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GEOPHYSICAL AND HYDROCHEMICAL ANALYSIS OF THE WHITE RIVER ALLUVIAL AQUIFER, CROSBY COUNTY, TEXAS

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Abstract.—A hydrogeologic and electrical resistivity study was conducted on White River alluvial aquifer in order to identify deposits that could provide water of sufficient quantity and quality to help augment municipal water supply for local communities. Fifty-four Schlumberger vertical electrical soundings were performed on topographically high terraces and recent alluvial deposits adjacent to White River, an ephemeral stream. Groundwater samples were collected for water quality analysis from a few livestock and irrigation wells in the alluvium. Water levels were measured in several water wells. These data, along with drillers logs and geotechnical logs, were used to constrain and interpret electrical resistivity sounding data. Test hole logs indicate that thicknesses of the alluvial deposits vary from about 11 to 25 m. Alluvial deposits are underlain in most areas by the Permian Quartermaster Group (Permian "redbeds"). Depth to groundwater is usually less than 4.5 m in recent deposits near White River, and usually exceeds 7.5 m on topographically high terraces at distances from the river. Groundwater quality analyses indicate that total dissolved solids (TDS) exceed 1,500 mg/L at low lying areas near the river and are most often less than 1,100 TDS on high terrace deposits. Electrical resistivity sounding curves were processed and correlated to these ground-truth data. The electrical resistivity sounding data also indicate that groundwater is relatively poor quality at low-lying areas near the river, and is relatively good quality on high terraces. Different ranges of TDS are likely due to evaporative concentration of groundwater at low-lying areas and less or negligible evaporation of groundwater on high terraces where depth to groundwater is greater.

INTRODUCTION

Statement of the problem

White River Reservoir is located in Crosby County, Texas, approximately 110 km southeast of Lubbock (Fig.1). The region was profoundly affected by the 1994 to 1996 drought. As of late April 1996, the reservoir contained 10,250,400 m^3 of water, or 26 percent of its 39,287,000 m^3 of storage. White River Reservoir is the primary water supply for the communities of Crosbyton, Post, Ralls, and Spur, Texas. In 1996, reservoir managers were investigating alternative ways to supplement the lake supply, including the addition of groundwater to the reservoir distribution system. Hydrogeologic investigations were conducted on the White River alluvial aquifer to identify likely areas of groundwater occurrence that meet both quality and quantity requirements. Methods of investigation included standard hydrogeologic techniques, surface geophysical surveys, and collection and analysis of water quality data.

Hydrogeologic characteristics

The study area is located along the bottomlands below the escarpment that separates the "caprock" region from the erosional bottomlands. The pre-erosional section in the study area include the basal Quartermaster Formation, which consists of shale, sandstone, gypsum, and dolomite, commonly referred to as Permian "redbeds" by locals in the study area (Fig. 2). Above the Quartermaster Formation is the Dockum Group, a lake-deposited mudstone and fluvial sandstone of Triassic age. Dockum Group deposits consist of interbedded sandstones, clay, shale, and conglomerate. Capping the Dockum is the Tertiary-age Ogallala Formation, a fluvial deposit consisting of interbedded sand, silt, clay, and gravel.

After the caprock was eroded away, the Quartermaster Formation was exposed along the bottomlands. Fluviatile terrace

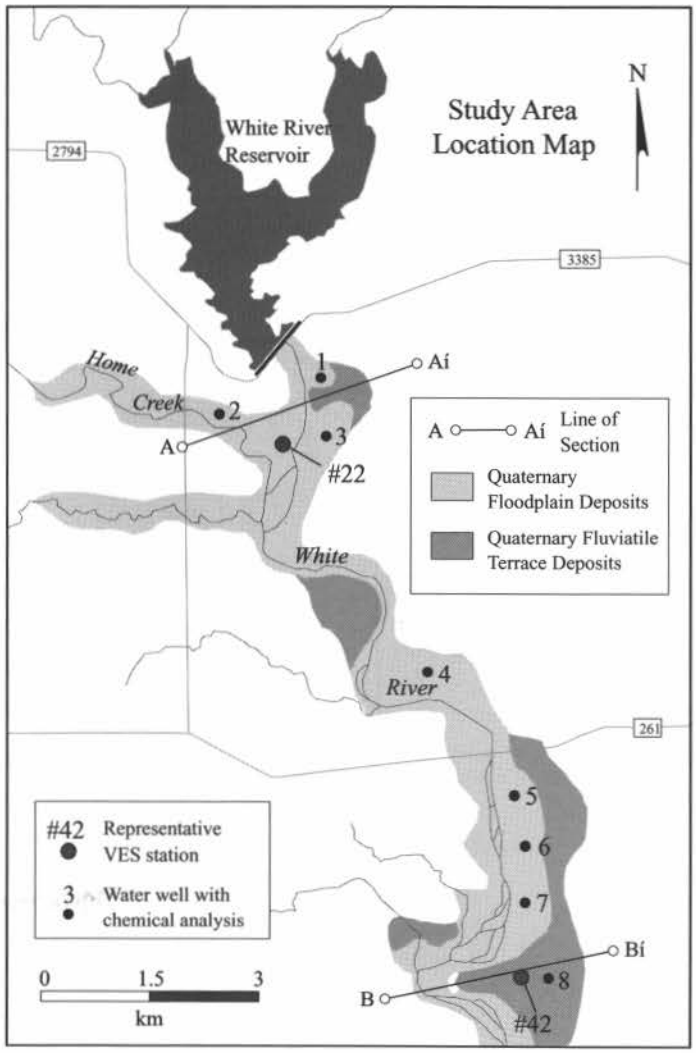


FIGURE 1. Study area location map showing the White River alluvium, lines of section for hydrogeologic cross sections, and water wells that were sampled for water quality analysis.

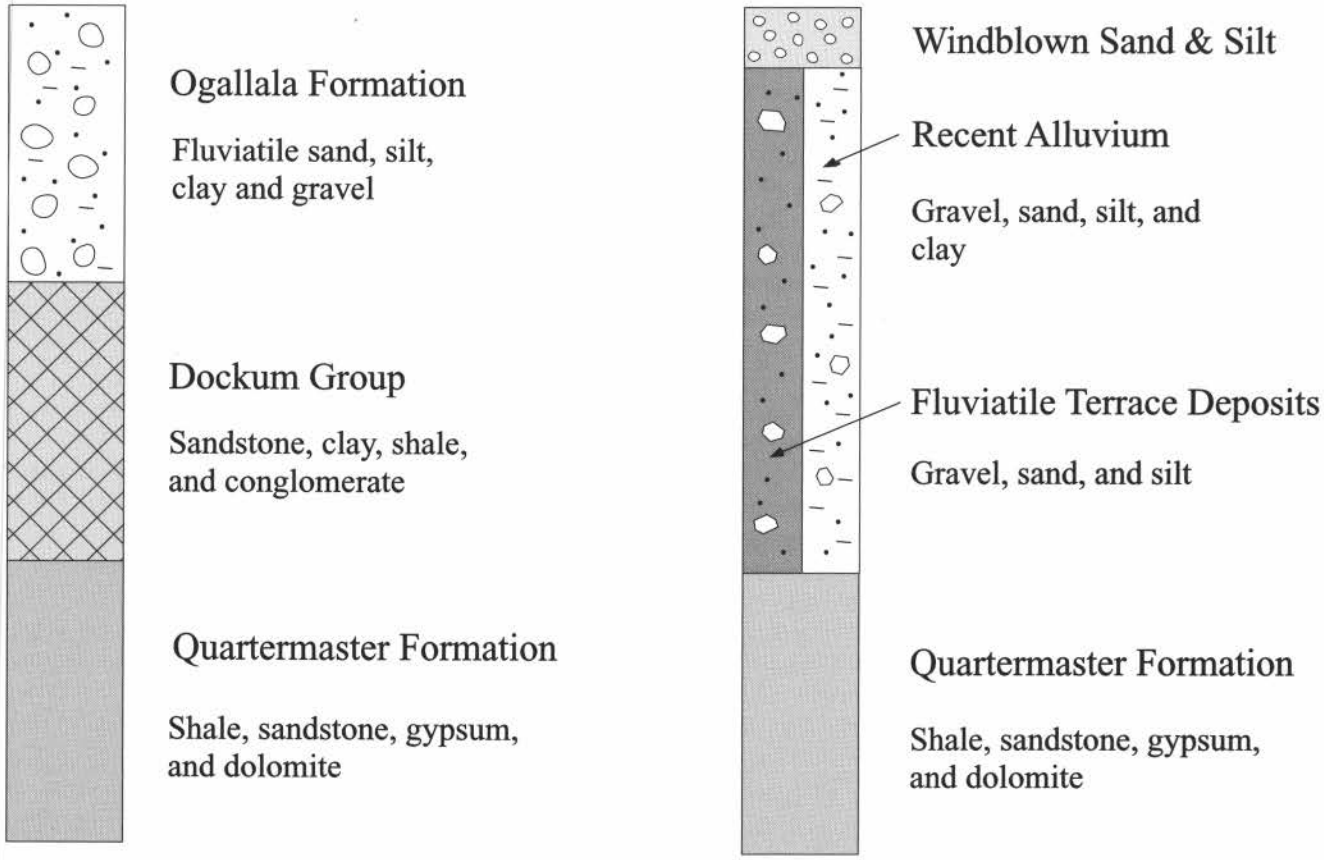


FIGURE 2. Pre-erosional and erosional stratigraphic sections for the study area.

deposits and recent alluvial deposits began to form along drainages of the ancestral and modern White River. The Quaternary-age terrace deposits are coarse textured, consisting mostly of gravel, sand and silt (Fig. 2). The recent alluvium is coarse to fine textured, consisting of interbedded gravels, sands, silts, and clays. In some areas, windblown sand and silt mantle the alluvial terraces and remnant deposits of the Quartermaster Formation.

White River is mostly an ephemeral channel above and below White River Reservoir. In some areas, the water table intersects the streambed of White River where marshy areas form. Flow in the White River channel does not persist for more than a few tens of meters below these marshes.

The principal water supply aquifer for local residents is the White River alluvial aquifer. The population is approximately 25 people who engage in irrigated agriculture and cattle ranching. Several domestic and livestock watering wells supply the needs of the local population and livestock industry. A few irrigation wells also exist within the study area.

METHODS OF INVESTIGATION

The following steps were taken to determine possible sources of potable water in the White River alluvial aquifer.

* Test hole drilling and water level measurements
* Surface electrical resistivity investigations
* Groundwater sampling and analysis

Test hole drilling and water level measurements

Test holes were drilled to determine depth to the basal Permian Quartermaster deposits, to determine texture and mineralogy of alluvial deposits, and to ascertain potential aquifer yields. Test holes also provided a means to calibrate and interpret earth resistivity data. The rotary drilling method was employed for drilling seven test holes. Test holes were supplemented by other drillers logs, which were available in the central files of the Texas Water Development Board. High quality geotechnical logs were also available from studies carried out when the White River Reservoir dam was designed and constructed (Freese, Nichols and Endress Consulting Engineers, 1962).

To characterize local groundwater gradients, water levels in monitoring wells were determined with electric lines and steel tape and chalk. Water-level measurements were measured in twenty-nine wells located in the White River alluvial aquifer. Measurements were collected after pumping wells were shut off and allowed to recover.

Surface electrical resistivity investigations

As an initial step in the investigation, a resistivity survey was selected as a convenient and economical means of potable water delineation in White River alluvial aquifer. Numerous studies have demonstrated the usefulness of surface electrical resistivity

as a means to detect fresh and saline groundwaters (Lehr, 1969; Stollar and Roux, 1975; Cartwright et al., 1977; Urish, 1983; Murphy et al., 1988). The resistivity method employs two current electrodes, placed within the soil mantle, and the injection and migration of current from the positive to the negative electrode. The voltage difference, measured between two internally placed voltage electrodes, is a function of the intrinsic resistance to electrical current flow of the subsurface media and the ionic content of pore waters contained within the media. Because high levels of total dissolved solids increase the electrical conductance within geologic materials, resistivity readings often are much lower when taken above environments with high salinity. Alternatively, resistivity readings are high in aquifers with low total dissolved solids (TDS).

When performing a resistivity survey, increasing the distance between the two external current electrodes increases the depth to which subsurface materials are energized. Because of the layering within subsurface environments, an electrical current which penetrates two or more layer boundaries will create a resistivity reading which is an integrated weighted average of the individual layer resistivities. The resultant reading is known as the "apparent resistivity."

Apparent resistivity readings often are taken with one specific separation of the current electrodes at each designated resistivity station. This method is generally employed for rapid reconnaissance and is known as profiling. Alternatively, a vertical electrical sounding (VES) is generated if the current electrodes are symmetrically expanded at each station, such that apparent resistivity readings are obtained at each electrode spacing. This method produces a field curve which permits the quantitative interpretation of layer properties and depth.

The Schlumberger configuration was used in this investigation to collect VES data. In the Schlumberger configuration, the two inner potential electrodes have a spacing that remains fixed as the current electrodes are symmetrically expanded. The Schlumberger configuration is the preferable method for conducting VES as it permits easier resolution of subsurface lateral heterogeneities when soundings are quantitatively interpreted (Koefoed, 1979). Using the Schlumberger electrode configuration, fifty-four soundings were performed (Fig. 3). Soundings were obtained on the recent alluvium near White River and on the older alluvial terraces that stand above White River floodplain. Electrode spacings were extended from 1.5 m to 68 m and apparent resistivity readings were taken at eleven incrementally greater electrode spacings at each station. This provided a sufficient number of measurements to define VES curves. In performing resistivity surveys, care was taken to avoid potential interferences such as buried underground electrical lines and conduits, fences, and overhead power lines. A Sting Earth Resistivity meter was used to collect VES data.

Groundwater sampling and analysis

Groundwater sampling for chemical analysis was employed as a necessary step to resolve spatial and temporal variations in water quality and as a means to interpret resistivity sounding data. To accommodate sampling and to remove stagnant water, water wells were either evacuated of several casing volumes of water, or were sampled after they had been pumped continuously for long periods of time. Eight samples were collected in new polyethylene containers to be analyzed, respectively, for anions and cations (Fig. 1). These samples were iced down immediately after collection. Once in the laboratory the samples were filtered and refrigerated until chemical analysis was performed. Chemical analysis was performed by A&L Plains Agricultural Laboratories of Lubbock, Texas.

RESULTS

Test hole drilling and water level measurements

Test hole drilling indicated that alluvial thicknesses are as much as 20 m thick in the recent deposits along White River. Alluvial thicknesses are as much as 26 m thick in the older alluvial terraces. Permian redbeds were encountered at all drilling sites at the base of the alluvium. In most test holes, materials

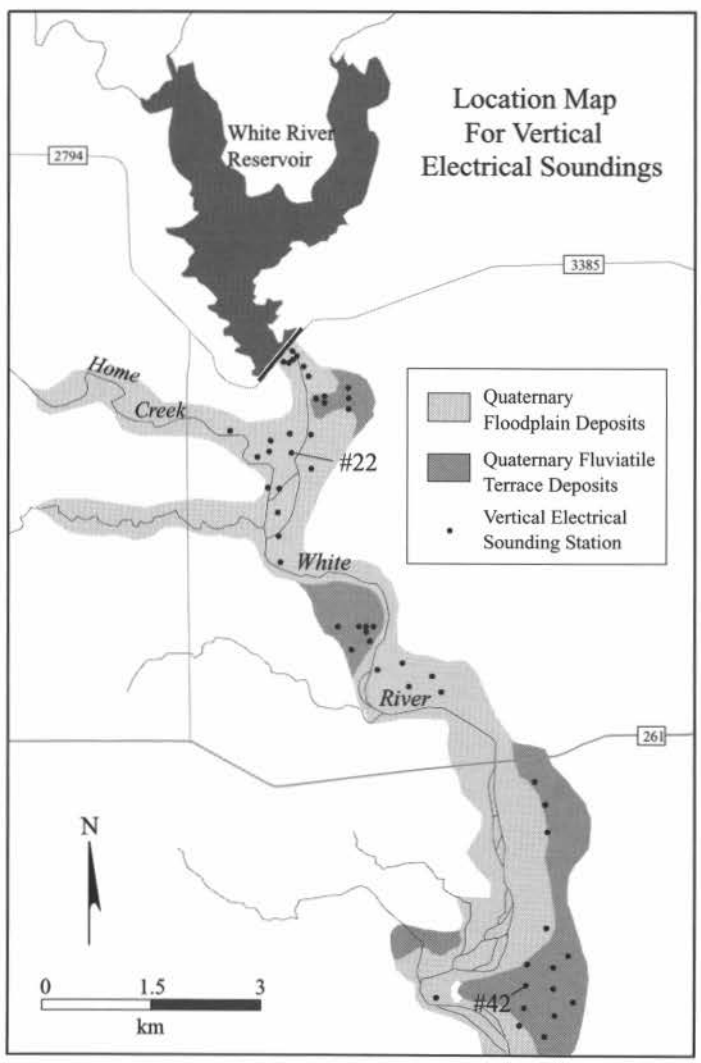


FIGURE 3. Location map for vertical electrical sounding stations.

encountered during drilling included thick sequences of sand and gravel, with intervening clay stringers and occasional clay beds (Fig. 4). At most locations, the lithologic sections were dominated by fine, medium, and coarse sand deposits with some gravel. Drilling sites near Home Creek indicated thicker and more abundant clay layers and lenses (Fig. 1 and Fig. 4). Test hole cuttings from the alluvial terraces included coarse sediments derived from weathering of Ogallala Formation and Dockum Group deposits. Recent alluvial deposits near White River had more clay stringers and lenses derived from weathering of Permian Quartermaster deposits.

Water level measurements in the alluvial terraces encountered the water table at depths that varied from about 6 to 11 m below land surface. The hydraulic gradient on the alluvial terraces is oriented perpendicular to sub-perpendicular to White River channel. Measurements in recent alluvial floodplain deposits varied from 0 to 7 m below land surface, with most values less than 4.5 m. The hydraulic gradient is oriented parallel to sub-parallel to the White River channel in the recent alluvial floodplain deposits. Groundwater flow in the recent alluvial deposits is down the axis of the floodplain.

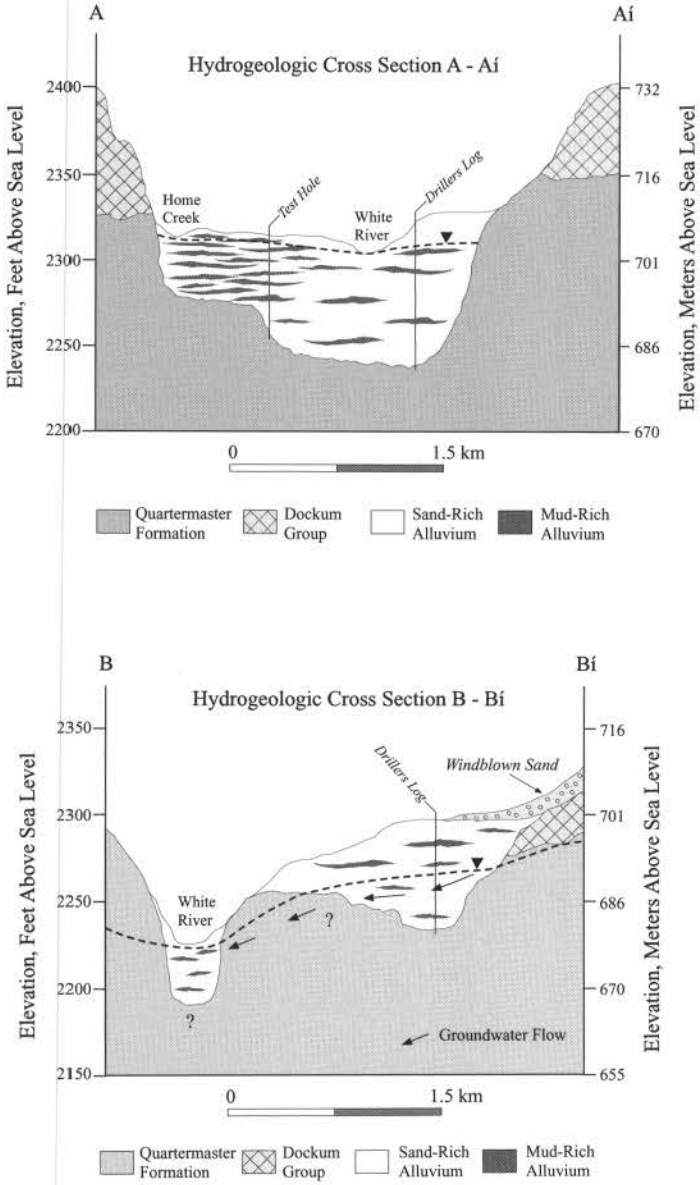


FIGURE 4. Hydrogeologic cross sections for the White River alluvial aquifer (lines of section shown in Figure 1).

Surface electrical resistivity investigations

VES data were interpreted with the method of steepest descent (Koefoed, 1979). Program DESCENT uses field VES data and a preliminary layered trial model supplied by the user as input. The program adjusts the trial model parameters to produce a theoretical VES curve which is compatible with the new model and within a limited root-mean-square error of the field VES curve. By minimizing error between field and theoretical curves, a subsurface interpretation of geoelectric layers is obtained.

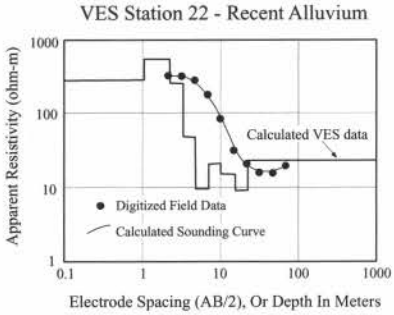
To provide a means to interpret the data, VES data obtained next to the test holes were calibrated with lithologic and water level data. Drilling information and water level date were used to constrain the model depth-layer boundaries so that layer resistivities in the vicinity of the test holes could be determined. Intertest hole models were then constrained by water level information extrapolated from the local potentiometric map. DESCENT was applied, with estimated layer resistivities input as unconstrained trial model data.

The program adjusts layer boundaries and resistivity values to provide an interpretation of geoelectric layers. Computer generated interpretations were considered to be reasonable when at most a 3% root-mean-square error existed between field and computed VES curves. Forty-nine of fifty-four VES curves were within the 3% root-mean-square error criterion.

Figure 5 presents representative VES data and interpretations obtained from program DESCENT. VES station 22 was located on the recent alluvial sediments near White River (Fig. 1 and Fig. 3). Water level measurements indicated that depth to groundwater is about 3.6 m near station 22. Drillers logs indicated that bedrock depth is about 18 m near the station. The resistivity sounding data suggests that the unsaturated zone is very dry and resistive at station 22 (resistivity equals 253 to 541 ohm-m). Below the water table, the resistivity is much less, decreasing from 46 ohm-m near the water table to 9.0 ohm-m near the base of the aquifer. The basal Permian redbeds are interpreted to have a resistivity of 23.1 ohm-m.

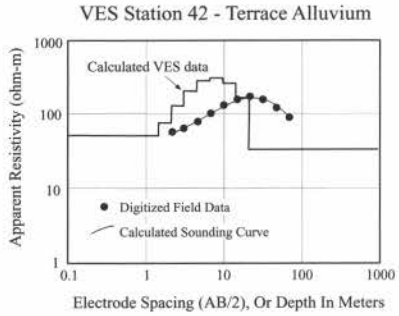
Drillers logs and water level measurements near station 42 indicated that depth to groundwater is about 9 m, and depth to bedrock is about 21 m. The resistivity sounding data indicate that the unsaturated zone is moderately to highly resistive at station 42 (50.6 to 315.5 ohm-m). In the saturated zone, the resistivity is moderately high, ranging from 168.2 ohm-m to 263.9 ohm-m. The basal formation is interpreted to have a resistivity of 37.3 ohm-m.

In general, the resistivity of the saturated zone at station 42 is more than an order of magnitude higher than the resistivity of the saturated zone at station 22. The sharply contrasting curve shapes support this interpretation. VES curve 42 ascends and



Calculated VES Data

Depth (m)		Resistivity (ohm-m)
1.0		253.2
2.3	*Vadose Zone*	541.1
3.3		253.1
4.9		46.21
7.1		9.5
10.5	*Aquifer*	20.3
15.4		14.7
19.8		9.0
Infinite	*Bedrock*	23.1



Calculated VES Data

Depth (m)		Resistivity (ohm-m)
1.4		50.6
2.0		76.8
2.9	*Vadose Zone*	129.6
4.4		208.7
6.4		287.9
9.4		315.5
13.8	*Aquifer*	263.9
20.3		168.2
Infinite	*Bedrock*	37.3

FIGURE 5. Representative vertical electrical sounding curves showing digitized field data, calculated sounding curves, and interpreted layer resistivities (see Figure 1 and Figure 3 for station locations).

then descends as the current electrode separation increases. VES curve 22 ascends slightly, descends, and then re-ascends as the electrode separation increases. This is because apparent resistivity values are higher in the resistive saturated zone materials at station 42 and lower in the relatively conductive saturated zone materials at station 22. Insofar as the lithologies of the saturated zone at stations 22 and 42 are dominated by sands and gravels with subordinate silts and clays, the contrasting resistivity values are attributed to substantially different total dissolved solids in the aquifer. On the basis of the geophysical assessment, the water quality is assumed to be poor at station 22 and relatively good at station 42 (e.g., TDS is relatively high at station 22 and relatively low at station 42). Similar interpretations of the other VES curves allowed us to develop the apriori water quality map for White River alluvial aquifer (Fig. 6). This map shows zones that are predicted to have good to very poor water quality. Good water quality zones are limited in extent.

Groundwater sampling and analysis

Water quality data collected at eight water wells are in excellent agreement with the water quality map interpreted by VES. Water quality is quite poor in most of the alluvial aquifer (Fig. 1 and Table 1). Chloride concentrations vary from 265 mg/L to 1900 mg/L, with all but one value above 400 mg/L. Sulfate concentrations vary from 179 to 775 mg/L, with all but one value over 300 mg/L. Sodium values vary from 190 mg/L to 775 mg/L. Only one sodium value is less than 300 mg/L. Many of these samples exceed the drinking water standards for chloride (250 mg/L), sulfate (250 mg/L), and sodium (250 mg/L). These are USEPA National Secondary Drinking-Water Standards, also known as recommended maximum concentration levels. These are maximum desirable concentrations for potable waters,

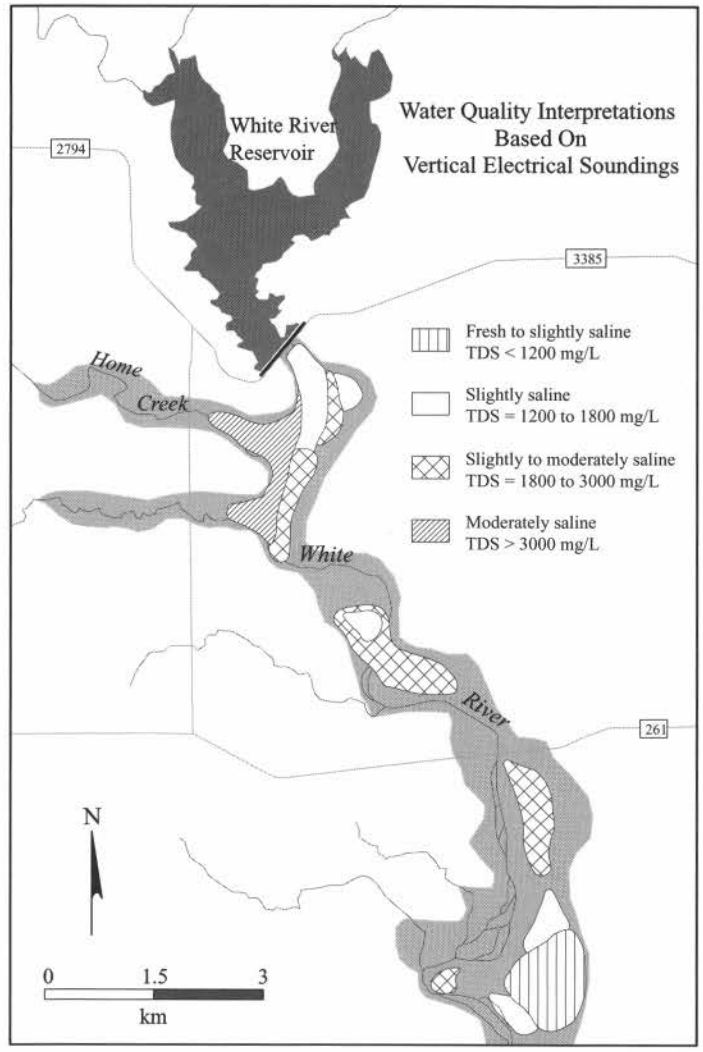


FIGURE 6. Water quality map showing aquifer salinities based on vertical electrical sounding interpretations.

TABLE 1. Selected water quality parameters in White River alluvial aquifer.

Well Number	Chloride (mg/L)	Sulfate (mg/L)	Sodium (mg/L)	Nitrate (mg/L)	Dissolved Solids (mg/L)
1-Anderson	435	775	500	<4.43	1873
2-Harper	1900	508	1010	<4.43	3608
3-Slack	415	488	370	7	1601
4-Arnett	590	888	590	<4.43	2238
5-Short	405	300	400	4	1406
6-Gregory	560	588	340	11	1986
7-McArthur	1030	703	540	2	2906
8-Sparling	265	179	190	54	1002

although most humans can tolerate higher concentrations of these inorganic constituents.

Total dissolved solids are above 1000 mg/L in all wells. All but one value are greater than 1400 mg/L (Fig. 1 and Table 1). The recommended maximum concentration level for TDS of 500 mg/L is seldom achieved in many regions in West Texas. Even so, most of the groundwater in White River alluvial aquifer is too saline for domestic consumption.

Nitrate values vary from non-detect concentrations to concentrations as high as 54 mg/L (Table 1). The USEPA maximum contaminant level (MCL) for nitrate is 45 mg/L. The MCL is the concentration that must not be exceeded in drinking water due to health concerns. Only one sample exceeds this drinking standard (8-Sparling). This same sample was the most dilute with respect to standard inorganic constituents.

ORIGIN OF SALINITY IN WHITE RIVER ALLUVIAL AQUIFER

Groundwater quality in the White River alluvial aquifer, characterized by VES and water quality sampling, is slightly to moderately saline. The highest salinity concentrations are found in the recent alluvial deposits, where depth to groundwater is usually less than 4.5 m. The most dilute groundwater is found in the high alluvial terraces that flank the White River floodplain (e.g., 8-Sparling) (Fig. 1 and Table 1).

Recent alluvial deposits are interpreted to have relatively high salinity concentrations for the following reasons:

1. Shallow depth to groundwater intensifies salinization of groundwater due to evaporation and evaporative concentration of salts by phreatophytes.

2. Lithologies in the recent alluvium contain more lithic fragments from the Quartermaster Formation. These are rich in gypsum and other soluble minerals. The alluvial terraces contain smaller amounts of sediments from the Quartermaster Formation and greater amounts of lithic fragments from the Dockum Group and Ogallala Formation. These have less soluble mineralogies.

3. The direction of groundwater flow in the terraces is oriented sub-perpendicular to White River. Groundwater residence times are shorter in the terraces. Groundwater in the recent alluvial deposits moves axially down the White River Valley and have greater residence times.

When depth to groundwater is more than 9 m, discharge by evaporation is considered to be a small component of groundwater loss (Davis and DeWiest, 1966; Bouwer, 1978; Mifflin, 1988). Soil gas humidities nearly reach 100% at these depths (Stephens, 1996). Groundwater evaporation is slow at these humidities. At shallower depths, venting of soil gases by the atmosphere reduces soil humidity and accelerates groundwater evaporation. This has the tendency to concentrate salts in solution (Fig. 7).

Many phreatophytes also concentrate salts in groundwater by extracting dilute water from solution through root osmosis, leaving behind a more saline solution. Insofar as depth to groundwater is often less than 4.5 m in the recent alluvial deposits, it is likely that phreatophytes help to increase groundwater salinity in these low-lying deposits. Phreatophytes are less abundant, less

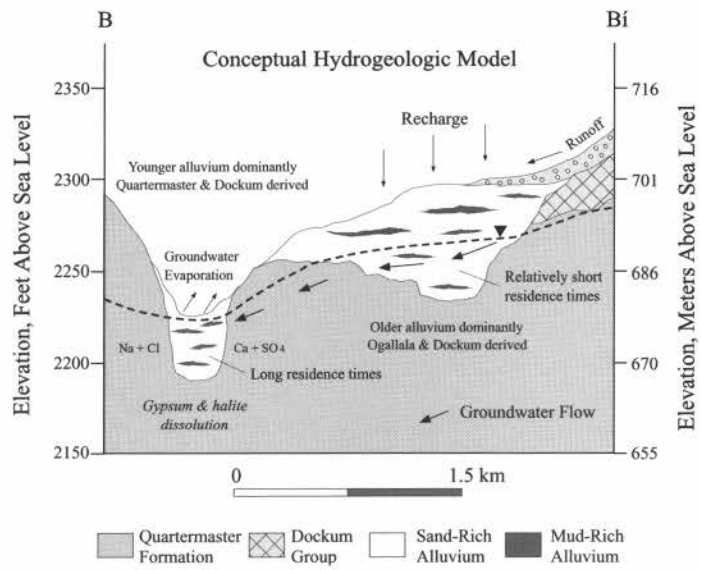


FIGURE 7. Conceptual hydrogeologic model showing mechanisms of salinization in the White River alluvial aquifer.

important agents of groundwater salinization in the high-standing terrace deposits.

Lithic fragments from the Quartermaster Formation exert important controls on aquifer salinization. Quartermaster deposits contain gypsum and other soluble minerals that contribute to the dissolved load of the recent alluvial deposits. Soluble minerals from the Quartermaster Formation are not as abundant in the alluvial terrace deposits, and do not have the same controls on aquifer salinity.

Groundwater residence times in the alluvial terraces are also relatively short. Recharge waters move down gradient from the alluvial terraces into the recent alluvial deposits, where they mix with groundwaters already moving down the axis of White River floodplain (Fig. 7). There, groundwater becomes even more saline by evaporation and mineral dissolution as it travels down the axis of the floodplain. Occasional flooding in White River apparently does not dilute shallow groundwater significantly.

CONCLUSIONS

Due to the relatively poor quality groundwaters in White River alluvial aquifer, the Reservoir Watermaster was advised not to install high capacity wells in the alluvium to augment water supply. However, this study did identify relatively good quality groundwater in parts of the alluvial aquifer. The study also provided explanations for contrasting salinities in the aquifer.

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In east-central New Mexico, the youngest Mesozoic strata are erosional outliers of the Cenomanian-Turonian Greenhorn Formation. This is an outstanding and very fossiliferous Greenhorn outcrop in the Bonita fault zone southeast of Tucumcari.