

Review: The distribution, flow, and quality of Grand Canyon Springs, Arizona (USA)

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Abstract An understanding of the hydrogeology of Grand Canyon National Park (GRCA) in northern Arizona, USA, is critical for future resource protection. The ~750 springs in GRCA provide both perennial and seasonal flow to numerous desert streams, drinking water to wildlife and visitors in an otherwise arid environment, and habitat for rare, endemic and threatened species. Spring behavior and flow patterns represent local and regional patterns in aquifer recharge, reflect the geologic structure and stratigraphy, and are indicators of the overall biotic health of the canyon. These springs, however, are subject to pressures from water supply development, changes in recharge from forest fires and other land management activities, and potential contamination. Roaring Springs is the sole water supply for residents and visitors (>6 million/year), and all springs support valuable riparian habitats with very high species diversity. Most springs flow from the karstic Redwall-Muav aquifer and show seasonal patterns in flow and water chemistry indicative of variable aquifer porosities, including conduit flow. They have Ca/Mg-HCO₃ dominated chemistry and trace elements consistent with nearby deep wells drilled

into the Redwall-Muav aquifer. Tracer techniques and water-age dating indicate a wide range of residence times for many springs, supporting the concept of multiple porosities. A perched aquifer produces small springs which issue from the contacts between sandstone and shale units, with variable groundwater residence times. Stable isotope data suggest both an elevational and seasonal difference in recharge between North and South Rim springs. This review highlights the complex nature of the groundwater system.

Keywords Karst · Hydrochemistry · Groundwater monitoring · Springs · USA

Introduction

In arid regions, such as Grand Canyon National Park (GRCA), springs are critically important resources. The springs have long held cultural significance to many Native American groups associated with Grand Canyon; the Havasupai refer to the groundwater flowing within the ground of the Coconino Plateau as “the life blood of the Earth” (USDA 1999). Beyond this importance to human habitation in the region, the springs supply essential surface water for dependent terrestrial species, and support diverse and spatially restricted aquatic communities. As a result, their contribution to regional biodiversity is substantial: springs influence the spatial distribution of wildlife, support riparian communities where species diversity can be substantially greater than in the surrounding landscape (Grand Canyon Wildlands Council 2004), provide habitat for unique microhabitats for numerous species that are entirely dependent on springs (Springer and Stevens 2009), and are of great ethnographic importance to native peoples (Stevens and Meretsky 2008;

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Kreamer et al. 2015). This highlights why springs are considered keystone ecosystems in the desert southwest of the United States (Stevens and Meretsky 2008).

In GRCA, 10 of the 12 spheres of discharge of springs (Springer and Stevens 2009) are found, ranging from nearly imperceptible seeping hanging gardens that are only visible due to riparian plant growth, to large gushets that create waterfalls on cliff faces (Fig. 1). Flow from individual springs often varies within and between years, with the highest flows associated with spring snowmelt and the lowest flows occurring during late fall and early winter (Rice 2008; Schindel 2015; Jones et al. 2017). Annual variability is likely tied to annual variability in precipitation (Goings 1985). Springs are found throughout most geologic units of the canyon; however, the majority of the large springs are associated with the regional Paleozoic karst Redwall-Muav aquifer (R-aquifer) system, which is characterized by water replenishing aquifers via sinkholes and flowing through pore space, fractures, conduits, and caves (Huntoon 2000). Secondly, there are a substantial number of springs associated with the overlying perched aquifer (C-aquifer). The base flow for nearly all perennial Colorado River tributaries is directly related to the presence of springs (Grand Canyon National Park 2015).

In the greater Grand Canyon region, drivers, such as climate change and increased human development, and mining activities may impact spring water quality and quantity via reduced precipitation, increased groundwater pumping, and contamination. These impacts may be seen both in the physical behavior of these spring systems and in the response of the associated ecosystems. To assess potential

impacts of these stressors on spring systems in the future, it is first necessary to identify all pertinent information and what data gaps exist to carefully craft future research objectives to focus on management needs. While past research has focused on both aquifer characteristics and spring-dependent ecosystems, here the focus is specifically on aquifer behavior. Because many former studies of the aquifers of the region are published in graduate theses and National Park Service (NPS) reports, another goal of this review is to bring these studies into the published literature. Although the literature on the geology of the canyon is extensive (Dutton 1882; McKee 1933, 1938; McKee and Resser 1945; Wenrich 1985; Billingsley 2000; McQuarrie and Chase 2000), the published literature on the hydrogeology is limited and a review paper is long overdue and prescient for the centennial of Grand Canyon National Park in 2019.

Regional setting

GRCA is located near the southern extent of the Colorado Plateau, a 2-km high plateau with mostly flat lying strata in the southwestern United States (McQuarrie and Chase 2000; Fig. 2). The canyon was cut by the Colorado River through a thick sequence of Paleozoic strata and some of the underlying Pre-Cambrian strata as well, with a depth up to 1,800 m. The North Rim of the canyon sits at an elevation of 2,400–2,500 m above sea level (asl), while the South Rim is lower at an elevation of 2,100–2,200 m. The Colorado River enters the canyon at an elevation of 950 m in the northeast and exits the canyon at Lake Mead at an elevation of 370 m.

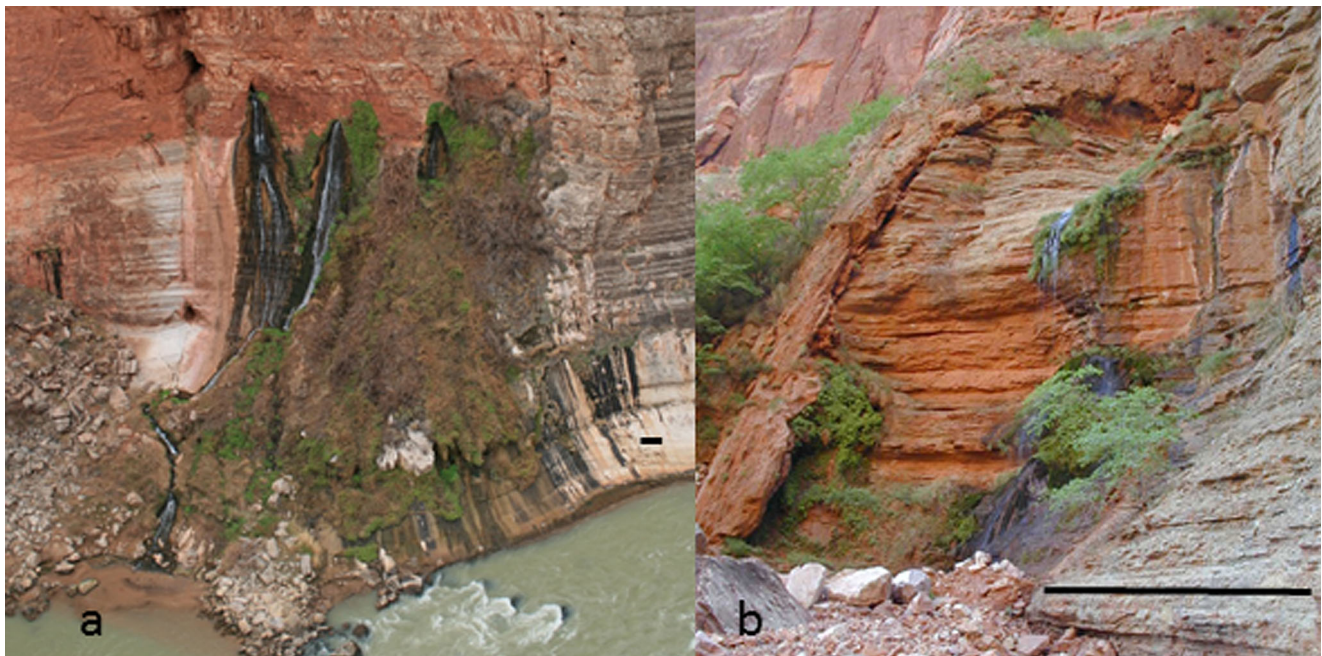


Fig. 1 **a** Vaseys Paradise, a large gushet-type spring and **b** Monument Spring, a hanging garden-type spring. Black horizontal lines on the right side of the images represent approximately 5 m. National Park Service photographs

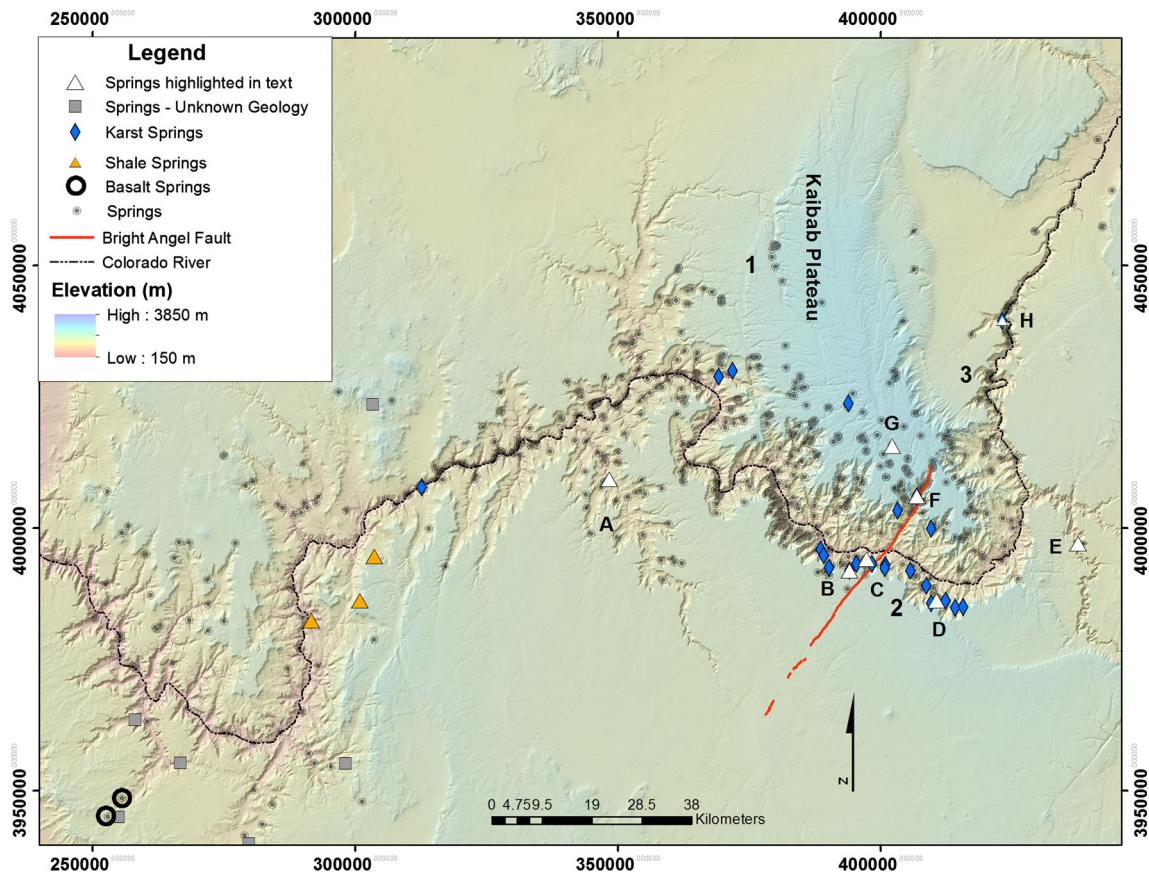


Fig. 2 Springs in and around Grand Canyon National Park. Springs discussed in text include Havasu **a**, Monument **b**, Horn **c**, Cottonwood **d**, Blue **e**, Roaring **f**, Robber’s Roost **g**, and Vaseys Paradise **h**. Springs with designated geology are those springs used for geochemical analyses in Fig.

6. Knowledge of existing springs is biased towards ease of access, such as road (1), major trails (2), and river access (3). Map shown in datum: NAD 83, UTM Zone 12 N

The climate varies by elevation (National Park Service 2017). Low elevations are classified as deserts, receiving 216 mm of rain annually, with temperatures ranging from highs of 41 °C in June to lows of 2 °C in January. Potential evapotranspiration is typically well above the annual precipitation amounts. Higher elevations are classified as temperate mixed conifer forests, receiving 640 mm of precipitation annually (1.3–2.5 m of snowpack, on average per winter), with temperatures ranging from highs of 25 °C in July to lows of –9 °C in January. Precipitation patterns are highly seasonal with large monthly precipitation amounts occurring in winter months and accumulating as snow and in summer months during the annual monsoon (Fig. 3).

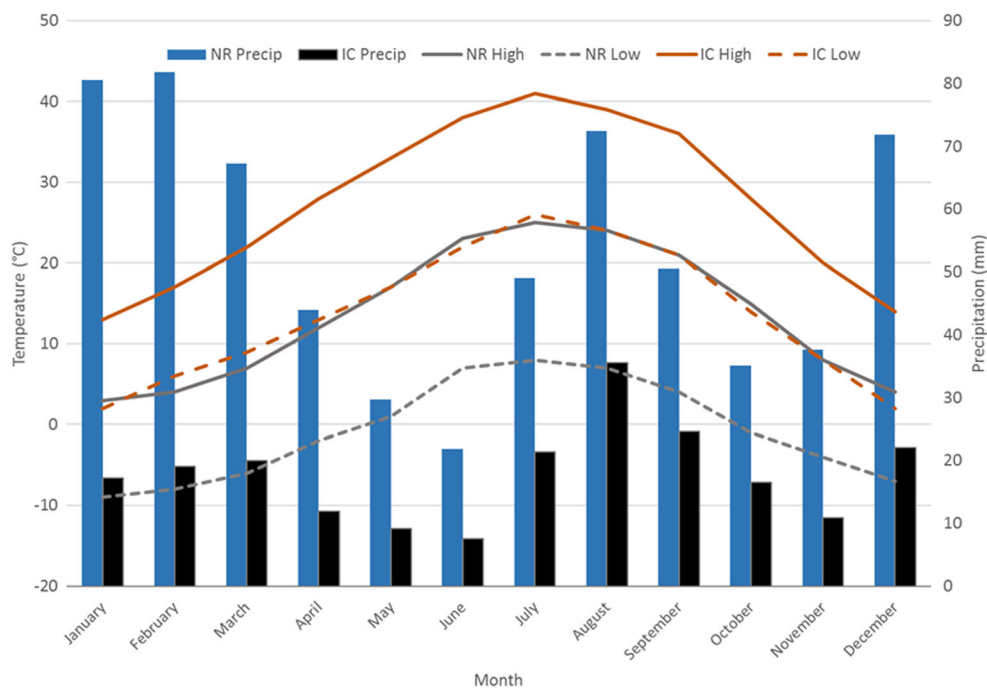
Hydrogeology

Regional aquifers are primarily contained within the Paleozoic strata of the region (Fig. 4). Within this strata there are two major aquifers with a series of confining layers between them. The upper aquifer, the Coconino (C-aquifer), is comprised of three main geologic formations: the limestone, dolomite, and sandstone of the Kaibab Formation, the Toroweap Formation,

and the Coconino Sandstone. Underlying is the Hermit Shale which acts as an aquitard. Underneath this is the Supai Group (Esplanade Sandstone, Wescogame Formation, Mankacha Formation, and Watahomigi Formation) which consists of interbedded sandstones and shales. While these layers do have small ephemeral springs, in general they are assumed to be aquitards (Huntoon 1974). This group overlays the limestone of the Redwall Formation, Temple Butte Formation, and Muav Formation which together comprise the Redwall aquifer (R-aquifer). Beneath this aquifer is the Bright Angel Shale which acts as a regional aquitard, with minimal water emerging from springs in the underlying Tapeats Sandstone or Precambrian basement rocks (Billingsley 2000). Through nearly the entire region, the Colorado River incises into the Grand Canyon, bisecting these aquifers into separate flow systems on the north and south sides of the river. For the purpose of these analyses, this paper will refer to three distinct segments of the aquifers: the Kaibab Plateau (KP), the Coconino Plateau (CP), and the Little Colorado River Area (LCR; Fig. 5).

The R- and C-aquifers appear to be connected via major joints that are associated with regional faulting and fracturing

Fig. 3 Annual climate patterns in Grand Canyon. NR represents data from the highest elevations of the park (the North Rim). IC represents data from the lowest elevations in the canyon (the inner canyon). NR high and NR low represent high and low temperatures, NR Precip represents monthly precipitation data (data from National Park Service, 2017)



that are a result of the Kaibab Plateau uplift (Huntoon 1974). Both aquifers have substantial karst development in some or all of the associated geologic units. Direct recharge to the C-aquifer occurs primarily via infiltration in sinkholes (Jones et al. 2017) and intermittently sinking streams (USDA 1986). These sinkholes occur in the Kaibab Formation and often reach the Toroweap Formation, which has large gypsum deposits that are highly soluble (McKee 1938). Additionally, Schindel (2015), Beisner et al. (2017), and Jones et al. (2017) showed that springs in the Kaibab Formation display behaviors typical of karst springs, including rapid responses to storm events.

Regional groundwater flow modeling conducted for the Coconino Plateau sub-basin of the Colorado Plateau (south of GRCA), indicates a large area (twice the size of the state of Delaware), contributing groundwater flow to Havasu Springs (Crossey et al. 2009; Fig. 5). Additional smaller areas, closer to the South Rim, contribute to nearly 20 smaller springs, such as Cottonwood Springs. Much of the area underlying the Little Colorado River sub-basin of the Colorado Plateau contributes to the flow of Blue Springs, the largest magnitude discharging spring in Arizona, and the largest spring adjacent to GRCA. Blue Springs contributes perennial baseflow to the 21 km of the Little Colorado River above the confluence with the Colorado

Fig. 4 Hydro-stratigraphic column representing the relative location of springs and aquifers in GRCA. Near vertical lines represent fractures and locations of likely vertical transport of water. Large circles represent dominant location of springs, while smaller circles represent location of additional locations of springs. Modified from Jones et al. (2017)

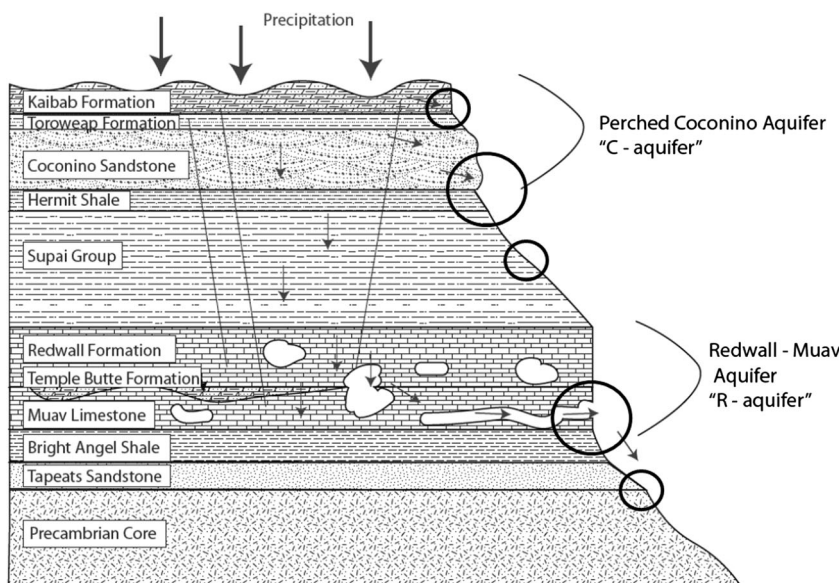
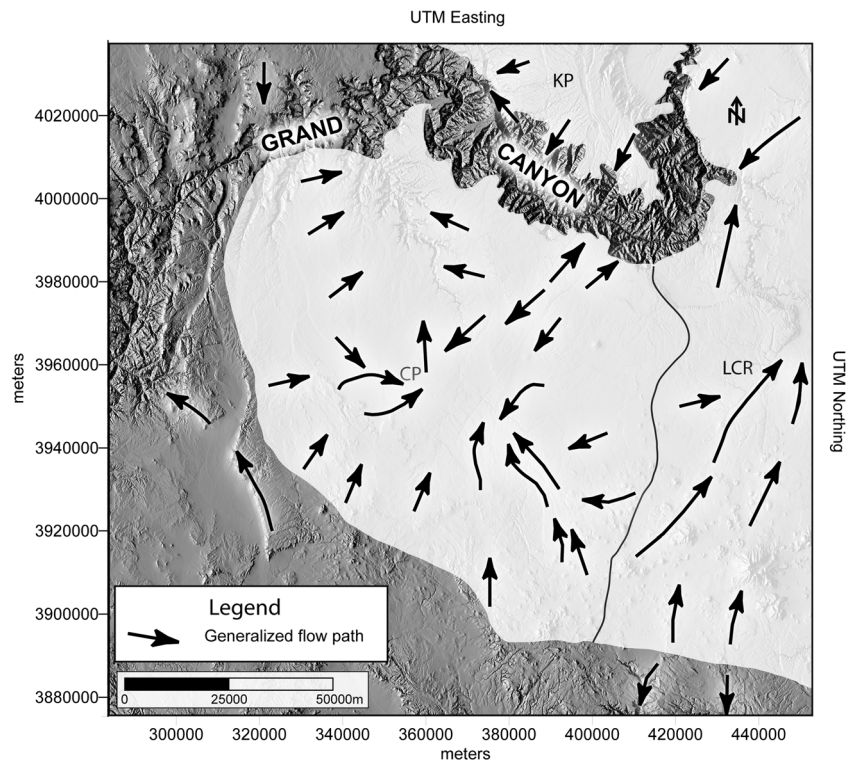


Fig. 5 Modeled groundwater basins of the Grand Canyon Region including modeled flow paths. Segments discussed in the text include the Coconino Plateau segment (CP), the Kaibab Plateau segment (KP), and the Little Colorado River segment (LCR). Figure modified from Crossey et al. (2009)



River. North of GRCA lies the Kaibab Plateau which feeds numerous larger springs, such as Roaring Springs.

Current understanding of recharge to these aquifers suggests that the majority of current inflows into the system are epigenic in nature, sourced from the surface environment, with recharge occurring via sinkholes (Jones et al. 2017). This water directly enters the C-aquifer and then either (1) discharges to the surface in small springs, flows along the surface until it bypasses aquitards, and then sink back into the aquifer to recharge the underlying R-aquifer or (2) flows along limited vertical pathways through the aquitards, recharging the underlying R-aquifer. These vertical flow paths are either fractures, faults, or breccia pipes, which are deep collapse features that have stopped upwards (Huntoon 2000). Most of this water then emerges in springs in the Redwall or Muav Formations within GRCA (Huntoon 1982). Other researchers have found that some of the water emerging from these springs is hypogenic in nature, sourced from deeper geologic units rising up to the R-aquifer (Crossey et al. 2009). Crossey et al. (2009) suggested regional volcanism as the source of these hypogenic waters. Hill and Polyak (2010) and Huntoon (2000) suggest that these rising waters have been the primary cause of bedrock dissolution in the upper portion of the R-aquifer which has resulted in substantial cave development in these strata. Additionally, draining of these caves and conduits has been directly tied to the incision of the canyon (Hill et al. 2008; Polyak et al. 2008). Polyak et al. (2008) showed an elevational and temporal trend in cave formations that form at the water table. These cave data show that as the canyon incised, the regional water table lowered.

Springs in the canyon

Quantitative documentation of the existence of springs in the Grand Canyon has been ongoing since the work of Metzger (1961); however, springs have always been a source of critical need for people in the region. Many significant springs were noted by Powell (1874) during the first recorded navigation of the Colorado River through the Grand Canyon. Subsequently, the nature of the rocks and stratigraphy of the Grand Canyon were described in detail, laying the groundwork for interpretations of spring studies to come much later (Dutton 1882; McKee 1933; McKee 1938; McKee and Resser 1945).

Researchers have more rigorously focused on springs since the early 1960s. Research has primarily focused on perennial springs in the regional base-level aquifer (the R-aquifer); however, some studies have also documented behaviors of the shallower, perched C-aquifer springs (Fig. 4). These research efforts however have typically had narrow foci, emphasizing specific management or resource impact questions. Because of this focus, the parameters collected during each project, the springs sampled, and the frequency of sampling at each spring has varied widely and the results have rarely been published. There have been a few efforts to compile much of the data from these efforts but limited interpretation at the regional scale has been completed and published, prior to this paper.

There are approximately 750 known springs located in GRCA, with most large springs located below the Kaibab Plateau (Fig. 2). The two major exceptions are Havasu and Blue Springs (the largest magnitude spring in Arizona), which

are located below the Coconino Plateau and Little Colorado sections of the aquifer, respectively. There is an apparent observer bias with smaller springs: these are primarily found within the region at areas with easier access (such as roads, trails, and river) (Fig. 2). Geospatial analysis shows that 200 of 750 springs in GRCA (26%) are directly associated with riparian vegetation (spring locations are within 50 m of mapped riparian vegetation) suggesting that they are perennial springs large enough to establish a perennial surface stream. Additionally, 321 of the Grand Canyon 750 springs emerge from karst aquifers (spring location within 50 m of limestone bedrock— either the Kaibab, Redwall, or Muav Formations), with most of the springs associated with riparian vegetation included in this group (130 of 200, or 65%). This suggests that most of the perennial springs in the park emerge from karst aquifers which is consistent with the Ca/Mg–HCO₃ dominant water chemistry of these springs (Macy and Monroe 2006). Additional work has measured a wide range of discharges from the large Blue Spring to the small Cottonwood Spring (Table 1). These point measurements show a wide distribution of discharge between springs and large variability at a given spring. This variability is likely due to the seasonal nature of discharge at the springs which requires, at a minimum, seasonal discharge measurements or, preferably continuous monitoring to assess these seasonal patterns as seen by previous work (Schindel 2015; Jones et al. 2017).

Aquifer controls

Huntoon (1974, 1982, 2000) suggested a highly integrated upper and lower aquifer system with highly developed surface karst with well-developed flow paths. Since his initial qualitative observations, work quantifying the surface karst has verified the highly developed nature of these inputs into the aquifer system, with over 7,000 sinkholes documented using

Table 1 Average discharge, number of measurements, and standard deviation (SD) of measurements at primary GRCA springs from past research. Historically spring discharge has been measured opportunistically, depending on the focus of a given project (National Park Service (NPS) data and data presented here) and thus data is not completely representative of discharge patterns at or between springs

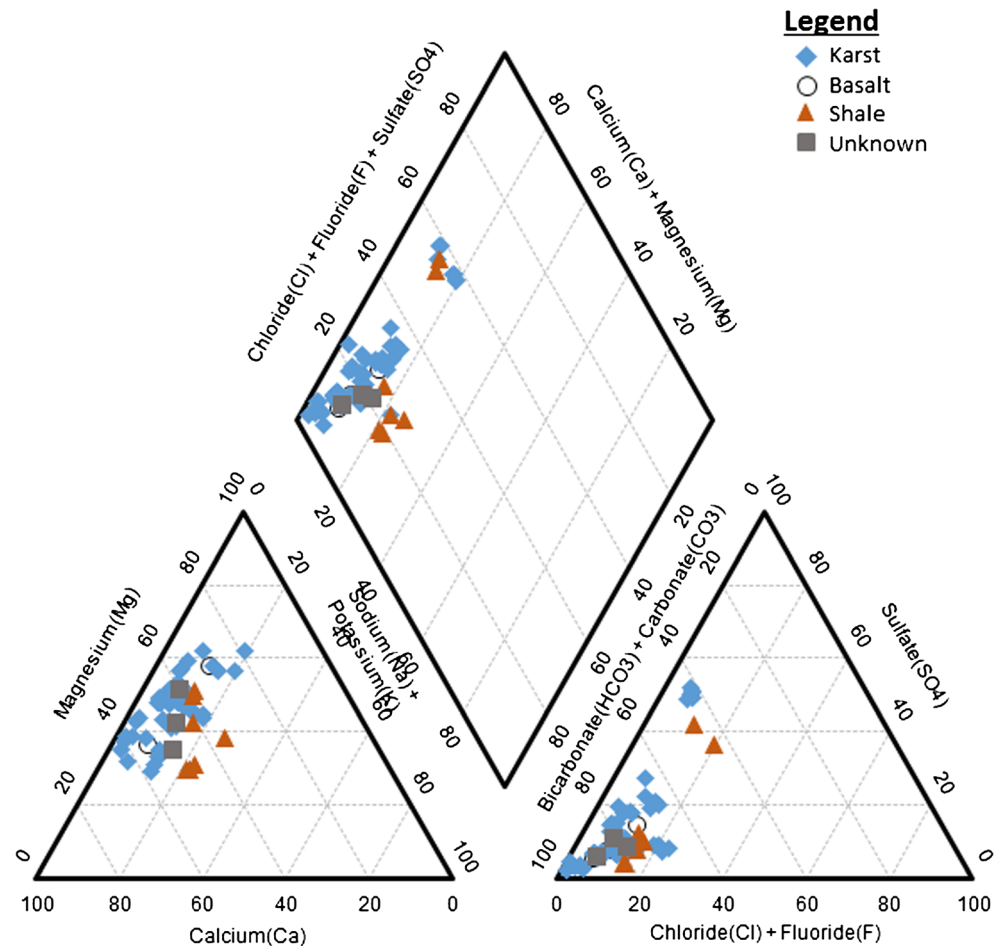
Spring	Average discharge (m ³ /s)	<i>n</i>	SD	Source
Blue Spring	5.78	6	1.41	NPS data
Roaring Springs	0.29	8	0.09	NPS data, Schindel 2015
Havasú	1.80	5	0.51	NPS data
Vaseys Paradise	0.22	5	0.29	NPS data
Tapeats Spring	2.18	4	0.41	NPS data, Schindel 2015
Cottonwood	1.3 × 10 ⁻⁵	26	9.9 × 10 ⁻⁶	Adams et al. 2006

recent Lidar data (Jones et al. 2017). Initial research on spring behaviors in GRCA showed distinct relationships between geologic structures and spring locations, regardless of the aquifer they are associated with. Huntoon (1974) and Brown and Moran (1979) noted that springs are primarily found where these faults intersect the canyon, suggesting a strong relationship between faults, fractures, topography, and aquifer flowpaths. Huntoon (1974, 1982, 2000) documented karst development associated with these structural features, indicating that faults and fractures formed the initial flow paths for water from the surface to the springs in the R-aquifer. Bedrock dissolution in areas adjacent to these structural features resulted in large conduit development. Ross (2005) proposed that the source area for Roaring Springs, the water supply for GRCA, was entirely derived from precipitation on the Kaibab Plateau. Additional work has shown that sink-hole density on the plateau is associated with the faults and fracture network (Jones et al. 2017) and while dye trace results have shown that the proposed source area of Ross (2005) and Huntoon (1974) were incorrect, the dye results showed that flow paths are likely controlled by geologic structure (Jones et al. 2017).

Studies focused on spring geochemistry have enhanced the understanding of the high degree of karst development on the Kaibab Plateau. Geochemistry work has shown springs in the R-aquifer typically have Ca/Mg–HCO₃ dominant water types (Monroe et al. 2005; Macy and Monroe 2006; Bills et al. 2007; Beisner et al. 2017). Fitzgerald (1996) suggested that dedolomitization is occurring in the Coconino Plateau segment of the aquifer. He noted that gypsiferous layers are present in the lower carbonate units and many spring waters have [Mg²⁺]/[Ca²⁺] ratios that are about unity. Based on the results from measured major ion concentrations in spring waters and generated output from the geochemical model PHREEQC (Parkhurst et al. 1993), Fitzgerald suggests that calcite is precipitating while dolomite is dissolving, as a result of irreversible gypsum dissolution in the Coconino Plateau segment. While individual karst springs have relatively consistent Ca/Mg–HCO₃ dominated chemistry, the Piper diagram of the data show no difference in water types between the springs compared—Fig. 6; Table S1 of the electronic supplementary material (ESM). Zukosky (1995) also showed through principal component analysis (PCA) that springs emerging from similar stratigraphic units have similar ensemble properties of trace element geochemistry, indicating that controls on flow behavior at these springs is dominated by the same aquifer unit.

Studies of the C-aquifer below the South Rim indicate that there is primarily local flow emerging from some of these springs (Zukosky 1995). Many of the C-aquifer springs are ephemeral, indicating small catchment areas and fewer ties to regional aquifers (Zukosky 1995). Additionally, there are similarities in trace element geochemistry between C-aquifer springs, suggesting similar storage lithologies and flow paths

Fig. 6 Piper diagram of available water chemistry data for GRCA springs. This plot represents 67 samples from 38 sites compiled from an unpublished National Park Service dataset (Table S1 of the [ESM](#)). Karst springs are primarily R-aquifer, basalt springs are from recent volcanic activity, and shale springs are associated with the Bright Angel Shale, Hermit Shale, or Supai Group



through the aquifer. Kaibab Plateau C-aquifer spring behavior differs from the Coconino C-aquifer springs. Foust and Hoppe (1985) showed that the chemistry of Kaibab segment C-aquifer spring water could vary significantly, and Milanovic (1981) attributed the variability of the water chemistry of these springs to rapid flow through the system. Recent work has suggested significant and rapid water movement from the C-aquifer to the R-aquifer during both summer monsoons and winter snowmelt (Jones et al. 2017). Jones et al. (2017) showed that storm event responses occurred in R-aquifer springs within days of the storm, indicating this rapid movement between the two aquifers and highlighting the disparity of connectivity and residence times in the C-aquifer.

Vertical flow between the upper C-aquifer with the lower R-aquifer has also been assumed to be controlled by faults and fractures (Huntoon 1974; Bills et al. 2007). Modeling efforts on these aquifers has shown that these flow paths are likely the dominant conduits between the two aquifers (Wilson 2000; Ross 2005; Pool et al. 2010). Springs in similar geographic areas but in separate aquifers have similar trace element geochemistry suggesting a vertical connection between the C- and R-aquifers (Zukosky 1995), indicating that faults

cross-cutting the canyon act as recharge collection regions and may also provide conduits for great vertical movement (Metzger 1961). A major flood of an ephemeral upland stream channel above the South Rim in 1984 was shown to decrease in flow drastically along a series of breccia pipes and fault zones with almost 70 m³/s disappearing in just a few miles of stream length (USDA 1986), suggesting that breccia pipes may also be significant recharge features as well as pathways for vertical movement between aquifers.

Recharge, response, and residence times

Regional recharge patterns

Regional recharge, residence times and flow paths appear to be dominated by the seasonality of precipitation in the region. Bills et al. (2007) and Springer et al. (2017) found that liquid water stable isotopes (δD and $\delta^{18}O$) of spring discharge matches winter precipitation values closely and are significantly different from summer monsoonal moisture. The bimodal distribution of precipitation in the region brings summer rain more enriched in these two isotopes and winter snow

more depleted in the isotopes. When coupled with the significant elevation differences between recharge areas above the canyon and springs discharge locations in the canyon, it is possible to discern the season of recharge of water which discharges at springs. The combination of the season of precipitation and elevation of precipitation provides an effective method of flow path determination of springs (Springer et al. 2017). Ross (2005) showed that discharge at Roaring Springs was likely derived entirely from snowmelt and annual monsoonal moisture has little to no impact on aquifer recharge. In contrast, Schindel (2015) and Jones et al. (2017), both identified small, limited recharge from significant summer monsoon events.

Additional stable isotope work has shown a marked difference between Kaibab Plateau and Coconino Plateau springs (Zukosky 1995; Fitzgerald 1996; Ingraham et al. 2001). This suggests differences in recharge elevation for these springs: Kaibab springs appear to be more closely associated with precipitation that fell at higher elevations, likely on the plateau, while Coconino Rim springs are more closely tied to the elevation of the rim proximal to the springs.

Residence times

A variety of work has focused on understanding the mean residence times of the aquifer associated with Coconino Plateau springs with a variety of conclusions resulting from the use of multiple methodologies. Fitzgerald (1996) looked at tritium concentrations and CFCs in these springs as a means of assessing the mean residence times. Tritium results suggest that the waters emerging from these springs had a range of residence times, from some C-aquifer springs showing mean tritium ages consistent with more rapid, local flow paths, while others showed pre-bomb era tritium levels and lacked CFCs, indicating much longer residence times. These results have been duplicated in C-aquifer springs below the Kaibab Plateau (Beisner et al. 2017). While mean residence times appears to be long, response rates to storm events seems to be much shorter; Goings (1985) found that spring discharge in Horn Creek responded to precipitation events within 2–8 weeks. Monroe et al. (2005) supported these apparent contradicting results with tritium and ^{14}C data which showed that these springs are a mixture of younger and older waters, using tritium and ^{14}C . C-aquifer springs below the Kaibab Plateau also show a distinct signal of older water (Beisner et al. 2017).

Work on Kaibab Plateau segment springs has shown that the R-aquifer and shallow C-aquifer systems are dominated by short residence times; however, some sections of the C-aquifer demonstrate longer residence times. Brown (2011) showed through hydrograph recession analyses of Roaring Springs that storm responses had three distinct components with three distinct drawdown rates. From shortest residence time to

longest, these flow paths showed drawdown times of 8.9, 20.4, and 166.7 days for each component respectively. This suggests that on average, base flow of this system has a residence time of approximately 166 days. More recent hydrograph analyses (Jones et al. 2017) has shown much longer average residence times in Roaring Springs, with base flow recession indicating a drawdown times of 1,000–2,700 days.

Additional work has suggested that water emerging from these springs has even longer residence times (Crossey et al. 2009). While many karst springs show evidence of surface derived acids as the source of dissolution that has resulted in enlarged conduits for water flow, many springs and caves show distinct signs that the acid for conduit enlargement, and some of the water flowing out of these springs, is sourced from deeper environments, indicating substantially longer residence times (Crossey et al. 2009). The presence of mantle-derived CO_2 indicate a deeper flow path for some of the waters emerging from some large regional Grand Canyon springs, such as Havasu Spring (Crossey et al. 2006, 2009; Beisner et al. 2017). These deeper sourced waters mix with waters from surface derived, epigenic sources and karst storage prior to emerging from springs in the canyon.

Response times

The flow systems of the Kaibab and Coconino Plateau segments have different response times to recharge from summer monsoon rainfall and winter snowmelt. Long-term monitoring of discharge and $\delta^{18}\text{O}$ from the springs sourcing Cottonwood Creek (Figs. 1 and 2) has provided insight into the response time of springs of the Coconino Plateau segment. The source of Cottonwood Creek is a hillslope spring discharging from the R-aquifer below the South Rim (Adams et al. 2006). There were large winter snowfall events and subsequent recharge events in 2005 and 2010. The spring isotope and discharge data indicate a 2–4-year delay between winters with large snowmelt and an increase in spring discharge and lighter isotope ratios (representative of winter precipitation; Fig. 7). The isotope variation of between -12 and -12.6‰ is indicative of the variability in winter precipitation, not the variability due to significantly heavier summer precipitation (Springer et al. 2017). The spring sourcing Cottonwood Creek appears to have little if any recharge due to summer rainfall.

Kaibab Plateau segment springs have shown a quicker and consistent response to recharge events from both summer monsoon rain and from winter snowmelt than Coconino Plateau segment springs. Although Huntoon (2000) and Ross (2005) indicated that recharge for North Rim springs are entirely driven by annual snowmelt, hydrograph analyses by Schindel (2015) and Jones et al. (2017) showed that monsoonal storms result in initial piston-flow response at Roaring Springs as soon as 2 days after the storm with storm event

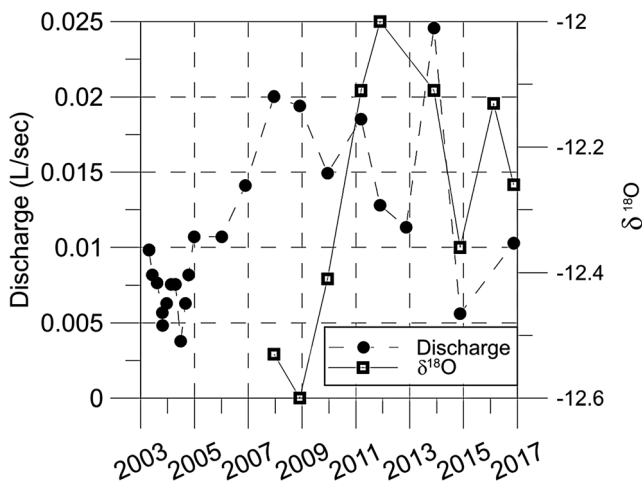


Fig. 7 Discharge and Isotope data from Cottonwood Creek below the South Rim of GRCA

water arriving within 3 days of the storm event. The response time of recharge varied, likely due to variability in storm location, intensity, and groundwater flow paths. Dye tracing studies show that there is significant heterogeneity in groundwater flow paths and even a single fault system does not represent a single, simple flow path (Jones et al. 2017). Through modeling efforts, Ross (2005) indicated that flow from the surface takes approximately 1 month to flow through the system during peak flow events. Dye trace and hydrograph analyses have shown that this 1-month response time represents a maximum response (Jones et al. 2017). Artificial dye tracers were injected into recharge locations on the Kaibab Plateau and were found in springs 2,000 m lower in elevation and at distances of greater than 40 km from the injection location within 1 month.

Merging response and residence

The apparent discrepancy in residence response times is due to variability in dominant flow paths and source waters. $^{86}\text{Sr}/^{87}\text{Sr}$ data have shown that springs east and west of the Bright Angel Fault (Fig. 2) have significant differences in isotope ratios. Differing Sr isotope ratios between springs indicate differences in dissolution patterns within the limestone bedrock, and thus differing flow paths on either side of the fault (Monroe et al. 2005). Kobor (2004) and Adams et al. (2006) have shown that these springs have a seasonal pattern that is likely tied to the seasonality of recharge from snowmelt.

Springs in GRCA tend to show long residence times during baseflow conditions with multiple avenues of research showing residence times of months (Goings 1985; Brown 2011) to years (Jones et al. 2017) to decades (Fitzgerald 1996). Additionally, these same springs show response times ranging from days (Schindel 2015; Jones et al. 2017) to years (this study). These apparent discrepancies in response time and residence times highlight the complexities of stacked karst

aquifers, multiple complex flow paths, and highly variable porosity throughout the aquifers of GRCA.

Karst systems are dominated by a range of porosities (Palmer 1999) that are driven by mass balance and kinetic equations. These dissolution processes often drive the creation of large conduits and enlarged fractures near the water table with more complex heterogeneous porosity above and below the potentiometric surface (Klimchouk 2004). The mixing of old and young waters in combination with quick response times at springs is congruous with conceptual models of karst development, with large highly connective conduit systems in combination with a range of slower flow pathways and older waters dominating base flow conditions.

Aquifer issues

GRCA spring hydrology has focused on assessing potential impacts of local and regional-scale activities, including regional tourism development, contamination associated with mining activities, natural and overall impacts of climate change on spring flow and water quality. The current water system at the park has resulted in a shift in the isotopic composition of springs below the South Rim (Ingraham et al. 2001). Springs at Indian Garden show isotopic signals similar to North Rim springs. Initially, it was hypothesized that these springs were sourced from the South Rim at the wastewater treatment facility; however, there are no other chemical signatures that suggest this direct connection. Therefore, Ingraham et al. (2001) suggested that leakage from the trans-canyon water pipeline is being recharged to these springs, which was later confirmed as a strong possibility by the discovery of a small, previously unknown leak above the spring. Macy and Monroe (2006) have also shown that there is no direct evidence of contaminants from the treatment facility impacting springs suggesting that the shift in isotopic signal is more likely tied to leakage from the pipeline than contamination from wastewater.

Other work has shown that there is a potential for some springs to exceed the US Environmental Protection Agency maximum contaminant levels (MCL) for drinking water, at least seasonally. Monroe et al. (2005), Macy and Monroe (2006), Bills et al. (2007), and Beisner et al. (2017) have all shown that some springs, primarily lower-flow springs in the river corridor and below the South Rim, have exceeded these limits at times. Table 2 shows examples of historical MCL exceedances in Grand Canyon springs and drainages. Exceedance of these drinking water standards have been observed for several compounds including antimony, arsenic, beryllium, cadmium, chromium, lead, mercury, selenium, and uranium. High nitrate values exceeding standards have been found in the treated sewage outfall for the South Rim Village of Grand Canyon National Park. This outfall releases

Table 2 Records of EPA maximum contaminant level (MCL) exceedances at GRCA springs for select elements, including the number of exceedances, the year of highest exceedance (Year), and original report of exceedance (Source)

Element	No. of exceedances	MCL (mg/L)	Site	Conc. (mg/L)	Year	Source
Arsenic	78	0.01	Pumpkin Spring	0.350	1985	Wenrich et al. 1994
Beryllium	17	0.004	Monument Spring	0.128	1992	Zukosky 1995
Cadmium	13	0.005	Monument Spring	0.019	1992	Zukosky 1995
Lead	5	0.015	Big Spring	0.032	1985	Wenrich et al. 1994
Mercury	2	0.002	Milkweed Spring	0.0038	1993	Alpine 2010
Selenium	7	0.05	Monument Spring	0.112	1992	Zukosky 1995
Uranium	14	0.03	Horn Spring	0.4	2002	Liebe 2003

water to the surface expression of the Bright Angel Fault up on the South Rim, which then recharges the Kaibab Limestone but high nitrate concentrations have not been recognized in springs below the rim.

Of equal concern to contaminant levels is the overall spring flow in the canyon; Metzger (1961) showed a general pattern of decreased flow for springs in the Coconino Plateau segment. More recent works by Adams et al. (2006), Rice (2008), and Kobor (2004) have shown that this trend does exist today with some previously perennial sites becoming ephemeral. Rice (2008) found a strong temporal trend in Cottonwood Spring, where in an increasing percentage of the year the creek fed by this spring was dry (Fig. 8). This pattern matches trends seen throughout the greater Colorado River Basin, where a decrease in aquifer storage has been seen to correlate with climate variability (Castle et al. 2014). In addition to temporal reduction in flow, there are similarities in rare earth elements (REEs) between the R- aquifer and wells in the nearby town of Tusayan, suggesting that the springs are sourced from the same water being utilized in the town (Zukosky 1995). To better understand whether these decreases will continue it is critical to improve our

understanding of the vertical connectivity between the surface and deeper aquifer (Pool et al. 2010).

Summary

Historic and recent research on GRCA springs has often been narrowly focused; however, through numerous, mostly MSc Theses, necessary baseline data have been collected. These data indicate the extent of groundwater resources in the region as well as the complexity of the aquifers feeding these critical resources. Aquifer recharge throughout the region is dominated by snowmelt that either diffusely recharges or flows into large sinkholes that feed the two underlying aquifers (Huntoon 1974; Jones et al. 2017). The geology associated with springs, water chemistry of these springs, residence and response time data all point to a highly karstified groundwater system. The expression of these karst processes differs between the North and South Rim, with more substantial rapid flow occurring in North Rim aquifers. Limestone geology indicates the likelihood of significant dissolution in the aquifer, which is corroborated by dominant water chemistries of most springs. The complex response and residence times also indicate that springs respond quickly to storm events but are a combination of young and older waters. This type of behavior is common in karst systems and further highlights the complex karst nature of the regional aquifers.

Future direction

The karstic nature of most of the perennial springs and aquifer systems will require significant additional work to fully understand the dynamics of flow paths throughout this system. As this understanding improves, research will better be able to quantify potential impacts to these resources from climatic variability, local and regional scale anthropogenic activities, and provide managers with improved tools to mitigate for these concerns. While previous work has focused on a select few relatively easily accessible springs to look at some of these datasets, work on other springs is important to verify those characteristics and behaviors. These efforts have begun

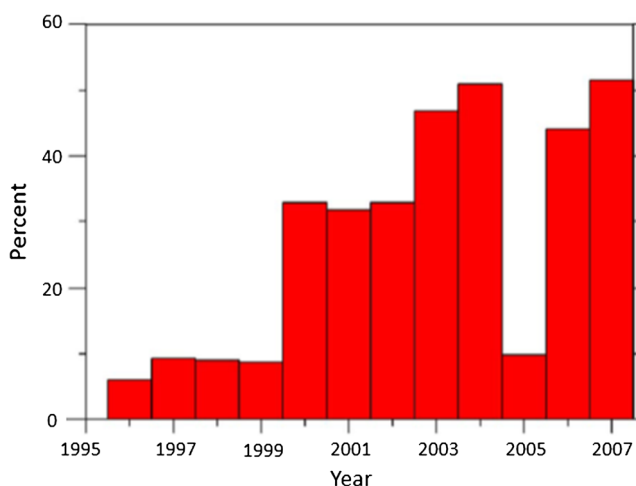


Fig. 8 Percent of year that the Cottonwood Creek stream gage was dry, 1996–2007

(Jones et al. 2017); however, more work will be needed to truly quantify the behavior of these complex aquifer systems.

In light of climate change and regional questions on mining and water withdrawals (Alpine 2010; Beisner et al. 2017), now is the critical time to develop research that focuses on understanding response behavior at a spring-scale and a regional scale to assess impacts from climate change or human disturbance in the area. This research is important to maintain the aquifers, springs, dependent ecosystems, and cultures for one of the most visited national parks in the US. An improved understanding of springs of Grand Canyon will help the National Park Service better manage these precious desert ecosystems into the second century of the park.

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