Groundwater-Surface Water Interactions of the Grand Canyon

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Abstract

The Colorado River supplies water to more than 50 million people, irrigates 4 million acres of cropland in the U.S. and Mexico and serves as the source for hydropower plants generating a total of 10 billion kilowatt-hours per year. Groundwater is an integral component of the hydrologic system supporting this vastly relied upon water supply (Miller et al. 2016). Groundwater enters hydrogeologic units at the ground surface and eventually discharges to the river through springs in the canyon walls. Water from the Upper and Lower Colorado River basins is depended on by residents of Wyoming, Utah, Colorado, New Mexico, Arizona, California and Mexico and is the most over-allocated river in the world (Christensen et al. 2004; Miller et al. 2016). Projections show that demand could exceed supply by 4 billion cubic meters by 2060. On a smaller scale, water from a single groundwater-sourced spring in Grand Canyon National Park supported 6.3 million of the Park's visitors in 2017. Annual visitation is projected to double by 2050 (Bureau of Reclamation 2002), which will intensify the strain on the National Park's groundwater resources. Recent development of areas overlying the Grand Canyon's major aquifers has increased the demand for groundwater pumping which has resulted in declining groundwater levels and spring discharge. Many people consider springs to be culturally significant, including some local Native American tribes. Springs are generally appreciated for their aesthetics and support up to 500 times as much species diversity as the non-spring environments surrounding them. Water managers are continually pressured to increase water availability by proposed tourism-related development. Development causes increases in water demand that may not be feasible considering the region's hydrologic setting. Climate change is an impending threat to the consistency of the Colorado River Basin's water supply. Some projections estimate that with current operating policies, average reservoir storage in the Colorado River Basin will decrease by 40% by 2098 (Christensen et al. 2004). Due to the ecological and anthropogenic sensitivity to the Colorado River Basins' groundwater, management decisions should be made with the utmost care and consideration of the potential for a once-sustainable hydrologic resource to become inadequate in meeting anthropogenic and ecologic needs.

Introduction and Hydrologic Setting

Grand Canyon National Park is one of the world's most impressive exhibits of geologic time, displaying rocks ranging in age from 1,840 million year-old Precambrian Basement to debris flows deposited in the last 100 years (Mathis and Bowman 2006). The Colorado River drains water from seven states and Mexico along its path from its headwaters in the Rocky Mountains to its mouth in the Gulf of California. The Colorado travels through the driest and hottest regions of the country. If water management were absent, the combined 630,000 km^2 Upper and Lower Colorado Basins, shown in Figure 1, would receive an average of 4 cm/year of water (Christensen et al. 2004). Average annual rainfall is 48 cm/year in Grand Canyon Village and the average annual snow water equivalent falling within the Colorado River Basins is about 7.5 cm/year. Although the Colorado's average flow is less than one tenth of the average flow of the Columbia River, it is the primary river system of the southwestern United States and northwestern Mexico (Gleick

1988). Despite the Colorado River Basin's dominantly arid climate, it provides water to six states before flowing into Mexico with the help of 12 reservoirs along its 2250 kilometer length.

Figure 1. Map of the upper and lower Colorado River Basins. Areas with red lines represent areas outside of the watershed that receive water from the watershed.

Overview of Groundwater-Surface Water Interactions

The Grand Canyon's hydrogeology differs from most hydrogeologic systems because exchange between groundwater and surface water is limited to one direction. In most watersheds, variability in hydrologic gradients engender bidirectional exchange of groundwater and surface water. However, in some canyon settings there is no aquifer system beneath the river. This situation occurs when the river is underlain by impermeable rocks, making formation of a hydrologic gradient where surface water has greater potential energy than groundwater impossible, meaning that surface water from the Colorado River will not recharge groundwater. In the Grand Canyon, the majority of the Precambrian basement underlying the River is impermeable and incapable of storing water, leaving the only aquifers within the system to exist in the canyon walls above the Colorado River. Of course, there are small amounts of geologic material beneath the river that could be considered surface water replenished aquifers, but this is on an extremely small scale that is not considered relevant to characterization of the hydrogeologic system.

Many geologic units comprising the canyon walls act as aquifers, the first and second most prolific are the Redwall-Mauv Aquifer System and the Coconino Aquifer System, respectively. A schematic of these hydrogeologic units is shown in Figure 2. In terms of the South Rim, both the Redwall-Mauv and the Coconino aquifer systems have groundwater divides that trend southeast-northwest, causing groundwater to flow to the southwest and northeast. The hydrogeologic framework of the region's aquifer systems is complex due to faulting, post-depositional transformation of geologic units, and variations in stratigraphy.

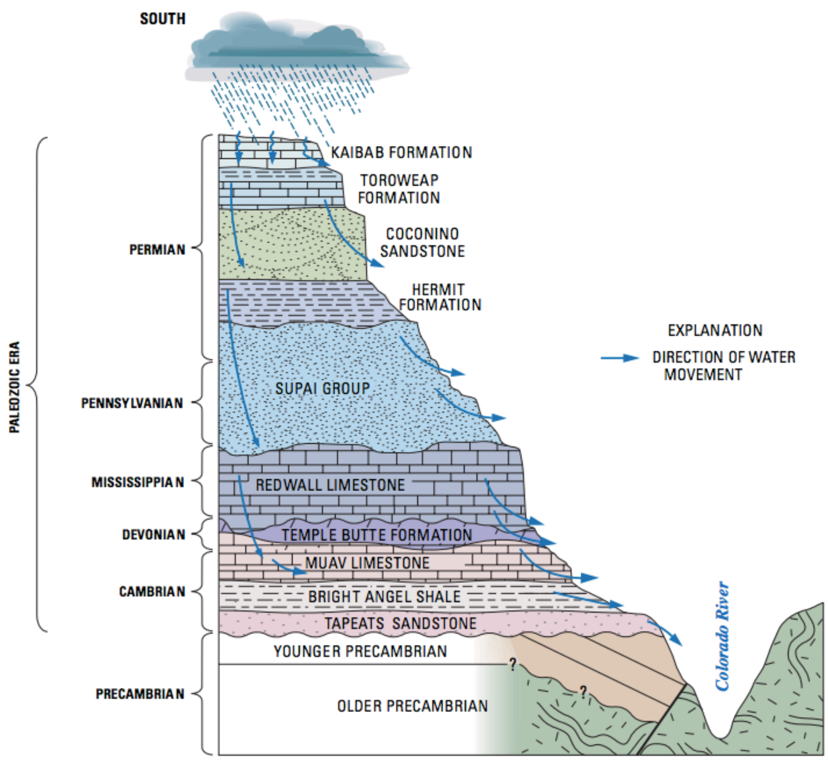

Figure 2. Depiction of the Grand Canyon's hydrogeologic units. Arrows show direction of movement of water originating as recharge from precipitation, and eventually entering the river. From Monroe et al. 2005.

The primary water bearing unit of the Grand Canyon is the Redwall-Mauv aquifer located beneath the Coconino Plateau. The aquifer system's upper confining unit is the Lower Supai Formation which is composed of Permian sandstones. The Redwall-Mauv is located 3000 feet below the canyon walls and acts as a regional water source (Bureau of Reclamation 2002) for domestic and agricultural pumping wells. Many of the Redwall-Mauv's limestones are karstified, meaning that they have been chemically eroded. This process creates conduits that significantly increase the formation's hydraulic conductivity. The Redwall-Mauv is composed of various limestone units including the Devonian-Cambrian Mauv, Devonian Temple Butte, and Mississippian Redwall formations.

The Redwall Limestone is the uppermost unit of the Redwall-Mauv aquifer, it extends to underlie almost the entire upper right quarter of the state of Arizona. The Redwall Formation outcrops in steep canyons creating springs and is variably saturated throughout its extent (Pool et al. 2011). In the Coconino Plateau area, the South Rim of the Grand Canyon, the Temple Butte Formation, Martin Limestone and Mauv Limestone underlie the Redwall Formation (Pool et al. 2011). The Temple Unit consists of Devonian limestone and thins out toward the south. The Martin Unit also consists of Devonian limestone, thickens toward the south and is mostly present in the central-southern section of Coconino Plateau. The Temple and Martin are saturated in areas where they receive percolated groundwater from the Redwall-Mauv aquifer. Due to the fact that the Temple and Martin don't extend significantly to the south of the Grand Canyon and aren't major water-bearing units, they aren't considered a major constituent of the Redwall-Mauv aquifer (Huntoon 1977; Pool et al. 2011). However, the Martin Formation does discharge some water to springs along the Mogollon Rim (Hart et al. 2002), which is located southeast of the Grand Canyon, outside of the National Park.

The Bright Angel Shale, Tapeats Sandstone, and Mauv Limestones underlie the Martin Formation (see Figure 2). The Bright Angel Shale is a several hundred foot thick aquitard, meaning it acts as a confining unit that is relatively impermeable. Aquitards act as confining units because of their small average grain size. Although shales have significantly more total pore space than units with larger average grain size, they have lower hydraulic conductivity. However, there are some aberrations within the Bright Angel Shale that allow conduction of water that eventually discharges through springs. These aberrations consist of fault planes, bedding plane fractures (Monroe et al. 2005; Pool et al. 2011), shown in Figure 3, and heterogeneities manifested as larger-grained sandstone lenses. The Tapeats Sandstone is considered a major water-bearing unit, it is continuous throughout both rims of the Grand Canyon (Pool et al. 2011). Although the Tapeats is separated from the Redwall-Mauv by the Bright Angel Shale, it may connect with it in areas where the Bright Angel is particularly thin or through fractured areas. The Redwall-Mauv Aquifer's lower confining unit consists of Proterozoic crystalline rocks. The majority of recharge to the Redwall-Mauv Aquifer System comes from downward travel of water from overlying aquifer systems through breccia pipes, faults and fractures (Pool et al. 2011). The majority of discharge from the system occurs through springs along the Mogollon Rim, outcrops on the steep walls of the Grand Canyon and along the Little Colorado. There is evidence of some lateral flow from the Redwall-Mauv toward aquifers of the Verde and Chino Valleys (Blasch et al. 2006; Pool et al. 2011) as well as downward transfer of water to permeable sections of the crystalline basement rocks.

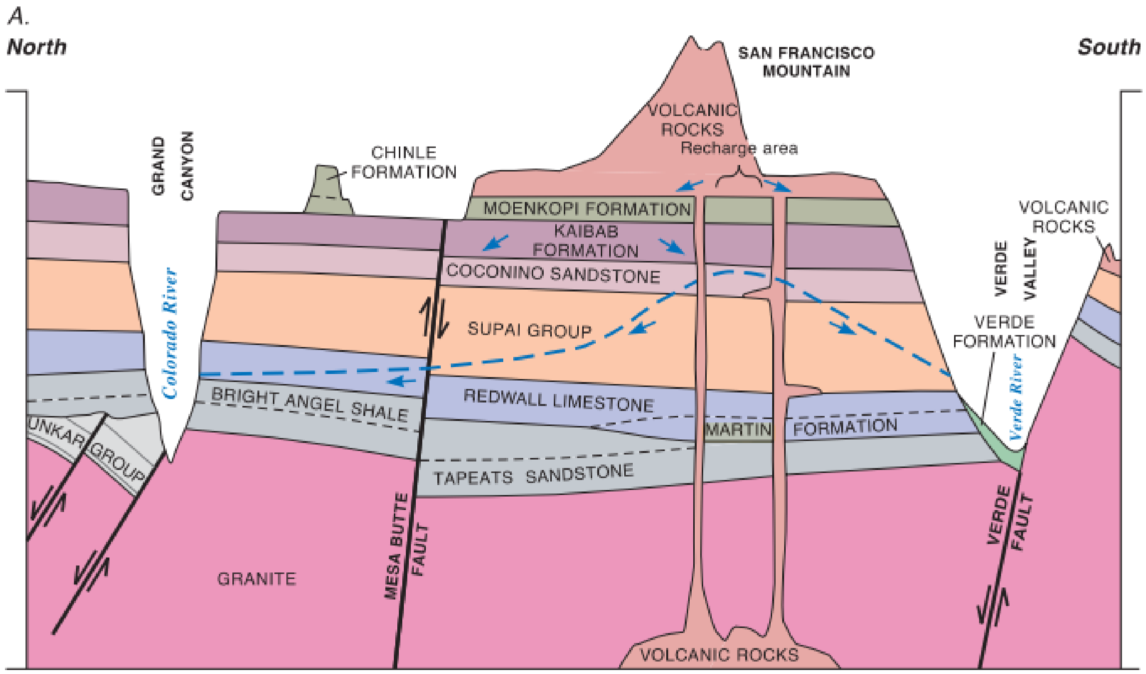

Figure 3: Generalized hydrogeologic cross section of the South Rim of the Grand Canyon's hydrogeology. Illustrates the impact of structural geologic events on water transfer in the subsurface. From Hart et al. 2011.

The Supai Group consists of sedimentary rocks ranging from siltstones to limestones (Mckee 1963). The Supai Group's water bearing units are perched aquifers, meaning that they are above the region's water table and exist when small confining units keep water from percolating downward toward the water table. The small confining units act as aquicludes (an impermeable hydrogeologic unit) by inhibiting water from leaking from the perched aquifer.

Additional groundwater in the Colorado River's hydrologic system is stored in the C aquifer. The C aquifer is defined as the hydrogeologic sequence between the Kaibab Formation and the upper section of the Supai Formation (Hart et al. 2002). The C aquifer's main water bearing units are the Coconino Sandstone and its lateral, provenance-equivalent counterparts. The Kaibab and Toroweap Formations, Schnebly Hill Formation and Upper to Middle Supai Formations are prolific water-bearing units as well (Pool et al. 2011). Specifically, the Kaibab acts as a conduit for recharged water sourced in overlying rivers and rain. The units in the C aquifer are completely connected hydraulically, meaning water can move between them without interruption by continuous impermeable and/or low permeability barriers. The Coconino Sandstone unit is almost completely continuous throughout the Little Colorado River Basin, a sub-basin of the Colorado River Basin, shown in Figure 4. The Coconino thins toward the east and is present as far as west of the Mesa Butte Fault shown in Figure 3, although at this extent it is typically unsaturated. The Coconino's eastern boundary is uncertain due to paucity of hydrologic and geologic data in this area. The C aquifer is almost completely unconfined, with the exception of the Moenkopi Formation where it is confined. Historically, the many wells drilled into this confined section of the aquifer exposed a potentiometric surface (defined by the height the water would reach if the confined aquifer was pierced by a well, a metric of water pressure) reaching the elevation of land surface. In the present, the potentiometric surface is much lower due to development and use of groundwater resources (Mann, L.J., Nemecek 1983; Pool et al. 2011).

Figure 4. Map showing location of the Little Colorado River Basin in relation to the Colorado River. From Hart et al. 2011.

The Redwall-Mauv Aquifer and Coconino aquifers have been analyzed with MODFLOW (Pool et al. 2011), the United States Geological Survey's numerical groundwater modeling software. Results from the model indicate that recharge to these aquifer systems is important for flow maintenance and storage capacity and for ephemeral streams that may go dry earlier than they would historically if they were to suffer small decreases of the quantity of recharge they receive from groundwater. The numerical model also reaffirmed the idea that structural and chemical geologic processes make a significant impact on hydrogeologic processes by creating conduits and pathways that would not exist in the absence of faulting, fracturing or karstification.

Springs

Springs are the main water supply for the visitors of Grand Canyon National Park. A 1996 and 1999 numerical modeling study (Bureau of Reclamation 2002), determined that each gallon of water withdrawn from the Redwall-Mauv aquifer results in a one gallon decrease in discharge from major springs. Decreases in discharge in springs connected to the Redwall-Mauv aquifer such as Havasu Spring and Roaring Springs could worsen water scarcity problems for various stakeholders including the Havasupai and Hualapai Indian Reservations and visitors and employees of Grand Canyon National Park.

Springs are the source of many streams in the Grand Canyon. These streams have water with a longer residence time than snowmelt-fed streams. This decreases the annual variation in temperature (Lusardi et al. 2016), a trait that benefits the productivity of certain organisms that cannot withstand temperature variability. Springs in the Grand Canyon support prolific biodiversity by remaining consistently wetter than their arid surroundings and, in some cases, their remote locations protect them from anthropogenic disruptions. It is estimated that there are over 1000 springs in the Grand Canyon, functioning as biodiversity hotspots. Compared to their surroundings, spring environments support 100-500 times the species diversity. Although they only comprise 0.01% of Grand Canyon National Park's landmass, they host 36% of the flora and fauna (National Park Service 2015). During low flows, groundwater is the sole source of flow in spring-fed tributaries. Endemic species such as the Wetsalts Tiger Beetle are reliant on springs for survival. Various native, non-native and endangered species rely on springs to make their habitats possible, including fish relying on spring-fed streams.

Twelve types of springs have been defined (Springer and Stevens 2009): cave, exposure, fountain, geyser, gushet, hanging garden, helocrene, hillslope, hypocrene, limnocrene, carbonate mound form and rheocrene. Ten of the twelve spring types exist in the Grand Canyon, all except geysers and exposure springs (National Park Service 2015). The most prolific spring in the Grand Canyon is Roaring Springs, as it supplies water to all of the National Park's visitors. Roaring Springs is a cave spring, shown in Figure 5. Cave springs exist in mature karst formations. Karstification creates large conduits within the limestone that eventually become large enough to be considered a cave network. When this geologic configuration contacts the ground surface, a cave spring is formed.

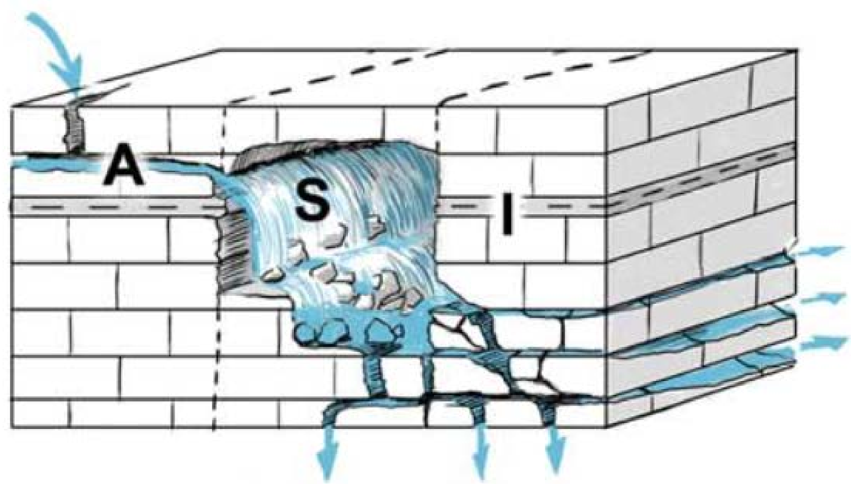

Figure 5. Schematic of a cave spring, similar to the Grand Canyon's Roaring Springs. From Springer and Stevens 2009.

Although springs are considered positive ecologically because of their ability to support species diversity, they can also cause water quality problems. Spring water has a long residence time as it has percolated and been stored in the subsurface since it entered the groundwater system at the aquifer's recharge source. While stored in the subsurface, groundwater's salinity increases if it is exposed to hydrogeologic units that leach salts. Due to this dissolution process, water leaving the groundwater system through springs is significantly saltier than when it entered. Salinity presents a problem for the agriculture industry, which already adds salt to hydrologic systems. Irrigating with saline water causes decreases in yields. High salinity water also causes corrosion which degrades the quality of infrastructure such as the Transcanyon Pipeline which delivers spring water to the Canyon rims. In general, reservoir systems tend to increase salinity due to the high evaporation rates from the reservoir itself.

Results of a numerical groundwater and surface water flow model focusing on Cottonwood Springs (Kobor et al. 2004) indicate that increased pumping from the Redwall-Mauv Aquifer could directly translate to decreases in discharge in springs on the south rim of the Grand Canyon. This study also recognized that increased evapotranspiration rates due to climate change have the potential to decrease spring discharge rates. Results show that discharge from Little Cottonwood and Indian Gardens Springs, both located on the South Rim, have experienced declines in discharge since 1994. The model also considered Pacific Decadal Oscillations indicating that precipitation in the region may fall below average for the next 20-30 years. Considering these results, it is possible that riparian spring-fed and spring ecosystems on the South Rim will experience significant degradations on short timescales (Kobor et al. 2004).

Water Resources Management & Infrastructure

The entirety of Grand Canyon National Park's water demand is met by Roaring Springs, a spring located on the North Rim of the Grand Canyon at 5200 feet elevation. Roaring Springs provides 21 cubic feet per second of consistent flow throughout the year. Water flowing from Roaring Springs is directed down 1400 feet in elevation to reach Indian Creek, it is then pumped up 3200 feet in elevation to reach Grand Canyon Village at 7000 feet. This transfer operation utilizes the 12.5 mile Transcanyon Pipeline. This pipeline was built between 1965 and 1970, its age renders it highly unreliable and a significant cost for Grand Canyon National Park, averaging $25,000 per year in maintenance (National Park Service 2016).

Havasu Spring, which discharges from the Supai Formation, has experienced an 8% decline in discharge over the years. This spring holds cultural significance and supplies water for anthropogenic and ecological needs. These declines are a result of increased groundwater pumping from the Coconino and Redwall-Mauv Aquifers. Increases in pumping are due to the development of cities like Tusayan, Arizona. Although Tusayan has a population of 558, the tourism infrastructure is growing and certain developers would like this growth to continue. Considering the results of groundwater models (Kobor et al. 2004; Pool et al. 2011), and the inevitable tie between infrastructure development and groundwater pumping, developments should be considered extremely carefully. Increases in pumping rates from the Coconino and Redwall-Mauv aquifer systems could result in significant declines in streamflow in the Colorado River and its tributaries, as well as eradicate species that depend on current spring discharge rates.

Arizona's Department of Water Resources (ADWR) has taken steps toward sustainable groundwater. After over-drafting (pumping from an aquifer at a greater rate than it can be recharged) their aquifers during the 20th century and experiencing undesirable results including significant land subsidence and groundwater depletion, Arizona passed legislature to begin regulating groundwater pumping in 1980. This type of legislation is progressive relative to states like California which just passed its first groundwater management act in 2014. Arizona aims to reach sustainable groundwater pumping practices by 2025. ADWR also conducts managed aquifer recharge projects throughout the state. Their recharge ponds total a capacity of 80,000 acre feet per year (Central Arizona Project 2016).

Conclusion

In the Colorado River Basin, snowmelt and rainwater from overlying land percolates downward through geologic formations and into aquifers. This groundwater eventually exits the hydrogeologic framework and emerges through springs, the ecosystems created when groundwater meets the ground surface. Groundwater makes up 56% of the Colorado River's flow (Miller et al. 2016). Historically, this system has been managed to support anthropogenic, agricultural and ecological systems, but the future of these systems is insecure in the face of climate change and increasing demands for water. Although many studies focusing on characterizing the Grand Canyon's hydrogeologic systems have been conducted, many unknowns remain and there are uninvestigated research avenues. Regarding concerns about water supply and groundwater sustainability, development of constraints on the effects of aquifer depletion on ecosystems and the level of difficulty associated with recharging the region's main aquifers, which we know are already significantly depleted, is needed. Water managers must heed scientific results and proceed with caution as they move toward securing a sustainable hydrologic future for the Colorado River Basins and their many dependents.

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