Groundwater-Surface-Water Interactions in the Grand Canyon National Park

ABSTRACT

A growing number of visitors to the Grand Canyon National Park and population increases around the park have resulted in greater demand on water resources in the region. Surface-water rights are already over-allocated for the Colorado River, and pumping thousands of feet from the bottom of the Grand Canyon is costly. As a result, many people look to groundwater to meet this increased demand. While land within the park boundary is protected from development, groundwater pumping from wells outside the park can significantly affect stream and springflow within the park. This is due to the large lateral extent of the major aquifer systems in the region and the connection between surface-water and groundwater. Although springs account for only a fraction of the landscape within the Grand Canyon, they represent vital habitat for many species found within the park. In addition to the ecological function springs serve, they also have aesthetic, economic, and cultural importance for both park visitors and Native American tribes living in the area. Increased groundwater pumping from the major aquifer systems found near the Grand Canyon can decrease carrying capacity of springs, change flow from perennial to ephemeral or even dry up springs entirely. Therefore, any proposed development of groundwater resources in the area should be carefully considered.

INTRODUCTION

The Grand Canyon is one of the most impressive natural features and unique ecosystems in the world. Deeply incised canyons containing the Colorado River and its tributaries cut through thousands of feet of sedimentary rock, showcasing over 1.5 billion years of geologic history. Despite the relative remoteness of Grand Canyon National Park (GCNP), visitation has increased from 2.2 million in 1970 to nearly 5 million in 2000 (Glennon, 2002), making it the second most-visited in the National Park System (Hetter, 2015). This rise in the number of visitors, as well as population growth in areas outside of the park, has resulted in greater water demands.

Groundwater is the most readily available source to meet increasing water demand for two reasons: accessibility and cost. Although millions of acre-ft flow through the Colorado River every year, the river is already over-allocated and obtaining surface-water rights can be both difficult and costly. Even if access to surface-water was procured, it is prohibitively expensive to pump water from the bottom of the canyon thousands of feet up to the rim. For example, the proposed Canyon Forest Village development on the South Rim suggested transporting water from the Colorado River about 6,500 ft vertically and 250 miles laterally via train and/or pipeline at a cost of about $20,000 per acre-ft (Glennon, 2002). In comparison, pumping groundwater from 2,000 ft below the surface would cost about $350 per acre-ft. However, groundwater pumping can have significant adverse impacts to springs in the Grand Canyon and its tributary canyons. First the general hydrogeologic framework of the Grand Canyon is developed below, followed by potential impacts of groundwater pumping on stream and springflow.

HYDROGEOLOGIC FRAMEWORK

The two primary units in the Grand Canyon area from which groundwater is pumped are the Coconino (C) and Redwall-Muav (R-M) aquifers (Bills & Flynn, 2002). Laterally extensive, the semi-confined C aquifer underlies a large portion of the South Rim, including the entire surface-water drainage of the Little Colorado River Basin (Hart et al., 2002). The western extent of the C aquifer is near Flagstaff, with the eastern boundary extending into New Mexico (Hart et al., 2002; Pool et al., 2011). The C aquifer is composed of a sequence of sedimentary rock units between the middle to upper Supai Group and the top of the Kaibab Formation (Figure 1), with the Coconino sandstone being the primary water-bearing unit (Leake et al., 2005). Ranging from 300 to 1,100 feet of buff-colored, fine-grained, eolian quartz sandstone and thinning to the west-northwest, this unit locally has high permeability due to extensive fracturing (Bills et al., 2000; Leake et al., 2005). The upper portion of the C aquifer is composed of the Kaibab and Toroweap Formations. Limestone up to 650 ft thick characterizes the Kaibab Formation, while the underlying Toroweap Formation is a mixture of carbonate sandstone, red beds, silty sandstone, limestone, and thin layers of gypsum that range from 0 to 150 ft in total thickness (Leake et al., 2005). These two formations are

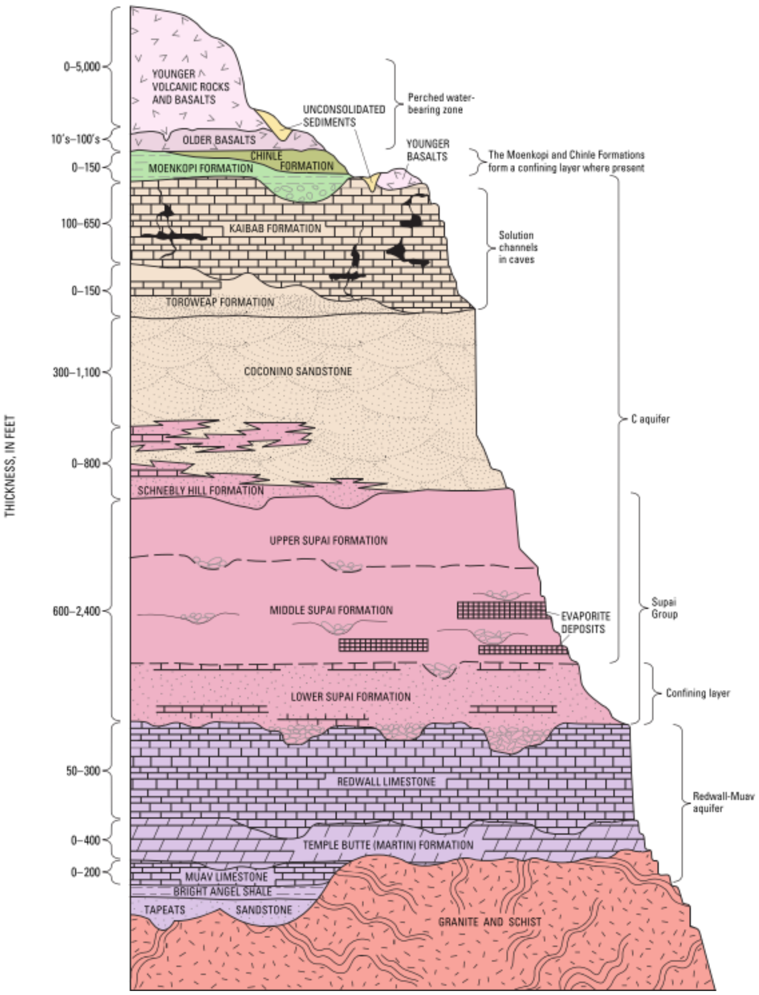

Figure 1. Generalized stratigraphic section for the South Rim of the Grand Canyon. From Leake et al. (2005)

have been eroded away in the eastern and northern portion of the area (Bills et al., 2000; Leake et al., 2005). The lower portion of the aquifer is composed of the Middle and Upper Supai Formations. The Upper Supai formation contains predominantly reddish-brown to tan fine-grained sandstone, red-brown siltstone, and a complex mixture of mudstone, limestone, and fine-grained redbeds. The Middle Supai Formation is made of orange-colored, fine-grained and well-rounded calcareous sandstone (Bills et al., 2000). The Lower Supai Formation, composed of red to purple sandstone and siltstone, gray limestone, and dolomite, typically forms an aquitard between the C and R-M aquifers.

The lower R-M aquifer is confined and is made up of the Redwall, Temple Butte/Martin, and Muav Formations. These units are predominantly limestone, ranging from about 200 to more than 500 ft thick (Bills et al., 2000; Hart et al., 2002). Localized solution cavities and collapsed caverns can have high permeability relative to the surrounding material (Bills & Flynn, 2002; Leake et al., 2005). The R-M aquifer is the predominant aquifer on the North Rim due to thinning of the Coconino sandstone in this area (Ross, 2005) which greatly reduces the storage capacity of the C aquifer.

GROUNDWATER RECHARGE AND FLOW

Recharge to the C aquifer occurs primarily to the south and southeast of the Grand Canyon in the vicinity of the San Francisco Volcanic Field near Flagstaff (Bills & Flynn, 2002; Hart et al., 2002; Leake et al., 2005). This is due to high rates of precipitation along the Mogollon Rim where the Kaibab Formation and Coconino sandstone are exposed at the surface (Figure 2). Recharge may also occur where volcanic material with high vertical conductivity overlies these units. A portion of the Defiance Uplift (Figure 2) also contributes to recharge of the C aquifer where Kaibab Formation and Coconino sandstone outcrop at the surface (Haert et al., 2002; Leake et al., 2005), although precipitation rates in this area are about half that near the Mogollon Rim. Downward leakage from overlying aquifers recharging the C aquifer may occur locally but is difficult to quantify (Hart et al., 2002).

The primary source of recharge to the R-M aquifer on the South Rim is leakage from the overlying C aquifer through localized faults, fractures, and other geologic structures that increase secondary permeability within the Lower Supai Formation and create conduits for flow (Pool et al., 2011). Direct recharge to the R-M aquifer also occurs in areas where the Redwall, Temple Butte, and Muav Limestones outcrop at the surface. However, these areas are located on the opposite side of the groundwater divide and therefore any water recharged in these areas would flow away from the Grand Canyon and toward the Verde and Salt Rivers to the south (Pool et al., 2011).

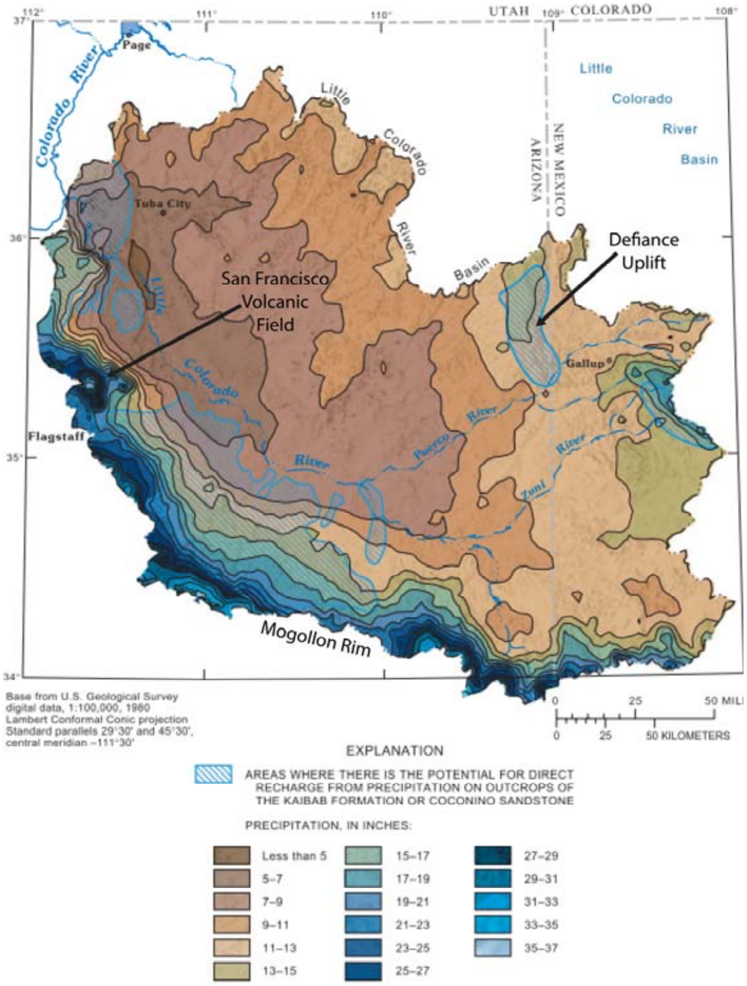

Figure 2. Estimated precipitation contours for the Little Colorado River Basin from the Parameter-Elevation Regressions on Independent Slope Model (PRISM). Blue shaded areas indicate areas where Kaibab Formation and Coconino sandstone outcrop at the surface. Modified from Hart et al. (2002).

No determination of the recharge area for the R-M aquifer on the North Rim has been made; Ross (2005) suggested the most likely area is along the southern axis of the East Kaibab Monocline, where sediments above the Redwall Formation have been eroded.

Flow within the C aquifer is predominantly from the recharge areas along the Mogollon Rim and Defiance uplift towards the Little Colorado River basin (Hart et al. 2002; Leake et al., 2005). Figure 3 shows a generalized cross-section of the regional flow system. Few springs originate directly from the C aquifer, as most of the water percolates down into the R-M aquifer (Hart et al. 2002; Pool et al., 2011). Areas where springs emerge from the C aquifer are generally in tributary canyons near the recharge areas and in the upper portion of the Little Colorado River.

On the South Rim, flow in the R-M aquifer discharges predominantly in a network of springs near the bottom of the Little Colorado River. The largest of these, Blue Spring, has an average flow rate of about 95 ft^3/s; the combined total discharge from springs in this area is about 237 ft^3/s (Hart et al., 2002). Havasu Spring, one of the most iconic springs near the Grand Canyon, also originates from the R-M aquifer and discharges about 64 ft^3/s. Numerous other springs originate from R-M aquifer on the South Rim, generally with lower flow rates. Total discharge from R-M aquifer springs on the North Rim has been estimated to be more than 1.4 ft^3/s (Pool et al., 2011).

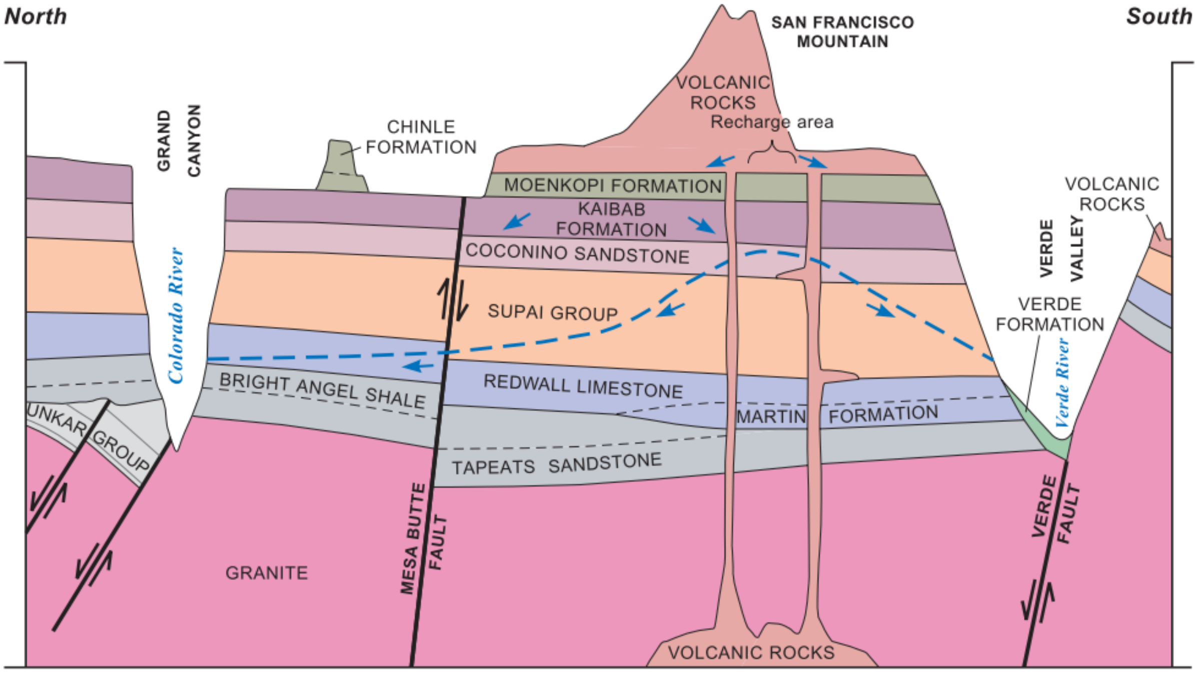

Figure 3. Generalized hydrogeologic cross-section of the Coconino Plateau. From Hart et al. (2002)

GROUNDWATER-SURFACE-WATER INTERACTIONS AND ECOLOGICAL FUNCTIONING

The interaction between groundwater and surface-water in the Grand Canyon is unusual due to the topography of the basin. One of the most striking differences between the Grand Canyon and a “traditional” watershed is that the location of the stream relative to the aquifer is reversed. In most watersheds, the stream flows on top of an unconsolidated aquifer, with fluxes between groundwater and surface-water determined by the position of the groundwater table relative to the stage of the stream. This relative positioning can vary both spatially and temporally. Groundwater is discharged to surface water in locations where the water table is higher than the stage of the stream, and the aquifer gains water from the stream where groundwater levels are lower (Figure 4). In contrast, the Colorado River is so deeply incised that the surface water system is below the major aquifers, and the Grand Canyon acts like a giant drain. As a result, interactions between groundwater and surface-water happen in one direction, with groundwater discharging in the form of springs near the bottom of the canyon and contributing to streamflow.

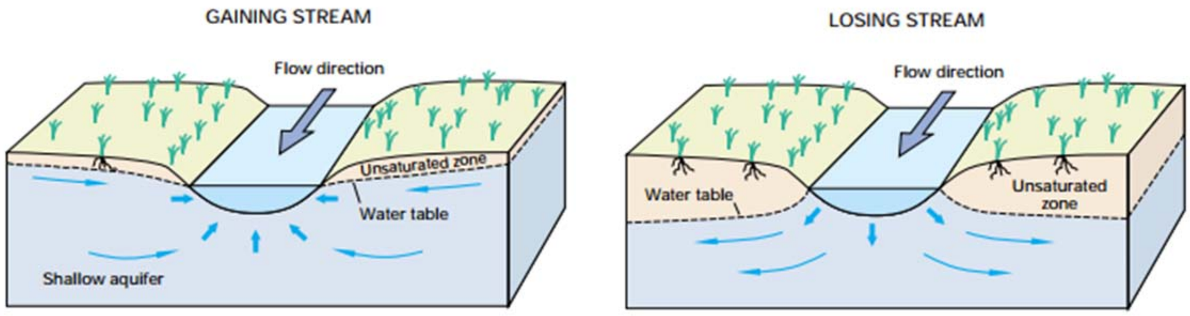

Figure 4. Schematic diagrams showing general groundwater-surface-water interactions.

Prior to the construction of Glen Canyon Dam, less than 10% of streamflow in the Grand Canyon at any given time was derived from groundwater discharge (assuming total springflow rates given above and average minimum streamflow of about 3,000 – 4,000 ft^3/s; USGS, 2016). Regulation of the Colorado River by Glen Canyon Dam since the mid 1960's has decreased the seasonal variability of streamflow, further reducing the proportion of streamflow derived from groundwater due to the increase in minimum streamflow. Therefore, springflow is essentially inconsequential for aquatic species, with the exception of those that rely on perennial flow in tributaries for habitat off the main stem of the Colorado River.

While springs may not significantly effect streamflow, they are still a vital component of the Grand Canyon ecosystem. Accounting for less than 0.01% of the landscape, springs are important habitats throughout the arid Southwest. It is estimated that species concentrations are 500 times greater at springs compared with surrounding desert lands (NPS, 2016). In addition to their ecological benefits, springs also hold a great deal of cultural significance for Native American tribes in the area. Havasupai means "people of the blue-green waters," which is the color of the water emerging from Havasu Spring.

EFFECTS OF GROUNDWATER PUMPING ON SPRINGFLOW

Groundwater is the major, and in many cases only, source of water for agricultural, domestic, and industrial use on the Colorado Plateau (Bills et al., 2000), with pumping likely to increase in order to meet increased demand (Figure 5). Flow rates from springs are directly proportional to the ability of the aquifer to transmit the water, known as hydraulic conductivity, and the energy gradient, or difference in total energy between two locations. The total energy of a parcel of water at a given location in an aquifer is composed of three terms: the elevation of the water, the speed of the water, and the pressure the water is under. Increased groundwater pumping from the C aquifer reduces the amount of water that leaks into the R-M aquifer, resulting in lower total energy of the water in the aquifer. Since the physical characteristics of the aquifer have not changed, the hydraulic conductivity is the same. However, because the energy of the water in the aquifer has decreased, the gradient has decreased, and springflow is reduced as a result. Essentially, any water that is pumped from the aquifer is water that would otherwise make its way to a spring eventually. Even though wells may be located many miles from a spring, they can still have a significant impact on flow (USDA, 1999; Kobor, 2004). Since springs play a vital role in sustaining diverse and often rare species in the harsh desert landscape, even small reductions in their flow may have a disproportionate effect on flora and fauna that rely on them.

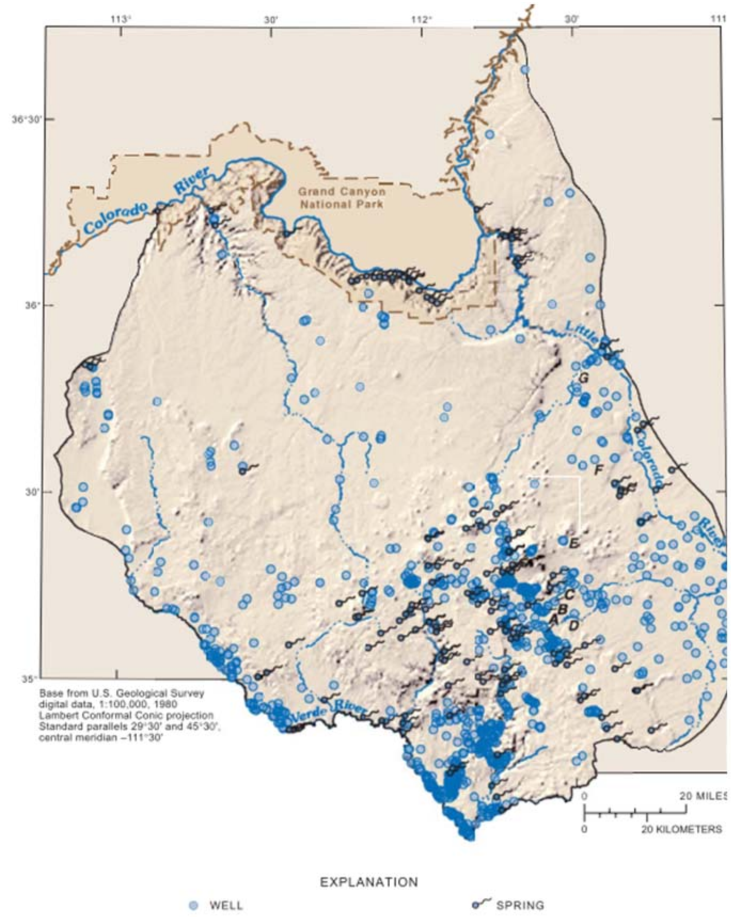

Figure 5. Locations of wells and springs on the South Rim.

CONCLUSIONS

Increases in both visitation to the Grand Canyon National Park and population of the surrounding area have and will continue to put increased demand on groundwater resources. The two major sources of groundwater are the laterally extensive C and R-M aquifers. Recharge to the C aquifer occurs along the Mogollon Rim, near the San Francisco volcanic field, and within the Defiance Uplift, where high precipitation rates are coincident with either outcrops of the Kaibab Formation or Coconino sandstone, or geologic structures within overlying units allow for deep percolation of water. Recharge to the R-M aquifer is from downward leakage from the C aquifer. Although the two are separated by the Lower Supai Formation which acts as a confining layer, fractures, faults, and breccia pipes create localized connections between the two aquifers. Discharge from the R-M aquifer is primarily from springs located near the bottom of the Grand Canyon and in the lower sections of tributary canyons. Flow rates from these springs range from less than one to more than 107 ft^3/s. While the total combined springflow is relatively small compared to streamflow in the Colorado River, the springs maintain perennial sections of tributary creeks and provide vital habitat in the harsh desert landscape. Increased groundwater pumping within and near the park to satisfy growing demand is likely to result in decreased springflow. Minor reductions of springflow may have a disproportionate ecological effect due to the high biodiversity found at desert springs.

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