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# Understanding the Water Resources of a Small Rural Community: Citizen Science in Cascabel, Arizona

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**Abstract:** Cascabel residents have cooperated in assembling and discussing a dataset addressing community concerns about groundwater quality and sustainability of water supply in their reach of the semi-arid San Pedro Valley. Most of the groundwater is drawn from Holocene sediments underlying the pre-entrenchment floodplain of the San Pedro River and similar sediments in major tributaries. Stable O and H isotopes distinguish two main floodplain aquifers: A, containing groundwater derived from the Valley flanks, and B, containing groundwater labeled by the presence of ancient water from a hot-spring system. In aquifer A, unpalatable groundwater containing dissolved ferrous iron and hydrogen sulfide is associated with clay containing buried wetland sediments that supply nutrients for microbial reduction of iron and sulfate. In aquifer B, groundwater is palatable, and static water levels at three locations have generally declined since the early 1990s, probably as a result of natural drainage in the upgradient part of the aquifer. Most groundwater from both aquifers contains measurable tritium, indicating vulnerability to multi-decadal drought.

**Keywords:** *stable isotopes, tritium, static water level, water quality, aquifer vulnerability, drought*

Cascabel is a dispersed community of a few hundred people along the San Pedro River, northwest of Benson and east of Tucson, Arizona, United States. At the time of first contact with the Spanish Empire during the 16th century, this part of the San Pedro Valley was occupied by the Sobaipuri people, who practiced irrigated agriculture, and lived in small towns such as Baicatcán, close to the map location of Cascabel (Latitude 32.2910°, Longitude -110.3794°). The Sobaipuri abandoned the Valley under pressure from Apache raids during the 18th century, and sought refuge in the Santa Cruz Valley to the west (Spicer 1962). By the late 19th century, cattle ranchers had become established in the Valley (Tellman and Huckleberry 2009; Cascabel Community Center 2017). Ranching on semi-arid rangeland and irrigated farming on river bottom land continue to the present, but rangeland ranching faces difficulties with persistent drought. Retired ranch land has been subdivided and occupied by retirees, artists, commuters, and weekend visitors from the rapidly expanding city of Tucson.

Residents of Cascabel depend almost entirely on a groundwater supply drawn from numerous private wells. The number of dwellings is increasing as a result of subdivision, but the amount of irrigated land in the community has declined greatly since the middle of the 20th century. Normally, such a situation would favor the long-term availability of groundwater because agriculture in the area has used far more water than all other users combined (Cordova et al. 2015). However, regional drought conditions since the late 1990s, emerging awareness of pre-historic long-term droughts (e.g., Griffin et al. 2013), and observed static water level (SWL) declines locally in Cascabel, have raised community concerns about the future supply of groundwater. Another concern centers on the highly variable quality of groundwater. The community has therefore expressed interest in developing a better understanding of its water resources.

The Nature Conservancy, with the cooperation of private well owners, has sponsored the monitoring of SWLs by Barbara Clark since 1993. Electrical conductivity (EC) and isotope measurements of groundwater samples provided by members of the community since 2007 have been undertaken by Christopher Eastoe, who has also led community workshops on groundwater origin, age, and quality. This report is a summary of the work undertaken by Clark and Eastoe, placed in the context of recently-published regional geophysical and geohydrological studies (Dickinson et al. 2010a, 2010b; Cordova et al. 2015). The aims of this report are to inform the community about its groundwater resource, in particular addressing groundwater sources and residence times, the origins of unpalatable groundwater, and the causes of changing SWLs.

## Study Area

### Location

This study focuses on a 27 km length of the San Pedro River Valley and the lower reaches of its tributaries, Hot Springs Canyon and Paige Canyon (Figures 1 and 2). The southern limit of the study area is the Benson Narrows, 20 km upstream of the map location of Cascabel (32.2910°, -110.3794°). The altitude of the river channel is 1,010 meters above mean sea level (m amsl) at the Benson Narrows, and 920 m amsl near site 37. The watershed includes surrounding hills at altitudes up to 1,500 m amsl.

### Climate

The climate is semi-arid. The average annual rainfall at valley-bottom station 021330 between 1969 and 2013 was 338 mm/year (13.3 inches/year) (Western Regional Climate Center 2017). However, the average annual rainfall may vary greatly, the range being from 209 to 624 mm (8.2 to 24.6 inches) over the same period. Two wet seasons typically occur: a winter-spring season of orographic rain or snow from Pacific fronts (seasonal average 139 mm), and a summer season of convective precipitation from the North American Monsoon, augmented in some years by early autumn tropical depressions (seasonal average 199 mm).

### Vegetation

Sonoran Desert vegetation (common genera including *Larrea*, *Acacia*, *Opuntia, Cylindropuntia, Carnegia,* and *Yucca*, along with grasses and annuals) is found on dry slopes away from major watercourses. Bottom land along major watercourses supports mesquite scrub and forest (*Prosopis*) that may extend several hundred meters from the active channels. Riparian cottonwood-willow forest (common genera including *Populus, Salix, Baccharis,* and exotic *Tamarix*) forms a discontinuous band up to a few hundred meters wide beside the active river channel, its development depending on availability of shallow groundwater. Much of the original mesquite scrub and riparian forest was cleared for irrigated agriculture during the 20$^{th}$ century; less than 50% of the cleared area remains under irrigation at present.

### Geology and Geomorphology

The geology of the Cascabel area has been described by Drewes (1974), Mark and Goodlin (1985), and Dickinson (1991). Cook et al. (2010) mapped the geomorphology of the San Pedro Valley within 3 km of the river. The present-day regional landscape of hard-rock mountain ranges separated by deep basins filled with unconsolidated to semi-consolidated detritus from the mountains is termed the Basin and Range Province (Fenneman 1931). In southeastern Arizona, the basins and ranges began forming about 15 million years (Ma) ago as a result of tectonic extension of the continental crust (Dickinson 2002). The San Pedro River drains a set of such basins.

Prior to the extension, about 20 Ma ago, sediment eroded from an earlier mountainous terrain was deposited in a series of basins in southern Arizona. In the study area, the sediment consisted of granitic detritus and is termed the San Manuel formation (Dickinson 1991). Between 11 and 5 Ma ago (Miocene and early Pliocene time), an extensional basin that has been named the San Pedro trough (Figure 1) opened within and north of the study area (Dickinson 1991, 2003); the study area corresponds to the narrow southern end of the trough. The southern terminus of the trough was a ridge of Proterozoic granite, still present at the Benson Narrows. Drainage was internal and

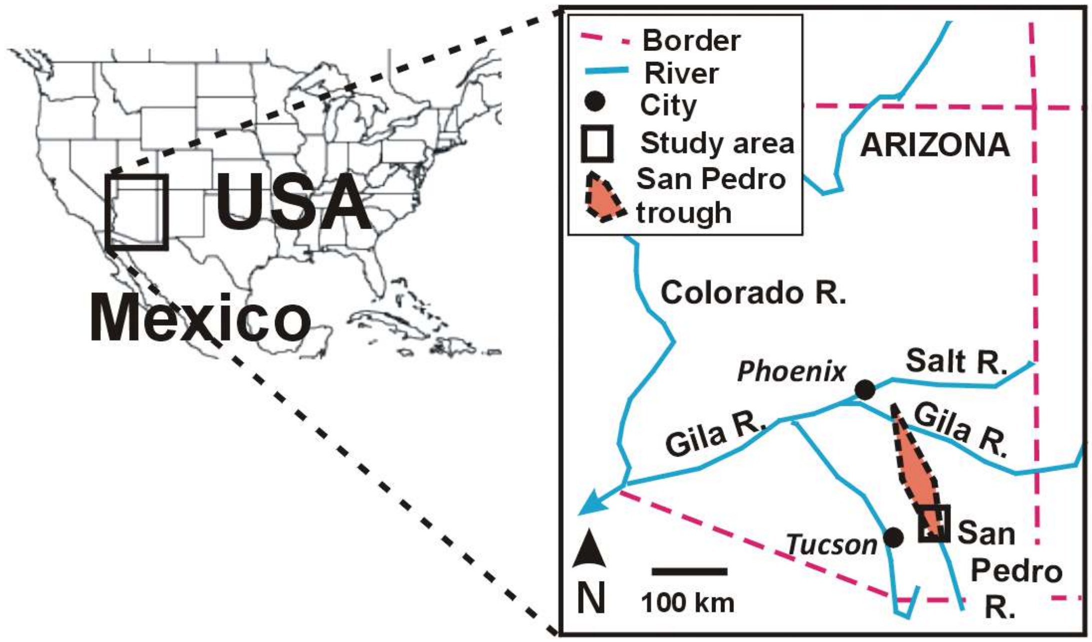


**Figure 1.** Location map showing the present integrated drainage of the Gila River basin.

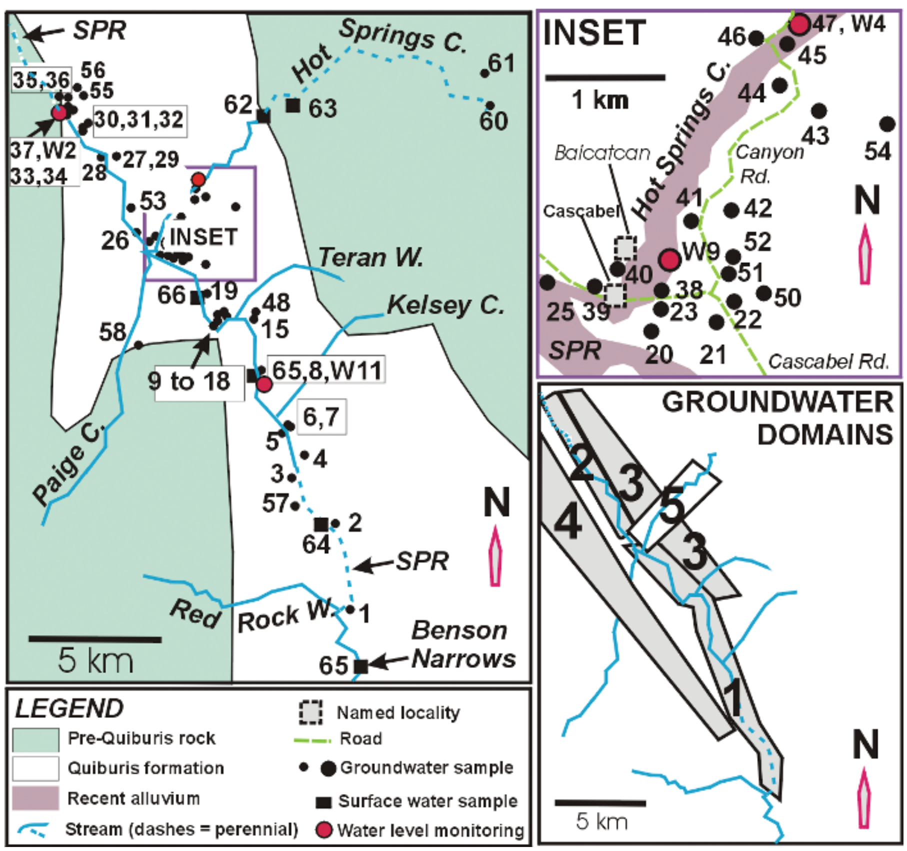


**Figure 2.** Sample sites and geographic features of the study area. Site numbers: simple numbers are groundwater sample sites as listed in Table 2; W-numbers are water-level measurement sites. Abbreviations: SPR = San Pedro River; C = canyon; W = wash.

directed to the north. Sediments filling the San Pedro trough compose the Quiburis formation. In the Cascabel area, the Quiburis formation consists of fluvial conglomerate and sandstone, in contrast to fine-grained lake sediments in the broader, northern end of the trough (Dickinson 1998).

Thick alluvial fans are exposed in cliffs and badlands of semi-consolidated Quiburis formation along the San Pedro River south of Paige Canyon. Consolidation appears to be due to low-temperature hydrothermal circulation. In that area, Quiburis formation outcrop occurs between altitudes of 960 m amsl (the river bed) and 1,200 m amsl (ridge-tops 2 km to the west of the river). Quiburis formation sediment therefore appears to have filled the center of the river valley to a depth of at least 240 m. In the northwestern part of the study area, Quiburis formation is faulted against a tilt-block of the San Manuel formation. At site 37, where the San Pedro River intersects the fault boundary, the San Manuel formation is clay-rich, impermeable to water, and dips 30° SE.

An integrated external drainage system comprising the Gila River, the San Pedro River, and other tributaries (Figure 1) formed during the Pliocene (Dickinson 1991), leading to erosion of much of the Quiburis formation in the study area. In Cascabel, progressive erosion is recorded as a stepped series of Pleistocene (2 Ma and younger) terraces at the confluence of Hot Springs Canyon and the San Pedro River (Cook et al. 2010).

The present course of the river lies entirely within a band of Holocene (< 12,000 years old) river channel sediments, 250 to 1,500 m wide and partly concealed by late Holocene alluvium (Cook et al. 2010). The top surface of these sediments corresponds with the river floodplain that existed prior to the mid-1800s. The sediments fill a trench that was cut into basin-fill sediments since about 20,000 years ago (Huckleberry et al. 2009). Possibly as early as the 1850s in the Cascabel area (Hereford and Betancourt 2009), the river began excavating an arroyo entrenched up to 6 m into the channel sediments. Late 19$^{th}$ century water-course entrenchment is a regional phenomenon (Bryan 1925), and may have been the result of climate change, removal of beavers, overgrazing, or other human activities (Hereford and Betancourt 2009). Waters and Haynes (2001) documented seven cycles of arroyo formation alternating with refilling of the channel since 8,000 years before the present (BP), including six cycles since 4000 years BP that were synchronous across southeastern Arizona. The banks of the present arroyo in Cascabel expose fluvial sand, coarse gravel, and clay-rich beds that may represent wetland or lake deposits. Charcoal from fluvial sediment near site 57 gave radiocarbon ages of 1090 and 1720 years BP (Table 1).

Several drillers' lithologic well-logs are available for the Holocene river-channel sediments (Arizona Department of Water Resources 2017). Clay, readily identified by drillers, was recorded to depths of 30 m below the surface (Figure 3), mainly upstream of Hot Springs Canyon. Sandy lenses may be present within the clay units. Holocene fluvial sediment may be present below the clay units, but cannot be reliably distinguished from Quiburis formation sediments in drill cuttings. We interpret the distribution of clay within the band of river-channel sediments as indicating the presence of a narrow, filled Holocene river valley at least 30 m deeper than the 1880s floodplain. A narrow body of conductive material, interpreted as clay, was detected in an airborne transient electromagnetic survey beneath the river 3 to 8 km north of the Benson Narrows (Dickinson et al. 2010b).

**Hydrology**

The San Pedro River in the study area is ephemeral, except for a reach between sites 1 and 2 with very small perennial flow and an intermittent reach beginning at site 37, where the San Manuel formation forms a shallow sill across the aquifer beneath the river (Figure 2). The flowing reaches have tended to decrease in length since 2007 (The Nature Conservancy 2017). Floods lasting days to weeks occur in the river throughout the Cascabel area in summer and autumn as a result of monsoon or cyclonic rain events. Floodwater has passed through the Benson Narrows every summer between 2008 and 2012, but is rare at other times. No base flow has entered the study area at the Narrows in recent years, as shown by data for the Benson Narrows gauge (United States Geological Survey 2017). Low-volume perennial flow is also present in the hard-rock reaches of Hot Springs Canyon (The Nature Conservancy 2017). Hooker Hot Springs and other nearby hot springs in the

**Table 1.** Radiocarbon dates.

| Lab No. | Site | Material | Latitude ° | Longitude ° | Age (yrs. BP) | $\delta^{13}C$ ‰ | | |
|---|---|---|---|---|---|---|---|---|
| A15773 | SPR, Three Links Ranch 7A | Charcoal | 32.2009 | -110.3149 | 1090 ± 75 | -26.6 | | |
| A15774 | SPR, Three Links Ranch 7D | Charcoal | 32.2009 | -110.3149 | 1720 ± 40 | -26.0 | | |
| **Lab No.** | **Site** | **Material** | **Latitude °** | **Longitude °** | **Uncorrected pMC** | **$\delta^{13}C$ ‰** | **Corrected pMC*** | **Age** |
| A14605 | Site 11 | Groundwater | 32.2614 | -110.3484 | 97.8 | -11.8 | 119.5 | post-bomb |
| A14656 | Site 19 | Groundwater | 32.2687 | -110.3547 | 81.3 | -9.4 | 127.8 | post-bomb |
| A7769 | Site 60, Hooker Hot Springs | Groundwater | 32.3664 | 32.2382 | 15.2 | -12.7 | 17.0 | 14650 yrs BP |

*Using $\delta^{13}C$ values as basis of correction (Clark and Fritz 1997, p. 210), and assuming soil gas $\delta^{13}C$ = -19.9‰. Soil carbonate $\delta^{13}C$ = -1 ‰; BP = before the present; pMC = percent modern carbon.

headwaters of Hot Springs Canyon are a source of base flow in that canyon.

Cordova et al. (2015) considered the groundwater hydrology of the area between the Benson Narrows and Redington (19 km downstream from Cascabel). The Cascabel area makes up less than half of the Benson Narrows-Redington area, and is represented by relatively few measurement points. Cordova et al. (2015) presented contour maps of SWLs in 1940 and 2006-2009 (See Figures 14 and 16 in Cordova et al. 2015) and estimates of water use (See Figure 29, in Cordova et al. 2015). Groundwater occurs in a regional aquifer including the Holocene channel-fill sediments and adjacent parts of the Quiburis formation. Groundwater flows towards the river and northwards beneath the river. Between 1970 and 2010, consumption of water for irrigation decreased from about 1400 to 250 $m^3$/year, while domestic water use increased from about 12 to 20 $m^3$/year. Modeled estimates of the water budget of their study area for 2001-2009 showed an average annual groundwater inflow and outflow of 1380 and 1500 $m^3$/year, respectively, i.e., a net decrease in groundwater storage of 1.8 $hm^3$ per year. Most of the inflow is winter runoff from high mountains to the Valley at Redington; winter inflow is much lower in the Cascabel area. The model estimates include 1.5 $hm^3$ per year of groundwater inflow into the Cascabel area at the Benson Narrows through a postulated connection between deep basin-fill aquifers in the area. The likely presence of a continuous granite ridge across the Valley at river-level in the Benson Narrows (Drewes 1974) does not support such an interpretation, which will be discussed further below.

In the more intensively studied part of the San Pedro Valley south of the Benson Narrows, both Holocene alluvium and underlying basin fill act as aquifers or a single regional (deeper) aquifer, and a perched, shallow riparian aquifer can be distinguished where the river flows over clay-rich beds (Baillie et al. 2007; Huckleberry et al. 2009; MacNish et al. 2009; Hopkins et al. 2014). At Cascabel, the geometry of the aquifers appears to be comparable, and similar, smaller aquifers are present beneath major tributaries such as Hot Springs and Paige Canyons. However, little water is produced from the regional aquifer more than

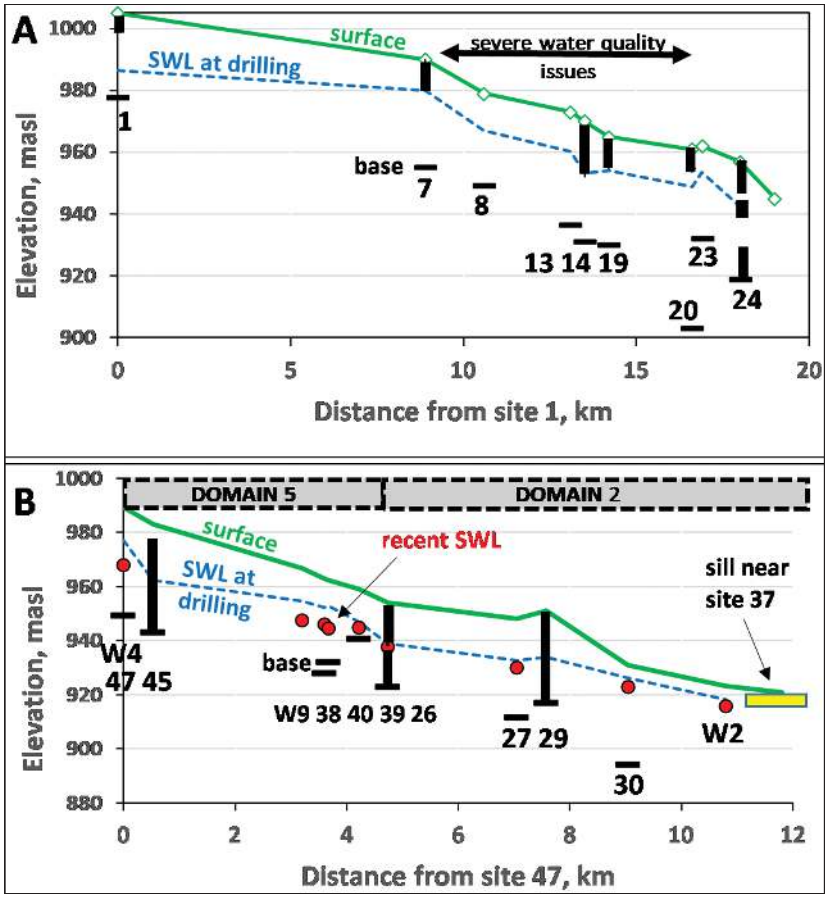


**Figure 3.** Cross-sections of the topographic profile of stream beds, static water levels, well depths, and clay (black columns) recorded in drillers' logs. Where no clay is recorded, silt, sand, and gravel are present. (A) Along the San Pedro River between sites 1 and 24. (B) From site 45 in Hot Springs Canyon to site W2 on the San Pedro River.

100 m from major floodplains, and almost none from any perched riparian aquifer overlying or within the clay units. The Holocene channel deposits (along with similar deposits in Hot Springs Canyon and Paige Canyon) appear to host most available groundwater in the Cascabel area. Most production wells are situated close to the San Pedro River (Figure 2), either in the Holocene valley fill, or in adjacent Quiburis formation (see Figure 4 for a schematic depiction). Much of the aquifer appears in drillers' logs to be unconfined (Arizona Department of Water Resources 2017). However, for sites 8, 14, 19, 20, 21, and 23, drillers' logs report confined water conditions, most likely reflecting groundwater in sand or gravel below clay beds. A few wells (e.g., sites 48 to 56) apparently produce groundwater from the Quiburis formation far from the river and its main tributaries. Artesian water is known to be present only at site 57.

## Methods

Groundwater depths were measured between 1990 and 2016 using a Fisher M Scope WLS water level indicator. Data representing SWLs are presented here; a small number of measurements taken soon after periods of pumping have been excluded. Groundwater samples were obtained from continually active supply wells, springs, or pits dug in the river bed. EC was measured with a Hanna HI9033 meter calibrated with standard 1430 μS/cm KCl solution. Isotope measurements were performed at the Environmental Isotope Laboratory, University of Arizona. Water samples for isotope measurement were collected from surface water, wells that were in continual use, piezometers from which three casing volumes of water were removed prior to sampling, and springs and seeps. Stable O and H isotope ratios were

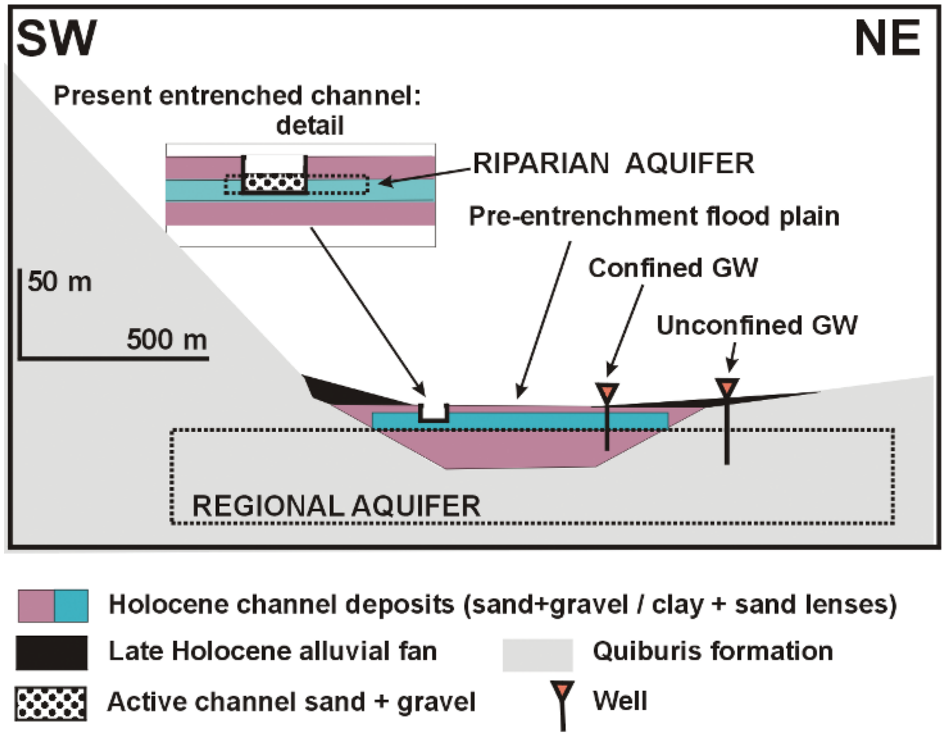


**Figure 4.** Schematic cross-section of the inner San Pedro Valley near site 19, illustrating groundwater hydrology. The depth of the entrenched river channel is exaggerated. The depth and lateral extent of the saturated zones are not known. The trench occupied by Holocene sediment may include multiple filled arroyos of different ages, as is the case upstream of the study area (Waters and Haynes 2001).

measured on a Finnigan Delta S® dual-inlet mass spectrometer equipped with an automated $CO_2$ equilibrator (for O) and an automated Cr-reduction furnace (for H). Results are expressed in delta-notation, e.g.,

$$\delta^{18}O \text{ or } \delta D = \quad 1000\{\frac{R(sample)}{R(standard)} - 1\}‰,$$

where R = $^{18}O/^{16}O$ or $^{2}H/^{1}H$.

Analytical precisions (1σ) are 0.08‰ (O) and 0.9‰ (H).

Tritium ($^3H$) and radiocarbon ($^{14}C$) were measured in a Quantulus 1220 ® Spectrometer by liquid scintillation counting. Tritium was measured on 0.19 L water samples after electrolytic enrichment. Results are expressed in tritium units (TU), where 1 TU corresponds to 1 tritium atom per $10^{18}$ hydrogen atoms. The detection limit is 0.6 TU. Radiocarbon was measured on $CO_2$ extracted from 50 L water samples by acid hydrolysis of dissolved inorganic carbon; the carbon was converted to benzene. Results for groundwater are expressed as percent modern carbon (pMC), where 100 pMC corresponds to the composition of the atmosphere in 1950, after correction for industrial effects. The detection limit is 0.2 pMC for undiluted samples. Groundwater $^{14}C$ results were corrected using stable carbon isotope data (Clark and Fritz 1997, p. 210). Data are listed in Tables 1 and 2.

## Results

### 1. Isotopes

***Framework for Presentation.*** Isotope data for groundwater will be presented with reference to the following domains. Each domain is an area with distinctive geological, isotope, and/or solute content (as will be explained below) within the study area (Figure 2).

Domain 1: the pre-entrenchment floodplain of the San Pedro River, south of the mouth of Hot Springs Canyon, and adjacent land within about 100 m of the floodplain.

Domain 2: the pre-entrenchment floodplain of the San Pedro River, north of the mouth of Hot Springs

**Table 2.** Sample sites, field data, and isotope measurements.

| Site no. | Name | ADWR ID 55- | Lat.° 32. | Long.° -110. | Elev. m amsl | Depth m below surface | SWL m below surface | SWL m amsl | Date | EC | $\delta^{18}O$ ‰ | δD ‰ | Tritium TU | Quality Problems |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **GROUNDWATER DOMAIN 1** | | | | | | | | | | | | | | |
| 1 | TNC #12 | 206443 | 1510 | 2950 | 995 | 27.3 | 18.5 | 977 | 5/07 | 667 | -8.2 | -57 | | |
| 2 | TNC #5 | 651320 | 1840 | 2980 | 994 | 60.6 | 9.1 | 985 | 5/07 | 688 | -8.2 | -58 | 0.5 | |
| 3 | Dewell Ocotillo Rd | 608060 | 1980 | 3170 | 994 | 33.3 | 10.6 | 983 | 5/09 | 689 | -8.7 | -61 | 1.1 | |
| 3 | Dewell Ocotillo Rd | 608060 | 1980 | 3170 | 994 | 33.3 | 10.6 | 983 | 12/12 | 718 | -8.6 | -61 | | |
| 4 | TNC #1 | 651304 | 2160 | 3080 | 986 | 15.2 | 9.1 | 977 | 5/07 | 854 | -8.4 | -60 | | |
| 5 | HSR cliff pasture | 608064 | 2248 | 3267 | 983 | 30.3 | 10.6 | 972 | 5/09 | 692 | -7.8 | -57 | | |
| 6 | HSR dom | 608059 | 2297 | 3270 | 984 | 33.3 | 12.1 | 972 | 5/07 | 788 | -8.1 | -58 | | **$H_2S$** |
| 7 | HSR irr | 520298 | 2310 | 3228 | 992 | 34.8 | 12.1 | 980 | 5/07 | 906 | -8.3 | -59 | <0.9 (A 0.3) | |
| 8 | Mason | 573705 | 2419 | 3313 | 979 | 29.7 | 12.1 | 967 | 5/07 | 874 | -8.2 | -59 | 1.9 | |
| 9 | USGS Piez. Clayworks | 215016 | 2610 | 3493 | 963 | 9.1 | 2.7 | 960 | 11/08 | | -8.0 | -57 | | **OM** |
| 10 | USGS Piez. Clayworks | 215015 | 2610 | 3493 | 964 | 18.2 | 3.0 | 961 | 11/08 | | -7.6 | -54 | | **OM** |
| 11 | Clark | 645667 | 2614 | 3484 | 970 | 27.3 | 12.1 | 958 | 5/07 | 812 | -7.4 | -52 | | **OM, $H_2S$, Fe** |
| 11 | Clark | 645667 | 2614 | 3484 | 970 | 27.3 | 12.1 | 958 | 3/08 | 707 | -7.4 | -52 | 3.3 | **OM, $H_2S$, Fe** |
| 11 | Clark | 645667 | 2614 | 3484 | 970 | 27.3 | 12.1 | 958 | 10/15 | | -10.2 | -74 | | **OM, $H_2S$, Fe** |
| 12 | Wilson shallow | 645666 | 2626 | 3548 | 973 | 10.3 | 9.1 | 964 | 3/08 | 1197 | -7.9 | -55 | | none |
| 13 | Wilson deep | 597352 | 2626 | 3548 | 973 | 36.4 | 12.7 | 960 | 3/08 | 892 | -8.4 | -59 | 3.2 | $H_2S$ |
| 13 | Wilson deep | 597352 | 2626 | 3548 | 973 | 36.4 | 12.7 | 960 | 3/08 | 805 | -8.4 | -59 | | $H_2S$ |
| 14 | La Margarita | 525466 | 2630 | 3479 | 970 | 38.8 | 16.7 | 953 | 3/08 | 929 | -8.2 | -60 | 2.1 | **$H_2S$, Fe** |
| 15 | McClure irr | 526573 | 2619 | 3351 | 978 | 35.8 | 15.8 | 975 | 3/08 | 1566 | -8.2 | -58 | | **$H_2S$** |
| 16 | Oasis dom | 603369 | 2636 | 3449 | 977 | 44.8 | 21.2 | 956 | 3/08 | 900 | -8.4 | -59 | | **$H_2S$** |
| 17 | Trumbule | 806776 | 2639 | 3465 | 973 | 27.3 | 12.1 | 961 | 3/08 | 1054 | -8.2 | -58 | | |

**Table 2 continued.**

| Site no. | Name | ADWR ID 55- | Lat.° 32. | Long.° -110. | Elev. m amsl | Depth m below surface | SWL m below surface | SWL m amsl | Date | EC | $\delta^{18}O$ ‰ | $\delta D$ ‰ | Tritium TU | Quality Problems |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **GROUNDWATER DOMAIN 1 (cont'd)** | | | | | | | | | | | | | | |
| 18 | Oasis irr | 603368 | 2663 | 3432 | 977 | 30.6 | 15.2 | 962 | 3/08 | 868 | -7.9 | -57 | | |
| 19 | Eastoe & Callegary | 539606 | 2687 | 3547 | 965 | 10.7 | 19.7 | 954 | 8/06 | 966 | -8.2 | -58 | 2.5 | **Fe, oil film** |
| 20 | Thomas dom | 515969 | 2877 | 3735 | 961 | 57.6 | 12.1 | 949 | 5/07 | 1003 | -8.0 | -58 | 3.1 | $H_2S$, Fe |
| 20 | Thomas dom | 515969 | 2877 | 3735 | 961 | 57.6 | 12.1 | 949 | 6/14 | 950 | -8.1 | -59 | | |
| 21 | Thomas irr | 515970 | 2877 | 3735 | 958 | 37.0 | 18.2 | 940 | 7/09 | | -8.2 | -60 | <1.4 (A 0.7) | |
| 22 | McLean & Tench dom | 521871 | 2895 | 3655 | 967 | 23.3 | 16.7 | 950 | 5/07 | 1083 | -7.8 | -57 | | **$H_2S$** |
| 23 | Greco | 513520 | 2898 | 3736 | 962 | 29.7 | 8.5 | 954 | 1/09 | 1069 | -8.0 | -58 | | **$H_2S$, Fe** |
| 24 | Whitt | 527527 | 2883 | 3863 | 957 | 37.9 | 13.6 | 942 | 5/09 | 502 | -8.9 | -60 | 3.2 | |
| 25 | USGS Piez.LCC | 215003 | 2914 | 3839 | 950 | 9.1 | 4.5 | 945 | 11/08 | | -7.9 | -55 | | |
| 25 | USGS Piez. LCC | 215004 | 2914 | 3839 | 950 | 18.2 | 4.5 | 945 | 11/08 | | -8.1 | -59 | | |
| **GROUNDWATER DOMAIN 2** | | | | | | | | | | | | | | |
| 26 | Community Center | 526730 | 2943 | 3842 | 954 | 31.2 | 15.2 | 939 | 1/09 | 446 | -9.1 | -67 | | $H_2S$, Fe |
| 27 | Cielo Azul | 533834 | 3189 | 3913 | 948 | 36.4 | 15.2 | 933 | 4/11 | 510 | -8.5 | -63 | 5.1 | |
| 28 | A7 Brown irr | 613526 | 3189 | 4002 | 935 | 37.2 | 5.2 | 930 | | | | | | |
| 29 | Vogel & Ffoliott | 516029 | 3195 | 3905 | 951 | 37.0 | 17.0 | 934 | 3/12 | 485 | -9.3 | -66 | <0.9 (A 0.3) | $H_2S$ |
| 30 | Corbett irr | 607859 | 3304 | 4064 | 931 | 25.8 | 4.8 | 926 | | 738 | -8.7 | -64 | | |
| 31 | McBride | 562275 | 3312 | 4062 | 932 | 37.9 | 6.1 | 926 | 3/09 | 561 | -8.6 | -62 | | Fe? |
| 32 | Elliott | 602534 | 3319 | 4038 | 945 | 51.5 | 16.7 | 928 | 2/09 | 390 | -8.7 | -64 | | |
| 33 | Lands | 545407 | 3367 | 4106 | 939 | 30.3 | 16.7 | 922 | 4/09 | 702 | -8.7 | -64 | 1.8 | $H_2S$, Fe |
| 34 | Hellriegel | 629316 | 3378 | 4134 | 928 | 15.2 | 4.8 | 923 | 3/14 | 677 | -8.8 | -65 | 1.7 | Fe |
| 35 | Troutner | 650592 | 3421 | 4160 | 937 | 45.5 | 34.8 | 902 | 12/08 | 687 | -8.6 | -64 | | Fe? |
| 36 | Grey | 545694 | 3459 | 4111 | 951 | 70.3 | 56.1 | 895 | 4/09 | 330 | -8.5 | -63 | <0.5 | Fe |

**Table 2 continued.**

| Site no. | Name | ADWR ID 55- | Lat.° 32. | Long.° -110. | Elev. m amsl | Depth m below surface | SWL m below surface | SWL m amsl | Date | EC | $\delta^{18}O$ ‰ | $\delta D$ ‰ | Tritium TU | Quality Problems |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **GROUNDWATER DOMAIN 2 (continued)** | | | | | | | | | | | | | | |
| 37 | Seep, E bank of SPR | | 3382 | 4181 | 921 | | | | 3/14 | 752 | -9.0 | -65 | 2.1 | |
| 37 | Seep, W bank of SPR | | 3382 | 4181 | 921 | | | | 3/14 | | -8.4 | -63 | | |
| 37 | Seep, W bank of SPR | | 3382 | 4181 | 921 | | | | 5/14 | | -9.0 | -63 | | |
| 37 | Seep, W bank of SPR | | 3382 | 4181 | 921 | | | | 11/14 | 1335 | -10.9 | -77 | | |
| 37 | Seep, W bank of SPR | | 3382 | 4181 | 921 | | | | 11/15 | 875 | -11.3 | -80 | | |
| **GROUNDWATER DOMAIN 3** | | | | | | | | | | | | | | |
| 48 | McClure dom | 574422 | 2628 | 3283 | 1025 | 93.6 | 55.8 | 963 | 3/08 | 532 | -7.8 | -57 | | none |
| 49 | Woolard | 517873 | 2876 | 3678 | 984 | 106.1 | 30.3 | 954 | 6/07 | 376 | -8.3 | -64 | | $H_2S$ |
| 50 | McLean & Tench remote | 909739 | 2897 | 3623 | 991 | 157.3 | 34.8 | 956 | 12/08 | 508 | -8.3 | -61 | | none |
| 51 | Etshokin | 542914 | 2914 | 3659 | 982 | 57.3 | 40.9 | 941 | 5/11 | 366 | -7.7 | -59 | | |
| 52 | De Palma | 572943 | 2942 | 3651 | 998 | 90.9 | 44.8 | 953 | 4/11 | 391 | -7.7 | -58 | | |
| 53 | Curtis | | 3020 | 3861 | 951 | | | | 12/08 | 393 | -7.4 | -55 | | |
| 54 | Meader | 909740 | 3045 | 3512 | 957 | 110.6 | 78.8 | 878 | 3/12 | 508 | -9.4 | -67 | <0.6 | none |
| 55 | Brown & Stanton | 572523 | 3468 | 4002 | 999 | 153.0 | 84.2 | 915 | 12/10 | 378 | -7.9 | -59 | <0.6 | none |
| 56 | Brown & Stanton cabin | 540613 | 3520 | 4051 | 995 | 121.2 | 74.2 | 921 | 3/14 | 360 | -7.3 | -55 | <0.8 | none |
| **GROUNDWATER DOMAIN 4** | | | | | | | | | | | | | | |
| 57 | Cienega artesian | | 1903 | 3102 | 987 | 43.9 | 0.0 | 991 | 12/12 | 407 | -9.4 | -68 | | |
| 58 | Paige Canyon well | 608070 | 2702 | 3804 | 968 | 33.5 | 27 | 941 | 3/14 | 513 | -9.7 | -68 | 4.4 | |
| 58 | Paige Canyon well | 608070 | 2702 | 3804 | 968 | 33.5 | 27 | 941 | 1/15 | 504 | -9.8 | -67 | | |
| 59 | Grapevine Spring | | 2788 | 4948 | 1283 | | | | 2012 | | -9.5 | -68 | | |
| **GROUNDWATER DOMAIN 5** | | | | | | | | | | | | | | |
| 38 | Otter | 807673 | 2905 | 3737 | 963 | 28.5 | 10.6 | 952 | 5/07 | 545 | -8.8 | -65 | 3.5 | none |
| 38 | Otter | 807673 | 2905 | 3737 | 963 | 28.5 | 10.6 | 952 | 2015 | | -8.0 | -58 | | none |

**Table 2 continued.**

| Site no. | Name | ADWR ID 55- | Lat.° 32. | Long.° -110. | Elev. m amsl | Depth m below surface | SWL m below surface | SWL m amsl | Date | EC | $\delta^{18}O$ ‰ | $\delta D$ ‰ | Tritium TU | Quality Problems |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **GROUNDWATER DOMAIN 5 (continued)** | | | | | | | | | | | | | | |
| 39 | Newman | 631866 | 2912 | 3799 | 959 | 18.2 | 12.1 | 947 | 2/09 | 485 | -9.0 | -66 | 2.9 | |
| 40 | Baicatcan | 631886 | 2917 | 3767 | 962 | 30.3 | 12.1 | 950 | 11/16 | | -8.8 | -64 | | |
| 41 | Flood & Loveland | 909738 | 2966 | 3699 | 998 | 83.9 | 50.0 | 948 | 3/12 | 549 | -9.0 | -66 | 6.9 | |
| 42 | McPherson | | 3017 | 3658 | 1024 | | 73.3 | 951 | 5/07 | 348 | -8.8 | -64 | 0.6 | none |
| 43 | Evans | 589398 | 3049 | 3575 | 1055 | 122.7 | 84.2 | 971 | 3/12 | 372 | -9.3 | -67 | <1.0 | Fe |
| 44 | Bribach | 549082 | 3071 | 3613 | 1016 | | | | 3/12 | 389 | -9.2 | -67 | <0.8 | |
| 45 | Revere dom | 561388 | 3105 | 3603 | 983 | 45.5 | 20.6 | 962 | 5/07 | 463 | -8.7 | -62 | 3.3 | none |
| 46 | Henderson | 567431 | 3111 | 3616 | 1006 | 42.4 | 37.0 | 969 | 5/12 | | -8.9 | -65 | | none |
| 47 | HSC. Windmill | 553292 | 3134 | 3556 | 989 | | | | 5/07 | 475 | -9.0 | -64 | | |
| **SHALLOW RIPARIAN GROUNDWATER** | | | | | | | | | | | | | | |
| 10 | SPR river bed | | 2618 | 3533 | 961 | * | | | 10/08 | | -6.9 | -49 | | |
| 10 | SPR river bed | | 2606 | 3395 | 965 | * | | | 2/09 | 2510 | -5.7 | -47 | | |
| 10 | SPR river bed | | 2618 | 3533 | 961 | * | | | 11/09 | 1480 | -7.0 | -48 | 6.6 | |
| | SPR river bed | | | | | * | | | 11/09 | | -4.5 | -31 | | |
| **HOOKER HOT SPRINGS** | | | | | | | | | | | | | | |
| 60 | Hooker Hot Springs | | 3664 | 2382 | 1248 | | | | 1/94 | | -11.1 | -81 | <0.8 | |
| 61 | Hot spring Bass Canyon | | 3501 | 2397 | 1238 | | | | 1/94 | | -11.1 | -79 | | |
| **BASE FLOW** | | | | | | | | | | | | | | |
| 62 | HSC at range front | | 3287 | 3382 | 1010 | | | | 11/13 | | -9.1 | -67 | | |
| 63 | HSC at Narrows | | 3402 | 3187 | 1050 | | | | 4/08 | | -9.0 | -67 | | |
| 64 | SPR, Three Links | | 1801 | 2977 | 992 | | | | 3/14 | | -8.2 | -58 | | |
| 64 | SPR, Three Links | | 1801 | 2977 | 992 | | | | 12/12 | 624 | -8.2 | -58 | | |
| 64 | SPR, Three Links | | 1801 | 2977 | 992 | | | | 6/09 | 649 | -8.2 | -58 | 1.7 | |
| 64 | SPR, Three Links | | 1801 | 2977 | 992 | | | | 12/08 | 655 | -8.1 | -59 | | |
| 64 | SPR, Three Links | | 1801 | 2977 | 992 | | | | 6/08 | 785 | -8.2 | -59 | 1.5 | |

**Table 2 continued.**

| Site no. | Name | ADWR ID 55- | Lat.° 32. | Long.° -110. | Elev. m amsl | Depth m below surface | SWL m below surface | SWL m amsl | Date | EC | $\delta^{18}O$ ‰ | $\delta D$ ‰ | Tritium TU | Quality Problems |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **SUMMER FLOODWATER** | | | | | | | | | | | | | | |
| 64 | SPR, Three Links | | 1801 | 2977 | 992 | | | | 9/6/06 | 362 | -10.1 | -68 | 4.1 | |
| 65 | SPR, Benson Narrows | | 1010 | 1419 | 2890 | | | | 9/16/06 | 344 | -7.5 | -50 | 5.0 | |
| 19 | SPR, site 19 | | 958 | 2686 | 3564 | | | | 9/17/06 | 456 | -7.2 | -50 | 4.1 | |
| 6 | SPR, site 6 | | 979 | 2324 | 3324 | | | | 6/17/07 | 1154 | -7.4 | -55 | 1.8 | |
| 19 | SPR, site 19 | | 958 | 2686 | 3564 | | | | 7/30/07 | | -10.5 | -74 | 5.8 | |
| 19 | SPR, site 19 | | 958 | 2686 | 3564 | | | | 8/29/07 | | -7.4 | -49 | | |
| 19 | SPR, site 19 | | 958 | 2686 | 3564 | | | | 9/9/07 | 431 | -7.0 | -50 | 3.7 | |
| 19 | SPR, site 19 | | 958 | 2686 | 3564 | | | | 7/12/08 | 515 | -7.4 | -55 | | |
| 19 | SPR, site 19 | | 958 | 2686 | 3564 | | | | 7/13/08 | 517 | -11.6 | -82 | | |
| 19 | SPR, site 19 | | 958 | 2686 | 3564 | | | | 7/20/08 | 754 | -10.1 | -69 | | |
| 6 | SPR, site 6 | | 979 | 2324 | 3324 | | | | 7/25/08 | 463 | -9.8 | -71 | | |
| 6 | SPR, site 6 | | 979 | 2324 | 3324 | | | | 7/29/08 | 420 | -7.0 | -49 | | |
| 6 | SPR, site 6 | | 979 | 2324 | 3324 | | | | 8/6/08 | 398 | -6.1 | -41 | | |
| 6 | SPR, site 6 | | 979 | 2324 | 3324 | | | | 8/23/08 | 435 | -4.8 | -39 | | |
| 6 | SPR, site 6 | | 979 | 2324 | 3324 | | | | 8/27/08 | 730 | -13.3 | -97 | | |
| 19 | SPR, site 19 | | 958 | 2686 | 3564 | | | | 8/30/08 | 449 | -11.3 | -84 | | |
| 6 | SPR, site 6 | | 979 | 2324 | 3324 | | | | 9/5/08 | 511 | -4.7 | -36 | | |
| 6 | SPR, site 6 | | 979 | 2324 | 3324 | | | | 9/11/08 | 429 | -5.8 | -40 | | |
| 6 | SPR, site 6 | | 979 | 2324 | 3324 | | | | 9/14/08 | 500 | -7.3 | -57 | 4.4 | |
| 6 | SPR, site 6 | | 979 | 2324 | 3324 | | | | 9/26/08 | 292 | -10.2 | -75 | | |
| 6 | SPR, site 6 | | 979 | 2324 | 3324 | | | | 9/27/08 am | 376 | -8.4 | -64 | | |
| 19 | SPR, site 19 | | 958 | 2686 | 3564 | | | | 9/27/08 pm | 489 | -7.9 | -59 | 3.9 | |
| 19 | SPR, site 19 | | 958 | 2686 | 3564 | | | | 9/28/08 am | 333 | -10.3 | -75 | | |
| 6 | SPR, site 6 | | 979 | 2324 | 3324 | | | | 9/29/08 | 433 | -8.2 | -63 | | |
| 6 | SPR, site 6 | | 979 | 2324 | 3324 | | | | 7/8/09 | 495 | -5.8 | -40 | | |
| 6 | SPR, site 6 | | 979 | 2324 | 3324 | | | | 7/10/09 | 493 | -8.5 | -58 | 4.8 | |

Table 2 continued.

| Site no. | Name | ADWR ID 55- | Lat.° 32. | Long.° -110. | Elev. m amsl | Depth m below surface | SWL m below surface | SWL m amsl | Date | EC | δ18O ‰ | δD ‰ | Tritium TU | Quality Problems |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **FLOODWATER, HURRICANE ODILE** | | | 979 | 2324 | 3324 | | | | | | | | | |
| 8 | SPR, site 8 | | 974 | 2415 | 3325 | | | | 9/19/14 | | -14.8 | -107 | | |
| 8 | SPR, site 8 | | 974 | 2415 | 3325 | | | | 9/20/14 | | -14.2 | -102 | | |
| 8 | SPR, site 8 | | 974 | 2415 | 3325 | | | | 9/29/14 | | -9.8 | -69 | | |
| 19 | SPR, site 19 | | 958 | 2686 | 3564 | | | | 10/4/14 | | -9.0 | -67 | | |

Explanation: SPR = San Pedro River; HSC = Hot Springs Canyon; USGS Piez = Unites States Geological Survey piezometer; LCC = Last Chance Crossing; TNC = The Nature Conservancy; dom = domestic; irr = irrigation; A = apparent tritium.

*Samples taken from excavations made by javelina, < 45 cm deep.

Quality problems: **bold** = severe; $H_2S$ = hydrogen sulfide, rotten egg smell; Fe = dissolved $Fe^{2+}$; OM = suspended organic matter; "none" indicates an explicit report of no water quality issues; blank cells indicate no information available.

Canyon, and adjacent land within about 100 m of the floodplain.

Domain 3: tributary washes and hill slopes east of the San Pedro floodplain, except for Domain 5.

Domain 4: tributary washes and slopes west of the San Pedro floodplain.

Domain 5: Hot Springs Canyon, including the floodplain within the canyon and adjacent land within 200 m of the floodplain.

***Surface Water.*** Base flow sampled from the San Pedro River at site 64 consistently had ($\delta^{18}O$, δD) near (-8.2, -58‰) between 2008 and 2014 (Table 2). The isotopes do not correspond with those in confined groundwater immediately upstream of the Benson Narrows (Figure 5A). The tritium contents of two base-flow samples were 1.7 and 1.5 TU (Table 2). Surface water from the river during monsoon floods has a very broad range of ($\delta^{18}O$, δD), consistent with data for summer rain in Tucson (See Figure 2 in Eastoe and Dettman 2016). Floodwater following rain from Hurricane Odile in September 2014 extended the range of ($\delta^{18}O$, δD) to even lower values (Figure 5B; Table 2), consistent with the low values of ($\delta^{18}O$, δD) commonly recorded in rainfall associated with tropical cyclonic weather systems in the region (Eastoe et al. 2014). With a single exception (Site 19, Table 2), the tritium content of summer floodwater is 3.9 to 5.8 TU. Base flow from Hot Springs Canyon (Figure 5D) had ($\delta^{18}O$, δD) near (-9.0, -67‰) in 2008 and 2013, and (-8.0, -64‰) in 2017.

***Shallow Riparian Groundwater.*** Shallow riparian groundwater, sampled from pits dug 30-45 cm deep in the river bed by javelina (*Pecari tajacu*), largely has O and H isotopes similar to those of shallow riparian groundwater from the San Pedro River near Benson and St. David, south of the Benson Narrows (Figure 5B). One sample contained 6.6 TU of tritium (Table 2).

***Regional Groundwater.*** In the regional aquifer, each of domains 1, 2, and 4 has a distinctive field of ($\delta^{18}O$, δD) data (Figure 5C; Table 2). The field for domain 3 differs slightly from that of domain 1; domain 3 groundwater plots to the right of domain 1 groundwater, and is therefore slightly more evaporated. Domain 1 groundwater has a similar stable isotope composition to base flow at site 64 (Figure 5A; Table 2). Domain 5 groundwater includes examples similar to Hot Springs Canyon base flow and mixtures of such base flow with water like that in domain 3 (Figure 5C; Table 2). Domain 2 groundwater is similar to domain 5 groundwater (compare Figures 5C and 5D).

Tritium (values listed in Table 2) in domain 1 groundwater and base flow is present at levels less than 2 TU between sites 64 and 8, and 2.1 to 3.3 TU north of site 8, with the exception of site 20. Domain 2 groundwater has tritium contents ranging from below detection to 2.1 TU, with an outlier, 5.1 TU, in confined groundwater below a clay lens at site 27. Three available tritium measurements for domain 3 are all below detection. A single measurement of 4.4 TU was obtained for water in the floodplain of Paige Canyon in domain 4. In domain 5, a distinction exists between groundwater in the floodplain of Hot Springs Canyon (sites 38, 39, and 45; 2.9 to 3.5 TU) and groundwater in the Quiburis formation mesa immediately south of the floodplain (sites 41, 42, 43, and 44; < 1.0 TU with one outlier, 6.9 TU).

Two $^{14}C$ measurements, 97.8 pMC at site 11 and 81.3 pMC at site 19, were obtained in domain 1 (Table 1). Corrected results for a variety of plausible scenarios (one of which is given in Table 1) indicate post-bomb ages (> 100 pMC) for both.

***Relationships with Upstream Groundwater.*** Base flow and groundwater in domain 1 might originate

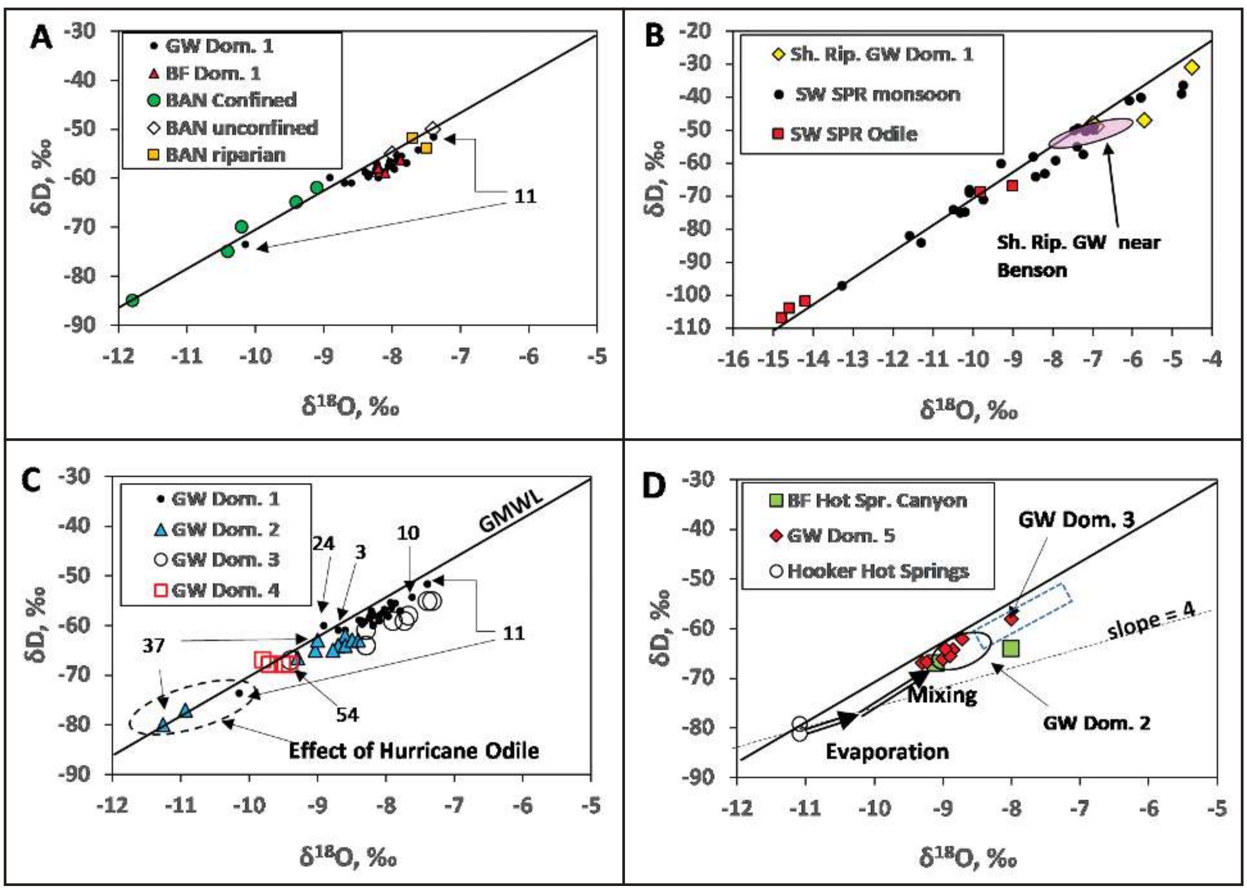


**Figure 5.** Plots of δD versus $\delta^{18}O$. (A) Comparison of groundwater and base flow in domain 1 with groundwater upstream of Benson Narrows. (B) Comparison of shallow riparian groundwater in domain 1 with San Pedro River surface water. (C) Comparison of groundwater in the regional aquifer in domains 1, 2, 3, and 4. (D) Relationships among groundwater from domains 2, 3, and 5, Hooker Hot Springs, and base flow in Hot Springs Canyon. Abbreviations: BAN = basin above Narrows; BF = base flow; Dom. = domain; GMWL = global meteoric water line of Craig (1961); GW = groundwater; Sh. Rip. = shallow riparian; SPR = San Pedro River; SW = surface water. Numbers are site identifiers, as in Table 2.

upstream of the Benson Narrows (Cordova et al. 2015). Isotope data for deep (confined) groundwater and for shallow riparian groundwater immediately upstream of the Narrows (Hopkins et al. 2014) do not resemble isotope data for domain 1 (Figure 5A), precluding groundwater flow through shallow or deep sediment channels at the Narrows or through deep, concealed channels breaching the granite barrier on either side of the Narrows. Domain 1 groundwater might resemble unconfined groundwater from basin fill above the level of the river bed on the flanks of the Valley, but such water is available both north and south of the Narrows. An exceptional isotope composition in domain 1 occurs at site 11 (Figure 5A), which is 50 m from the entrenched channel of the San Pedro River. In 2007 and 2008, the well yielded groundwater with isotopes like those of shallow riparian groundwater from above the Benson Narrows within domain 1. In 2015, groundwater at site 11 shifted to lower ($\delta^{18}O$, $\delta D$) values (Table 2).

***Stable Isotope Changes Over Time.*** The isotopic distinctions between domains 2 and 5 and the other domains, and the clear isotope labeling of Hurricane Odile floodwater can be used to trace changes in the flow paths of groundwater. To date, the following changes have been observed. Site 38 lies within the floodplain of Hot Springs Canyon and is 100 m from site 23 which is part of domain 1. In 2007, stable isotopes indicated domain 5 water at site 38, but by 2015, this had been replaced by domain 1 water. The shift at site 11 in 2015 followed the September 2014 flood caused by inland remnants of Hurricane Odile, when a large volume of low - ($\delta^{18}O$, $\delta D$) river water was delivered from upstream of the Benson Narrows (Figure 5B; Table 2). A similar shift was observed in the river-bank spring at site 37 (Figure 5C).

***Interpretation of Stable Isotopes.*** Recharge from the San Pedro River to the small shallow riparian aquifer at Cascabel is dominantly from summer or autumn surface water, because little surface water is available at other times. Notwithstanding the large isotope variability of such water (Figure 5B), the shallow riparian groundwater has isotope compositions restricted to the field observed upstream of the Benson Narrows and in a few samples from Cascabel (Figure 5B). Evolution towards the restricted field was observed in a single flood event on September 26 and 27, 2008 (Table 2). In domain 1, such water appears in the regional aquifer only at site 11, which is strongly influenced by floodwater.

All other groundwater in domain 1, including that discharging to the perennial reach at site 64, arises from a source other than summer and fall surface water. The similarity between groundwater isotopes in domains 1 and 3 is consistent with a source within the broader watershed of the Valley. The isotope pattern of domain 1 can be traced north as far as site 37 (Figure 6), and the area in which it occurs constitutes a distinct part of the regional aquifer, termed the A aquifer for the purposes of discussion below.

Base flow in Hot Springs Canyon has varied over time because of evaporation (Figure 5D). This surface water differs isotopically from water in domains 1 and 3 because of the contribution to base flow of ancient groundwater from hot springs in the headwaters (sites 60 and 61, Figure 2). The hot-spring water evolves by a combination of evaporation and mixing with domain 3 water to yield base flow and domain 5 groundwater of the isotope composition shown in Figure 5D. The slope used for the evaporation trend is 4, as observed elsewhere in the San Pedro Valley (Gungle et al. 2016). Groundwater of domains 2 and 5 is identical in isotopes (except at sites 25 and 37; see Figure 5), indicating that most domain 2 groundwater originates in domain 5. Together, domains 2 and 5 constitute a second distinct part of the regional aquifer, termed the B aquifer (Figure 6).

Domain 4 groundwater has lower ($\delta^{18}O$, $\delta D$) than that in domains 1, 2, 3, and 5, consistent with input of runoff from mountains rising to 2500 m amsl west of the Valley. Domain 4 groundwater has not been recognized on the west side of the San Pedro River downstream of the Paige Canyon confluence, but few sample sites are available in that area, and mixing with domain 1 water may occur.

***Interpretation of Groundwater Residence Time.*** The interpretation of tritium in southern Arizona groundwater, summarized as follows, is based on the discussion in Eastoe et al. (2011). The tritium data provide an unequivocal distinction

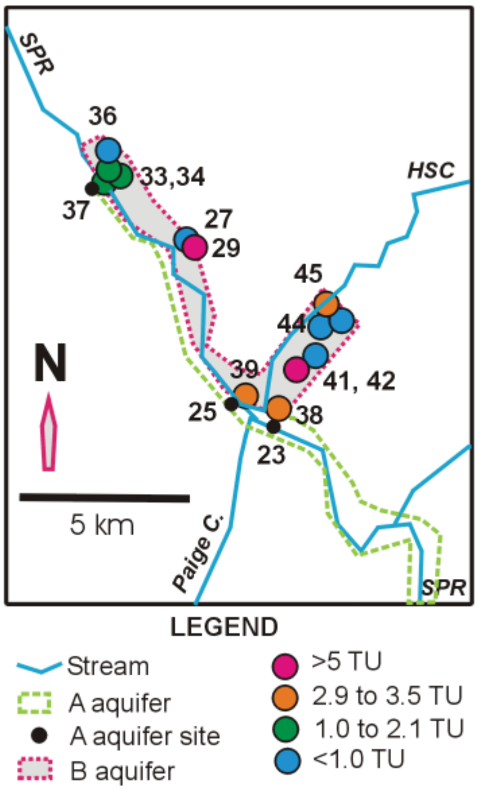


**Figure 6.** Map of aquifer B, showing tritium measurements, and adjacent parts of aquifer A, showing sites with isotope data like those found in domain 1. Site numbers: simple numbers are groundwater sample sites as listed in Table 2. HSC = Hot Springs Canyon.

in groundwater residence times. Samples with measurable tritium contain some water recharged since the initiation of atmospheric nuclear testing, this affecting tritium in rainwater since about 1953. In the study area, most such samples contain less than 5.2 TU, the annual average tritium content of rainwater in Tucson since 1992. Samples with tritium below the detection level (0.6 TU) indicate groundwater that infiltrated prior to 1953. To this distinction can be added a further interpretation: samples less than 1 TU contain mainly pre-1950s recharge. Tritium present at levels greater than 3 TU is consistent with recharge since 1992, but could also represent mixing of 1960s recharge with water of other ages.

Groundwater with residence times greater than 65 years at the time of publication are found in Quiburis formation sediments of domain 3, and a few examples near the margins of domain 1 (sites 7 and 21), domain 2 (site 36, at the down-gradient limit), and domain 5 (sites 42, 43, and 44, in Quiburis formation sediments). In the other areas that have been sampled, part or all groundwater has been resident for less than 65 years.

In domain 5 groundwater, tritium from recent post-bomb recharge is likely to be diluted by ancient hot-spring water containing no tritium (Table 2). In domains 2 and 5 (the B aquifer), tritium content in groundwater generally decreases downgradient, from Hot Springs Canyon to site 36 (Figure 6; Table 2). Groundwater from site 36 represents pre-1953 recharge, while groundwater immediately upgradient (sites 33, 34, and 37, Table 2) contains some post-1953 recharge. Therefore, groundwater appears to take about 65 years to reach site 36 from Hot Springs Canyon.

A down-gradient transition to higher tritium content from south to north in domain 1 groundwater may represent a larger fraction of post-1953 recharge, probably from Kelsey and Teran Washes, at the northern end of the domain.

## 2. Water Quality

***Data.*** Measurements of EC are listed in Table 2. Domain 1 groundwater has high EC, 502 – 1566 µS/cm. Domain 2 has low EC east of the river, 330 – 752 µS/cm, but high EC, 1335 µS/cm, west of the river at site 37. Domains 3, 4, and 5 have low-EC groundwater, 348 – 549 µS/cm. In domain 1, high EC corresponds to high hardness. A survey of owners of domestic wells in domains 1, 2, 3, and 5 yielded the information listed under "Quality Problems" in Table 2. In domain 1, between sites 6 and 23 (Figure 2), water is in many cases very hard and unpalatable, owing to the presence of one or more of: hydrogen sulfide ($H_2S$, rotten-egg smell), dissolved ferrous iron ($Fe^{2+}$, that becomes suspended orange ferric oxides on exposure to the atmosphere), suspended black organic matter, and oily film with a petrochemical smell. At site 19, water quality is poorest in March and April. In domains 2 and 5, such problems are minor or absent, and water is palatable. Dissolved $Fe^{2+}$ in domain 2 may in some cases originate from corrosion of steel well casings, while transient $H_2S$ appears at site 33 to be associated with a particular tank. In domain 3, water quality problems were reported only from site 49, a well drilled in the floodplain of a wash; other wells drilled deep into Quiburis formation showed no problems.

***Interpretation.*** The presence of $H_2S$ and dissolved $Fe^{2+}$ is due to bacterial processes in aquifers (Bethke et al. 2008). Certain bacteria can reduce dissolved sulfate and ferric iron ($Fe^{3+}$) present in minerals in aquifers. Required conditions include absence of dissolved oxygen in the groundwater, and availability of organic carbon, commonly acetate produced by fermentation of organic matter. The bacterial processes convert organic carbon to bicarbonate, increasing water hardness. The severest palatability problems occur in association with clay units (Figure 3; Table 2), including wetland deposits in which organic matter is stored. Such deposits are exposed in the river banks between sites 19 and 20. Suspended organic matter has been observed in groundwater at sites 9, 10, and 11, and traces of oily liquid at site 19. Aquifers may be zoned with respect to production of $H_2S$ and dissolved $Fe^{2+}$ at a variety of scales as a result of bacterial competition, nutrient availability, and the insolubility of ferrous sulfide (FeS) (Bethke et al. 2008). Because FeS is insoluble, $H_2S$ and dissolved $Fe^{2+}$ should not coexist in groundwater. The observation of both at sites 11, 14, and 23 suggests that well construction allows rapid mixing of waters from separate permeable beds of different chemistry.

### 3. Static Water Level

***Data.*** The SWLs shown in Table 2 were recorded at the time of drilling of each well and are probably of variable reliability owing to inconsistent measurement techniques. Reliable SWL measurements have been recorded at sites W2, W4, and W9 since 1993, and at W11 since 2006 (Figure 7). Sites W4 and W9 are in domain 5, site W2 is in domain 2, and W11 is in domain 1. At W4, the upstream site in Hot Springs Canyon, there has been a steady decline of more than 10 m in base water level since 1993. As a result, the well has been intermittently dry since 2010. Transient pulses of SWL increase by as much as 11 m were recorded in 1992, 1996, 1998, 2000, 2007-2008, 2011-2012, and 2016, but have not affected the long-term decline in base water level. At W9, near the confluence of Hot Springs Canyon and the San Pedro River, a similar long-term decline of about 10 m in base water level has been recorded, with transient pulses of higher SWLs in 1992, 1998, 2001, 2007, 2011, and 2016. At W2, the long-term decline in SWLs is 2 to 3 m. Stepwise increases occurred in late 2006 and early 2015. Since 2006, most measurements were made near the winter and summer solstices, and show a seasonal cycle, summer SWLs being lower (in altitude) than winter SWLs. At W11, in domain 1, SWLs fell 3 m between 2006 and 2013, but rose 2 m in 2014 and had not returned to late-2013 levels by late 2016.

Figure 3B shows water level declines in a longitudinal section of the B aquifer. For points other than W2, W4, and W9, the most recent water levels have been measured by community members in 2016. SWLs have declined throughout the B aquifer, except from km 4 to km 7 (Figure 3B) where the northward slope of the water table is least, and where little change has occurred. The largest SWL declines are in domain 5.

***Interpretation.*** At W4 and W9, the evolution of water levels is similar; base SWLs show a steady decline, beginning in the mid-1990s. SWLs above the base level form a small number of transient 1 to 2 year pulses, and reflect periodic enhanced recharge occurring as a result of higher flow in Hot Springs Canyon. The pulses are insufficient to reverse the decline in base SWLs, which is therefore probably a manifestation of climatic drying at decadal or longer time scale. Progressive drying may be occurring at a time scale of centuries, beginning at some time since the end of the 17th century when the Native American settlement at Baicatcán was occupied (Doelle et al. 2012). The settlement would have relied on a perennial surface water supply. Decline in base SWLs since 1993 does not appear related to a particular increase in water withdrawal by pumping. The reason for the size of the most recent pulse recorded at W9 is not known. At W2, the small seasonal cyclicity of SWLs corresponds with irrigation withdrawals for nearby pasture and with transpiration in riparian vegetation, the water demand being highest in the three to four dry months preceding the summer solstice. Field observations indicate that the stepwise increases in SWLs followed protracted flooding in late summer or autumn in 2006 and 2014. The rise in SWL at

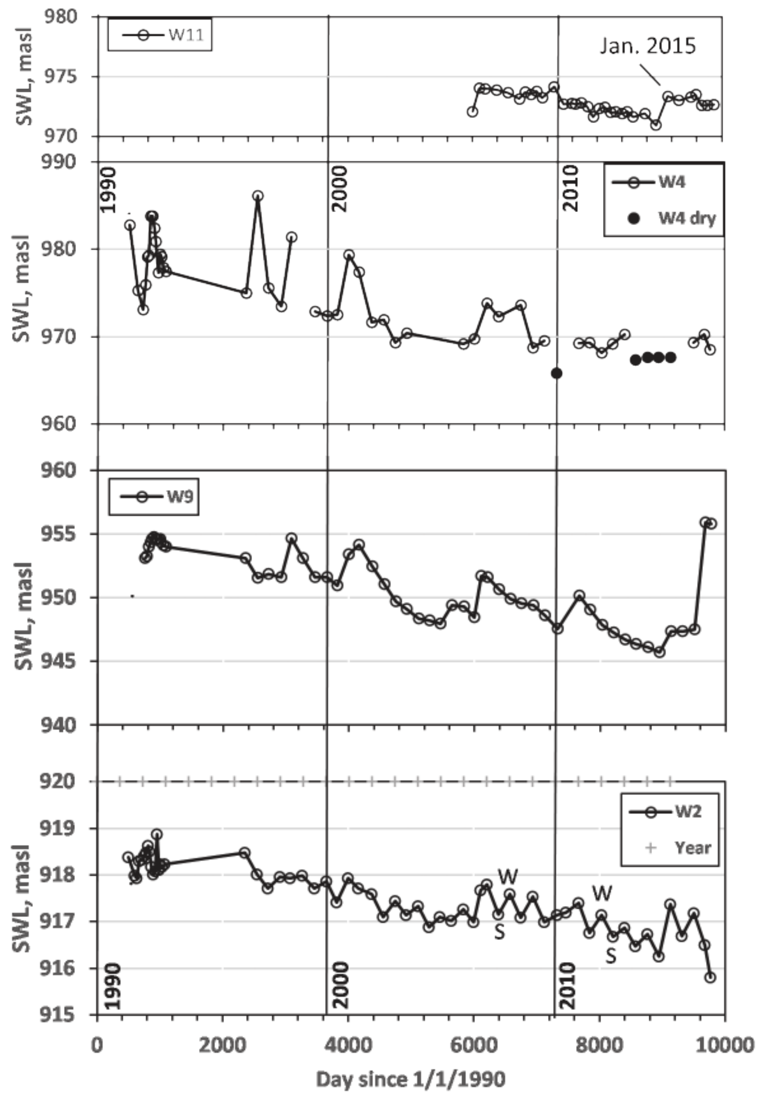


**Figure 7.** Time-series of static water level at four sites (see Fig. 2 for locations). Depths for the "W4 dry" points indicate the bottom of the well, which has changed owing to sedimentation over time. For site W2, W = winter, and S = summer.

W11 occurred after the late-2014 flood caused by Hurricane Odile, and appears to reflect a multi-year change in conditions.

## Discussion - Addressing Community Concerns

### Groundwater Origin

Stable O and H isotope data have proved useful to an understanding of water resources in Cascabel. Because of the contribution of ancient hot-spring water to Hot Springs Canyon, it is possible to distinguish aquifers A and B, and to show the importance of Hot Springs Canyon as a source of palatable water supply over the entire extent of aquifer B. Why aquifers A and B persist as separate, adjacent groundwater streams for 7 km downgradient of the mouth of Hot Springs Canyon cannot be demonstrated in the study area. It may be related to the persistence of multiple filled arroyos within the Holocene channel-fill, as has been mapped in the San Pedro Valley 80 km south of Cascabel (Waters and Haynes 2001, Figure 2). For the Cascabel community, the recognition of a separate aquifer B implies that events affecting groundwater in Hot Springs Canyon will eventually affect groundwater throughout aquifer B.

**Groundwater Residence Times and Drought Vulnerability**

Most groundwater samples in aquifers A and B contain measurable tritium, and therefore include some water recharged since about 1953. It follows that both aquifers are vulnerable to multi-decade droughts such as have occurred in the region in the past millennium and are recorded in tree-rings (Ni et al. 2002; Griffin et al. 2013). The presence of a few samples with no tritium at the margins of the aquifers does not change this interpretation, but indicates that some of the groundwater has been resident since before the 1950s.

The downgradient part of aquifer B (near sites W2, 37) appears less vulnerable than the rest of the aquifer. The decline in SWL has been relatively small (2 to 3 m since 1993, in contrast to about 10 m at W4 and W9), and the aquifer continues to discharge intermittently to surface water in the San Pedro River at site 37. SWLs respond to seasonal demand (e.g., from irrigation or transpiration) and protracted flooding in the river (probably because of mounded bank storage). However, groundwater flow into this area is for the present maintained by drainage of the upgradient part of the aquifer. The sill of San Manuel formation acts as a barrier to subsurface drainage to the north. Prolonged drainage of the upgradient part of aquifer B under continuing conditions of drought and irrigation demand will eventually lead to more rapid decline of SWLs in the downgradient part. SWL decline since 2007 has shortened the wet reach of the riverbed near site 37 (The Nature Conservancy 2017), and what was once perennial discharge has become intermittent.

Pre-bomb recharge is characteristic of domain 3 samples, leading to the interpretation that domain 3 is less vulnerable to drought than aquifers A and B.

**Cause of Unpalatable Water**

Unpalatable domestic water is reported as a serious and persistent problem in aquifer A from site 6 northward to site 23. Elsewhere, water quality issues are transient, minor, and possibly generated within plumbing or well fixtures. The problem area of aquifer A includes geological features (widespread clay units with local concentrations of organic matter, along with the general availability of oxidized iron and sulfate) sufficient to explain the generation of dissolved $Fe^{2+}$ and $H_2S$ within the aquifer. The causes of unpalatable water are ultimately found in local geology, so that interventions such as the pouring of bleach into wells (which cannot change upgradient geology) are unlikely to bring about permanent improvement in water quality.

**Cause of Water Level Declines**

SWLs at sites W4 and W9 in Hot Springs Canyon have been in steady decline since the early 1990s. Decline in base levels has been steady at both sites, and not apparently related to the initiation of any particular pumping demand – although the number of wells in the area has increased over the period of observation. Recharge pulses related to increased surface water supply have had only transient effects on SWLs and have not affected the observed long-term decline. The water table of the B aquifer slopes northward (note that site 29 is on land above the floodplain) with no known geological barrier to flow except for the San Manuel formation at sites W2 and 37. Once the recharge flux into Hot Springs Canyon decreases to an amount less than the sum of pumping and natural discharge by subsurface flow, SWLs in the aquifer will decline. This threshold was passed in the mid-1990s, most likely as a result of long-term climate change (reduced rainfall or increased evaporation). Nonetheless, pumping increases discharge, and residents with wells in the B aquifer would be wise to consider what management measures will aid in prolonging their water supply.

The observed isotope shift at site 38 (aquifer B in 2007, changing to aquifer A by 2015) and the lack of a recorded clay aquitard at site 23 (Arizona Department of Water Resources 2017) suggest that decline in the SWLs of the B aquifer may be causing water from the A aquifer to flow into the former B aquifer near site 38. Such flow is consistent with SWLs at sites 23 and 38 (Table 2).

**Communicating Groundwater Research to a Rural Community**

Progress in this study has been presented to the residents of Cascabel at three well-attended workshops, in 2009, 2015, and 2018. The community has an excellent general level of education. Communication of the information presented in this article has succeeded in varying degrees. The importance of measuring groundwater levels is universally understood by a community so strongly dependent on groundwater; certain community members are involved in systematically observing changes in SWLs. Comprehension of water quality issues is easier for community members with a knowledge of chemistry. The interactions among microbes, geology, and water movement form a moderately complex system that is difficult for many residents to understand. Most residents with physics and chemistry classes in their background would admit to little recent practice in those sciences. Consequently, one form of useful information – the isotope data that allow the mapping of functionally separate aquifers – poses the greatest challenge of all. Even for community members who are comfortable with the concept of isotopes, application of the technique to groundwater studies is new and difficult to absorb during a two-hour workshop. The presenter (CJE) has adopted the approach of asking the audience to accept that different isotope ratios exist and can be distinguished on a plot of $\delta D$ *versus* $\delta^{18}O$, without needing immediately to understand how the values are calculated.

### Future Work

A study in greater detail is possible in the Cascabel area, but was beyond the scope of the present work. Surface water hydrology has not been discussed in detail here, although preliminary data are available (Table 2). To address this problem in the manner suggested by Benettin et al. (2017), a much larger dataset encompassing isotope and geochemical measurements with a time-resolution of days would be required for summer runoff events. The following options are feasible for the community: 1) measurements of volume of base flow, 2) continuation of SWL measurements at established sites, and 3) monitoring of SWLs and EC near site 38, where groundwater flow paths appear to be changing. All would provide useful data for assessing water management options.

## Conclusions

Most groundwater in Cascabel is produced from Holocene fluvial sediments near the present channel of the San Pedro River and in Hot Springs Canyon.

Stable isotope data show that two aquifers, distinguished by different water sources, are present in the fluvial sediments. Aquifer A derives water from the river catchment upstream of the mouth of Hot Springs Canyon. Aquifer B derives some isotopically-distinctive water from hot springs in the headwaters of Hot Springs Canyon. Parallel subsurface streams of both water types are identified to a point 7 km downgradient from the mouth of Hot Springs Canyon. At that location, a sill of impermeable rock dams the aquifers, forcing groundwater to discharge to the river bed. A connection between the aquifers may be forming near sites 23 and 38.

Tritium data show that most of the groundwater in aquifers A and B had been resident for less than 60 years at the time of sampling. Both aquifers are susceptible to multi-decade droughts. Groundwater with no detectable tritium (resident for more than 60 years at the time of sampling) is present within the older sediments of the Quiburis formation east of the river.

Severe water quality problems are present in part of aquifer A, in association with abundant wetland sediments locally bearing organic matter. Dissolved $Fe^{2+}$, $H_2S$, and elevated hardness are common in that area, and are caused by microbial interactions with local geology.

Static water levels are falling in most of aquifer B, most likely as a result of natural drainage of the aquifer. Drainage appears to be due to climate change (increasing drought prevalence) at decade to century time-scale.

If drought conditions continue, the community will need to consider what management practices might prolong the groundwater supply.

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