented period of record (GRCA; USGS). *afy* acre-feet per year

	Dirty Devil River	Escalante River	Grand Canyon	Havasu Creek	Kanab Creek	Little Colorado River	Marble Canyon	Paria River	Total
Surface flow, afy (km^3/year)	70,100 (0.09)	6,200 (0.01)	>81,000 (>0.10)	46,500 (0.06)	8,300 (0.01)	276,200 (0.34)	>7,000 (>0.01)	17,800 (0.02)	>513,000 (0.63)
Base flow, afy (km^3/year)	37,400 (0.05)	2,700 (0.003)	81,000 (0.10)	43,600 (0.05)	3,000 (0.004)	185,300 (0.23)	7,000 (0.01)	7,000 (0.01)	367,000 (0.45)
% of tributary discharge	56	43	–	93	38	69	–	41	<72
% of basin discharge (entire record)	0.34	0.03	0.74	0.40	0.03	1.70	0.06	0.06	3.37
% of basin discharge (pre-dam)	0.36	0.02	0.66	0.35	0.03	1.52	0.06	0.07	3.01

Table 5 Percent difference in base-flow calculation and data compilation for available drainages

Tributary	Base-flow separation, afy (km^3/year)	Data compilation, afy (km^3/year)	Percent difference
Bright Angel Creek	17,900 (0.022)	12,300 (0.015)	−37
Havasu Creek	43,600 (0.054)	45,000 (0.056)	3
Kanab Creek	3000 (0.004)	3200 (0.004)	6
Little Colorado River	185,300 (0.228)	140,100 (0.173)	−28
Paria River	7000 (0.009)	3300 (0.004)	−71

Discussion

By synthesizing the available instrumented records in the study area, a more robust estimation of base flow was made for an area with limited previously published data. These direct measurement techniques can be applied to the entire drainage basin as well as for any river basin with various data sources of direct measurements and continuous collection. The base flow determined for the study area was a substantial portion of flow in the Colorado River, with the average annual base-flow gain totaling 367,000 afy (0.45 km^3/year). This discharge accounts for over 3% of the mean flow conditions of the main stem of the Colorado River (Table 4). For a region with an arid climate observed throughout the Lower Basin of the Colorado River, the study area showed a considerable amount of base flow that is often overlooked. The total annual base flow of the study area is shown to be a comparable amount to the water that is lost from the evaporation from Lake Powell or more than the amount of water supply cut from the first level of the DCP (USBR 2012; USDOI 2019). Error does exist throughout the study methods; however, multiple lines of evidence converge to the same conclusions.

Using USGS gauges on the main stem of the Colorado River, it was possible to estimate the percentage of Colorado River base flow from the tributary base-flow separation results. The total discharge gains observed for the Colorado River divided by the sum of the base-flow separation values in the study area (Table 7) shows that the base-flow percentages at 42% are near the 56% found by Miller et al. (2016) for the Upper Basin. This percentage of base flow is a minimum value for the area due to springs and tributaries that were not able to be accessed in this study. Within the study area there are many tributaries and springs that were not measured at a high enough frequency, are inaccessible, or discharge under the river, all contributing to errors in the results. Underestimation of base flow may have occurred in the extant data compilation as manual measurements were underpredicting where overlapping data existed (Table 5) and small sample sizes were used to estimate for the entire annual average (see ESM). Additionally, existence of minor water diversions within the study tributaries will dampen the base-flow signature. The tributaries with this issue include Bright Angel Creek, Dirty Devil River, Escalante River, Kanab Creek and Paria River. These diversions should be studied further to quantify the entire effect for future studies. Ongoing studies and new measurements will also be able to improve the estimate for the study area in the future.

Comparisons of the estimates of recharge for the study area and the percentage of precipitation seen as base flow allow the results to be compared to a broader set of references. For each of the subbasins, the percentage for precipitation to base flow fell near the expected range of 1–2% (Wyatt et al. 2015; Table 6). The exceptions are Kanab Creek and the Escalante River that fell well below this range. These two tributaries have the lowest base-flow values for the study area, a result that could be attributed to lower recharge causing a lower percent of base flow as a percent of precipitation.

Table 6 Percentage of base flow from precipitation for study area tributaries

Tributary	Precipitation (mm)	Recharge (mm)	Percentage of base flow from precipitation
Dirty Devil River	297	4.1	1.37
Escalante River	312	0.6	0.18
Grand Canyon	329	3.1	0.94
Havasu Creek	415	6.6	1.59
Kanab Creek	388	0.7	0.17
Little Colorado River	263	3.4	1.28
Marble Canyon	325	2.6	0.81
Paria River	303	2.7	0.90

Table 7 Total average annual gain at USGS gauges on the main stem of the Colorado River in the study area compared to annual average base-flow separation values

Parameter	Marble Canyon	Grand Canyon	Total
Average total discharge gain, afy (km^3/year)	430,200 (0.53)	356,000 (0.44)	786,300 (0.97)
Sum of tributary base-flow discharge from separation techniques, afy (km^3/year)	199,300[a] (0.25)	127,600[b] (0.16)	326,900 (0.41)
Percent of total discharge gain from base flow	46	36	42

[a] Base-flow addition from Paria River, Little Colorado River, and Marble Canyon

[b] Base-flow addition from Grand Canyon, Havasu Creek, and Kanab Creek

The average annual base-flow discharge and base-flow percentages did not show a statistically significant trend (Fig. 4; Table 3). This lack of a trend can be explained in two scenarios. The first, is that the study area is sparsely populated and current groundwater pumping is at levels that do not negatively affect base flow. The second, however, is that the response times of the groundwater system are longer than the period of study and the effects of groundwater use have not been observed in base-flow declines yet. The study area base-flow separation results show a different groundwater response than basin-wide remote sensing techniques utilizing GRACE data. In the study area, base-flow trends remained constant for the period of study (Fig. 4; Table 3), while basin-wide groundwater data suggest clear declines (Castle et al. 2014; Rahaman et al. 2019). These differences in trends suggest that the delay in the response of groundwater storage loss to observed trends in base flow of streams and rivers. A delayed response in base flow could have widespread negative impacts if the magnitude and extent of groundwater storage declines shown in GRACE data effect base flow to the Colorado River. Either of these scenarios show the need to establish policies in the basin to either avoid a substantial impact before use increases or to mitigate the potentially impending declines. Without policy change, as population and water demand grow, groundwater could be used much more heavily, as it is in the Lower Basin, often being the main source of water or majorly supplementing the supply to surface (Brown et al. 2019; Hughes et al. 2012; Kenny et al. 2009; Womble et al. 2018).

Conclusions

The direct discharge measurement methods used in this study should be extended to other subbasins of the Colorado River to assess the base flow of the entire drainage basin. These techniques will allow for water managers to locate and constrain areas of groundwater contribution. With an understanding of the full extent groundwater contributes to surface flow, water managers can take these data into consideration for decision-making about the allocation and distribution of water throughout the basin. Water managers need to take a holistic view of surface *and* groundwater interactions when considering the allocation of Colorado River basin water. This is particularly true as the DCP water restrictions are implemented and groundwater pumping increases in response, threatening base-flow discharge. There is a need to prioritize these areas of high groundwater loss before it translates to a decrease in surface flow of the Colorado River (Brown et al. 2019; Hughes et al. 2012; Womble et al. 2018). Additionally, reduction of future base flow can negatively impact ecosystems in the tributaries, which is another important consideration for managers (Acreman 2016; Bair et al. 2019; de Graaf et al. 2019; Mott LaCroix et al. 2016; Kreamer et al. 2015). Management extending away from the river corridor needs to be considered as well. Upland forests are important to manage to protect hydrologic function and maintain water quality, especially with climate change and severe fires negatively altering these ecosystems (Wyatt et al. 2015; O'Donnell et al. 2018). With a complete dataset of direct discharge measurements, policy makers can make more informed decisions for the allocation and overall sustainable use of water. Ultimately, the inclusion of all water sources in the CRB is vital for comprehensive integrated river basin management.

Continued studies highlighting the importance of base flow are therefore needed to inform resource management. Application of these methods to the rest of the basin is important, but areas with substantial developments tapping into groundwater sources should be prioritized. Quantifying all sources of water is a crucial step in a more balanced and inclusive basin management system that is able to address water demand issues in a more sustainable manner. Further base-flow studies should apply all available data to generate a better estimate of the system. These studies are needed to inform management of the importance of groundwater sources and protect the ecosystem as a whole. Groundwater should no longer be seen as an additional source of water as the renewable surface supplies are substantially fed by this source. Increased groundwater usage will not mitigate the overuse of surface water, but instead will worsen the existing shortages. Shortages themselves are a human construct for a lack of resources to support ourselves (Abbey 1968). Without decreasing the demand for water, shortages will continue to get worse, exacerbated even more by population growth and climate change within the basin. Given that groundwater provides an essential contribution of water to surface supplies as base flow, it is no longer appropriate to overlook it or minimize its contribution in management decisions and policy making.

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