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Jay Lazarus and Paul Drakos

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GEOHYDROLOGIC CHARACTERISTICS AND HYDROCARBON CONTAMINATION OF THE SHALLOW ALLUVIAL/TESUQUE FORMATION AQUIFER, SANTA FE, NEW MEXICO

JAY LAZARUS and PAUL DRAKOS
Glorieta Geoscience, Inc. P. O. Box 5727 Santa Fe, NM 87502

Abstract—The city of Santa Fe, New Mexico is underlain by Quaternary alluvium, the Pliocene/Pleistocene Ancha Formation, and the Miocene Tesuque Formation. The principal aquifer for Santa Fe is Tesuque Formation sediments located at a depth of greater than 200 ft below the surface. The Tesuque is overlain by 5 to 40 ft of Quaternary alluvium within the study area. Shallow groundwater in the Santa Fe area occurs either at or within 20 ft of the contact between Quaternary alluvium and Tesuque Formation sediments. This shallow groundwater is locally controlled by the location of buried channels, faults, and higher permeability zones at the top of the Tesuque Formation and is generally present within 1.5 mi of the mountain front. The shallow aquifer has very low productivity and an estimated hydraulic conductivity of 0.2 to 0.4 ft/day. The shallow groundwater is vulnerable to contamination by near-surface sources, most commonly by leaking underground storage tanks. Groundwater flow velocities and maximum solute transport rates in the aquifer range from 0.015 to 0.09 ft/day (5.5 to 33 ft/year). At locations where a strong vertical gradient exists, the shallow, contaminated groundwater may migrate vertically through high-permeability faults, fractures and bedding planes to deeper portions of the Tesuque Formation aquifer.

INTRODUCTION

West of the Sangre de Cristo Mountain front, the city of Santa Fe, New Mexico is underlain by Quaternary sediments and the Quaternary/Tertiary Santa Fe Group, which includes the Pliocene/Pleistocene Ancha Formation and the Miocene Tesuque Formation (Spiegel and Baldwin, 1963; Kelley, 1978). Because of historic settlement patterns in Santa Fe, many older gasoline stations and other commercial enterprises were located along the Cerrillos Road corridor (Fig. 1). Numerous shallow borings, predominantly for environmental investigations, have been completed in this area. The purpose of these investigations generally was to determine if "soil" and/or groundwater beneath these sites had been contaminated by hydrocarbons. Most investigations have been performed

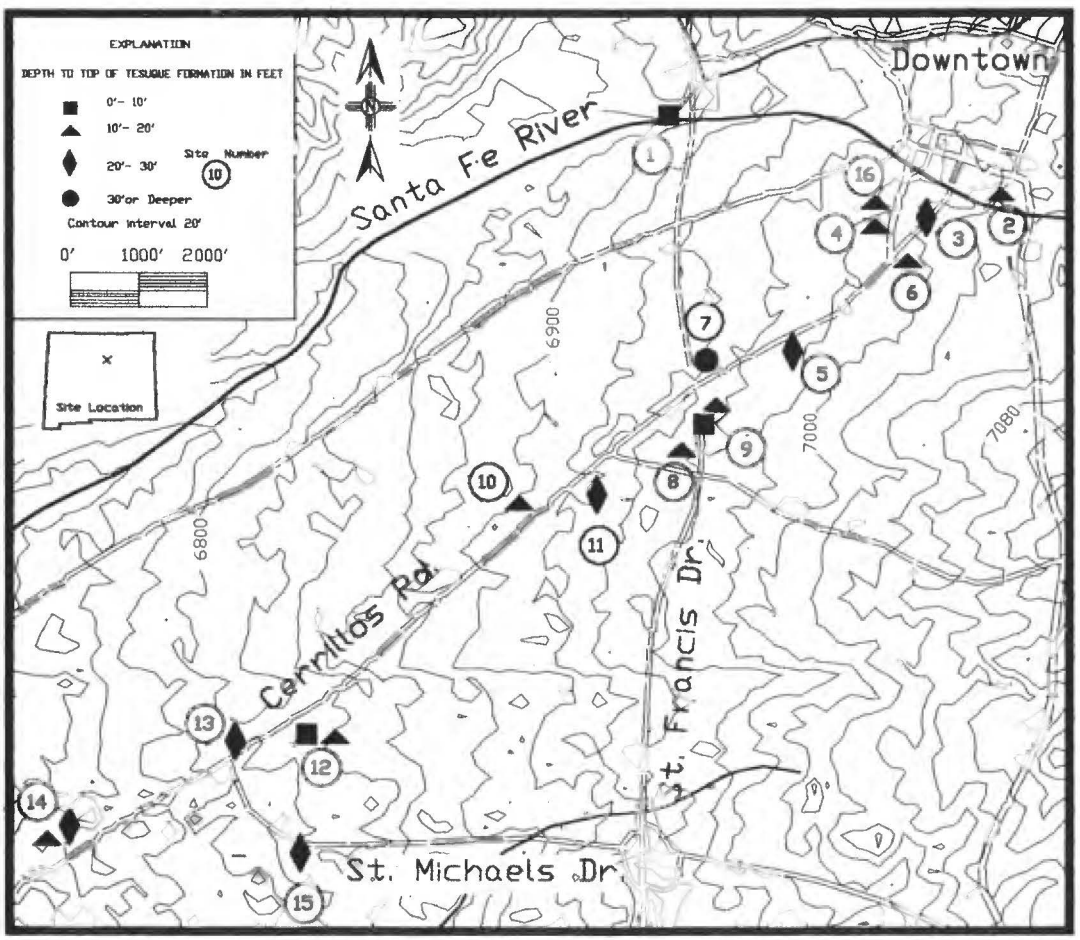

FIGURE 1. Site location and depth to top of Tesuque Formation in the Santa Fe area.

under regulatory requirements (i.e., to investigate possible releases of gasoline or diesel fuel), or were performed for completion of due diligence for real estate transactions.

This paper focuses on the geologic and hydrologic characteristics of the Quaternary alluvium and the Tesuque Formation. Although much of the information utilized is publicly available, we avoid identification of which specific sites are or were contaminated, and accordingly, refer only to sites by site numbers (Table 1). For further information on specific sites, readers are encouraged to contact Glorieta Geoscience, Inc.

The data for this report include reports completed by the authors and other investigators in the city of Santa Fe. We emphasize that field investigations were performed by investigators with different levels of experience in the Santa Fe River basin, and with differing interpretations and descriptions of shallow subsurface geology. We reviewed numerous lithologic logs and selected 16 sites with logs that clearly described sedimentary units that could be identified as Quaternary alluvium and Tesuque Formation. Because of the lack of precise vertical control at most locations, the 20-ft topographic contour interval on the USGS 7.5 min Santa Fe Quadrangle and the presence of man-made fill at many locations in the downtown Santa Fe area, no attempt was made to contour the top of the Tesuque Formation or depth to groundwater.

GEOLOGIC SETTING

The study area is located near the eastern margin of the Española Basin within the Rio Grande rift and is underlain by basin-fill sediments (Kelley, 1978). Quaternary alluvium is dominantly composed of unconsolidated sand, silt, clay, gravel and boulders. The Ancha Formation was derived from erosion of Tesuque Formation sediments, Precambrian crystalline rocks, and possibly upper Paleozoic sediments (Spiegel and Baldwin, 1963). The Tesuque Formation is a pink, tan, buff-colored silty to conglomeratic sand and sandstone typically interbedded with clay and siltstone beds, deposited as alluvial-fan, fluvial and isolated lacustrine deposits. Because most of the Tesuque and Ancha Formations were deposited by broad interfingering alluvial fans, subsurface correlation of these formations is problematic. The Ancha Formation is undeformed, whereas Tesuque strata locally dip from 10° to 25° to the west. In describing cuttings and split spoon samples from borings in the Santa Fe area, we have generally identified the alluvium as brown sandy gravel, and Tesuque Formation as red, orange-brown, or red-brown semi-consolidated sandstone (Table 2). The Ancha Formation, which generally crops out south of the Cerrillos Road corridor (Spiegel and Baldwin, 1963), has not been identified in the lithologic logs used.

Based on available data, the Tesuque Formation is unconformably overlain by 5 to 40 ft of Quaternary alluvium within the study area (Figs. 1, 3). Unconsolidated Quaternary terrace deposits were deposited from both meandering and braided streams. Alluvium represents deposits underlying three fluvial terraces flanking the Santa Fe River and/or local tributaries (Spiegel and Baldwin, 1963) and alluvial fan deposits along the Sangre de Cristo mountain front. The absence of soil development at the top of the Tesuque Formation and the irregular contact between the

TABLE 1. Depth to top of Tesuque Formation in ft below ground surface

Site Number	Maximum Depth of Boring	Depth to Top of Tesuque Fm.	Groundwater Encountered	Depth to Groundwater	Groundwater Gradient
1	80	7-17	YES	14-30	Toward SF River
2	25	12-18	YES	20	UNKNOWN
3	36	23-25	YES	20-23	Toward SF River
4	30	15-18	YES	17	Toward SF River
5	90	20-26	NO	N/A*	N/A
6	31	11-14	NO	N/A	N/A
7	82	30-34	YES	12	UNKNOWN
8	20	15-20	NO	N/A	N/A
9	62	6-12	YES	56	To/Parallel to SF River
10	82	20	NO	N/A	N/A
11	51	21	NO	N/A	N/A
12	60	10	NO	N/A	N/A
13	135	27-29	YES	107	N/A
14	32	10-25	NO	N/A	N/A
15	70	15-20	NO	N/A	N/A
16	20	20	YES	20	N/A

*N/A No groundwater encountered

TABLE 2. Sedimentology of Alluvium and Tesuque Formation described from cuttings and split spoon samples at selected GGI sites in the Santa Fe area.

Site Number	Description of Alluvium	Description of Tesuque Formation
1	Brown sandy gravel.	Medium to coarse, orange-brown and red-brown sand and clay
3	Brown sandy gravel. Gravel composition- granite, quartzite, foliated metamorphics (amphibolite).	Red sandy gravel, sandy clay, and medium to coarse sand.
4	Yellow-brown sandy gravel with minor interbedded clay.	Reddish-brown, medium to coarse sand.
6	Brown or reddish-brown sandy gravel with minor clay. Gravel composition- granite and metamorphics. Predominantly cobble-size gravel with some boulders present.	Red, gravelly, semi-consolidated (weathered) sandstone.
13	Brown sandy gravel, sandy clay, and sand.	Reddish-brown sand, sandy gravel, and clay. Thick section (67 ft) of interbedded greenish-brown clay and pink sand encountered in one bore hole.

Tesuque Formation and Quaternary alluvium indicates that the Tesuque was eroded prior to deposition of the alluvium.

GEOHYDROLOGIC SETTING

The Tesuque Formation is the principal aquifer for the city of Santa Fe. Most groundwater is produced at depths greater than 200 ft in the Tesuque Formation. At some locations, however, shallow groundwater has been encountered at the contact between the unconsolidated Quaternary alluvium and the underlying lower-permeability Tesuque Formation (Table 1; Figs. 2, 3). None of the shallow wells (<40 ft) we completed produces economical quantities of groundwater. Groundwater encountered in shallow borings often is not evident unless the boring remains open for 12 hrs or more.

The contact between the Quaternary alluvium and the Tesuque Formation is characterized by a lithologic change from higher-permeability brown to tan unconsolidated sand, gravel and boulders to a lower-permeability orange, red, or pink, semi-consolidated upper Tesuque Formation (Fig. 4; Table 2). Recharge to the shallow aquifer occurs along the Sangre de Cristo mountain front and is controlled by the location of buried channels incised into the top of the Tesuque Formation. Surface water seasonally infiltrates through the sand and gravel stream beds of tributary arroyos that sit directly on the terrace deposits, and this shallow recharging groundwater likely does not flow laterally away from the longitudinal axis of the paleochannels within the terrace deposits. Although of secondary importance, areal recharge from precipitation also contributes to the shallow aquifer.

The presence of groundwater in the shallow aquifer is controlled by distribution of paleochannels incised into the alluvium, proximity to mountain-front recharge zones, and loss of perched groundwater into the regional aquifer at locations where it flows across high-permeability fractures, faults, bedding planes and/or weathered Tesuque Formation. Based on available data, it appears that shallow groundwater in the study area is present at the top of the Tesuque Formation, within 1.5 mi of the Sangre de Cristo mountain front. The occurrence of shallow groundwater is discontinuous; dry boreholes are encountered within 100 ft of borings that penetrated the shallow aquifer (Glorieta Geosciences, Inc., unpubl., 1993). Because of the discontinuous nature of the inferred paleochannels, it is difficult to predict whether shallow groundwater will occur at a given location within the study area.

Boreholes at Site 1, adjacent to the Santa Fe River, were drilled to depths ranging from 20 to 85 ft. At Site 1, a total of 12 borings were drilled within an area measuring 200 ft by 400 ft. Six borings encountered groundwater at shallow depths, five borings encountered no groundwater at the alluvium/Tesuque contact, and no groundwater was encountered in the 85-ft-deep boring after sealing off the shallow aquifer (Glorieta Geoscience, Inc., unpubl., 1993). At Site 1, the presence of shallow groundwater is controlled by recharge from the arroyo that crosses the site, the location of faulted Tesuque Formation, buried channels that were tributary to the Santa Fe River, and meanders of the Santa Fe River.

At Sites 1, 7 and 9, groundwater elevations are below the top of the Tesuque Formation (Table 1). At Sites 2, 3 and 4, groundwater elevations are the same as the alluvium/Tesuque Formation contact (Table 1, Fig. 3). At all sites where more than one well has been completed (Sites 1, 3, 4, 9), the groundwater flow direction is toward or parallel to the Santa Fe River.

At sites located greater than 1.5 mi from the mountain front, shallow groundwater is generally absent, and the first water encountered is in the upper Tesuque aquifer at depths greater than 50 ft (e.g., Sites 9 and 13, Table 1). At Sites 10, 11, 12, 14 and 15, with borehole depths ranging from 32 to 82 ft, no groundwater was encountered at or below the Tesuque Formation contact (Table 1). The only location within this area where shallow groundwater was encountered was Site 7, located approximately 600 ft north of Site 9, where water was encountered at a depth of 12 ft (Table 2; Fig. 3). Sites 7 and 9 are located between the 6940 ft and 6960

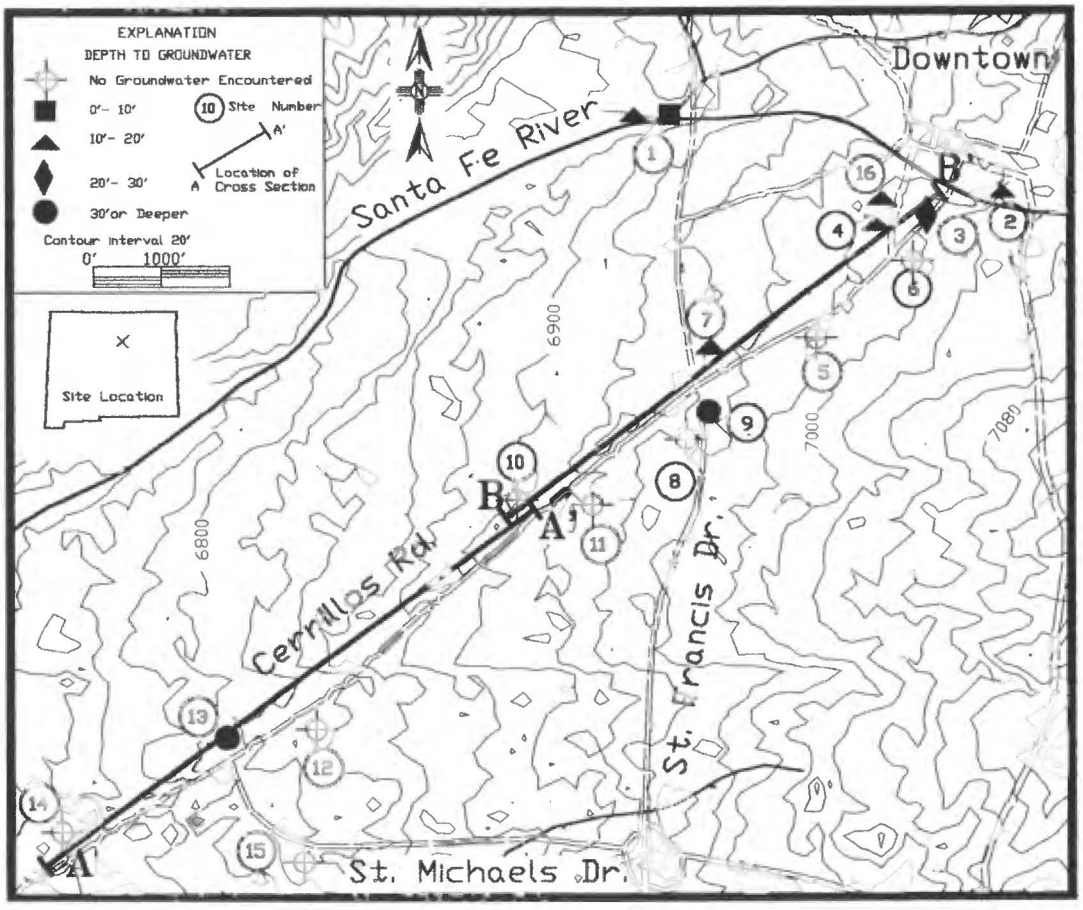

FIGURE 2. Depth to shallow groundwater in the Santa Fe area.

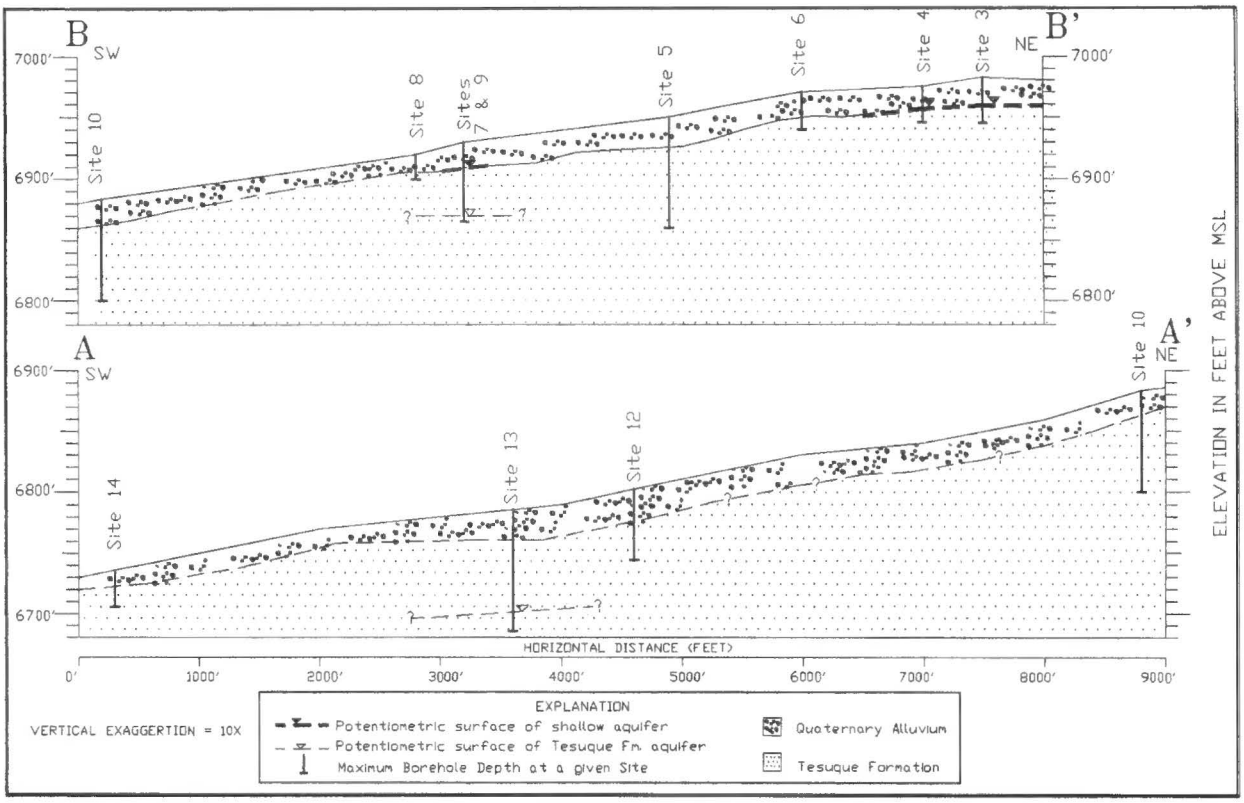

FIGURE 3. Geohydrologic cross section of the upper Tesuque Formation and alluvial aquifer in the Santa Fe area.

ft topographic contours and are likely within 10 ft in elevation of one another. The presence of shallow groundwater at 12 ft at Site 7 and the upper Tesuque Formation aquifer at 56 ft at Site 9 indicates that a strong vertical gradient exists at this location.

These data suggest that shallow groundwater is recharged near the Sangre de Cristo mountain front, after which the water either discharges to the Santa Fe River or tributary arroyos, or infiltrates downward into the Tesuque Formation, where it likely recharges the upper Tesuque aquifer. Shallow groundwater may be locally present at distances greater than 1.5 mi from the mountain front in close proximity to arroyos (i.e. Site 7).

GROUNDWATER DECLINES IN THE SHALLOW AND DEEPER AQUIFERS

Many older homes and businesses throughout the Santa Fe area produced water from hand dug wells. These wells, typically completed with rock cribbing as casing, were dug from 15 to 40 ft deep. They were generally dug through the Quaternary alluvium until bedrock, usually semi-consolidated weathered Tesuque Formation, was encountered. The shallow, hand-dug wells were dependent on near-surface recharge, which diminished over time due to (1) transfer of surface water irrigation rights to groundwater rights which reduced flow in unlined acequias; (2) a significant decrease in flood-type irrigation; and (3) paving over areas that were contributing areal recharge to the aquifer. This low-production aquifer has also been depleted by pumping for domestic and agricultural uses; most of the shallow wells have gone dry in the past 30 years.

Groundwater declines of 92 ft have also been observed in the City well field area from 1951 to 1983 (USGS, unpubl. data, 1983); more recent data show groundwater declines of 180 ft over 44 years (Faith Engineering, Inc., unpubl., 1994). Much of the shallow alluvial/Tesuque Formation aquifer and the upper Tesuque Formation in the Santa Fe area have been depleted in the vicinity of pumping centers.

HYDROLOGIC CHARACTERISTICS OF THE SHALLOW AQUIFER

The hydraulic conductivity of the upper 800 ft of the Tesuque Formation aquifer system in the Española Basin ranges from 0.2 to 6.0 ft/day, and is estimated to be 0.7 ft/day in the Santa Fe area (McAda and Wasiolek, 1988). A hydraulic conductivity of 3 ft/day has been calculated from data collected from a recently completed pumping test on a city of Santa Fe municipal well (Camp, Dresser and McKee, unpubl., 1995). Estimates of hydraulic conductivity of the shallow alluvial/Tesuque Formation aquifer are based on short-term bail-down tests and slug tests conducted at Site 1. Wells used for these aquifer test were screened either within the Tesuque Formation or across the contact between the Tesuque Formation and alluvium. Results of these tests indicate a hydraulic conductivity (k) of 0.2 to 0.4 ft/day. Based on limited groundwater production from this aquifer, the heterogeneous nature of the sediments at the Tesuque alluvium contact, and similar reported values for hydraulic conductivity of the Tesuque Formation in the area, the Site 1 hydraulic conductivity values are within an acceptable range. Saturated thickness of the aquifer ranges from 2 to 10 ft and varies seasonally.

FIGURE 4. Contact between Quaternary alluvium and Tesuque Formation. Exposure along Santa Fe River near Site 1.

HYDROCARBON CONTAMINATION OF THE SHALLOW AQUIFER

Throughout Santa Fe, hydrocarbon contamination of soil and groundwater is generally caused by leaking of underground storage tanks. Contamination is often concentrated at the alluvium/Tesuque Formation contact, regardless of whether the contact is saturated or unsaturated. However, at locations where a sufficiently large volume of gasoline/diesel fuel has been released, contamination has been encountered at depths greater than 100 ft (Glorieta Geoscience, Inc., unpubl., 1992).

Where contamination of the shallow groundwater has occurred, groundwater flow direction is towards or subparallel to the Santa Fe River. Groundwater gradients (I) in the shallow aquifer range from 0.02 (Site 4) to 0.09 ft/ft (Site 3); the gradient at Site 1 is 0.06 ft/ft. The gradient of the regional aquifer parallel to the Santa Fe River is 0.01 ft/ft (Mourant, 1980). Contamination of shallow groundwater could therefore pose a threat to shallow groundwater quality in the vicinity of the river. Groundwater flow velocity (v) and solute transport rates can be estimated using the average hydraulic conductivity for the shallow aquifer of 0.3 ft/day, the range in gradient values shown above, and a porosity (n) of 30% to 40% for the Tesuque Formation determined experimentally for samples collected at the Tesuque Pueblo Grant (Hearne, 1980). For sediments, the effective pore fraction for water molecules is 1.0, and effective porosity is equal to porosity ($n = n$) (Fetter, 1988). Using the equation: $v = kI/n$, groundwater flow velocities in the shallow aquifer range from 0.015 to 0.09 ft/day (5.5 to 33 ft/year). The groundwater flow velocity represents the maximum solute transport rate for hydrocarbon constituents. At locations where a strong vertical gradient exists, the shallow, contaminated groundwater may migrate vertically through high permeability faults, fractures, and bedding planes to deeper parts of the Tesuque Formation.

CONCLUSIONS

The Quaternary alluvium in the Santa Fe area was deposited as fluvial terrace and alluvial fan deposits on an irregular surface eroded into the top of the Tesuque Formation. The thickness of alluvium overlying the Tesuque Formation ranges from 5 to 40 ft. Paleochannels incised into the top of the Tesuque Formation control the lateral movement of the groundwater near the recharge areas and become the preferred conduit for shallow, saturated groundwater flow for limited distances away from recharge areas.

Groundwater is present at or below the alluvium/Tesuque Formation contact, and based on available data, is not present as perched water within the alluvium. The discontinuous nature of the paleochannels makes prediction of the location of shallow groundwater difficult. Shallow groundwater is recharged near the Sangre de Cristo mountain front, beyond which the water either discharges to the Santa Fe River or tributary arroyos, or infiltrates downward into the Tesuque Formation, where it likely recharges the upper Tesuque Formation aquifer. At sites located greater than 1.5 mi from the mountain front, shallow groundwater is generally absent, and the first water encountered is in the upper Tesuque Formation aquifer at depths greater than 50 ft.

The groundwater gradient in the shallow aquifer is toward or parallel to the Santa Fe River, and is steeper than the gradient in the regional Tesuque Formation aquifer. The shallow groundwater is most vulnerable to contamination by near-surface sources. Groundwater flow velocities and maximum solute transport rates in the shallow aquifer range from 0.015 to 0.09 ft/day, or 5.5 to 33 ft/year. Although groundwater flow velocities are relatively slow, this groundwater contamination poses a threat to the shallow groundwater in the vicinity of the Santa Fe River. At locations where a strong vertical gradient exists, the shallow, contaminated groundwater may migrate vertically through high-permeability faults, fractures, and bedding planes to deeper parts of the Tesuque Formation.

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