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RECHARGE SOURCES AND CHARACTERISTICS OF SPRINGS ON THE ZUNI RESERVATION, NEW MEXICO

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ABSTRACT—Relatively high-volume springs (100-300 gpm; 6-19 l/s) discharge from the Permian San Andres-Glorieta (Psg) aquifer and interconnected Quaternary alluvium and fractured basalt (Qal/Qb) aquifers on the Zuni Reservation in west-central New Mexico. Psg springs in the Nutria area, near the recharge source in the Zuni Mountains, exhibit a mixture of modern (<5-10 year old) and pre-1952 recharge, indicating spring discharge from shallow and deep circulation systems near the mountain front. Psg springs in the Ojo Caliente area are fen-type springs that represent predominantly or entirely pre-1952 recharge. Stable isotope ($\delta^{18}O$ and $\delta^{2}H$) data are consistent with high elevation, winter precipitation recharge for Nutria Psg springs and a lower elevation North Plains/Continental Divide recharge source southeast of the reservation for the Ojo Caliente springs. Alluvial springs in the Black Rock area exhibit lower-elevation, modern recharge, whereas discharge from Pescado-area alluvial springs exhibit higher-elevation, predominantly pre-1952 recharge. The recharge source for Pescado springs is likely winter precipitation in the Zuni Mountains, whereas Black Rock alluvial springs have local recharge sources on uplands within the reservation. Springs in both areas discharge from an interconnected alluvial/fractured basalt flow system. Springs discharging from the Rock Point Fm/Zuni sandstone aquifer exhibit variable recharge, with some receiving rapid recharge from winter precipitation and others receiving older recharge from summer monsoonal precipitation.

Spring discharge measurements collected during 2007-2009, when compared to earlier studies by Orr (1987) and Summers (1972), suggest a generally declining trend in spring flows between 1972 and 2009. This apparent decline in spring discharge could be due to increased groundwater diversions in the Zuni Mountains, Zuni River basin, and regionally in the Psg aquifer, fluctuations in precipitation, variations in measurement methodologies, or a combination of these factors. Increasing spring flows after 2009 correspond to above-normal winter precipitation, particularly snow moisture content, recorded at one precipitation station and three snow courses in the recharge area.

INTRODUCTION

An assessment of 29 springs on the Zuni Reservation was conducted between 2007 and 2009 in four areas of the reservation that represent areas with concentrations of springs or relatively large-volume spring discharge (Fig. 1; Drakos and Riesterer, unpubl. report for Zuni Pueblo, 2009). These include the Nutria area in the northeastern, the Pescado area in the east-central, the Dowa Yalanne-Black Rock-Spring House Draw area in the central, and the Ojo Caliente area in the southwestern part of the reservation. Springs discharge from the Permian San Andres-Glorieta (Psg) aquifer, Triassic Chinle Group (ŦRc) aquifer, Triassic-Jurassic Rock Point-Zuni (ŦRr, Jz) aquifer, and interconnected Quaternary alluvium/fractured basalt (Qal/Qb) aquifers, respectively. Springs discharging from the Psg and Qal/Qb aquifers have the highest discharge rates and are the most numerous on the reservation, and this paper is primarily focused on these two aquifers. The assessment of each spring included some or all of the following: geologic and geomorphic mapping; measurement of spring discharge; measurement of field water quality parameters; water sample collection and analysis for major cations and anions, stable isotopes and tritium; identification of the source aquifer; and preliminary assessment of flora and fauna. Springs were classified based on the classification system described in Springer et al. (2008). In the Ojo Caliente area, springs are also classified as fen-type springs (not included in the Springer et al. (2008) classification), which are fed by groundwater moving vertically upward from a confined aquifer through a confining unit. Five of the 29 springs examined during this investigation were dry at the time of the 2007-2009 field visits.

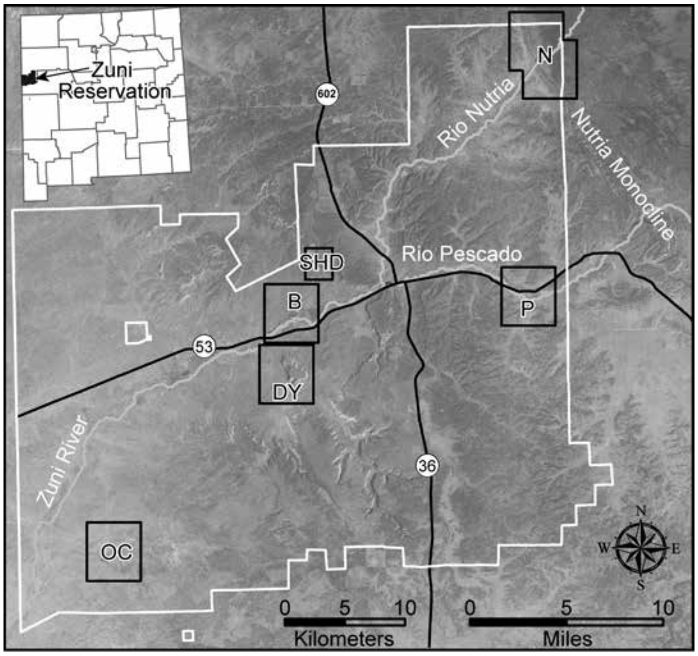


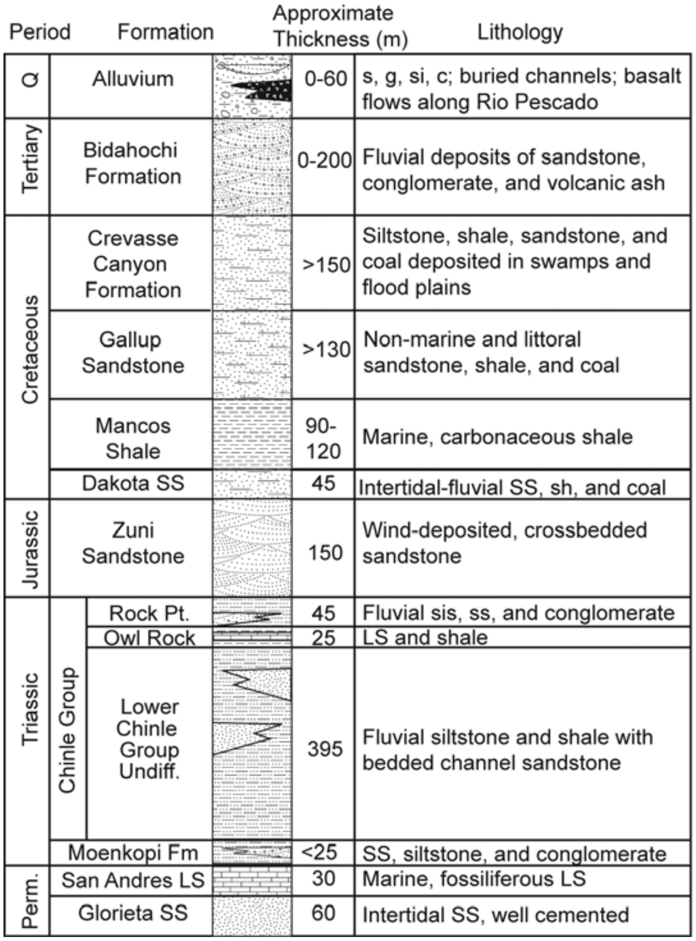
FIGURE 1. Location map showing areas discussed in text. N=Nutria area, SHD=Spring House Draw area, B=Black Rock area, P=Pescado area, DY=Dowa Yalanne, OC=Ojo Caliente.

HYDROGEOLOGIC SETTING

The Zuni Reservation lies on the south flank of the Zuni uplift at the base of the Zuni Mountains in the southeast corner of the Colorado Plateau physiographic province. The Zuni uplift is a Laramide structural feature, formed from late Cretaceous through Eocene time (Kelley, 1967; Chamberlin and Anderson, 1989). The Zuni Mountains are a granite-cored uplift, and overlying sedimentary rocks range in age from Permian to Cretaceous (Fig. 2; Hackman and Olson, 1977). The sedimentary sequence is deformed into a large, northwest-trending asymmetrical dome by the Zuni uplift. The Nutria monocline, in the northeast corner of the reservation, is a prominent fold bordering the southwest side of the Zuni uplift. The remainder of the reservation is underlain by a series of northwest-trending anticlinal and synclinal structures formed during Laramide deformation (Orr, 1987). The majority of springs on the reservation discharge from the Permian San Andres-Glorieta aquifer, the Triassic-Jurassic Point Rock Formation/Zuni Sandstone aquifer, and the interconnected Quaternary alluvium and fractured Quaternary basalt aquifers, described below.

Permian San Andres-Glorieta Aquifer (Psg)

The Permian San Andres-Glorieta Aquifer (Psg) consists of hydrologically connected sandstone (Glorieta Sandstone) and overlying limestone (San Andres Limestone) that locally produces significant water, especially where fracturing and dissolution of the limestone enhance groundwater flow (Orr, 1987). Groundwater flow in the Psg aquifer in the southeastern and east-central portion of Zuni Reservation is generally from east to west at 0.004 ft/ft. In the northeastern part of the Reservation near Nutria flow is from northeast to southwest at 0.08 ft/ftand in the western part of the reservation flow is from southeast to northwest at approximately 0.009 ft/ft (Orr, 1987). Several springs discharge from the Psg aquifer in the Nutria and Ojo Caliente areas, with flow rates of up to 50 gpm (3.2 l/s) and 250 gpm (16 l/s), respectively. The Psg aquifer is likely in hydrologic communication with the underlying Yeso Formation (Py) aquifer in the vicinity of the Zuni Reservation.



Period		Formation	Approximate Thickness (m)	Lithology
Q		Alluvium	0-60	s, g, si, c; buried channels; basalt flows along Rio Pescado
Tertiary		Bidahochi Formation	0-200	Fluvial deposits of sandstone, conglomerate, and volcanic ash
Cretaceous		Crevasse Canyon Formation	>150	Siltstone, shale, sandstone, and coal deposited in swamps and flood plains
		Gallup Sandstone	>130	Non-marine and littoral sandstone, shale, and coal
		Mancos Shale	90-120	Marine, carbonaceous shale
		Dakota SS	45	Intertidal-fluvial SS, sh, and coal
Jurassic		Zuni Sandstone	150	Wind-deposited, crossbedded sandstone
Triassic	Chinle Group	Rock Pt.	45	Fluvial sis, ss, and conglomerate
		Owl Rock	25	LS and shale
		Lower Chinle Group Undiff.	395	Fluvial siltstone and shale with bedded channel sandstone
		Moenkopi Fm	<25	SS, siltstone, and conglomerate
Perm.		San Andres LS	30	Marine, fossiliferous LS
		Glorieta SS	60	Intertidal SS, well cemented

FIGURE 2. Schematic stratigraphic section and description of lithologic units underlying the Zuni Reservation. Thicknesses and descriptions modified from Orr (1987) and Heckert and Lucas (2003). Abbreviations: Q=Quaternary, Perm.=Permian, s=sand, g=gravel, si=silt, sis=siltstone, c=clay, SS=sandstone, LS=limestone, sh=shale.

Triassic Rock Point/Jurassic Zuni Sandstone aquifer

The Rock Point Formation (formerly Rock Point Member of the Wingate sandstone, subsequently redefined as the Rock Point Member of the Chinle Formation and now elevated to Formation status as part of the Chinle Group (Orr, 1987; Lucas and Hayden, 1989; Heckert and Lucas, 2003)) overlies the Chinle Formation throughout the Reservation, and consists of fine-grained sandstone, fluvial siltstone and silty mudstone (Orr, 1987; Lucas and Hayden, 1989). In exposures along the Nutria monocline a chert and quartzite pebble conglomerate exists near the base of the Rock Point Formation. In exposures near the base of Dowa Yalanne the Rock Point Formation is a parallel-bedded, ledgey sandstone overlying the Owl Rock Formation (Drakos and Riesterer, unpubl. report for Zuni Pueblo, 2009). The Jurassic Zuni sandstone is a massive, cross-bedded, eolian sandstone that forms prominent cliffs where it is capped by the Dakota sandstone. Dowa Yalanne (DY), a large mesa in the central portion of the reservation, is the type section of the Zuni Sandstone (Lucas and Heckert, 2003). The Rock Point/Zuni Sandstone aquifer is locally in hydrologic communication with interbedded shale and thin limestone beds of the underlying Owl Rock Formation. Several relatively low-flow springs discharge from the Rock Point/Zuni sandstone aquifer near the base of Dowa Yalanne, the Nutria Monocline, and the Spring House Draw area.

QUATERNARY ALLUVIUM/FRACTURED BASALT AQUIFER

Alluvial deposits are present throughout the reservation along the major drainages (Rio Nutria, Rio Pescado, Zuni River) and their smaller tributaries. The alluvium consists of unconsolidated or semi-consolidated sand, gravel, silt, and clay, with the composition varying based on the bedrock materials exposed at the surface nearby. Basalt flows overlie or are interbedded with the alluvium along the Pescado and Zuni River drainages, where the basalt and alluvium form an interconnected aquifer. Groundwater flow in the alluvial aquifer along the upper Zuni River and the Rio Pescado is from east to west, at 0.006 ft/ft (Orr, 1987). Ground water flow in the alluvial aquifer along the lower Zuni River and the Rio Pescado is from northeast to southwest, at 0.003 ft/ft (Orr, 1987). Several large springs in the Pescado and Black Rock areas discharge from the alluvial/basalt aquifer.

SAN ANDRES-GLORIETA SPRINGS

Nutria Area

The sedimentary sequence in the vicinity of Nutria is deformed into the Nutria monocline and a prominent hogback formed by Cretaceous through Triassic beds that dip steeply to the southwest (Fig. 3). At least seven springs are inferred to discharge from the Psg aquifer east of the hogback (Fig. 4). During field visits conducted between 2007 and 2009 five of the springs were dry, two (Nutria Main and Nutria Canyon Wall) were flowing, and one (Bird Spring) was a seep during an initial visit and dry on a follow up visit. Summary data from the Nutria area springs are contained in Table 1.

Nutria main spring is classified as a rheocrene spring, with flow emerging in an active stream channel. Flow at the Nutria main spring was measured by pumping water out of an underground vault where the spring orifice is located and measuring the time required for the vault to recharge after it had drained. Estimated discharge varied with head (slowing as the vault filled), ranging between 50 and 90 gallons per minute (gpm) (3.2 to 5.7 liters per second [l/s]).

Nutria canyon wall spring is a contact or hanging garden spring that emerges as a series of seeps from a bedding contact within the Glorieta Sandstone. Flow from the numerous seeps collects in a large pool which contributes flow to the Rio Nutria. Combined flow from the seeps along the wall was visually estimated as 1 to 5 gpm (0.06 to 0.3 l/s).

Lonjose SW is a hypocrene spring, where flow does not reach the surface. Water was encountered in a hand-augered boring 61 cm (2 ft) below ground surface (bgs).The orifice (dry in 2009) emerges in alluvium overlying the Chinle Formation, but the source for the spring is interpreted to be the underlying Psg based on the geologic setting and geochemistry results discussed below.

Indian Spring was not flowing during the time period of this investigation. However, a spring flow of < 1l/s was observed

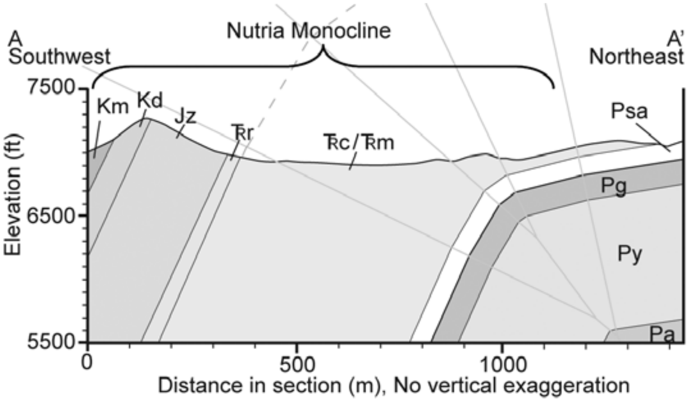


FIGURE 3. Cross-section through the Nutria Monocline. Location of cross-section is shown in Figure 4. Kg=Gallup Sandstone, Km=Mancos Shale, Kd=Dakota Sandstone, Jz=Zuni Sandstone, Ꞧr=Rock Point Fm., Ꞧc=Chinle Group undifferentiated, Psa=San Andres Limestone, Pg=Glorieta Sandstone, Py = Yeso Fm., Pa = Abo Fm.

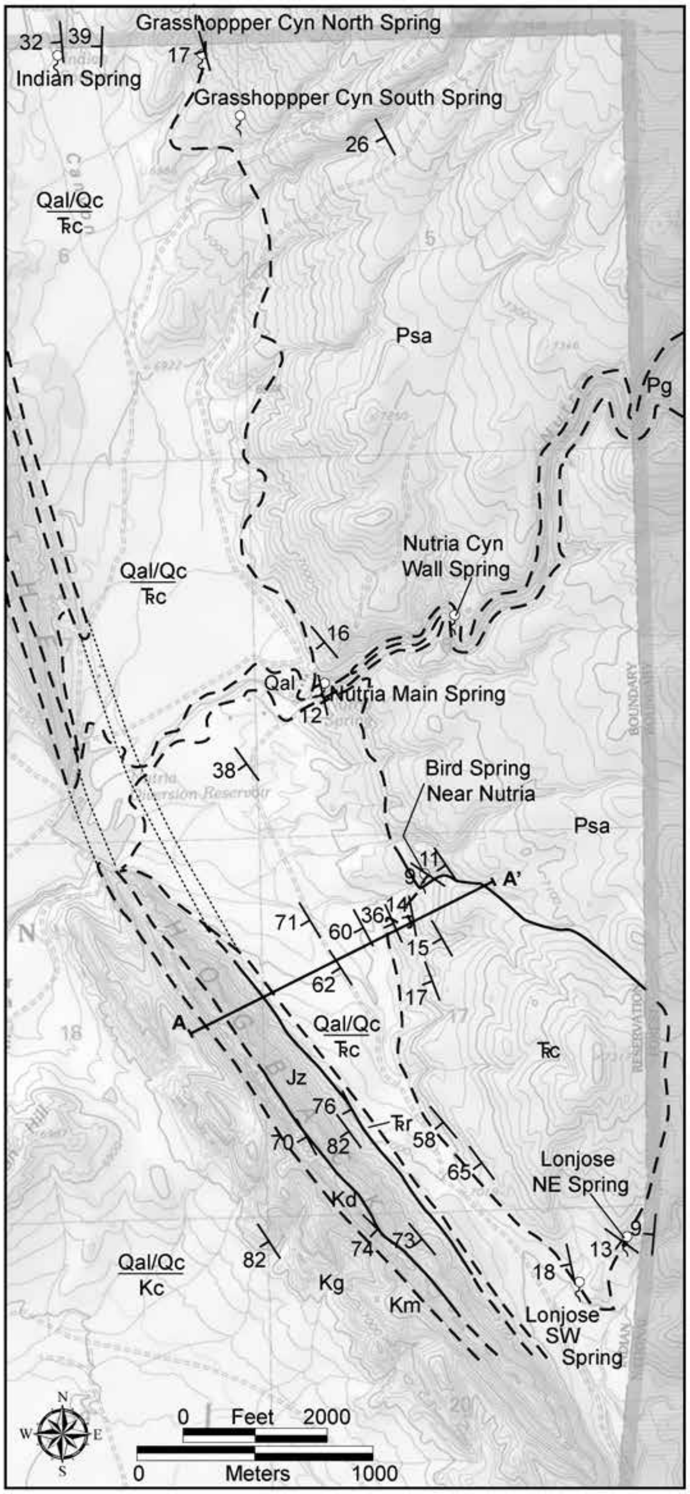


FIGURE 4. Preliminary geologic map of the Upper Nutria area, showing spring locations, geology mapped during field investigations, and location of cross-section A-A' (Figure 3). Qal=Alluvium, Qc=Colluvium, Kc=Crevasse Canyon Fm., Kg=Gallup Sandstone, Km=Mancos Shale, Kd=Dakota Sandstone, Jz=Zuni Sandstone, Ꞧr=Rock Point Fm., Ꞧc=Chinle Group undifferentiated (includes thin Moenkoepi Fm at base), Psa=San Andres Limestone, Pg=Glorieta Sandstone

TABLE 1. Data collected from springs on the Zuni Reservation.

Spring Name	Source Aquifer	Flow, gpm (l/s)	Date Measured	Major cation/anion concentration, mg/L*								^3H (TU)	$\delta^{18}O$ (‰)	δ^2H (‰)
				Na	K	Ca	Mg	Cl	HCO_3	SO_4	TDS			
Nutria Main	Psg	50-90 (3.2-5.7)	11/7/07	9.2	<1.0	79	18	5.9	317	43	340	<1.1	-12.6	-91
Nutria Cyn Wall	Psg	1-5 (0.06-0.9)	11/7/07	11	<1.0	75	21	6.2	293	64	350	2.5±0.27	-11.5	-85
Lonjose SW	Psg	0 (piezometer)	8/27/09	7.8	0.1	92	26	4	390	23	370	2.3±0.27	-12.6	-92
Sacred	Psg	128 (8.1)	5/7/08	49	4.6	130	38	34	342	280	770	<0.7	-10.4	-74
Ojo Caliente Big	Psg	15 (0.9)	5/7/08	51	4.7	160	39	34	329	280	770	<0.8	-10.5	-74
Rainbow	Psg	220 (13.9)	5/7/08	53	5.3	130	41	33	341	280	1100	<0.5	-10.6	-75.8
Plumasano Wash	Psg	55 (3.5)	5/8/08	27	2.6	110	13	47	390	310	850	<0.9	-9.5	-69
Pescado South #3	Qal/Qb	65 (4.1)[†]	5/6/08	38	2.9	39	13	9.5	232	22	270	0.8±0.23	-12.2	-90
Upper Pescado[††]	Qal/Qb	185 (11.7)	8/28/09	41	5	41	12	10	310	26	300	<0.9	-12.1	-90
Lower Pescado	Qal/Qb	120 (7.6)	5/6/08	39	2.8	41	14	10	232	24	280	1.1±0.25	-12.1	-89
Black Rock	Qal/Qb	Unknown	11/8/07	48	1	43	4	6.9	244	22	240	3.1±0.28	-11.4	-83
Black Rock North	Qb±Qal	2.3 (0.1)	11/8/07	81	2.9	89	17	18	366	140	540	4.1±0.31	-10.2	-79
Black Rock BIA	Qal/Qb, Ŧcu (?)	Unknown	11/8/07	85	4.5	130	20	57	512	68	640	5.9±0.26	-4.6	-50
SHD #13	Qal/Jz	<1 (<0.06)	10/8/08	18	ND	150	12	15	537	9.6	500	6.2±0.4	-10.6	-74
Grasshopper HB	Jz/Ŧr	<1 (<0.06)	10/7/08	15	1.4	67	9.3	7.1	268	6.6	260	3.1±0.35	-12.3	-91
DY North[†††]	Jz/Ŧr/Ŧo	<1 (<0.06)	10/8/08	50	0.8	29	3.6	20	183	6.3	220	<0.5	-9.7	-76
DY South	Jz/Ŧr	2 (0.1)	10/8/08	43	1.4	54	6.3	16	268	6.4	270	0.8±0.32	-10.2	-77
Chavez	Ŧcu	Unknown	10/9/08	120	3.1	70	6.6	93	268	40	550	2.0±0.37	-9.5	-75

Qal=Alluvium, Qb=Basalt, Jz=Zuni Sandstone, Ŧr=Rock Point Formation, Ŧcu=Undifferentiated Chinle Group, Psg=San Andres-Glorieta, SHD=Spring House Draw, DY=Dowa Yalanne

* $CaCO_3$ was non-detect for all samples

[†] Combined flow from Pescado South springs #1-4

[††] General chemistry sample collected on 6/9/04, reported in Eib et al. (unpubl. report for NM Environment Department, 2004)

[†††] Discharge observed from basal Point Rock Fm and from Owl Rock Fm (Ŧo)

at Indian Spring during a subsequent investigation conducted in 2011, and an analysis of geochemistry data indicated a Yeso source for this spring (Banteah et al., unpubl. report for University of New Mexico, 2011).

Ojo Caliente Area

The Ojo Caliente area is situated in the southwest corner of the reservation along the north-trending, gently plunging Ojo Caliente anticline (Fig. 5; Orr, 1987). The Psg aquifer is uplifted to near the surface along the fold axis (Orr, 1987). Fracturing of the overlying Chinle Formation along the fold axis is the likely mechanism that allows discharge from the confined Psg aquifer to reach the surface. Springs in the Ojo Caliente area had discharge rates ranging from 15 to 220 gpm (0.9 to 13.9 l/s) on May 7, 2008, including Rainbow Spring (220 gpm; 13.9 l/s), Sacred Spring (128 gpm; 8.1 l/s), and Big Spring (15 gpm; 0.9 l/s) (Fig. 5). Extensive Pliocene (?) travertine deposits cap thin Miocene-Pliocene Bidahochi sand and gravel deposits overlying Chinle Group shale above Rainbow and Sacred Spring (Fig. 6). These travertine deposits demonstrate that this has been an area of spring discharge for an extended period of time and are indicative of CO_2 degassing from groundwater (e.g. Crossey et al., 2011). Ojo Caliente-area Psg springs are warm (18 to 22°C) fen-type or limnocrene springs that emerge in pools, fed by groundwater moving vertically upward from a confined aquifer through a confining unit. In addition, numerous seeps, originating from the Psg aquifer, discharge from the Moenkopi Formation and basal Chinle Group along Plumasano wash. Combined flow from these seeps was measured at 55 gpm (3.5 l/s) on May 8, 2008.

ROCK POINT/ZUNI SANDSTONE AQUIFER SPRINGS

Dowa Yalanne Area

Dowa Yalanne is a prominent mesa underlain by Zuni Sandstone cliffs capped by Dakota Sandstone, situated in the central part of the reservation, south of Black Rock (Fig. 1). The Zuni Sandstone is underlain by Rock Point Formation fine-grained, ledgey sandstone, which forms the lower slopes of Dowa Yalanne. Two contact springs (DY North and DY South) discharge from Owl Rock Formation limestone or sandstone beds, and/or sandstone beds at the base of the Rock Point Formation near the base of Dowa Yalanne mesa. Although spring discharge is observed from the Owl Rock Formation as well as the basal Rock Point Formation, it is interpreted that groundwater flow is primarily through the Rock Point/Zuni Sandstone aquifer. Flow from each of these springs is 2 gpm (0.1 l/s) or less, and DY North forms a hanging garden spring. The DY springs are recharged by precipitation and/or snowmelt on top of Dowa Yalanne mesa.

Spring House Draw Area

Spring House Draw is a narrow drainage that cuts through cliffs of Zuni Sandstone in the central part of the reservation (Fig. 1). Spring House Draw (SHD) is bedrock floored in some places and covered by a thin veneer of Quaternary alluvium throughout much of its course. Seeps near the base of the Zuni Sandstone discharge into valley floor alluvium and subsequently emerge from the alluvium as rheocrene springs, therefore forming an interconnected Zuni Sandstone-alluvial aquifer. Numerous low-flow SHD springs are recharged by precipitation on top of mesas that lie on either side of the drainage. Most are seeps with discharge of less than 0.1 gpm (0.006 l/s).

Nutria Area

Springs or seeps discharge from the Zuni Sandstone/Rock Point Formation aquifer on the east side of the Hogback formed by the Nutria Monocline. The greatest discharge measured was less than 0.2 gpm (0.01 l/s) at Grasshopper Hogback spring. Springs in this area are apparently recharged by precipitation falling on the Hogback.

QUATERNARY ALLUVIUM/FRACTURED BASALT AQUIFER SPRINGS

Pescado Area

Pescado is situated along the Rio Pescado valley near the eastern reservation boundary (Fig. 1). Quaternary basalt flows are present both in the subsurface and on the valley floor, interbedded with and overlying alluvial deposits of the Rio Pescado. The alluvium and fractured basalt form an interconnected aquifer system, and springs discharge along the margins or at the terminus of basalt flows in the Pescado area. These springs include Pescado South #1, 2, 3, and 4 on the south side of the valley, and Upper and Lower Pescado Springs in the central to north side of the valley. All of the springs in the Pescado area were flowing in 2007-2009. Spring discharge ranged from a combined flow of 65 gpm (4.1 l/s) from Pescado South 1-4 springs to 185 gpm (11.7 l/s) in Upper Pescado Spring. Flow from Lower Pescado spring was 120 gpm (7.6 l/s).

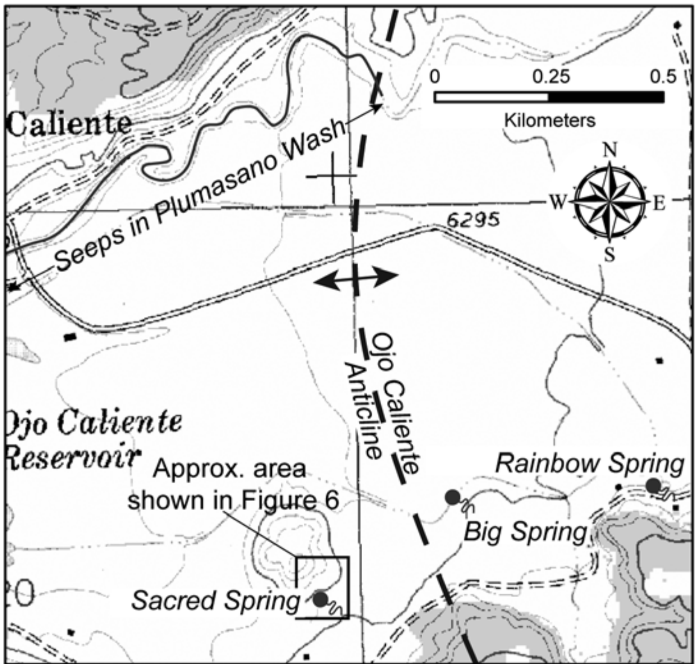


FIGURE 5. Map of the Ojo Caliente area showing spring locations and approximate trace of the Ojo Caliente anticline.

Black Rock Area

The Black Rock area is situated in the central part of the reservation, near the confluence of Spring House Draw and the Zuni River (Fig. 1). Quaternary basalt flows are present both in the subsurface and on the valley floor, interbedded with and overlying Zuni River alluvial deposits. In a setting similar to the Pescado area, alluvium and basalt form an interconnected aquifer system, and several springs discharge from the margins of basalt flows or from alluvium overlying the Chinle Group in the Black Rock area. These springs include Black Rock and Black Rock BIA springs, which have been used in the past as a local water supply. Black Rock spring had an estimated flow of 50-75 gpm (3.2 to 4.7 l/s) (Orr, 1987).

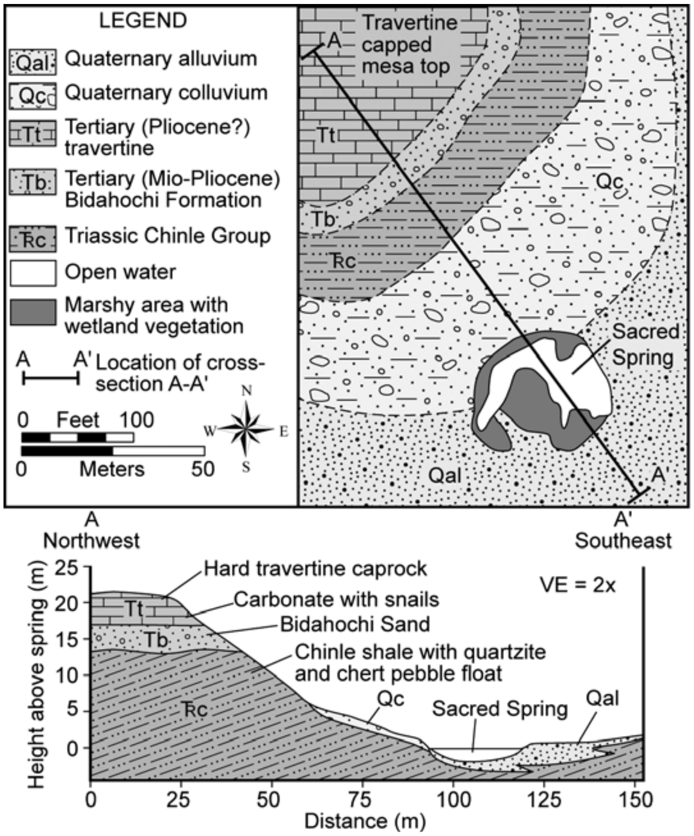


FIGURE 6. Geologic map and cross-section of Sacred Spring.

GEOCHEMISTRY

Water Quality Analysis Suite

Samples collected from springs included in the study were analyzed for major cations (calcium, magnesium, potassium, sodium), anions (carbonate-bicarbonate, fluoride, chloride, bromide, nitrate-nitrite, phosphorus, and sulfate), and total dissolved solids (TDS) by Hall Environmental Laboratory (HEAL) in Albuquerque, NM. Samples were also analyzed for the stable isotopes of oxygen (^{18}O) and deuterium (^{2}H), and for tritium (^{3}H) by the University of Arizona Laboratory of Isotope Geochemistry in Tucson, AZ. Samples were collected from Rainbow Spring in 2005, and from all other springs in 2007 and 2008.

Major Cations and Anions

Major cation (Ca^{2+}, Na^{+}, Mg^{2+}, and K^{+}) and anion (Cl^{-}, SO_4^{2-}, HCO_3^{-}, and CO_3^{2-}) data from samples collected for this study were compiled and plotted on a Piper diagram to determine geochemical characteristics of the source aquifers (Fig. 7). Major element chemistry data for spring samples are summarized in Table 1.

Samples collected from the Psg aquifer in the Nutria area (Nutria Canyon Wall, Nutria Main, and Lonjose springs) near the recharge zone are a Ca-Mg-HCO_3 water type, whereas Psg springs in the Ojo Caliente area (Rainbow, Sacred, Plumasano Wash and Big springs) are a Ca-Mg-SO_4-HCO_3 water type (Fig. 7). The higher sulfate in the Ojo Caliente springs relative to Nutria springs corresponds to longer residence time in the Psg aquifer and interaction with gypsum or anhydrite within the San Andres limestone, or indicates that the Psg aquifer is in hydrologic communication with the underlying Yeso Formation aquifer, which contains gypsum beds in the upper part of the Formation (Colpitts, 1989). Ojo Caliente springs have higher TDS (770 to 1100 mg/l) than Nutria area springs (TDS of 340 to 370 mg/l), consistent with a longer residence time for groundwater discharging at the Ojo Caliente springs. Samples collected from the majority of alluvial springs for this investigation are similar to one another in geochemical composition, with Ca + Na ± Mg as the dominant cations and bicarbonate as the dominant anion in all but one sample (Fig. 7). Water in the Zuni Sandstone-Rock Point Formation aquifer exhibits an evolution from Ca-HCO_3 water type to a Na-Ca-HCO_3 water type with increasing travel time in the aquifer (Fig. 7; Table 1).

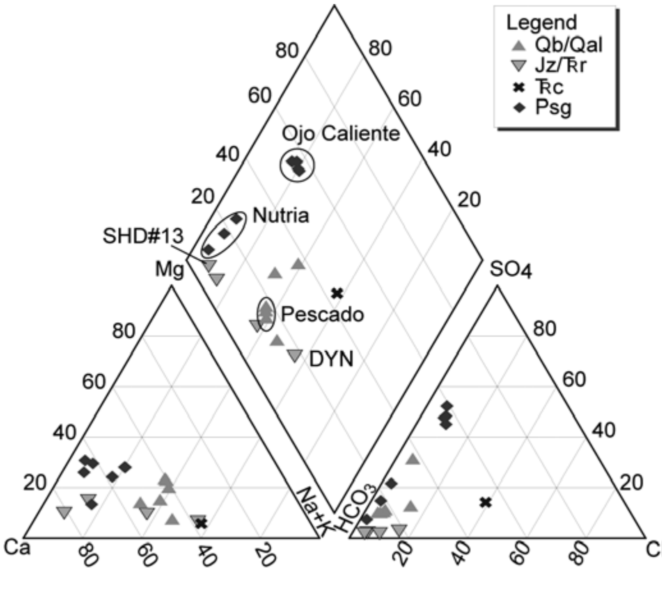


FIGURE 7. Piper diagram (Piper, 1944) of major cations and anions from springs on the Zuni Reservation. DYN=Dowa Yalanne North spring, SHD#13=Spring House Draw #13 spring.

ISOTOPE GEOCHEMISTRY

Tritium Isotopes

Tritium, ^{3}H, is a short-lived isotope produced in abundance within the last 50 years during atmospheric testing of hydrogen bombs. The peak in tritium concentration in precipitation occurred in 1963 and has declined rapidly since that time. Due to its relatively short half-life of 12.32 years, the presence of elevated tritium in groundwater indicates a post-1952 recharge source. Bomb-generated tritium rained out in the 1970s and 1980s, and tritium concentrations had stabilized in the atmosphere by 1992 (Eastoe et al., 2012). Post-1992 tritium values range from 6+/-1 TU in Tucson (Eastoe et al., 2004) to around 10 TU in Albuquerque (Plummer et al., 2004), and streams draining the Sangre de Cristo Mountains near Taos exhibit tritium concentrations ranging from 8 to 11 TU (Drakos et al., 2004). A tritium concentration of approximately 10 TU would therefore be a good estimate for precipitation in the Zuni Mountains.

Prior to 1992, according to the model of Doney et al. (1992), the decline of tritium in rainfall was a close approximation to a decay curve after 1970. Therefore, all rain that fell during the 1970s and 1980s would also have had about 10 TU in Zuni in 1992, provided it didn't mix with water of other ages, and tritium in 1970-1992 water would decay according to the decay function of tritium with an initial concentration of 10 TU in 1992. Such water would have about 4 TU by 2007-2008. Water with < 4 TU would therefore have been mixed with pre-bomb water, including many of the springs sampled in this investigation. Water with < 1.5 TU likely represents predominantly pre-1952 recharge with <20% 5 TU rainwater (Eastoe et al., 2004). Water with ≥ 4 TU but ≤ 10 TU represents modern (< 5 to 10 year old recharge). Water with > 10 TU tritium indicates the presence of some "bomb" tritium from the 1950s-1970s. The interpretation of tritium data for this study can therefore be summarized as follows:

Non-detectable tritium, <0.5 to <1.1 TU	predominantly or entirely pre-1952 recharge
Detectable tritium, < 1.5 TU	predominantly pre-1952 recharge
Detectable tritium, 1.5 TU to > 4 TU	mixture of pre-1952 and modern recharge
Detectable tritium, 4 TU to 10 TU	modern (< 5-10 yr old recharge)
Detectable tritium, > 10 TU	some bomb tritium present

Based on tritium results, Black Rock area alluvial springs have modern (likely less than 5 year old) recharge (tritium values ranging from 4 to 6 TU), or exhibit a mixture of modern and pre-1952 recharge (tritium value of 3.1 TU). Discharge from Pescado area springs represents predominantly pre-1952 recharge (tritium values ranging from <0.8 to 1.1 TU) (Table 1). These data indicate that water discharging from Pescado-area springs has a longer residence time in the alluvial/fractured basalt flow system; whereas water discharging from Black Rock alluvial springs have a shorter residence time and likely local recharge sources.

Tritium concentrations in samples collected from Ojo Caliente springs that discharge from the Psg aquifer are less than 0.9 TU (<0.5 to <0.9 TU), indicating that springs in the Ojo Caliente area exhibit predominantly or entirely pre-1952 recharge. Springs in the Nutria area, located much closer to the recharge source in the Zuni Mountains, exhibit a mixture of pre-1952 and modern recharge (Nutria Canyon Wall spring and Lonjose SW spring, tritium concentrations are 2.3-2.5 TU) or represent predominantly or entirely pre-1952 recharge (Nutria Main spring, <1.1 TU). These data are generally consistent with younger recharge and shorter travel times from springs in the Nutria area and older recharge and longer travel times for springs in the Ojo Caliente area. As discussed above, the general chemistry of the springs shows an evolution from a Ca-Mg-HCO_3 water type in the Nutria area, near the Zuni Mountains recharge zone to a Ca-Mg-SO_4-HCO_3 water type in the Ojo Caliente area. Ojo Caliente spring recharge may be dominated by aquifer recharge in the North Plains, and may have much longer residence times. The low tritium concentration in the Nutria Main spring indicates a longer residence time (± 55 years) and possibly deeper circulation for water discharging from this spring than for other springs in the Nutria area; however, the Nutria Main spring geochemistry is similar to the other Nutria springs. This may indicate that Ojo Caliente springs represent recharge that is much older (on the order of 100 to 1000 years), and the age differences between the Nutria area springs is small by comparison.

Tritium concentrations in the Jz/T̄r aquifer range from 6 to < 0.5 TU, indicating aquifer residence times ranging from less than 5 to 10 years (SHD and Nutria Hogback areas) to greater than 55 years (DY North spring). When compared to the Piper plot (Fig. 7), higher tritium concentrations and shorter aquifer residence time corresponds to a Ca-HCO_3 water type, whereas lower tritium concentrations and longer aquifer residence time corresponds to a Na-Ca-HCO_3 water type. These data show an evolution in water chemistry resulting from water-rock interaction (Drever, 1982,) in the Jz/T̄r aquifer.

Oxygen-Deuterium Isotopes

Data from springs sampled in this investigation are plotted against the Global, Placitas, and Santa Fe Meteoric Water Lines (Fig. 8). The majority of springs sampled plot along the global meteoric water line (Fig. 8). These data are consistent with snowmelt or non-monsoonal precipitation as a recharge source. Two of the Black Rock alluvial springs, the Dowa Yalanne Jz/T̄r springs, and the Chinle (Chavez) spring plot along a line with a slope of 5.7 (Global Meteoric Line slope = 8.13, Placitas Meteoric Line slope = 7.7), indicating evaporative enrichment (Mazor, 1991; Clark and Fritz, 1997).This is suggestive that recharge to these springs is dominated by summer monsoonal precipitation, either via infiltration along stream channels or direct infiltration.

Samples from Nutria Main and Lonjose SW springs are depleted in $\delta^{18}O$ and $\delta^{2}H$ relative to samples collected from Ojo Caliente Psg springs. These data suggest higher elevation (approximately 2400 to 2600 m) recharge in the Zuni Mountains as a water source for the Nutria Psg springs (with the exception of Nutria Canyon Wall spring) and a lower elevation (approximately 2200 m) North Plains/Continental Divide recharge source east and/or southeast of the reservation as a recharge source for the Ojo Caliente springs.

The difference in $\delta^{18}O$ and $\delta^{2}H$ signatures between Spring House Draw #13/Grasshopper Hogback and Dowa Yalanne springs is an unexpected result. All springs appear to have a local recharge source located at a similar elevation (Dowa Yalanne and Spring House Draw mesa tops have an elevation of around 7200 ft (2200 m); the top of the Nutria Monocline hogback is around 7300 ft (2225 m)). Despite the similar elevation of their respective recharge areas, it appears that Grasshopper Hogback/SHD #13 receive recharge from snowmelt or winter precipitation, whereas DY North and DY South receive recharge from summer monsoonal precipitation.

Pescado area alluvial springs are lower in $\delta^{18}O$ and $\delta^{2}H$ values relative to Black Rock alluvial springs, indicating a higher-elevation recharge source for Pescado springs. Stable isotope and tritium data (discussed above) are therefore consistent with, and indicate, a recharge source in the Zuni Mountains for Pescado

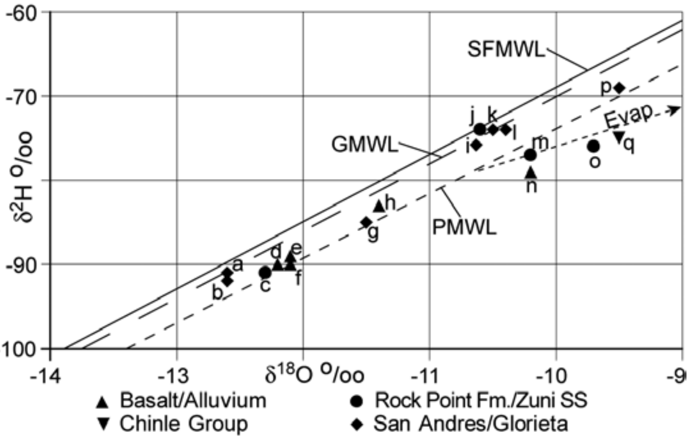


FIGURE 8. Plot of $\delta^{18}O$ vs. $\delta^{2}H$ for springs on the Zuni Reservation. SFMWL=Santa Fe meteoric water line (Anderholm, 1994), GMWL=Global meteoric water line (Craig, 1961), PMWL=Placitas meteoric water line (Johnson et al., 2002), Evap=evaporative trend toward Black Rock BIA spring where $\delta^{18}O$=-4.6 and $\delta^{2}H$=-50 (not shown on graph). Springs: a=Nutria Main, b=Lonjose SW, c=Grasshopper Hogback, d-f=Pescado, g=Nutria Canyon Wall, h=Black Rock, i-Rainbow, j=Spring House Draw #13, k=Big, l=Sacred, m=Dowa Yalanne South, n=Black Rock North, o=Dowa Yalanne North, p=Plumasano Seeps, q=Chavez.

area springs, and local recharge sources on uplands within the reservation for Black Rock alluvial springs.

RECHARGE TO THE AQUIFER SYSTEM

Recharge to the aquifer system that discharges at springs discussed in this study occurs via snowmelt and direct precipitation in the Zuni Mountains northeast of the reservation, on mesa tops and uplands within the reservation, via direct precipitation and infiltration through fractured basalt flows in the North Plains area east of the reservation, and through infiltration along stream channels. Snowmelt and direct precipitation in the Zuni Mountains, which reach an elevation of over 9000 ft (2700 m), are a source of direct recharge to the Psg and Yeso aquifers. The Psg aquifer also receives recharge via direct precipitation and infiltration through fractured basalt flows in the North Plains area east of the reservation (Orr, 1987). Precipitation in the Zuni Mountains is also a recharge source for alluvial aquifers along the main stream systems on the reservation (the Nutria, Pescado, and Zuni Rivers).

Snowfall and precipitation along the Nutria monocline, as well as infiltration from streams flowing across the monocline, are recharge sources for the Zuni-Rock Point sandstone aquifer. Additional recharge to the Zuni-Rock Point aquifer occurs via direct precipitation and snowmelt onto uplands and mesa tops situated at elevations of 7000 to 7400 feet (2130 to 2260 m) located throughout the eastern two-thirds of the reservation.

Spring Discharge Trends

Measurements of spring discharge were conducted for the majority of springs visited during this investigation. These data are compared to spring flow measurements from Orr (1987) and Summers (1972). Based on these measurements, spring flows show a declining trend between 1972 and 2009. In the Ojo Caliente area, Summers (1972) reported 500-1500 gpm (32-95 l/s) for combined Ojo Caliente spring discharge, Orr (1987) measured 545 gpm (34 l/s) average combined discharge from Rainbow, Big, and Sacred springs in May 1980, and a combined flow of 365 gpm (23 l/s) was measured in May 2008. Similar trends were observed for Pescado Springs (combined Upper and Lower Pescado spring discharge of 470 gpm (302 l/s) in August 1979 versus 305 gpm (19 l/s) in August 2009), and the Nutria area, where several springs previously utilized by local ranchers were dry during 2007-2009. This apparent decline in spring discharge on the reservation between 1972 and 2009 could be due to increased groundwater diversions in the Zuni Mountains, the Zuni River basin, and regionally in the Psg aquifer resulting in depletion effects on springs, fluctuations in precipitation, variations in measurement methodologies, or a combination of these factors.

During subsequent visits to the five Nutria Psg springs that were dry during the 2007-2009 study, the Zuni Conservation Program observed that four springs started flowing again in May 2010. Past observations revealed that at least two of these springs were flowing in 1995. Analysis of data from one precipitation station and three snow courses in the recharge area indicates that winter precipitation, especially snowpack moisture content, significantly affects recharge for these springs. For January 2010, the precipitation station measured more than twice its mean precipitation and the most snowfall, approximately three times its mean, for January over its period of record, 1923-2012 (WRCC, 2012). For March and April 2010, each snow course had its highest snow water equivalent (SWE) for those respective months for its period of record (1994-2012 for Boon and Dan Valley stations and 1999-2012 for McGaffey) (NRCS, 2012). From January through April 2010, the monthly SWE percent of mean at all three snow courses increased each month from just greater than their monthly means in January (the first month reported) to between five and more than ten times their monthly means in April (the last month reported). For each snow course and each reported month, the cumulative departure from mean (CDFM) SWE exhibits a drying trend from the start of record until 2006-2009, in general, when a wetting trend begins through 2010, as illustrated for March in Figure 9. A similar CDFM analysis of the precipitation station data was limited by a significant amount of missing data, especially after 1999 (NCDC, 2012).

CONCLUSIONS

Springs discharge from the Psg aquifer in the Nutria and Ojo Caliente areas of the Zuni Reservation, with typical flow rates between 15 and 220 gpm (0.9 and 13.9 l/s) measured during site visits in 2007-2009. Nutria springs are recharged in the Zuni Mountains, and groundwater discharging at Nutria represents a mixture of modern and pre-1952 recharge. Ojo Caliente springs have a lower-elevation recharge source on the High Plains, and water discharging at Ojo Caliente represents predominantly or entirely pre-1952 recharge. Pescado alluvial springs also appear to have recharge sources in the Zuni Mountains and exhibit predominantly pre-1952 recharge, whereas Black Rock alluvial

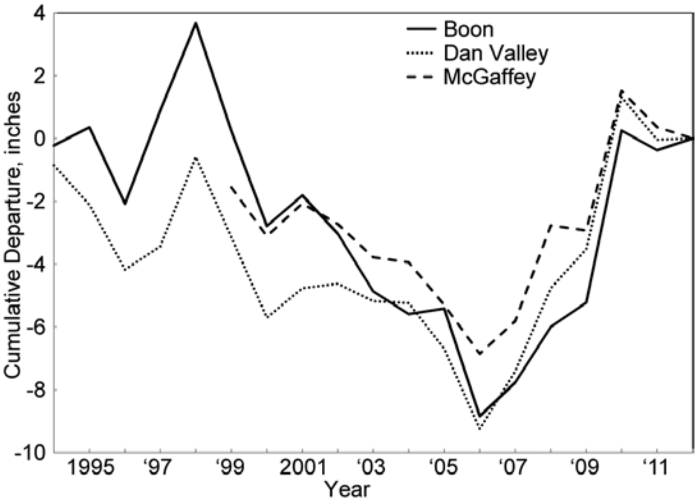


FIGURE 9. Cumulative Departure from Mean March Snow Water Equivalent for Snow Courses in Zuni River Watershed. Boon and McGaffey are in the Rio Nutria watershed.

springs have local recharge sources and are fed by submodern recharge. Alluvial spring discharge ranges from 65 gpm (4.1 l/s) to 185 gpm (11.7 l/s) in the Pescado area to 50-75 gpm (3.2 to 4.7 l/s) or less in the Black Rock area. Rock Point/Zuni Sandstone aquifer springs have local recharge sources on high mesas and flow paths ranging from less than 5 to 10 years to greater than 60 years. Flow rates are 2 gpm (0.1 l/s) or less. Most springs on the Zuni Reservation are recharged by winter precipitation, and snowpack moisture content is an important factor in spring recharge. Summer monsoonal precipitation is a secondary recharge source that may be an important source of recharge on the high mesas within the reservation and appears to be the primary recharge source for the Dowa Yalanne springs. The apparent decline in spring discharge on the reservation between 1972 and 2009 could be due to increased groundwater diversions in the Zuni Mountains, the Zuni River basin, and regionally in the Psg aquifer, fluctuations in precipitation, variations in measurement methodologies, or a combination of these factors.

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REFERENCES

Anderholm, S.K., 1994, Ground-water recharge near Santa Fe, north-central New Mexico: U.S. Geological Survey Water-Resources Investigations Report 94-4078, 68 p.

Chamberlin, R.M., and Anderson, O.J., 1989, The Laramide Zuni uplift, southeastern Colorado Plateau: a microcosm of Eurasian-style indentation-extrusion tectonics?: NM Geological Society Guidebook, 40th Field Conference, p.81-90.

Clark, I., and Fritz, P., 1997, Environmental Isotopes in Hydrogeology: New York, Lewis Publishers, 328 p.

Colpitts, R. 1989, Permian reference section for southeastern Zuni Mountains, Cibola County, New Mexico: NM Geological Society Guidebook, 40th Field Conference, p.177-180.

Craig, H., 1961, Isotopic Variations in Meteoric Waters: Science, v. 133, p. 1702-1703.

Crossey, L.J., Karlstrom, K.E., Newell, D.L., Kooser, A., and Tafoya, A., 2011, The La Madera Travertines, Rio Ojo Caliente, Northern New Mexico: Investigating the Linked System of CO_2 –Rich Springs and Travertines as Neotectonic and Paleoclimate Indicators: N. M. Geological Society, 62nd Field Conference, p.301-316.

Doney, S.C., Glover, D.M., and Jenkins, W.J., 1992, A model function of the global bomb tritium distribution in precipitation: Journal of Geophysical Research, v. 97, no. 4, p. 5481-5492

Drakos, P., Sims, K., Riesterer, J., Blusztajn, J., and Lazarus, J., 2004, Chemical and isotopic constraints on source-waters and connectivity of basin-fill aquifers in the southern San Luis Basin, New Mexico: N. M. Geological Society, 55th Field Conference Guidebook, p. 391-404.

Drever, J.I., 1982, The Geochemistry of Natural Waters: New Jersey, Prentice-Hall, Inc., 388 p.

Eastoe, C.J., Gu, A., and Long, A., 2004, The origins, ages and flow paths of groundwater in Tucson Basin: Results of a study of multiple isotope systems: in Hogan, J.F., Phillips, F.M., and Scanlon, B.R., eds., Groundwater Recharge in a Desert Environment: The Southwestern United States, p. 217-234.

Eastoe, C.J., Watts, C.J., Ploughe, M., and Wright, W.E., 2012, Future use of tritium in mapping pre-bomb groundwater volumes: Groundwater, v. 50, p. 87-93.

Hackman, R.J., and Olson, A.B., 1977, Geology, structure, and uranium deposits of the Gallup 1° x 2° Quadrangle, New Mexico and Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I-981, Scale 1:250,000.

Heckert, A.B., and Lucas, S.G., 2003, Triassic stratigraphy in the Zuni Mountains, west-central New Mexico: N. M. Geological Society, 54th Field Conference, p.241-244.

Johnson, P.S., LeFevre, W.J., and Campbell, A., 2002, Hydrogeology and Water Resources of the Placitas Area, Sandoval County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open File Report 469.

Kelley, V.C., 1967, Tectonics of the Zuni-Defiance region, New Mexico and Arizona: N. M. Geological Society, 18th Field Conference Guidebook, p. 27-32.

Lucas, S.G., and Hayden, S.N., 1989, Triassic stratigraphy of west-central New Mexico: N. M. Geological Society, 40th Field Conference Guidebook, p. 191-212.

Lucas, S.G., and Heckert, A.B., 2003, Jurassic stratigraphy in west-central New Mexico: N. M. Geological Society, 54th Field Conference Guidebook, p.289-301.

Mazor, E., 1991, Applied Chemical and Isotopic Groundwater Hydrology: New York, Wiley and Sons, 274 p.

National Climatic Data Center (NCDC), 2012, Annual Climatological Summaries, McGaffey 5 SE, New Mexico: <http://www.ncdc.noaa.gov/cdo-web/datasets/ANNUAL/stations/COOP:295560/detail> (accessed on February 8, 2013).

Natural Resources Conservation Service (NRCS), 2012, Snow Course and Monthly SNOTEL Data Tables, Boon, McGaffey, and Dan Valley, New Mexico: <http://www.wcc.nrcs.usda.gov/cgibin/state-site.pl?state=NM&report=snowcourse> (accessed on February 6, 2013).

Orr, B.R., 1987, Water Resources of the Zuni Tribal Lands, McKinley and Cibola Counties, New Mexico: U.S. Geological Survey Water-Supply Paper 2227.

Piper, A.M., 1944, A graphical procedure in the geochemical interpretation of water analyses: Geophysical Union Transactions, v. 25, p. 914-923.

Plummer, L.N., Bexfield, L.M., Anderholm, S.K., Sanford, W.E., and Busenberg, E., 2004, Geochemical Characterization of Ground-Water Flow in the Santa Fe Group Aquifer System, Middle Rio Grande Basin, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 03-4131.

Springer, A.E., Stevens, L.E., Anderson, D.E., Parnell, R.A., Kreamer, D.K., Levin, L, and Flora, S.P., 2008, A Comprehensive Springs Classification System: Integrating Geomorphic, Hydrogeochemical, And Ecological Criteria: in Stevens, L.E. and Meretskey, V.J., Arid Land Springs in North America: Tucson, University of Arizona Press, p. 49-76.

Summers, W.K., 1972, Hydrogeology and Water Supply of the Pueblo of Zuni, McKinley and Valencia Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open File Report 33, 118 p.

Western Regional Climate Center (WRCC), 2012, Period of Record General Climate Summary – Precipitation: McGaffey 5 SE, New Mexico:< http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nm5560 > (accessed on February 4, 2013).