Groundwater

Identifying Recharge from Tropical Cyclonic Storms, Baja California Sur, Mexico

by Christopher J. Eastoe[1], Greg Hess[2], and Susana Mahieux[3]

Abstract

Groundwater in the Todos Santos watershed in southern Baja California, and throughout the peninsula south of latitude 28°N, has values of ($\delta^{18}O$‰, δD‰) ranging between (−8.3, −57) and (−10.9, −78). Such negative values are uncharacteristic of the site latitude near the sea level. Altitude effects do not explain the isotope data. Tropical depressions originating along the Pacific coast of North America yield rain with isotopic depletion; rain from these weather systems in southern Arizona commonly has $\delta^{18}O$ values < -10‰ in comparison with amount-weighted mean summer and fall rain at −6‰. Isotope data indicate hurricane rain as the predominant source of recharge in southern Baja California, where named tropical depressions bring large rains (>50 mm) at least once every 2 to 3 years, and along the Pacific coast between Jalisco and Oaxaca.

Introduction

In 2009, Clear Creek Associates, in association with Niparajá A.C., conducted an isotope study of groundwater in the Todos Santos watershed, Baja California Sur (BCS), Mexico, to evaluate the origin of water. An earlier sampling had been undertaken in 2000 by Niparajá A.C. A group of springs and wells in the alluvial aquifer of the watershed produces potable water essential to human settlement and agriculture in the area. The unexpectedly low values of $\delta^{18}O$ and δD encountered in the study led to comparisons with isotope data for groundwater in other parts of Baja California and for hurricane precipitation near the Gulf of Mexico. Also examined were data for precipitation from Tucson, Arizona, where tropical depressions that originated as hurricanes along the Pacific coast of North America have led to rain events in autumn. This paper offers what is apparently the first published evidence of a groundwater isotope signature that is clearly attributable to tropical cyclonic storms and an explanation of the stable O and H isotope distribution in groundwater of Baja California.

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Background

Hurricane-associated rain has distinctive low values of $\delta^{18}O$ and δD. Most available data are from the Atlantic coast of the USA. Rain water from hurricanes collected on the Gulf Coast plain of Texas between 1988 and 1993 had a modal $\delta^{18}O$ value nearly −9‰, in contrast to a modal value nearly −2‰ for local summer rain of other origins (Lawrence and Gedzelman 1996; Lawrence 1998). Precipitation samples collected using aircraft at high altitude in hurricanes Faith (Ehhalt and Östlund 1970) and Olivia (Lawrence et al. 2002) yielded even lower values; in the case of Olivia, the minimum values of ($\delta^{18}O$, δD) were (−26‰, −200‰). The data from Olivia had an average deuterium excess parameter of 11‰.

Despite the large volumes of rain water that fall from hurricanes, little evidence is available for such rain water preserved as groundwater in areas subject to hurricane deluges. In karst areas where rapid recharge is likely, the isotope signature of transient pulses of low-$\delta^{18}O$ water originating as hurricane rain water can be detected in speleothem calcite (Frappier 2007). In groundwater itself, however, the hurricane pulse has little or no enduring effect. In Yucatán (Mexico), Florida, and Texas, groundwater $\delta^{18}O$ values fall largely between −5‰ and −3‰ (Ward and Halley 1985; Sacks 1996; Socki et al. 2002; Fahlquist and Ardis 2004; Stalker et al. 2009). A possible exception occurs in the unconfined part of the Edwards aquifer in Texas, where values as low as −6‰ might reflect the recharge of hurricane rain water (Fahlquist and Ardis 2004).

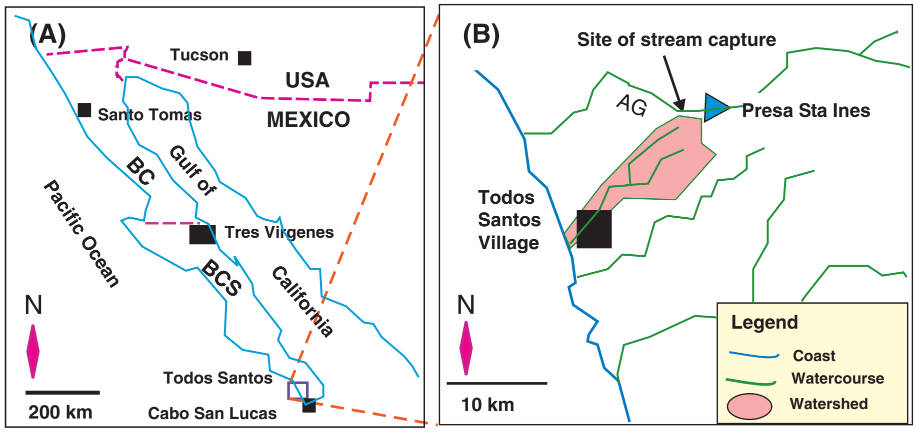

Figure 1. (A) Map of Baja California, showing locations discussed in the text. (B) Sample site map of the Todos Santos area, Baja California. AG = Arroyo Grande.

Study Area

The community of Todos Santos is located along the Pacific coast of southern Baja California, Mexico, approximately 70 km northwest of Cabo San Lucas, at latitude 23.45°N, longitude 110.22°W (Figure 1). The Todos Santos watershed includes a narrow alluvial basin extending about 20 km inland. The inland limits of the watershed are in rounded hills of Mesozoic intrusive and metasedimentary rock (Servicio Geológico Mexicano 2002) at altitudes up to 400 m.a.s.l. (meters above sea level) except for an interval at the northern margin, near the Arroyo Grande and the Santa Inés reservoir, where the boundary crosses a dissected alluvial plain. The Arroyo Grande once flowed into the Todos Santos watershed in this area but was diverted northwest by stream capture, as can be seen in the satellite images of the area near latitude 23.548°N, longitude 110.159°W. The Arroyo Grande watershed includes the west slopes of the Sierra de la Laguna at altitudes up to 1800 m.a.s.l.

A set of springs in the lower part of the watershed discharges into a perennial stream that begins north of the town and flows approximately 5 km to the Pacific Ocean. Numerous wells produce water from an alluvial aquifer in the watershed; static water levels vary from 30 to 40 m.a.s.l. near Todos Santos to 190 m.a.s.l. in the upper part of the watershed. Total dissolved solids range from 200 to 350 ppm and dissolved ions are dominated by HCO_3^-, Na^+, and Ca^{2+}. Annual average rainfall at Todos Santos is approximately 170 mm, of which 64% falls in July, August, and September (Conagua 2013). Inland, in the Sierra de la Laguna, annual average rainfall is thought to rise to 747 mm (Hastings and Turner 1965).

Methods

Samples of groundwater were collected from the springs and wells. Isotope measurements for samples collected in 2009 were made at the Environmental Isotope Laboratory of the University of Arizona. Stable isotopes of oxygen in water were measured using an automated CO_2 equilibration device connected to a Finnigan Delta S gas source dual-inlet mass spectrometer. Stable isotopes of hydrogen in water were measured using a Finnigan H-Device connected to the same mass spectrometer; water was reduced to H_2 gas on Cr metal at 750 °C. Results were reported relative to Vienna Standard Mean Ocean Water (VSMOW), and calibration was carried out using international standards VSMOW and Standard Light Antarctic Precipitation (SLAP). Tritium was measured on 9 g processed water samples following electrolytic enrichment, using Ultimagold LLT® scintillant (Permin Elmer Inc., Waltham, Massachusetts) mixed 1:1 by weight with the water, in a Quantulus® 1220 spectrophotometer (Wallac Oy, Turku, Finland). The samples were enriched by a factor of about 9 and were counted 1500 min to give a detection limit of nearly 0.6 tritium units (TU). National Institute of Standards and Technology (NIST) standard reference materials 4361 B and C and ancient groundwater (^{14}C content = 34 pMC) from Agua Caliente Spring, Tucson basin (as background), were used to calibrate the counter. Samples collected in 2000 were analyzed at the Bureau de Recherches Géologiques et Minières, Orléans, France. In addition, Stable O and H isotopes have been measured in rain water samples corresponding to almost every precipitation event > 0.5 mm in Tucson since 1982, at collection points within 2 km of the University of Arizona. For this study, all data corresponding to events annotated as "tropical depression" or "hurricane" have been selected.

Isotope Data

Stable O and H isotope data collected in 2009 from wells and springs in the Todos Santos watershed are listed in Table 1 and plotted in Figure 2. The data plot close to the Global Meteoric Water Line (GMWL) (Craig 1961) and values of ($\delta^{18}O$‰, δD‰) range from (−10.6, −75) to (−10.9, −79). Samples collected in 2000 ranged from (−8.4, −58) to (−8.8, −62). In four of the 2009 samples, tritium content ranged from 1.3 to 2.4 TU, with 1σ errors nearly 0.3 TU. Two groundwater samples collected in

Table 1
Sample Locations and Isotope Data

Todos Santos Sample	Type	Latitude °N	Longitude °W	Date	$\delta^{18}O$ ‰	δD ‰	TU
		23°	110°				
TS-13	Well	27.377′	13.267′	2009	−10.9	−78	2.4 ± 0.33
TS-17	Well	27.708′	13.185′	2009	−10.9	−78	
TS-21	Well	28.487′	12.830′	2009	−10.6	−76	
TS-26	Well	29.372′	12.322′	2009	−10.6	−75	
Spring 1	Spring	27.487′	13.432′	2009	−10.8	−78	1.3 ± 0.28
Manantial III	Spring	28.487′	12.830′	2009	−10.9	−79	2.3 ± 0.31
El Tecolote	Well			2000	−8.8	−62	3 ± 1
Manantial	Spring			2000	−8.6	−60	Below det.
San Juan =TS21	Well	29.372′	12.322′	2000	−8.4	−58	3 ± 1

Tucson Rain Samples from Tropical Depressions Year	mm	$\delta^{18}O$ ‰	δD ‰
2009	2.8	−5.2	−43
2008	11.2	−11.9	−99
2007	7.6	−5.5	−34
2006	48.3	−12	−113
2003	36.1	−14.5	−109
2003	7.4	−9.9	−79
2001	1.0	−6.4	−88
1999	10.4	−12.4	−92
1993	7.1	−7.2	−50
1992	36.8	−15.7	−112
1984	24.6	−10.8	−76
1983	183.9	−10.1	−70

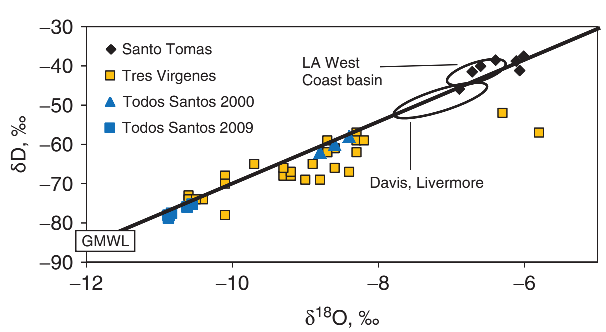

Figure 2. Plot of δD vs. $\delta^{18}O$, showing data for groundwater from Todos Santos, Santo Tomás (W. Thomas unpublished data), Tres Vírgenes (Portugal et al. 2000), and coastal California (Davisson and Criss 1993; Reichard et al. 2003; Moore et al. 2006).

2000 had finite tritium contents of 3 ± 1 TU, and the other had a reported value of <1 TU.

Figure 3 shows $\delta^{18}O$ and δD values for tropical depression rain events in Tucson and the relationship between $\delta^{18}O$ and precipitation amount. All but three events yielded rain with $\delta^{18}O$ values much lower than average "summer" rain in Tucson (June to October, including the tropical depression events; data from Eastoe et al. 2004). In a few cases, the rain water has been strongly evaporated. Figure 3A suggests a possible relationship between rain amount and $\delta^{18}O$, with the exception of the largest event of the set in 1983.

Discussion

The Problem

Groundwater from the Todos Santos watershed has $\delta^{18}O$ and δD values that are much lower than expected, given the site latitude, and which vary with time (compare results from 2000 and 2009, Figure 2). There is no distinction between spring and well samples, suggesting a common origin for all groundwater. Tritium data in the groundwater are consistent with recent recharge; post-1992 coastal precipitation in southern California is thought to contain 2 TU (Izbicki et al. 2000), and a seasonal precipitation aggregate for winter 2003 to 2004 in Mazatlán, on the Sinaloa coast east of Todos Santos, contained 2.3 TU (Eastoe et al. 2011). The temporal variation of $\delta^{18}O$ and δD in the groundwater is consistent with that in young groundwater, changing in response to precipitation input.

The low $\delta^{18}O$ and δD values in Todos Santos groundwater might be explained by altitude. In the adjacent Sierra de la Laguna, large areas collect precipitation between 1000 and 1500 m.a.s.l. The small Todos Santos watershed, with a maximum elevation of nearly 500 m, collects no runoff from the higher mountains as surface

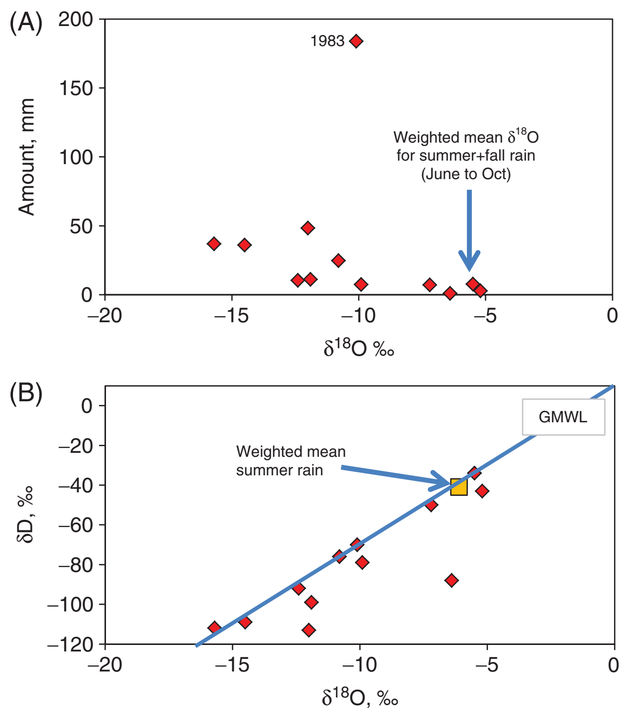

Figure 3. Data for rain events associated with Pacific coast hurricanes and tropical depressions, the samples collected in Tucson. (A) Plot of δ^{18}O vs. rainfall amount. (B) Plot of δD vs. δ^{18}O. The volume-weighted mean represents all summer precipitation events, 1982 to 2001.

water. However, the high-elevation Arroyo Grande watershed very likely supplies groundwater to the Todos Santos alluvial basin as subflow through the low divide at its northern end. An alternative explanation is that recharge in this area is from tropical cyclonic weather systems with low δ^{18}O and δD values.

Pacific Tropical Cyclonic Rain

Hurricanes and tropical depressions periodically bring rain to the southern half of Baja California and adjacent parts of Mexico. Storm tracks recorded since 1950 concentrate within 300 km of the southern end of Baja California. Most storms move northwest without making landfall, but a secondary cluster is deflected northward near the tip of the peninsula, eventually moving parallel to the axis of the Gulf of California, or across the Gulf towards Sinaloa or Sonora (National Oceanic and Atmospheric Administration 2013). Some such storms make landfall in BCS, bringing heavy precipitation near the storm center or to the left of the storm path. Ten of the 12 named tropical depressions (including hurricanes) making landfall in BCS between 1970 and 2010 yielded more than 400 mm of rain over a 3-d period (landfall ± 1 d) at one or more recording stations (Farfán et al. 2013). The frequency of cyclonic weather systems near the southern tip of BCS is summarized in Table 2. Cyclonic weather systems make landfall on the entire Pacific coast of Mexico at a rate of 2.1 ± 1.6 per year (Raga et al. 2013). In comparison, the average rate of landfall in BCS within 200 km of Cabo San Lucas is 0.3 per year, while the average number of systems passing within 300 km of Cabo San Lucas is 2 per year. Cyclonic weather systems that do not make landfall provide smaller amounts of rain, as in the cases of named storms Liza 1976, Tico 1983, Lidia 1993, Ismael 1995, Paul 2006, and Jimena 2009, all of which led to rainfalls of 50 to 100 mm distributed across the southern end of BCS (CONACyT 2013). This list may not be exhaustive, but taking it together with the information for storms making landfall in BCS, it seems likely that rain events of >50 mm occur in association with named cyclonic weather systems at least once every 2 to 3 years.

Hurricane or tropical depression weather systems of the Pacific coast of North America produce rain with low δ^{18}O and δD values like those (discussed above) on the Atlantic coast. The low δ^{18}O and δD values extend inland as far as Tucson and have also been observed in southern New Mexico (Newton et al. 2012).

Groundwater Elsewhere in Baja California

Wassenaar et al. (2009) published a stable isotope transect of Baja California based on about 30 single samples from sites distributed along the peninsula. They noted, without explanation, a general gradient of decreasing values of δ^{18}O and δD from north to south. The gradient is consistent with other detailed data sets from this study and for two other areas: the Tres Vírgenes geothermal field and a broad surrounding area including the adjacent coast of the Gulf of California (Portugal et al. 2000) and Santo Tomás valley (W. Thomas unpublished data). The data plotted in Figure 2 are for cold groundwater, which is more likely to be of recent origin than hot groundwater in each area. Santo Tomás lies in the northern zone of Baja California where winter rain is predominant, as along the coast of California to the north. On an average, 75% of annual rain falls in winter and spring in the area of Santo Tomás. By contrast, summer and fall rain predominate at Tres Vírgenes (77%) and Todos Santos (85%) (Hastings and Turner 1965).

Most data plot near the GMWL, with Tres Vírgenes data scattering to the right of the line (Figure 2). Groundwater from Santo Tomás is effectively indistinguishable from that of coastal California in areas unaffected by recharge from high elevations (Davisson and Criss 1993; Reichard et al. 2003; Moore et al. 2006). Cold groundwater from the area around Tres Vírgenes has lower δ-values, (−8.2, −59) to (−10.5, −74). The southward transition from predominant winter + spring to predominant summer + fall precipitation along Baja California is therefore accompanied by a decrease in the δ^{18}O and δD values of groundwater, the opposite of typical variation with latitude. The lightest groundwater at Todos Santos and Tres Vírgenes resembles average winter precipitation at an altitude of 2420 m in Tucson Basin (Wright unpublished data).

Altitude Effect or Tropical Cyclones?

Several lines of argument suggest that the δ^{18}O and δD values observed in groundwater in the southern half of

Table 2
Frequency of Tropical Cyclonic Weather Systems in Southern Baja California

In Areas Centered on Cabo San Lucas Location	All Categories[1]	No. per Year	Hurricanes	No. per Year
1950–2011				
300 km radius	122	2.0	62	1.0
200 km radius	85	1.4	38	0.6
Landfalls, 200 km radius	20	0.3	10	0.2
1990–2011				
300 km radius	45	2.0	22	1.0
200 km radius	24	1.1	13	0.6
Landfalls, 200 km radius	9	0.4	6	0.27

Source: National Oceanic and Atmospheric Administration (2013).
[1]Subtropical and tropical storms and hurricanes of categories 1 to 5.

Baja California are the result of isotope effects in tropical cyclonic weather systems:

1. Most precipitation in the area falls during the hurricane season (Hastings and Turner 1965).
2. At Todos Santos, the presence of tritium and the change in groundwater $\delta^{18}O$ and δD data between 2000 and 2009 suggest a rapid response of groundwater to different precipitation events. Such would be difficult to explain if an altitude dependence controls the $\delta^{18}O$ and δD values or if groundwater is mainly supplied by subsurface flow from the Arroyo Grande. Instead, groundwater is likely to originate as surface water in the low-elevation Todos Santos watershed.
3. The presence of similar $\delta^{18}O$ and δD values in groundwater at Tres Vírgenes, where summer + fall rain also predominates, but where average recharge altitudes are close to 300 m.a.s.l., argues against an altitude effect as the main control at either location. Similar arguments apply at 25 other low-altitude sites in southern Baja California, where single groundwater samples had $\delta^{18}O$ values $< -8‰$ (Wassenaar et al. 2009).
4. The local lapse rate at Todos Santos is likely to be $-1‰$ to $-2‰$ per 1000 m for $\delta^{18}O$ (cf $-1.6‰$ for Tucson Basin; Wright unpublished data). Assuming, for the sake of argument, that the 2009 $\delta^{18}O$ values were generated about 1000 m higher than the Todos Santos drainage, the corresponding $\delta^{18}O$ values at sea level, $-8.6‰$ to $-9.9‰$, would still appear anomalously low, lower than values in average groundwater in northern coastal Baja California.

The preservation of the hurricane rain signature in groundwater of southern Baja California indicates that recharge from other kinds of rain events is minimal in this area. The same hurricane isotope signature appears to be present on the coast of Mexico between Jalisco and Oaxaca but is not evident in coastal groundwater at Sonora and Sinaloa, where $\delta^{18}O$ values are $-5‰$ to $-7‰$ (Wassenaar et al. 2009), despite occasional hurricane deluges.

Conclusions

Large rains from tropical depressions occur at least every few years in BCS and are the principal source of groundwater in the southern half of Baja California, explaining values of $\delta^{18}O$ as low as $-10.9‰$ in the coastal aquifer at Todos Santos and elsewhere in BCS. On the Pacific coast of North America, rain from tropical depressions, including hurricanes, has low values of $\delta^{18}O$ and δD comparable to those observed on the Atlantic coast. This isotope signature is preserved in rain water as far inland as Arizona and New Mexico.

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Authors' Note

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