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Abstract

The present study seeks to better understand the hydrogeothermal setting of the Bosque del Apache Wildlife Reserve in the Rio Grande rift in central New Mexico. Using water-quality data, subsurface temperatures, heat-flow estimates, and Bouguer gravity data, we propose a groundwater-flow regime for the Bosque. Temperature, heat-flow, and water-quality data indicate a relatively shallow, cool, fresh-water zone near and west of the Rio Grande, extending from the water table to a maximum depth of 400–500 ft (122–152 m). This water is derived from river and irrigation recharge and the flow into the alluvial aquifer from the west. Over a wide area low-quality, relatively warm water occurs beneath the cool, fresh-water layer. The stratigraphy of the area and the high chloride content and warm temperatures of the water suggest a broad upflow from depth in the Socorro Basin. The Bouguer gravity information is consistent with low-permeability basement rocks shallowing to the south in the direction of groundwater flow. This interpretation of the gravity data provides a hydrogeologic setting consistent with broad, southward upflow of deep groundwater. A well producing warm, poor-quality water from apparently shallow depths (~250 ft or 76.2 m) seems to be a localized phenomenon. It is suggested that this warm water comes from the deeper groundwater zone, rising along a high-angle fault or through discontinuities in the clay layers of the alluvial aquifer. Future drilling for warm, shallow water in the area should consider the complicated hydrogeothermal setting.

Introduction

This report summarizes a geothermal investigation performed at the Bosque del Apache Wildlife Refuge in central New Mexico (Fig. 1). The study was undertaken to gain a better understanding of the interaction between groundwater flow and subsurface temperatures in the Bosque area and to investigate the source of warm water in one of the Bosque's water-supply wells. Although the warm water produced by the thermal well is poor quality and is high in arsenic (John Taylor, oral comm.), it is used to keep wildlife areas free from ice in the winter. Bosque personnel have expressed interest in the possibility of drilling another thermal well.

As part of this study, temperatures were logged in three wells on the Bosque del Apache, and one well on the Fite Ranch immediately east of the refuge. Temperatures were also logged in wells several miles east of the refuge on White Sands Missile Range as part of another study. This investigation combines subsurface temperature data and groundwater geochemistry data, including hydrogeologic data and interpretations from previous studies.

A recent USGS report, Anderholm (1987), contains an overview of the hydrogeology of the Socorro Basin, a compilation of hydrologic data (water levels and water quality), and an analysis of water-quality, recharge, and water-resource data. A previous USGS report, Weir (1965), summarizes geologic, hydrologic, and water-quality data from the northern part of the White Sands Missile Range and vicinity, including the Bosque del Apache. The report by Weir (1965) also provides some detailed information from three test wells (Stallion series wells) drilled at the northwestern part of the missile range. A USGS open-file report, Cooper (1968), presents hydrologic, lithologic, and water-quality data from a series of water-supply test wells drilled on the Bosque del Apache by the USGS for White Sands Missile Range. This last report presents data from the Bosque del Apache's water-supply wells and also discusses stream/aquifer interaction.

Location

The Bosque del Apache Wildlife Refuge (referred to here as "the Bosque") is in the Rio Grande valley in central New Mexico (Fig. 1). The Rio Grande, a perennial river, flows through the center of the Bosque from north to south and is paralleled by an artificial channel designed to carry the river's water under low-flow conditions. The Bosque consists of flat, river-bottom lands and some arid lands of higher elevation on both sides of the river. West of the river, the flood plain of the Rio Grande is developed into ponds for wildlife and irri-

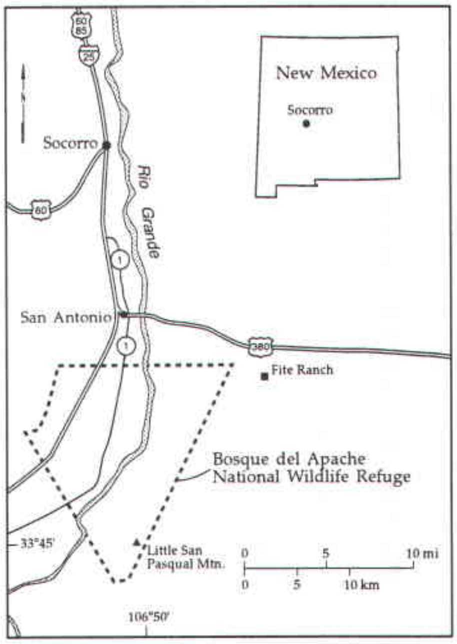

FIGURE 1—Location map of the study area (after Geddes, 1963).

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Also in this issue

Coming Soon

1995 NMGS spring meeting abstracts

Summary of charges for natural resources other than oil and gas on New Mexico State Lands gated cropland, with numerous canals, irrigation ditches, and drains. East of the river the land is largely undeveloped and is arid and rugged, except for a small amount of low ground near the river that floods periodically.

Hydrogeology

General background

The Bosque is in the southern part of the Socorro Basin. This basin contains an uncertain thickness of alluvial fill, perhaps up to several thousand feet, and is bounded by outcrops of Paleozoic rocks to the east and Tertiary volcanic, Paleozoic, and Precambrian rocks to the west (Anderholm, 1987). In the Socorro Basin the primary aquifer consists of Tertiary and Quaternary alluvial fill. The upper units of alluvial fill consist predominantly of sand and gravel, with some clay layers, and are highly transmissive. Deeper alluvial deposits may consist of indurated clays and evaporites that are much less permeable (Anderholm, 1987).

The predominant direction of groundwater flow in the basin is from north to south, following the flow of the Rio Grande. Irrigation and other human activities also influence groundwater flow near the river. Anderholm (1987) states that "groundwater flow in the Rio Grande valley is controlled by the river, conveyance channels, acequias, ditches, laterals, drains, and groundwater inflow from adjacent areas." At the Bosque, wildlife ponds constitute another source of groundwater recharge. The ponds and the irrigated cropland of the Bosque are west of the Rio Grande, in the area between the river and NM–1 (Fig. 1). In general, surface water from ponds, irrigation ditches, laterals, and irrigated fields infiltrates into the subsurface and, as groundwater, flows toward drains. Water from the Rio Grande is also lost to infiltration in this area, some of which ends up in the adjacent artificial conveyance channel.

Water-level data indicate that groundwater flows into the primary aquifer of the Socorro Basin from both the east and west near the Bosque. Inflow from the west consists of relatively fresh water that has mainly been in contact with Tertiary volcanic rocks and alluvial deposits. Inflow from the east consists of lower quality water that is high in sulfates, probably as a result of interaction with Paleozoic sedimentary beds containing gypsum (Anderholm, 1987). The eastern margin of the sedimentary basin is near the eastern boundary of the Bosque (Fig. 2).

Bosque water-supply wells

A number of wells have been drilled to supply water for irrigation and incidental uses at the Bosque. These wells are shown as the "W" series in Fig. 2; they range in depth from 100 ft to 252 ft (30.5 m to 76.8 m). All these wells produce cool water (temperature less than 20°C), except one of the deepest wells, W14, which produces water 32–33°C (90°F) in temperature. The wells are all drilled in alluvial sediments: sand and gravel with some layers of clay. The lithologic log of W14 (the thermal well) indicates that this well also penetrates sand and gravel, the same material found in the Bosque's nonthermal wells.

Apache 1A oil test

There is other evidence of geothermal water at the Bosque. An oil well, Apache 1A, was drilled in the 1920s on the west side of the river to a depth of 2,445 ft (745 m) in a location that is now part of the Bosque (Fig. 2). Historical reports indicate that this wellbore produced artesian hot water for a number of years, creating a popular bathing pool of hot mineral water until the well was plugged. (Unfortunately, no chemical or temperature data have been found relating to this well.) The fact that this well produced artesian flow at the surface indicates that a source of hot water under artesian pressure exists at depth in the area.

The lithologic log for this well is on file at the New Mexico Bureau of Mines and Mineral Resources. The log indicates that salt and anhydrite were encountered at 1,955 ft (596 m) depth. Anderholm (1987) states that "the top of this anhydrite probably represents the bottom of the principal aquifer system." The salt and anhydrite might be the Permian Yeso Formation.

Heat flow

Heat flow is defined as the product of the vertical temperature gradient (the rate at which temperatures increase with depth) and the thermal conductivity of the rocks in which temperatures are measured (thermal conductivity, k_t, is a physical property that quantifies the ability of a material to transmit heat by conduction.) Heat-flow measurements can, in some cases, provide information about regional geologic conditions. For example, tectonically and volcanically active areas have relatively high heat flows as compared with geologically stable areas. Groundwater flow can disturb subsurface temperatures, and therefore heat-flow data have the potential to provide information about subsurface hydrologic conditions. Upward groundwater flow tends to elevate near-surface temperatures and near-surface heat flow, whereas downward groundwater flow reduces near-surface temperatures and heat flow. It is anticipated that both regional heat flow and local hydrologic effects influence the observed temperatures in and near the Bosque.

Socorro Basin is part of the Rio Grande rift, a large tectonic feature that consists of a series of interconnected basins that trends north-south through central New Mexico and parts of Colorado, Texas, and Mexico. Heat flow in the Rio Grande rift tends to be elevated (Reiter et al., 1986), generally varying between 75 and 100 mW m^{-2} (as compared with 40 to 50 mW m^{-2} for the Great Plains of eastern New Mexico). Exceptionally high heat flows, greater than 200 mW m^{-2}, are also observed in parts of the Rio Grande rift. It is believed that these exceptionally high heat flows are, in most cases, caused by upward groundwater flow bringing heat near the surface by forced convection (Harder et al., 1980; Reiter et al., 1986; Barroll and Reiter, 1990). Heat transfer by water movement can be much greater than by conduction. Anomalously low heat flows have also been observed within the Rio Grande rift; these data may be associated with downward groundwater flow.

Subsurface temperatures at the Bosque

Temperatures were logged in three wells at the Bosque as part of this study: W1, W4,

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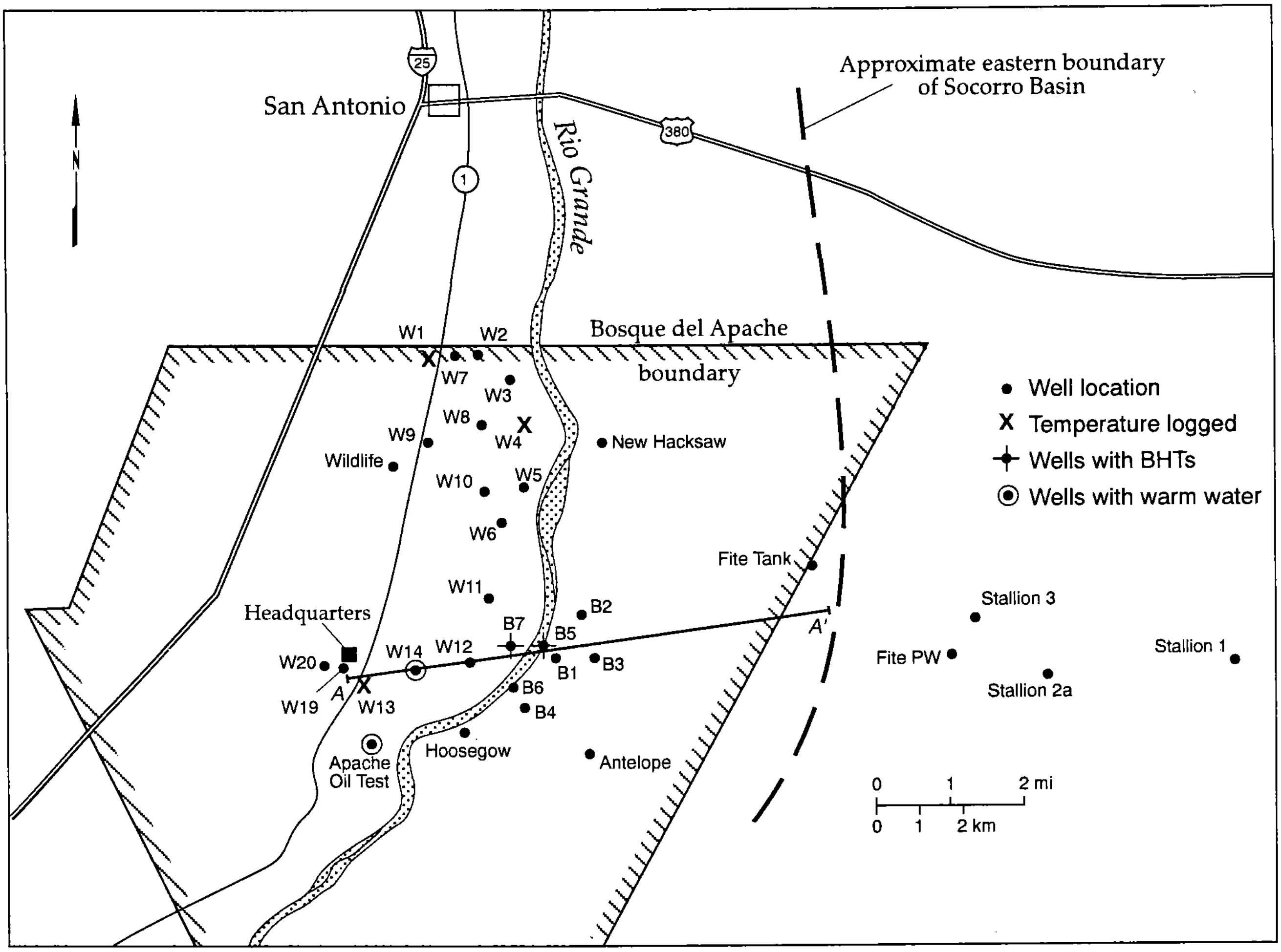

FIGURE 2—Location of wells near and in the Bosque del Apache. Cross section A-A' is in Fig. 4.

W13 (Fig. 2, Table 1). Temperatures were measured with a high-precision thermistor logging tool. The depth to water in these wells was quite shallow, and all temperatures were obtained below the water table. The resulting temperature vs. depth profiles are in Fig. 3. Positive temperature gradients measured in the three wells are 25°C km^{-1}, 8.2°C km^{-1}, and 31°C km^{-1} at W1, W4, and W13, respectively. Thermal conductivities were measured on drill cuttings from nearby wells, and the in situ thermal conductivity (k_t) was estimated to be 1.4–1.9 W mK^{-1}. The heat-flow data for the three logged wells are summarized in Table 2.

The three heat-flow estimates range from 11.5 to 58.9 mW m^{-2} and are significantly less than the 75–100 mW m^{-2} that is expected in this area. These wells are relatively shallow (≤130 ft, 40 m), and all are in the developed part of the west bank of the Bosque, amidst irrigated lands and wildlife ponds. Therefore, it is likely that the low heat flows observed here are a result of the downward groundwater flow associated with the infiltration of irrigation and other surface waters.

There is a discontinuity in the temperature profile of W1 below the interval in which the temperature gradient of 25°C km^{-1} was measured, at about 23 m (Fig. 3). This is the depth of the top of the well screen, and therefore it is possible that the flow of water in the wellbore may perturb the measured temperature field. The extremely low temperature gradient observed in W4 may also be influenced by borehole flow.

TABLE 1—Temperatures measured in wells at the Bosque del Apache Wildlife Refuge.

Well:	**W 1**		**W 4**		**W 13**	
Date logged:	**10/17/90**		**10/17/90**		**10/11/90**	
	Depth (m)	**T (°C)**	**Depth (m)**	**T (°C)**	**Depth (m)**	**T (°C)**
	10.0	17.60	10.0	15.994	10.0	17.20
	12.0	17.63	12.0	15.822	12.0	17.24
	14.0	17.68	14.0	15.722	14.0	17.29
	16.0	17.74	16.0	15.633	16.0	17.36
	18.0	17.79	18.0	15.503	18.0	17.44
	20.0	17.84	20.0	15.417	20.0	17.51
	22.0	17.90	22.0	15.405	22.0	17.54
	24.0	18.11	24.0	15.405	24.0	17.63
	26.0	18.20	26.0	15.417	26.0	18.20
					27.0	18.35
	28.0	18.23	28.0	15.423		
	30.0	18.24	30.0	15.432		
	31.0	18.24				
			32.0	15.447		
			34.0	15.464		
			36.0	15.484		
			38.0	15.514		
			40.0	15.544		
			40.3	15.553		

Temperatures were not logged in the Bosque thermal water well, W14. (W14 was inaccessible and is reportedly bridged at 90 ft, 27.4 m.) The temperature of the water pumped from this well has been reported to be 32–33°C (Anderholm, 1987; unpublished records from the Bosque). If we assume that the water pumped from the well comes from a depth of 252 ft, 76.8

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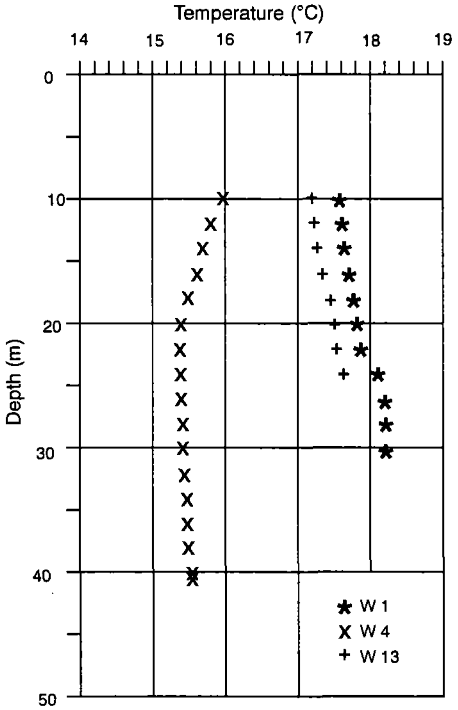

FIGURE 3—Temperature vs depth for three wells logged in the Bosque del Apache.

TABLE 2—Temperature gradient data from the Bosque del Apache.

Well ID	Total depth (m)	Temperature gradient (°C km^{-1}) (K km^{-1})	Thermal conductivity (W mK^{-1})	Heat flow (mW m^{-2})
W1	31	25	1.4–1.9	35.0–47.5
W4	40	8.2	1.4–1.9	11.5–15.6
W13	26	31	1.4–1.9	43.4–58.9

TABLE 3—Subsurface temperatures and heat-flow estimates for wells just east of the Bosque.

Well	TD (ft, m)	Depth to water (ft, m)	Water temperature(1) (°C)	Γ(2) (°C km^{-1}) (K km^{-1})	Q(3) (mW m^{-2})
Fite Tank		279.0, 85.1	25.6 (measured in situ)	100	170
Fite PW	500, 152.4 (reported)	404.3, 123.3	23.3	43	74
Stallion 3	720, 219.5	420.0, 128.0	28.3	65	111
Stallion 2a	600, 182.9	405.0, 128.5	25.6	56	94
Stallion 1	600, 182.9	317.7, 96.9	22.2	37	63

(1) Pumped, except at Fite Tank were measured in situ.
(2) Temperature gradient estimated from pumping water temperature (taken to be at a depth midway between TD and depth to water), and surface temperature of 17°C.
(3) Heat flow using thermal conductivity of 1.7 W mK^{-1}.

m, i.e. the bottom of the well, and is representative of the formation temperature, then the estimated heat flow is exceptionally high. For example: the resulting geothermal gradient would be ~200°C km^{-1} (using a surface temperature of 17°C obtained by extrapolating temperature logs in and near the Bosque and assuming a temperature of 32.5°C at 252 ft, 76.8 m). With a thermal conductivity value of 1.7 W mK^{-1} (an average value as discussed above) we estimate a heat flow of 340 mW m^{-2}. Such a high heat flow is most likely a result of groundwater upflow bringing heat from depths greater than the bottom of the well.

In an attempt to understand the distribution of warm groundwater let us examine other subsurface temperature data in the study area. Cooper (1968) did a study involving the drilling and testing of several relatively deep wells in the Bosque ("B" wells on Fig. 2). These wells were no longer open during the present investigation (see Appendix A). However, bottom-hole temperatures had been recorded for two of the wells on geophysical logs. Although bottom-hole temperatures are typically suspect, they can provide valuable information if there is reasonable agreement between close measurements. Well B5 had a recorded bottom-hole temperature, BHT, of 28.9°C at 510 ft (155.5 m) depth taken 2 hours after the cessation of circulation. Well B7 had a BHT of 30°C at 509 ft (155.2 m) depth taken 5 hours after the end of circulation. These recorded temperatures are likely to be slightly less than actual in situ temperatures because of the cooling effect of drilling fluids and the time response of large logging tools. Nevertheless, the data can be used to consider the local subsurface temperature distribution. Estimating the heat flow at B5 and B7, as done above for W14, we estimate values of ~130 mW m^{-2} and ~142 mW m^{-2}, respectively. These heat-flow values are larger than typical for the Rio Grande rift and suggest that groundwater is influencing the subsurface temperature regime at B5 and B7; however, the values are not nearly so large as the heat flow calculated at W14. This conclusion allows us to speculate that, in addition to a general, relatively deep seated upflow, a unique hydrogeologic condition exists at W14 that permits warm water to come relatively close to the surface (<400 ft or 122 m depth) during pumping.

Subsurface temperature data are also available from a well just outside of the Bosque, east of the river at the edge of the Socorro Basin (Fig. 2, Fite Tank). In the Fite Tank well, a temperature of 25.6°C at 279 ft (85 m, just below the water level) was measured during a previous geothermal exploration project. Assuming surface temperature of 17°C and thermal conductivity of 1.7 W mK^{-1}, we calculate temperature gradient of 100°C km^{-1} and heat-flow value of 170 mW m^{-2}. The problem with comparing this data with data from the wells discussed above is that the gradient (100°C km^{-1}) in the Fite Tank well is over a depth interval above the water table, whereas the gradients in the wells above (W14, B5, B7) are estimated over depth intervals largely below the water table. Geologic materials above the water table may have significantly different thermal conductivities from materials that are below the water table because of difference in water content. Below the water table in Fite Tank well a temperature gradient of 56°C km^{-1} was measured; this would correspond to a heat flow of 95 mW m^{-2}, which is probably the more representative value. In any case, for comparison with the other heat-flow values near the Rio Grande, we suggest that the heat flow at Fite Tank (between 95 and 170 mW m^{-2}) more closely approximates the values at B7 and B5 (130 and 142 mW m^{-2}) than the value at W14 (340 mW m^{-2}). This allows speculation that the Fite Tank well, and wells B7 and B5, exist in somewhat similar hydrogeothermal settings, whereas W14 has a rather local hydrogeologic setting.

Subsurface temperature data and heat-flow estimates are given for the Fite Tank well and four other wells east of the Bosque (Table 3, Fig. 2). With the exception of Fite PW, heat flows decrease eastward from the Bosque. Heat-flow estimates for Stallion 3 and Stallion 2a are reasonable for the Rio Grande rift and could be influenced (to a lesser extent) by similar hydrogeologic processes as operating at B5, B7, and Fite Tank. The estimated heat flow at Stallion 1 suggests that the effects of warm groundwater upflow are not present at this site and that this site may be outside of the area thermally influenced by the Rio Grande rift.

Water chemistry data

Water chemistry in and near the Bosque varies substantially and can be separated into three types. First is a shallow zone (depth less than 165 ft, 50 m) of high-quality water. Except for W14 (the thermal well), the Bosque water wells produce cool, relatively high quality water from this shallow zone. Fresh groundwater is also found west of the Bosque and flows into the Socorro Basin from the west. Beneath the shallow high-quality water zone is a second type of water: a warm, very low quality water that has sulfate and chloride concentrations approximately equal to or great than 1,000 ppm.

These two zones are illustrated in Fig. 4, a cross section west to east through the Bosque that shows chloride data obtained from Anderholm (1987) and Cooper (1968). Fig. 4 shows the eastward extent and variable thickness of the shallow fresh-water

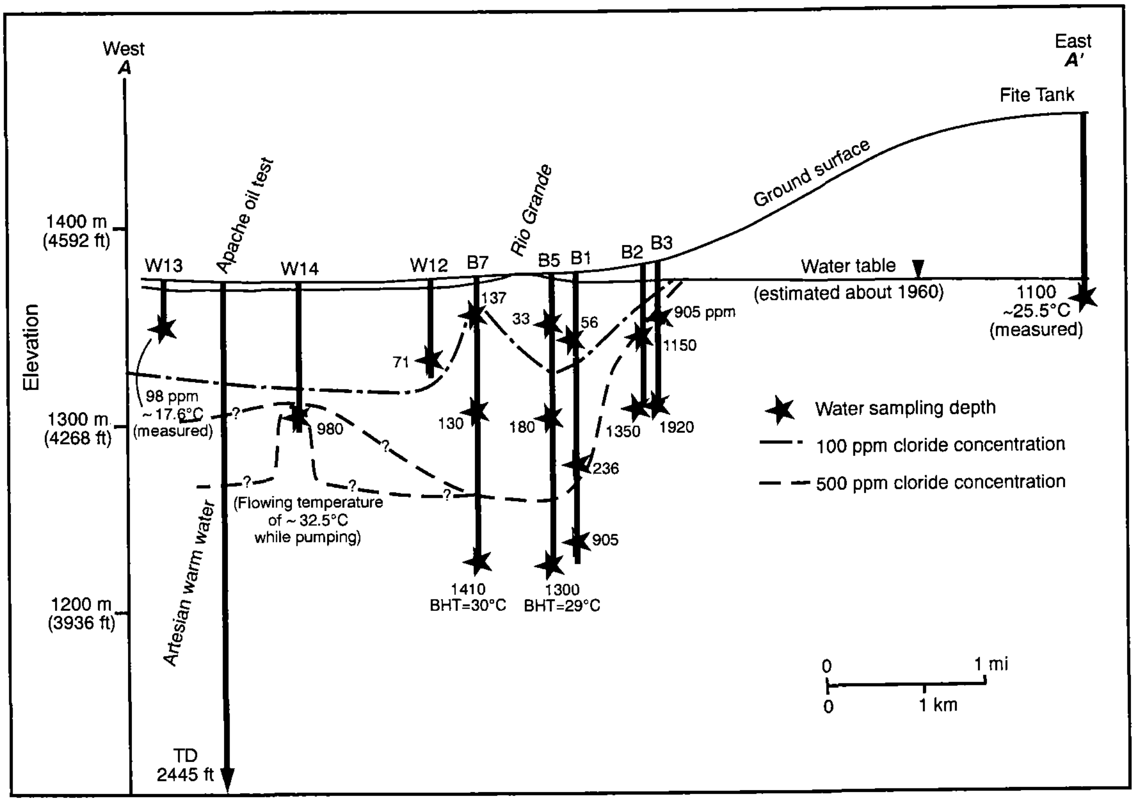

FIGURE 4—Cross section along A–A' with observed chloride concentrations in groundwater, Bosque del Apache Wildlife Refuge, New Mexico. Data from Anderholm (1987) and Cooper (1968). Line of section is in Fig. 2.

zone. In some locations cool, relatively fresh water (chloride and sulfate concentrations less than 200 ppm) was obtained from a depth of about 250 ft (76.2 m; wells B7 and B5; Table 4, Fig. 4). However, well W14, which bottoms at 252 ft (76.8 m), produces low-quality warm water. The shallow high-quality water zone ends a short distance east of the Rio Grande; the zone was not found in wells B2, B3, or B4 (Fig. 4, Table 4). A third type of groundwater is found east of the Bosque, outside the Socorro Basin. This water is high in sulfates but low in chloride (note the Stallion test wells, Table 4, Fig. 2).

Interpretation

The Rio Grande and associated surface-water canals, ditches, ponds, and applied irrigation waters are the sources of the shallow, relatively high quality groundwater found near and west of the river. Water from these sources infiltrates into the ground and recharges the shallow groundwater system. Relatively fresh groundwater also flows into the system from the west. East of the river, the fresh-water zone is thin and limited in areal extent. This is consistent with the fact that there are no wildlife ponds and irrigation works east of the river. The only significant source of relatively fresh water east of the river is the river itself. Groundwater inflow from the east is poor-quality, high-sulfate water (Anderholm, 1987).

The poor-quality water that underlies the fresh river-related groundwater is high in both chloride and sulfate and cannot have originated from the low-chloride, high-sulfate water east of the Socorro Basin. High-chloride water occurs in the Socorro Basin north of the Bosque (and hydrologically upgradient; Anderholm, 1987, plate 4). Anderholm (1987) suggests these high-chloride zones are associated with "the upward movement of regional groundwater." A possible source of the chloride is the salt that the lithologic log of Apache 1A shows to exist at about 2,000 ft deep in the Bosque del Apache area and that may well exist at other depths north of the Bosque. Therefore, the high-chloride water found at the Bosque is probably deep basin waters that have flowed upward, closer to the surface either at the Bosque or north of the Bosque.

The Bosque thermal well W14 produces warm water of poor quality ($SO_4 = 560$ ppm, $Cl = 980$ ppm). The water chemistry of W14 is very similar in character to the low-quality waters obtained from deeper intervals in the "B" series wells. This implies that the thermal water at W14 is somehow associated with the underlying low-quality water. However, as discussed above, not all of the low-quality water appears to be as anomalously warm as the water from W14.

Subsurface temperatures and groundwater chemistry in the Bosque suggest a somewhat complicated groundwater system in the alluvial aquifer. Fig. 4 highlights some of the important data along a west-to-east profile across the Bosque. Fig. 5 is a north-to-south cross section that illustrates our present thoughts on the groundwater flow regime in the Bosque. A shallow, relatively cool, fresh-water zone occurs in the vicinity of the Rio Grande and west of the river beneath irrigated lands and wildlife ponds. This shallow zone occurs from the water table to a maximum depth of 400 to 500 ft (122–152 m). The cool, shallow water is derived from local river and irrigation-related recharge and also has a component of fresh water flowing into the alluvial aquifer from the west.

Low-quality, relatively warm water occurs beneath the cool fresh-water zone. The low-quality water is also found at shallow depths east of the river where the cool, fresh-water zone is practically absent (Fig. 4). The high-chloride content of this water suggests upflow from depth in the Socorro Basin (Fig. 5). Bottom-hole temperature data from wells B7 and B5 suggest that this water is somewhat warmer than would be expected for its depth. The temperature and water-quality data from the deeper zone are consistent with a broad zone of groundwater upflow in the vicinity of the Bosque. The artesian groundwater flow observed in the past at the Apache oil test is consistent with an upward groundwater flow regime.

Upflow in the warm groundwater zone at the Bosque del Apache may be caused largely by structural relief of low-permeability basement rocks that constricts groundwater flow and forces it upward. Gravity data from the vicinity of the Bosque, presented by Keller and Cordell (1983), show a marked increase in gravity

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from north to south and from north to southeast (Fig. 6). The increase in gravity as one moves south at the Bosque is consistent with the suggestion that the alluvial aquifer generally thins and the basement becomes shallower as one proceeds from the north to the south or southeast. Shallowing of the basement could cause southward-flowing groundwater to move upward, bringing warm water high in chloride to shallower depths. This basic idea has been suggested for other locations along the Rio Grande rift by Harder et al. (1980).

Well W14 produces water that is anomalously warm, compared to wells B7 and

TABLE 4—Summary of well chemistry data.

Well ID	Location T	Location R	Location Sec	Location q q q*	TD (ft, m)	Temp (°C)	Specific conductance (μS cm^{-1})	Sulfate SO_4 (ppm)	Chloride Cl (ppm)	Date of sample	References
W1	5S	1E	18	434	149, 45.4	17.6	1030	230	81	2/58	Anderholm (1987)
							883	182	67	8/66	Cooper (1968)
W2	5S	1E	17	344	125, 38.1	16.7	640	84	84	2/58	Weir (1965)
							735	79	108	8/66	Cooper (1968)
							1800	330	260	7/80	Anderholm (1987)
W3	5S	1E	20	241	128, 39.0		817	185	44	8/66	Cooper (1968)
W4	5S	1E	28	111	114, 34.8 (250, 76.2)†	16.0	888	211	55	8/66	Cooper (1968)
W5	5S	1E	28	331	115, 35.1 (200, 61.0)†		923	219	50	8/66	Cooper (1968)
W6	5S	1E	32	234	115, 35.1		914	213	58	8/66	Cooper (1968)
W7	5S	1E	18	44	150, 45.7		475	74	29	8/66	Cooper (1968)
W8	5S	1E	20	344	142, 43.3		614	105	48	8/66	Cooper (1968)
W9	5S	1E	30	223	142, 43.3	17.0	1340	285	83	8/66	Cooper (1968)
							1400	270	100	7/80	Anderholm (1987)
W10	5S	1E	29	342	142, 43.3		1300	290	120	6/63	Anderholm (1987)
							1290	290	108	8/66	Cooper (1968)
W11	6S	1E	5	144	170, 51.8		1360	314	121	8/66	Cooper (1968)
							1200	230	93	7/80	Anderholm (1987)
W12	6S	1E	8	123	150, 45.7 (170? 51.8)†		716	91	71	8/66	Cooper (1968)
W13	6S	1W	12	423	100, 30.5	17.2					
W14 (warm)	6S	1E	7	213	252, 76.8	33.0	4600	560	980	7/80	Anderholm (1987)
W15	5S	1E	29	131	252, 76.8						
W19	6S	1W	12	233	90, 27.4		540	59	48	2/58	Weir (1965)
W20	6S	1W	12	431	155, 47.3	15.5	980	110	98	2/58	Weir (1965)
Fite Tank	5S	1E	36	442	~380, 117	26.5	6740	2200	1100	11/62	Anderholm (1987)
Stallion 1	6S	2E	1	444	600, 182.9	22.2	3310	2040	39	4/56	Weir (1965)
Stallion 2A	6S	2E	10	141	600, 182.9	25.6	2010	904	39	5/56	Weir (1965)
Stallion 3	6S	2E	4	144	720, 219.5	28.3	771	218	24	9/56	Weir (1965)

* Note: represents ¼ ¼ ¼ of section (Location).

† Well was deepened or alternative depth listed in another reference.

Well ID	Location T	Location R	Location Sec	Location q q q*	Interval tested (ft, m)	Temp (°C)	Specific conductance (μS cm^{-1})	Sulfate SO_4 (ppm)	Chloride Cl (ppm)	Date of sample	References
B1	6S	1E	9	111	100–160‡, 30.5–48.8		1060	245	56	11/63	Cooper (1968)
					320–340, 97.6–103.7		1620	258	236	11/63	Cooper (1968)
					440–462, 134.1–140.9		4350	704	905	11/63	Cooper (1968)
B2	6S	1E	4	414	119–130, 36.3–39.6		6350	1250	1150	6/66	Cooper (1968)
					242–253, 73.8–77.1		5760	756	1350	6/66	Cooper (1968)
B3	6S	1E	9	212	86–97, 26.2–29.6		5060	1060	905	6/66	Cooper (1968)
					241–252, 72.3–76.8		8190	1380	1920	6/66	Cooper (1968)
B4	6S	1E	9	333	91–102, 27.7–31.1		6560	1230	1540	7/66	Cooper (1968)
					237–252, 72.3–76.8		9660	1500	2380	7/66	Cooper (1968)
B5	6S	1E	8	223	55–175‡, 16.8–53.4		1120	234	82	5/67	Cooper (1968)
					77–100, 23.5–30.5		719	160	33	4/67	Cooper (1968)
					227–250, 69.2–76.2		1130	125	180	4/67	Cooper (1968)
					489–512, 149.1–156.1	28.9	6100	955	1300	5/67	Cooper (1968)
B6	6S	1E	8	412	89–112, 27.1–34.1		5290	960	995	6/67	Cooper (1968)
B7	6S	1E	8	211	175–250‡, 53.4–76.2		854	106	120	8/67	Cooper (1968)
					77–100, 23.5–30.5		1490	299	137	9/67	Cooper (1968)
					227–251, 69.2–76.5		944	127	130	9/67	Cooper (1968)
					481–502, 146.6–153.0	30.0	6530	1064	1410	9/67	Cooper (1968)

* Note: represents ¼ ¼ ¼ of section (Location).

‡ Completed well.

B5. The water produced while pumping W14 (depth: 252 ft, 76.8 m) is approximately 32.5°C. This is about 3°C warmer than the bottom-hole temperatures in B5 and B7 at about 500 ft (~150 m) depth. We suggest that some unique hydrogeologic condition exists at W14 so that the water pumped from this well originated (or was at thermal equilibrium with a location) several hundred feet deeper than the depths of B7 and B5 (Fig. 4). Perhaps a north-south high-angle fault (parallel to the trend of Rio Grande rift) is acting as an avenue for upflow during pumping; or perhaps a discontinuity in the clay units of the alluvial aquifer allow a very local upflow during pumping. The warm water need not come from great depth; the above discussion shows that a local hydrogeologic avenue at W14 would need to allow water flow from about 800 ft (244 m) to 250 ft (76.2 m) deep (Figs. 4, 5).

Conclusion

The present study has a very practical aspect, i.e. to evaluate the probability of drilling additional hydrothermal wells at the Bosque del Apache. From the available data it appears that wells drilled to about 500 ft (152 m) near and west of the Rio Grande are likely to encounter low-quality water of about 29–30°C, although with the limited data coverage considerable uncertainty exists for the temperature estimates. At well W14, which produces water at about 32.5°C from a well depth of 252 ft (76.8 m), a local hydrogeologic phenomenon is present that provides a concentration of warm water. Whether such conditions exist elsewhere is uncertain. If a broad hydrogeologic phenomenon occurs with warm groundwater flowing upward as the basement shallows, then temperatures of ~32.5°C could possibly be reached at depths of about 800 ft (244 m). It is likely that a well drilled in this area could produce water from both the cool, fresh, shallow aquifer as well as from the warmer, low-quality, deeper aquifer. Careful well completion would be required to ensure the zone (depth) of production.

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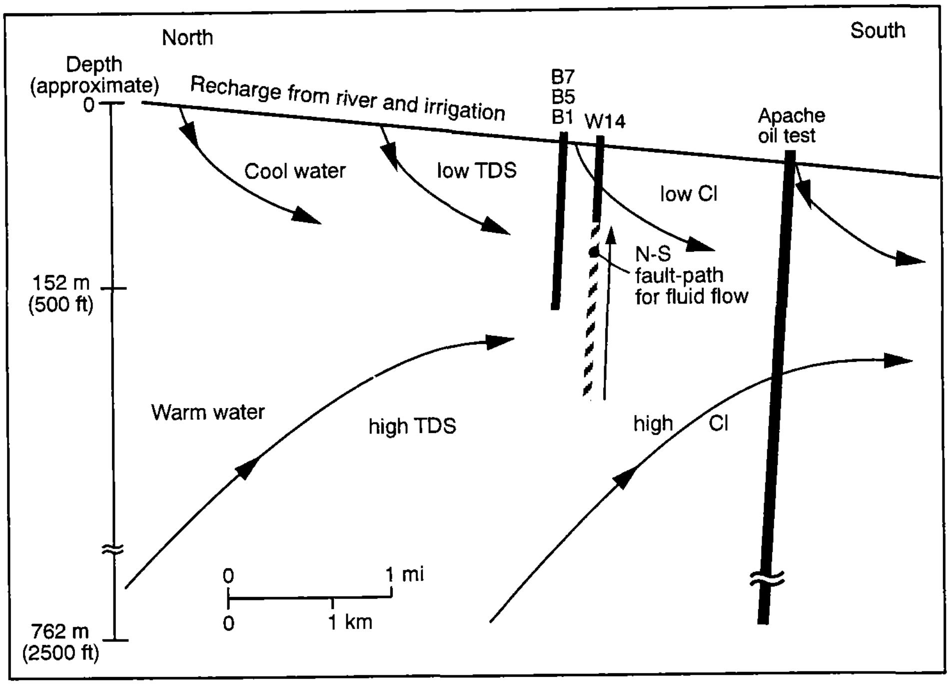

FIGURE 5—Conceptual model explaining temperatures and chemical concentrations of groundwater in the Bosque del Apache Wildlife Refuge.

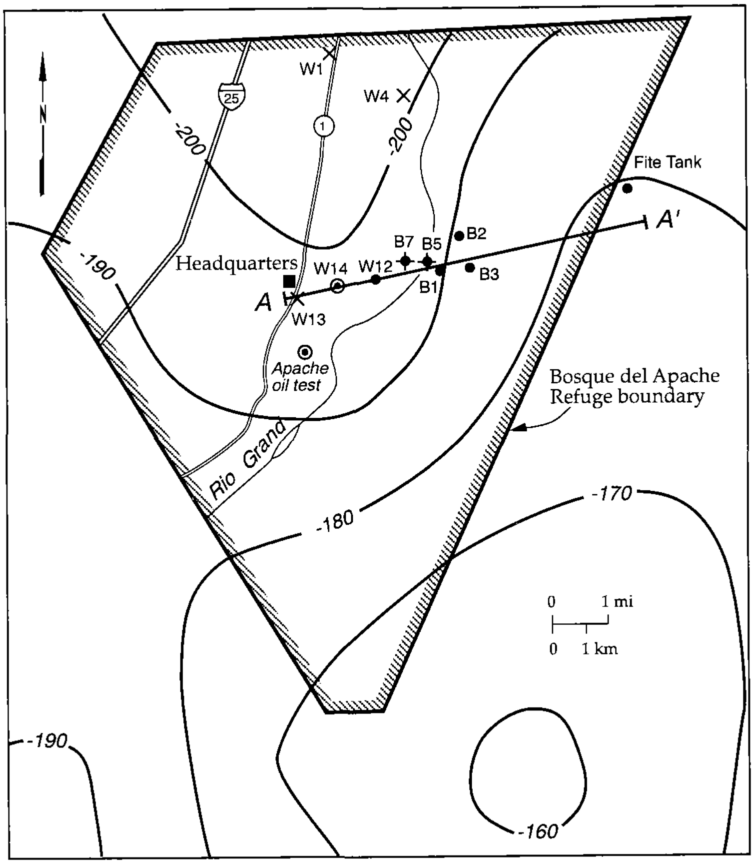

FIGURE 6—Some of the wells in the Bosque del Apache located on Bouguer gravity map after Keller and Cordell (1983). Contours in mgals. Cross section A–A' is in Fig. 4; line of section is also in Fig. 2.

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biochronology thus indicates a short hiatus in the U-Bar Formation at the Aptian–Albian boundary. This hiatus is equivalent to one ammonite zone, the earliest Albian *Hypacanthoplites cragini* zone. A marked lithologic change from *Exogyra* packstones of the uppermost oyster-limestone member to calcareous shales and ledgy, nodular limestones of the overlying limestone-shale member is physical evidence of the disconformity equivalent to this hiatus. In southeastern Arizona, the Aptian–Albian boundary is approximately at the lower Mural–upper Mural contact, and in central Texas it is at the contact of the Hensel Formation with the overlying Glen Rose Limestone, but at these sections earliest Albian strata are present. This suggests that tectonism local to southwestern New Mexico affected marine deposition during the Aptian–Albian transition. □

New Mexico Museum of Natural History and Science exhibit

On June 3, 1995 the New Mexico Museum of Natural History and Science (Albuquerque) will open its new exhibit featuring Early Permian footprints found in the Robledo Mountains near Las Cruces. The exhibit, "Ancient Evidence: Life Before the Dinosaurs," focuses on the phenomenal fossil record of invertebrate and vertebrate tracks preserved in Lower Permian strata of the Abo–Hueco transitional zone in Doña Ana County. In quantity, quality of preservation, and diversity of trackmakers, the Doña Ana County tracks are the best record on earth, one that provides a unique glimpse of terrestrial life and locomotion some 280 million years ago. The exhibit, which occupies about 2,000 square feet, reconstructs the environment in which the tracks were formed; Hueco Formation invertebrates and fossil driftwood are displayed with numerous tracks. The visitor is also taught how fossil tracks are studied and identified.

The New Mexico Museum of Natural History and Science is open 9am–5pm seven days a week; for more information, call (505) 841-8837. □

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Appendix A
Present status of "B" series wells in the study area

We attempted to locate the "B" series of wells drilled by the USGS on the Bosque del Apache and described by Cooper (1968). It was found that none of these wells are accessible to a depth sufficient to allow temperature logging. (Subsurface temperature data shallower than about 90 ft is likely to be influenced by temperature fluctuations at the surface, and so such data is of little usefulness.)

B1—Apparently converted into a windmill well, named Army well. We located the well; it's an old broken-down windmill, no longer operational. Now open to about 40 ft (12.2 m), it still has the windmill 'sucker rods' in it, making access to the wellbore difficult.

B2—Cooper (1968) states this well was plugged and abandoned.

B3—Cooper (1968) states this well was plugged and abandoned.

B4—Cooper (1968) states this well was plugged and abandoned.

B5—This well is described as being drilled "on a topographical high in the old channel of the Rio Grande". We located the well in 1990 in the present channel of the Rio Grande, about 50 ft (15 m) from the east shore in shallow water. There is a concrete platform, which presumably was installed at about land surface, now about 3 ft (~1 m) above the surface of the water, attached to the well casing. The casing had a cover with a rusted-out hinge. When we opened the cover, the hinge broke. Inside the casing we found a 1" pipe that led to a serrated metal collar, below which the pipe seemed to widen, but which is blocked by a packer. Everything was rusted and couldn't be budged.

B6—Cooper (1968) reports this well was plugged and abandoned.

B7—We located this well just west of the road along a low-flow channel. The well was blocked just below the water level (no more than 10 ft [3.05 m] deep). □

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