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Groundwater Depletion Beneath Downtown Tucson, Arizona: A 240-Year Record

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Abstract: Beginning with the foundation date of Spanish Tucson in 1775 and continuing through the 1890s, shallow groundwater and related features, including a perched aquifer, stream-bed springs and a short perennial reach in the Santa Cruz River, progressively disappeared from the Downtown Tucson area. The 20th-Century city grew rapidly, and increasing groundwater withdrawals caused large declines in the regional aquifer of Tucson basin, leaving a second perched aquifer with non-aqueous contaminants beneath Downtown. Isotope data show that this fully perched aquifer retains residual water from the regional aquifer, plus recharge derived from a nearby small watercourse. The present regional aquifer beneath Downtown is locally layered and partly confined, and contains water 7-20 Ka years old originating at the northern and southeastern basin margins.

Keywords: *groundwater, urban growth, semi-arid, isotopes, contaminants*

Urban population growth in the semi-arid southwestern region of North America has been rapid since the end of World War II, when population in the USA began to shift to the desirable climates of the "sun belt", and a large population from Mexico moved into border cities in pursuit of economic opportunities afforded at the frontier. Even in cities with access to surface water, the need to supply adequate water for domestic and industrial consumption led to over-exploitation of groundwater. Well-documented examples exist in Albuquerque, New Mexico (Plummer et al. 2004) and the urban area encompassing El Paso, Texas and Ciudad Juárez, Chihuahua (Hibbs et al. 1997), where the static water levels (SWL) fell by tens of meters by the end of the 20th Century. In Tucson, Arizona, where little surface water was available, the population increased from a few thousand in the 1870s to about 1 million by 2012. Figure 1 shows population growth in Pima County, of which Tucson has long been the largest city; in latter years, as the Tucson metropolitan area has extended far beyond the city limits, the county rather than the City of Tucson population has become the better measure of the urban population. The entire metropolitan area depended completely on groundwater until a major engineering project brought Colorado River water to the city by canal in 1992 (Gelt et al. 1999). Small local declines in SWL in Tucson basin in the 1940s (Turner et al. 1943) became large, widespread declines of 15 to more than 50 m by the 1980s (Anderson 1988), and grew locally to as much as 60 m by the 1990s (Gelt et al. 1999).

The effects of over-pumping across the breadth of Tucson basin and the potential for subsidence as a result of dewatering of basin sediments have been reported elsewhere (Anderson 1988; Gelt et al. 1999; Pool and Anderson 2007). Downtown Tucson, the site of the original Spanish settlement towards the west side of the Tucson basin, presents a special case study. The nature of the basin fill (discussed below) differs from that in the broad eastern part of the basin, and there has been little pumping in the area for several decades. Furthermore, historical records offer some insight about changes in hydrologic conditions resulting from two centuries of groundwater exploitation.

In this article, the historical record of groundwater use in Downtown Tucson will

be reviewed and interpreted, and a new set of groundwater isotope data will be presented, with the aim of reconstructing the hydrologic evolution of the area since Spanish settlement.

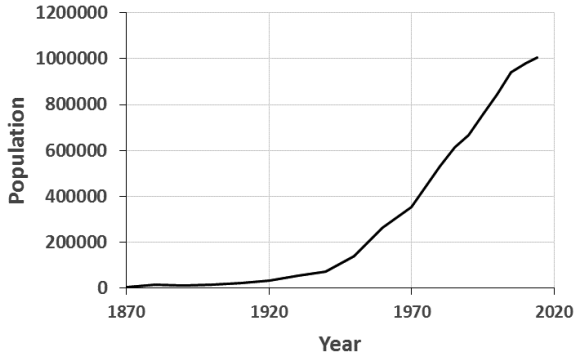

Figure 1. Population of Pima County, 1870-2012. Sources: Pima Association of Governments (2016) and U.S. Bureau of the Census (2016).

Background

Regional Setting

The Tucson basin lies within the watershed of the Santa Cruz River in southern Arizona. The basin is about 30 km (east-west) by 40 km (north-south), and is bounded by mountain ranges of crystalline rock, the Tucson, Santa Catalina, Santa Rita, and Rincon Mountains. Most of the basin floor lies at elevations near 800 meters above sea level (masl). The greater Tucson urban area, which occupies the northern half of the basin, experiences a semi-arid climate with hot summers and cool winters. Rainfall in the central area of the city averages 305 mm annually and is equally distributed between a summer monsoon with brief, localized convectional precipitation, and a fall-winter season of widespread, cyclonic precipitation events associated with Pacific cold fronts or tropical depressions (Gelt et al. 1999).

The basin is of Neogene (post 23 Ma) age, and lies within the Basin-and-Range physiographic province. Regional extension, expressed as detachment faulting followed by high-angle normal faulting, led to rapid deepening of the central part of the basin (Davidson 1973; Eberly and Stanley 1978; Anderson 1987; Dickinson 1999). The basin fill consists of up to 3000 m of alluvial and lacustrine sediments of Oligocene to Holocene age, with fluvial sediments in the flood plains of major streams. Gypsum or anhydrite evaporites occur at depth. Holocene deposits are largely confined to active flood plains. The crystalline basement consists largely of granitic gneiss with Proterozoic and Paleogene protoliths in the Santa Catalina and Rincon Mountains, and of Paleozoic and Mesozoic igneous and sedimentary rocks in the Tucson and Santa Rita Mountains. The principal geomorphic features of the basin include a number of alluvial fans and active flood plains along the major washes, e.g. the Santa Cruz River in the present study area.

Most groundwater in Tucson basin occurs within a single regional aquifer, largely unconfined, hosted in basin-fill alluvium and spanning most of the basin. Static water levels have been strongly modified by decades of pumping, but generally decrease to the northwest, in the direction of the present surface outlet (Gelt et al. 1999). Shallow perched aquifers occur where clayey sediment is common near the surface, and are largely limited to the area immediately east of the Santa Cruz River.

Study Area

This article focuses on the area close to a cross-section of about 5 km, limited to the southwest by Sentinel Peak (a ridge of Oligocene volcanic rock and associated strata jutting east from the Tucson Mountains), and to the northeast by Campbell Avenue (Figures 2 and 3). The area encompasses Downtown Tucson (the commercial center of the city prior to its rapid expansion, and the site of the 18th-Century Spanish settlement), the main campus of the University of Arizona, and part of the flood-plain of the Santa Cruz River. The area straddles the Santa Cruz Fault (Anderson 1987), a high-angle normal fault with the east side downthrown, and one of the principal faults responsible for the deepening of Tucson basin during the Neogene. The basin-fill in this area consists of recent alluvium, about 6 m thick, overlying late Pleistocene Fort Lowell Formation and the Miocene to Pliocene Upper Tinaja Beds. The Fort Lowell Formation truncates the Santa Cruz fault, and is 60 to 90 m thick in the study area. It consists of multiple lenses, varying greatly in thickness and lateral extent, of clay-rich sediment intercalated with silt and sand. The Upper Tinaja Beds consist of gravel, sand, and clayey silt, about

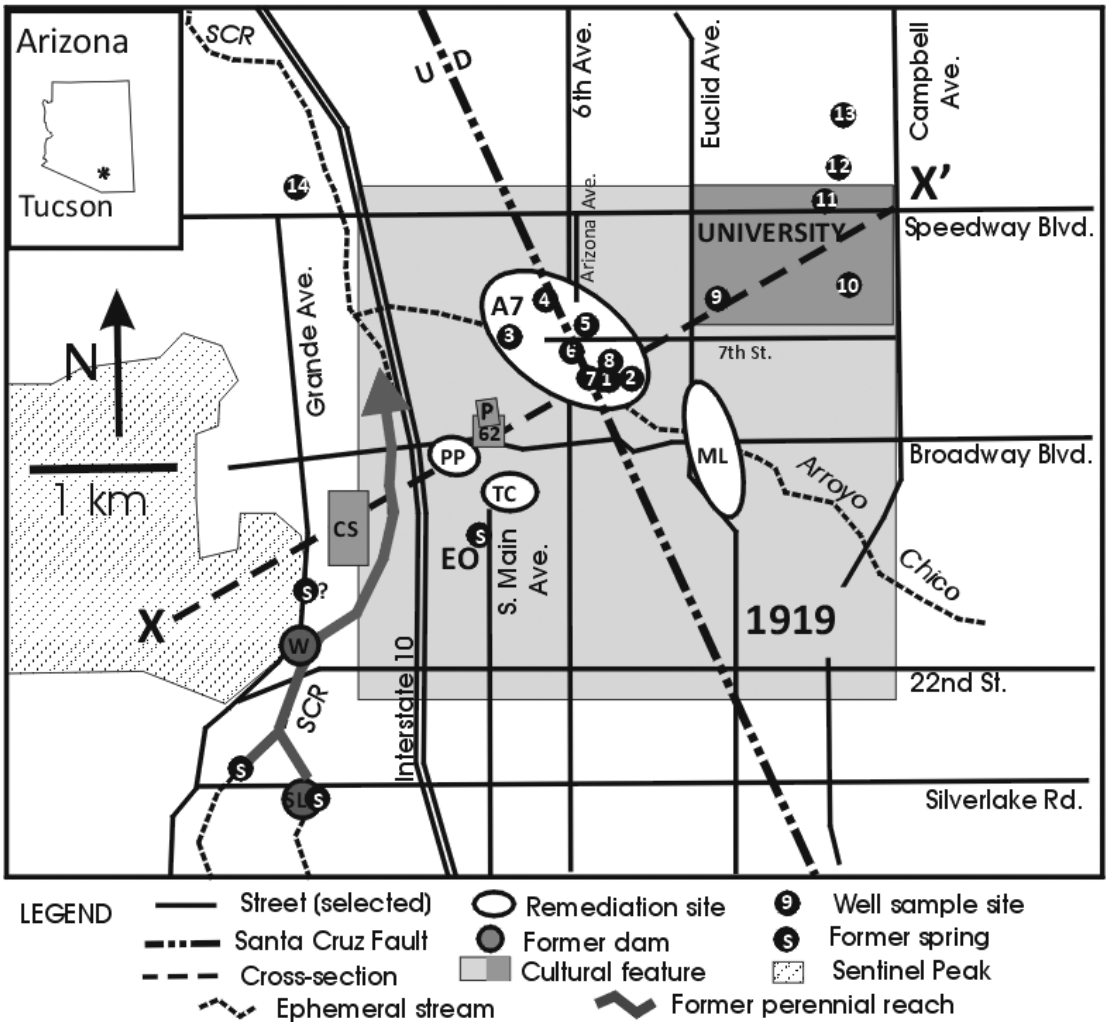

Figure 2. Map of study area. Contaminated sites are Arizona Avenue/7th Street (A7), Mission Linen (ML), Pioneer Paints (PP), and Tucson Convention Center/Police Headquarters (TC). Each contaminated site includes a cluster of wells sampled for the study. Cultural sites are Chuk Shon Village (CS), the Spanish Presidio 1775 (P), and rectangles showing the approximate extent of Tucson in 1862 (62) and 1919. Former dams/reservoirs are Silver Lake (SL) and Warner's (W). SCR = Santa Cruz River. EO = El Ojito Spring. Numbered well sites refer to identifications in Table 1. Information sources: Anderson (1987); Officer (1987); Gelt et al. (1999); Wood et al. (1999); Webb and Leake (2006);. Arizona Department of Water Resources (2016).

30 m thick on the west side of the Santa Cruz fault, and 100 m thick on the east side. (Anderson 1987; City of Tucson Environmental Services 2008). The land surface rises from 710 masl in the entrenched channel of the Santa Cruz River to 750 masl where the cross-section intersects Campbell Avenue. The regional aquifer of the Tucson basin, 3080 m below the surface, is located within the basal Fort Lowell Formation and the Upper Tinaja Beds, and is continuous beneath the study area, with SWLs between 666 and 700 masl. A perched aquifer (or possibly multiple aquifers) 10-30 m below the surface occurs atop clay strata of the Fort Lowell Formation beneath Downtown Tucson, with SWLs at 700 to 711 masl. This fully perched aquifer is locally contaminated with non-aqueous liquid phases (hydrocarbons and chlorinated solvents) discharged in the past from several commercial sites (Figure 2, sites A7, PP, TC, and ML). Both the perched and regional aquifers are at lower

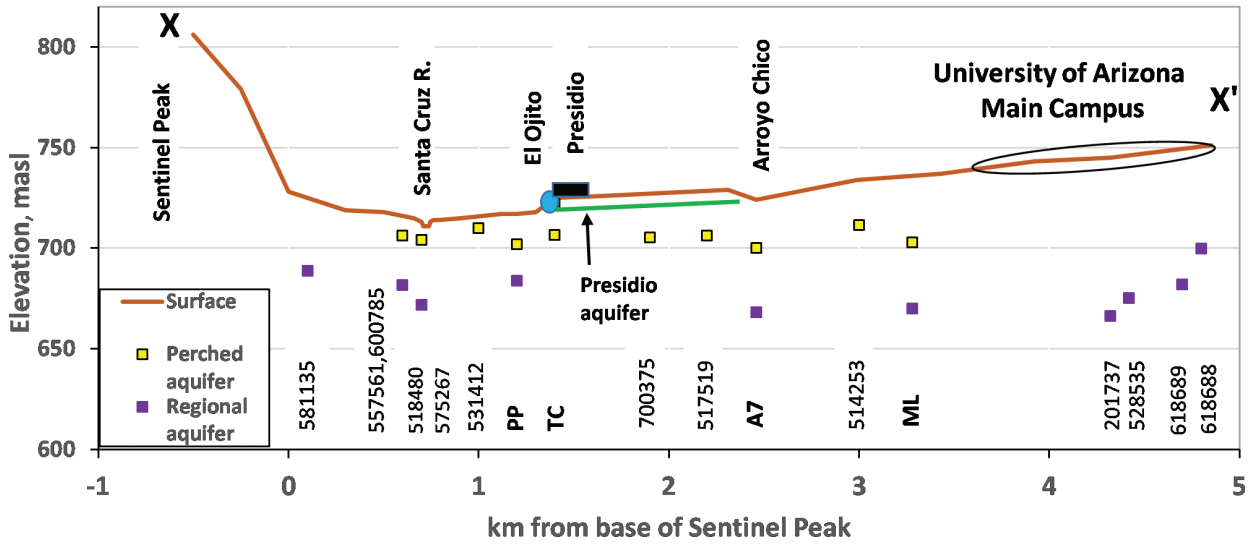

Figure 3. Cross-section of study area (see Fig. 2 for location). Well data are projected on to the section. Well registration numbers (Arizona Department of Water Resources 2016), are given in shortened form as 6 digits (xxxxxx), the full number being 55-xxxxxx.

elevation than the present entrenched bed of the Santa Cruz River. In the study area, water for domestic consumption is pumped only from the regional aquifer at the University of Arizona and from the river flood plain; in other places, samples were available from monitoring wells screened either in the perched aquifer or in the regional aquifer. Figures 3 and 4 show vertical section data derived from drillers' logs available from Arizona Department of Water Resources (2016) using selected logs in which water levels and detailed stratigraphy have been recorded.

Samples for isotope measurement were obtained from five supply wells at the University of Arizona, and from monitoring wells at the following contaminated sites:

1. Pioneer Paint and Varnish, a site contaminated with a variety of organic chemicals (SCS Engineers 2008). Samples were from three wells in the regional aquifer and five in the perched aquifer, all within area PP (Figures 2 and 3).
2. Tucson Convention Center, a site with local gasoline contamination (City of Tucson Environmental Services 2008), with samples from six perched-aquifer wells in area TC (Figures 2 and 3).
3. Arizona Avenue/Seventh Street, a tetrachloroethane (PCE)-contaminated site (Kafura 2007), with samples from two regional-aquifer and six perched-aquifer wells in area A7 (Figures 2 and 3).
4. Mission Linen Superfund site (area ML of Figures 2 and 3, contaminated with chlorinated hydrocarbons), with samples from two perched-aquifer and four regional-aquifer wells.

Previous Groundwater Isotope Research

Previously reported isotope data for groundwater in the study area are available only for wells at the University of Arizona, for the Mission Linen remediation site, and for a few wells in the Santa Cruz flood plain (Kalin 1994; Eastoe et al. 2004; Gu 2005). Eastoe et al. (2004) provided a framework, to be used in this article, for interpreting the origin of Tucson basin groundwater. They presented basin-wide maps of $\delta^{18}O$, $\delta^{34}S$, ^{3}H, and ^{14}C in groundwater, and identified the following: 1.) Localized zones of recent recharge extending several km into the basin from the mountain fronts; 2.) A zone of upward discharge of ancient groundwater, apparently associated with the Santa Cruz fault; and 3.) Distinctive groundwater domains identified by O (water) and S (sulfate) isotope data

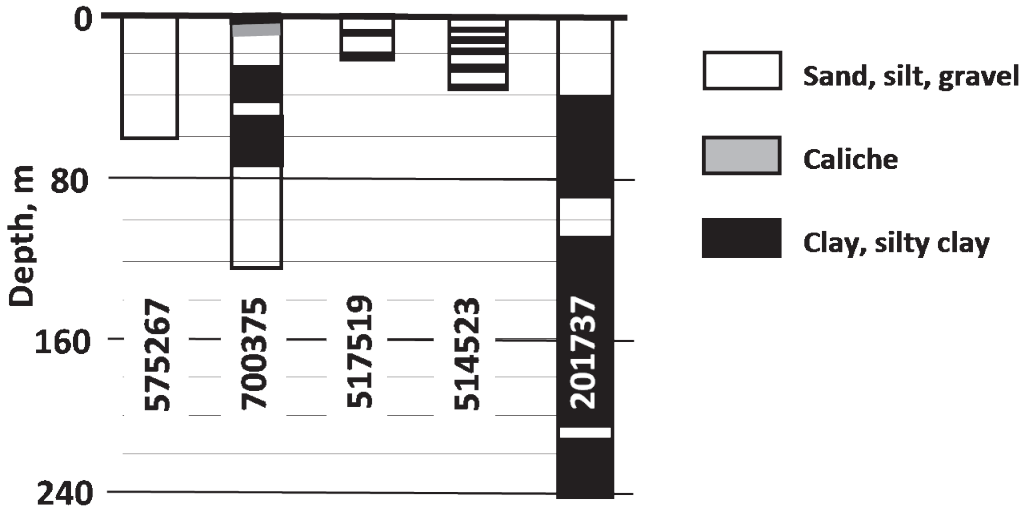

Figure 4. Stratigraphic data from selected drillers' logs (Arizona Department of Water Resources 2016). Well registration numbers are given in shortened form as 6 digits (xxxxxx), the full number being 55-xxxxxx.

in combination, and related to recharge originating from larger streams conveying surface water into the basin. Domain names that will be used here include: A, related to recharge of mountain-derived water from Rillito Creek and its northern tributaries; B, related to the Santa Cruz River; C, related to Cienega Creek; D, related to mountain-derived groundwater possibly discharging upward in the southeastern part of the basin; E, related to Rincon Creek; and F, in the southern part of the basin. The domain map of Tucson basin is shown in Figure 5a, and ranges of $\delta^{18}O$ and $\delta^{34}S$ for domains A to D are shown in Figure 6. Gu (2005) noted that groundwater extraction between the early 1990s (samples of Kalin 1994) and 2000-2005 had led to local replacement of Domain D water by Domain A water (Figure 5b).

Methods

Historical Review

The information presented here is largely drawn from recent historical works in which a review of the primary historical sources is documented.

Sampling and Analyses

Groundwater samples were obtained from active supply wells at the University of Arizona, and during routine sampling campaigns of monitoring wells at several contaminated sites. Isotope measurements were performed at the Environmental Isotope Laboratory, University of Arizona. Stable O and H isotopes of water were 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). Stable S isotopes of sulfate extracted as $BaSO_4$ were measured on a Thermo Electron Delta Plus XL® continuous flow mass spectrometer equipped with a Costech® elemental analyzer for preparation of SO_2. Tritium was measured on 0.18 L water samples after electrolytic enrichment. Carbon-14 was measured on CO_2 extracted from 50 L water samples by acid hydrolysis of dissolved inorganic carbon; the carbon was converted to benzene. Both tritium and carbon-14 were measured in a Quantulus 1220® Spectrometer by liquid scintillation counting. Routine analytical precisions (1σ) are 0.08‰ (O), 0.9‰ (H), 0.15‰ (C), and 0.15‰ (S). Routine detection limits are 0.6 TU for ^3H and 0.2 percent modern carbon (pMC), ^{14}C, undiluted sample.

Correction of ^{14}C Data

The procedure follows Clark and Fritz (1997, 210 ff), using the method based on mixing of stable carbon isotopes, assuming a C_3:C_4 ratio of 3:1 in decaying plant matter in soil, slightly alkaline conditions of initial infiltration of

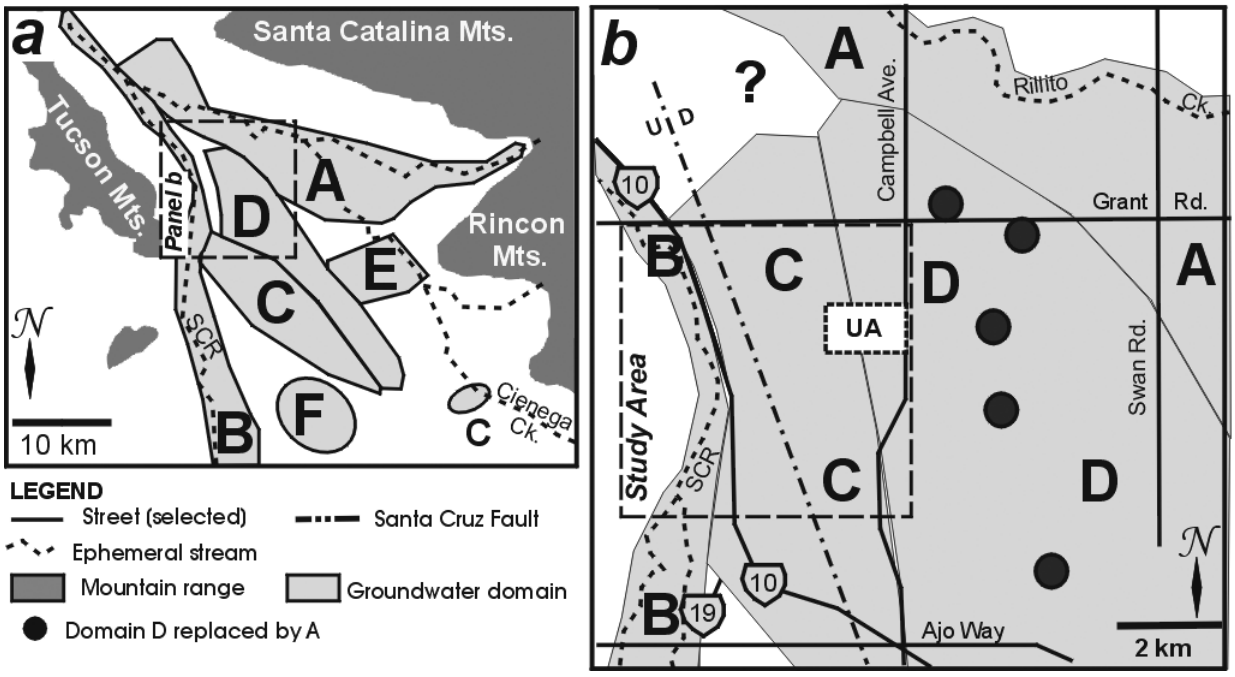

Figure 5. (a) Water domain map of Tucson Basin, after Eastoe et al. (2004); **(b)** Updated water domain map of the area encompassing the study area. UA = University of Arizona; SCR = Santa Cruz River; shaded areas labeled A, B, etc. are domains A, B, etc.

rainwater, and $\delta^{13}C$ values of -1 or -2‰ for rock carbonate (unpublished data of the Laboratory of Environmental Geochemistry). This set of assumptions has been found to yield plausible results for Tucson Basin, with dilution ratios between 0 and 1, and corrected ^{14}C activities less than about 150 pMC.

Review – History of Groundwater Use in Tucson

Father Eusebio Kino, an early emissary of the Spanish Empire, travelled to the area now occupied by Tucson in the 1690s. There he encountered two villages, Wa:k and Chuk Shon, of the Tohono O'odham people (known previously to Europeans as the Papago), several hundred households in total (Sonnichsen 1982; Officer 1987). Each village depended on surface water from short (a few kilometers) perennial reaches of the Santa Cruz River. Water was conveyed from the river to fields around the villages through a system of controlled ditches (Kupel 1986). There is no indication of more extensive perennial reaches in the historical record (Wood et al. 1999; Logan 2002). The water discharged in stream-bed springs from upstream groundwater basins across sills of impermeable rock (Wood et al. 1999). Another spring is reported near Chuk Shon, at the foot of Sentinel Peak (Sonnichsen 1982), but other authors do not mention it; Sonnichsen may have been referring to one of the stream-bed springs. The Chuk Shon perennial reach terminated near the village, or at times a few kilometers downstream (Bourke 1891; Sonnichsen 1982). Native Americans already had a long history of water engineering in the area. About 3000 years ago, canals channeled ephemeral stream water to a settlement known to archaeologists as Las Capas, 15 km downstream of the present city center (Palacios-Fest et al. 2001). Systems of controlled irrigation ditches and shallow dug wells in the flood plain have been excavated in a site dating from 1000 years ago (Logan 2002).

What had been a sufficient water supply for the Tohono O'odham residents became inadequate in the decades following the founding of the Spanish Presidio (fort) on a low mesa opposite Chuk Shon (Figure 2) in 1775. The Presidio was to become the nucleus of Tucson. Any appropriation of local surface water for the domestic and agricultural

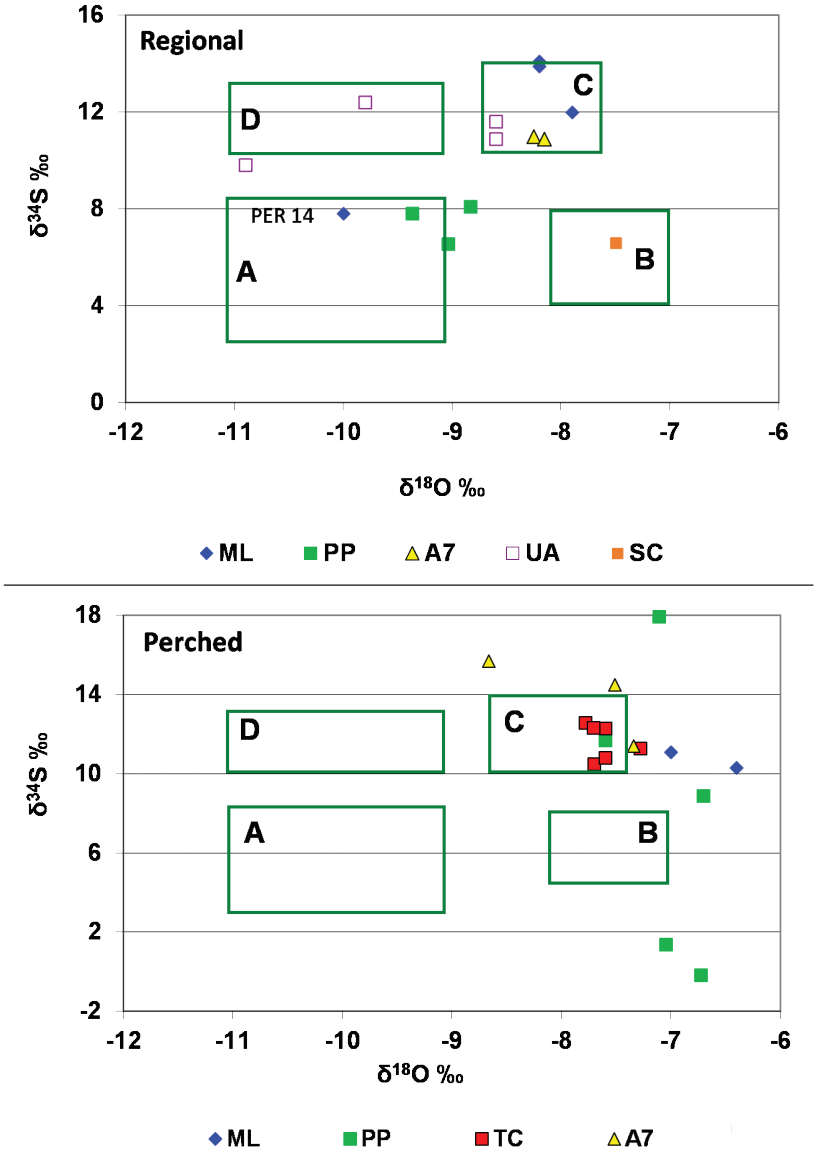

Figure 6. Stable S isotope (sulfate) and O isotope (water) data for the perched and regional aquifers in the study area. Fields A, B, C, and D correspond (with slight modification of field C) to basin-wide groundwater domains as defined in Eastoe et al. (2004).

needs of the few hundred residents of the Presidio inevitably left the Chuk Shon village with insufficient water (Sonnichsen 1982). The site of the presidio was close to El Ojito ("the little spring"), variously described as a spring, a well, and an artesian well (Officer 1987; Logan 2002), from which domestic water was drawn until the 1880s. This may originally have been a spring into which a well was excavated as the supply declined. The water supply was augmented from dug wells within the Presidio and the adjacent Mexican village. Water was encountered within 4 to 5 m of the surface, and it is said to have deteriorated in quality after a brief period of exploitation (Kupel 1986). Local tradition (e.g., Arizona Historical Society 2016) attributes the final drying of El Ojito and the shallow aquifer beneath the village to the 1887 earthquake with epicenter near Bavispe, Sonora. While acute hydrological phenomena correlating with the earthquake are plausibly documented elsewhere in southeastern Arizona, Dubois and Smith (1980) cited no textual reference earlier than Bennet (1977) as evidence of possible hydrological effects in Tucson.

Modest population growth in the latter half of the 19th Century and competition for water between the townspeople and farmers led to the initiation of engineering projects to enhance water supply from surface water and groundwater. Low dams were built on the Santa Cruz River in 1859 (Silver Lake) and 1870 (Warner's) to impound flow from the stream-bed springs supplying the Chuk Shon perennial reach (Figure 2); these provided power to flour mills, and controlled water for irrigated fields, mainly on the flood plain west of Tucson (Kupel 1986; Officer 1987, 289). The river bed adjacent to Tucson was excavated by Sam Hughes in 1887 in an attempt to recover shallow riparian groundwater (Logan 2002). Finally, as steam-driven pumps and drills became available, the community developed well-fields in order to exploit deeper groundwater. The first was about 1 km south of the town-site, and, in 1893, another was installed in the Santa Cruz flood plain 10 km south of the town (Kupel 1986; Logan 2002).

The excavation in the river bed by Sam Hughes was followed by a series of large floods in the late 1880s, and the excavation became the point of initiation of an entrenched river reach that grew to 29 km by 1920. Local tradition (e.g., Logan 2002) holds that the excavation was the principal cause of the entrenchment, which persists to the present. However, similar entrenchments began concurrently elsewhere in the southwestern USA (Bryan 1925) and a number of human-associated and climatic factors may have favored the regional entrenchment of watercourses (Betancourt 1990). The 1-5 m entrenchment along the Santa Cruz River permanently lowered the water table of the flood plain, destroyed the dams, and forced the construction of more complicated diversion canals for irrigation (Logan 2002).

Kupel (1986) outlined the subsequent history of groundwater use in Tucson, summarized briefly here. Artesian water was located at the foot of Sentinel Peak in 1896, but no further such discoveries followed near the town. Evolving pump technology put deeper groundwater resources within reach of the community, and provided it with a water supply through most of the 20th Century. By the 1960s, SWLs in the study area had fallen 15-30 m relative to pre-development levels (Anderson 1987). In the second half of the century, population growth became so rapid, and the demand for potable water so large, that the finite nature of the groundwater supply and the need for water conservation were recognized in civic deliberations. The advent of the Central Arizona Project, channeling Colorado River water to Tucson, enabled the city to provide an alternative water source, and to cease pumping from its central well field by the 1990s. The urban population, however, continues to increase (Figure 1).

Two Tucson place names might suggest a historical association with groundwater. Dunbar/Spring Neighborhood, immediately north of Downtown Tucson, is in fact named for pioneer residents Paul Dunbar and John Spring, and was not the site of a spring (Dunbar/Spring Neighborhood Association 2016). Flowing Wells Irrigation District, 7-8 km north of downtown, began as the Flowing Wells Water Company exploiting the artesian groundwater near Sentinel Peak, and later moved its operations to its present territory where no artesian wells are recorded (Kupel 1986).

Isotope Data

Data are listed in Table 1. Figure 6 shows new S and O isotope data for the perched and regional aquifers in the study area in relation to domain classification of Eastoe et al. (2004). Figure 7 shows O and H isotope data for the two aquifers. The interpretation of δD *vs*. $\delta^{18}O$ plots such as Figure 7 is based on the following general observations (more details can be found in Clark and Fritz 1997, and references therein). At most locations worldwide, annual averages of O and H isotopes in precipitation plot on a line of slope near 8, the Global Meteoric Water Line (GMWL). Partially evaporated meteoric waters plot to the right of the GMWL. Progressive evaporation of a particular sample of water yields residual water having isotope compositions plotting on a line with slope commonly between 3 and 5, depending on relative humidity.

Considering Figures 6 and 7 in conjunction, the following observations emerge:

Perched aquifer

Most samples plot within or very close to the domain C box in Figure 6, indicating the dominance

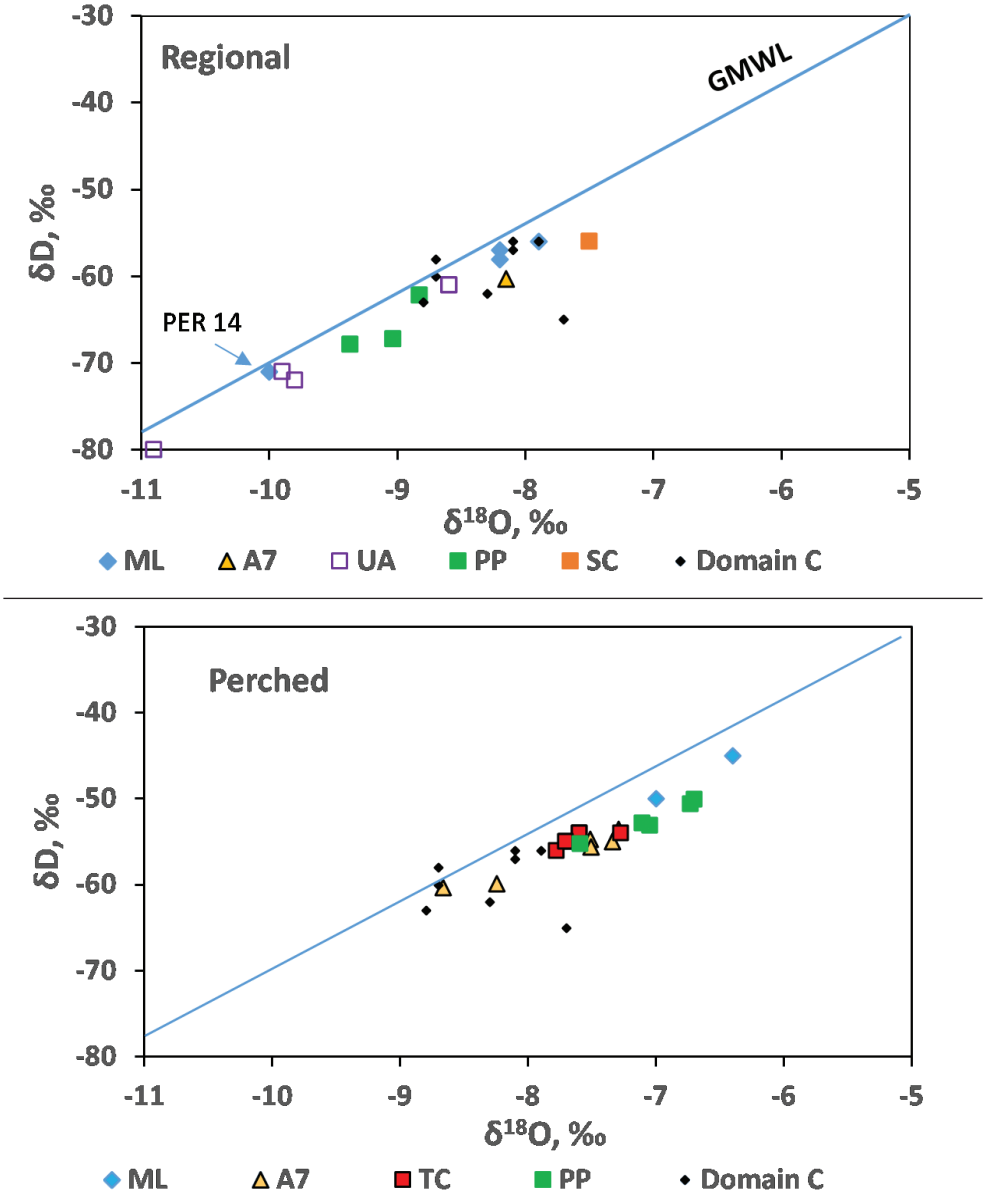

Figure 7. Stable O and H isotope data for the perched and regional aquifers. Data for domain C water from Eastoe et al. (2004).

of sulfate from domain C water. Outliers, from sites ML and PP, to the right of box C can be explained by reference to Figure 7, where the δD and $\delta^{18}O$ data plot on one or more evaporation trends of slope near 4.5; the outliers correspond to the more evaporated samples. The trend emerges from the field of domain C samples in parts of Tucson basin upgradient from the study area (data from Eastoe et al. 2004). Site PP has a very broad range of $\delta^{34}S$, 0 to +18‰. No water from domains A, B, and D was detected. The two samples from the ML site contained elevated tritium (15 and 40 TU) when sampled in 2003.

Regional Aquifer

The O and H isotope data (Figure 7) have domain C water as one end member, but in contrast to the perched aquifer, extend to more negative values typical of domains A and D. Domain C water is found at the UA, ML, and A7 sites. Domain D

Table 1. Well Data and Analyses.

Area Well (screen, mbgs)	ADWR Reg. No. 55-	Aquifer	Collar altitude masl	Depth mbgs	SWL masl	$\delta^{18}O$ water ‰	δD water ‰	$\delta^{34}S$ sulfate ‰	Tritium TU	^{14}C pMC	$\delta^{13}C$ DIC ‰	Corr. age Ka
ML (sampled 2003)												
UAM 1 (63-81)		RC	724.7	82.1	658.3	-8.2	-58	14.1	1.0			
UAM 2 (61-79)		RC	724.7	80.6	660.2	-8.2	-57	13.9	1.9			
PER 14 (143-159)		R	732.7	158.5	681.5	-10.0	-71	7.8	<0.6	15.7	-7.2	12
MLR-1 (79-105)		R	731.6	106.1	677.7	-7.9	-56	12.0	<0.7	20.1	-8.6	8
PEP-11		P	733.7	30.3	704.9	-6.4	-45	10.3	14.8			
PEP-19		P	731.7	30.3	702.9	-7.0	-50	11.1	39.6			
PP (sampled 2008)												
WR250A	535809	P	717	13.6	706.1	-7.1	-53	17.9				
WR251A	541080	P	717	13.6	706.1	-7.0	-53	1.4				
WR252A	542382	P	717	13.6	706.1	-7.6	-55	11.7				
WR269A	556250	P	717	15.2	706.4	-6.7	-50	8.9				
PPM529A	907396	P	717	17.3	701.8	-6.7	-51	-0.2				
WR248A	529533	R	717	42.4	683.7	-8.8	-62	8.1				
WR249A	529534	R	717	53.0	683.7	-9.4	-68	7.8				
WR271A	556258	R	717	42.4	682.2	-9.0	-67	6.6				
TC (sampled 2008)												
CEP-518A	906115	P	726	23.0		-7.7	-55	10.5				
CEP-519A	906116	P	726	21.8	707.5	-7.6	-54	10.8				
CEP-520A	906117	P	726	21.8	707.5	-7.6	-54	12.3				
HQUST531A	907928	P	726	22.4	706.9	-7.8	-56	12.6				
HQUST532A	907927	P	726	22.1	706.9	-7.7	-55	12.3				
HQUST533A	907929	P	726	21.8	707.5	-7.3	-54	11.3				

Table 1 Continued.

Area Well (screen, mbgs)	ADWR Reg. No. 55-	Aquifer	Collar altitude masl	Depth mbgs	SWL masl	$\delta^{18}O$ water ‰	δD water ‰	$\delta^{34}S$ sulfate ‰	Tritium TU	^{14}C pMC	$\delta^{13}C$ DIC ‰	Corr. age Ka
A7 (sampled 2007)												
1 MW-PD-6		P	722.1		700.8	-7.7	-55					
2 MW-PD-7		P	721.9		700.9	-7.3	-54					
3 MW-PD-31		P	715.9		698.6	-8.7	-60	15.7				
4 7AZP-6		P	722.5		697.9	-7.5	-55	14.5				
5 7AZP-7		P	722.8		699.6	-7.3	-55	11.4				
6 YC-6		P	718.9		699.1	-7.5	-56					
7 MW-PD-19 R		R	720.0		667.6	-8.2	-60	11.0				
8 7AZR-1 R		R	720.0		667.1	-8.2	-60	10.9				
UA (sampled 2006-2010)												
9 Park Av. (206-297)	217003	R	737	306.1		-10.9	-80	9.8		4.4	-8	19-20
10 Optical Sciences	201737	R	745	206.0	666.2	-9.8	-72	12.4	<0.5	9.7	-7.2	7-8
11 North cooling	528535	R	747	212.1	674.3	-9.9	-71		<0.9			
12 UMC South	618689	R	748	121.2	681.9	-8.6	-61	10.9	0.7			
13 UMC North	618688	R	743	139.4	697.8	-8.6	-61	11.6	<0.4	14.8	-8.6	11-12
SC (sampled 1999)												
14 Arizona School for Deaf and Blind	600785	R	712	127.3	681.7	-7.5	-57	6.6	11.1			

Explanation: No entries where data are unavailable

ADWR Reg. No. = Arizona Department of Water Resources registration number

mbgs = meters below ground surface

SWL = static water level

masl = meters above sea level

RC = regional, confined

TU = tritium units

R = regional

P = perched

water is found at the UA site, and domain A water at the ML and PP sites (Figure 6). Domain B water was encountered only in the flood plain of the Santa Cruz River. Available tritium measurements (tritium units, TU) are either low (0.7 to 1.9 TU) relative to the 5.2 TU average for Tucson rain (Eastoe et al. 2011) or below detection. Available ^{14}C measurements show low ^{14}C content, 4 to 15 percent modern carbon (pMC). Wells 10 and 13 at the UA site have corrected bulk residence times of 7-8 and 11-12 Ka. The Park Avenue well (9) at the UA site is 300 m deep, much deeper than other wells in the study area, and has unusually low $\delta^{18}O$ values (-10.9‰) for this part of the basin where most water has $\delta^{18}O$ values between -9 and -10‰ (Eastoe et al. 2004). The Park Avenue well (9) also has the lowest pMC measurement, 4.4, of the entire data set for Tucson basin, corresponding to bulk residence ages of 19 to 20 Ka.

Vertical Structure of Regional Aquifer

The ML site, with wells screened at four different depth ranges (Table 1), provides a view of the complexity of the regional aquifer in the area (Figure 8). The upper part of the aquifer, corresponding to screens 61-81 m below the surface, is essentially unconfined (the SWLs lying below those of the perched aquifer), and the samples contained tritium at 1.0 and 1.9 TU. Two deeper wells (MLR-1 and PER 14) intersect a confined, pressurized aquifer with SWLs higher than those of the overlying aquifer, and containing water with bulk residence ages of 8 Ka (screen 79-105 m below the surface) and 12 Ka (PER 14, screen 143-159 m below the surface). The unconfined aquifer and the upper part of the confined aquifer contain domain C water, while sample PER 14 is domain A water. The Park Avenue (9) well 1 km to the north, screened at 206-297 m below the surface, yields water close to domain D composition (Figure 6).

Discussion

Perched Aquifers

Drillers' logs indicate a complex interlayering of clay-rich and coarser clastic units within the Fort Lowell Formation beneath Downtown Tucson. While the continuity of individual clay units is not evident from the logs (Figure 4), the presence of a perched aquifer at 700 to 711 masl beneath most of the study area suggests that at least one such unit is continuous across the study area. This impermeable layer has prevented a variety of contaminants from infiltrating to greater depths below the study area.

Historical descriptions of shallow water beneath the Spanish Presidio in the late 18th Century imply the existence of a higher perched aquifer (Presidio aquifer, Figure 3) at that time, presumably atop one

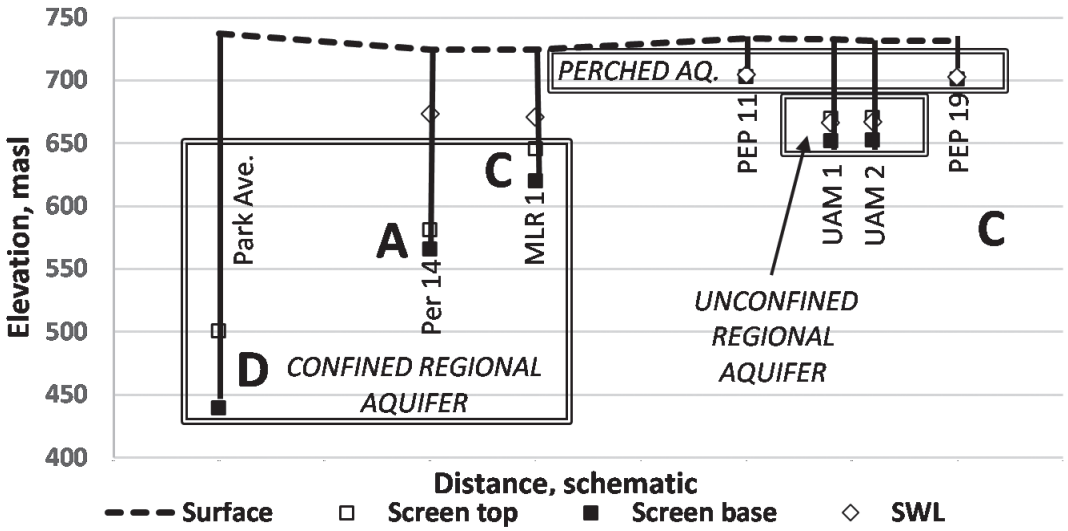

Figure 8. Schematic section of the perched and regional aquifers at the ML site and the Park Avenue (9) well. Bold vertical lines indicate wells. A, C, and D refer to water domain types, as described in the text.

of the shallow clay aquitards in the area (Figure 4). The aquifer was most likely recharged from Arroyo Chico to the east and north of the Presidio or from smaller washes that pass through the study area, and discharged at El Ojito spring. The Presidio aquifer dried up by the late 19th Century, an event that may have coincided roughly with the 1887 earthquake, but may equally have been the first negative consequence of human activities (over-exploitation, or deepening of wells through the aquitard beneath the aquifer).

The present-day perched aquifer receives recharge from Arroyo Chico at the ML site. The high tritium content at that site is either from bomb-spike tritium, 1960-1970, or from tritium released from the nearby American Atomics factory between 1970 and 1980 (Eastoe et al. 2011). The recharge is evaporated, and mixing of such water with domain C water generates the isotope trend in Figure 7. Domain C water originates from Cienega Creek in the southeastern part of the basin (Figure 5a) and is labeled by Permian marine sulfate that is not present in the study area (Eastoe et al. 2004). The presence of domain C water in the perched aquifer shows that the pre-development regional water table was above the present perched aquifer, and that what is now a perched aquifer was a part of the regional aquifer.

The broad range of $\delta^{34}S$ (-0.2 to +17.9‰) at site PP is unusual in Tucson basin, where most groundwater has values between +4 and +15‰ (Eastoe et al. 2004). The higher values may reflect partial sulfate reduction by microbes exploiting organic liquids as a carbon substrate. The lower values remain unexplained, but may be related to chemical contamination at the site, for example by sulfuric acid, which is commonly used as a paint remover and generally has a $\delta^{34}S$ value around 0 ‰.

Regional Aquifer

Prior to development, the regional aquifer beneath Downtown Tucson contained mainly domain C water, as indicated by residual water in the perched aquifer. In its present form, it is a set of unconfined and confined units containing, from upper to lower layers, water of domains C, A, and D. The decline in level of the regional aquifer has been due to basin-wide pumping, and presumably led to the isolation of the perched aquifer prior to the 15-30 m fall in water levels mapped beneath Downtown Tucson by Anderson (1988).

An updated version of the basin-wide water domain map for the regional aquifer (Figure 5b) shows that domain A water appears beneath the Downtown study area at sites PP and ML, remote from its main occurrence near Rillito Creek and its tributaries, but localized near the Santa Cruz fault. At site ML, the domain A water is ancient (Table 1). Upward discharge of ancient domain A water close to the fault also occurs elsewhere in Tucson basin (Eastoe et al. 2004), and appears to be a basin-scale phenomenon. Domain A water has also replaced domain D water outside the Downtown study area at several sites sampled in the early 1990s (Kalin 1994) and repeated in the early 2000s (Gu 2005). These changes have coincided with, and are most likely due to, basin-wide decline in the level of the regional aquifer (Gelt et al. 1999).

Role Of The Santa Cruz River

The original SWL of the regional aquifer was probably limited by the altitude of the pre-entrenchment channel of the Santa Cruz River, into which the aquifer most likely discharged. Eastoe et al. (2004) noted very limited eastward infiltration of domain B water from the Santa Cruz flood plain, but left open the possibility that the Downtown area, at that time unstudied, might form part of domain B. The present study shows that no infiltration from the flood plain has reached either the perched or the regional aquifer at the Downtown sampling sites. Prior to development, river water could not displace domain C water present at higher elevations. The present-day regional aquifer appears to have lower SWLs in the flood plain, where it is heavily pumped upgradient of the study area, than immediately to the east beneath Downtown, where it is not pumped (Figure 3). Infiltrating river water appears to remain in the relatively unconsolidated sediment of the flood plain, rather than moving laterally into the perched and regional aquifers.

Management Implications

The decline of the regional aquifer to levels below those of the present perched aquifer beneath Downtown Tucson has fortuitously isolated a variety of dangerous contaminants above an

aquitard, as noted above. This observation, while not part of the findings of this study, has clear implications for aquifer management in the Downtown area. Wells continue to be drilled in the area for water quality monitoring, or for supply of non-potable water (e.g., well 700375, Arizona Department of Water Resources 2016). New wells must be properly constructed, and old wells carefully decommissioned, so as to prevent downward leakage from the perched aquifer. Groundwater in the contaminated perched aquifer moves slowly (City of Tucson Environmental Services 2008). This study has identified a recharge zone of the perched aquifer along Arroyo Chico at the ML site, and shown that recharge since the separation of the perched and regional aquifers has been insufficient to date to flush old regional aquifer water from the perched aquifer. Such information may be of use in future management of the perched aquifer contaminants.

Conclusions

Since European settlement began in Tucson 240 years ago, groundwater conditions have deteriorated steadily. The small perched aquifer that supported the first settlement dried by the late 1800s. Water levels in the regional aquifer have fallen, in the first instance as a result of stream-bed entrenchment and then as a result of riparian groundwater pumping, leading to the loss of stream-bed springs. Evolution of pumping technology and rapid growth of population during the 20th Century led to accelerating declines in the regional aquifer, and the isolation of a second perched aquifer in the Downtown area.

New isotope data show that domain C groundwater of Eastoe et al. (2004) dominated the regional aquifer in the study area before the rapid decline in water level. Domain C water is ultimately derived from Cienega Creek to the southeast and is estimated to have taken 8 to 12 Ka to flow across Tucson basin to Downtown. Since its isolation from the regional aquifer, the perched aquifer has received a little recharge from Arroyo Chico, but insufficient to flush out residual domain C water. Samples from the lowered regional aquifer include mountain-derived groundwater (domains A and D), with the domain A water supplied by upward discharge along the Santa Cruz fault. No recharge from the Santa Cruz River has been detected.

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References

Anderson, S.R. 1987. *Cenozoic Stratigraphy and Geologic History of the Tucson Basin, Pima County, Arizona*. Water Resources Investigation Report, 87-4190. United States Geological Survey, Tucson, Arizona.

Anderson, S.R. 1988. Potential for aquifer compaction, land subsidence, and earth fissures in the Tucson

basin, Pima County, Arizona. *United States Geological Survey Hydrologic Atlas* 713, 3 plates.

Arizona Department of Water Resources. 2016. Well Registry. Available at https://gisweb.azwater.gov/waterresourcedata/WellRegistry.aspx. Accessed October 5, 2016.

Arizona Historical Society. 2016. Education and Outreach. Available at http://www.arizonahistoricalsociety.org/education/esperanza/tucson/sites/. Accessed October 5, 2016.

Bennet, E.F. 1977. An afternoon of terror. *Arizona and the West: A Quarterly Journal of History* 19(2): 107-120.

Betancourt, J.L. 1990. Tucson's Santa Cruz River and the arroyo legacy. Unpublished dissertation, University of Arizona, Tucson, Arizona.

Bourke, J.G. 1891. *On the Border with Crook*. Charles Scribner's Sons, New York.

Bryan, K. 1925. Date of channel entrenching (arroyo cutting) in the arid southwest. *Science* 62(1607): 338-344.

City of Tucson Environmental Services. 2008. City of Tucson Central Energy Plant: Site Assessment and Closure Report. Available at https://www.tucsonaz.gov/files/es/cep_short.pdf. Accessed October 5, 2016.

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

Davidson, E.S. 1973. *Geohydrology and Water Resources of the Tucson Basin*. United States Geological Survey Water Supply Paper 1939-E.

Dickinson, W.R. 1999. Geologic framework of the Catalina foothills, outskirts of Tucson (Pima County, Arizona). *Arizona Geological Survey Contributed Map* CM-99-B.

Dubois, S.M. and A.W. Smith. 1980. *The 1887 Earthquake in San Bernadino Valley, Sonora: Historical Accounts and Intensity Patterns in Arizona*. Arizona Bureau of Geology and Mineral Technology, Tucson, Arizona.

Dunbar/Spring Neighborhood Association. 2016. About the Dunbar/Spring Neighborhood. Available at http://dunbarspring.org/content/about-dunbar-spring-neighborhood. Accessed October 5, 2016.

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

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(1): 87-93.

Eberly, L.B. and T.B. Stanley, Jr. 1978. Cenozoic stratigraphy and geologic history of southwestern Arizona. *Bulletin of the Geological Society of America* 89(6): 921-940.

Gelt, J., J. Henderson, K. Seasholes, B. Tellman, and G. Woodard. 1999. *Water in the Tucson Area: Seeking Sustainability.* University of Arizona Water Resources Research Center, Issue paper No. 20, Tucson, Arizona.

Gu, A. 2005. Stable isotope geochemistry of sulfate in groundwater of southern Arizona: Implications for groundwater flow, sulfate sources, and environmental significance. Unpublished dissertation, University of Arizona, Tucson, Arizona.

Hibbs, B.J., R.N. Boghici, M.E. Hayes, J.B. Ashworth, A.N. Hanson, Z.A. Samani, J.F. Kennedy, and R.J. Creel. 1997. *Transboundary Aquifers of the El Paso/Ciudad Juarez/Las Cruces Region*. Contract Report, Texas Water Development Board. Austin & New Mexico Water Resources Research Institute, Las Cruces, New Mexico.

Kafura, C. 2007. Personal Communication.

Kalin, R.M. 1994. The hydrogeochemical evolution of the groundwater of the Tucson basin with application to 3-dimensional groundwater flow modeling. Unpublished dissertation, University of Arizona, Tucson, Arizona.

Kupel, D.E. 1986. Diversity through adversity. Tucson basin water control since 1854. Unpublished thesis, University of Arizona, Tucson, Arizona.

Logan, M. 2002. *The Lessening Stream. An Environmental History of the Santa Cruz River*. University of Arizona Press, Tucson, Arizona.

Officer, J.E. 1987. *Hispanic Arizona, 1536-1856*. University of Arizona Press, Tucson, Arizona.

Palacios-Fest, M.R., J.B. Mabry, F. Nials, J.P. Holmlund, E. Miksa, and O.K. Davis. 2001. Early irrigation systems in southeastern Arizona: The osctracod perspective. *Journal of South American Earth Sciences* 14(5): 541-555.

Pima Association of Governments. 2016. Demographics. Available at http://www.pagregion.com/Default.aspx?tabid=104#Facts. Accessed October 6, 2016.

Plummer, L.N., L.M. Bexfield, S.K. Anderholm, W.E. Sanford, and E. Busenberg. 2004. *Geochemical*

Characterization of Ground-water Flow in the Santa Fe Group Aquifer System, Middle Rio Grande Basin, New Mexico. United States Geological Survey Water-Resources Investigation Report 03-4131.

Pool, D.R. and M.T. Anderson. 2007. *Ground-water Storage Change and Land Subsidence in Tucson Basin and Avra Valley, Southeastern Arizona, 1998-2002*. United States Geological Survey Scientific Investigations Report 2007-5275.

SCS Engineers. 2008. *Groundwater Summary Report, Pioneer Paint and Varnish Site.* 471 West Congress St., Tucson, Arizona. Available at https://www.tucsonaz.gov/files/es/471_W_Congress_Groundwater_Summary_Report_FINAL.pdf. Accessed October 6, 2016.

Sonnichsen, C.L. 1982. *Tucson, the Life and Times of an American City*. University of Oklahoma Press, Norman, Oklahoma.

Turner, S.F. and others. 1943. *Groundwater Resources of the Santa Cruz Basin, Arizona*. Tucson, United States Geological Survey Open File Report 43/5.

U.S. Bureau of the Census. 2016. *Arizona, Population of Counties by Decennial Census: 1900 to 1990*. Available at https://www.census.gov/population/cecounts/az190090.txt. Accessed October 6, 2016.

Webb, R.H. and S.A. Leake. 2006. Ground-water surface-water interactions and long-term changes in riverine riparian vegetation in the southwestern United States. *Journal of Hydrology* 320(3-4): 302-323.

Wood, M.L., K. House, and P.A. Pearthree. 1999. *Historical Geomorphology and Hydrology of the Santa Cruz River*. Arizona Geological Survey Open-File Report 99-13.