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Assessing the Vulnerability of an Aquifer to Climate Variability through Community Participation in Arivaca, Arizona

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Abstract: In Arivaca, Arizona, groundwater isotope measurements (stable O and H, tritium, and carbon-14) were made in conjunction with water level measurements and climate data. Recharge is predominantly young (post-1950) and is mainly from summer monsoon precipitation. Following a five-month period of unusually low $\delta^{18}O$ and $\delta^{2}H$ in precipitation in 2014-2015, corresponding shift in groundwater $\delta^{18}O$ and $\delta^{2}H$ was observed only at a site with recently built gabions. Water levels near the basin outlet increase in summer following periods of high storm frequency. Water levels also rebound in winter, possibly because of cessation of transpiration. The young groundwater is vulnerable to climate change, e.g., to protracted periods with summers that are drier or hotter than normal. Rapid assessment of groundwater and its connection to climate can provide valuable information to local water managers and citizens for whom more expensive studies are not feasible. Such assessments, based on relatively inexpensive isotope analyses and groundwater level data collected by volunteers, engage the community in management of its water resources. In Arivaca, the community responded to the results of the assessment with heightened interest in managing their water for sustainability and the construction of gabions to increase recharge from stormwater.

Keywords: *Arizona, groundwater, recharge, O and H isotopes, tritium, carbon-14, climate, water levels*

Drought is a common feature in the arid western U.S. (Ni et al. 2002; Hirschboeck and Meko 2005; Weiss et al. 2009; Griffin et al. 2013), and has been exacerbated in recent years by the effect of warming temperatures on evapotranspiration demand. Between 2012 and 2014, California experienced large precipitation deficits that were not uncommon in the historical record but when combined with temperature produced the most severe three-year drought in the last 1200 years (Griffin and Anchukaitis 2014). Like California, other states in the western U.S. have also recently experienced severe multiyear warm droughts (Cook et al. 2004; MacDonald 2010). By some estimates, Arizona has been in a prolonged drought since 2000 (Arizona Department of Water Resources 2019a, 2019b; Westwide Drought Tracker 2019). The severity of summer drought has been increasing in recent decades (Goodrich et. al 2004; Morino 2008), while winter precipitation has shown a general decrease since the late 1990s (e.g., Eastoe and Dettman 2016). With projections of continued warming (United States Global Climate Research Program 2017), the higher temperatures and periodic rainfall deficits will be a main challenge to the management of water resources (Milly et al. 2008; Udall and Overpeck 2017).

The impacts of climate on surface water are well documented. Research has demonstrated the effects of evaporation of water stored in reservoirs (Friedrich et al. 2018), the widespread declines in streamflows (Udall and Overpeck 2017), and shifting streamflow seasonality caused by changes in snowpack conditions (Stewart et al. 2005). Equivalent studies on the impact of climate on groundwater have lagged behind (Earman and Dettinger 2011; Green et al. 2011) despite direct influence of seasonal precipitation and evapotranspiration on groundwater recharge. Understanding the complex interplay between climate and recharge is important to assessing the vulnerability of an aquifer to climate variability.

Across portions of the southwest U.S. there are two main modes of rainfall: 1) frontal systems during winter months, and 2) convective storms during the summer monsoon, largely between July and September (Sheppard et al. 2002). Monsoon rains generate most streamflow in the Sonoran Desert of Arizona (Constantz et al. 2007), while groundwater recharge can occur from both summer and winter precipitation, although proportions can vary between basins (Eastoe and Towne 2018). Precipitation is often less than evapotranspirative demand, preventing infiltration beyond the root zone (Hogan et al. 2004). Large areas of basin floors provide little to no recharge to underlying aquifers; in such basins, most recharge is likely to be focused in ephemeral channels where flow may occur only several hours per year (Uhlman 2005; Stonestrom et al. 2007; Glenn et al. 2015). Basin-floor recharge could, however, be significant during extended periods of high precipitation and low evapotranspiration in the fall and winter seasons (Coes and Pool 2007).

Arizona is strongly dependent on groundwater for water supply. Moreover, carbon-14 (^{14}C) age dates of groundwater in major aquifers in Arizona have revealed a wide range of residence times (e.g., Smalley 1983; Eastoe et al. 2004; Baillie et al. 2007; Hopkins et al. 2014). Ages of more than 10,000 years before present can be explained either as indicating older water left after younger water has been over-pumped or as recording the last significant recharge in aquifers that were filled in the late Pleistocene, when climate was colder and wetter (Phillips et al. 1986; Artiola and Uhlman 2009).

Younger aquifer systems (recharged since 1950) are more vulnerable to drought than aquifers holding mainly fossil water, but this vulnerability could be partially offset by a change in water management strategy, such as construction of gabions to detain and infiltrate stormwater. Detailed, expensive research studies of local groundwater are mostly unavailable to small, rural communities. Rapid assessments of groundwater character and its connection to climate can provide valuable information to local water managers and citizens' groups. These assessments, built on relatively inexpensive isotope analyses and groundwater level data collected by volunteers, have the advantage of encouraging citizens to participate in water management.

The rural community of Arivaca is dependent on groundwater in a small alluvial basin (Figure 1). This report presents the results of an initial, rapid assessment of the Arivaca Basin in 2009, augmented by a second round of sampling in 2015. The first phase of assessment was envisioned as a low-cost investigation of the basin aquifer, encompassing: 1) planning with community members, including initiation of water level and climate monitoring, and 2) field sampling over a period of one to two months, followed immediately by laboratory work. The second assessment phase was an unanticipated addition to original plans following a fortuitous observation. Long-term measurement of oxygen and hydrogen isotopes in Tucson rain indicated a five-month period of rain, late August 2014 to early February 2015, of extreme isotope composition (Eastoe 2016) providing an unusual opportunity for the identification of recent recharge. Results of these campaigns are combined with overlapping observations of climate and water levels collected in other contexts over different time frames. The principal aims of the study were 1) establishing recent trends in local climate and groundwater levels through measurements undertaken by Arivaca residents; 2) determining aquifer vulnerability and recharge seasonality by application of isotope measurements; and 3) augmenting local knowledge of water resources in a low-cost study, with a view to enabling community participation in sustainable water management.

Study Area

Geography

The rural community of Arivaca, with a population of around 1,000, is located approximately 80 kilometers southwest of Tucson, Arizona (Figure 1). Arivaca lies within the Tucson Active Management Area (AMA), one of five AMAs established by the State of Arizona under the 1980 Groundwater Management Act (Arizona Department of Water Resources 2019c). The Tucson AMA covers 10,013 square kilometers in southern Arizona and encompasses extensive basin-fill aquifers in the Santa Cruz River Basin. The Tucson AMA has a statutory goal of achieving 'Safe-yield' by 2025 and maintaining it thereafter (Arizona State Legislature 2019). 'Safe-yield' requires that average annual pumping not exceed natural or artificial recharge in the AMA as a whole. The Arivaca Basin lies within the boundaries of the AMA but is not in direct hydraulic connection with the larger basins (Pima Association of Governments 2006).

Climate

The climate in Arivaca is characterized by mild winters and hot summers. July is the hottest month. The region has a bimodal annual distribution of precipitation. More than half falls during the monsoon season between June and September, and most of the remaining precipitation occurs in the winter between November and March (Figure 2). The two to three months prior to the monsoon are the driest season.

The monsoon rains tap moisture from the tropical Pacific Ocean and the Gulf of Mexico (Michaud et al. 1995; Adams and Comrie 1997; Diem and Brown 2006). Monsoon storms commonly yield short, intense rain events of limited spatial extent. Arivaca is located on the western fringe of the core area of the monsoon and receives slightly more precipitation than areas to its north and less than Nogales to the southeast (Figure 3). Winter rains are the product of regional frontal storms, generally lower in intensity and more widespread than monsoon storms. In some years, tropical cyclonic storms from the Pacific Ocean bring precipitation between September and November; a single such event can account for a high percentage of annual precipitation.

Hydrogeology

The following description of the groundwater basin at Arivaca is based on a report of Pima

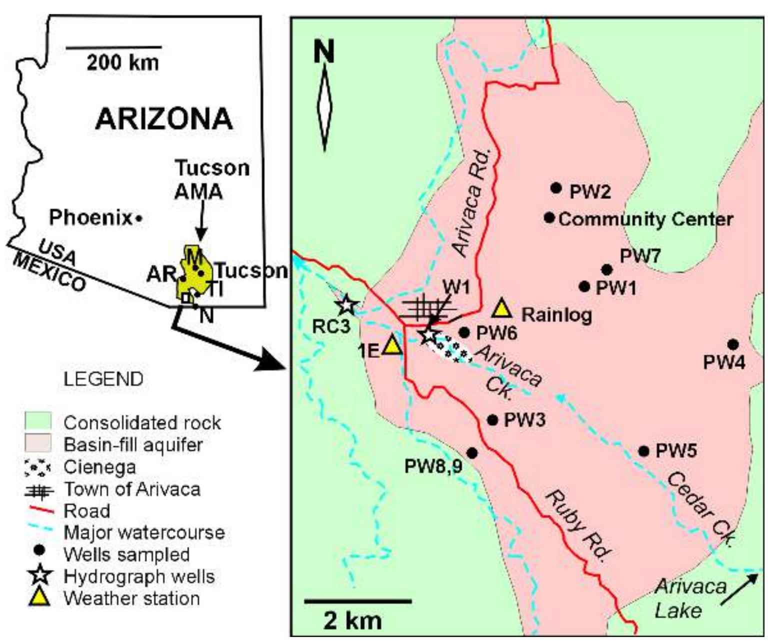

Figure 1. Location map, showing locations of wells sampled for this study, hydrograph wells, and weather stations. Inset map shows locations of Tucson Active Management Area (AMA) and five observation stations: Tucson, Anvil Ranch (AR), Marana (M), Tumacacori (TI), and Nogales (N).

Association of Governments (2006). The isolated aquifer system of the Arivaca groundwater basin extends over 39 km^2 and supports more than 200 wells in addition to perennial streamflow, lush riparian habitat, and a cienega (wetland) with diverse terrestrial and aquatic ecosystems. The basin is a graben within Mesozoic and Cenozoic crystalline rocks that compose a horst of the Basin-and-Range province. Unconsolidated Holocene alluvium beneath the larger washes (streambeds that are usually dry) overlies Tertiary to Quaternary semi-consolidated conglomerate and sandstone up to 200 m thick in the southeast part of the basin. These sediments form the unconfined regional aquifer of the Arivaca Basin. Groundwater flow is generally from the basin edges towards a discharge area in the cienega located where Arivaca Creek crosses a sill of shale. From the cienega, groundwater leaves the basin to the west, along Arivaca Creek (Figure 1).

Watercourses are ephemeral except for Arivaca Creek within the cienega. Arivaca Lake, an artificial impoundment built on Cedar Creek to the southeast of the study area in the 1970s, discharges water infrequently when the reservoir overflows. Modeling combined with water level data shows a general decline of about 1 m in groundwater levels since the 1970s, the largest declines being north of

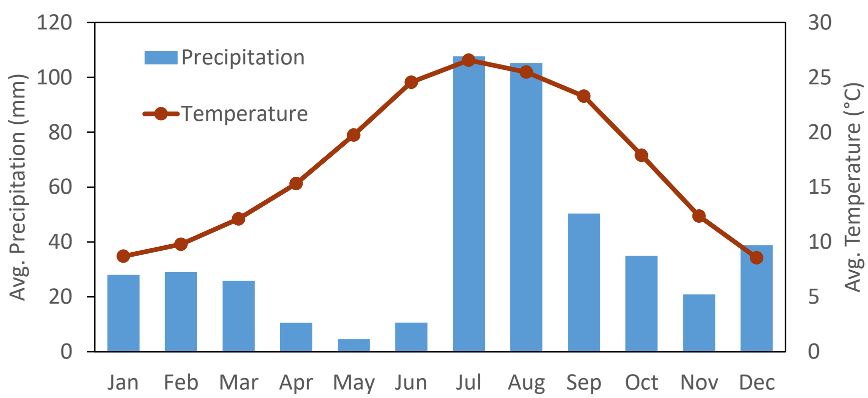

Figure 2. Average monthly precipitation in Arivaca, 1956-2018 (Western Regional Climate Center 2019).

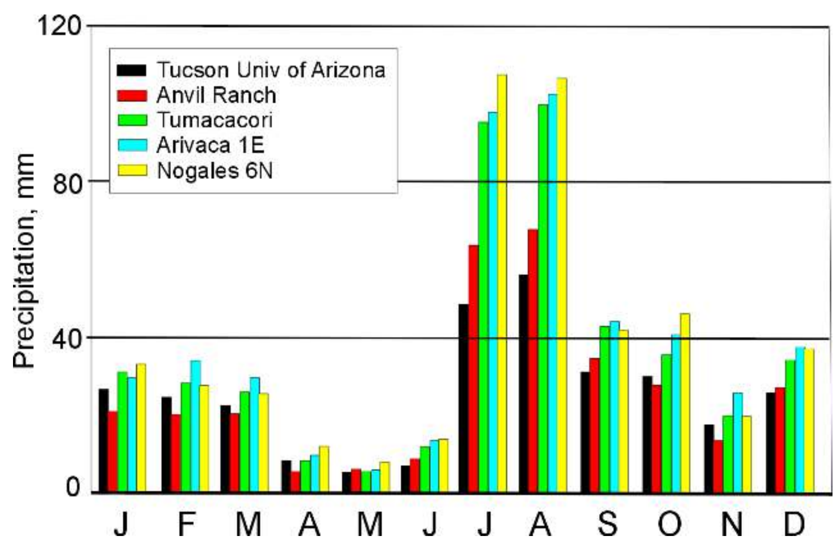

Figure 3. Comparison of average monthly precipitation in Arivaca with that of surrounding stations at Tucson, Anvil Ranch, Tumacacori, and Nogales. Month names are abbreviated JFMAMJJASOND, January to December.

the cienega. The decline has occurred concurrently with a decrease in base flow in Arivaca Creek, putting the riparian ecosystem of the cienega at risk (Pima Association of Governments 2006).

Usefulness of Isotope Data

Research using multiple isotope parameters has contributed to the understanding of groundwater origins, flow paths, and residence times in the alluvial basins of southern Arizona (Eastoe et al. 2004; Baillie et al. 2007; Hopkins et al. 2014; Gungle et al. 2016; Eastoe and Towne 2018). These studies have used stable isotopes of hydrogen (H), oxygen (O), and sulfur (S), along with tritium and ^{14}C in determining groundwater origins and residence times.

In Tucson, Eastoe et al. (2011) showed that the average level of cosmogenic tritium in rainwater is about 5.3 tritium units (TU; 1 TU = 1 atom of tritium per 10^{18} atoms of hydrogen). Similar levels have been observed in short-term datasets from other stations in southern Arizona (Eastoe et al. 2011). The half-life of tritium is 12.32 years (Lucas and Unterweger 2000); thus, pre-bomb tritium has now decayed to less than the level of detection in the University of Arizona laboratory, 0.6 - 0.7 TU. Bomb tritium peaked in 1963-1964 at about 1,000 TU (annual average) and is still present in aquifers recharged with rainwater since about 1955.

The half-life of ^{14}C is 5,730 years (Godwin 1962), so that ^{14}C measurements enable estimation of water ages up to about 20,000 years. Pre-bomb levels of ^{14}C were near 100 percent modern carbon (pMC), and at the culmination of the atmospheric testing bomb peak (1963-1964), levels near 180 pMC were reached (Burchuladze et al. 1989). ^{14}C can be measured in dissolved inorganic carbon (DIC) species in groundwater. The carbon comes from two sources: carbon dioxide (CO_2) gas in soil or near-surface sediment through which the recharging water passes, and rock calcite. Soil gas has ^{14}C content near that of plant matter in equilibrium with the atmosphere. In southern Arizona, plant matter ^{14}C content had fallen to about 102 pMC by 2002 (Eastoe unpublished data). Accurate age dating using ^{14}C commonly requires correction for the addition of rock carbon containing no ^{14}C (see Methods).

Data Sources and Methods

Water Sample Sites

After reviewing well-log data (Arizona Department of Water Resources 2019d), a list of priority wells, mainly private domestic wells, was identified and access to the wells was requested from community members. Selection criteria included representative spatial distribution and depth, along with feasibility of access. Well depths ranged between 36 and 87 m below land surface. Seven wells were sampled during our initial assessment in 2009 and nine were sampled in late 2015. A surface-water sample was collected from Arivaca Lake in 2015. Sampling sites are shown in Figure 1. Measurements of stable isotopes (O, H, and C) and radioactive isotopes (tritium and ^{14}C) were carried out.

The 2015 sampling provided a unique opportunity to identify recent recharge. Isotope data for Tucson rain during the period August 25, 2014 to January 31, 2015 contained unusually low amount-weighted mean values of $\delta^{18}O$ and $\delta^{2}H$ (Eastoe 2016). During this period, 311 mm of rain fell at Arivaca Post Office. The unusual precipitation was, in part, associated with hurricanes Marie, Norbert, Odile, and Simon. Groundwater reflecting this isotope signature would indicate recharge from these cyclonic storms.

Field Hydrological Data

Monthly water use, depth to groundwater, and volunteer metering data have been collected and maintained by Pima County and the community for several years (Fonseca 2008), but pumping data from across the study area were insufficient to address the effect of pumping on water levels.

Daily depth-to-groundwater data were obtained from Arivaca volunteers using an automated Level Troll data logger to monitor five groundwater wells made available by local residents; results from two wells (sites shown in Figure 1) are given here. Volunteer citizen scientist measurements began in March 2007 and terminated in late 2014. Wells RC-3 and W1 were chosen to analyze connections between climate and groundwater because they are farthest from known high-production wells.

Precipitation data were obtained from two sites in Arivaca (Figure 1): the National

Weather Service (NWS) Cooperative Observer Program (Coop) station 1E (National Ocean and Atmosphere Administration 2019) for the period August 1, 2005 to February 28, 2010, and a Rainlog observation site for 2014-2015 (Rainlog 2019). Monthly precipitation data were obtained from Western Regional Climate Center (2019) for the Arivaca 1E station and four Coop stations near Arivaca: The University of Arizona in Tucson, Anvil Ranch, Tumacocori National Monument, and Nogales.

While these records represent the best available high-resolution precipitation data for the Arivaca area, they are not without blemishes. The Arivaca Coop station did not record temperature measurements, and weekend precipitation was recorded on the following Monday. To compensate, average monthly temperatures for Arivaca were obtained from interpolated data generated by the Parameter-elevation Regressions on Independent Slopes Model (PRISM) from nearby monitoring stations. PRISM generates climate data for a 4 x 4 km grid covering the continental United States (Westmap 2019).

Evapotranspiration (ET) data — which are used to measure changes in ET— were obtained from the closest station (AZMET 2019) in Marana, Arizona, 96 km northwest of Arivaca.

Isotope Analytical Methods

Isotope measurements were undertaken at the Environmental Isotope Laboratory, University of Arizona. Stable O, H, and C isotopes were measured by isotope ratio mass spectrometry. The results are expressed using δ-notation, e.g.:

$$\delta 2H = \left(\frac{R(sample)}{R(standard)} - 1\right) * 1000 ‰$$

where R = $^{2}H/^{1}H$ and the standard is Vienna Standard Mean Ocean Water (VSMOW). The definitions of $\delta^{18}O$ and $\delta^{13}C$ are analogous, with standards VSMOW for O, and VPDB for C. Tritium and ^{14}C were measured by liquid scintillation counting. Results are expressed as TU and pMC, respectively. Details of preparation techniques, instrumentation, analytical precision, and calibration may be found at University of Arizona Geosciences (2019).

Correction of Carbon-14 Data

The raw data were corrected using $\delta^{13}C$ measurements of DIC, as outlined by Clark and Fritz (1997). Additional information required for the correction calculation included 1) an average value of $\delta^{13}C$ in rock calcite, assumed to be -1‰ as in Tucson Basin sediments (Eastoe unpublished data), and 2) an average $\delta^{13}C$ value for soil CO_2, assumed to be -19.9‰, representing decay of organic matter of which 25% originated as C_4 and 75% as C_3 plant material.

Statistics

Linear regressions of time-series data were calculated using Excel software.

Results

Climatology

Arivaca received an average of 467 mm of precipitation per year between 1956 and 2018. July and August experience the most precipitation, averaging 105-107 mm per month (Figure 2).

Seasonal precipitation has exhibited large interannual variability since 1955, particularly during the June - September period (Figure 4). Over this period, the data suggest increasing precipitation for the months July through September, but neither of the trends in Figure 4 is significant at >95% confidence level ($p \leq 0.05$). Seasonal temperatures show slight warming trends between 1955 and 2018. Winter temperatures have increased about 0.14°C per decade and summer (monsoon season) temperatures increased about 0.13°C per decade. The changes over time, although small, are statistically significant (Figure 5).

Evapotranspiration is greatest between May and September and least between December and February. Evapotranspiration measured between 2007 and 2010 at Marana exceeded average Arivaca precipitation (1955-2018) in all but three months (Figure 6).

Climate Change

Over coming decades, temperatures are projected to increase across the southwest U.S., while precipitation is expected to decrease. Rainfall predictions have large uncertainties, but most

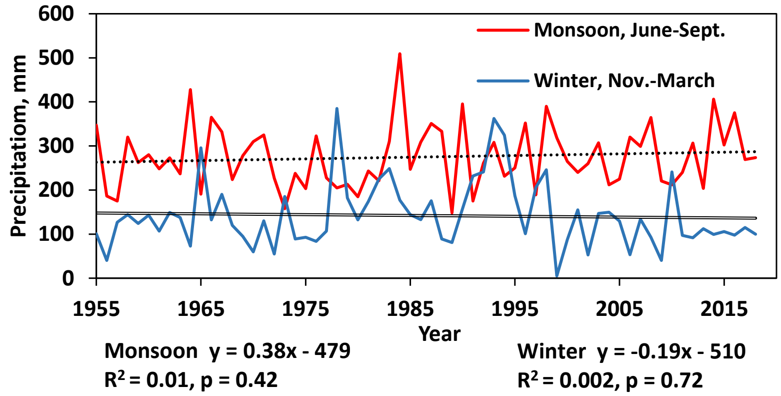

Figure 4. Seasonal variation in precipitation since 1955, presented as totals for the summer monsoon (June-September) and winter (November-March).

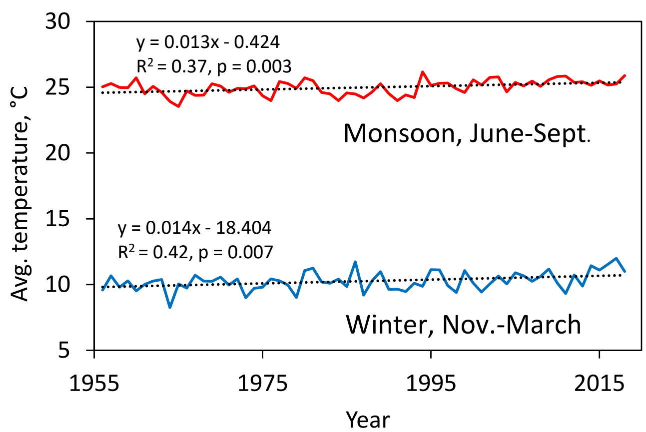

Figure 5. Seasonal temperature variation since 1955, presented as averages for the summer monsoon (June-September) and winter (November-March).

down-scaling from global models has converged with relatively high confidence on a drying trend over Arizona during winter and spring (Seager et al. 2007; United States Global Change Research Program 2009, 2017) as the winter jet stream retreats northward (Lu et al. 2007). Precipitation projections for summer and fall are less clear because the North American monsoon and tropical cyclonic weather systems have not yet been sufficiently characterized (United States Global Climate Research Program 2017). The current drought had not led to perceptible long-term decline in summer (June-September) precipitation by 2018 (Figure 4).

Temperature increases are predicted during all seasons and are expected to be greatest during the summer season. Summer increases may exceed 2 to 3 °C by 2050, driving higher evapotranspiration rates and lower recharge rates, especially in areas like Arivaca where most recharge appears to occur during the summer monsoon season (see below).

Groundwater Hydrographs

Groundwater, as measured by citizen scientist volunteers, fluctuated from 1.5 to 10 m below land surface during the period of study (Conway, pers. comm. 2019). Results presented here are for site RC3 (in streambed alluvium at the basin outlet; Figure 1), where groundwater levels increased during two of three monsoon seasons and all three winter seasons over the original study period (Figure 7A). In the summer of 2007, for example,

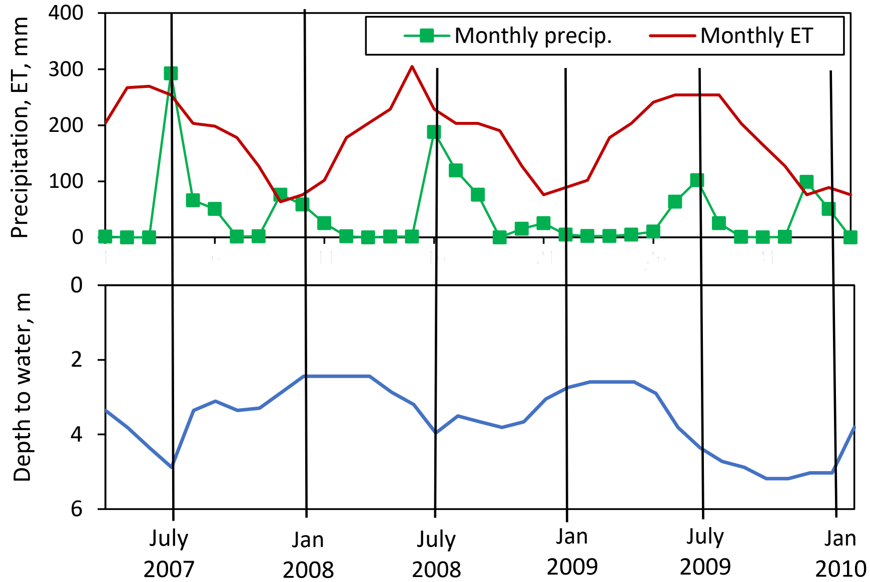

Figure 6. Relationship of water levels at site RC3 to summer and winter rains (measured in Arivaca) and evapotranspiration (measured at Marana, Figure 1) over three years.

several storms in July caused groundwater to rise about 1.5 m. The general pattern during the study period was groundwater rebound during both rainy seasons and decline during the drier spring and fall. A detailed comparison of groundwater levels in 2007 and 2008 at RC3 with individual monsoon rain events (Figure 7A) showed that groundwater levels rose only after at least 75 to 100 mm of rain had fallen within a 15-day period (an arbitrary choice of period, but one that appears to encompass groups of heavy rains in the examples given). In 2009, the monsoon was delayed and no comparable change in groundwater level was observed.

For the 2014 monsoon and subsequent tropical cyclonic rain, the hydrograph is from well W1 in the cienega, close to the basin outlet (Conway, pers. comm. 2019), where groundwater levels rose sharply early in the monsoon, fell during a period of tropical cyclonic rain, and rebounded once again in the winter (Figure 7B). Rainfall data in Figure 7 are from Rainlog (2019).

Stable O and H Isotopes

Isotope data are listed in Table 1 and plotted in Figure 8 alongside amount-weighted means for seasonal precipitation based on data for the Tucson Basin (Eastoe and Dettman 2016). The means are adjusted to 1,150 masl, the average elevation of Arivaca Basin, using isotope altitude gradients from Wright (2001). Following Eastoe and Dettman (2016), summer in this context is considered to be June to October, and winter, November to May. The precipitation data are represented in three ways: 1) long-term (1982-2012) seasonal means defining a local meteoric water line (LMWL) (Eastoe and Dettman 2016); 2) long-term means for summer and winter including only the wettest 30% of months in each season - this choice reflecting the patterns of isotope data in neighboring alluvial basins in which most groundwater isotope data fall on a modified LMWL (Eastoe and Towne 2018), shown as LMWL (wettest 30%) in Figure 8; and 3) amount-weighted means for individual seasons as labeled on Figure 8, with summer 2014 divided into monsoonal (July to mid-August) and tropical cyclonic (mid-August to October) sub-seasons. The means for the tropical cyclonic sub-season and the following winter are identical. Mean values of $\delta^{18}O$ and $\delta^{2}H$ from mid-August 2014 to February 2015 were about -11.8 and -88‰, respectively, significantly lower than the long-term winter means (Figure 8).

The 2009 groundwater data plot in a single group near the summer mean for either the LMWL or LMWL (wettest 30%) (Figure 8). In 2015, most groundwater data plotted in a field to the right of

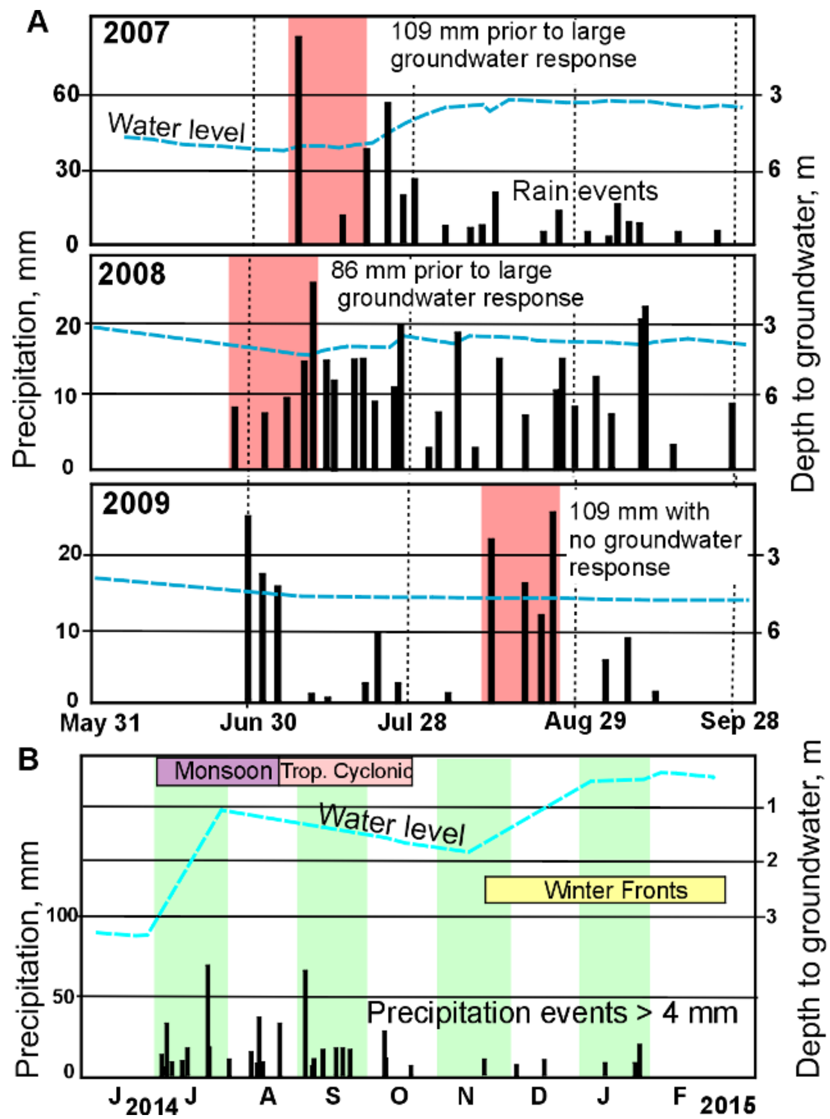

Figure 7. A) Response of water levels at site RC3 to monsoon rain events, 2007 to 2009; black bars represent individual precipitation events, and orange rectangles highlight intervals of heavy precipitation, as labeled. B) Response of water levels at site W1 to monsoon, tropical cyclonic, and winter-frontal rain events in 2014-2015. Black bars represent individual precipitation events >4 mm. Green and white shading indicates months.

the 2009 data; four of the well samples in 2009 had changed measurably in $\delta^{18}O$ and $\delta^{2}H$ (Table 1). Groundwater sampled in 2015 plots near the monsoon-2014 mean. The shift in values of $\delta^{18}O$ and $\delta^{2}H$ between 2009 and 2015 corresponds to the difference in seasonal means for the monsoon in 2008 and 2014. The data for PW9 plot apart from the main data group of 2015, in the direction of the winter (2014-2015) and tropical cyclonic (2014) means. The sample taken from Arivaca Lake in 2015 has $\delta^{18}O$ and $\delta^{2}H$ values of -4.0 and -46‰, respectively, and is highly evaporated. Assuming an evaporation trend of slope 4, typical for southern Arizona (Eastoe and Towne 2018), this water originated as precipitation with a bulk $\delta^{18}O$ value near -10‰.

Tritium

Most of the samples contained 0.8 to 1.2 TU (5.3 TU was measured at PW5 and < 0.5 TU at PW3). The measurements can be compared with the long-term weighted mean tritium content, 5.3 TU, in

Table 1. Isotope Data.

Site	Type	δ^{18}O (‰) 2009	δD (‰) 2009	δ^{18}O (‰) 2015	δD (‰) 2015	δ^{13}C (‰) 2009	Tritium (TU) 2009	C-14 (pMC) 2009	C-14 (pMC corrected[b])	Age (years)
CC	GW	-7.1	-52	-7.0	-52	-8.6	1.2	66.3	115	post-bomb
PW1[a]	GW	-7.3	-49	-6.9	-50	-7.1	1.1	51.2	111	post-bomb
PW2[a]	GW	-7.5	-50	-7.1	-52	-9.4	1	57.0	90	850
PW3[a]	GW	-6.9	-50	-6.9	-53	-4.7	<0.5	74.1	264[c]	invalid
PW4[a]	GW	-6.9	-50	-6.6	-52	-7.3	0.9	53.5	112	post-bomb
PW5	GW	-7.5	-51			-8.6	5.3	99.6	173	post-bomb
PW6	GW	-7.2	-50	-7.1	-52	-7.1	0.8	49.4	107	post-bomb
PW7	GW			-6.7	-51					
PW8	GW			-6.5	-45					
PW9	GW			-8.4	-60					
Arivaca Lake	SW			-4.0	-46					

Note: PW = private well; GW = groundwater; SW = surface water
[a]Wells that changed in isotope compsition from 2009 to 2015.
[b]Corrected using a carbon ratio of C_3:C_4 = 3:1 in soil gas; and δ^{13}C = -1‰ in sedimentary carbonate.
[c]Invalid result; higher than peak bomb pulse in atmosphere.

Tucson rain. Tritium in Tucson precipitation since 1992 had decayed to 1.8 TU or higher by 2009, and Tucson precipitation that fell between 1970 and 1992 had decayed to about 1.8 TU by 2009 (Eastoe et al. 2011). The Arivaca samples, therefore, are most likely mixtures of post-1955 recharge with pre-1955 recharge, except at PW3, where pre-1955 recharge predominated, and at PW5, which is adjacent to Cedar Creek and appears to have received recharge of meteoric water that underwent little radioactive decay since infiltration; if bulk infiltration in this case contained 5.3 TU, the precipitation in question fell since about 2007.

Carbon-14

The ^{14}C content in groundwater ranges from 49 to 100 pMC (Table 1). Corresponding corrected values range from 90 to 173 pMC. The corrected ^{14}C content at PW3, 264 pMC, is invalid, indicating incorrect assumptions in the correction method in that case. The corrected ^{14}C data are approximate but suggest groundwater only a few decades old. The corrected ^{14}C ages are broadly similar to the tritium ages; both are consistent with mixtures of pre-bomb (TU below detection at sampling, 95 to 100 pMC) with post-bomb (TU > 1.8 at sampling, pMC > 100) recharge.

Discussion

Hydrographs

In addition to total precipitation, the season, magnitude, frequency, and duration of precipitation events all seem to influence the character of the groundwater response. In southern Arizona, such factors are reflected in the isotope composition of groundwater, which results from recharge during wetter months (Eastoe and Towne 2018).

The 2007 and 2008 monsoon seasons produced water level rises at site RC3, while well water levels declined in the 2009 monsoon (Figure 7A). In 2007, groundwater rose after 109 mm of rain had fallen in a 15-day period; in 2008, groundwater began rising after 86 mm had fallen in a 15-day

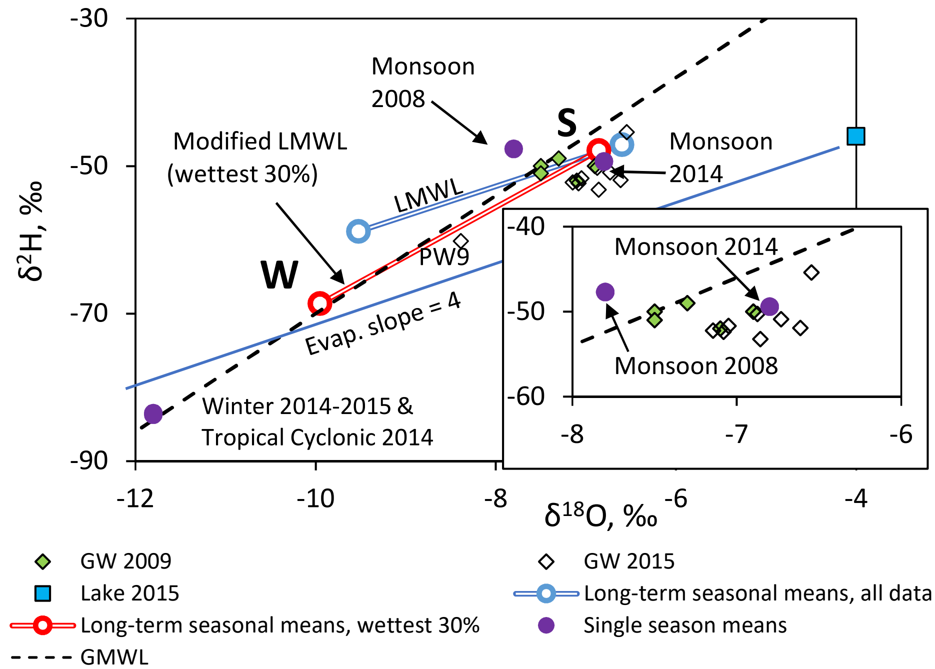

Figure 8. Plot of δ^2H vs. $\delta^{18}O$, showing: 1) data for Arivaca groundwater (GW) sampled in 2009 and 2015 - detail in the inset; 2) long-term seasonal amount-weighted averages for rain at 1150 masl, based on all data from Tucson Basin, 1981-2012 (Eastoe and Dettman 2016) with altitude correction (Eastoe et al. 2004) - linked by a local meteoric water line (LMWL); 3) long-term seasonal amount-weighted averages for rain at 1150 masl, based on data for the wettest 30% of months from Tucson Basin, 1981-2012 (Eastoe and Dettman 2016; Eastoe and Towne 2018) with altitude correction (Eastoe et al. 2004) - linked by a modified local meteoric water line, (Modified LMWL wettest 30%); 4) single-season amount-weighted means for the monsoon (July-Aug.) 2014, tropical cyclonic rain (Aug.-Oct. 2014) and winter (Nov. 2014-Feb. 2015) - note that tropical cyclonic and winter points are identical; and 5) surface water from Arivaca Lake sampled in 2015, with a proposed evaporation trend of slope 4. GMWL = global meteoric water line. W = winter; S = summer.

period. These observations suggest that storm intensity and frequency are important factors, and under favorable conditions create a saturated soil or streambed horizon that can effectively transmit water from the surface to the water table. Because rainfall frequency was higher in 2008 than in 2007, less total rainfall was needed in 2008 before recharge occurred (Figure 7A). After protracted dry weather, as when precipitation was delayed during the 2009 monsoon season, initial rainwater is unable to infiltrate to the aquifer through dry soil or through ephemeral streambeds in which evapotranspiration may intercept recharge. The 2014 monsoon produced a water level rise at W1, but a comparable amount and frequency of rain from tropical cyclonic systems did not, perhaps because the saturated soils allowed for runoff (Figure 7B).

Isotope Data

The $\delta^{18}O$ and δ^2H data suggest that summer precipitation strongly dominates recharge in Arivaca Basin. June through October precipitation accounts for about 66% of annual precipitation (Figure 2). The isotope data indicate a summer contribution of 75% or more to recharge, relative to the LMWL for all precipitation data, or the modified LMWL for the wettest 30% months, or individual seasonal mean data (Figure 8). The difference between the main groups of $\delta^{18}O$ and δ^2H groundwater data for 2009 and 2015 suggests a rapid response to changes in monsoon precipitation isotopes, but not to tropical cyclone or winter rain. Only one site, PW9, a well 46 m deep situated in a small wash in which the owner had installed several gabions, showed a large shift towards the more negative $\delta^{18}O$ and δ^2H values of tropical cyclone isotope precipitation.

The isotope data indicate very young groundwater in Arivaca Basin. The ^{14}C and tritium data are consistent with bulk groundwater ages of decades rather than years as suggested by the rapid shift in $\delta^{18}O$ and $\delta^{2}H$ data between 2009 and 2015. The apparent inconsistency may reflect the combination of waters of different age in our samples or a strong recharge event just prior to the 2015 sampling but not prior to the 2009 sampling.

Relationship of Isotope and Hydrograph Data

The hydrograph observations, indicating both summer and winter rebound of groundwater, appear to differ from the stable isotope data, which indicate mainly summer recharge. The hydrograph wells are located at the basin outlet or near the basin axis (Figure 1) where riparian vegetation is well-developed along Arivaca and Cedar Creeks. In these areas, summer recharge may predominate, as indicated by isotope data. Transpiration also potentially controls water levels, however, when transpiration ceases in winter months, water levels may rebound with or without winter recharge, in response to the removal of vegetation demand for water. Isotope data, not available in this study for any of the hydrograph wells, might elucidate winter rebound of water levels.

Community Involvement

While detailed studies of water budgets are beyond the funding capability of small communities like Arivaca, rapid assessment of groundwater character and connection to climate has the potential to offer valuable information to local residents. In the present case, a relatively small isotope study (constrained by limited funding) coupled with climate data and volunteer measurements of water levels has produced a significant increase in local understanding of water resources. A major advantage of this strategy is that it engages local participants in the research from the beginning. Making use of community volunteers can facilitate data collection and augment the limited research resources and, perhaps most important, can catalyze community action. Anecdotal evidence suggests that those community members who participated in the research through volunteering their well, collecting well data, and attending information meetings became better informed about their water resources and the management of water in general. They also appear to have developed positive attitudes toward managing for sustainability and a greater sense of their capacity to manage their water.

Notably, at least one landowner (well PW9) installed gabions across his property following a workshop on surface water harvesting in the early 2000s. The owner built the gabions in order to slow surface water flow and enhance groundwater recharge. Well PW9 was not sampled in 2009. The 2015 resampling detected the isotope signature of August 2014 to February 2015 rain at this site, indicating enhanced recharge that had not occurred in areas without gabions, and demonstrating the potential for enhancing recharge elsewhere in the basin.

Access to private wells was critical to this study. Such access is commonly difficult to obtain in small, rural communities. This study demonstrates the benefits to well-owners of making groundwater samples available for analysis.

Regional Implications

The findings of this study suggest that low-cost assessments can produce useful results in small communities that rely on groundwater in semiarid to arid regions. A similar exercise in Cascabel, Arizona, 120 km northeast of Arivaca, led to an improved comprehension of groundwater ages and recognition of the warning signs of groundwater depletion in response to drought (Eastoe and Clark 2018). A global synthesis of the findings from 140 recharge study areas in semiarid and arid regions found that recharge may be enhanced through management of land use activities (Scanlon et al. 2006). Land use practices, such as the installation of gabions for storm-water management will enhance groundwater recharge. In addition, recognition that local aquifers are replenished annually in normal years can lead to management strategies that enable individuals to balance withdrawals with deposits.

Recommendations

Monitoring data (i.e., well level and precipitation data) collected by citizens of Arivaca were critical in assessing local conditions, as well as filling in gaps in state and federal monitoring networks.

Maintenance of the volunteer monitoring system will further the understanding of the vulnerability of the Arivaca aquifer system to climate variability. Other rural communities in Arizona would profit equally from similar citizen involvement. Researchers and communities undertaking future aquifer assessments of this kind may learn from the present example. The data presented here are from a variety of sources, and do not in all cases match in time. Similar studies would profit from better coordination of data collection, for instance in measuring time-series of isotope data from hydrograph wells.

Conclusions

Groundwater in the Arivaca aquifer is young, with residence times of decades or less. Summer recharge predominates. Recharge is controlled not only by season, but also by the frequency and size of rain events. Winter rebound of groundwater appears to be linked to seasonal decrease in evapotranspiration. The aquifer system is vulnerable to extended drought and delays in the onset of summer rains, or to a warming climate that leads to increased summer evapotranspiration. Implementation of storm-water management options to capture water for groundwater recharge has been shown to be an effective management option.

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References

Adams, D.K. and A.C. Comrie. 1997. The North American monsoon. *Bulletin of the American Meteorological Society* 78(10): 2197-2213.

Arizona Department of Water Resources. 2019a. Drought Status Update. Available at: https://new.azwater.gov/drought/drought-status. Accessed September 25, 2019.

Arizona Department of Water Resources. 2019b. Inter-Agency Drought Group Recommends Continuation of "Drought Declaration." Available at: https://new.azwater.gov/news/articles/2019-15-05. Accessed September 25, 2019.

Arizona Department of Water Resources. 2019c. Tucson Active Management Area. Available at: https://new.azwater.gov/ama/tucson. Accessed September 25, 2019.

Arizona Department of Water Resources. 2019d. Registry of Wells in Arizona (Wells 55). Available at: https://gisweb2.azwater.gov/wellReg. Accessed September 25, 2019.

Arizona State Legislature. 2019. Management Goals for Active Management Areas, 45-562. Available at: https://www.azleg.gov/viewdocument/?docName=https://www.azleg.gov/ars/45/00562.htm. Accessed September 25, 2019.

Artiola, J.F. and K. Uhlman. 2009. Arizona Well Owners' Guide to Water Supply. University of Arizona, College of Agricultural and Life Sciences publication # AZ1485. Available at: https://wrrc.arizona.edu/publications/arizona-well-owners-guide-water-supply. Accessed September 25, 2019.

AZMET. 2019. The Arizona Meteorological Network. Available at: https://cals.arizona.edu/azmet/az-docs.htm. Accessed September 25, 2019.

Baillie, M.N., J.F. Hogan, B. Ekwurzel, A.K. Wahi, and C.J. Eastoe. 2007. Quantifying water sources to a semiarid riparian ecosystem, San Pedro River, Arizona. *Journal of Geophysical Research* 112: G03S02. DOI: 10.1029/2006JG000263.

Burchuladze, A.A., M. Chudý, I.V. Eristavi, S.V. Pagava, P. Povinec, A. Sivo, and G.I. Togonidze. 1989. Anthropogenic ^{14}C variations in atmospheric CO_2 and wines. *Radiocarbon* 31(3): 771-776.

Clark, I. and P. Fritz. 1997. *Environmental Isotopes in Hydrogeology*. CRC Press LLC, Lewis Publishers, Boca Raton, Florida.

Coes, A.L and D.R. Pool. 2007. Ephemeral-stream channel and basin-floor infiltration and recharge in the Sierra Vista subwatershed of the Upper San Pedro Basin, southeastern Arizona. In: *Ground-water Recharge in the Arid and Semiarid Southwestern United States* (U.S. Geological Survey Professional Paper 1703-J), D.A. Stonestrom, J. Constantz, P.A. Ferre, and S.A. Leake (Eds.). U.S. Geological Survey, Arizona, pp. 253-311.

Constantz, J., K.S. Adams, and D.A. Stonestrom. 2007. Overview of ground-water recharge study sites. In: *Ground-water Recharge in the Arid and Semiarid Southwestern United States* (U.S. Geological Survey Professional Paper 1703-C), D.A. Stonestrom, J. Constantz, P.A. Ferre, and S.A. Leake (Eds.). U.S. Geological Survey, Arizona, pp. 61-82.

Cook, E.R., C.A. Woodhouse, C.M. Eakin, D.M. Meko, and D.W. Stahle. 2004. Long-term aridity changes in the western United States. *Science* 306(5698): 1015-1018.

Diem, J.E. and D.P. Brown. 2006. Tropospheric moisture and monsoonal rainfall over the southwestern United States. *Journal of Geophysical Research* 111: D16112. Available at: https://doi.org/10.1029/2005JD006836. Accessed September 25, 2019.

Earman, S. and M. Dettinger. 2011. Potential impacts of climate change on groundwater resources – A global review. *Journal of Water and Climate Change* 2(4): 213-229.

Eastoe, C.J. 2016. Stable O, H isotopes in Tucson rain associated with hurricanes and tropical depressions, 2013-2016. Available at: https://www.geo.arizona.edu/sites/www.geo.arizona.edu/files/Hurricanes%202013-2016.pdf. Accessed September 25, 2019.

Eastoe, C.J. and B. Clark. 2018. Understanding the water resources of a small rural community: Citizen science in Cascabel, Arizona. *Journal of Contemporary Water Research and Education* 164: 19-40.

Eastoe, C.J. and D.L. Dettman. 2016. Isotope amount effects in hydrologic and climate reconstructions of monsoon climates: Implications of some long-term data sets for precipitation. *Chemical Geology* 430: 78-89.

Eastoe, C.J., A. Gu, and A. Long. 2004. The origins, ages and flow paths of groundwater in Tucson Basin: Results of a study of multiple isotope systems. In: *Groundwater Recharge in a Desert Environment: The Southwestern United States*. Water Science and Applications Series, vol. 9, J.F. Hogan, F.M. Phillips, and B.R. Scanlon (Eds.). American Geophysical Union, Washington, D.C., pp. 217-234.

Eastoe, C.J. and D. Towne. 2018. Regional zonation of groundwater recharge mechanisms in alluvial basins of Arizona: Interpretation of isotope mapping. *Journal of Geochemical Exploration* 194: 134-145.

Eastoe, C.J., C.J. Watts, M. Ploughe, and W.E. Wright. 2011. Future use of tritium in mapping pre-bomb groundwater volumes. *Ground Water* 50: 87-93.

Fonseca, J. 2008. *Aquifer Monitoring for Groundwater-Dependent Ecosystems, Pima County, Arizona*. Pima County Natural Resources, Parks and Recreation, Tucson, Arizona. Available at: https://globalrangelands.org/sites/globalrangelands.org/files/dlio/37171/Aquifer_Report_042808.pdf. Accessed September 25, 2019.

Friedrich, K., R.L. Grossman, J. Huntington, P.D. Blanken, J. Lenters, K.L.D Holman, et al. 2018. Reservoir evaporation in the western United States: Current science, challenges, and future needs. *Bulletin of the American Meteorological Society* 99(1): 167-187.

Glenn, E.P., R.L. Scott, U. Nguyen, and P.L. Nagler. 2015. Wide-area ratios of evapotranspiration to precipitation in monsoon-dependent semiarid vegetation communities. *Journal of Arid Environments* 117: 84-95.

Godwin, H. 1962. Half-life of radiocarbon. *Nature* 195(4845): 984.

Goodrich, D.C., D.G. Williams, C.L. Unkrich, J.F. Hogan, R.L. Scott, K.R. Hultine, D. Pool, A.L. Coes, and S. Miller. 2004. Comparison of methods to estimate ephemeral channel recharge, Walnut Gulch, San Pedro River Basin, Arizona. In: *Groundwater Recharge in a Desert Environment: The Southwestern United States*. Water Science and Applications Series, vol. 9, J.F. Hogan, F.M. Phillips, and B.R. Scanlon (Eds.). American Geophysical Union, Washington, D.C., pp. 77-99.

Green, T.R., M. Taniguchi, H. Kooi, J.J. Gurdak, D.M. Allen, K.M. Hiscock, H. Treidel, and A. Aureli. 2011. Beneath the surface of global change: Impacts of climate change on groundwater. *Journal of Hydrology* 405(3): 532-560.

Griffin, D. and K.J. Anchukaitis. 2014. How unusual is the 2012-2014 California drought? *Geophysical Research Letters* 41(24): 9017-9023.

Griffin, D., C.A. Woodhouse, D.M. Meko, D.W. Stahle, H.L. Faultisch, C. Carillo, R. Touchan, C.L. Castroand, and S.W. Leavitt. 2013. North American monsoon precipitation reconstructed from tree-ring latewood. *Geophysical Research Letters* 40(5): 954-958.

Gungle, B.G., J.B. Callegary, N.V. Paretti, J.R. Kennedy, C.J. Eastoe, D.S. Turner, J.E. Dickinson, L.R. Levick, and Z.P. Sugg. 2016. *Hydrological Conditions and Evaluation of Sustainable Groundwater use in the Sierra Vista Subwatershed, Upper San Pedro Basin, Southeastern Arizona*. U.S. Geological Survey Scientific Investigation Report 2016–5114. Available at: http://dx.doi.org/10.3133/sir20165114. Accessed September 25, 2019.

Hirschboeck, K.K. and D.M. Meko. 2005. A Tree-ring Based Assessment of Synchronous Extreme Streamflow Episodes in the Upper Colorado & Salt-Verde-Tonto River Basins. The University of Arizona, Tucson, Arizona. Available at: https://kkh.ltrr.arizona.edu/kkh/SRP/SRP.LTRR.Press.info.05.slides.pdf. Accessed September 25, 2019.

Hogan, J.F., F.M. Phillips, and B.R. Scanlon (Eds.). 2004. *Groundwater Recharge in a Desert Environment: The Southwestern United States*. Water Science and Applications Series, vol. 9, American Geophysical Union, Washington, D.C.

Hopkins, C., J. McIntosh, J. Dickinson, C. Eastoe, and T. Meixner. 2014. Evaluation of the importance of clay confining units on groundwater flow in alluvial basins using solute and isotope tracers. *Hydrogeology Journal* 22: 829-849.

Lu, J., G.A. Vecchi, and T. Reichler. 2007. Expansion of the Hadley cell under global warming. *Geophysical Research Letters* 34(6): L06805. Available at: https://doi.org/10.1029/2006GL028443. Accessed September 25, 2019.

Lucas, L.L. and M.P. Unterweger. 2000. Comprehensive review and critical evaluation of the half-life of tritium. *Journal of Research of the National Institute of Standards and Technology* 105(4): 541-549.

MacDonald, G.M. 2010. Water, climate change, and sustainability in the southwest. *Proceedings of the National Academy of Sciences* 107(50): 21256-21262.

Michaud, J.D., B.A. Avine, and O.C. Penalba. 1995. Spatial and elevational variations of summer rainfall in the southwestern United States. *Journal of Applied Meteorology* 34(12): 2689-2703.

Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer. 2008. Climate change. Stationarity is dead: Whither water management? *Science* 319(5863): 573-574.

Morino, K.A. 2008. Using false rings to reconstruct local drought severity patterns on a semiarid river. Unpublished Ph.D. Dissertation, The University of Arizona, Tucson, Arizona.

National Ocean and Atmospheric Administration. 2019. Daily Summaries Station Details, Arivaca, AZ. Available at: https://www.ncdc.noaa.gov/cdo-web/datasets/GHCND/stations/GHCND:USC00020380/detail. Accessed September 25, 2019.

Ni, F., T. Cavazos, M.K. Hughes, A.C. Comrie , and G. Funkhouser. 2002. Cool-season precipitation in the southwestern USA since AD 1000: Comparison of linear and nonlinear techniques for reconstruction. *International Journal of Climatology* 22(13): 1645-1662.

Phillips, F.M., L.A. Peeters, M.K. Tansey, and S.N. Davis. 1986. Paleoclimatic inferences from an isotopic investigation of groundwater in the central San Juan Basin, New Mexico. *Quaternary Research* 26(2): 179-183.

Pima Association of Governments. 2006. *Hydrogeologic Assessment of Arivaca.*

Pima County Regional Flood Control District, Tucson, Arizona. Available at: https://www.pagnet.org/Documents/Water/ArivacagwhydroFinal.pdf. Accessed September 25, 2019.

Rainlog. 2019. YTD Gauge Readings. Available at: https://rainlog.org/data/daily/ytd/1350;year=2007; https://rainlog.org/data/daily/ytd/1350;year=2008; https://rainlog.org/data/daily/ytd/1350;year=2009; https://rainlog.org/data/daily/ytd/1350;year=2014; https://rainlog.org/data/daily/ytd/1350;year=2015. Accessed September 25, 2019.

Scanlon, B.R., K.E. Keese, A.L. Flint, L.E. Flint, C.B. Gaye, W.M. Edmunds, and I. Simmers. 2006. Global synthesis of groundwater recharge in semiarid and arid regions. *Hydrological Processes* 20(15): 3335-3370.

Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H.P. Huang, N. Harnik, A. Leetmaa, N.-C. Lau, C. Li, J. Velez, and N. Naik. 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* 316(5828): 1181-1184.

Sheppard, P.R., A.C. Comrie, G.D. Packin, K. Angersbach, and M.K. Hughes. 2002. The climate of the U.S. Southwest. *Climate Research* 21(3): 219-238.

Smalley, R.S. 1983. An isotopic and geochemical investigation of the hydrogeologic and geothermal systems in the Safford Basin, Arizona. Unpublished M.S. Thesis, University of Arizona, Tucson, Arizona.

Stewart, I.T., D.R. Cayan, and M.D. Dettinger. 2005. Changes toward earlier streamflow timing across western North America. *Journal of Climate* 18(8): 1136-1155.

Stonestrom, D.A., J. Constantz, T.P.A. Ferré, and S.A. Leake (Eds.). 2007. *Ground-Water Recharge in the Arid and Semiarid Southwestern United States*, U.S. Geological Survey Professional Paper 1703. Available at: https://pubs.usgs.gov/pp/pp1703/. Accessed September 25, 2019.

Udall, B. and J. Overpeck. 2017. The twenty-first century Colorado River hot drought and implications for the future. *Water Resources Research* 53(3): 2404-2418. Available at: https://doi.org/10.1002/2016WR019638. Accessed September 25, 2019.

Uhlman, K. 2005. Recharge in desert regions around the world. In: *Wiley Encyclopedia - Ground Water,* J. Lehr and J. Keeley (Eds.). John Wiley & Sons, Inc., pp. 72-76.

United States Global Change Research Program. 2009. *Global Climate Change Impacts in the United States*. Available at: https://nca2009.globalchange.gov/. Accessed September 25, 2019.

United States Global Change Research Program. 2017. *Climate Science Special Report: Fourth National Climate Assessment (NCA4), Volume I*. Available at: https://www.globalchange.gov/browse/reports/climate-science-special-report-fourth-national-climate-assessment-nca4-volume-i. Accessed September 25, 2019.

University of Arizona Geosciences. 2019. Environmental Isotope Laboratory Data Repository. Available at: https://www.geo.arizona.edu/node/154. Accessed September 25, 2019.

Weiss, J.L., C.L. Castro, and J.T. Overpeck. 2009. Distinguishing pronounced droughts in the southwestern United States: Seasonality and effects of warmer temperatures. *Journal of Climate* 22: 5918-5932.

Western Regional Climate Center. 2019. Arizona. Available at: http://www.wrcc.dri.edu/summary/Climsmaz.html. Accessed September 25, 2019.

Westmap. 2019. Climate Analysis & Mapping Toolbox. Available at: http://www.cefa.dri.edu/Westmap. Accessed September 25, 2019.

Westwide Drought Tracker. 2019. Available at: https://wrcc.dri.edu/wwdt/time/. Accessed September 25, 2019.

Wright, W.E. 2001. $\delta^{2}H$ and $\delta^{18}O$ in mixed conifer systems in the U.S. Southwest: The potential of $\delta^{18}O$ in Pinus ponderosa tree rings as a natural environmental recorder. Unpublished Ph.D. Dissertation, University of Arizona, Tucson, Arizona.