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The Aqueous Geochemistry, Hydrologic Regime, and Management Practices of the Havasu Creek Watershed

Abstract

The Havasu Creek watershed is the second largest watershed in the state of Arizona, and Havasu Creek, the only perennial portion of the watershed, is the second largest tributary to the Colorado River within the Grand Canyon. The aesthetic appeal of the unique aqueous chemistry and geologic formations of Havasu Creek draw large numbers of tourists to the area. Tourism is the main source of revenue for the Havasupai people who permanently reside in the town of Supai, located in Havasu Canyon directly below Havasu springs. The dangers presented by the extreme nature of the watershed's hydrologic regime and the scale of tourism to the canyon create a unique managerial challenge. Seasonal flash flood events have caused considerable damage to Supai and the surrounding area over the past century; however, in order to maintain revenue, the Havasupai people remain in the canyon and run tourist facilities. This paper will examine the aqueous geochemistry, hydrologic regime, and unique management challenges of the Havasu Creek watershed.

Introduction

The Havasu Creek watershed is located along the center of the south rim of the Grand Canyon (see Fig. 1), and is the second largest watershed in the state of Arizona (West et al., 2009). It covers approximately 2,966 square miles (mi^2) and has its headwaters at Williams, Arizona (West et al., 2009). Its outlet, Havasu Creek, runs through Havasu Canyon and into the Colorado River. The watershed is comprised of 40.12% privately owned land, 28.18% state trust land, 20.67% Kaibab National Forest, and 8.18% Havasupai Tribe land (West et al., 2009). Although the watershed holds hundreds of miles of streamways, the only section that is perennial is the ten miles of Havasu Creek that feed into the Colorado River at river mile 157 (Melis et al., 1996). The flow of this portion of Havasu Creek originates from springs that mark one of the outlets of the Coconino Trough, which is the 3,500 mi^2 groundwater basin that underlies much of the south rim area of the Grand Canyon (Giegengack et al., 1972). Because the springs are fed by a large groundwater basin and are not dependent on seasonal precipitation, the creek flows consistently at approximately 65 cubic feet per second (cfs) year round (Giegengack et al., 1979; Melis et al., 1996; NRCS, 2010). The spring-fed nature of the creek provides for a unique chemical and geologic environment. The aquamarine waters and waterfalls that cascade over tufa and travertine formations have become iconic, and tourism is the main form of revenue for the Havasupai people who inhabit Supai, a village located within

Havasu Canyon (Official Website of the Havasupai Tribe, 2010). This paper will examine the aqueous geochemistry, hydrologic regime, and unique management challenges of the Havasu Creek Watershed.

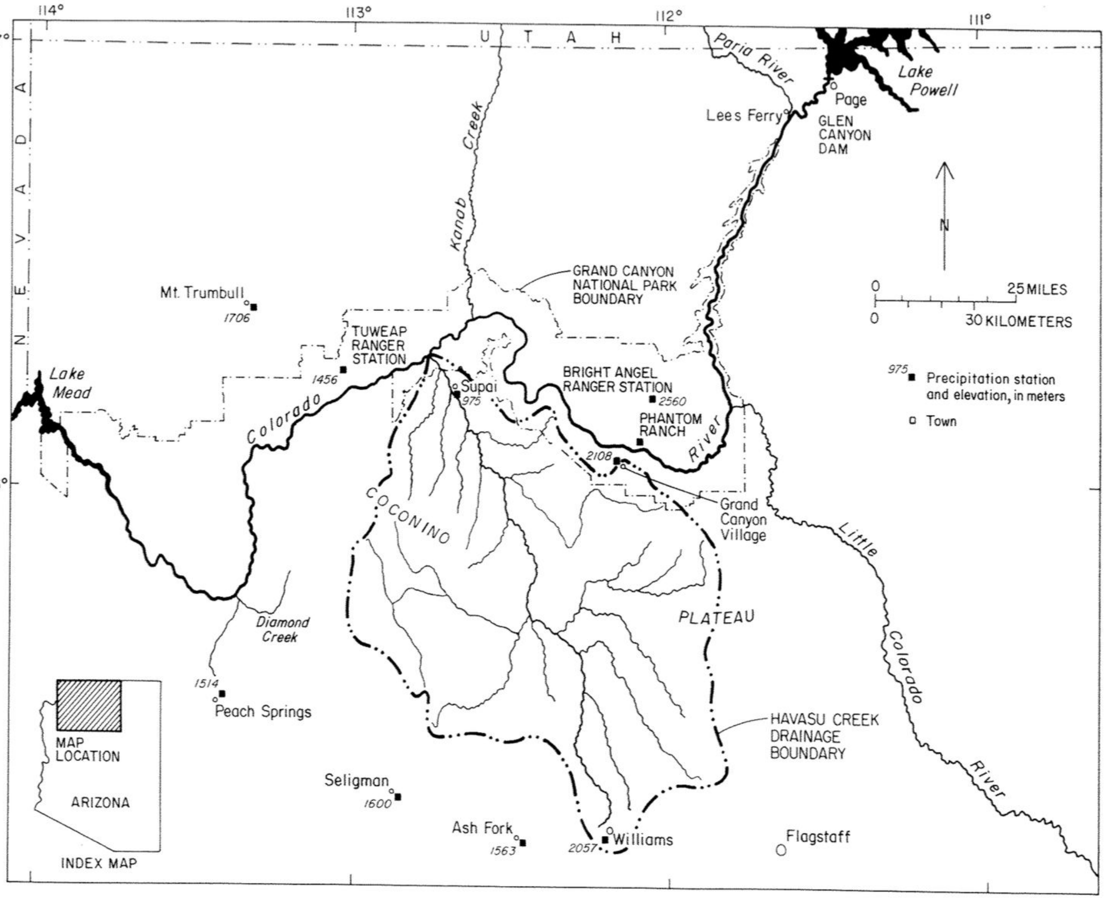

Figure 1. Delineation of the Havasu Creek Watershed boundary. All streams located above the village of Supai are ephemeral (Giegengack et al., 1972).

History of the Watershed

The formation of Havasu Creek Canyon predates the formation of the Grand Canyon (Ghiglieri, 1992). Havasu Canyon previously housed Cataract Creek, a river much larger than the present day Havasu Creek (Ghiglieri, 1992). Cataract Creek was fed by runoff from mountains to the southeast of the canyon 45 to 15 million years ago, before the uplift of the Colorado Plateau (Ghiglieri, 1992). The size of the prehistoric river explains the considerable width of Havasu Canyon, which is in some areas wider than the Grand Canyon at river level (Ghiglieri, 1992). The phase of the uplift of the Colorado Plateau that occurred between 35 and 15 mya changed the regional topography and altered the bounds of the watershed, reducing the volume of runoff received by Cataract Creek (Ghiglieri, 1992; Roberts et al., 2012).

Before Havasu Canyon became a popular tourist destination, it was part of the ancestral home of the Havasupai people (Hirst, 2006). The word Havasupai means ‘people of the blue-green water' in the Havasupai language, and the creek has been a part of the Havasupai people's way of life for centuries (Hirst, 2006). Prior to the creation of the Havasupai reservation in 1882, the Havasupai would migrate seasonally between the canyon floor and the Colorado Plateau (Hirst, 2006). Springs and summers were spent in the canyon growing crops irrigated with creek water, and autumns and winters were spent on the plateau hunting deer and gathering seasonal food (Hirst, 2006). The original reservation confined the Havasupai people to 518 acres inside the canyon (Hirst, 2006). The area of the reservation was increased by 185,000 acres in 1975; however by then the Havasupai had settled in the canyon and constructed the village of Supai (Hirst, 2006). The only other town within the watershed bounds is Williams, AZ (Melis et al., 1996; NRCS, 2010).

<u>Hydrochemistry of Havasu Springs and Havasu Creek</u>

As previously stated, the only perennial flow in the Havasu Creek Watershed is the ten miles of Havasu Creek that originate from Havasu Springs and flow into the Colorado River. The current Havasu Creek originates from springs that emerge from alluvium overlying the Lower Slope member of the Supai Formation (Giegengack et al., 1979). The creek travels 10 miles from Havasu springs down to the Colorado River over a 1,470 ft drop in elevation and cuts through the Redwall, Temple Butte, and Muav Limestones (Giegengack et al., 1979).

Springs mark locations where the land surface occurs below the regional water table and groundwater discharges to the surface; these conditions may occur at the bottom of a valley, on a hill slope, or where the land has been sharply incised (USGS, 2016). Generally, groundwater dominated streams contain elevated levels of bicarbonate, calcium, chloride, magnesium, silicon, sodium, sulfate, and carbonic acid (Candela and Morrell, 2009). The ratios of major ion constituents are usually indicative of the minerals present in the groundwater aquifer material; however, surface and groundwater interactions in the Grand Canyon region are highly complex, and different springs emerging from the same aquifer formation can have highly varied chemical compositions, as do Havasu Springs, Blue Springs, and Tapeats Springs, which all issue from the Redwall Limestone (Crossey et al., 2006).

The water flowing from Havasu Springs contains high concentrations of magnesium and calcium ions (Giegengack et al., 1972). These elements give the creek its blue-green color, which is enhanced by the reflectivity of the limestone creek bed, the submerged chalky white tufa formations, and the calcium carbonate precipitate suspended in the creek water. Calcium carbonate precipitates readily within the creek water because of the disequilibrium of carbon dioxide (CO_2) concentration between the emerging spring water and the atmosphere: air trapped within soil pores can contain one hundred times as much CO_2 as the atmosphere, and so groundwater can be supersaturated with CO_2 (Giegengack et al., 1972; O'Brien et al., 2006). Equation 1 shows the dissolution of CO_2 in water to form carbonic acid which can then be deprotonated to form bicarbonate (Giegengack et al., 1972).

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \qquad (1)$$

When groundwater emerges from springs, CO_2 outgases and the products of the reaction in equation 1 are favored. H_2CO_3 has a pKa of 6.35, meaning that the dissociated HCO_3^- is favored in water above pH 6.35. The pH of Havasu Creek water is consistently in the range of 7.4 to 7.8, and so aqueous bicarbonate is present at significant levels (Giegengack et al., 1972).

$$Ca^{2+} + 2HCO_3^- \leftrightarrow CaCO_{3\,(ppt)} + H_2O + CO_{2\,(gas)} \qquad (2)$$

Bicarbonate combines with calcium cations to form calcium carbonate as described in equation 2 (Giegengack et al., 1972). Calcium carbonate plays an important role in the creek's geomorphology, as will be discussed in the next section.

Havasu Creek Aqueous Geochemistry and Streambed Geology

Calcium carbonate precipitates out of its aqueous form at loci of microturbulence in the creek that promote the degassing of carbon dioxide (Giegengack et al., 1972; O'Brien et al., 2006). Any object that protrudes into the streamflow can cause microturbulence; rocks and tree branches fallen into the creek cause calcium carbonate to precipitate onto their surfaces, and as precipitated calcium carbonate adheres to these protruding objects it increase the scale of their protrusion, leading to a positive feedback loop of precipitation (Giegengack et al., 1972). The chalky precipitated form of calcium carbonate found in Havasu Creek is known as tufa, and tufa protrusions often connect from one bank of the stream to the other, creating natural dams and tiered pools up to tens of meters in length (Ford and Pedley, 1996; Giegengack et al., 1972; O'Brien et al., 2006).

The term tufa is sometimes used interchangeably with travertine: both describe the recrystallized form of calcium carbonate (Ford and Pedley, 1996). In European literature it is common for the term tufa to be used to refer to calcium carbonate precipitate that occurs under ambient temperature conditions, and travertine to be used to refer to calcium carbonate that precipitates under thermal conditions (Ford and Pedley, 1996). In this paper the temperature-dependent distinction will be made between tufa and travertine. Havasu Creek's bed is a mixture of tufa and travertine formations, indicating that the temperature regime of the spring water has changed throughout the canyon's history (Ford and Pedley, 1996). In some areas, the walls of Havasu Canyon more than ten feet above the creek bed are encrusted with tufa benches, indicative of the location of extinct springs active during wetter climates (Ford and Pedley, 1996; O'Briend et al., 2006). Alternatively, the extinct springs could support the hypothesis that approximately 1.8 mya the Grand Canyon hosted a series of large lakes dammed by lava flows; the presence of these lakes would have raised the water table in many parts of the Grand Canyon, including the portion of the Redwall Limestone exposed in Havasu Canyon (Ford and Pedley, 1996).

Anything that falls into the creek is susceptible to incorporation in tufa formations. The trees in the riparian area bordering the creek are sometimes drowned in floods; some of the dead trees fall into the creek where they're encased in tufa and can form large dams (Giegengack et al., 1972). The tufa dams that tier portions of the creek can grow vertically by as

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much as two feet per year. During the mid twentieth century the Havasupai people would periodically use explosives to clear the tufa dams to make the creek fordable (Black, 1955).

As previously stated, Havasu Canyon is the outlet for a 2,966 mi^2 watershed, and so during periods of precipitation Cataract Creek, the largest of the ephemeral streams that feed into Havasu Creek, can put forth thousands of cfs of surface runoff into the normally groundwater fed stream. This causes changes in the hydrochemistry of the water: the normally calcium and magnesium enriched water is diluted, and so precipitated calcium carbonate can be dissolved back into aqueous calcium and bicarbonate (Giegengack et al., 1972). The increased volume, velocity, and turbidity of the runoff-fed creek can also cause physical weathering of tufa formations. Recent floods have altered tufa formations enough to change the course of three of the major waterfalls along the creek, and reroute the creek to create new falls (Melis et al., 1996; NRCS, 2010).

<u>Havasu Creek Watershed Hydrologic Regime</u>

Because of the ephemeral nature of most streams in the Havasu Creek watershed and the seasonal precipitation extremes, Havasu Canyon experiences frequent flash floods (West et al., 2009). The slope in the canyon is much greater than the majority of the watershed, and the runoff generated by precipitation events over the entire area of the watershed is funneled into the narrow Havasu Canyon (NRCS, 2010). The decrease in area and the increase in slope causes a significant increase in velocity of seasonal streamflow through the canyon. Flood flows through Havasu Creek have been reported as high as 20,300 cfs (Melis et al., 1996).

Havasu Canyon has a long history of flash floods. The largest floods on record occurred in 1910 and 1990, during which Havasu Creek flowed at approximately 20,000 cfs and 20,300 cfs respectively (Melis et al., 1996). Significant flooding events have occurred during the summer and winter of 1905, the winters of 1910 and 1920, the summers of 1921, 1928, 1935, 1954, 1955, 1970, 1990, and 2008, the fall of 2010, and the summer of 2013 (Melis et al., 1996; Official Website of the Havasupai Tribe, 2013). There is anecdotal evidence of winter floods prior to 1900; however no data exists to quantify these flood events (Melis et al., 1996).

As can be seen in Figure 2, the occurrence of major flood events doesn't necessarily correlate with the occurrence of the greatest monthly volume of precipitation. Flood events are more dependent on the intensity of individual storms and the antecedent moisture condition of the watershed's surface soil (Melis et al., 1996). If surface soil is already saturated, then less precipitation will infiltrate and more will runoff into streambeds. The shift from periodical winter and summer floods to predominantly summer floods could be indicative of historical variation in precipitation occurrence and general climate. Winter floods are caused by frontal storms, and summer floods by monsoon thunderstorms;

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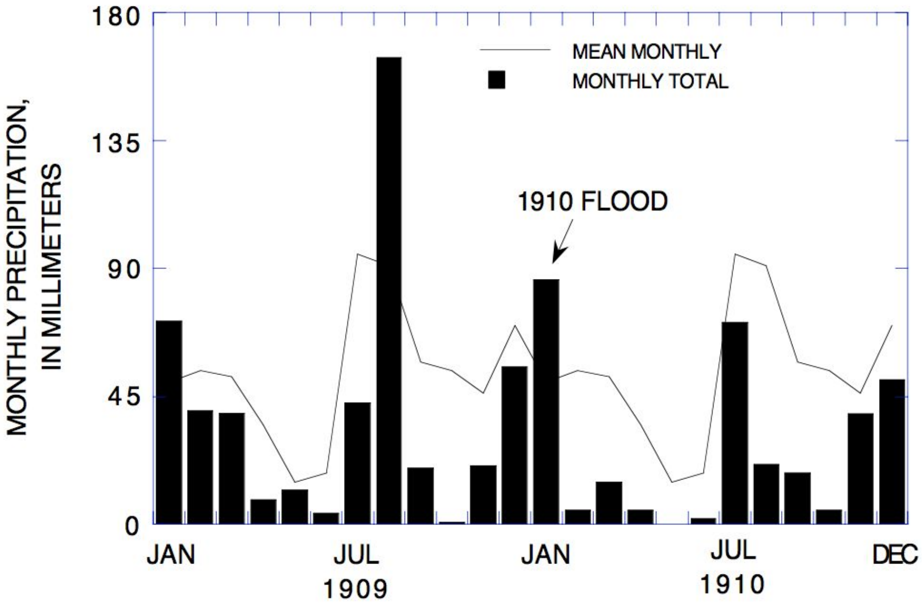

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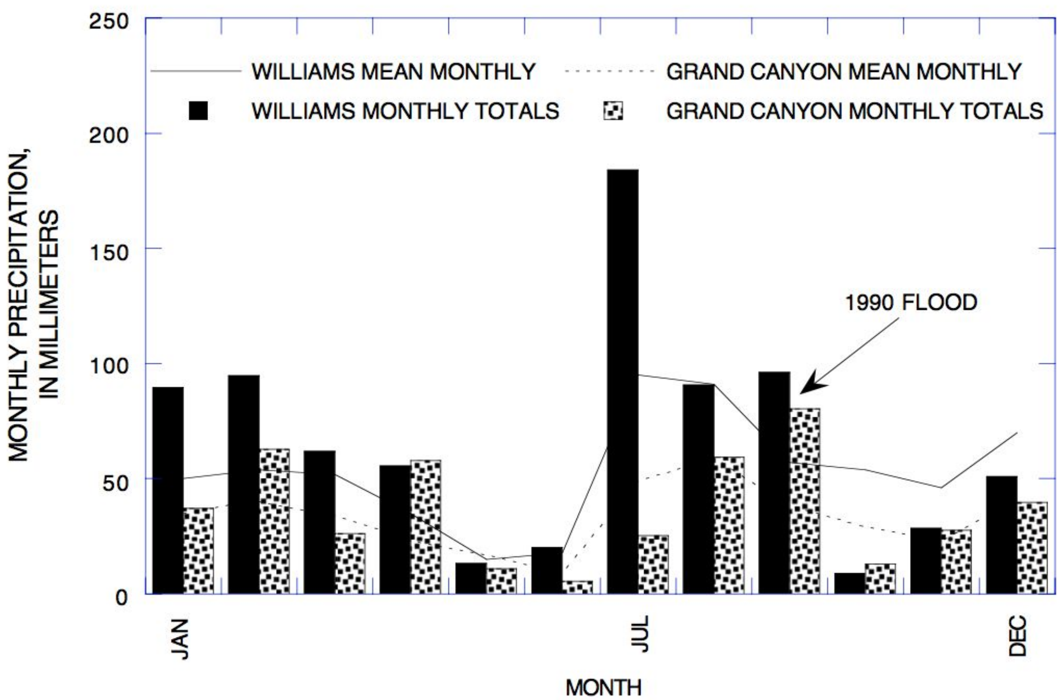

Figure 2 A and B. Monthly precipitation depths at the Williams stream gage from January through December of 1910 with the occurrence of the major flood event shown (A), and monthly precipitation depths at the Williams stream gage and in the Grand Canyon from January through December of 1990 with major flood event shown (B) (Melis et al., 1996).

the shift in temporal flood occurrence could indicate a shift from heavy winter rains to more frequent, or earlier summer monsoons derived from moisture bourne from the Gulf of Mexico (Melis et al., 1996). Rain on snow events can increases the chance of floods, as the rainfall increases snowpack melt and thus runoff in general, and the occurrence of these type of events may increase with regional climate change, as may the occurrence of high intensity summer storms (Melis et al., 1996). It is possible that the next few decades of climate change may favor conditions that produce flash floods in Havasu Canyon and other areas.

Management Challenges

The floods through Havasu Canyon have caused fatalities, and damage to livestock and property have been significant (Melis et al., 1996). The town of Supai has been completely destroyed, rebuilt and relocated several times over the course of the last century (Hirst, 2006). The canyon was only recently reopened to tourism after the flood of 2010, the devastation of which lead the Havasupai's governing body to declare a State of Disaster (Official Website of the Havasupai Tribe, 2013). The floods also affect riparian ecosystems; trees (cottonwood, ash, and willow) are killed and uprooted, and subsequent recruitment can be a slow process (Melis et al., 1996). However, the heavy tourism to the area is also damaging the natural ecosystem due to seedling trampling (Melis et al., 1996). In 2012 it was estimated that the canyon received 20,000 visitors per year (Official Website of the Havasupai Tribe, 2012).

During the 2008 and 2010 flood events, Havasupai people and hundreds of canyon visitors had to be evacuated from the canyon via helicopters (Official Website of the Havasupai Tribe, 2013; West et al., 2009). The nature of the floods makes it extremely difficult to design an effective warning system (West et al., 2009). Efforts have been made to set up an alert system. The stream gage installed at Supai in 1995 could only be used to provide warning an hour before a flood event, which was not enough time to evacuate the village and the campground (NRCS, 2010. Two additional stream gages were installed in 2008 and 2009: Cataract Creek at Redlands Crossing, which sends warning once flows reach 3,000 to 4,000 cfs, and Cataract Creek Below Heather Wash, which sends warning once flow reaches 4,000 cfs and captures flow from 85% of the watershed above Supai (NRCS, 2010). The flood gage warning system remains mostly untested, however it is predicted to aid in future evacuation events (NRCS, 2010).

Conclusions

The Havasu Creek watershed is characterized by a unique perennial hydrologic system and a hydrologic regime of extremes. Because Havasu Creek is spring-fed, its hydrochemistry gives rise to aquamarine waters and tufa and travertine tiered pools and cascades. The aesthetic appeal of Havasu Creek and Canyon draw thousands of tourists per year; however the topography of the large watershed, and the seasonality and intensity of regional precipitation events lead to frequent flash floods within Havasu Canyon. While few fatalities have been reported, the floods have lead to considerable damage to property and livestock. Stream stage gages installed upstream of Havasu Creek may provide early warning for flood events and reduce risk to human lives, but the danger remains. Havasu Creek is a beautiful and unique hydrogeologic system with a unique set of managerial challenges.

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