CONCEPTUALIZATION OF GROUNDWATER FLOW IN THE SHALLOW AQUIFER ALONG THE APACHE REACH OF THE SAN PEDRO RIVER, COCHISE COUNTY, ARIZONA

By

Thomas Clarke Deane

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STATEMENT BY AUTHOR

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This thesis has been approved on the date shown below:

Thomas Maddock III
Professor of Hydrology
And Water Resources

12/7/2000
Date

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LIST OF ACRONYMS AND ABBREVIATIONS

ADWR	Arizona Department of Water Resources
ANP	Apache Nitrogen Products, Inc.
bls	below land surface
CGMP	Comprehensive Groundwater Monitoring Plan
EPA	U.S. Environmental Protection Agency
EWG	elastic wave generator
EXB	exploratory boring
gpd	gallons per day
gpm	gallons per minute
H+A	Hargis + Associates, Inc.
HGP	hydroGEOPHYSICS, Inc.
HRR	high-resolution resistivity
LCU	laterally confining unit
M	moles per liter
mg/l	milligrams per liter
msl	mean sea level (feet)
MW	monitor well
pH	hydrogen ion concentration
SEW	shallow aquifer extraction well
TDS	total dissolved solids

ABSTRACT

The Apache Reach of the San Pedro River is situated adjacent to the Apache Powder Superfund Site, in Cochise County, Arizona. An alluvial aquifer, known as the "shallow aquifer", and consisting of flood plain sediments deposited on the St. David Formation by the ancestral San Pedro River, is situated along this reach. The shallow aquifer is underlain by a thick clay unit of the St. David Formation, which provides vertical hydraulic confinement from a deeper regional artesian aquifer.

Prior to shallow aquifer deposition, the ancestral San Pedro River and a local paleotributary, identified as Molinos Creek, eroded paleochannels into the top of the St. David Formation. During shallow aquifer sediment deposition, finer-grained, "overbank" sediments were deposited between the paleochannels. The overbank sediments formed contemporary a "laterally confining unit" (LCU) that isolates the western part of the shallow aquifer hydraulically from the remaining part of the shallow aquifer to the east.

1.0 INTRODUCTION

1.1 Purpose

This thesis presents a conceptualization of groundwater flow in the "shallow aquifer" along the Apache Reach of the San Pedro River in Cochise County, Arizona. This area has also been identified as the Southern Area of the Apache Powder Superfund Site (the Site) (H+A, 1992a).

The shallow aquifer occurs within an alluvial basin formed by the San Pedro River since the Pleistocene Epoch of geologic time. The conceptualization describes the geometry of the shallow aquifer within the Southern Area. In particular, hydraulic properties that control groundwater flow and contaminant transport from an artificially-recharged perched groundwater zone and its lateral migration through the shallow aquifer are addressed. Apparent hydraulic isolation between a "sub-aquifer" area and the main part of the shallow aquifer is explained in terms of a "laterally confining unit" (LCU).

While only limited exploratory drilling is available to confirm the presence of the LCU, its presence can reasonably be inferred on the basis of multiple lines of corroborative field evidence. In particular, this thesis examines previous regional hydrologic studies and Site-specific studies, and presents and interprets results from recently-completed Site investigations. Collectively, these data provide multiple lines of evidence in support of the existence of the LCU as discussed in later sections of this thesis. It is believed that this conceptualization contributes substantially to the ongoing development of conceptual and numerical models of groundwater flow and transport within the Southern Area. These further studies will be essential to the evaluation of alternatives for groundwater remedial action.

1.2 Scope of Investigations

This conceptualization is based on the cumulative data set from previous site and regional investigations and recent field investigations conducted at the Site from April through July 2000. Data from the August 2000 quarterly groundwater and surface water monitoring round collected pursuant to the Apache Powder Superfund Site, Comprehensive Groundwater Monitoring Program (CGMP) are also presented and evaluated with regard to the conceptualization (H+A, 1995a, 2000).

The April through July 2000 investigation included the following activities:

- Pre-drilling seismic and electrical resistivity geophysical surveys.
- Construction of one exploratory boring and 8 new monitor wells.
- Collection of surface water and groundwater samples for major ion analysis.

The geophysical surveys were conducted to collect data on subsurface stratigraphic units and the occurrence of saturated sediments. Interpretation of these data facilitated the siting of the exploratory boring and monitor wells. The major ion analyses were included as a one-time task during the May 2000 quarterly monitoring round under the CGMP.

These investigations support remedial design investigations under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), performed pursuant to the 1994 U.S. Environmental Protection Agency's (EPA) Record of Decision (ROD) for the Apache Powder Superfund Site (EPA, 1994).

1.3 Site Location and History

The Site is located in Cochise County, approximately 7 miles southeast of Benson, Arizona (Figure 1). The Site includes approximately 1,000 acres of industrial land owned by Apache Nitrogen Products, Inc. (ANP) in portions of Section 12 of Township 18 South, Range 20 East (T18S/R20E), and of Sections 6, 7 and 8 of T18S/R21E. For the purposes of this report, the Site consists of the property owned by ANP and the immediate surrounding area, with particular emphasis on the "Southern Area" as depicted in Figure 2.

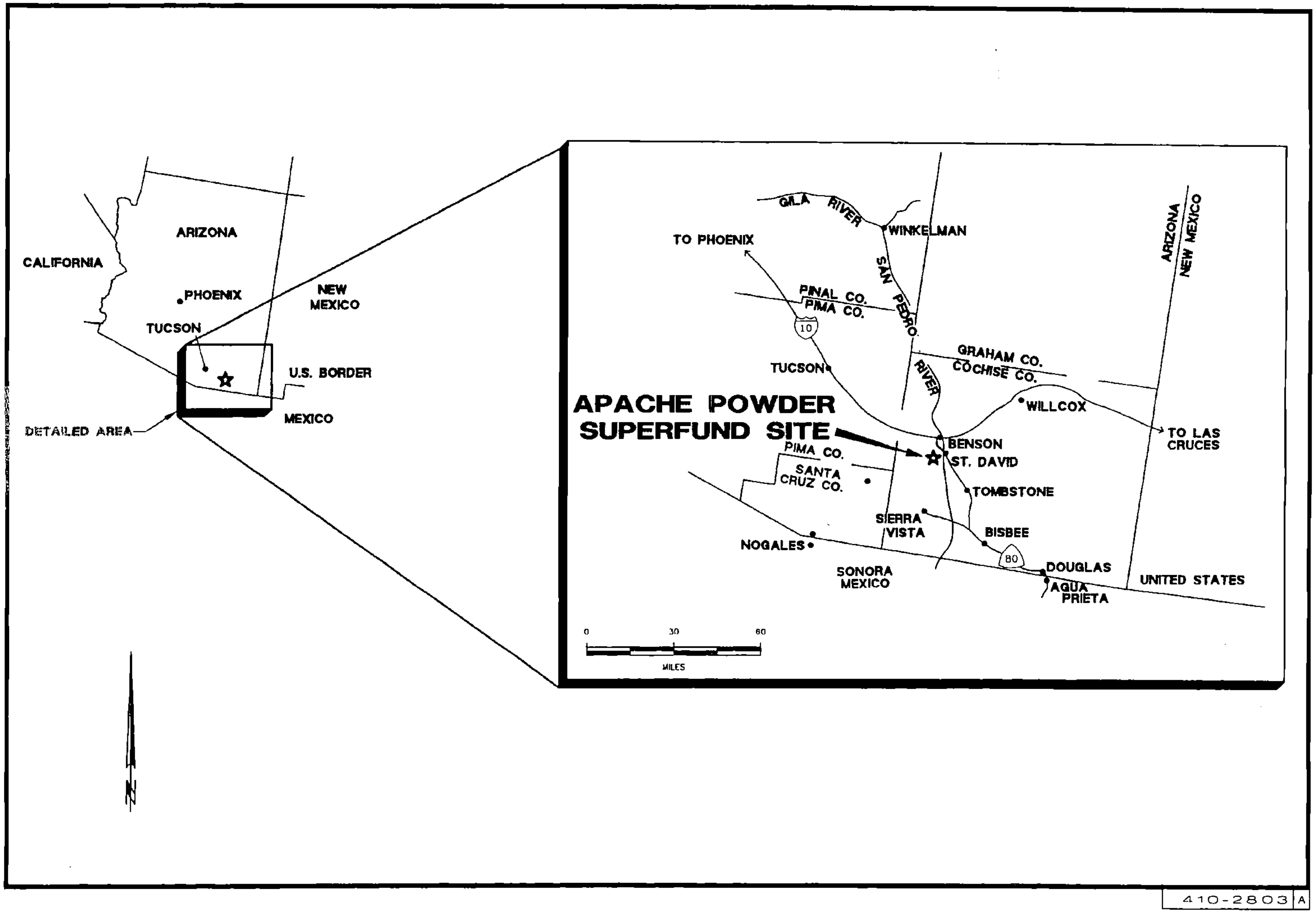

FIGURE 1. LOCATION OF APACHE POWDER SUPERFUND SITE
COCHISE COUNTY, ARIZONA

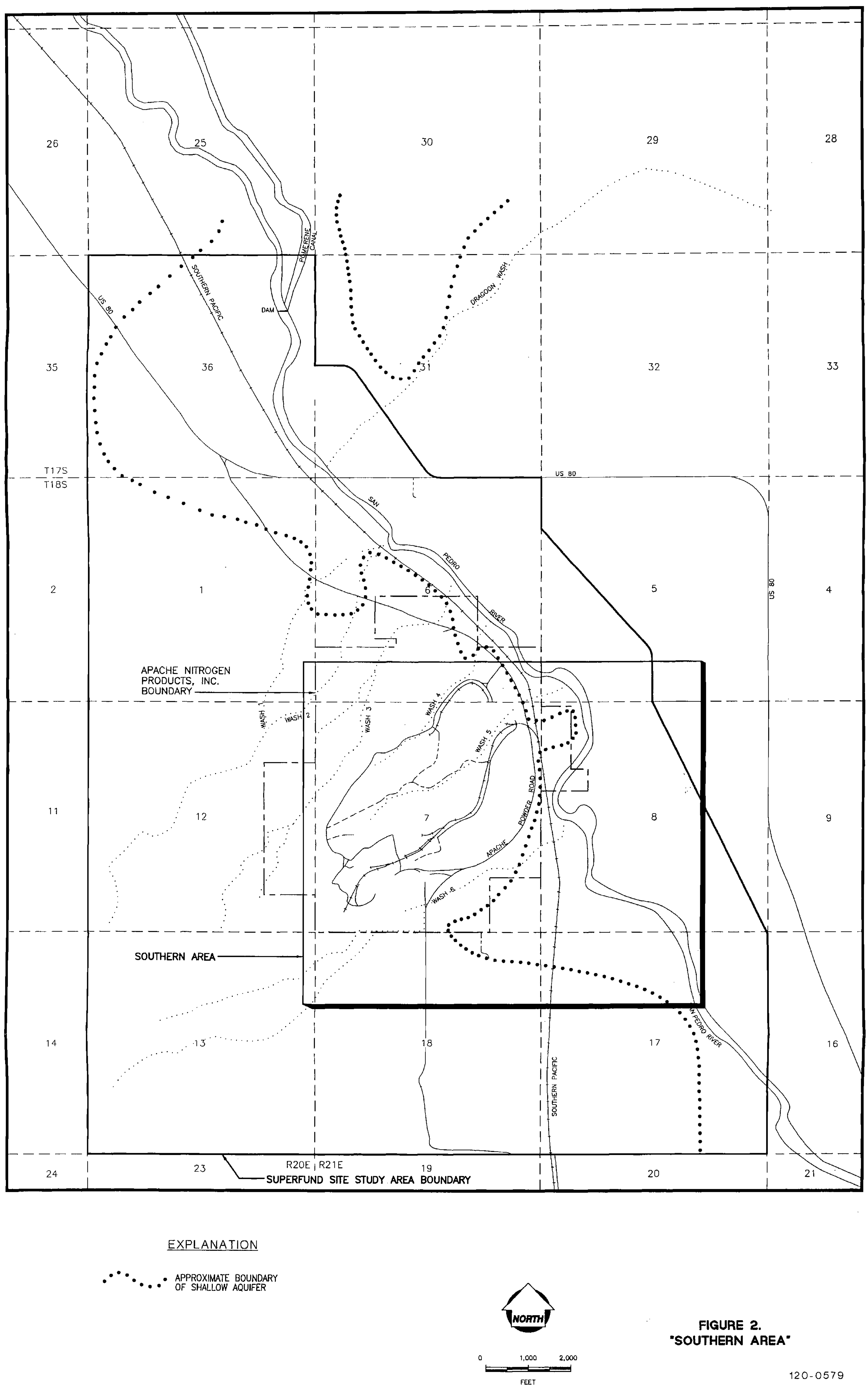

FIGURE 2.
"SOUTHERN AREA"

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Industrial operations at ANP have been ongoing since 1922. Prior to April 1, 1990, ANP operated under its former name, Apache Powder Company. ANP currently manufactures nitric acid, liquid ammonium nitrate (LAN), solid ammonium nitrate (prill or PAN), and ammonium nitrate-based fertilizer solutions. These products supply regional mining and agricultural operations. Formerly, safety fuse, nitroglycerin-based explosives, ammonia, sulfuric acid, detonating cord, blasting agents, carbon dioxide, and water-gel high explosives were also manufactured at the Site.

Throughout its operational history, ANP has relied on groundwater for both industrial and personnel uses. This water has been derived from 4 (now 3) production wells tapping the deep, confined aquifer within the St. David Formation. This aquifer is situated at depths greater than 300 feet below land surface and is confined by a thick clay unit. Water cycled through various plant operations historically has included process mixing waters, cooling waters, steam, condensates, washdown, and blowdown.

Prior to 1971, the plant wastewater stream, consisting of some or all of the wastewaters described above, was discharged directly to dry wash tributaries of the San Pedro River. These tributaries are informally identified as Washes 1 through 6 (Figure 2). Historically, most of the wastewater was discharged to Washes 5 and 6. Little or no discharge is believed to have occurred within Washes 1 and 2.

From 1971 to 1995, wastewater was routed via unlined ditches to unlined evaporation ponds (herein referred to as "formerly active ponds"). During this time most of the discharge was routed to Ponds 1A, 1B, 2A, 2B, 3A and 3B. These ponds are located south of the ANP Operations Area within the Wash 6 watershed (Figure 3) (H+A, 1991, 2000a). In February 1995, ANP discontinued its practice of discharging plant wastewater to the formerly active ponds. This was made possible by the construction of a new brine concentrator facility. The treated wastewater and brine discharge from the brine concentrator are now fully recycled into process operations (H+A, 2000a).

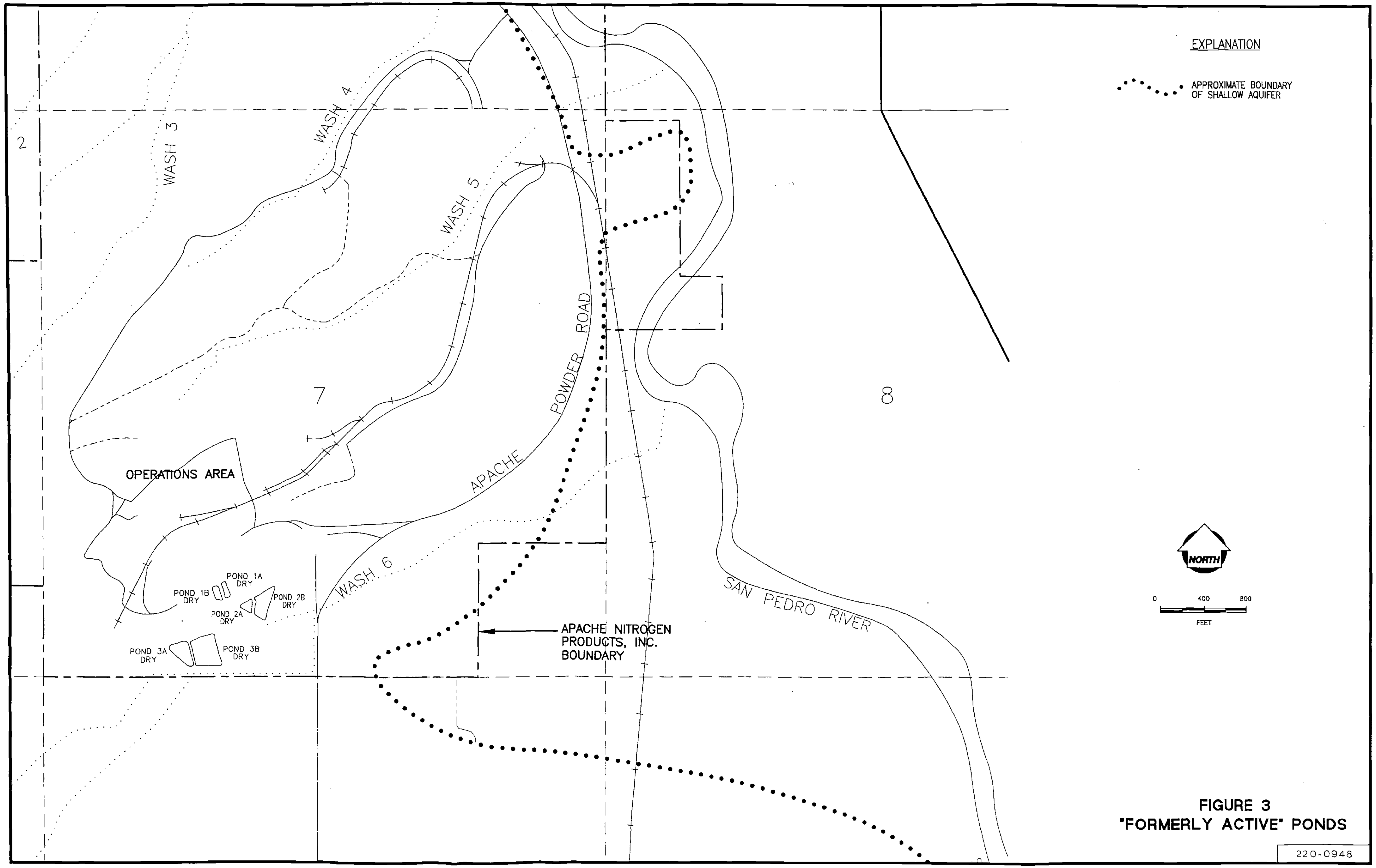

FIGURE 3
"FORMERLY ACTIVE" PONDS

During the operation of the formerly active ponds, and, perhaps to a lesser extent, while wastewater was discharged to the washes, wastewater infiltrated downward into the sediments underlying the ponds and ditches. This downward migration continued until the infiltrating waters encountered the uppermost clay unit of the St. David Formation (St. David clay). The St. David clay is found at depths up to approximately 30 feet underlying the plant Operations Area. As the volume of water increased, a "mound" of water formed and spread laterally over the erosional surface of the buried St. David clay, thus creating a "perched zone".

The St. David clay, therefore, forms the lower base of both the perched zone and the shallow aquifer, located to the east of the Operations Area. With increasing volume, perched zone groundwater flowed eastward via gravity, eventually discharging to the shallow aquifer. In turn, the increased recharge to the shallow aquifer via the perched zone created localized "mounding" on the water table in the shallow aquifer near the location where perched zone discharge occurred. Because of the high concentrations of dissolved solids in the wastewaters, solutes were transported to the shallow aquifer, eventually forming a contaminant plume west of the San Pedro River. Specifically, perchlorate and nitrate-N plumes formed along the extreme western margin of the shallow aquifer, from the discharge area northward along the western margin of the shallow aquifer. Upon ANP's cessation of discharges to the unlined ponds in early 1995, the perched zone immediately began to recede. At the present time, although there are remnants of the perched zone in low-lying features on the clay surface, perched zone drainage to the shallow aquifer has essentially terminated. The dynamics of these plumes prior to and since the cessation provide inferences with regard to the hydraulic conditions within the shallow aquifer.

1.4 Previous Site Investigations

Several previous investigations of the perched zone and shallow aquifer have been conducted in conjunction with the Site. These investigations have produced significant information relating to the conceptual model.

The Remedial Investigation (RI) pursuant to CERCLA, conducted in 1990 and 1991, included the construction of 17 monitor wells, 12 piezometers, 5 exploratory borings, and 6 soil borings across the Site. Short-term, constant discharge aquifer tests also were performed on selected monitor wells to estimate aquifer hydraulic characteristics (H+A, 1991, 1992a, 1992b, 1993).

A quarterly monitoring program, including measurement of water levels and collection of groundwater samples from monitor wells and private shallow aquifer wells and surface water stations on the San Pedro River, was initiated in July 1990 and continued through October 1991. Additional monitoring rounds were conducted in July 1992 and April 1993 (H+A, 1991, 1992a, 1992b, 1993). Quarterly monitoring in accordance with the CGMP was initiated in February 1995 and is ongoing.

As part of an Aquifer Protection Permit (APP) investigation, soil borings APPB-1 through APPB-9 were completed into the St. David clay in the perched zone to facilitate soil sample collection and analysis. Results of the APP investigation have recently been documented (H+A, 2000a).

Five remedial action borings (RAB-1 through RAB-5) were completed during May 1997. These borings supported the siting and construction of shallow aquifer monitor wells MW-19, -20 and -21 and extraction well SEW-1 during May and July 1997 (H+A, 1996a and 1996c).

During August 1999, 4 exploratory borings (EXB-1a, -2, -3 and -4) were completed to support the siting and construction of monitor wells MW-22, -23 and -24. These monitor wells were constructed in the shallow aquifer to further delineate the western boundary of the shallow aquifer in the Southern Area and the extent of nitrate-N and perchlorate contamination in this area. Additionally, these facilities provided information used to evaluate the applicability of monitored natural attenuation as a remedial alternative for the Southern Area (H+A, 1999). Exploratory borings EXB-1 and -2 were used to extend a north-south transect through monitor wells MW-15 and -16, in the vicinity of where the perched zone discharges to the shallow aquifer. New shallow aquifer monitor well MW-23 was constructed south of monitor well MW-15. Exploratory boring EXB-3 was drilled immediately west of existing monitor well MW-14 to evaluate conditions in a gravelly unit between approximately 16 and 21 feet below land surface (bls) previously indicated on the monitor well MW-14 log. Exploratory boring EXB-4 was drilled to the west of monitor well MW-14 and was completed as monitor well MW-23 (H+A, 2000d).

As a cumulative result of these investigations, a network of monitor wells and piezometers is available to provide hydrogeologic data for the Site. Figure 4 shows the locations of shallow aquifer and perched zone monitor wells MW-01 through MW-32, perched zone piezometers P-01 through P-11, and shallow aquifer private wells that have been constructed to date.

1.5 Previous Regional Hydrogeologic Studies

A significant amount of geologic and hydrologic studies have been conducted in the San Pedro Valley in the recent past (Melton, 1960, 1965; Gray, 1965; Roeske and Werrell,

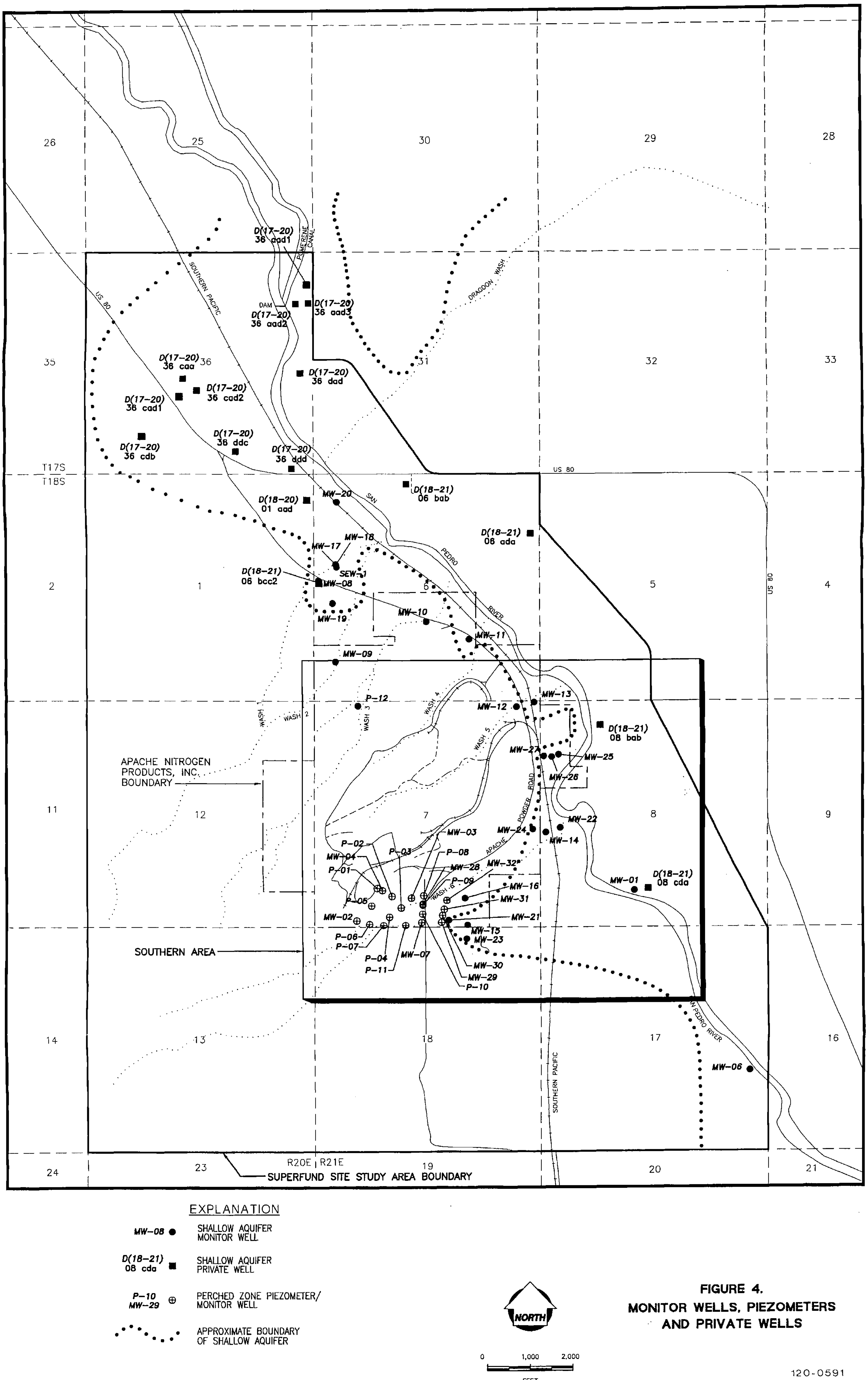

FIGURE 4.
MONITOR WELLS, PIEZOMETERS AND PRIVATE WELLS

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1973; Usunoff, 1984; H+A, 1991; Smith, 1994; Coes, *et al*, 1999; H+A, 2000g).

Melton (1960, 1965) focused on the fluvial and related geomorphic processes of arid and semi-arid regions throughout Arizona, including the San Pedro Valley. He determined that from an arc trending southeast through Congress Junction, Florence Junction and Tucson, the region extending eastward into western New Mexico exhibits remarkably consistent geologic and geomorphic features. This region is characterized by Pliocene to Middle Pleistocene lacustrine sediments deposited on older basement complexes after the Basin and Range Orogeny. Deposition occurred under shallow saline and/or lacustrine conditions via sluggish, low gradient, flow-through rivers. These deposits comprise clays and silts coarsening outward toward the bounding mountain ranges. They have been extensively dissected after deposition as far as 130 miles from the arc in the Safford, San Pedro, and Verde drainages. Deposition was attributed to local changes in base level elevations. Deposition of the lacustrine deposits in the San Pedro and Aravaipa drainages was attributed to a new base level created at a "dam" located on the Gila River near The Buttes, approximately 10 miles east of Florence, Arizona. Melton also noted that in all of the basins immediately east of the arc, the lacustrine deposits exhibit an eastward dip due to uplift of the mountains that form the western boundary of the individual basins.

Melton reported that the flood plain deposits in the Upper San Pedro Valley south of Benson comprise Late Pleistocene to Recent Deposits ("Frye Mesa type", as seen at Frye Mesa, approximately 12 miles southwest of Safford, Arizona). They are coarse-grained, have a red surficial soil horizon, and indicate stable base levels that lasted over a prolonged period of time. Recent fine-grained cienega sediments were deposited on top of the flood plain deposits in at least 3 or more depositional episodes. The cienega deposits are dark, carbonaceous sediments comprised of 75-95% of silt and clay, with gravel lenses located around the basin margins. The uppermost cienega unit reportedly was a thinly bedded sand/gravel unit. Current downcutting of cienega deposits by the San Pedro River is attributed to overgrazing, resulting in the establishment of new channels and causing the cienega deposits to be the least stable landform in southeast Arizona since 1880 (Melton, 1965).

Gray (1965) studied the Pliocene to Modern fluvial and lacustrine deposits in the St. David-Benson area of the Upper San Pedro Valley. He named the Pliocene to Middle Pleistocene lacustrine deposits identified by Melton (1965) as the "St. David Formation". He divided the St. David Formation into upper, middle and lower divisions. He mapped outcrops of the St. David Formation and more recent sedimentary units southward 4 miles from Benson through the Site to California Wash. The St. David Formation was deposited by a sluggish, through-flowing stream system during a sub-humid paleoclimate.

Roeske and Werrell (1973) evaluated groundwater use and hydrochemical conditions in the San Pedro Valley. Their study indicated that shallow aquifer groundwater and San Pedro River hydrochemistry is dominated by bicarbonate-carbonate type water. They also noted that some areas in the Upper San Pedro Valley contained groundwater that was relatively high in sulfate. With the exception of the Sierra Vista-Fort Huachuca area where a large groundwater depression had been formed by pumping from the shallow aquifer, they also found that groundwater elevations in the rest of the San Pedro Valley had demonstrated little historical net change.

Usunoff (1984) expanded on Roeske and Werrell's work by focusing on surface water and groundwater hydrochemistry in the San Pedro Valley, extending from approximately 6 miles south of St. David to "The Narrows", approximately 10 miles north of Benson, Arizona. Samples were collected from 1 spring, 4 surface water sampling points on the San Pedro River, and several wells tapping either the unconfined shallow aquifer or the confined deep aquifer. He noted that the shallow aquifer groundwater quality is poor in comparison to the deep aquifer, and that both aquifers and San Pedro River water were dominated by bicarbonate-carbonate type waters. Local anomalously high sulfate concentrations in shallow aquifer groundwater were noted within the study area, with marked decreases in sulfate concentration normal to the San Pedro River, yielding to background bicarbonate-carbonate type water. He attributed the high sulfate concentrations to the application of ammonium sulfate ($(NH_4)_2SO_4$) as a fertilizer to agricultural areas, adjacent to the San Pedro River. He also attributed the sulfate concentrations to naturally-occurring gypsum crystals in the St. David Formation clays. An increase in dissolved solids in the San Pedro River as it passes the St. David area was attributed to surface water discharge from domestic and irrigation ditches to the San Pedro River, in this area.

Hargis + Associates, Inc. (H+A) conducted a hydrogeologic investigation of the Site (H+A, 1991). The investigation focused on evaluating the spatial distribution of contaminants in the perched zone and shallow aquifer; background hydrochemistry of perched zone and shallow aquifer groundwater; hydraulic characteristics of the St. David clay unit that underlies the perched zone and shallow aquifer; and the hydraulic connection between the perched zone and shallow aquifer. As part of the investigation, several wells were constructed in the perched zone and shallow aquifer. Aerial photographs and drilling log data were used to estimate the western boundary of the shallow aquifer. The shallow aquifer was determined to range from unconfined to confined conditions using drilling log data.

Smith (1994)interpreted the climactic influences on the deposition of the St. David Formation in the Benson-Sierra Vista area of the Upper San Pedro Basin. He stated that gravity data indicate that the St. David Formation was deposited during a period of tectonic quiescence. He theorized that sedimentation was not controlled by active subsidence as previously believed, but instead by transition from an arid to wet paleoclimate, with the wettest paleoclimate coinciding with deposition of the middle division of the St. David Formation.

Coes, *et al* (1999) evaluated the groundwater hydrochemistry of the Sierra Vista Subbasin as part of a joint study conducted by the U.S. Geological Survey (USGS) and the Arizona Department of Environmental Quality (ADEQ). Their study area extended from the Mexican border to "the Narrows", a topographic constriction formed by bedrock outcrops, approximately 10 miles north of Benson, Arizona. Groundwater samples were collected and analyzed during 1996-1997. Their findings were essentially consistent with Usunoff's (1984), in that hydrochemistry is dominated by calcium bicarbonate type groundwater. Their data indicates that some areas in the subbasin contain relatively high concentrations of sulfate in flood-plain deposits. They attribute the increased sulfate concentrations to dissolution of gypsum by groundwater. They compared their results with groundwater analyses conducted during 1950-1965 and determined that no significant change in the groundwater hydrochemistry had occurred between these two periods.

H+A conducted a focused study of the perched zone hydrology in support of an Aquifer Protection Permit (APP) for ANP (H+A, 2000a). The investigation included drilling and sampling several soil borings in an area where wastewater had been discharged to a number of unlined evaporation ponds until 1995. The wastewater discharge had caused localized "mounding" of infiltrated wastewater on the St. David Formation underlying, creating a "perched zone". The contaminated groundwater flowed eastward under gravity, resulting in nitrate-nitrogen and perchlorate in the nearby shallow aquifer. The APP investigation indicated that significant dewatering of the perched zone had occurred following cessation of wastewater discharge to the ponds, resulting in significant reductions in saturated thickness and areal extent of the perched zone, and that little or no artificial or natural recharge from the perched zone to the shallow aquifer presently occurs.

1.6 Previous Regional Conceptual Modeling

Conceptual models of portions of the San Pedro Valley have been developed for use in numerical models in the recent past (AWC, 1974; Freethey, 1982; Vionnet, 1992; Jahnke, 1994; ADWR, 1996; H+A, 1996b; Sharma, 1997). The models were based on previous regional geologic work conducted by Gray (1965) and Melton (1960, 1965). The Arizona Water Commission (AWC) reportedly conducted the first groundwater model in the San Pedro Valley, focusing on analyzing groundwater conditions in the vicinity of Fort Huachuca. The conceptual model extended from the Mexican border to St. David. It consisted of an unconfined aquifer that was recharged via mountain front recharge and the San Pedro River was treated as a constant head boundary.

Freethey (1982) developed a model for a portion of the area modeled by AWC, extending from the Mexican border to Fairbank, Arizona. His conceptual model consisted of a two-layer aquifer system, incorporating an unconfined alluvial aquifer overlying a deeper confined aquifer, in which the San Pedro River and the unconfined aquifer were allowed to hydraulically interact. His model incorporated a variable grid size ranging from 0.6 to 1 mile based on variations in basin characteristics.

Vionnet's (1992) model was essentially an update of the Freethey (1982) model, in that the conceptual model extended from several miles south of the Mexican border to Fairbank, Arizona and utilized a three-layer system. The model was developed to simulate the effects of the capture of San Pedro River baseflow due to the interception of mountain front recharge by a large cone of depression caused by groundwater extraction in the Sierra Vista-Fort Huachuca area. The model area generally corresponds to the Sierra Vista Subwatershed, as defined by the U.S. Geological Survey (Coes, *et al.*, 1999). The top layer represented the unconfined alluvial aquifer, was located along the San Pedro and Babocomari Rivers, ranged in thickness from 10 to 60 feet and incorporated a uniform hydraulic conductivity of 167 feet per day (ft/day). The middle layer represented the "upper basin fill", ranged in thickness from a few feet at the basin boundary to 940 feet in the valley center and incorporated variable hydraulic conductivity values ranging from 3 to 18 ft/day. The bottom layer represented the "lower basin fill" and extended deeper than 1,000 below land surface (bls). The model simulated mountain front recharge on the west and east sides of the basin and evapotranspiration along streams where shallow groundwater conditions occur, essentially coinciding with the alluvial aquifer.

Jahnke's (1994) model extended Vionnet's model north from Fairbank, Arizona through the Site to approximately 5 miles south of Redington, Arizona and is considered the "Middle San Pedro Basin" model. Similar to Vionnet (1992), Jahnke (1994) utilized a three-layer system to simulate the aquifer system, but used a finer grid system ranging between 0.125 and 1 mile. The first layer represented the floodplain aquifer overlying a confining clay unit. Thickness ranged from 50 to 115 feet and hydraulic conductivity ranged from 40 to 300 ft/day. A vertical conductance for the underlying confining clay layer utilized hydraulic conductivities ranging from 0.01 ft/day (in the Site vicinity) to as little as 0.001 ft/day. The middle layer represented the "upper basin fill" and extended along the land surface east and west from the boundaries of the alluvial aquifer to maximum depths ranging from 500 to 1,000 feet bls. Hydraulic conductivities ranged from 1 ft/day along the valley axis to 15 ft/day along the outer margins of this layer. It appears that Jahnke used similar hydraulic conductivities for the clay unit separating the middle and lower layers. The lower layer represented the "lower basin fill" and extended from 1,000 feet bls to bedrock, ranging in thickness from 500 to 2,500 feet. Hydraulic conductivity for this layer was consistent with a value of 1.25 ft/day.

Sharma's (1997) model was essentially an update of the Arizona Department of Water Resources (ADWR, 1996) model in which model parameters were varied to simulate four annual seasons instead of a "constant" annual "season". The model was developed to provide potential explanations for observed baseflow trends in the San Pedro River and to assist future management of the San Pedro River National Conservation Area with respect to surface water/groundwater interaction. He used the same hydraulic conductivities and layer thicknesses as the ADWR model. The modeled area extended south from Sierra Vista to 6 miles south of the

Mexican border, with a variable grid size ranging from 40 to 160 acres. The upper layer represented the unconfined floodplain alluvial aquifer, ranged in thickness from 10 to 65 feet and had a constant hydraulic conductivity of 40 ft/day. The middle layer represented the "basin fill unit", ranged in thickness from 12 to 1,125 feet and had a variable hydraulic conductivity ranging from 0.1 to 20 ft/day. The lower layer represented the "conglomerate unit", ranged in thickness from 15 to 1,340 feet and had a variable hydraulic conductivity range equal to the middle layer.

The Hargis + Associates (H+A, 1996b) model was developed as part of a feasibility study of the entire Site to simulate the effects of alternative shallow aquifer groundwater extraction well arrays on groundwater levels and contaminant transport in the shallow aquifer. A one-layer system with a 125-foot grid was used to simulate groundwater flow in the unconfined alluvial aquifer. Aquifer saturated thicknesses ranging from 20 to more than 100 feet were used as layer thicknesses. Final calibrated hydraulic conductivities ranged from 50 ft/day to 250 ft/day. In the Southern Area, the highest hydraulic conductivities corresponded to Recent alluvium along the San Pedro River, and the lowest corresponded to the areas extending outward from the river to the western shallow aquifer boundary and to the eastern superfund study site boundary.

2.0 REGIONAL GEOLOGY AND HYDROGEOLOGY

2.1 Regional Physiographic Setting

The Site is located in the Upper San Pedro River Basin (the Basin) in the Basin and Range physiographic province (Fenneman, 1931). This physiographic province is typified by broad, gently sloping alluvial basins separated by north-northwest trending crystalline fault block mountains. The Basin includes approximately 1,800 square miles in southeastern Arizona (Konieczki, 1980) and extends 58 miles north from the Mexican border to "the Narrows", a topographic constriction formed by bedrock outcrops, approximately 10 miles north of Benson, Arizona. The Basin ranges from 15 to 35 miles in width and trends north-northwest. Boundaries of the Basin include the Rincon, John Lyon and Little Dragoon Mountains to the north; Whetstone and Mustang Mountains to the west; Dragoon Mountains and Tombstone Hills to the east; Huachuca Mountains to the southwest, and Mule Mountains to the southeast (Figure 5).

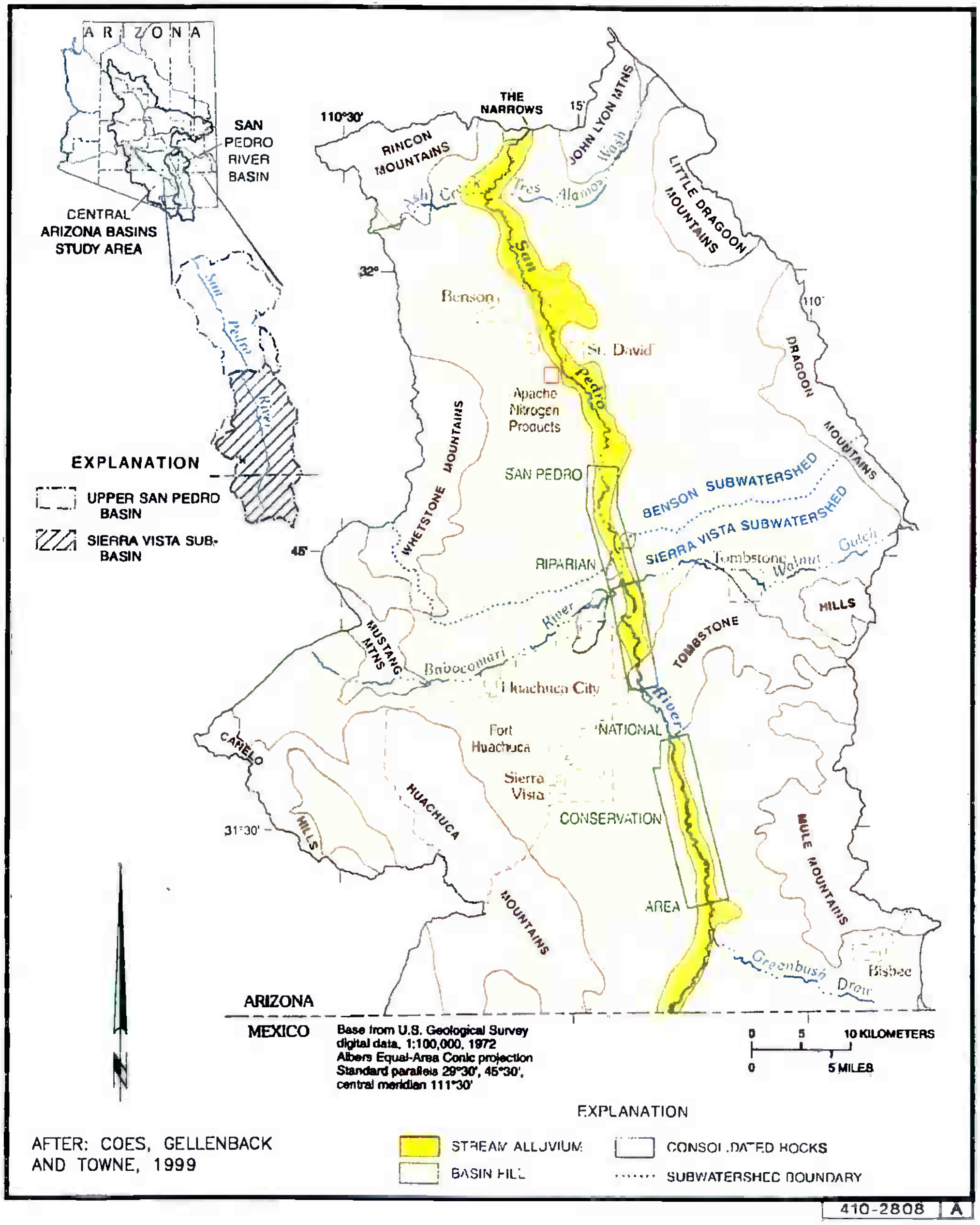

FIGURE 5.
REGIONAL GEOGRAPHIC FEATURES

The San Pedro River is the dominant surface drainage feature in the Basin. Its watershed is approximately 2,500 square miles, including 700 square miles in Mexico. The San Pedro River originates near Cananea, Sonora, Mexico approximately 65 miles south of the Site, and flows north to join the Gila River near Winkelman, Arizona. Flow in the San Pedro River is perennial where the streambed intercepts the water table. One perennial reach extends from the area north of Hereford (approximately 35 miles south of the Site) to a point just south of Fairbank, Arizona (approximately 14 miles south of the Site) (Konieczki, 1980). The largest San Pedro River tributary is the Babocomari River, which joins the San Pedro River approximately 14 miles south of the Site (Figure 5). Several minor tributaries also contribute to the San Pedro River (H+A, 1991). In 1988, the San Pedro Riparian National Conservation Area was established to protect the 58,000-acre riparian habitat that lines the San Pedro River north from the Mexican border to approximately 4 miles south of St. David, Arizona (Kingsolver, 2000).

2.2 Site Setting

The Site can be described geomorphically as a "badlands" terrain. Badlands are characterized by a hummocky topography dissected by fine ephemeral drainages. Badlands form as a result of precipitation that is typically of high intensity and short duration over low permeability clayey soils with relatively sparse vegetative cover. Topographically, the eroded ridges and hummocks at the Site are dissected by northeast trending washes. Maximum relief is approximately 200 feet, ranging from approximately 3,600 feet above mean sea level (msl) near the San Pedro River to 3,800 feet msl near the southwestern corner of the Site (Figure 6) (H+A, 1991).

Prior to 1880, the San Pedro River was described as a broad, shallow stream by local pioneers and settlers. However, since about 1880, the San Pedro River has been downcutting into Recent alluvial flood plain sediments that form the San Pedro Valley floor. Downcutting has been attributed to cattle overgrazing, wagon rutting, abandoned water canals, and increasing aridity (Gray, 1965). Presently, the San Pedro River meanders in a channel

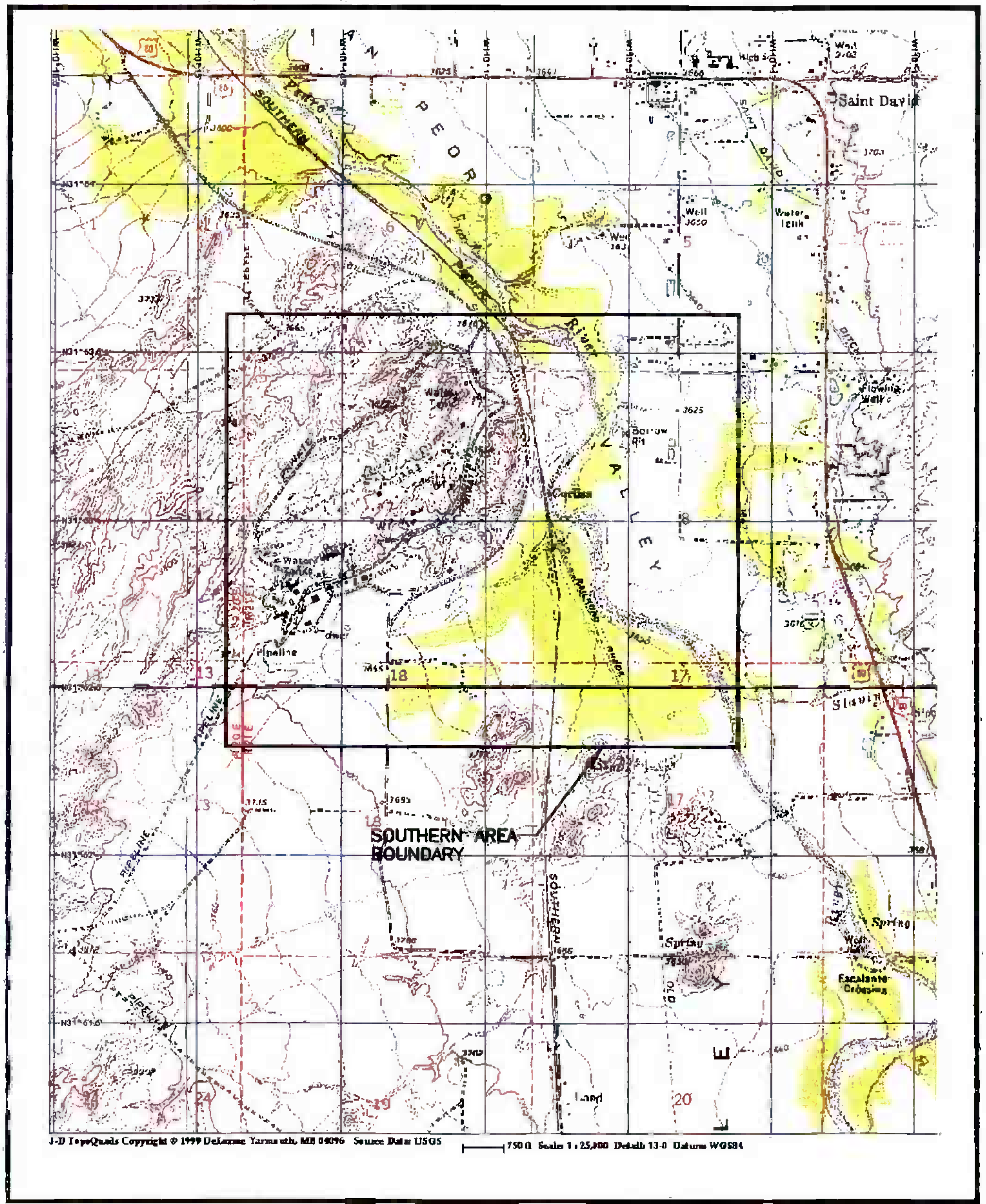

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FIGURE 6.
SITE TOPOGRAPHY

approximately 150 and 200 feet wide near the Site. Channel flow is generally restricted to less than 20 percent of the bank-to-bank width. During base flow periods, the river depth ranges from 0.5 to 2 feet. The ephemeral washes that flow across the Site enter the San Pedro River from the west (H+A, 1991). Fewer tributary washes enter from the east side, owing to the flatter terrain in the vicinity of St. David.

Climate conditions near the Site are considered to be arid to semi-arid, with a mean annual precipitation of approximately 13 inches per year (Sellers and Hill, 1985). Mean annual precipitation in the bordering mountains ranges up to approximately 25 inches. Precipitation generally occurs within two main seasons. Approximately 60 percent of the precipitation occurs from July through September, due to monsoon-type, convective storms. These result from reverse circulation of moist air masses originating in the Gulfs of California and Mexico to the south and east, respectively. The remaining 40 percent of the precipitation occurs during the winter months, due to frontal storms originating over the Pacific Ocean to the west.

Typical riparian vegetation, including tamarisk, cottonwood, and willow, can be found along the San Pedro River bottomland. Within the upland areas, more drought-resistant vegetation, such as mesquite, acacia, and creosote, are dominant. These varieties reportedly replaced the original savannas and grasslands that dominated the landscape before approximately 1880 (Hastings, 1959).

2.3 Geology and Hydrogeology

The Basin is a typical Basin and Range province structural valley as described by Fenneman (1931). The Basin was created by the subsidence of a structural graben. Tectonic movement associated with this structure began during the Miocene Basin and Range Orogeny (Melton, 1965). Sedimentation within the graben kept up with subsidence, resulting in a thick sequence of fine- to coarse-grained late Cenozoic terrestrial sediments derived from the igneous, metamorphic, and sedimentary rocks from the surrounding mountain ranges (Gray, 1965; Smith, 1994). The thickness of the alluvial sediments is unknown, but is thought to be greater than 1,000 feet near the center of the basin, thinning to a veneer along the mountain fronts (Gray, 1965; H+A, 1991). Sediments beneath the Site are deepest along the western boundary of the graben, indicating an asymmetrical structural basin with preferential westward dipping of the graben (Figure 7) (Gray, 1965). Gravity geophysical data indicate its axis is located slightly west of the San Pedro River near Benson, and directly beneath St. David (Melton, 1965).

2.3.1 Depositional Environment

Deposition of the late Cenozoic sediments within the Basin occurred primarily as a result of a sluggish, flow-through river system characterized by a low energy environment and a high stream capacity. The low-energy environment resulted in the deposition of mostly fine-grained, poorly-sorted sediments, whereas the high stream capacity was responsible for extensive aggradation. Localized centripetal/interior drainage areas developed due to local structural factors. Fossil evidence indicates that the southeastern Arizona climate was more humid during deposition of these sediments, with a higher annual

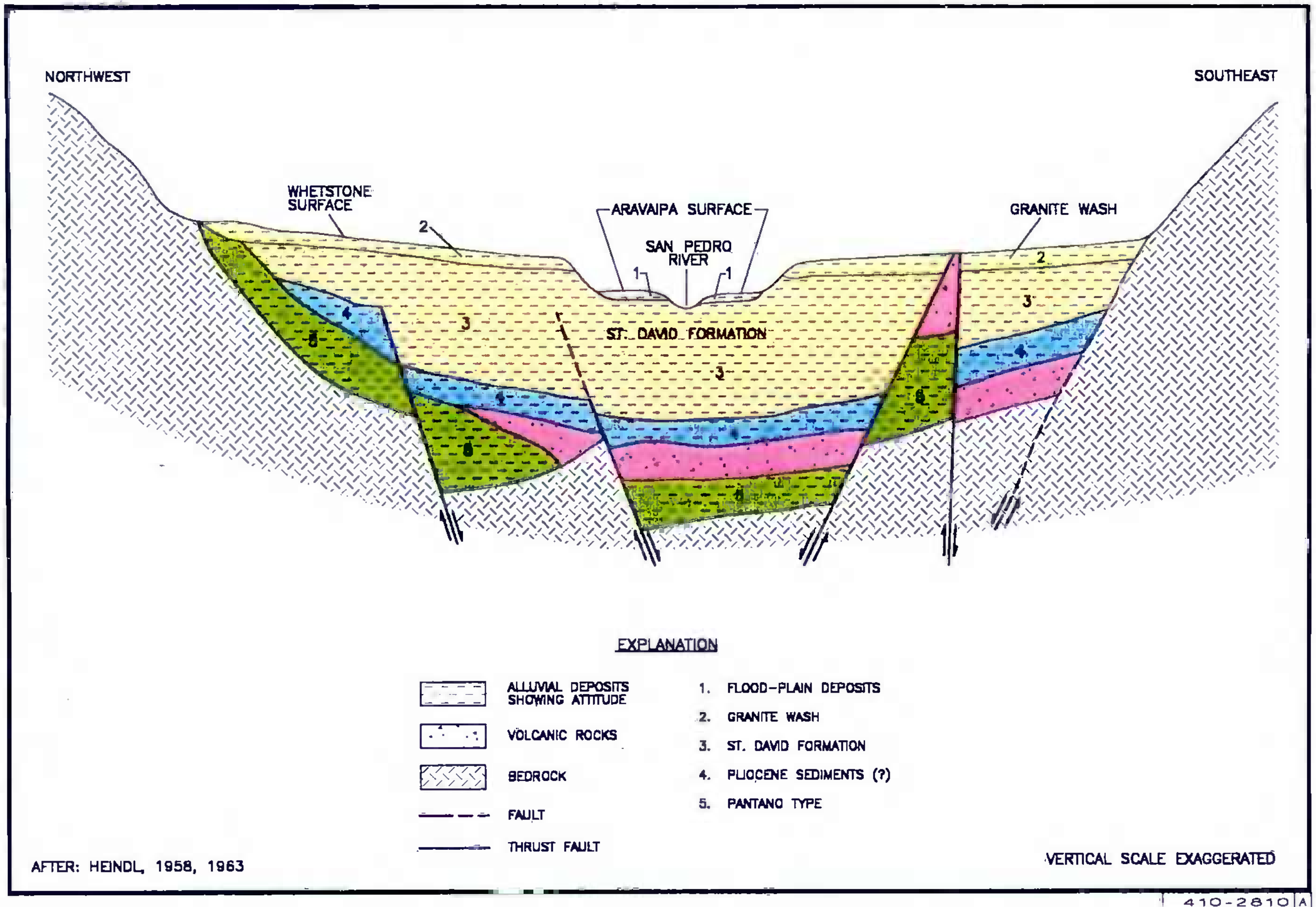

FIGURE 7.
GENERALIZED CROSS SECTION ACROSS SAN PEDRO VALLEY NEAR ST. DAVID, ARIZONA

rainfall and rare freezes. The unexpected high volume of sediments indicate that the watershed of the Basin may have extended as far south as the Rio de Sonora drainage in Mexico, approximately 65 miles south of the Site. Although this river currently drains south to the Gulf of California, it is aligned subparallel to the Basin, and the mountain ranges surrounding it comprise similar bedrock geology (Gray, 1965).

Periodic floods on the Ancestral San Pedro River tended to deposit sediments via vertical accretion. During deposition, these sediments increased in thickness in response to basin subsidence and associated gradient changes. During the early Pleistocene, the climate was probably sub-humid, with a large, slow-moving through-flowing stream system. This would be conceptualized as a system of large lakes, transitioning to savannas and open-grasslands away from streams. Late Pleistocene and later, the climate became more arid, but not reaching true desert conditions (Gray, 1965) (Figure 8).

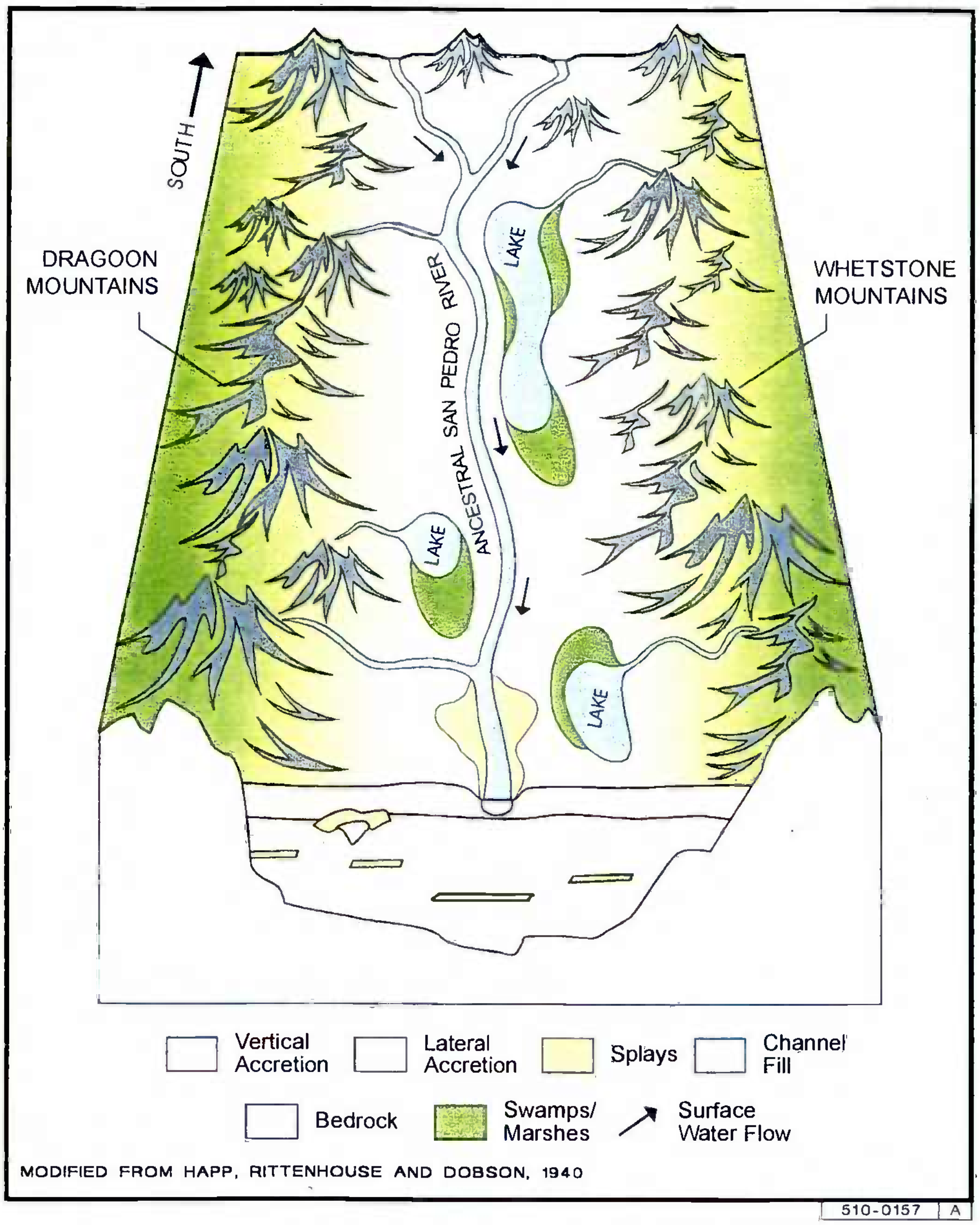

FIGURE 8.
HYPOTHETICAL VIEW OF THE SAN PEDRO VALLEY DURING DEPOSITION OF THE ST. DAVID FORMATION

The conceptualization of the San Pedro Valley paleoclimate was recently reinterpreted as having a cooler summer and winter climate during the late Pleistocene, approximately 18,000 years ago during the peak of the last ice age glaciation. Winters received approximately 60% more precipitation than present, and summers were more arid and did not have a developed monsoon season. Following retreat of the last continental ice sheet, both winter and summer seasons warmed up. There was a corresponding decrease in winter precipitation and development of summer monsoon seasons. (Amann, *et al.*, 1998).

As the Ancestral San Pedro River eroded the upper surface of the St. David Formation, paleochannels resulted from the dominant surface water flow patterns in the San Pedro Valley, including tributaries to the Ancestral San Pedro River. As the fluvial dynamics of the region changed from an erosional to a depositional environment, the surface water flow patterns were controlled by the paleochannels and remained essentially unchanged. This resulted in the deposition of coarse-grained sediments in the paleochannels and fine-grained sediments between the paleochannels during the deposition of the flood-plain sediments that comprise the shallow aquifer.

2.3.2 Stratigraphy

The generalized cross section of the geologic structure across the Basin in the Site includes the basement complex, older sedimentary rocks, and late Cenozoic fine-grained fluvial and lacustrine sediments (Figure 7). The basement complex comprises metamorphic and granitic crystalline rocks of Precambrian age displaced by normal faulting. The older sedimentary rocks include sedimentary and metamorphic rocks of Paleozoic/Mesozoic age and sedimentary, pyroclastic, volcanic and intrusive rocks of Tertiary and early Cenozoic age. (Gray, 1965).

The late Cenozoic sediments from oldest to youngest include the St. David Formation, granite wash unit, gravel alluvium, and Recent/Modern alluvium. The sequence represents a series of erosional and depositional events that are separated by erosional unconformities, referred to as "surfaces" (Gray, 1965; Melton, 1965). Overall, the sequence comprises primarily silt and clay with some fine sand, freshwater limestone, and water lain pyroclastic materials.

The Late Pliocene/Middle Pleistocene St. David Formation is the thickest of these sediments. It generally coarsens upward and has been incised by the badlands topography in the Site vicinity. As described earlier, the St. David Formation was deposited by the large, slow-moving, through-flowing stream system on an aggrading floodplain. Calcite cementation is weak to strong throughout the formation. Coarse-grained content increases toward the mountains. Localized channel conglomerate/sandstone units are also present. The St. David Formation is divided into the "lower", "middle", and "upper" divisions (Gray, 1965).

The "lower division" is dominated by red clays and mudstones, with minor sand lenses. Diagenetic illite is the dominant clay mineral. Gypsum mineralization is common in the fine-grained units. Gypsum sediments are thickest in the bluffs in Section 30 of T17S/R21E (approximately 3 miles north of the Site) and thinning in all directions. This indicates a sub-humid, lacustrine depositional environment with wetting/drying cycles in this area.

Another gypsum deposit is located approximately 1.5 miles southwest of the Site in Section 24 of T18S/R20E. Lakes, ponds, and marshes were reportedly common sites during deposition of this division. The lower division ranges in elevation from 3,800 feet msl to a depth of at least 2,800 feet msl, indicating a thickness in excess of 1,000 feet (Gray, 1965). Well logs in the St. David area indicate that "red clay" (St. David clay) is present to depths to 300 feet bls beneath the Site. The lower portion of this division consists primarily of fluvial sands and gravels that comprise the confined, deep aquifer (H+A, 1991).

The "middle division" comprises red and green clays, limestone, tuffaceous units, and brown silt. The middle division has a higher calcium carbonate content than the underlying lower division, especially in lacustrine units, and contains most of the fossiliferous beds of the St. David Formation. The middle division is found at elevations above 3,800 feet msl and grades imperceptibly into the overlying upper division.

The "upper division" comprises light brown to grayish orange silt, silty clay, and fine sand units separated by paleosol and caliche units. The Paleosols and caliche indicate an increasing aridity. Montmorillonite, derived from volcanic ash, is the dominant clay mineral. This division is much coarser than the underlying divisions.

Cross bedding in the St. David Formation indicates both northward and mountain-front-to-valley axis depositional flow patterns. Subsidence related to tectonism continued during most of the St. David Formation deposition. A structural zone extending south from Benson to California Wash represents an eastward dipping, monoclinal, syn-depositional downwarping of bedding, coinciding with regional features identified by Melton (1965) (Plate 1). This downwarping occurs toward the valley center and is believed to have resulted in response to displacement along the underlying system of normal faults. The lack of downwarping in the uppermost limestone and clastic units of the St. David Formation near Post Ranch (located approximately 6 miles northwest of the Site) indicates that fault displacement halted prior to their deposition. The northern portion of the St. David Formation was eroded away, and the southern portion was buried as a result of Middle-Pleistocene degradation. During this time, vertical bluffs on the east and west sides of the San Pedro River were formed (Gray, 1965).

The Pleistocene granite wash unit unconformably overlies the St. David Formation and forms the "cap rock" over most of the surrounding bluffs. The granite wash sediments comprise a reddish-orange to reddish-brown, heterogeneous, clean, fine to coarse grained gravel alluvium. Granite wash sediments are believed to have been derived from the underlying St. David Formation and from the deposition of exposed granitic materials eroded from the adjacent mountain ranges deposited as alluvial fans and fluvial sediments on the dissected surface of the St. David Formation (Gray, 1965). Thickness ranges up to 150 feet. The erosional unconformity between the St. David Formation and granite wash sediments probably represents a prior badlands topography that developed near the center of the basin. Successive deposition and dissection have produced a complex exposure of the St. David Formation and granite wash sediments. The granite wash was eroded and thinned post-depositionally, resulting in the Whetstone Surface. The erosional process that formed the Whetstone Surface is said to have "beveled" both the St. David Formation and granite wash sediments toward the San Pedro River (Gray, 1965).

Adjacent to the San Pedro River and along its ephemeral tributaries, the St. David Formation and granite wash sediments have been eroded and replaced by younger gravel alluvium and/or the Recent/Modern alluvium. Archaeological studies in the area indicate that the Recent alluvium may date from approximately 500 B.C. Since 1880, the San Pedro River has been downcutting into the Aravaipa Surface and depositing "Modern" alluvium within the river channel (Gray, 1965).

The well-rounded sediments of the gravel alluvium comprise reworked granite wash sediments. They were deposited inside the Basin by the Ancestral San Pedro River during the formation of the Whetstone Surface. Gravel alluvium typically outcrops 50 to 100 feet above the San Pedro Valley floor and appears to comprise the lower portion of the perched zone sediments (Plate 1) (Gray, 1965). Some minor outcrops of gravel alluvium have been mapped near the Site, most notably within a low, broad hill south of monitor well MW-13, near the mouth of Wash 5 along Apache

Powder Road (Figure 4 and Plate 1). During the recent Southern Area investigation, this hill was determined to comprise St. David Formation sediments (exploratory boring EXB-7) instead of gravel alluvium.

The "Recent" alluvium, comprising sands, gravels, silts and clays, were deposited within the Basin and form the semi-confined shallow aquifer of the Site and the upper perched zone sediments south of ANP's Operations Area. The Recent alluvium has been described as "flood plain" sediments, deposited by the Ancestral San Pedro River during regional aggradation (Gray, 1965). The Aravaipa Surface forms the upper surface of the Recent alluvium and occurs approximately 100 feet below the Whetstone Surface (Gray, 1965). The Modern alluvium comprises stream channel sands and gravels deposited from about 1880 to present. Cienega (swamp) deposits reportedly comprise the upper portion of the flood plain sediments (Melton, 1965). As a result of the downcutting, a large cienega reported to have extended 8 miles northward from Benson to the old Tres Alamos Ranch site has disappeared (Gray, 1965). A similar cienega may have existed in an inferred unit of fine-grained laterally confining sediments in the Southern Area (Section 5.0).

Swamps contain cattails, bulrushes, etc. that typically produce large amounts of dead vegetative detritus. The detritus usually accumulates within relatively thick underwater deposits due to the low-fluvial energy environment, resulting in areas of relatively high concentrations of organic carbon. A present example of such a swamp-like environment is located at the current confluence of the Babocomari and San Pedro Rivers at Fairbank, Arizona, approximately 14 miles south of the Site.

2.3.3 Regional Hydrogeology

Bedrock constrictions located at Charleston, Arizona, which is located 23 miles south of Benson, Arizona, and at "the Narrows" (Figure 5) divide the San Pedro watershed into three general basins. The Narrows divides the San Pedro Valley into the "Upper San Pedro River Basin" to the south and the "Lower San Pedro River Basin to the north" (Gray, 1965). The approximately 45-mile section of the Upper San Pedro River Basin, located between the Narrows and Charleston, has been referred to as the Benson sub-basin (Gray, 1965). Coes (*et al.*, 1999) consider the Upper San

Pedro River Basin to extend north from Mexico to Winkelman, Arizona, and have renamed Gray's "Upper San Pedro River Basin" as the "Sierra Vista Subbasin". Under this nomenclature, the subbasin is divided into the Benson Sub-watershed to the north of Fairbank, and the Sierra Vista Sub-watershed to the south (Figure 5). This report uses Gray's definition of the Basin, and Coes' definition of the two Sub-watersheds (Gray, 1965; Coes, *et al*, 1999).

The regional hydrogeology of the Basin near St. David and Benson has been studied in detail (Roeske and Werrell, 1973). Groundwater occurs in the alluvium along the San Pedro River and its tributaries. The alluvium consists of the Recent alluvium, gravel alluvium and granite wash, as defined by Gray (1965). These lithologic units comprise a single hydrostratigraphic unit that forms a semi-confined, alluvial aquifer locally referred to as the "shallow aquifer". The lithology of the shallow aquifer primarily consists of gravel, sand and silt sediments. These sediments are generally between 40 and 100 feet thick, but locally may be as thick as 150 feet. These sediments are unconsolidated and relatively permeable. Locally, they may yield as much as 2,000 gallons per minute (gpm) to properly constructed wells. Depths to groundwater in the shallow aquifer in the Site area are approximately 20 to 80 feet bls (NUS, 1989).

Groundwater also occurs in the lower portion of the St. David Formation and the underlying older sedimentary rocks. These lithologic units comprise a single hydrostratigraphic unit, referred to as the confined regional deep aquifer ("deep aquifer"). The upper unit of the deep aquifer consists of clayey and silty gravel beds near the mountains and clay, silt and sandy silt, with interbeds of gypsum in the central part of the Basin. Near the Site, the upper unit of the deep aquifer is encountered at depths ranging from approximately 300 to 400 feet bls. The upper unit of the deep aquifer ranges from 300 to 800 feet in thickness. The lower unit of the deep aquifer is composed of older sedimentary rocks including lenses of gravel, sandstone, and siltstone. Gypsiferous silt lacustrine sediments may also be present (Roeske and Werrell, 1973). The lower unit of the deep aquifer is encountered at depths below 600 feet bls at the Site, and ranges in thickness from several tens of feet, near the edge of the valley, to more than 1,000 feet beneath the San Pedro River (H+A, 1991).

The groundwater levels in wells that penetrate the deep aquifer east of the San Pedro River rise above the overlying St. David clay, resulting in artesian conditions. Flowing wells have been observed in the St. David area. These flowing wells indicate that the elevation of the hydraulic head of this aquifer is greater than the elevation of the hydraulic head in the overlying shallow aquifer. If leakage through the St. David clay could occur, it would be upward from the deep aquifer to shallow aquifer (H+A, 1991).

3.0 RECENT SOUTHERN AREA INVESTIGATION

A buried paleochannel in the St. David clay surface was believed to exist near perched zone piezometer P-10. This paleochannel is believed to have functioned as a pathway through which perched zone groundwater, originating beneath the formerly active ponds, migrated and eventually discharged to the shallow aquifer in the vicinity of shallow aquifer monitor well MW-21. The extension of the paleochannel between piezometer P-10 and monitor well MW-21 and, thus, the location of the discharge to the shallow aquifer, had not been determined from prior perched zone investigations.

Quarterly groundwater sampling data for 1999 indicated that nitrate-N and perchlorate plumes originating in the perched zone extended northward beyond the location of shallow aquifer monitor well MW-24, between monitor well MW-14 and the St. David Formation outcrop to the west. The St. David Formation outcrop has generally been interpreted as the western boundary of the shallow aquifer. Because of data collected from monitor well MW-24 indicating the presence of both perchlorate and nitrate-N, the northern extent of either plume in the shallow aquifer could not be determined from the existing monitor well MW-14, -22, -24 transect. In addition, previous drilling had indicated the presence of a paleochannel in the St. David clay, extending along the western shallow aquifer boundary from the vicinity of monitor well MW-21 northward through monitor well MW-24. The northern extent of this channel had not been determined from then available drilling data.

Thus, a phased investigation was conducted at the Site during April through July 2000. The shallow aquifer investigation objectives were to evaluate the northern extent of detectable nitrate-N and perchlorate concentrations in the shallow aquifer north of monitor well MW-24, and to provide additional data on the subsurface lithology and western boundary of the shallow aquifer. The perched zone investigation objective was to further characterize the extent of nitrate-N and perchlorate in perched zone groundwater west of shallow aquifer monitor well MW-21. The investigation data were used to enhance the conceptual understanding of groundwater conditions in the shallow aquifer and perched zone. In particular, the limited lateral extent of the nitrate and perchlorate plumes coupled with anomalously low hydraulic heads measured in monitor well MW-24 along the western edge of the shallow aquifer focused a need to evaluate the potential for a buried paleodrainage in this area. Additionally, there was a need to pinpoint the extent of subsurface drainage from the perched zone into the shallow aquifer. Specifically, the investigation included:

- Performing pre-drilling geophysical surveys in April 2000 to site exploratory boring and monitor well locations,
- Constructing an exploratory boring and new monitor wells in the shallow aquifer and perched zone during May and June 2000, and
- Sampling and analysis of groundwater samples for major ions in selected Southern Area wells.

The investigation yielded a significant amount of new data on subsurface lithology and groundwater conditions that were used to refine the conceptual model of groundwater flow within the Southern Area. The following sections describe the investigative approach.

3.1 Seismic And Electrical Geophysical Surveys

A pre-drilling geophysical survey was conducted in mid-April 2000, in accordance with the Proposed Seismic and Electrical Geophysical Survey, Apache Powder Superfund Site technical workplans approved by EPA (H+A, 2000b; EPA, 2000a). All geophysical surveys were performed and interpreted by contractors under the field supervision of the author. Seismic refraction field data were collected by Bird Seismic Services, Inc. of Globe, Arizona. Seismic data were reduced by Excel Geophysical Services, Inc. of Denver, Colorado, and interpreted by Dr. J. Edward Blott, of Littleton, Colorado. Mr. William Ellett of the Arizona Department of Environmental Quality participated in the oversight of several of the field surveys and provided valuable advice to the author. High resolution electrical resistivity field data were collected, reduced and interpreted by hydroGEOPHYSICS, Inc. (HGP) of Tucson, Arizona. Seismic and electrical resistivity pseudosections are provided in Appendices A and B, respectively. Raw seismic data plots are on file at the offices of Hargis + Associates, Inc. in Tucson, Arizona, and ANP in Benson, Arizona.

Geophysical data were collected along four transects, two overlying the perched zone and two overlying the shallow aquifer (Figure 9). The processed data were evaluated to estimate depths to the buried surface of the St. David clay beneath the shallow aquifer and perched zone and to locate possible saturated sediments above the St. David clay adjacent to the Operations Area. The geophysical data were used in addition to borehole data to site 8 new perched zone and shallow aquifer wells that were drilled and constructed in April and May 2000. Both seismic refraction (seismic) and high resolution electrical resistivity (HRR) geophysical methods were used to survey the perched zone, whereas only the seismic method was used to survey the shallow aquifer. The transects across the perched zone were designated as Lines 1 and 2, and the transects across the shallow aquifer were designated as Lines 3 and 4 (Figure 9). Line 1 was treated as a "calibration" transect for testing various seismic/HRR source and data recording arrays and for comparing geophysical responses against

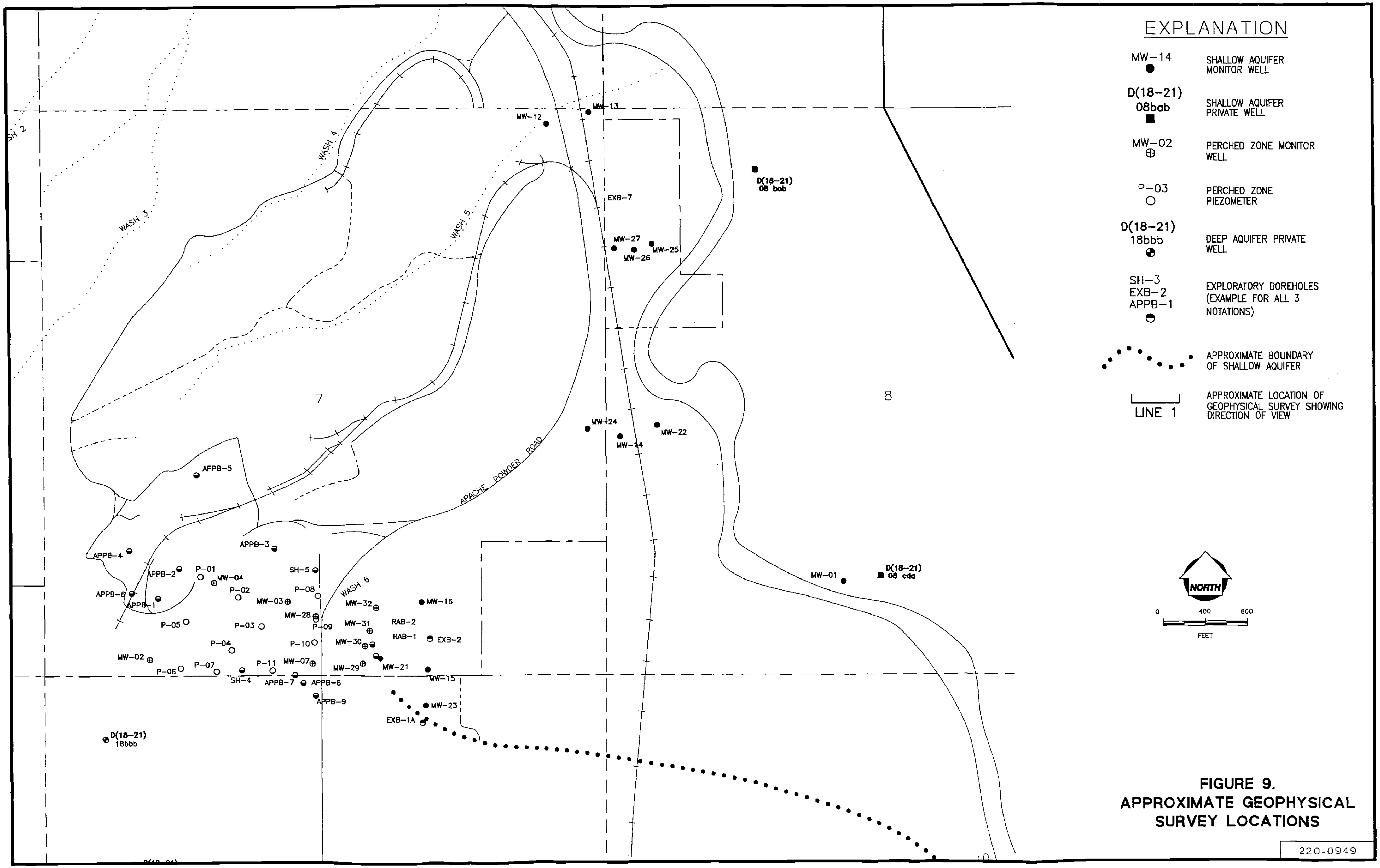

FIGURE 9.
APPROXIMATE GEOPHYSICAL
SURVEY LOCATIONS

existing drilling data. These activities improved the subsurface detail of the buried surface of the St. David clay in the perched zone and shallow aquifer.

3.1.1 Geophysical Methodology

Both geophysical methods utilized 5-foot station spacing along each transect for energy propagation and data recording. The seismic survey preceded the HRR survey. The same station numbering convention was employed on all four transects and for both methods. The station number consistency resulted in relatively easy correlation between the seismic and HRR survey results.

The seismic method utilized either an engine-powered elastic wave generator (EWG) or a manual sledgehammer for an energy source, depending on station accessibility. The EWG was used at easily accessible stations, and the sledgehammer was used at less accessible stations. The EWG consisted of a 207-pound weight-drop machine, trailered between stations behind an all-terrain vehicle. The weight was automatically lifted and then dropped, striking a steel plate positioned on the ground surface. A large elastic "band" slung over the top of the EWG weight added velocity to the weight, thus maximizing the energy released at the ground surface. The steel plate was wired to a data recorder to increase the response time accuracy recorded by the geophones. Seismic data were recorded on each transect at approximate 480-foot intervals (*i.e.*, 96-geophones at 5-foot spacings), along which the energy source was progressively moved between stations at 5-foot spacings. At least 3 to 4 blows were repeated at each station to generate sufficient recorded energy and ensure data clarity.

The HRR method utilized a pole-to-pole array with 1/2-inch diameter, metallic movable ("roving") and stationary ("infinite") transmitter/receiver electrodes. For Lines 1 and 2, the infinite transmitter electrode was located approximately 2,000 feet north of piezometer P-08, and the infinite receiver electrode was located approximately 2,000 feet east of monitor well MW-07. The infinite transmitter/receiver electrode array was used to generate a constant electrical current through the sediments. The voltage, as a function of sediment resistivity, was recorded along Lines 1 and 2 utilizing a roving transmitter electrode within a roving array of receiver electrodes. The roving transmitter electrode was advanced at 10-foot intervals within the roving receiver array. To maximize electrical contact with the soils, the soil surrounding and contacting each electrode was moistened with water.

3.1.2 Geophysical Survey Results

During an informal technical meeting conducted between representatives of ANP, ADEQ and EPA on April 19, 2000, preliminary survey results were discussed and drilling locations were agreed upon. The geophysical data were used to evaluate the depth of the buried St. David clay surface and to locate well sites in the perched zone and shallow aquifer.

Geophysical Survey Line 1

Geophysical Survey Line 1 is regarded as a calibration survey. Seismic data indicated that a broad, erosional paleochannel in the buried St. David clay surface is located between monitor well MW-07 and Wash 6, and that its main drainage axis is located approximately 75 feet south of piezometer P-10 (Blott, 2000) (Appendix A). The data confirm previous information that monitor well MW-07 is situated on a "ridge" of St. David clay, probably representing the southern "bank" of the paleodrainage. The axis of this "ridge" on the buried St. David clay is situated approximately 25 feet south of monitor well MW-07. The buried St. David clay surface appears to drop in elevation south of this high area, based on previous drilling data. Two smaller buried paleochannels were noted on the northern "bank" of the main paleochannel and at higher elevations. They are located midway between piezometers P-09 and P-10, and directly underneath Wash 6. The St. David clay topography on this seismic "pseudosection" was keyed to previous drilling elevations.

HRR data indicate generally similar St. David clay topography and confirm the presence of saturated sediments on top of the buried St. David clay surface in the main drainage axis north of monitor well MW-07 (HGP, 2000) (Appendix B). It should be noted that a shallow unlined earthen sump located immediately west and adjacent to Line 1 at the time of the survey contained a small amount of water discharged from deep aquifer production well 55-

632881 (ANP Well No. 4). HRR data indicate that the St. David clay virtually outcrops in the vicinity of piezometer P-09 and Wash 6, contrary to seismic data. This interpretation may have resulted from slightly higher clay content in granite wash sediments found in this area.

New perched zone monitor well MW-28 was constructed on the south side of Wash 6 (at station 200) to evaluate any groundwater that may be migrating through the "ancestral" Wash 6 drainage. This location was selected partly because Wash 6 historically had been used to convey process fluids away from the Operations Area before the formerly active ponds were constructed. The wash was partly re-routed following construction of the ponds in 1971. This practice possibly resulted in the infiltration and accumulation of surface water within the ancestral Wash 6 channel. Additionally, there was an interest in assessing whether any residual fluids may have remained after perched zone dewatering (Figure 9).

Geophysical Survey Line 2

Seismic data indicate that the buried St. David clay surface generally slopes downward from Wash 6 south to the approximate midpoint of Line 2, and then maintains at a relatively constant elevation southward to Apache Powder Lane (Blott, 2000) (Appendix A). The data suggest that three minor paleochannels may be present on the buried St. David clay surface. One is located directly under Wash 6, and two are located on the relatively flat portion of Line 2 near stations 153 and 190. The buried St. David clay topography on this seismic pseudosection was not keyed to any known St. David clay drilling elevations due to the exploratory nature of Line 2 and lack of near-field drilling information. Thus, the apparently higher St. David clay elevations along Line 2 (compared to Line 1) may be erroneous.

HRR data indicate that the buried St. David clay surface is similar to that interpreted from the seismic data, except that it appears to outcrop in the vicinity of Wash 6 (HGP, 2000) (Appendix B). The surface soils in the vicinity of Wash 6 appear to have higher clay content than those along the southern portion of Line 2. HRR data also indicate that a buried paleochannel, containing moist soil, is located near station 120, north of Apache Powder Lane. The data also indicate that saturated sediments underlie an unnamed, contemporary shallow wash, located approximately 665 feet from the south end of Line 2.

Four new perched zone monitor wells MW-29, -30, -31 and -32 were constructed at stations 120, 154, 185, and 230, respectively. These sites were locations of topographic lows and/or saturated sediments on the buried St. David clay surface (Figure 9).

Geophysical Survey Line 3

Seismic data indicate that the buried St. David clay surface slopes steeply downward from the St. David clay outcrop west of Apache Powder Road east to monitor well MW-24 and then follows an irregular surface to monitor well MW-22 (Blott, 2000) (Appendix A). The data indicate that monitor well MW-24 is located along the bottom surface of a previously interpreted paleochannel and that the channel is approximately 75 feet in width. The data also indicate that monitor wells MW-14 and -22 are located on a higher buried St. David clay erosional surface, and that a shallow small paleochannel is located approximately 60 feet west of monitor well MW-22. Seismic data indicate that this paleochannel is approximately 25 feet in width. The buried St. David clay topography on this seismic pseudosection was "keyed" to known St. David clay drilling elevations.

No new shallow aquifer monitor wells were constructed along Line 3 because the data confirmed that monitor well MW-24 is located near the lowest point in the previously interpreted paleochannel.

Geophysical Survey Line 4

Seismic data indicate that the buried St. David clay topographic surface slopes gently downward from the base of the Apache Powder Road cut toward the San Pedro River. This occurs at a significantly shallower depth than along Line 3 (Blott, 2000) (Appendix A). The data also indicated that relatively minor paleochannel axes are located at stations 140, 170 and 207. The buried St. David clay topography along this seismic pseudosection could not be keyed to known St. David clay elevations due to the lack of previous near-field drilling data.

Three new shallow aquifer monitor wells MW-25, -26 and -27 were constructed at stations 140, 170 and 207, respectively (Figure 9). Drilling has confirmed that the higher St. David clay elevations (compared to Line 3) are likely the result of a lithofacies change within the shallow aquifer. Instead of drilling through the typical shallow aquifer sands and gravels encountered along Line 3, a weakly cemented silty clay unit was encountered during drilling. This unit directly overlies the St. David clay and has a very similar appearance. The unit may represent reworked and transported St. David clay material deposited in a localized, low-energy environment.

3.2 Monitor Well Construction

Technical workplans for construction of new shallow aquifer and perched zone monitor wells at the Site were submitted to EPA (H+A, 2000c, 2000e). These plans, as approved, included the construction of one exploratory boring and 8 new monitor wells (EPA, 2000b, 2000c). Their locations were based upon existing drilling data and the results of the pre-drilling geophysical survey. This construction was completed during May and June 2000.

3.2.1 Shallow Aquifer Exploratory Boring and Monitor Well Construction

One exploratory boring (EXB-7) and three new shallow aquifer monitor wells, MW-25, -26, and -27, were completed north of monitor well MW-24 using air-rotary casing hammer (ARCH) drilling methods. Exploratory boring EXB-7 was drilled to evaluate the extent of the shallow aquifer near a topographic saddle south of monitor well MW-13 (Figure 9). The boring was drilled to an approximate total depth of 27 feet bls. The St. David clay was encountered at approximately 17 feet bls. Groundwater was not encountered. Exploratory boring EXB-7 was abandoned by backfilling to land surface with neat cement.

The new shallow aquifer monitor wells were constructed along Geophysical Survey Line 4 to create a new monitor well transect essentially transverse to the hydraulic gradient. The purpose of the transect included the evaluation of shallow aquifer groundwater conditions and

St. David clay topography downgradient of the existing MW-24 monitor well transect. This location was significant in that perchlorate was detected in groundwater sampled at monitor well MW-24, therefore the new monitor wells were drilled to assist in delineating the northward extent of perchlorate contamination in the shallow aquifer.

During construction, each $9^5/_8$-inch nominal diameter monitor well borehole was advanced approximately 20 to 30 feet below the top of the buried St. David clay. This confirmed that the bottom of the shallow aquifer had been encountered. A weakly-cemented silty clay unit was encountered in the expected stratigraphic interval in contrast to the typical sand and gravel sediments found at other shallow aquifer monitor well locations. Sediments encountered in this unit were similar in appearance to the St. David clay that underlies it and forms a nearby outcrop to the west. To determine if this unit correlates with the shallow aquifer, borehole drilling was temporarily stopped in this unit (at each well site). Water was blown out of the drive casing with compressed air via the drill pipe and the water level was monitored. Rising water levels within the drive casing confirmed that this unit produced water, correlated to the shallow aquifer, and thus is not part of the St. David Formation.

Prior to surface seal installation, each monitor well filter pack was consolidated by surging with a tight-fitting surgeblock and then air-lifted to facilitate groundwater sample collection. Split groundwater samples were collected and sent to Turner Laboratories in Tucson, Arizona, for nitrate-N analysis via EPA Method 300 and to Montgomery-Watson Laboratories in Pasadena, California, for perchlorate analysis via Method 314 on a 24-hour turnaround schedule. The results were used to determine handling procedures of borehole drilling and monitor well development fluids. Because neither perchlorate nor nitrate-N was detected, all construction fluids were disposed within the earthen pit excavated at each drill site.

The shallow aquifer monitor wells were mechanically developed after well construction by alternately surging with a tight-fitting surgeblock and bailing newly-introduced sediments from the well, until no new sediments were introduced into the well. Pump development consisted of purging groundwater with an electrical submersible pump until 3 to 5 combined saturated well casing and filter-packed borehole volumes had been purged; groundwater pH, temperature, and electrical conductivity had stabilized to within ±10% of previous readings; and the discharge was clear. The development water was discharged to the nearby ground surface.

During pump development of shallow aquifer monitor wells MW-25, -26 and -27, the following data were collected:

Well Number	Discharge Rate (gpm)	Final Drawdown(ft)	Specific Capacity (gpd/ft)
MW-25	6.6	35.16	270
MW-26	3.6	49.67	104
MW-27	0.4	58.60	10

3.2.2 Perched Zone Monitor Well Construction

Five new perched zone monitor wells (MW-28, -29, -30, -31 and -32) were completed in the perched zone west of shallow aquifer monitor well MW-21 using hollow-stem auger (HSA) drilling methods. Monitor well MW-28 was constructed approximately 30 feet north of piezometer P-09 along Geophysical Survey Line 1. This well was constructed to evaluate perched zone groundwater in the St. David clay topographic low located directly beneath Wash 6. Monitor wells MW-29 through MW-32 were constructed along Geophysical Survey Line 2, essentially perpendicular to the assumed axis of the paleochannel, to evaluate perched zone groundwater conditions immediately upgradient from where perched zone groundwater discharges to the shallow aquifer (Figure 9).

Each 7-inch nominal diameter pilot borehole was advanced approximately 5 to 10 feet below the top of the St. David clay to confirm that the bottom of the perched zone had been encountered. The boreholes were then reamed to a nominal 11-inch diameter prior to well construction. The casing of each well was constructed so that the bottom of the screened interval was positioned below the top of the buried St. David clay surface. This design facilitates flow of perched zone groundwater to the well.

Perched groundwater was encountered only within monitor well MW-29. Monitor well MW-29 was mechanically developed following well construction using surging and bailing techniques. Groundwater was bailed until 3 to 5 combined saturated well casing and filter-packed borehole volumes had been purged; groundwater pH, temperature, and electrical conductivity had stabilized to within ±10% of previous readings; and discharge was clear. Because the groundwater was found to have dissolved perchlorate, it was collected in a water tank and transferred to a 21,000-gallon, open top Baker Tank, where it will be allowed to evaporate as a means of treatment.

3.2.3 Surveying

Following monitor well development, the concrete pad, protective steel casing, and PVC monitor well casing were each surveyed by a registered land survey contractor. All measurements for horizontal and vertical control were made on the north side of each monitor well. All surveying was performed with a global positioning system Geoid 96 surveying system. An existing "X" that had been etched into the previously surveyed concrete pad of monitor well MW-14 was used as a local datum. Arizona Coordinate System northing and easting values were determined to at least the nearest foot, and elevation values were determined to at least the nearest ±0.01-foot.

3.3 Quarterly Monitoring

Quarterly water level and water quality monitoring of the shallow aquifer, perched zone, and San Pedro River was performed in May 2000 in accordance with the CGMP (H+A, 1995a). New monitor wells MW-25 through MW-32 were sampled in July 2000, after they had been developed and after dedicated electrical submersible pumps had been installed in shallow aquifer monitor wells MW-25, -26 and -27. Thus, water quality monitoring results of the new monitor wells could not be included within the May 2000 quarterly report (H+A, 2000f). The quarterly monitoring event included several shallow aquifer monitor wells and private domestic wells located outside of the Southern Area limits. The data will be used to identify areal hydrochemical trends.

The scope of the groundwater and surface water monitoring program includes collection, analysis, and assessment of field data for characterizing:

- Water levels in the perched zone and shallow aquifer groundwater.

- The distribution of constituents of concern (COCs), including nitrate-N, fluoride, arsenic and perchlorate in perched zone groundwater and nitrate-N and perchlorate in shallow aquifer groundwater.
- Surface water quality including the concentration of nitrate-N and perchlorate and discharge of the San Pedro River within the study area.

As a one-time characterization event, split samples were collected from all three San Pedro River surface water sampling locations. Split groundwater samples were collected from selected shallow aquifer monitor wells, shallow aquifer extraction well SEW-1, one private shallow aquifer well, one perched zone piezometer, and one perched zone monitor well. All samples were analyzed for major ion concentrations, including sodium plus potassium (Na^+ + K^+), calcium (Ca^{2+}), magnesium (Mg^+), ammonium (NH_4^+), chloride (Cl^-), bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), sulfate (SO_4^{2-}), and nitrate (NO_3^-). The analytical results were used to create hydrochemical Stiff diagrams and to estimate the ionic strength of the samples according to methods modified from Hem (1992).

4.0 SOUTHERN AREA HYDROGEOLOGY

This section describes the hydrogeology the perched zone and shallow aquifer in the Southern Area of the Site. This section is based on lithologic logs recorded during drilling of monitor wells, exploratory borings, soil borings, and piezometers; driller's logs of local private wells; review of water elevation data of monitor wells, piezometers, local private wells and surface water monitoring points on the San Pedro River; review of quarterly groundwater and surface water quality monitoring data; recently acquired major ion analytical data from selected water quality sampling locations; and recently acquired geophysical survey data.

4.1 St. David Clay

As discussed earlier, the St. David clay represents an important unit in controlling the downward and lateral migration of waters historically recharged as a result of ANP's industrial operations. It also forms the base of the shallow aquifer and the confining unit for the deep aquifer. The St. David clay is believed to have been subjected to post-depositional subaerial erosion. As such, the surface of the St. David clay is not a structural surface, but rather an erosional surface, upon which a paleo-topography was developed as a result of geomorphic processes. Topographic interpretation of the buried St. David clay surface, therefore, can provide a basis for conceptualization of the evolution of the buried landscape. This is achieved on the basis of contemporary topographic and geomorphic analogs. Such conceptualizations are important in assessing water quality dynamics and in forming decisions regarding possible remedial alternatives.

A topographic map of the buried St. David clay surface underneath the perched zone and shallow aquifer in the Southern Area was interpreted on the basis of all available data (Plate 2). The data included aerial photographs; field observations; and lithologic logs of Southern Area monitor wells, exploratory borings, soil borings, piezometers, and shallow and deep aquifer private wells. The main features interpreted on the buried St. David clay surface include three paleochannels that were formed prior to deposition of the overlying late Quaternary sediments. This includes a broad, relatively shallow trough underlying the perched zone. This paleochannel opens eastward to a deeper, relatively narrow trough along the western shallow aquifer boundary. A relatively large trough was also located east of the San Pedro River. Respectively, these paleo-features have been termed "Apache Wash", "Molinos Creek", and the Ancestral San Pedro River. The distinction between a wash and a creek is intended to imply that Molinos Creek was probably a perennial stream, whereas Apache Wash was most likely ephemeral. Subsurface exploratory data appear to indicate a confluence of Molinos Creek and the Ancestral San Pedro River paleochannels to the north of the monitor well MW-14, -22 and -24 transect (Plate 2).

The Apache Wash paleochannel was bounded on the north and west by the nearby bluffs of St. David clay that presently overlook the ANP's Operations Area and the formerly active ponds. The south side of Apache Wash is formed by a partially buried ridge of St. David clay. This feature has been named "Powder Ridge". Powder Ridge extends from its outcrop, a low hill located south of perched zone monitor well MW-02, to a point east of perched zone monitor well MW-07 (Plate 2). The wide bottom surface of Apache Wash beneath the formerly active ponds narrows to an incised paleochannel south of perched zone piezometer P-10. Beyond this point, in the vicinity of perched zone monitor well MW-29, it again widens. The Apache Wash axis appears to trend southeast beneath the formerly active ponds and is then structurally controlled by Powder Ridge to trend east, toward shallow aquifer monitor well MW-21. Apache Wash decreases in elevation from 3,700 feet msl near boring APPB-4 to 3,610 feet msl where it debouches into Molinos Creek. At that location, Apache Wash is approximately 40 feet higher in elevation than the adjoining Molinos Creek.

Molinos Creek passes along the south side of Powder Ridge and then northeast along the western boundary of the shallow aquifer. The southern extent of Molinos Creek appears to be located between deep aquifer private wells D(18-21)18bbb and D(18-21)18bca. It then passes by the locations of exploratory boring APPB-8 and shallow aquifer monitor wells MW-21 and MW-24. Molinos Creek ultimately veers east of shallow aquifer monitor well MW-25. In the vicinity of shallow aquifer monitor well MW-24, Molinos Creek appears to be bordered on the east by a relatively horizontal surface that slopes slightly down toward the Ancestral San Pedro River paleochannel to the east.

Molinos Creek decreases in elevation from 3,660 feet msl in the vicinity of deep aquifer private wells D(18-21)18bbb and D(18-21)18bca to 3,480 feet msl east of shallow aquifer monitor well MW-25 (Plate 2).

In the Southern Area, the Ancestral San Pedro River paleochannel appears to trend northwest across the center of Section 18 of T18S/R21E, generally paralleling the east side of the contemporary San Pedro River. The paleochannel appears to extend through shallow aquifer private wells D(18-21)17dbd, D(18-21)08cda and east of shallow aquifer private well D(18-21)08bab. The paleochannel axis appears to be located between shallow aquifer monitor well MW-01 and private wells D(18-21)08aaa, D(18-21)08aa, and D(18-21)08aad. Because of the paucity and inconsistency of well logs in this area, a reasonable accurate topographic surface of the paleochannel could not be developed. Instead, an area representing the general location of the paleochannel, is indicated (Plate 2).

4.2 Perched Zone and Shallow Aquifer Hydrostratigraphy

Eight cross-sections illustrating perched zone and shallow aquifer hydrostratigraphy and groundwater elevations through strategic locations within the Southern Area have been prepared (Figure 10). The cross-sections depict the buried St. David clay surface and the overlying late Quaternary alluvial stratigraphic units. For the purposes of this report, the late Quaternary sediments are represented as hydrostratigraphic units instead of formational units. A hydrostratigraphic unit is defined as an areally extensive geologic unit, which possesses relatively homogeneous hydraulic characteristics (H+A, 1991). The cross-sections are based on both geophysical data and the lithologic logs of Southern Area monitor wells, exploratory borings, soil borings, piezometers, and private wells.

Cross-section A-A'-A" trends east along the axis of Apache Wash, across the axis of Molinos Creek to shallow aquifer monitor well MW-01. Cross-sections B-B', C-C', D-D' and E-E' are generally oriented perpendicular to cross-section A-A'-A", across the axes Apache Wash and Molinos Creek.

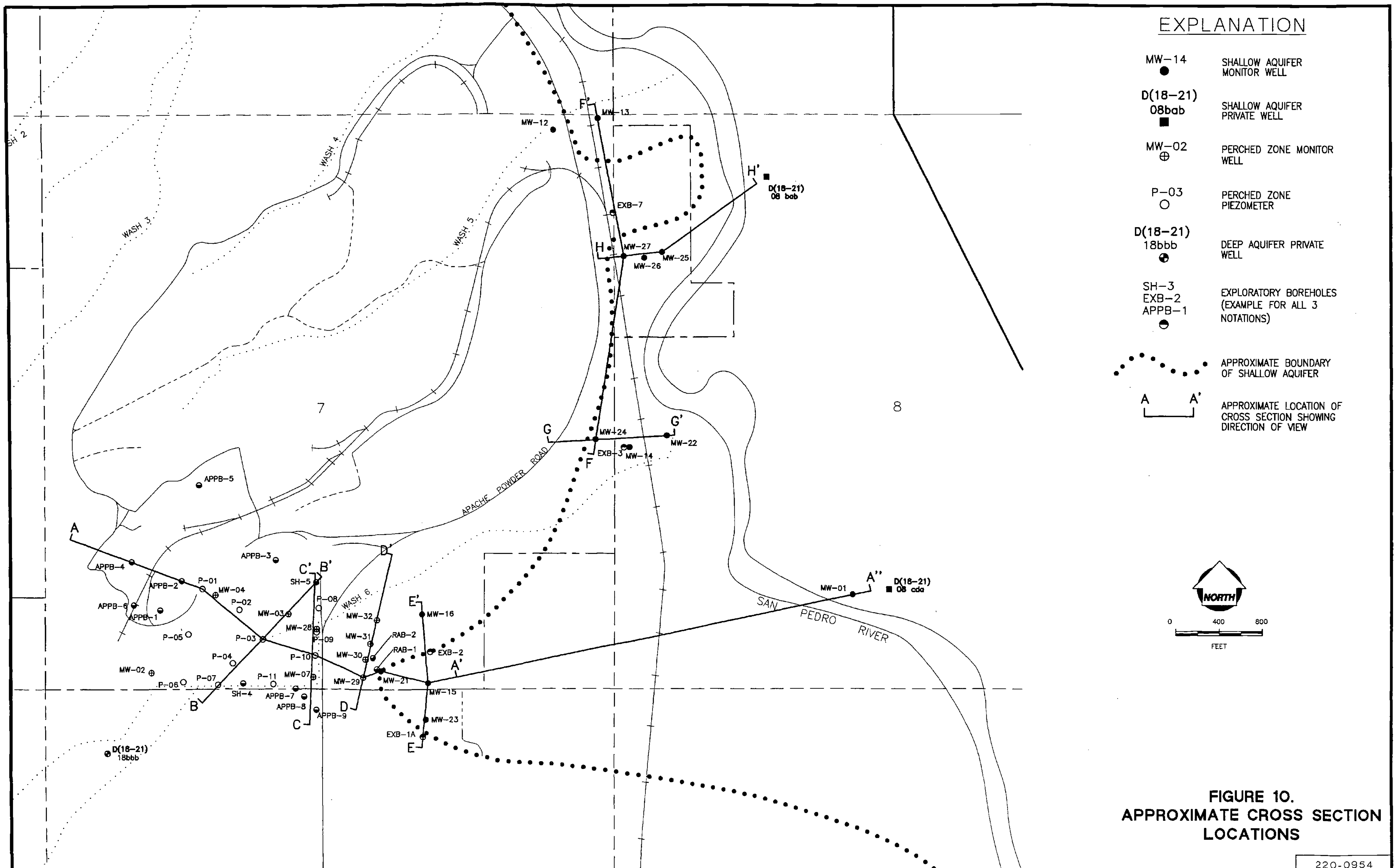

FIGURE 10.
APPROXIMATE CROSS SECTION LOCATIONS

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Cross-section F-F' extends north through shallow aquifer monitor wells MW-24, MW-27 and MW-13 and exploratory boring EXB-7. Cross-sections G-G' and H-H' are generally oriented perpendicular to cross-section F-F', across the axis of Molinos Creek. Cross-sections C-C', D-D', G-G' and H-H' were produced along Geophysical Survey Lines 1, 2, 3 and 4, respectively, and incorporate limited interpretation from the seismic data (Figure 10).

4.2.1 Perched Zone Hydrostratigraphy

The surface topography overlying the perched zone slopes gently eastward toward the San Pedro River. This area is incised by Wash 6 and other smaller eastward-draining ephemeral washes. The perched zone is underlain by the eastward-draining Apache Wash paleochannel that was incised into the buried St. David clay surface. Apache Wash is overlain by late Quaternary alluvial sediments. These sediments increase in thickness eastward from a thin veneer near boring APPB-4 to an approximate 50-foot thickness near perched zone monitor wells MW-29 through MW-32, adjacent to the shallow aquifer boundary. The late Quaternary alluvial sediments are divided into two hydrostratigraphic units comprising a "basal" sand and gravel unit and an overlying clay and silt unit. Along the Apache Wash axis, the thickness of the sand and gravel unit varies from a thin veneer west of boring APPB-4 to approximately 10 feet between boring APPB-2 and perched zone piezometer P-10 (Figure 11). This unit then thins to a veneer toward the shallow aquifer through perched zone monitor wells MW-29 through MW-32. The sand and gravel unit is generally thicker in the Apache Wash axis, but thins outward toward the "banks" of the former wash (Figures 12, 13 and 14).

The overlying perched zone clay and silt unit is relatively continuous, except where it is interrupted by a localized vertical sand unit beneath Wash 6 at perched zone monitor well MW-28 and by a surface sand and silt unit along perched zone monitor wells MW-29 through MW-32 (Figure 14). The topographic low in the buried St. David clay surface beneath Wash 6 on cross-section D-D', interpreted as a paleochannel, and the location of the Apache Wash axis (south of piezometer P-10) were indicated by seismic geophysical survey methods. Split-barrel samples collected during borehole drilling for perched zone monitor wells MW-29 and -31 contained gypsum crystals, which indicates that

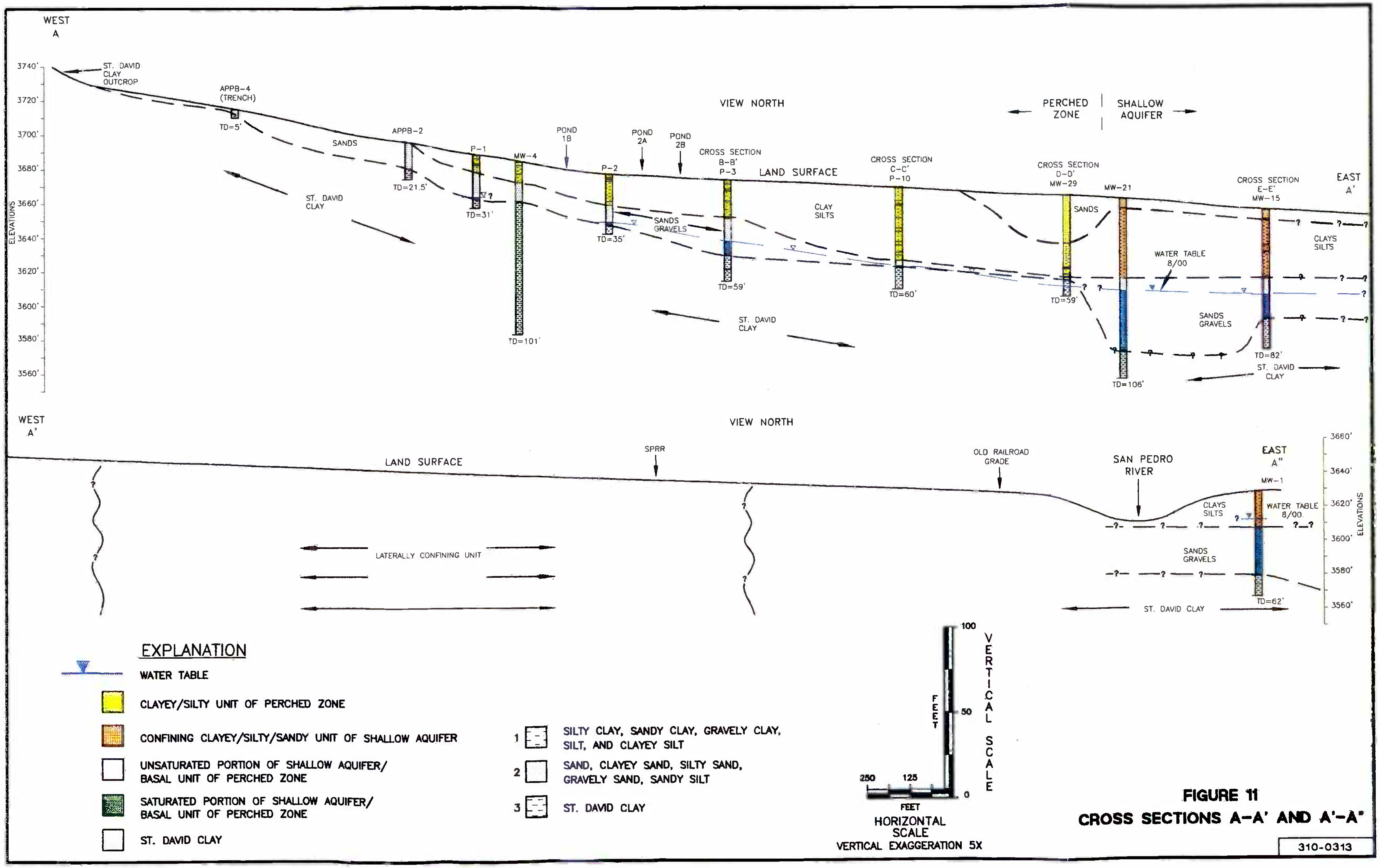

FIGURE 11
CROSS SECTIONS A-A' AND A'-A"

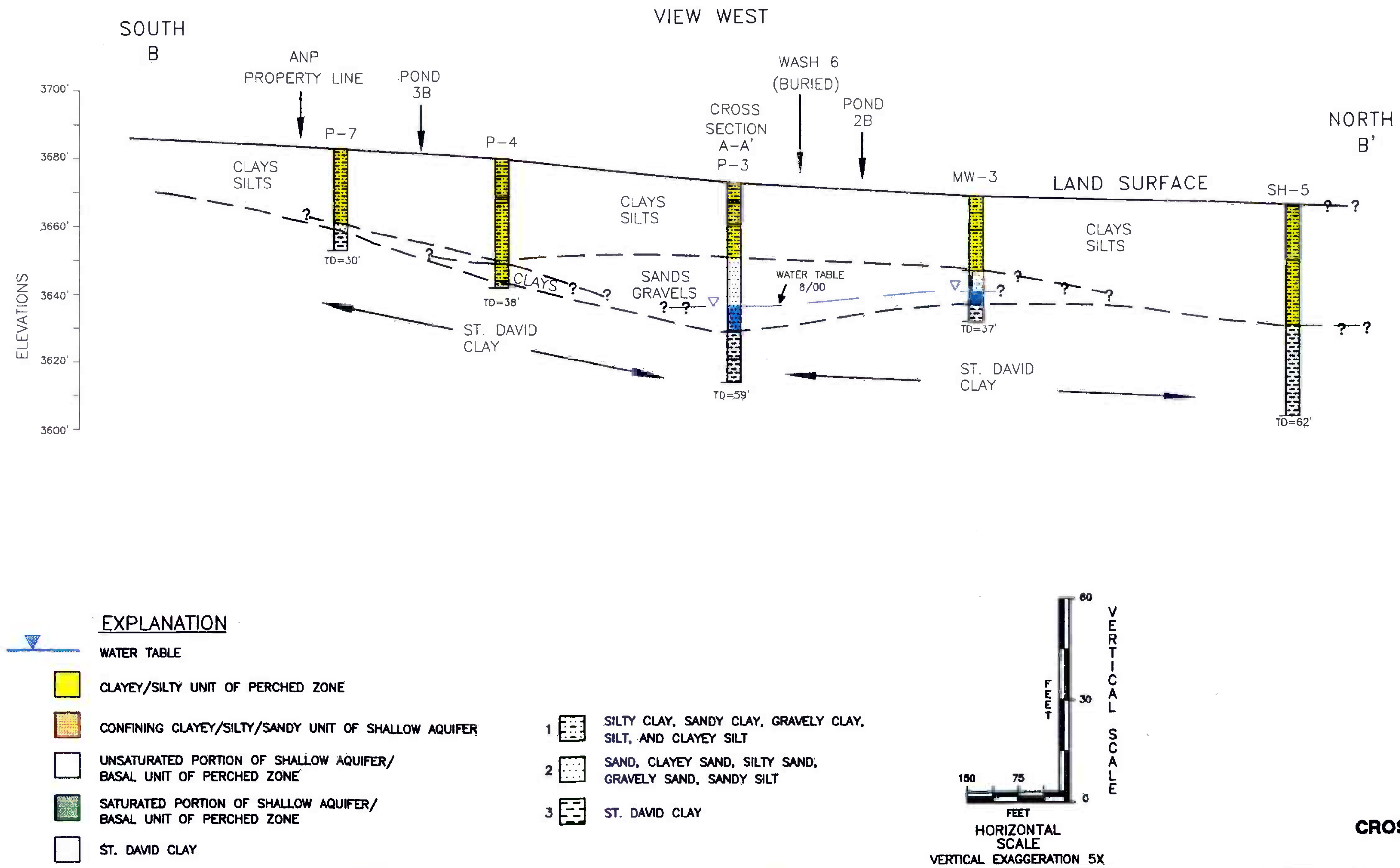

FIGURE 12
CROSS SECTION B-B'

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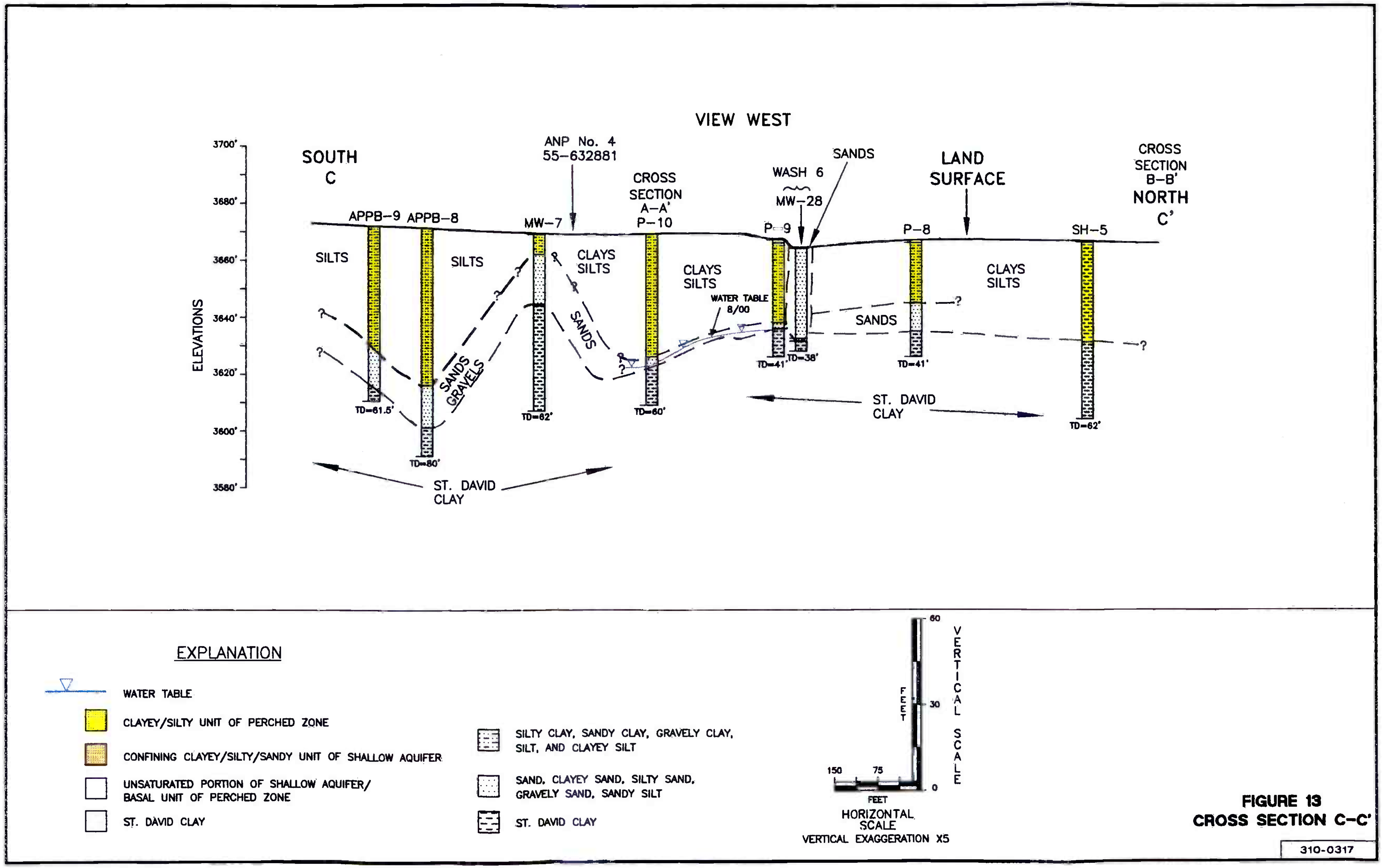
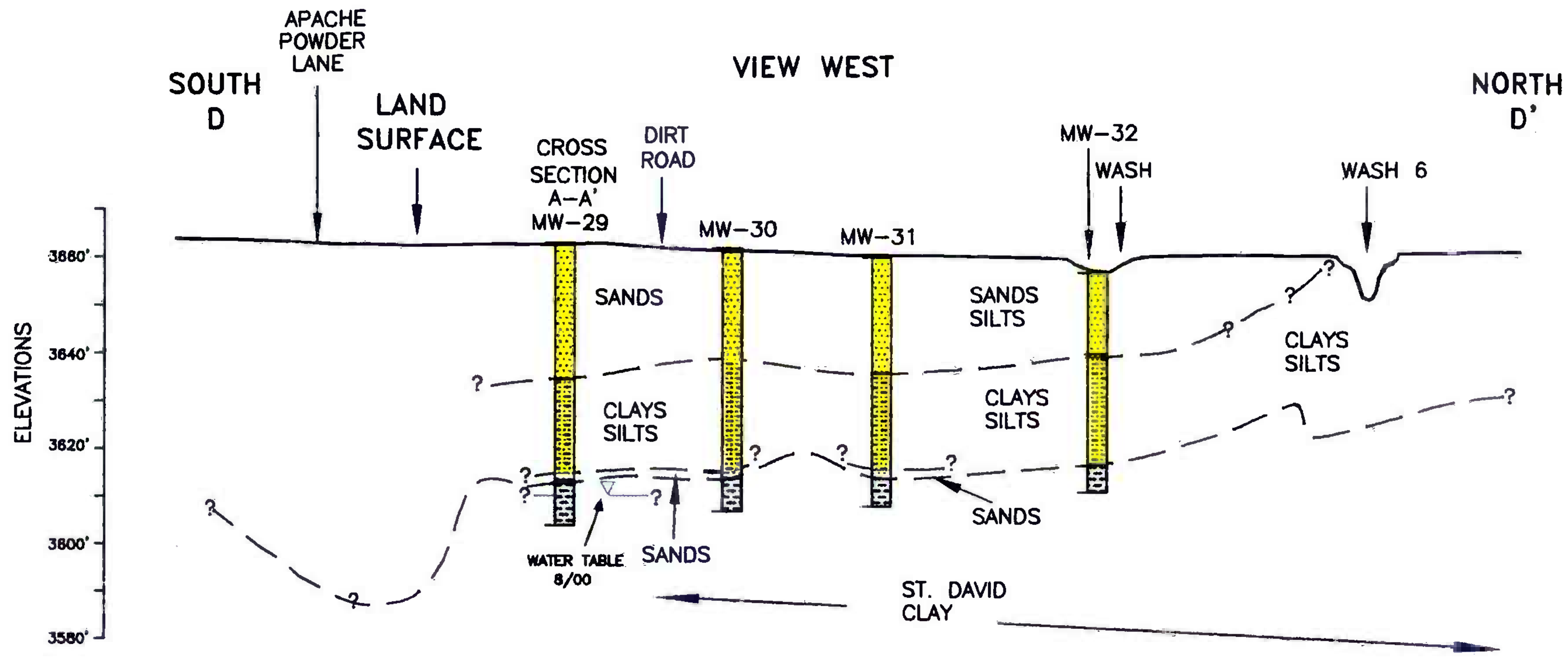
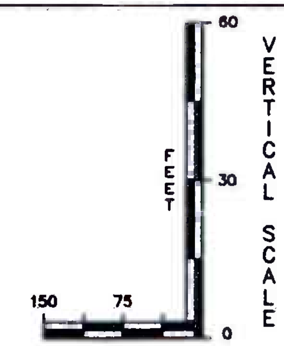


FIGURE 13
CROSS SECTION C-C'



EXPLANATION

- WATER TABLE
- CLAYEY/SILTY UNIT OF PERCHED ZONE
- CONFINING CLAYEY/SILTY/SANDY UNIT OF SHALLOW AQUIFER
- UNSATURATED PORTION OF SHALLOW AQUIFER/ BASAL UNIT OF PERCHED ZONE
- ST. DAVID CLAY
- SILTY CLAY, SANDY CLAY, GRAVELY CLAY, SILT, AND CLAYEY SILT
- SAND, CLAYEY SAND, SILTY SAND, GRAVELY SAND, SANDY SILT
- ST. DAVID CLAY



HORIZONTAL SCALE
VERTICAL EXAGGERATION X5

FIGURE 14
CROSS SECTION D-D'

310-0318

the buried St. David clay surface represents an erosional surface in the lower division of the St. David Formation as defined by Gray (1965).

Groundwater occurs under water table conditions above the St. David clay in the basal sand and gravel unit and generally flows east under gravitational and hydraulic forces. Modern alluvial sediments comprising sand and gravel are limited to the beds of the washes.

4.2.2 Shallow Aquifer Hydrostratigraphy

The land surface of the area east of the perched zone gently slopes northeastward to the San Pedro River and is incised by Wash 6 and other smaller eastward-draining ephemeral washes. The area east of the perched zone overlies the shallow aquifer and comprises a thicker stratigraphic sequence similar to the perched zone. The erosional unconformity known as the Aravaipa Surface forms the current San Pedro Valley floor between the bluffs of St. David formation on both sides of the San Pedro River.

The late Quaternary alluvial sediments are divided into a two hydrostratigraphic units comprising a basal sand and gravel aquifer unit (shallow aquifer), overlain by a semi-confining clay and silt unit (Figures 11, 15 through 18). The clay and silt unit appears to be cienega deposits identified by Melton (1965). The combined thickness of both units range from 50 feet at shallow aquifer monitor well MW-01 to more than 140 feet east of shallow aquifer monitor well MW-25. These sediments appear to be thinner on the buried St. David clay surface that separates Molinos Creek from the deeper Ancestral San Pedro River paleochannel. The shallow aquifer sediments increase in thickness northward along Molinos Creek from approximately 45 to at least 70 feet between shallow aquifer monitor wells MW-21 and MW-25. The shallow aquifer sediments in the Ancestral San Pedro River paleochannel appear to have a similar range in thickness from approximately 45 feet at shallow aquifer monitor well MW-06 to at least 68 feet at shallow aquifer private well D(18-21)08cda. Shallow aquifer monitor well MW-01 appears to be on the west bank of the Ancestral San Pedro River paleochannel where the shallow aquifer sediments thin to approximately to 25 feet in thickness over a relatively short lateral distance.

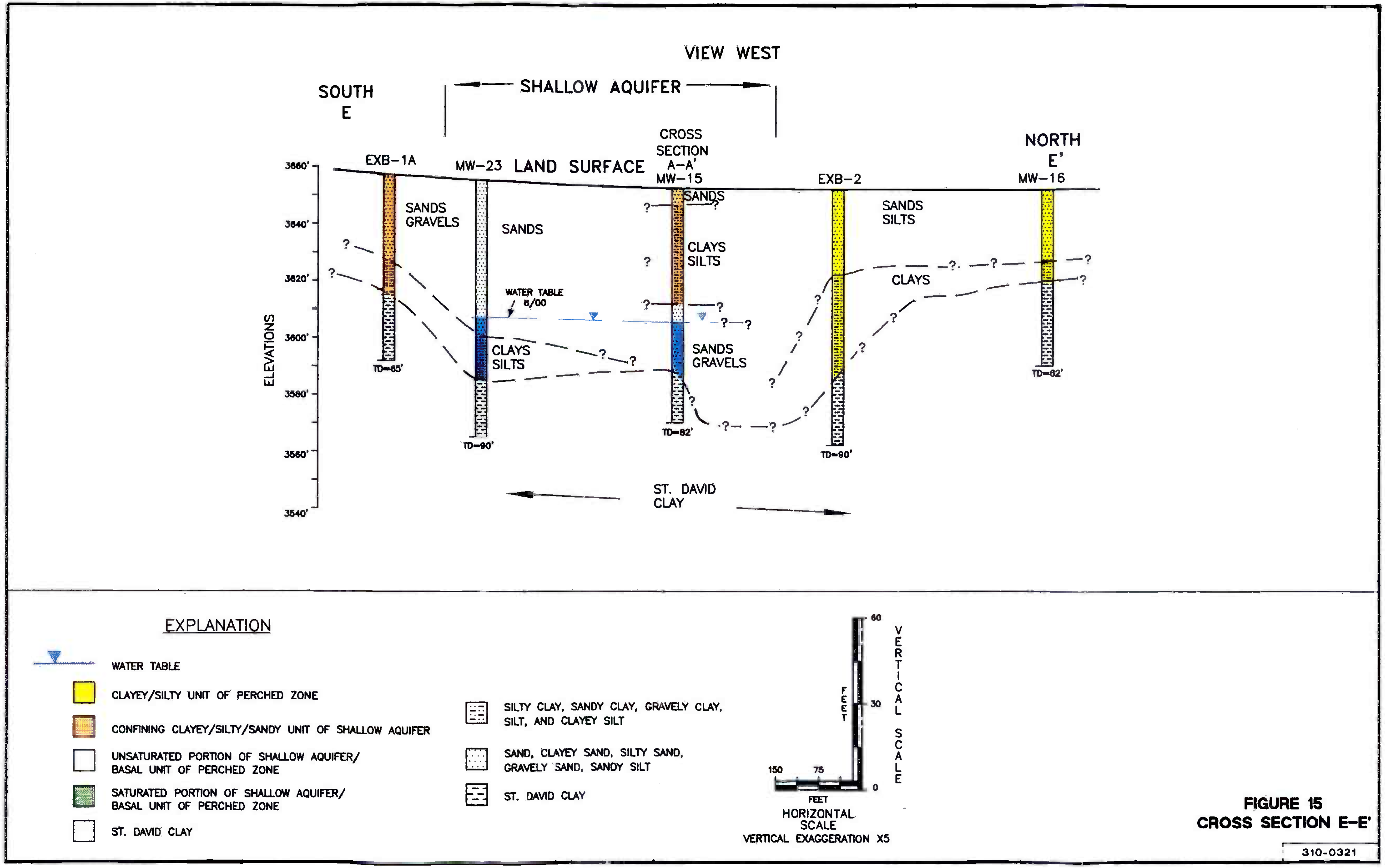


FIGURE 15
CROSS SECTION E-E'

310-0321

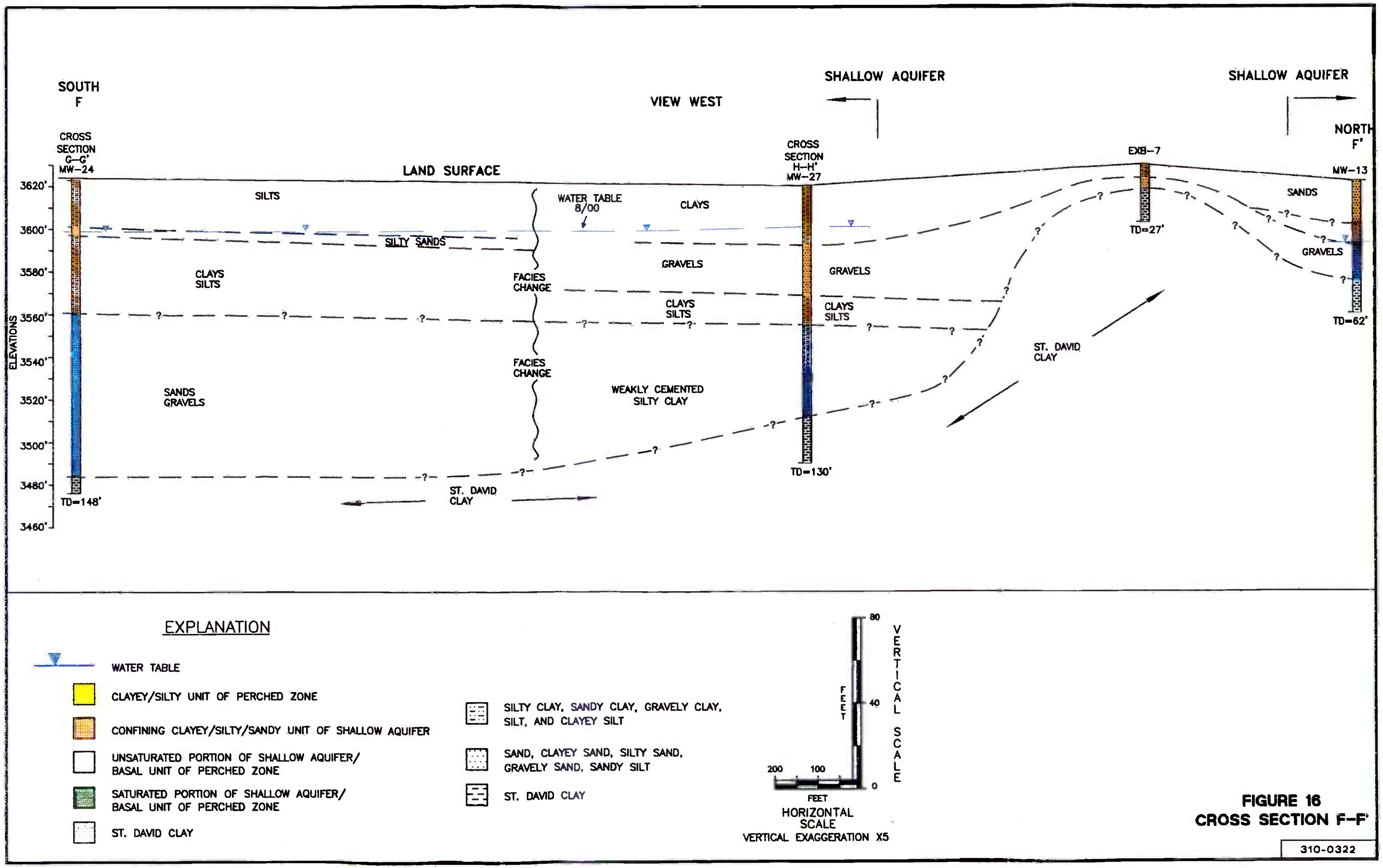


FIGURE 16
CROSS SECTION F-F'

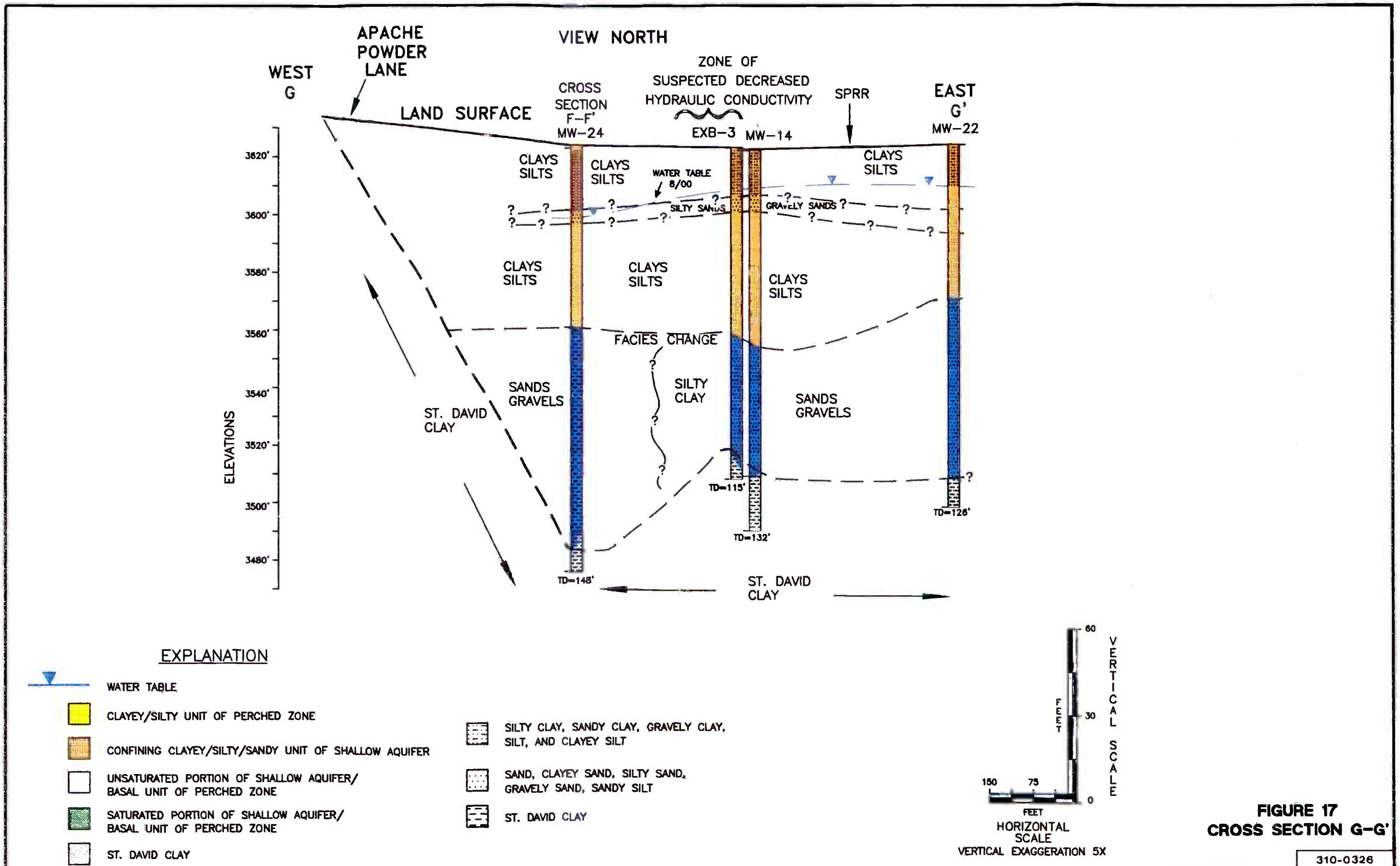


FIGURE 17
CROSS SECTION G-G'

310-0326

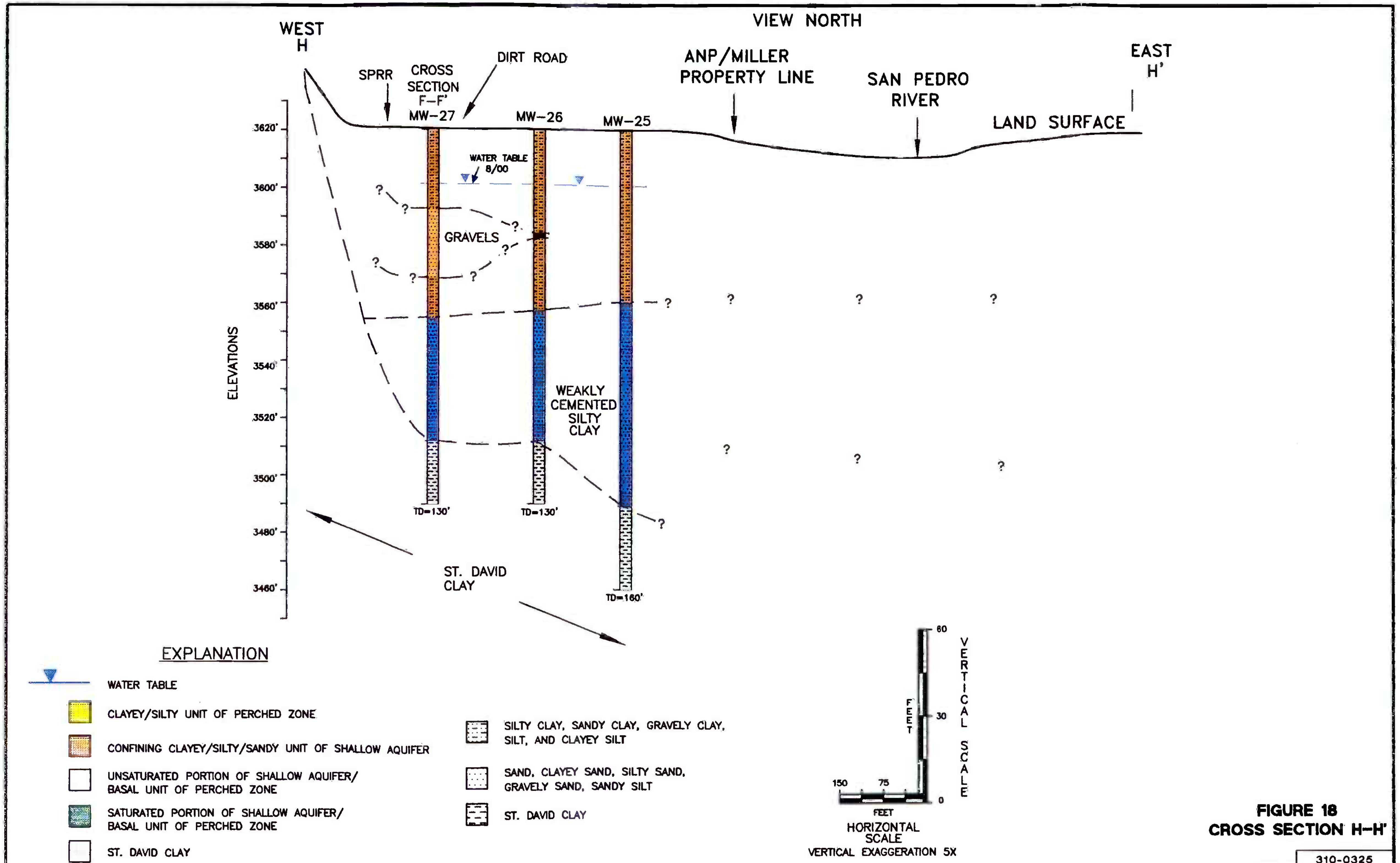


FIGURE 18
CROSS SECTION H–H'

Two lithofacies changes from the typical shallow aquifer sands and gravels to fine grained sediments have been indicated through drilling logs. Shallow aquifer monitor wells MW-25, -26 and -27 were constructed in a weakly-cemented silty clay that stratigraphically correlates with the sands and gravels in the area around shallow aquifer monitor wells MW-14, -22 and -24. This indicates that the first lithofacies change is located between these two areas (Figure 16). The silty clay appears to be similar to the underlying St. David clay in that it may be re-worked St. David formation sediments. Approximately 20 feet west of shallow aquifer monitor well MW-14, exploratory boring EXB-3 was drilled into uncemented silty clay instead of the shallow aquifer sands/gravels encountered during the drilling of shallow aquifer monitor wells MW-14, -22 and -24. This implies a second stratigraphically correlative lithofacies change between shallow aquifer wells MW-14 and MW-24 (Figure 17).

The silty clay unit that overlies the shallow aquifer has a relatively consistent thickness throughout the Southern Area. It generally ranges in thickness from approximately 40 to 65 feet between shallow aquifer monitor wells MW-15 and MW-25 along Molinos Creek and is approximately 20 feet thinner at shallow aquifer monitor well MW-01, located along the Ancestral San Pedro River paleochannel. Its lower surface drops in elevation along Molinos Creek from approximately 3,610 feet msl near MW-15 to about 3,560 feet msl northward from shallow aquifer monitor well MW-24. The decrease in elevation of the lower silty clay unit surface is steeper than the groundwater surface in the shallow aquifer along Molinos Creek. This results in a change from unconfined conditions near shallow aquifer monitor wells MW-15, -21 and -23 to confined conditions northward from shallow aquifer monitor wells MW-14, -22 and -24 (Figures 11, 15 through 18). Thus, the silty clay unit overlying the shallow aquifer is considered to be confined in this portion of the shallow aquifer.

The lower surface of the silty clay unit drops more gradually along the Ancestral San Pedro River paleochannel. It drops in elevation from approximately 3,607 feet msl at shallow aquifer monitor well MW-06 to about 3,606 feet msl at shallow aquifer monitor well MW-01. Groundwater elevations are consistently higher than this surface in the area between these two wells, resulting in confining conditions in this portion of the shallow aquifer.

4.3 Groundwater Occurrence

The shallow aquifer within the Southern Area groundwater can be divided into two areas, the western portion within the Molinos Creek and the main part of the shallow aquifer within the Ancestral San Pedro River paleochannel to the east. This interpretation is based on a review of water elevation data of monitor wells, piezometers, local private wells, and the results of recent major ion analyses performed on selected groundwater and surface water samples. Groundwater elevation data were periodically measured within Southern Area wells and piezometers from 1990 through 1994, and on a quarterly basis since February 1995. Major ion analyses were performed on groundwater samples collected during the May 2000 CGMP quarterly rounds.

Groundwater elevation changes, as indicated by the interpretation of monitor well hydrographs and successive groundwater elevation maps, provide an indication of the dynamics of groundwater flow, recharge, and discharge relationships (Appendix C). The following paragraphs present such an analysis of Southern Area groundwater dynamics based on hydrographic and selected groundwater elevation maps from early 1995 through mid-2000. This period represents the time during which the perched zone and western portion of the shallow aquifer were adjusting to the effects of ANP's cessation of its wastewater discharges to the formerly active ponds.

4.3.1 Perched Zone

Current groundwater elevations in the perched zone as measured in conjunction with the CGMP indicate groundwater flow eastward toward the shallow aquifer (Figure 19). Perched zone groundwater elevation hydrographs indicate declining trends since monitoring began in February 1991 (see Appendix C). The decline in perched zone groundwater elevations is in direct response to the re-routing of discharged wastewater from the formerly active ponds to the Brine Concentrator in February 1995. As a result, artificial recharge via ponded wastewater ceased and the saturated sediments beneath the perched zone dewatered

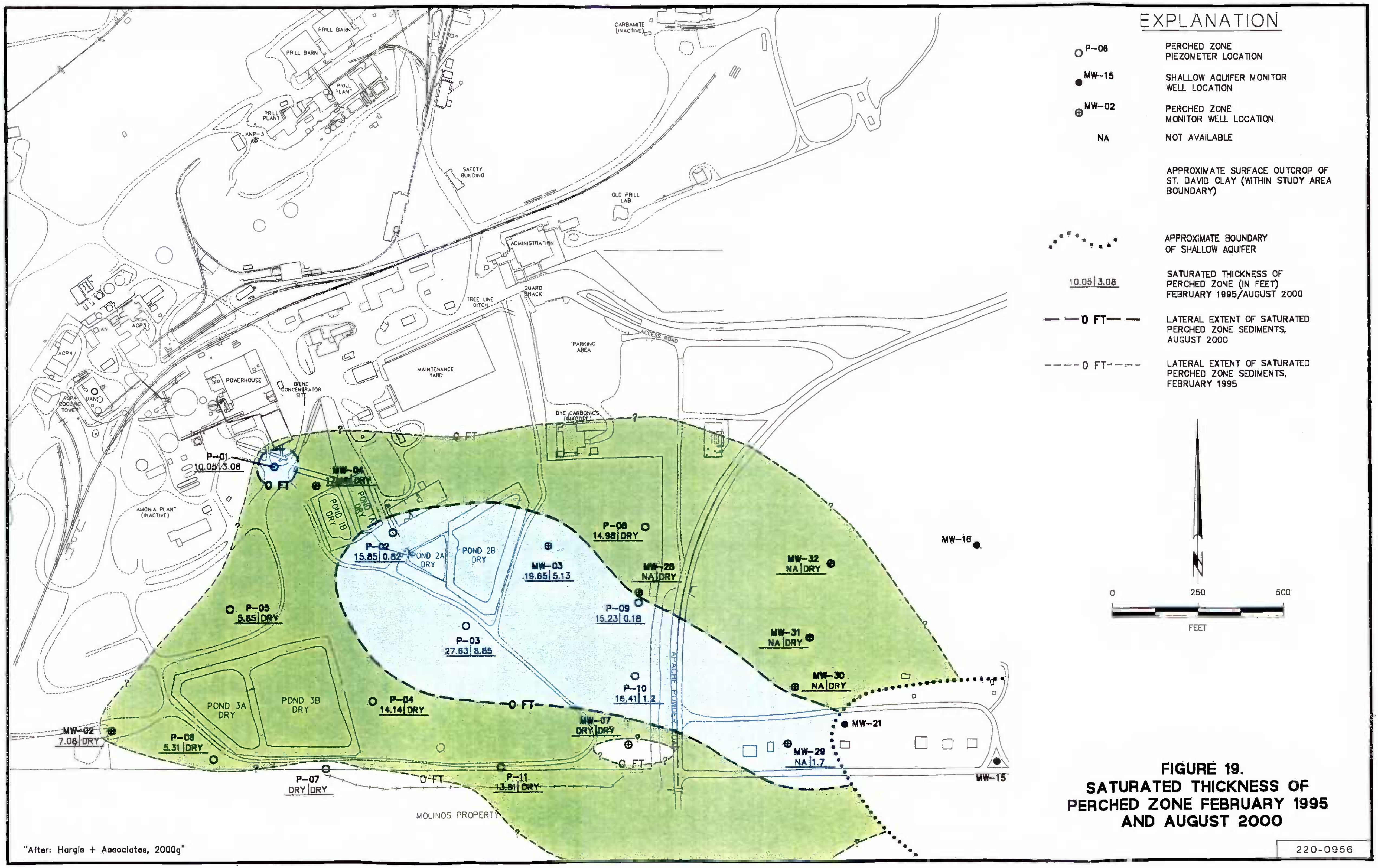


FIGURE 19. SATURATED THICKNESS OF PERCHED ZONE FEBRUARY 1995 AND AUGUST 2000

eastward to the nearby shallow aquifer along the axis of the buried Apache Wash. The saturated thickness of the perched zone sediments has decreased significantly (approximately 17 feet) in the vicinity of piezometer P-03 since 1991. Several other perched zone monitor wells and piezometers have also gone dry and the overall footprint of the perched zone has decreased by approximately 75% (Figure 19).

4.3.2 Shallow Aquifer

The western portion of the shallow aquifer exhibits markedly different trends in groundwater elevations (Figures 20 through 23). As compared with the main part of the shallow aquifer to the east, the groundwater elevations in the western portion of the shallow aquifer overlying Molinos Creek (monitor wells MW-15, -21, -23 and -24) have generally followed a trend similar to the perched zone. This trend is also attributed to the cessation of wastewater discharges to the formerly active ponds. In contrast, the groundwater elevations in the main part of the shallow aquifer overlying the Ancestral San Pedro River

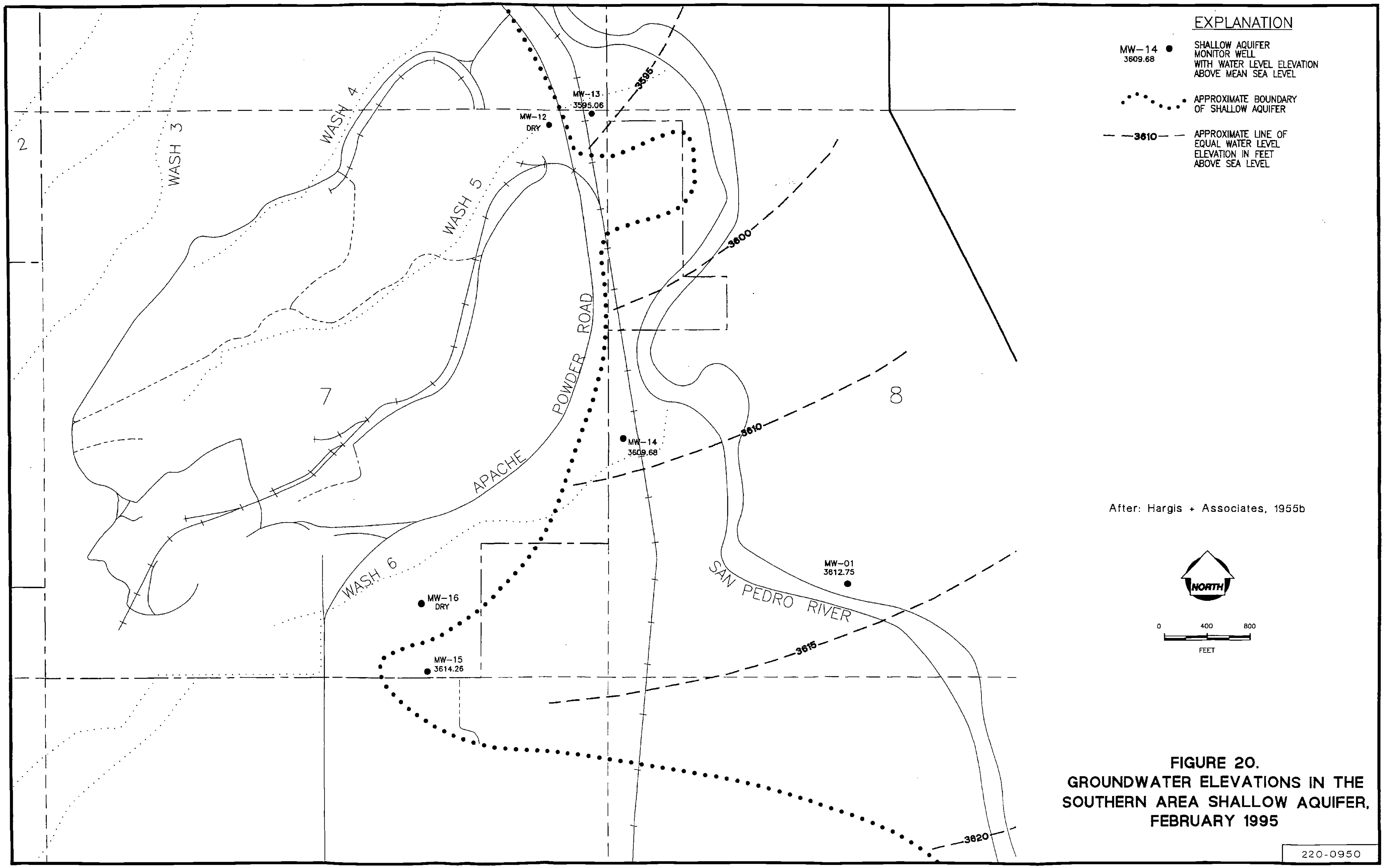


FIGURE 20.
GROUNDWATER ELEVATIONS IN THE SOUTHERN AREA SHALLOW AQUIFER, FEBRUARY 1995

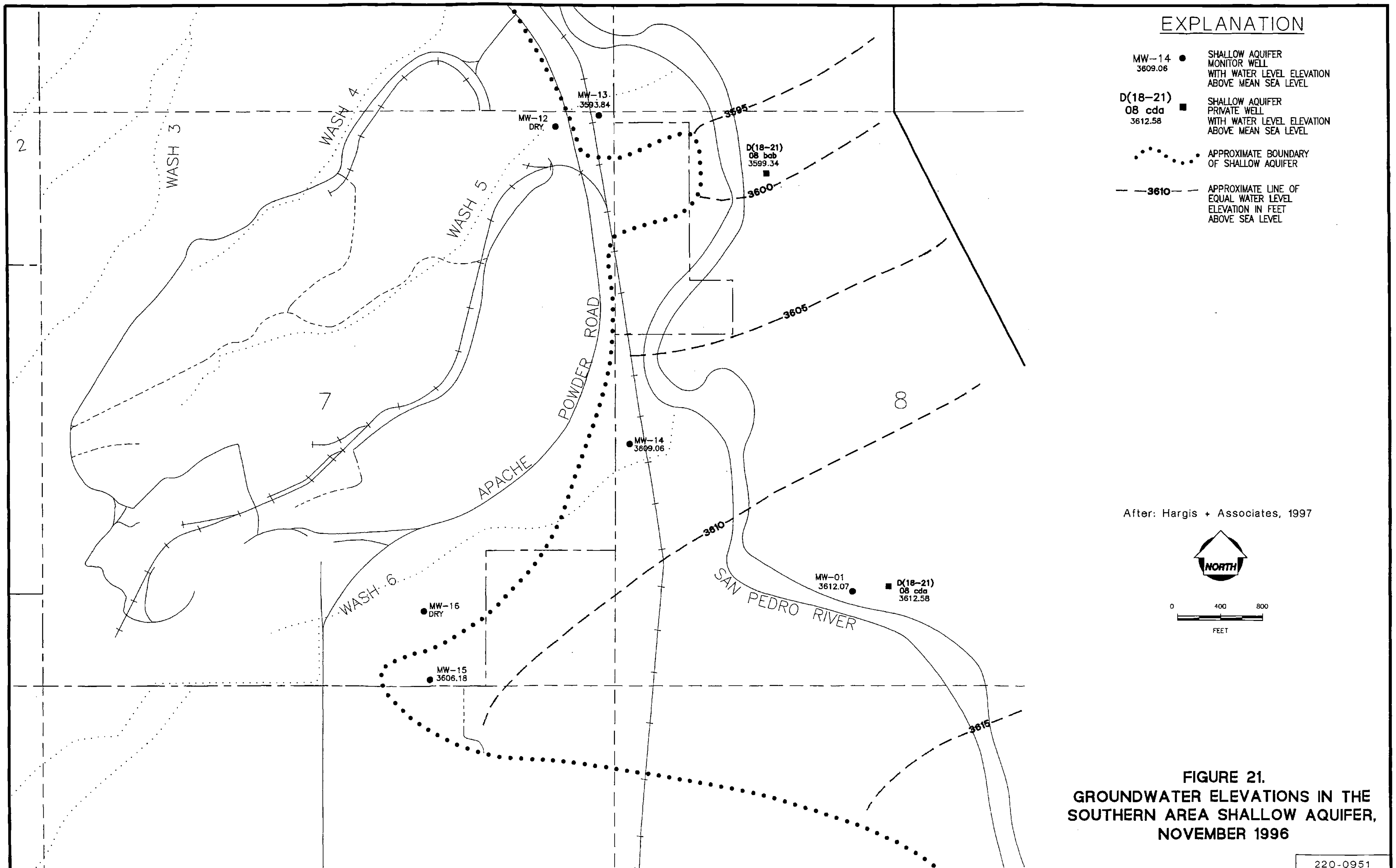


FIGURE 21.
GROUNDWATER ELEVATIONS IN THE SOUTHERN AREA SHALLOW AQUIFER, NOVEMBER 1996

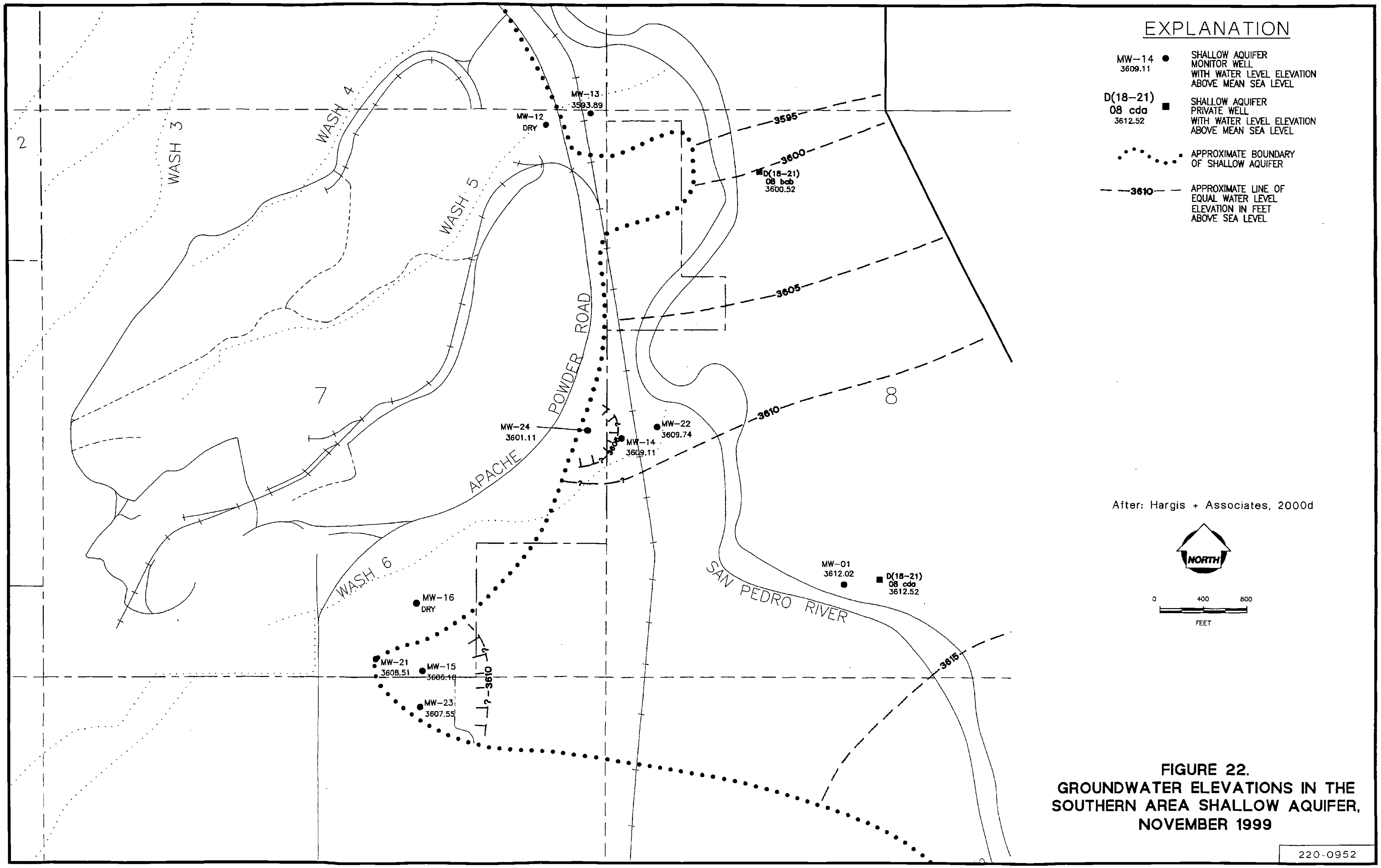


FIGURE 22.
GROUNDWATER ELEVATIONS IN THE SOUTHERN AREA SHALLOW AQUIFER, NOVEMBER 1999

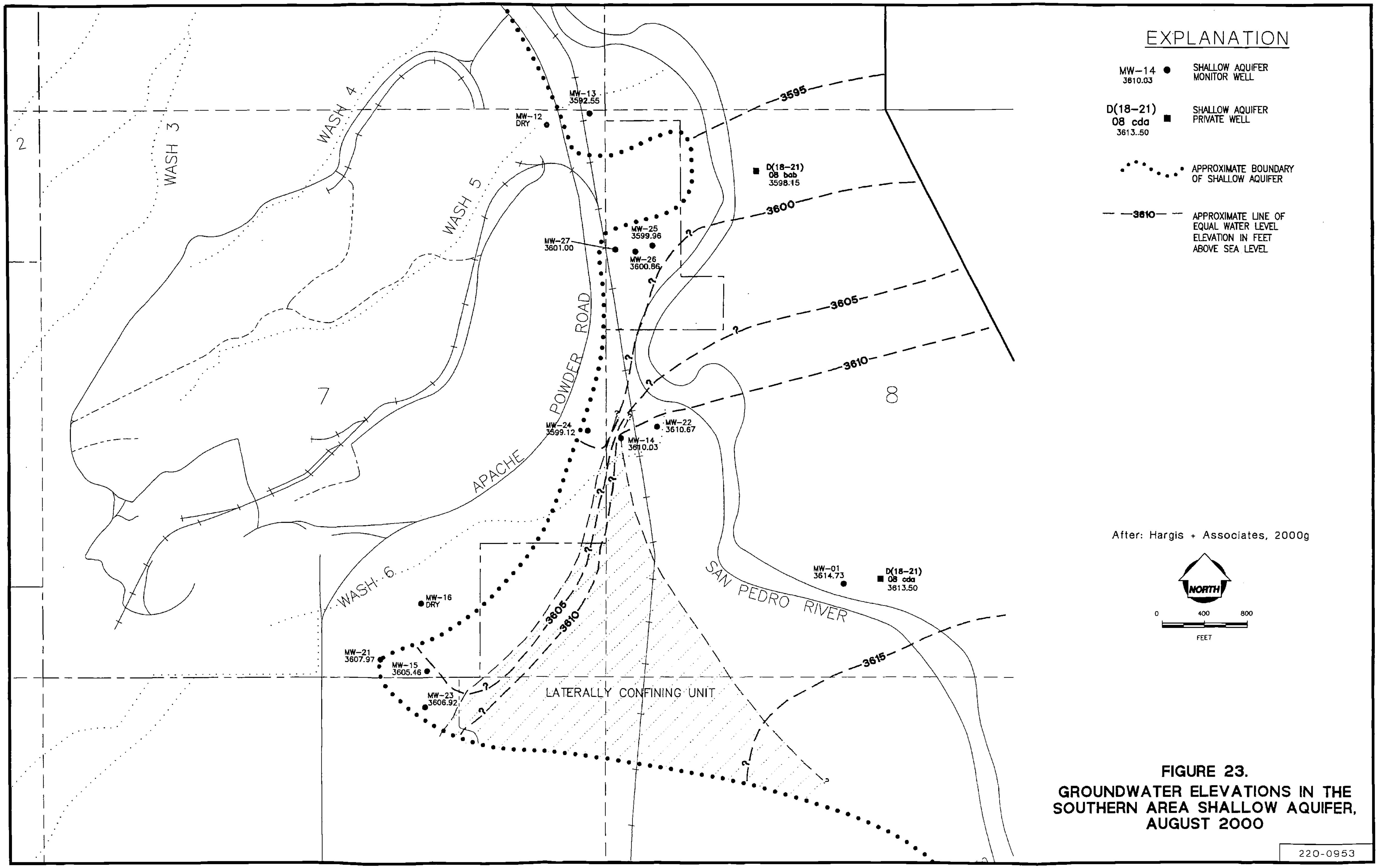


FIGURE 23.
GROUNDWATER ELEVATIONS IN THE SOUTHERN AREA SHALLOW AQUIFER, AUGUST 2000

220-0953

paleochannel indicate relatively stable groundwater elevations.

In February 1995, groundwater elevations in the shallow aquifer represent conditions just after the cessation of discharges to the formerly active ponds (H+A, 1995b) (Figure 20). At this time, the western portion of the shallow aquifer had not yet responded to the decline of artificial recharge from the perched zone. The groundwater elevation in shallow aquifer monitor well MW-15 was approximately 3,614.26 feet msl. The 3,615-foot msl groundwater elevation contour was drawn across the shallow aquifer to indicate a generally northward groundwater gradient.

In November 1996, groundwater elevations in the shallow aquifer after existing shallow aquifer private wells D(18-21)08bab and D(18-21)08cda were added as measuring points to the first round of shallow aquifer monitor wells (H+A, 1997) (Figure 21). The measurements were collected nearly 2 years after cessation of wastewater discharge to the formerly active ponds. The groundwater elevations at shallow aquifer monitor wells MW-01 and MW-14 had declined slightly, 0.68 and 0.62 feet, respectively, since the February 1995 elevations. The hydrograph for shallow aquifer monitor well MW-15 indicated a much larger groundwater elevation drop, approximately 8.08 feet, during the same period. This decline resulted in the positioning of the 3,610- and 3,615-foot msl groundwater elevation contours further upgradient (south) in the shallow aquifer and deflection of the 3,610-foot msl contour southward, across the western portion of the shallow aquifer. This interpretation, in light of current data erroneously suggested a major shift of groundwater flow in western portion of the shallow aquifer from a north to a northwest direction.

In November 1999, shallow aquifer monitor wells MW-21, -22, -23 and -24 were added to the CGMP network (H+A, 2000d) (Figure 22). This timeframe represents approximately 5 years after cessation of wastewater discharges to the formerly active ponds. The groundwater elevations for shallow aquifer monitor wells MW-01 and MW-14 and private wells D(18-21)08bab and D(18-21)08cda indicated minor groundwater elevation changes of -0.05, +0.05, -0.06 and +1.18 feet, respectively, from November 1996. Shallow aquifer monitor well MW-15 indicated no significant groundwater elevation change during the same period (Appendix C). New shallow aquifer monitor wells MW-21 and MW-23 constructed near MW-15, indicated a groundwater movement eastward from the perched zone discharge. New shallow aquifer monitor wells MW-22 and MW-24 were constructed either side of monitor well MW-14 to complete another essentially transgradient monitor well transect further downgradient within the shallow aquifer. The measurements indicated an approximate 8-foot westward drop in groundwater elevation between shallow aquifer monitor wells MW-14 and MW-24. This change is believed to result from a lithofacies change between these wells as indicated by exploratory boring EXB-3 (Figure 17). The data indicated apparent groundwater "depressions" in the vicinities of shallow aquifer monitor wells MW-24, -15, -21 and -23 relative to shallow aquifer groundwater elevations to the east that could not be readily explained at the time. No shallow aquifer pumping wells that could explain these apparent depressions were located near either location.

In August 2000, groundwater elevations were reinterpreted in the shallow aquifer after shallow aquifer monitor wells MW-25, -26 and -27 were constructed (H+A, 2000g) (Figure 23). The measurements were collected approximately 5-1/2 years after wastewater was diverted from the formerly active ponds. New shallow aquifer monitor wells MW-25, -26 and MW-27 were constructed to complete an essentially transgradient monitor well transect downgradient of the MW-14, -22 and -24 well transect. The measurements indicate that a groundwater depression extends along Molinos Creek from where the perched zone discharges to the shallow aquifer to a point northeast of shallow aquifer monitor wells MW-14, -22 and -24. An inferred "Laterally Confining Unit" (LCU) is indicated on Figure 23 to explain the large divergence in groundwater elevation trends in the western portion of the shallow aquifer and the main part of the shallow aquifer to the east. This basis for this concept is discussed further in Section 5.0.

4.4 Groundwater Hydrochemical Results

Stiff diagrams have been prepared from the data generated from major ion analyses. The analyses were performed on San Pedro River surface water samples, and groundwater samples collected from selected piezometers, monitor wells, and private wells in the Southern Area. The diagrams indicate that two groundwater types are present in the Southern Area. The first type is dominated by sulfate anion and the second type by bicarbonate anion. The analysis further indicates that a mixing zone is located north of the monitor well MW-14, -22 and -24 transect (Plate 3).

5.0 CONCEPTUALIZATION OF SOUTHERN AREA HYDROGEOLOGY

This section describes a conceptualization of groundwater flow and transport for the Southern Area. The conceptualization is based on the interpretation of paleohydrology, groundwater elevation patterns and changes, and hydrochemical facies in the Southern Area.

In summary, the erosion of the St. David Formation and subsequent deposition of valley fill sediments by through-flowing paleo-alluvial systems resulted in the hydraulic isolation of the western portion of the shallow aquifer, termed herein as "the Molinos Creek Sub-Aquifer", from the main part of the shallow aquifer to the east. This is believed to have occurred as a result of a syn-deposition of finer-grained, lower hydraulic conductivity materials. The presence of the LCU not only may explain the independent hydraulic behavior between the Molinos Creek Sub-Aquifer and the main part of the shallow aquifer, but also the distribution and dynamics of groundwater contamination from historical ongoing discharges in the Southern Area via the perched zone.

5.1 Paleohydrology

Paleohydrology is the study of surface runoff under past climactic conditions (Graf, 1988). Paleohydrology involves first establishing a relationship between present surface water processes and their associated geomorphic features and then inferring an analogous relationship with paleogeomorphic features. Thus, evidence of past surface water flow, such as abandoned or buried channels that, at some point in time, conveyed surface water, may be used as reasonable geomorphologic analogs for past surface water flow conditions. With this concept in mind, the shallow aquifer within the Southern Area was examined to assess whether information and interpretations derived from the recent field investigations might assist in conceptualizing the groundwater flow regime.

The lithology and stratigraphy of a fluvial aquifer is the direct result of its depositional environment. For example, a braided stream typically results from "flashy" streamflow conditions. Such an alluvial environment is produced typically as a result of high velocity flow, with high sediment loading over a relatively short flow duration flood event (*i.e.*, flash-flooding). Such deposition would likely produce aquifer materials consisting of highly interbedded sand and gravel units, with minor silt and clay units. In contrast, a typical meandering stream system tends to produce a more structured sedimentary pattern, with sands and gravels deposited within the stream channel and silts and clays on the adjoining flood plain (Freeze and Cherry, 1979). This latter model is consistent with observations within the Southern Area and supports the inferred LCU.

5.1.1 Deposition of the St. David Formation (Stage 1)

The present day morphology of the St. David Formation and surface topography of the Southern Area was produced as a result of at least three successive stages of landscape evolution. Successive block diagrams representing a simplified interpretation of these erosional/depositional stages of the San Pedro Valley in the Southern Area best illustrate the geomorphic history (Figure 24). The San Pedro River has been the dominant regional surface water feature throughout the late Cenozoic history of the San

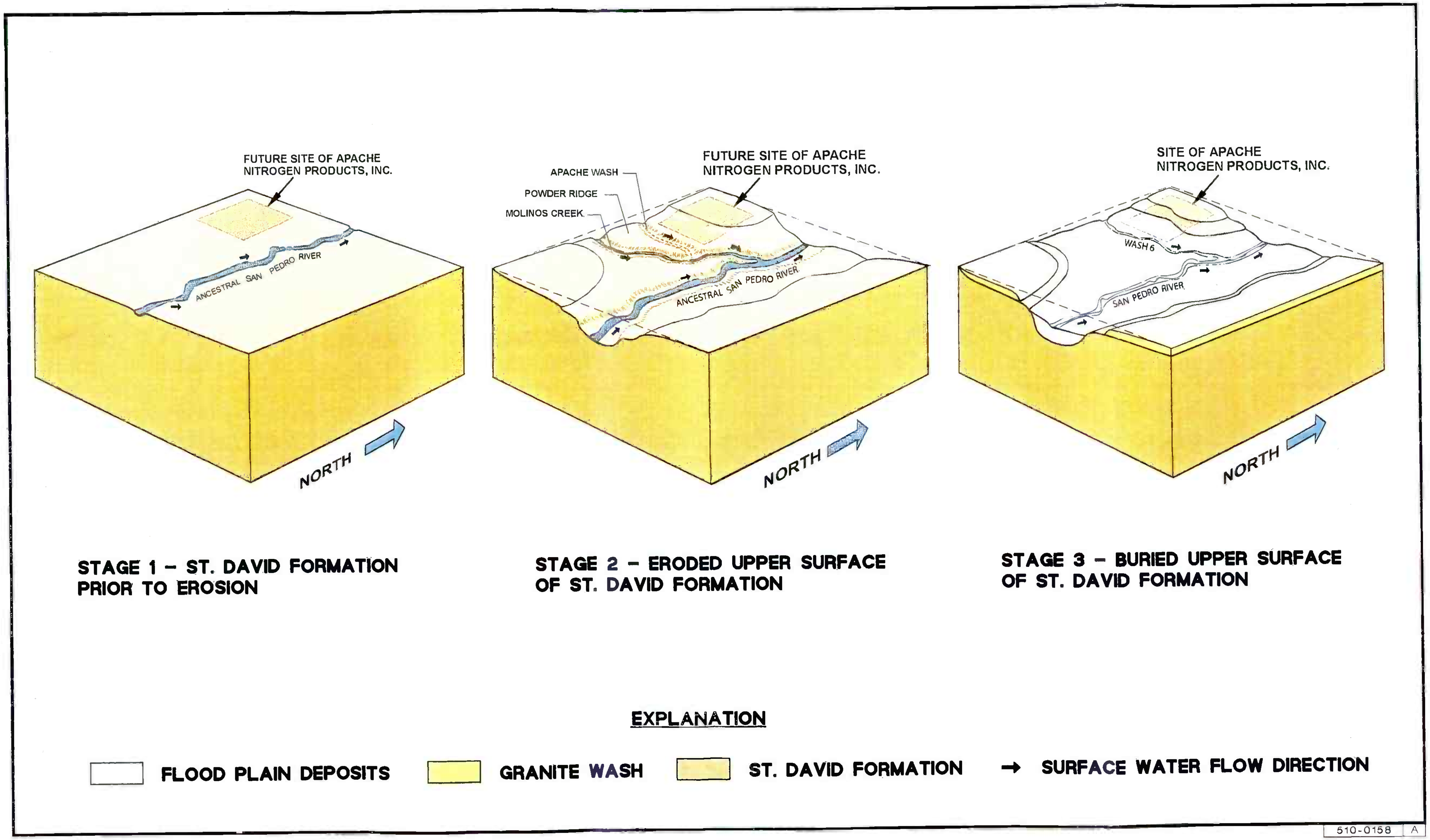


FIGURE 24. CONCEPTUALIZED GEOMORPHIC EVOLUTION OF THE SOUTHERN AREA

Pedro Valley. The San Pedro River has conveyed surface water northward from as far south as Cananea, Sonora, Mexico, to where it joins the Gila River near Winkelman, Arizona. This resulted in the erosion of the Precambrian igneous and metamorphic crystalline bedrock complex within the surrounding mountain ranges and the subsequent deposition of these source materials to form the St. David Formation in the San Pedro Valley. These processes occurred during the Miocene to middle Pleistocene period (Figure 24, Stage 1). Local sediment transport patterns were generally inward from the eroding mountain ranges toward the San Pedro Valley axis. Along this axis, the Ancestral San Pedro River would then transport sediments northward, depositing the St. David Formation sediments (Gray, 1965; Smith, 1994).

5.1.2 Erosion of the St. David Formation (Stage 2)

Middle Pleistocene erosion of the St. David Formation by the Ancestral San Pedro River resulted in an upper erosional surface sloping inward from the mountain fronts toward a deeply-incised, axial paleochannel formed by the Ancestral San Pedro River. The topography of the buried upper surface of the St. David Formation indicates that at least two identifiable paleo-tributaries to the Ancestral San Pedro River were present in the Southern Area during its erosion (Plate 2). Molinos Creek appears to have conveyed surface water from the base of the Whetstone Mountains, approximately 7 miles east of the Site, northeast past the ANP site to its confluence with the Ancestral San Pedro River, north of the shallow aquifer monitor well MW-14, -22 and -24 transect. Apache Wash conveyed surface water eastward to Molinos Creek, from a relatively small paleo-watershed within the vicinity of the now-existing ANP Operations Area.

If the paleoclimate were cooler and more humid during erosion of the St. David Formation (Amann, *et al*, 1998) than previously suggested (Gray, 1965), this could have produced a relatively large quantity of perennial flow in Molinos Creek due to the size of its watershed. If channel flow in Apache Wash were perennial as well, channel flow was probably significantly smaller than that in Molinos Creek, due to the much smaller Apache Wash watershed. This could result in different erosion rates within the two paleochannels, resulting in Apache Wash having a much higher local elevation than Molinos Creek (Figure 24, Stage 2).

5.1.3 Deposition of the Flood-Plain Deposits (Stage 3)

The change from an erosional to a depositional fluvial environment typically occurs due to changes in streambed gradient and base level conditions. These two factors change as the stream system tends toward equilibrium between input and output of a system's energy and mass flow characteristics (Graf, 1988). Thus, as the lower section of an eroding stream channel accumulates sediments from upstream and/or the upper section of the channel erodes quicker than the lower portion, the streambed gradient flattens as the upper portion approaches base level. This will typically result in increased deposition throughout the stream channel as the system adjusts to the new fluvial dynamics (Graf, 1988). The local base level for Molinos Creek was probably located at its confluence with the Ancestral San Pedro River north of the shallow aquifer monitor well MW-14, -22 and -24 transect. This is indicated by the elevations of the buried St. David clay surface in both paleochannels (Plate 2).

The Ancestral San Pedro River began depositing Recent flood-plain sediments throughout a period of aggradation during the last 10,000 years (Figure 24, Stage 3) (Gray, 1965). From the geomorphologic perspective, a flood plain is an alluvial surface next to a channel, separated from the channel by banks, and built of materials transported and deposited by the present regime of the river (Graf 1988).

Lateral accretion occurs in a through-flowing stream channel and is typified by deposition of coarse-grained sediments, such as sands and gravels, in the channel due to a high-energy fluvial environment. This is due to the winnowing effect of channel water that separates suspended sediment load (silts and clays) from the total sediment load, leaving behind the bedload (sands and gravels) to be deposited in the channel. The silts and clays are then transported farther downstream until the transport energy decreases sufficiently. Typically, this can occur in such areas as receiving lakes, ponds, or swamps. Vertical accretion occurs outside of the stream channel and is typified by the deposition of fine-grained sediments known as overbank sediments, on the adjacent land surfaces during flood events. As flood water leaves the channel and spreads out over the adjoining land surface, the energy of the water drops dramatically, causing any coarse-grained sediments (bedload) to deposit next to the channel and allowing the remaining fine-grained sediments (suspended load) to be deposited farther from the channel banks (Graf, 1988).

Thus, Molinos Creek and the Ancestral San Pedro River deposited lateral accretion deposits comprising sands and gravels within their paleochannels, and vertical accretion deposits comprising silts and clays were deposited between the paleochannels.

5.1.4 Deposition of the Laterally Confining Unit (LCU)

It can be reasonably inferred that, during the transition from a fluvial environment of erosion of the St. David clay to deposition of the flood-plain sediments, the Molinos Creek and Ancestral San Pedro River stream channels were initially located within the erosional Molinos Creek and Ancestral San Pedro River paleochannels. Initially deposited sediments consisted of sand and gravel channel sediments flanked by silt and clay overbank sediments deposited during flood events. Cross sections A-A′, A″-A″, C-C′, E-E′ and G-G′ (Figures 11, 13, 15 and 17) indicate that Molinos Creek and the Ancestral San Pedro River probably did not migrate from their erosional paleochannels. Thus, they accumulated sands and gravels in and stratigraphically above their respective paleochannels (Figures 15 through 18). Exploratory boring EXB-3 drilling data indicate that a silty clay unit was deposited immediately west of shallow aquifer monitor well MW-14. The silty clay extends upward from the buried surface of the St. David clay to an elevation that correlates with the upper surface of the shallow aquifer at monitor wells MW-14, -22 and -24, indicating that it was probably deposited at the same time as the shallow aquifer.

The large difference in groundwater elevation between Molinos Creek Sub-Aquifer monitor well MW-24 and monitor wells MW-14 and MW-22 (Figures 17, 22 and 23) in the main part of the shallow aquifer indicate that this silty clay is probably a lithofacies change. The material is composed of overbank materials deposited upstream of the Molinos

Creek-Ancestral San Pedro River confluence. This feature appears to act as a hydraulic barrier for lateral exchange of groundwater between the main part of the shallow aquifer and the Molinos Creek Sub-Aquifer. Groundwater elevation trends (Section 5.2) indicate that this unit probably extents further south isolating Molinos Creek Sub-Aquifer monitor wells MW-15, -21 and -22 (Figure 25).

The following hydraulic conductivity ranges for various grain-sized materials provide a basis for comparison of changes expected as a result of varying sediment grain sizes based on data reported by Fetter (1994):

- Clays (3×10^{-6} to 3×10^{-3} ft/day).
- Silts (3×10^{-3} to 3 ft/day)
- Well-sorted sands (3 to 300 ft/day)
- Gravels (30 to 3,000 ft/day)

The above ranges indicate that at least a magnitude difference in hydraulic conductivity can occur between the observed silty clay barrier/inferred unit and the sand and gravel aquifer materials. This barrier permits

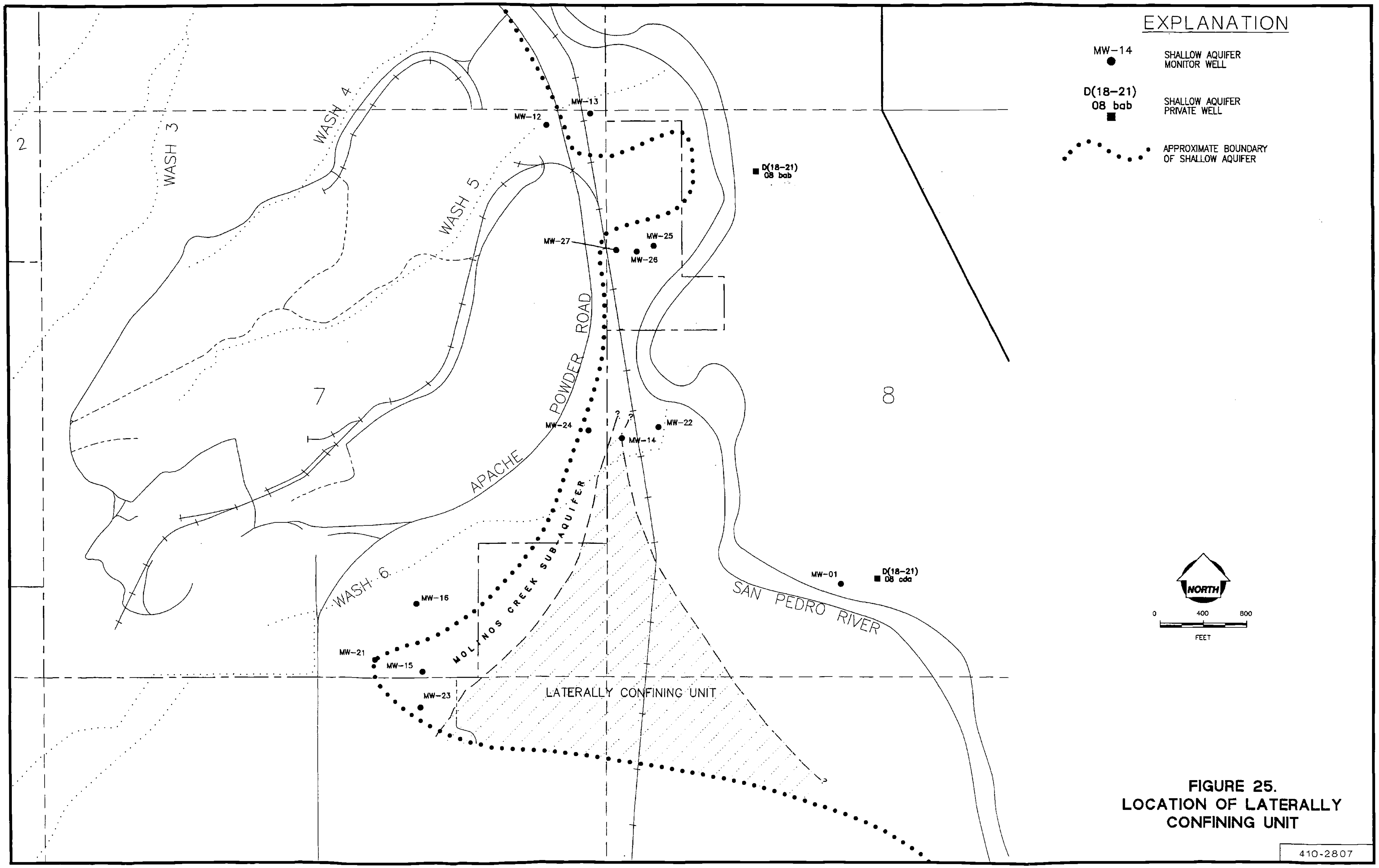


FIGURE 25.
LOCATION OF LATERALLY CONFINING UNIT

maintenance of the significant differences in groundwater elevations between the Molinos Creek Sub-Aquifer and the main part of the shallow aquifer. This is observed in the hydrographic data for monitor well MW-24, representing the Molinos Creek Sub-Aquifer, in relation to monitor wells MW-14 and MW-22, representing the main part of the shallow aquifer.

The weakly cemented silty clay encountered during borehole drilling at Molinos Creek Sub-Aquifer monitor wells MW-25, -26 and -27 appears to consist of overbank sediments. They are probably re-worked St. David clay sediments that were deposited in a geographic recess located on the west side of Molinos Creek, south of exploratory boring EXB-7. This unit produces groundwater and extends upward from the buried surface of the St. David clay to an elevation that correlates with the top of the shallow aquifer, indicating that it was deposited by Molinos Creek and is not a remnant of lacustrine sediments within the St. David Formation (Figure 16).

As previously mentioned (Section 3.2.1), the specific capacities for monitor wells MW-25, -26, and -27 estimated during pump development were 270 gpd/ft, 104 gpd/ft, and 10 gpd/ft, respectively. This westward decrease in estimated specific capacity along this well transect implies similarly westwardly decreasing hydraulic conductivity within the weakly cemented silty clay unit. Hydraulic conductivity is partly a function of grain size. Finer-grained sediments typically have lower hydraulic conductivity than coarser-grained sediments (Fetter, 1994; Vukovic and Soro, 1989; Freeze and Cherry, 1979). Such a trend in hydraulic conductivity therefore implies a lateral facies change favoring finer-grained sediments in a westward direction.

This trend is also consistent with the typical depositional pattern of vertical accretion sediments, in that the sediments become finer with increasing distance normal to a stream channel. Combined with the eastward sloping surface of the buried St. David clay underneath the weakly cemented silty clay (Figure 18), the specific capacity data suggest that this unit comprises vertical accretion sediments and supports the interpreted location of the Molinos Creek paleochannel east of this unit (Plate 2).

A non-thesis numerical groundwater flow and transport model is being developed to evaluate the potential effectiveness of the natural attenuation of contaminants in a portion of the shallow aquifer in the Southern Area of the Site, specifically within the Molinos Creek Sub-Aquifer (H+A, 2000h, personal communication). The model incorporates the geometrical aspects of the sub-aquifer and the LCU as shown on Figure 25. Groundwater recharge from the perched zone to the Molinos Creek Sub-Aquifer will be assigned at model nodes in the vicinity of monitor wells MW-15, -21, and -23 as a flux boundary. The flux boundary along the eastern edge of the model will be simulated as a head-dependent flux boundary implying groundwater flow across the LCU into the Molinos Creek Sub- Aquifer from the main part of the shallow aquifer to the east. The amount of groundwater flow across the LCU will be determined during model calibration by adjusting the hydraulic conductivity. A no-flow boundary will be assigned along the western margin of the Molinos Creek Sub-Aquifer.

Hydraulic conductivity values for the Molinos Creek Sub-Aquifer will be estimated by calibrating the numerical model to post-1995 historical groundwater elevations.

5.2 Groundwater Elevation Changes

Hydrographic data for different locations within a hydraulically continuous, homogeneous aquifer often change concurrently, with slight variations in the magnitude of change. However, hydrographs in hydraulically-isolated aquifers may exhibit hydrographic independence in response to locally different stresses. Groundwater level data for wells representing the Molinos Creek Sub-Aquifer and the main part of the shallow aquifer are compared in following sections in the form of groundwater level maps and well hydrographs in an effort to examine the nature of their hydraulic independence or similitude.

5.2.1 Groundwater Elevation Contours

Divergent hydrographic patterns in the Molinos Creek Sub-Aquifer combined with significant differences in groundwater elevations reinforce the conceptualized groundwater flow. February 1995 groundwater elevations, corresponding to the cessation of discharges to the active ponds, indicate a relatively constant groundwater gradient and parallel groundwater elevation contours in the Southern

Area (Figure 20). This suggests that the shallow aquifer is homogeneous with respect to hydraulic conductivity. Groundwater elevations for November 1996, November 1999, and August 2000 (Figures 21, 22 and 23) indicate a progressive decline in groundwater elevations in the vicinity of Molinos Creek Sub-Aquifer monitor wells MW-15, -21, -23 and -24, compared to shallow aquifer monitor wells MW-01, -06, -14 and -22 in the main part of the shallow aquifer. This is the direct result of the combined effect of decreased recharge to the Molinos Creek Sub-Aquifer from the perched zone and the hydraulic isolation of this area by the LCU.

5.2.2 Groundwater Elevation Hydrographs

Groundwater elevation hydrographs for Site monitor wells and piezometers are prepared and reported quarterly as part of the CGMP. The most recent hydrographs are presented in Appendix C.

5.2.2.1 Perched Zone Hydrographs

Perched zone groundwater elevations have been declining since groundwater elevation measurements were initiated in August 1990 as part of the Remedial Investigation (H+A, 1991). The comparative rate of decline of perched zone groundwater elevations may be described as slow through early 1995, more rapid through late 1996, very slow through May 2000, followed by a sharp decline by August 2000. The decline after early 1995 was a direct response to the cessation of wastewater discharge to the formerly active ponds. While discharge from the perched zone to the Molinos Creek Sub-Aquifer is believed to have been ongoing during the operation of the formerly active ponds, since 1995 the perched zone has been dewatering and therefore, the rate of discharge has been declining. At the present time, the discharge is believed to be significantly diminished from the rate of discharge that was occurring during operation of the formerly active ponds. The lack of regular seasonal groundwater fluctuations on the perched zone hydrographs suggests that there is no significant perched zone recharge occurring, although, some local hydrographic fluctuations have been observed in relation to storm water management within the Operations Area. Additionally, there are some locations, such as piezometer P-03, where the hydrograph indicates a sharp decline, followed by relative stability. These areas are believed to represent water detained within topographic depressions on the buried clay surface. Such topographic configurations would prevent drainage toward the shallow aquifer via gravity.

The lack of groundwater in monitor well MW-28 indicates that the small paleochannel located beneath Wash 6 (Figure 13) is not currently a pathway for perched zone groundwater outflow. The presence of groundwater in monitor well MW-29 and the lack of groundwater in monitor wells MW-30, -31, and -32 indicate that groundwater dewatering from the perched zone to the Molinos Creek Sub-Aquifer via the paleochannel located south of piezometer P-10 is within the vicinity of this well.

5.2.2.2 Molinos Creek Sub-Aquifer Hydrographs

Hydrographic data for monitor wells within the Molinos Creek Sub-Aquifer indicate that the Molinos Creek Sub-

Aquifer is responding to decreasing artificial recharge from the perched zone. Monitor well MW-15 has longest data record in the Molinos Creek Sub-Aquifer near the outflow from the perched zone. As observed on the perched zone hydrographs, monitor well MW-15 groundwater elevations declined slowly through late 1994, and then relatively rapidly to the present. The timing of this increased rate of groundwater elevation decline coincides with the decline of the perched zone. Although their records began more recently, the hydrographs for monitor wells MW-21, -23 and -24 indicate a rate of groundwater elevation decline similar to the latter part of monitor well MW-15 data.

Unlike the perched zone hydrographs, regular seasonal groundwater elevation fluctuations are superimposed on the declining groundwater elevations of the Molinos Creek Sub-Aquifer monitor well hydrographs. The seasonal fluctuations are generally seen as annual "peaks" in May and "dips" in November. This periodicity coincides with the growing season of phreatophytes in the San Pedro Valley. During warmer months, groundwater is lost to the atmosphere via phreatophyte evapotranspiration. The decline in groundwater elevations during May through August

2000 in the Molinos Creek Sub-Aquifer monitor wells is consistent with the expected seasonal fluctuation in groundwater elevation.

5.2.2.3 Hydrographs for the Main Part of the Shallow Aquifer in the Southern Area

In contrast, the perched zone and Molinos Creek Sub-Aquifer hydrographs for the main part of the shallow aquifer indicate relatively stable groundwater elevations. Monitor well MW-22 has too few measurements to identify seasonalities or long-term trends at present. Hydrographs for monitor wells MW-01, -06, -14 and -22, which are in the main part of the shallow aquifer, show increases in groundwater elevations during between May and August 2000. Because such trends were not observed in the Molinos Creek Sub-Aquifer, this provides further indication of its hydraulic isolation from the main part of the shallow aquifer. Seasonal fluctuations in the main part of the shallow aquifer are not as well defined as those for Molinos Creek Sub-Aquifer hydrographs. This probably represents the combined effects of aquifer elevation changes from distant upgradient aquifer recharge, local downward infiltration of San Pedro River water during flood events, local infiltration of irrigation water applied to nearby fields, and irregular shallow aquifer private well pumping schedules.

5.2.2.4 Other Shallow Aquifer Hydrographs

Monitor wells MW-08, -11, -13, -17, -18 and -19 are constructed along the western boundary of the shallow aquifer at the mouths of Washes 1, 2, 4 and 5, north of the Southern Area. Although hydrographs for these wells indicate slowly increasing groundwater elevations, similar to monitor wells MW-01, -06, -14 and -22 in the main part of the shallow aquifer, they also include superimposed regular seasonal groundwater fluctuations similar to those seen on the hydrographs for Molinos Creek Sub-Aquifer monitor wells MW-15, -21 and -23. They also indicate a decrease in groundwater elevations during May through August 2000. This change is consistent with the Molinos Creek Sub-Aquifer well hydrographs and in contrast with the hydrographs of monitor wells in the main part of the shallow aquifer in the Southern Area, which are hydraulically isolated by the LCU. The hydrographs of these wells indicate that the seasonal fluctuations are similar to Molinos Creek Sub-Aquifer monitor wells. The similarity in groundwater elevation change in monitor wells MW-08, -11, -13, -17, -18 and -19 in one respect to the main part of the shallow aquifer in the Southern Area and in another with Molinos Creek Sub-Aquifer monitor wells indicate that, although these wells are constructed in the shallow aquifer, areas of low hydraulic conductivity similar to the LCU may be located near these well sites.

5.3 Hydrochemical Data

Major ion data from the analysis of selected groundwater and surface water samples were used to develop Stiff diagrams and to compute the ionic strengths of the samples. The hydrochemical data further support the conceptual model by illustrating different groundwater hydrochemistry patterns in the Molinos Creek Sub-Aquifer and main part of the shallow aquifer. The data indicate clearly recognizable and differing trends in hydrochemistry on either side of the LCU. These patterns can be attributed to the ability of the LCU to isolate the Molinos Creek Sub-

Aquifer hydraulically from the main part of the shallow aquifer.

5.3.1 Major Ion Data

Plate 3 shows Stiff diagrams, calculated ionic strengths, total dissolved solids (TDS) concentrations, and laboratory pH values detected in groundwater and surface water samples collected from selected sites in the Southern Area. Stiff diagrams provide a visual representation of the spatial variations in the major ion concentrations in natural waters. Analytical concentrations of potassium (K^+), sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^+), ammonium (NH_4^+), chloride (Cl^-), bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), sulfate (SO_4^{2-}), and nitrate (NO_3^-) were converted into milliequivalents per liter (meq/l) and plotted on the Stiff diagram axes.

The ionic strength of a solution is a measure of the strength of the electrostatic field generated by the types and concentrations of ions present in solution. For the purposes of this report, ionic strength (I) in moles per liter (M) was calculated for each sample using the same ions used to prepare the Stiff diagrams and according to the following formula (Hem, 1992):

$$I = 0.5\Sigma(mz^2)$$

where: m = concentration of the ion [M]

z = ionic charge

The Stiff diagrams for the San Pedro River surface water and groundwater samples collected in the main part of the shallow aquifer indicate shallow aquifer groundwater in this area can be classified as a calcium/sodium+potassium bicarbonate-carbonate type. The proportions of calcium and sodium+potassium ions are essentially equal. The ionic strength is relatively consistent, increasing slightly downgradient from approximately 0.01 M at monitor well MW-06 to 0.02 M at private well D(18-21)08bab. TDS concentrations more than double from 370 to 770 milligrams per liter (mg/l), respectively. Laboratory pH values increase from 7.1 to 7.3 lab units between these two wells. The Stiff diagram for surface water sample SW-12 indicates similar chemistry to the groundwater samples collected from the main part of the shallow aquifer. Its ionic strength is approximately 0.01 M, TDS concentration is approximately 340 mg/l, and pH is 8.4 lab units.

Based on differences in anion-type dominance, pH and TDS concentrations, groundwater in the perched zone and Molinos Creek Sub-Aquifer demonstrate a different hydrochemical character from the main part of the shallow aquifer and regional groundwater. The Stiff diagrams for the perched zone and Molinos Creek Sub-Aquifer indicate that groundwater within these areas are calcium/sodium+potassium sulfate-dominated. The ionic strength and pH are highly variable, but demonstrate recognizable trends as discussed below.

In the perched zone, the Stiff diagrams indicate that calcium and sulfate concentrations decrease slowly from piezometer P-03 to monitor well MW-29. Between these two locations, ionic strength decreases by half from 0.21 to 0.09 M, TDS concentration decreases from 13,000 to 4,100 mg/l, and pH increases from 6.6 to 6.8 lab units. These trends continue in the downgradient direction in the Molinos Creek Sub-Aquifer.

In the Molinos Creek Sub-Aquifer, the Stiff diagrams indicate that calcium and sulfate concentrations decrease rapidly between monitor wells MW-15 and MW-24. Between these two wells, ionic strength decreases from 0.11 to 0.01 M, TDS concentration decreases from 5,400 to 640 mg/l, and pH increases from 6.8 to 7.3 lab units. The analytical data for MW-21 may appear to be outliers because this well is screened across the entire saturated thickness of the Molinos Creek Sub-Aquifer, whereas the remaining Molinos Creek Sub-Aquifer monitor wells are constructed with 15-foot screened sections installed in the uppermost portion of the aquifer.

Stiff diagrams for Molinos Creek Sub-Aquifer monitor wells MW-25, -26 and -27 indicate calcium-sulfate dominated groundwater in the Molinos Creek overbank sediments, which comprises weakly cemented silty clay. From monitor well MW-25 toward MW-27 ionic strength increases from 0.06 to 0.07 M, TDS concentration increases from 2,300 to 2,700 mg/l, and pH increases from 8.0 to 8.7 lab units. The Stiff diagram for shallow aquifer private well D(18-21)08bab indicates that the groundwater at this location is a bicarbonate-carbonate/sulfate type, with an ionic strength of 0.02 M, TDS concentration of 770 mg/l, and pH of 7.3 lab units. The Stiff diagram for shallow aquifer monitor well MW-13 indicates that the groundwater at this location is a bicarbonate-carbonate/sulfate type, with an ionic strength of 0.02 M, TDS concentration of 860 mg/l, and pH of 6.9 lab units.

The shallow aquifer results are generally consistent with independent hydrochemical studies performed in the vicinity of the Site (Usunoff, 1984; Coes *et al*, 1999). In particular, the following observations have been noted:

- The Sierra Vista Sub-basin groundwater is a calcium-bicarbonate type (Coes, *et al.*, 1999).
- Samples from the unconfined aquifer are bicarbonate-type with a mean pH value of 7.4 lab units (Usunoff, 1984).
- Sulfate-type groundwater dominates the Pomerene and St. David areas due to a masking effect of fertilizer-laden return irrigation water on the underlying unconfined shallow aquifer groundwater that already contains dissolved gypsum (Usunoff, 1984).

A similar increase in sulfate concentration in San Pedro River water samples through the St. David area is attributed to direct discharge of domestic wastewater and return irrigation water to the San Pedro River (Usunoff, 1984).

The Molinos Creek Sub-Aquifer results indicate that the groundwater in this aquifer differs significantly from the main part of the shallow aquifer. Specifically, groundwater in the Molinos Creek Sub-Aquifer is a sulfate-type groundwater with higher ionic strength and TDS concentrations and a slightly lower pH. The trends within the Molinos Creek Sub-Aquifer are consistent and spatially limited to the inferred boundaries of the sub-aquifer. This provides further indication that the LCU directs groundwater flow from the perched zone northward through the Molinos Creek Sub-Aquifer, and not eastward toward the main part of the shallow aquifer.

5.3.2 Nitrate-N and Perchlorate Data

The lateral extent of detectable nitrate-N and perchlorate in Southern Area groundwater further reinforce the conceptual model. The September 1997 and August 2000 nitrate-N plumes followed the western boundary of the shallow aquifer (H+A, 1998, 2000g) (Figures 26 and 27). Similarly, the August 2000 perchlorate plume followed the western boundary of the shallow aquifer (H+A, 2000g) (Figure 28). Both plumes are limited to the Molinos Creek Sub-Aquifer and show decreasing concentrations in the direction of northward groundwater flow, instead of toward the east.

Groundwater quality hydrographs have been prepared for nitrate-N (Appendix D) and perchlorate (Appendix E). The data indicate that nitrate-N concentrations in perched zone piezometer P-03 have been increasing since the cessation of wastewater discharges to the formerly active ponds in 1995. Nitrate-N concentrations in groundwater samples collected from monitor well MW-29 have been slowly increasing since its construction in spring 2000. The nitrate-N concentrations for all other perched zone piezometers and

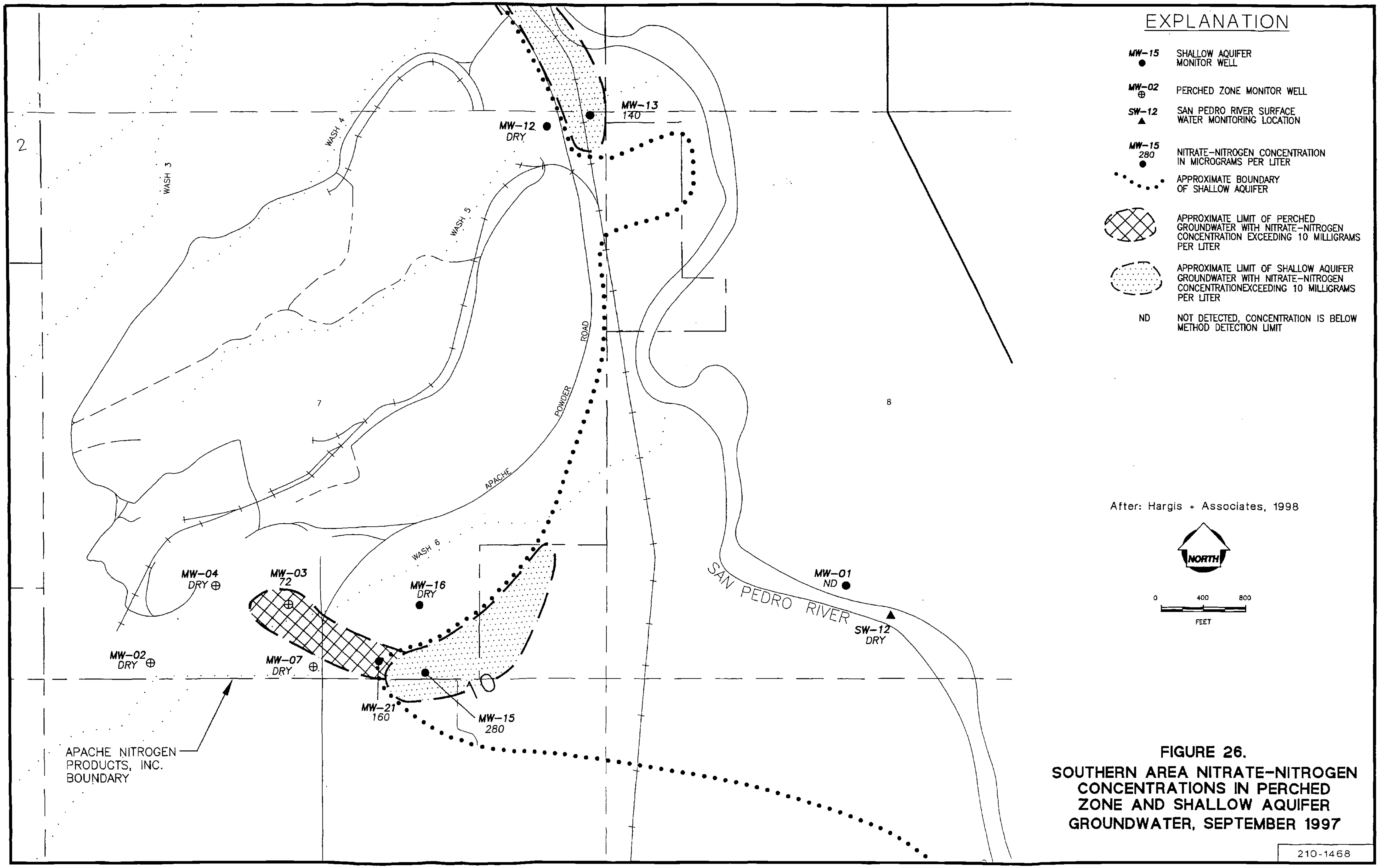


FIGURE 26.
SOUTHERN AREA NITRATE-NITROGEN CONCENTRATIONS IN PERCHED ZONE AND SHALLOW AQUIFER GROUNDWATER, SEPTEMBER 1997

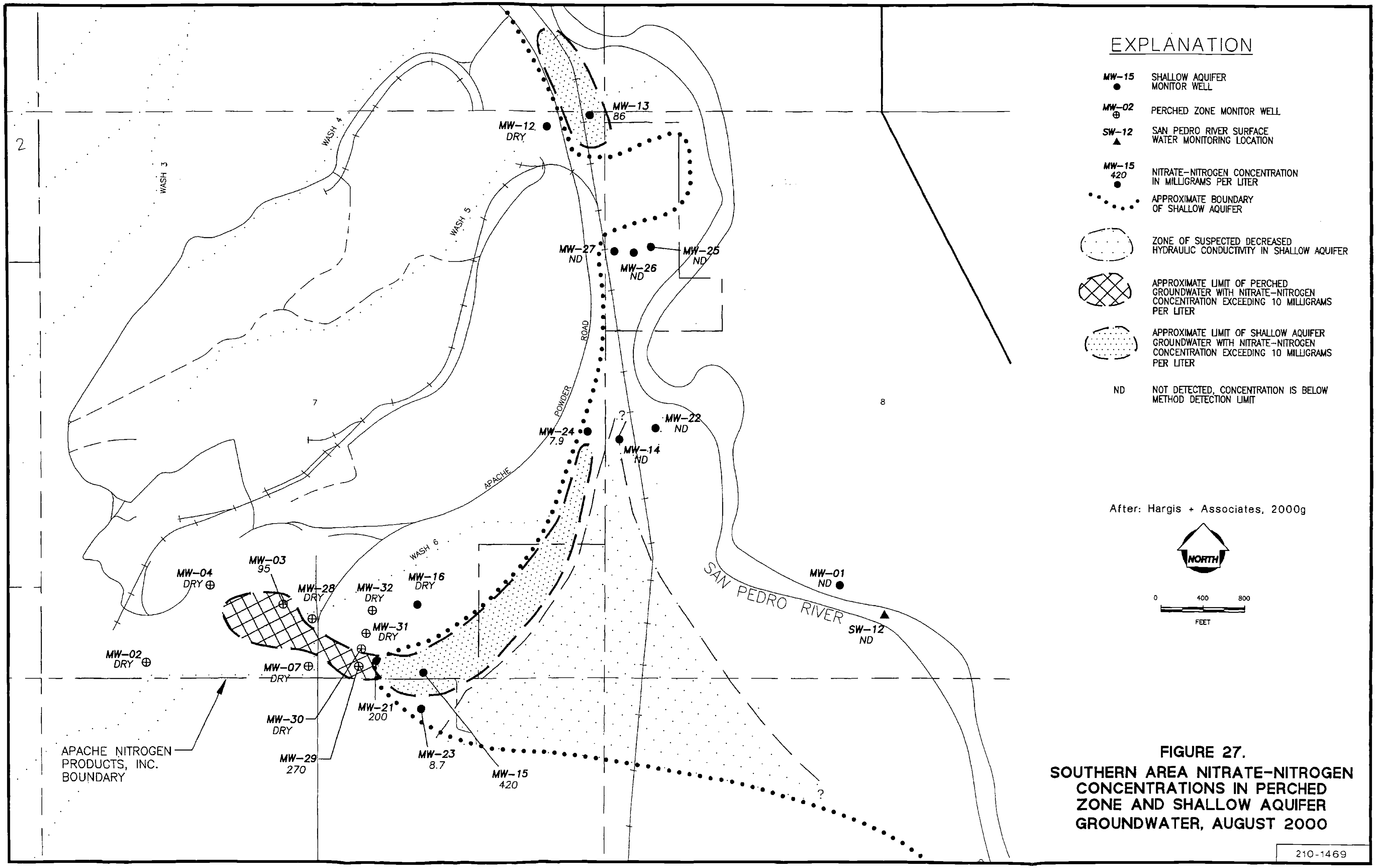


FIGURE 27.
SOUTHERN AREA NITRATE-NITROGEN CONCENTRATIONS IN PERCHED ZONE AND SHALLOW AQUIFER GROUNDWATER, AUGUST 2000

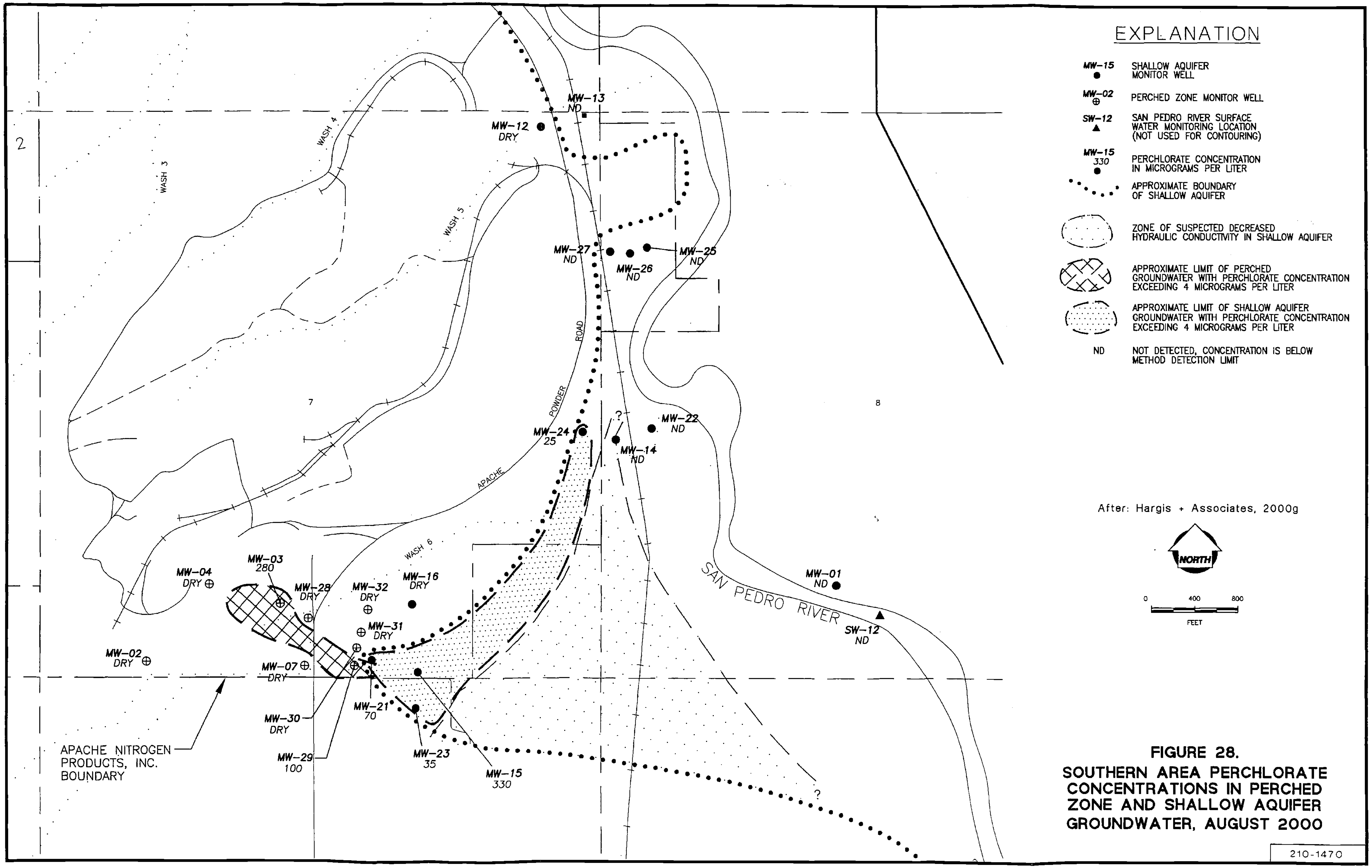


FIGURE 28. SOUTHERN AREA PERCHLORATE CONCENTRATIONS IN PERCHED ZONE AND SHALLOW AQUIFER GROUNDWATER, AUGUST 2000

monitor wells show relatively stable trends. Data for Molinos Creek Sub-Aquifer monitor wells MW-15 and -21 show increasing nitrate-N concentrations, whereas data for monitor wells MW-23 and -24 show decreasing nitrate-N concentrations. Generally, Molinos Creek Sub-Aquifer nitrate-N concentrations decrease from monitor wells MW-15, -21 and -23 toward monitor well MW-24, in the direction of Molinos Creek Sub-Aquifer groundwater flow.

Perchlorate concentrations in perched zone piezometer P-03 are relatively high compared to those at piezometers P-01 and -10 and perched zone monitor wells MW-03 and -29. Additionally, the concentrations appear to be relatively stable. Perchlorate has been detected only in Molinos Creek Sub-Aquifer monitor wells MW-15, -21, -23 and -24. Concentrations within monitor well MW-15 are generally increasing, whereas those for monitor wells MW-21, -23 and -24 are much lower and slowly decreasing, indicating an overall pattern of contaminant migration northward through the Molinos Creek Sub-Aquifer.

5.4 Interaction Between the Shallow Aquifer and the San Pedro River

Groundwater/surface water interaction between the shallow aquifer and the San Pedro River along the ANP reach has not been confirmed. Previous investigations have attempted to evaluate groundwater/surface water interaction by measuring discharge at successive stations along this reach (Black and Veatch, 1988; ADEQ, 1991; H+A, 1991). According to this methodology, increases or decreases in discharge between successive stations may be attributed to gaining or losing reaches of the stream, respectively, provided that:

- There are no surface inputs between the stations (i.e., tributary discharges, irrigation outfalls, drains, etc.),
- The measured conditions are indicative of stream baseflow as opposed to stormwater runoff (i.e., flow is essentially the result of groundwater discharge for gaining reaches), and
- The measured differences between successive stations are large in comparison with the measurement (gauging) error.

It is also required that measurements at all stations be sufficiently close in time so as to avoid temporal variability in discharge.

Results of the San Pedro River discharge measurements taken over a one-year period during the Remedial Investigation generally indicated a consistent, albeit small, gain in flow downstream along the reach from San Pedro River station SW-12 to SW-5 to SW-2, a stream distance of approximately 2-1/4 miles (H+A, 1992). The increase in discharge over the maximum reach ranged from approximately 0.7 cubic feet per second (cfs) during low flow conditions (less than 1 cfs) to approximately 7.1 cfs during high flow conditions (approximately 16 cfs). These increases correspond to factors greater than 5 fold to just over 0.1, respectively. This is consistent with the expectation that groundwater discharge, which would not vary significantly in comparison with the variability in runoff magnitude, would exert a more significant effect during baseflow conditions than during river high stages.

Conceptually, groundwater/surface water interactions require two conditions to be met. First, there must be sufficient vertical hydraulic conductivity between the aquifer and the streambed. Second, there must be a sufficient hydraulic gradient, with an upward gradient favoring groundwater discharge and a downward gradient favoring groundwater recharge.

Throughout most of the Southern Area, the shallow aquifer is know to be under confined conditions owing to an overlying confining unit comprising fine-grained sediments, largely silts and clays. As indicated in this report, drilling conditions within the Southern Area typically encounter relatively dry sediments until sandy conditions, representing the shallow aquifer, are penetrated. At this interface saturated sediments are encountered with the pore water under sufficient pressure to cause the static water level in wells to rise significantly into the confining unit. This condition is taken to indicate the effectiveness of the confining unit in terms of preventing the upward movement from the aquifer into the streambed.

Thus, in order for the shallow aquifer to discharge to the San Pedro River, there would either have to be sufficient downcutting by the river into the confining unit or the confining unit would have to undergo a lateral facies change favoring an increase in vertical hydraulic conductivity. Additionally, the hydraulic head within the shallow aquifer would have to be at a higher elevation than the riverbed. While there is no existing information of the lateral extent of the confining unit in the vicinity of the San Pedro River channel, projections of stratigraphic cross-sections indicate that the hydraulic head of the shallow aquifer is probably lower than the river throughout the reach along which the baseflow gains were measured.

In light of this, several possible explanations remain as to why the river appears to be gaining along the ANP reach. These include:

- Irrigation and/or tributary runoff that was unaccounted for during the survey.
- Perched groundwater discharge from the St. David side of the river resulting from deep percolation of

irrigation waters onto agricultural fields and/or unlined ponds and ditches maintained by deep aquifer artesian wells.

- Bank storage effects after periods of high runoff.
- Stream gauging error.

Evidence of lateral seepage along the riverbanks includes extensive sand bars, perimeter wetting, and efflorescence. This indicates that perched groundwater seepage may be present and that bank storage effects are likely. With regard to stream gauging error, the U.S. Geological Survey (USGS) classifies its own gauging records as "excellent", "good", or "fair", corresponding to records that are believed to be within 5, 10, and 15 percent of the "true value", respectively. Typically, USGS gages are set at relatively stable stream cross sections, where the channels are surveyed and the cross sectional areas remain relatively stable. This cannot be assumed for the surface water discharge measurement stations along the San Pedro River because significant changes in the cross sections frequently occur. Hence, many of the gains measured during low flow conditions fall within this uncertainty range (USGS, 2000).

6.0 CONCLUSIONS

On the basis of the information presented, it is believed that the following conclusions can be drawn with regard to groundwater flow and contaminant migration in the Southern Area of the Site:

- As a result of recent, detailed field characterization performed over the past year, buried topographic features have been identified on the surface of the St. David clay unit underlying the perched zone and shallow aquifer. In particular, it has been confirmed that subaerial erosion of the St. David Formation in the geologic past produced three paleochannels significant to the conceptualization of groundwater flow within the Southern Area. These paleochannels are informally identified as "Apache Wash", "Molinos Creek", and the "Ancestral San Pedro River". Apache Wash underlies the perched zone, Molinos Creek underlies the western portion of the shallow aquifer, and the Ancestral San Pedro River channel underlies the main part of the shallow aquifer to the east. The Apache Wash and Molinos Creek paleowatersheds remain separated by a erosional remnant of the St. David Formation, which roughly trends along the southern ANP property boundary. This erosional remnant has been informally named "Powder Ridge".

- Deposition of flood plain sediments in the paleochannels via alluvial processes since the late Pleistocene emplaced the sedimentary strata that presently comprise the perched zone and shallow aquifer matrix.

- The perched zone exists underlying the ANP Operations Area primarily, if not solely, as a result of artificial recharge from ANP's historical wastewater discharges. These discharges occurred primarily as a result of first, the routing of wastewater to surface washes (prior to 1971), then later to unlined evaporation ponds ("formerly active ponds"). In both instances, routing of the wastewater occurred primarily within unlined ditches, which also were responsible for the recharge. In early 1995, these discharges were eliminated by virtue of ANP's construction of a brine concentrator. As a result of the elimination of further recharge, the perched zone has dewatered significantly via gravity drainage. Presently, although the saturated thickness of the perched zone is up to 10 feet in localized areas (*e.g.*, piezometer P-03), the occurrence of perched groundwater is essentially limited to small, localized depressions in the clay surface or to areas receiving recharge from runoff accumulation and/or pipeline leaks. At the present time, the quantity of drainage from the perched zone to the shallow aquifer, as determined from piezometry transverse to the direction of flow, has essentially diminished to a small, thin cross-section within the axis of the Apache Wash paleochannel in the vicinity of monitor well MW-29.

- Overbank sediments deposited between Molinos Creek and the Ancestral San Pedro River are believed to have resulted in the deposition of a "Laterally Confining Unit" ("LCU"). The existence of the LCU has been confirmed toward its likely northern extent by exploratory boring EXB-3. Drill cuttings from this boring indicate that the northern end of the LCU comprises silty clay, which, typically, has a much lower hydraulic conductivity than the sands and gravels comprising the shallow aquifer.

- Multiple lines of evidence in addition to exploratory boring EXB-3 lithologic information support the existence of the LCU. These include: differential head data, differential groundwater elevation changes, contaminant plume distribution and flow dynamics, hydrochemical facies, geomorphic models (paleohydrology), geomorphic analogs based on current landforms (*e.g.*, a cienega located at the San Pedro River/Babocomari River confluence), and a past non-thesis conceptual/numerical model for remedial feasibility assessment (H+A, 1996b). The H+A model essentially represented discretized lower hydraulic conductivity units lateral to the alluvium on the basis of the assumed location of flood plain (overbank) deposits. This was done without knowledge of the existence of the LCU and Molinos Creek Sub-Aquifer. In addition to these other bases, the apparent paucity of drilling in the area of the LCU may indicate low productivity of the shallow aquifer based on early drilling attempts.

- The LCU hydraulically separates the shallow aquifer into the Molinos Creek Sub-Aquifer and the main part of the shallow aquifer, preventing westward lateral flow between these two areas. The diminishing rate of recharge from the perched zone to the shallow aquifer in the Southern Area has resulted in divergent groundwater elevation changes between the two aquifers. Groundwater elevations in the Molinos Creek Sub-Aquifer have been steadily dropping since early 1995, whereas groundwater elevations in the main part of the main aquifer have remained relatively stable during this period. This has resulted in an approximate 8-foot difference in groundwater elevation between monitor well MW-14 located in the main part of the shallow aquifer and monitor well MW-24 located in the Molinos Creek Sub-Aquifer.

- Specific capacity values estimated during monitor well MW-25, -26 and -27 development indicate that the weakly cemented silty clay unit across which these wells are screened suggests an origin consistent with sedimentation by vertical accretion processes associated with Molinos Creek. This would further imply that the channel of Molinos Creek was located to the east of this unit.

- The Molinos Creek Sub-Aquifer appears to converge with the main part of the shallow aquifer in the area north of monitor wells MW-14, -22 and -24.

- Hydrochemical data for the Molinos Creek Sub-Aquifer and main part of the shallow aquifer in the Southern Area indicate that the LCU also controls solute movement in the shallow aquifer, thereby limiting contaminant distribution to the Molinos Creek Sub-Aquifer. Groundwater in the main part of the shallow aquifer is bicarbonate-dominated, whereas Molinos Creek Sub-Aquifer groundwater is sulfate-dominated. TDS and ionic strength concentrations are higher in the Molinos Creek Sub-Aquifer, whereas pH values are generally higher in the main part of the shallow aquifer. Hydrochemical data for private well D(18-21)08bab suggest that this location may represent an area where the Molinos Creek Sub-Aquifer merges with the main part of the shallow aquifer. If this is correct, a mixing zone would be located upgradient and south of this well.

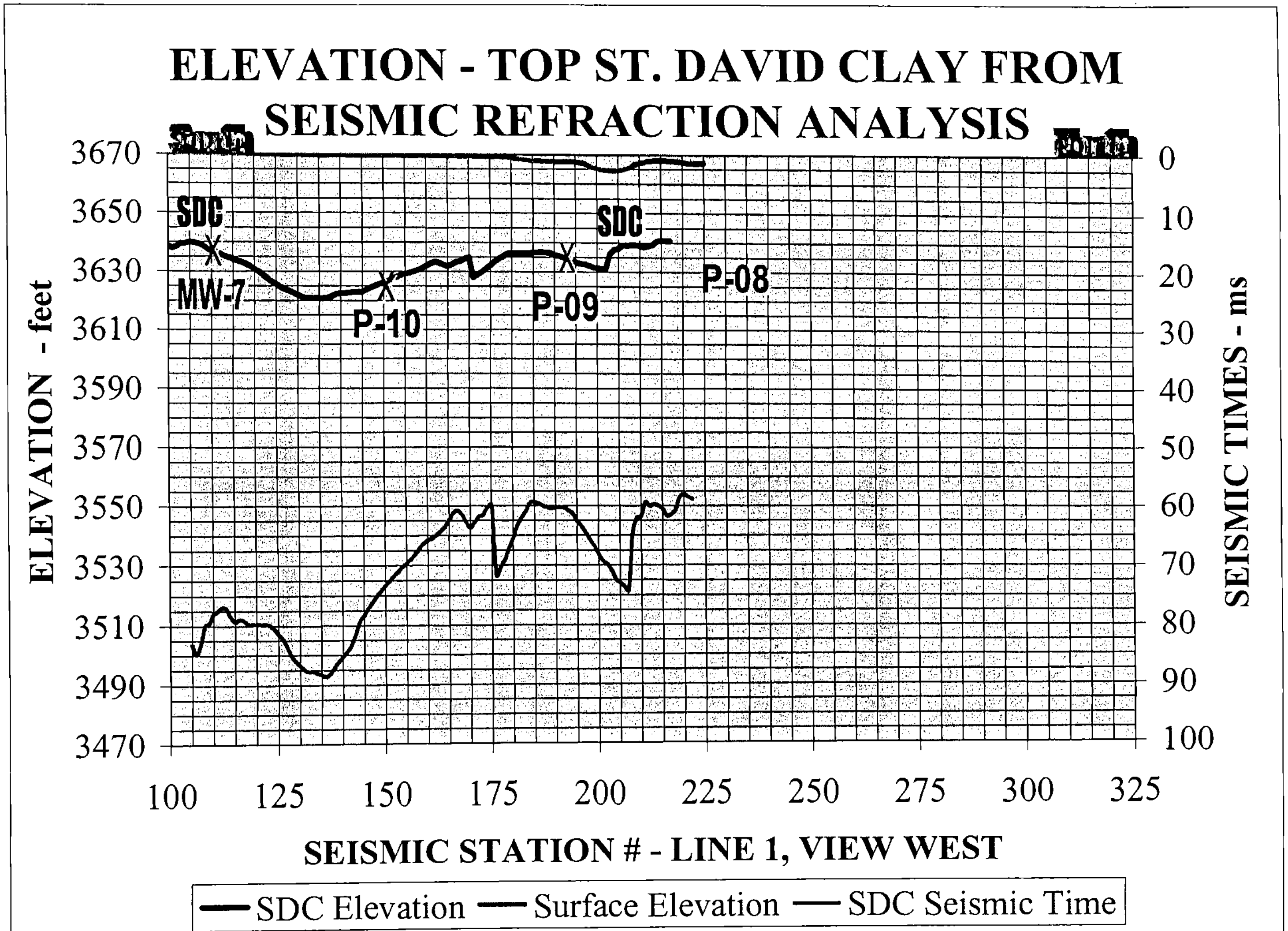
- Contaminant concentrations decrease downgradient in the Molinos Creek Sub-Aquifer.

- Groundwater elevation hydrographs of shallow aquifer monitor wells MW-08, -13, -17, -18, -19 and -20 indicate that areas of decreased hydraulic conductivity may also be located in the vicinity of the washes adjacent to these wells.

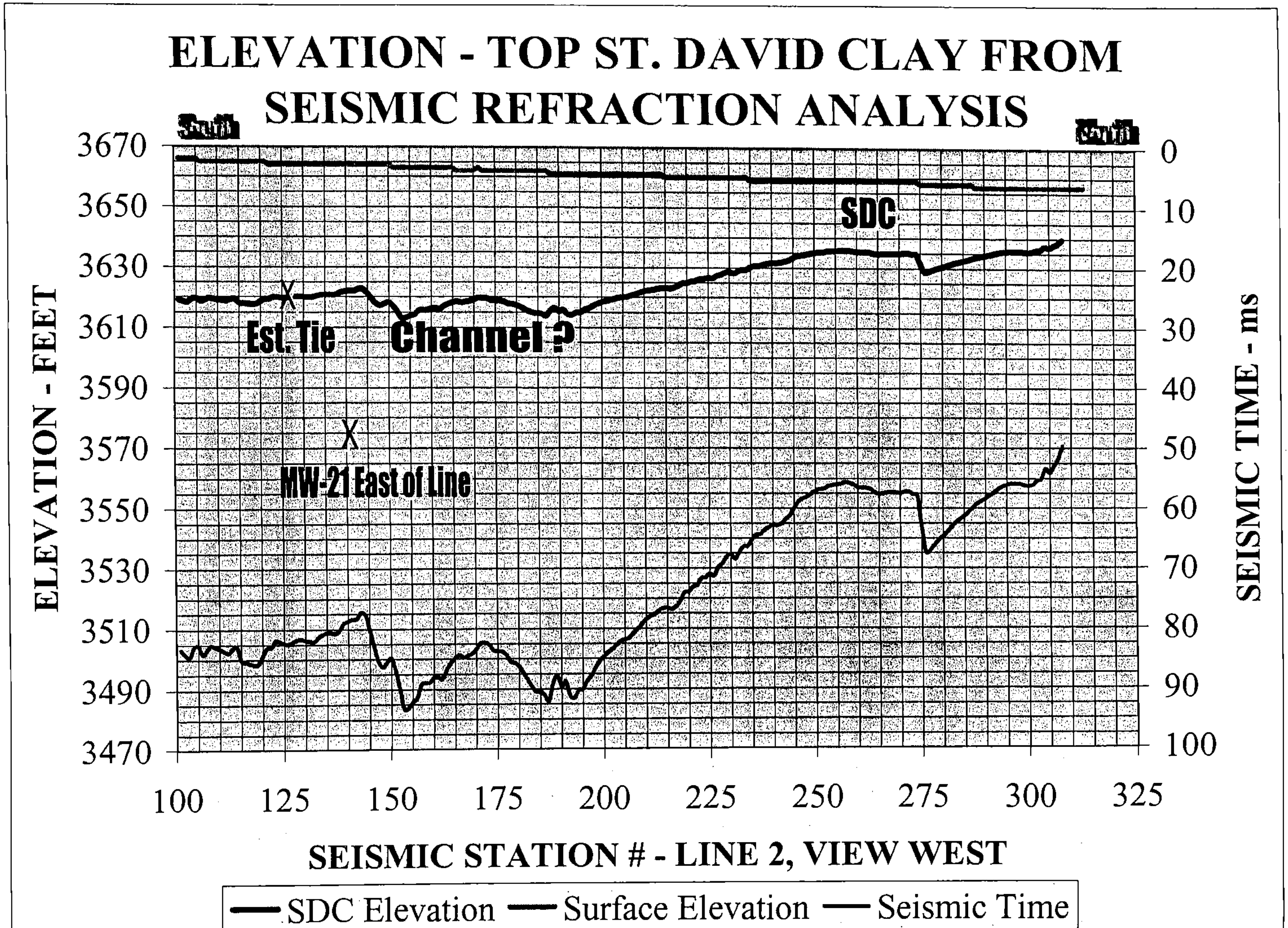
Taken collectively, these conclusions form substantial basis for a conceptualization of the aquifer geometry controlling groundwater flow and contaminant transport within the Southern Area.

APPENDIX A

Seismic Geophysical Survey Pseudosections



After: Blott, 2000
Station spacings approsximately 5 feet



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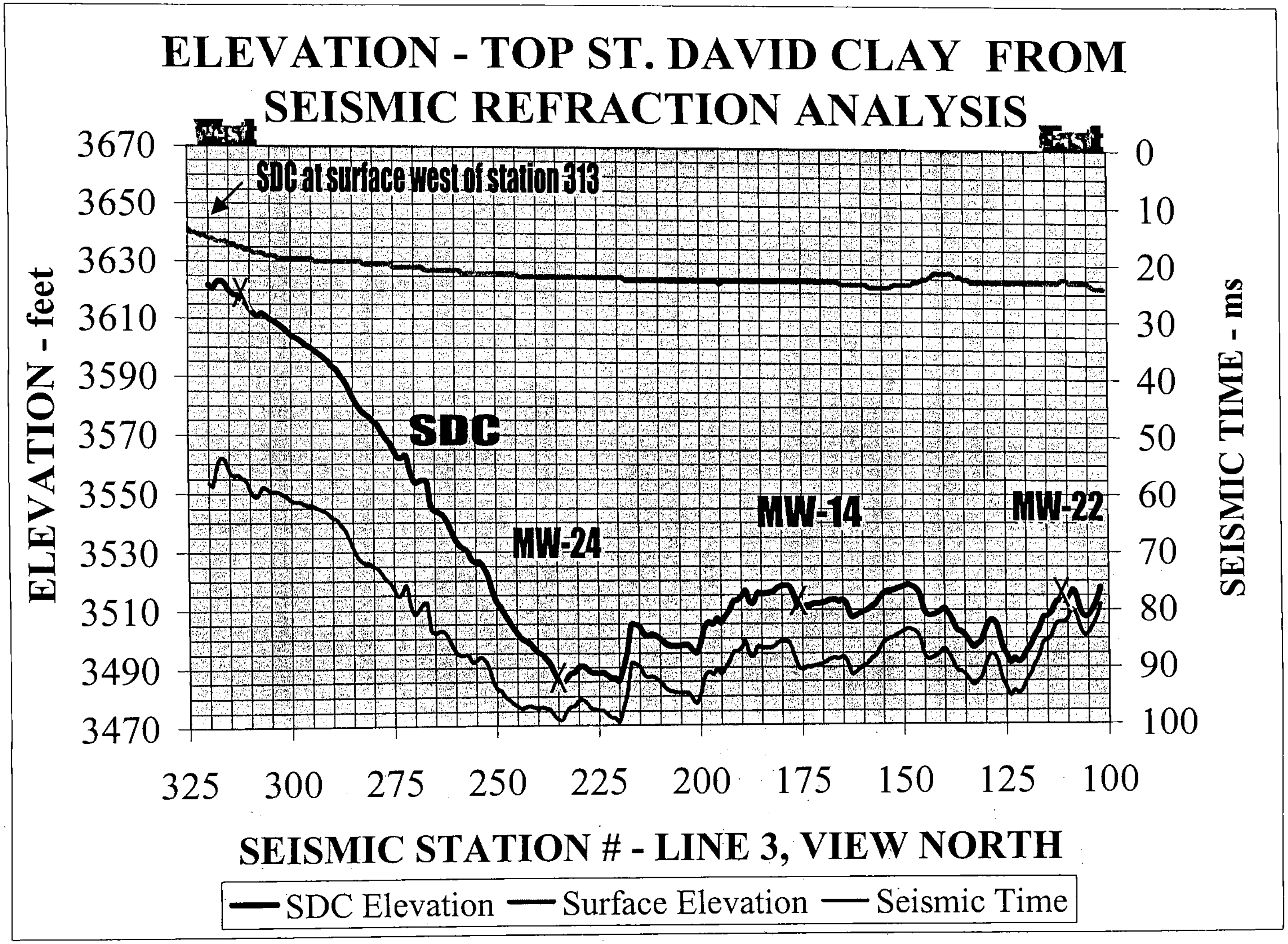
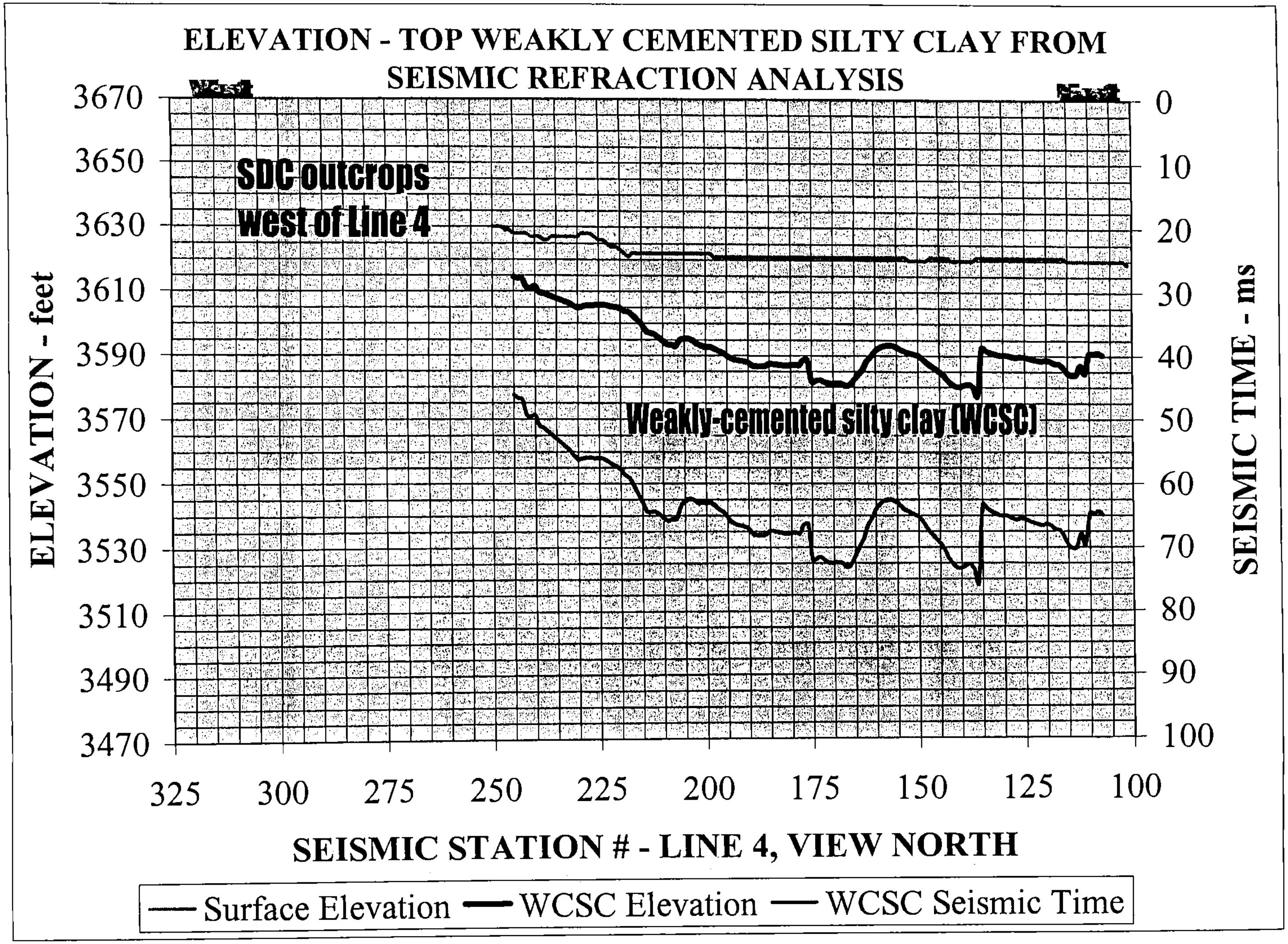


After: Blott, 2000
Station spacings approximately 5 feet

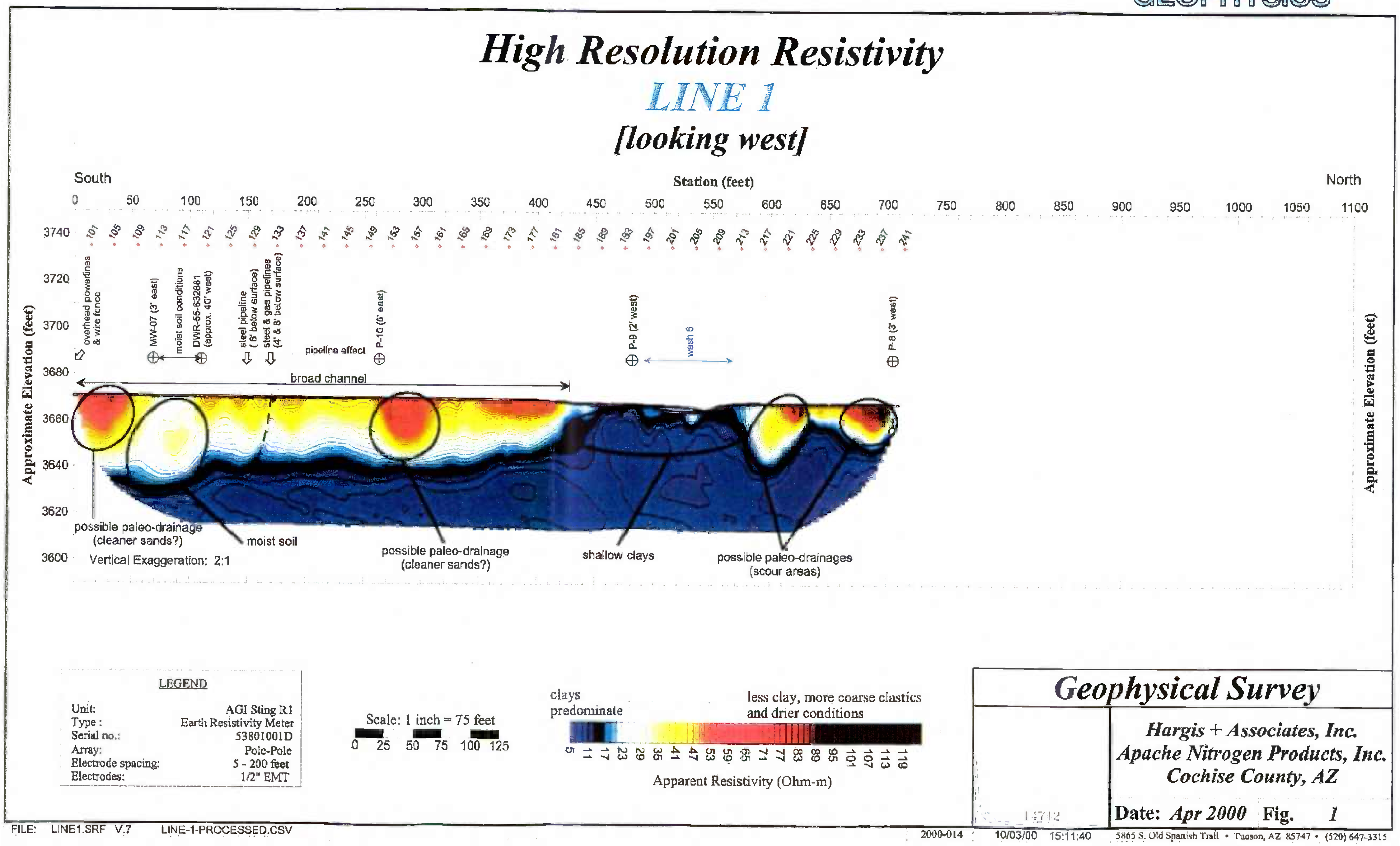


After: Blott, 2000
Station spacings approximately 5 feet

APPENDIX B

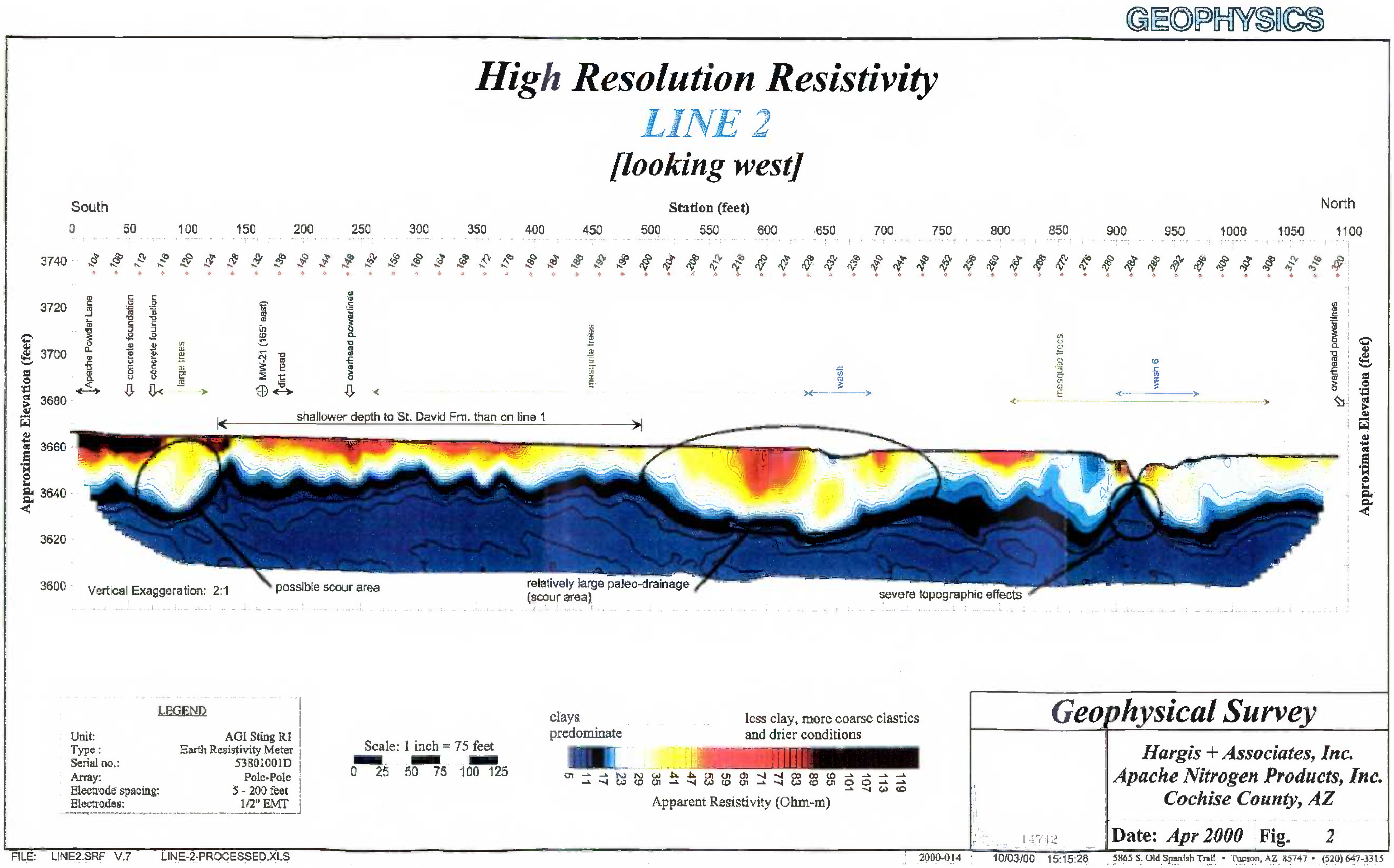
High-Resolution Resistivity Electrical Geophysical Survey Pseudosections

GEOPHYSICS



After: hydroGEOPHYSICS, Inc., 2000

Station spacing approximately 5 feet. red dots indicate every 5th station along survey line.



After: hydroGEOPHYSICS, Inc., 2000 Station spacing approximately 5 feet, ◦red dots indicate every 5th station along survey line

APPENDIX C

Perched Zone and Shallow Aquifer Groundwater Elevation Hydrographs

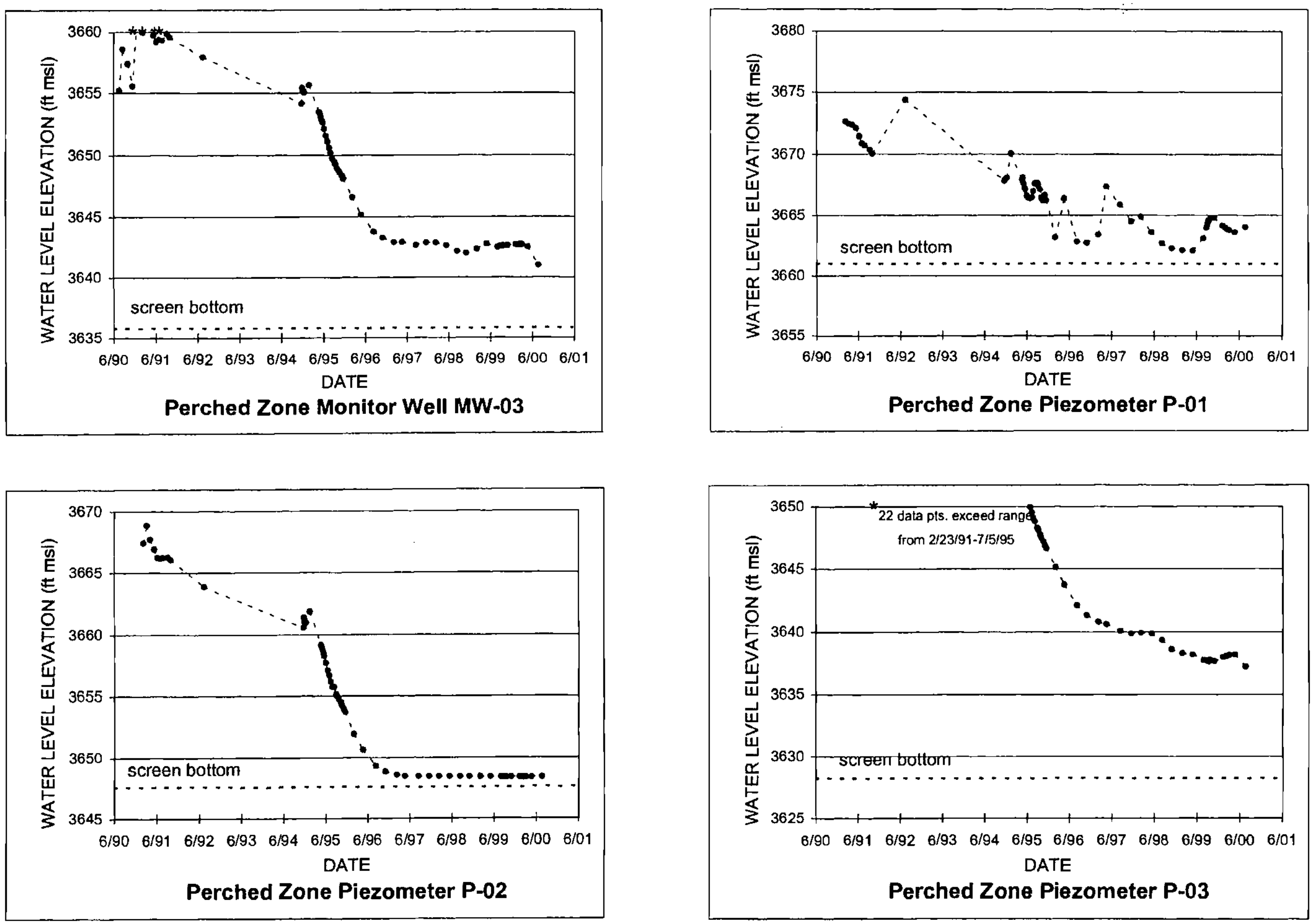


FIGURE C-1. WATER LEVEL HYDROGRAPHS FOR PERCHED ZONE MONITOR WELL MW-03 AND PERCHED ZONE PIEZOMETERS P-01, P-02, AND P-03

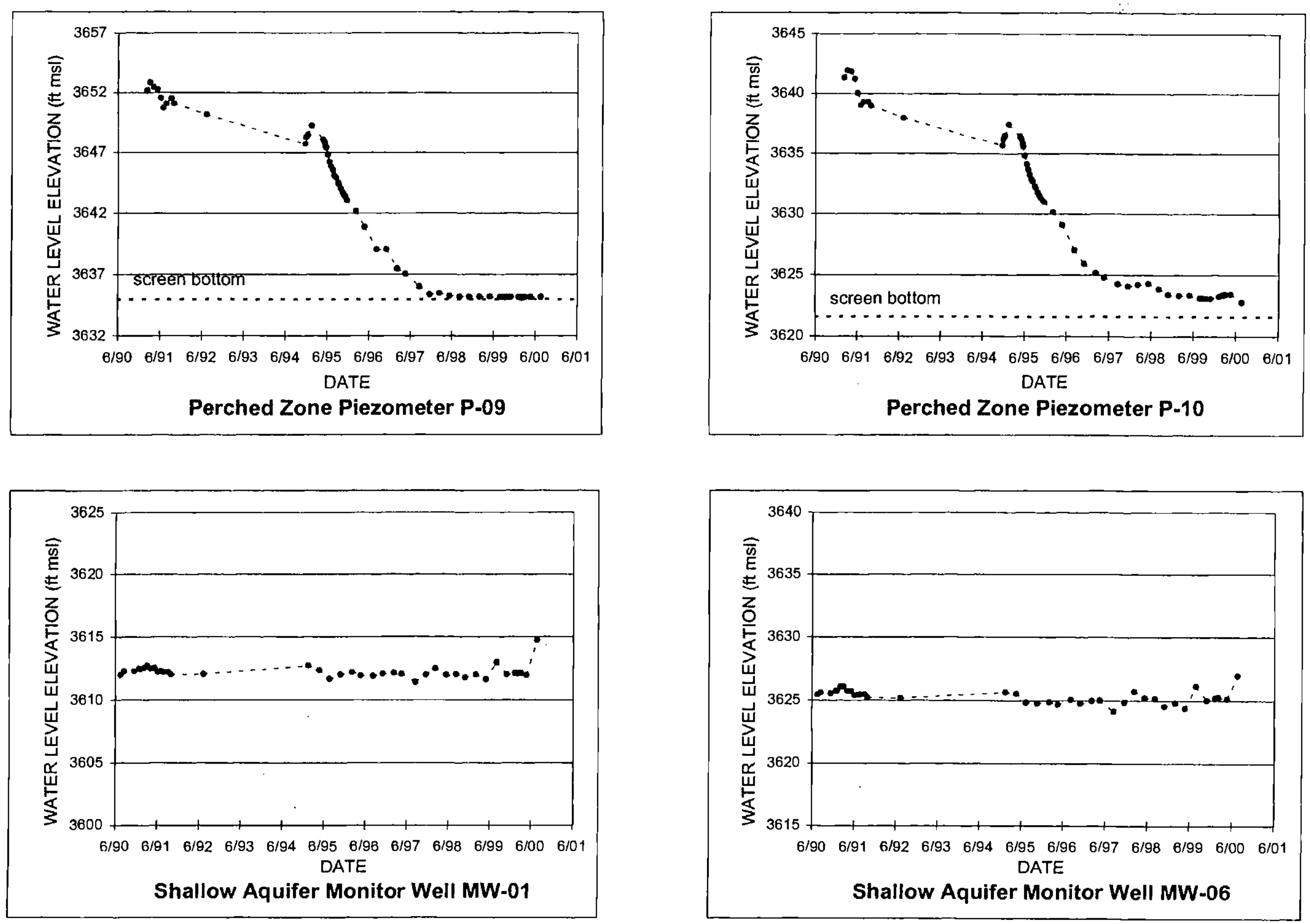
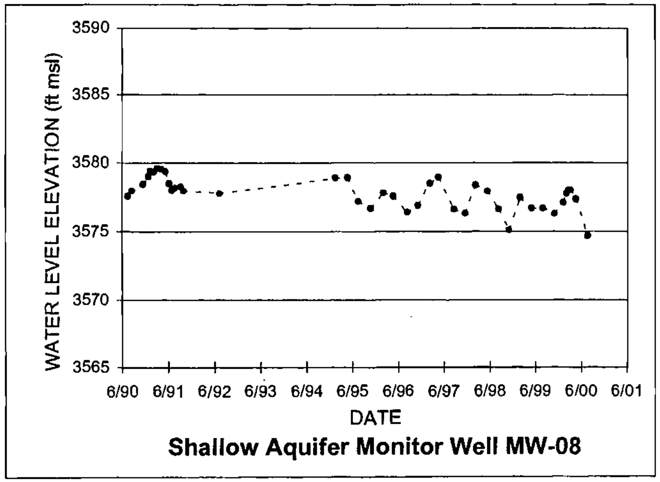
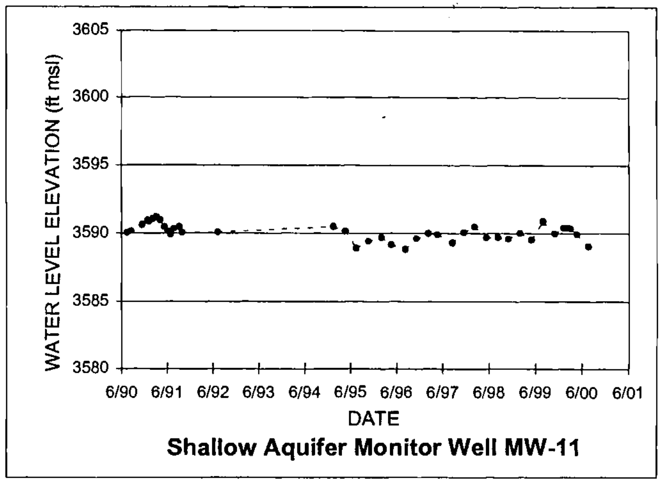
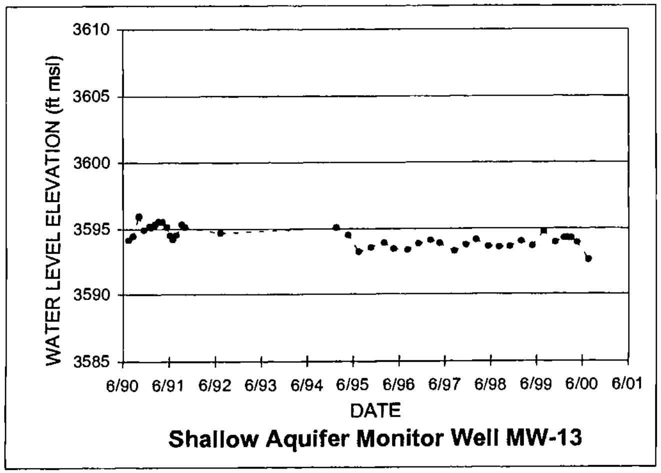


FIGURE C-2. WATER LEVEL HYDROGRAPHS FOR PERCHED ZONE PIEZOMETERS P-09 AND P-10, AND SHALLOW AQUIFER MONITOR WELLS MW-01 AND MW-06







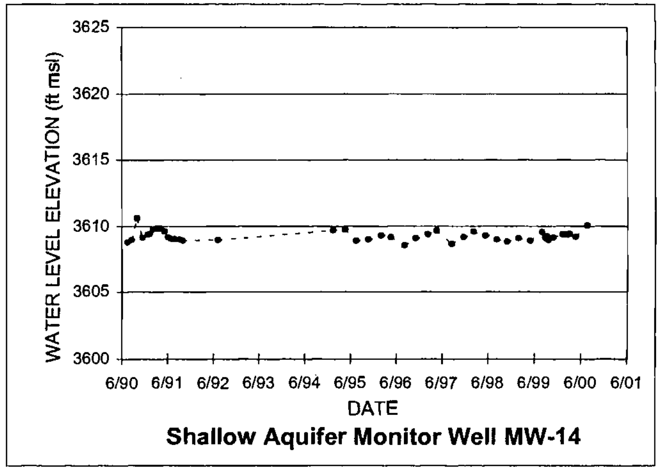


FIGURE C-3. WATER LEVEL HYDROGRAPHS FOR SHALLOW AQUIFER MONITOR WELLS MW-08, MW-11, MW-13, AND MW-14

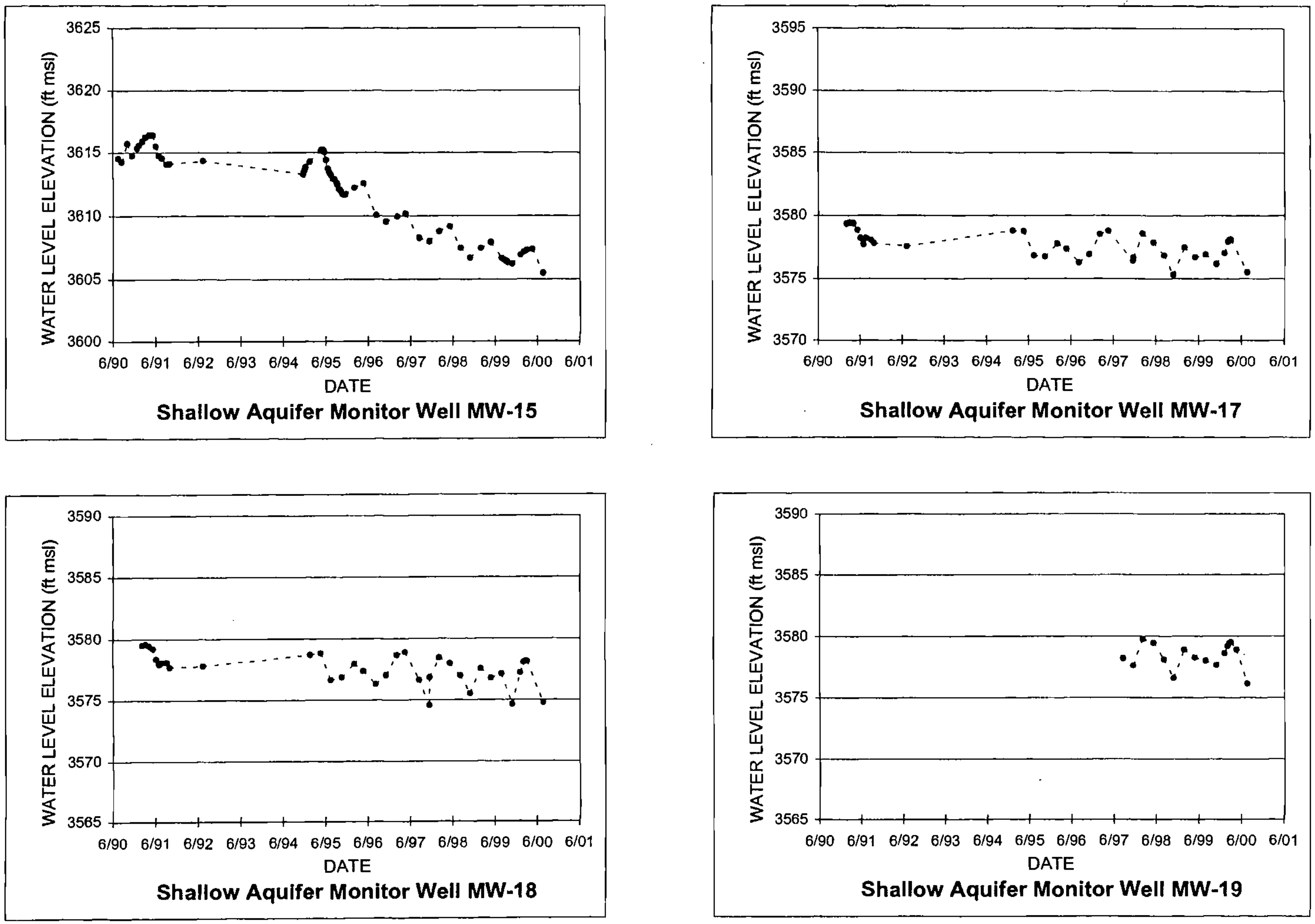


FIGURE C-4. WATER LEVEL HYDROGRAPHS FOR SHALLOW AQUIFER MONITOR WELLS MW-15, MW-17, MW-18, AND MW-19

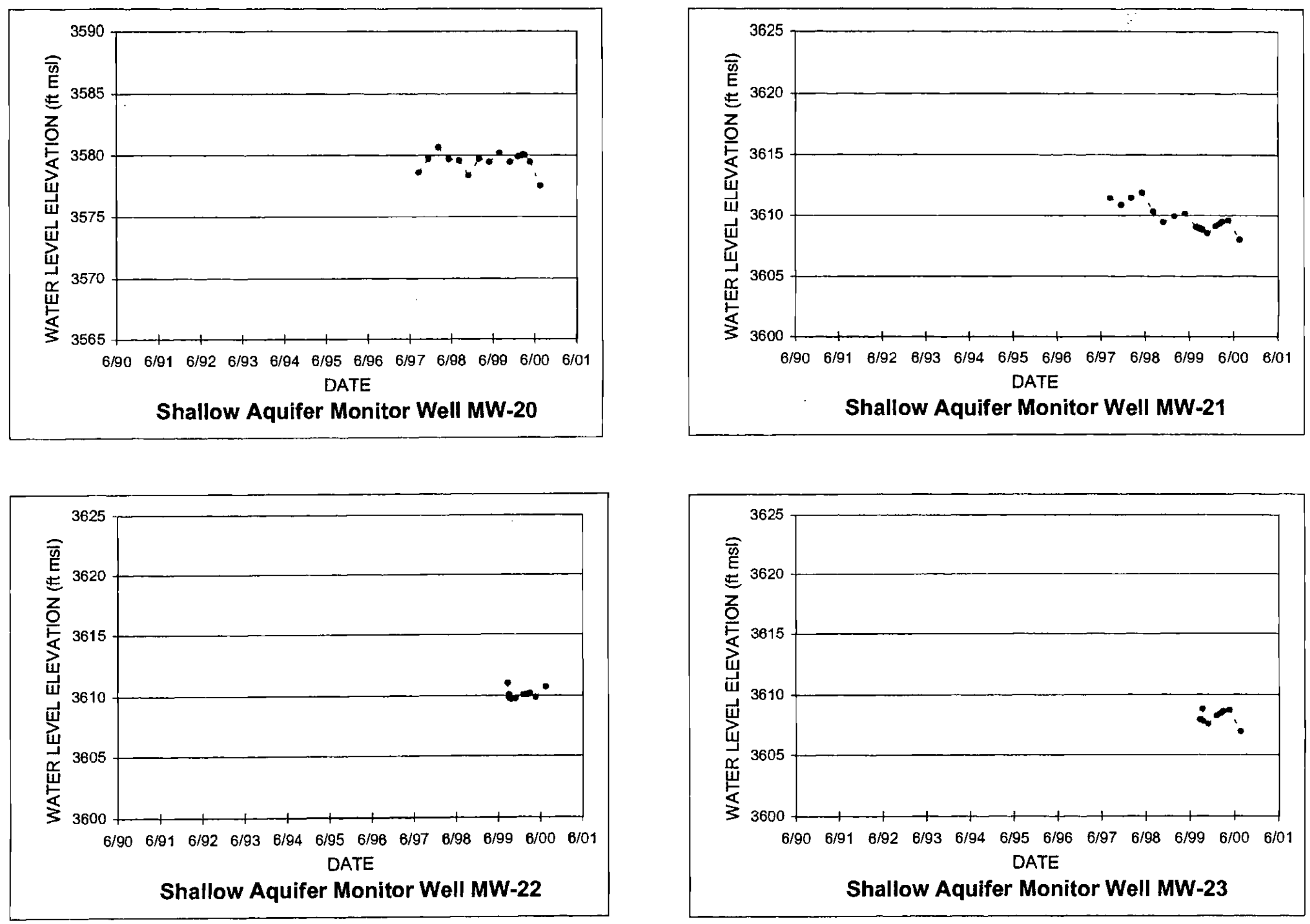


FIGURE C-5. WATER LEVEL HYDROGRAPHS FOR SHALLOW AQUIFER MONITOR WELLS MW-20, MW-21, MW-22, AND MW-23

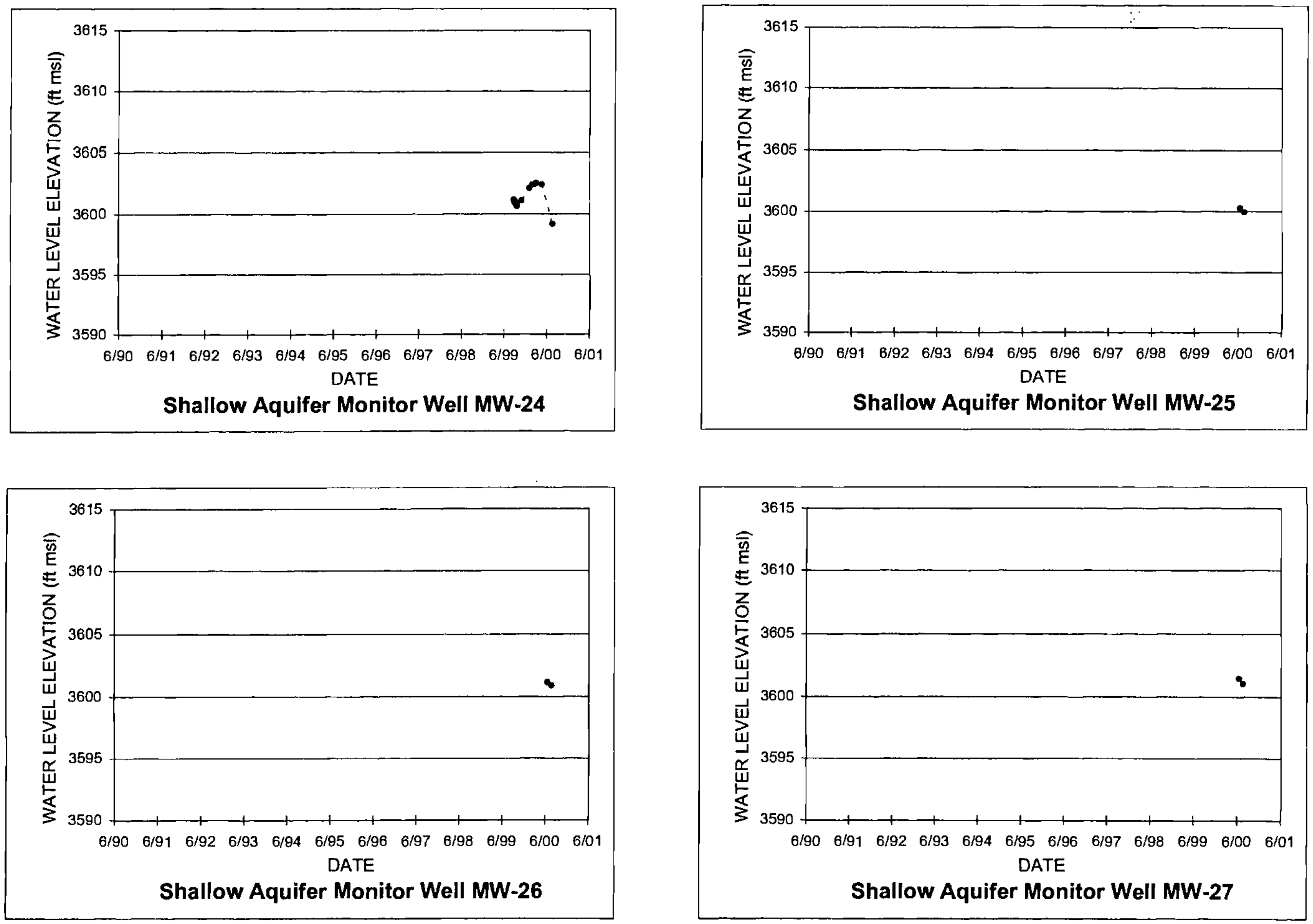
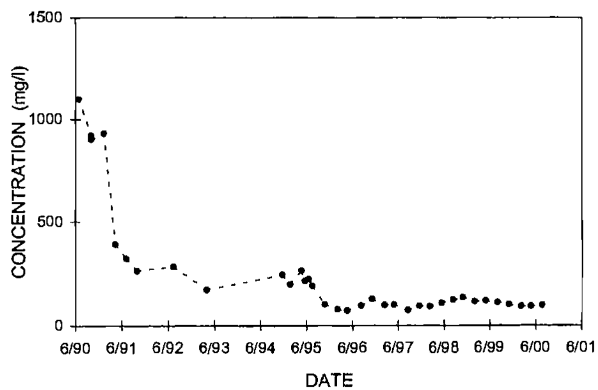


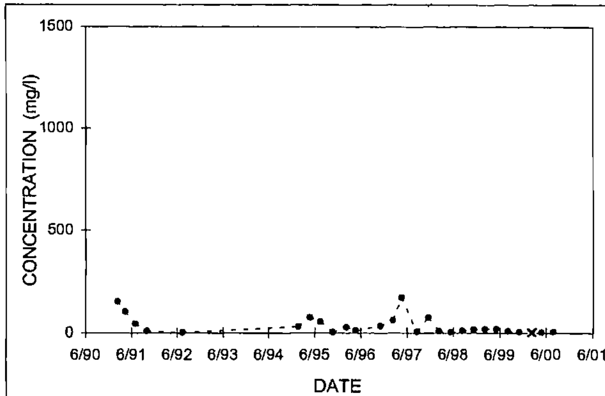
FIG C-6. WATER LEVEL HYDROGRAPHS FOR SHALLOW AQUIFER MONITOR WELLS MW-24, MW-25, MW-26 AND MW-27

APPENDIX D

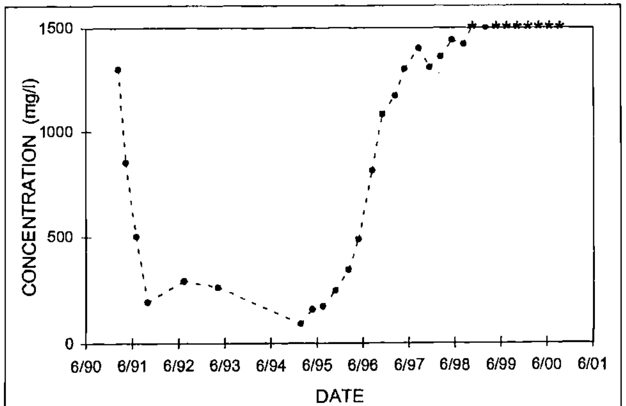
Perched Zone and Shallow Aquifer Nitrate-Nitrogen Hydrographs



Perched Zone Monitor Well MW-03



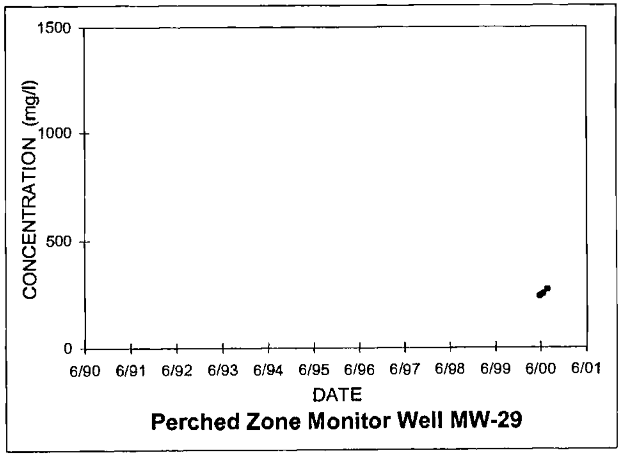
Perched Zone Piezometer P-01

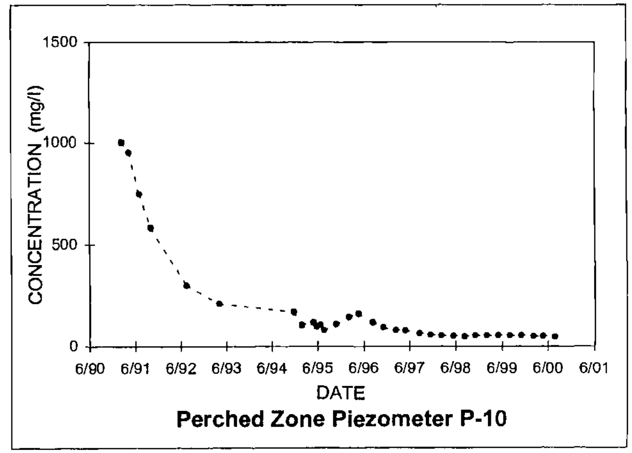


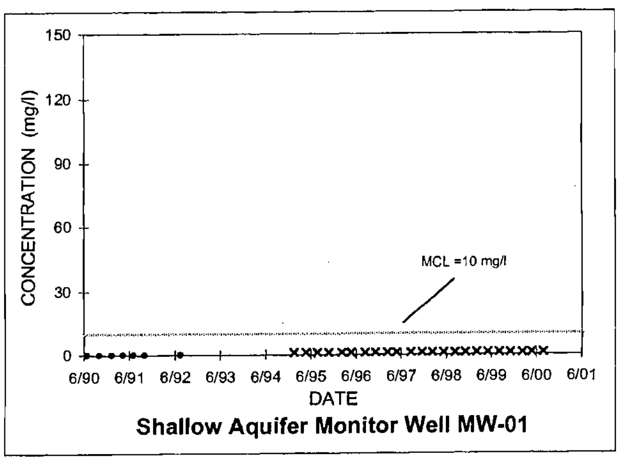
Perched Zone Piezometer P-03

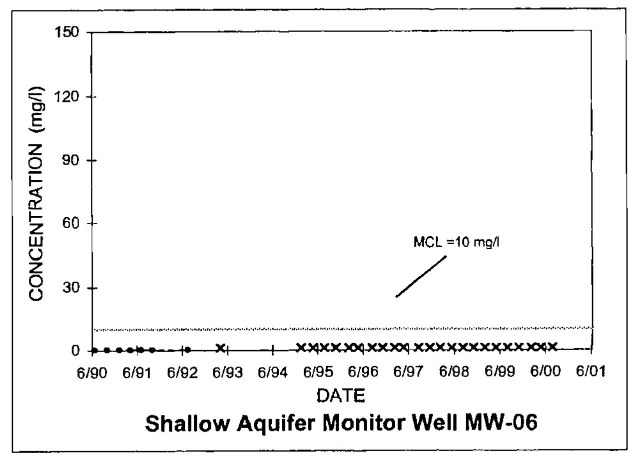
Note: see Figure D-8 for explanation of abbreviations and symbols

FIGURE D-1. WATER QUALITY HYDROGRAPHS FOR NO_3-N IN PERCHED ZONE MONITOR WELL MW-03, AND PERCHED ZONE PIEZOMETERS P-01 AND P-03



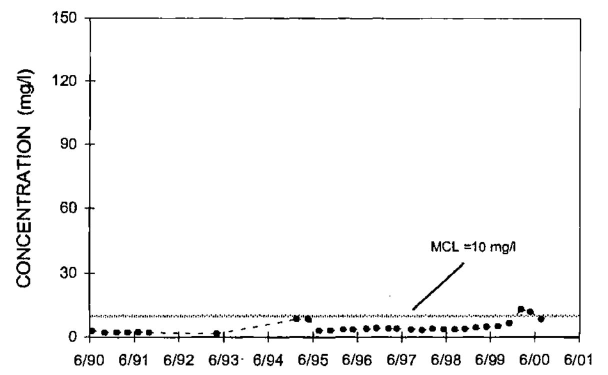




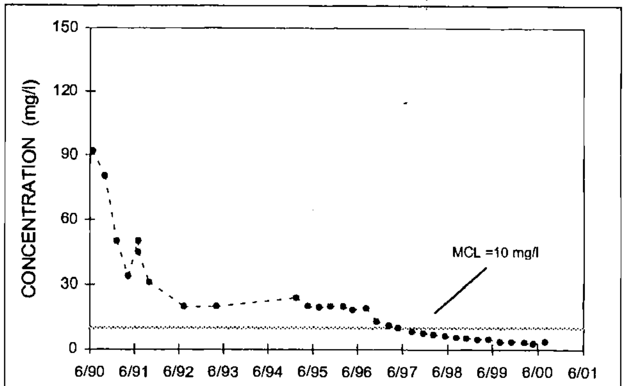


Note: see Figure D-8 for explanation of abbreviations and symbols

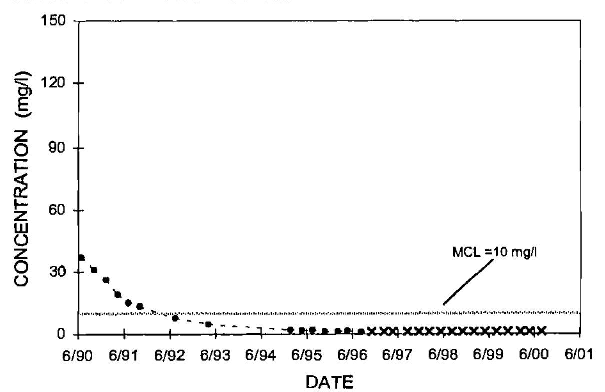
FIGURE D-2. WATER QUALITY HYDROGRAPHS FOR NO_3-N IN PERCHED ZONE MONITOR WELL MW-29, PERCHED ZONE PIEZOMETER P-10, AND SHALLOW AQUIFER MONITOR WELLS MW-01 AND MW-06



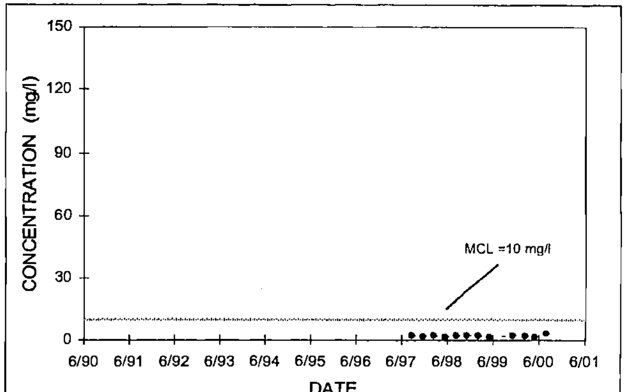
Shallow Aquifer Monitor Well MW-08



Shallow Aquifer Monitor Well MW-11



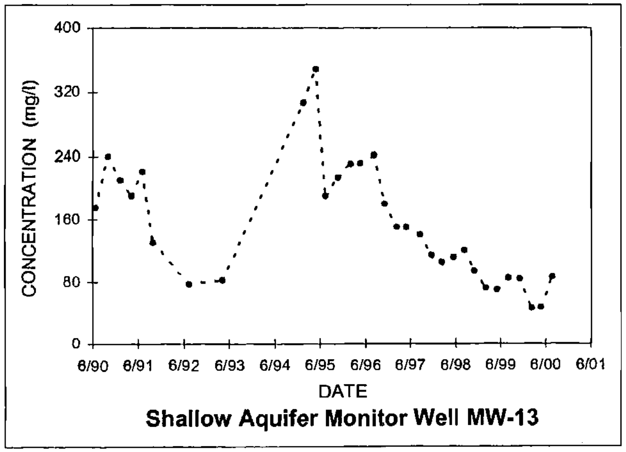
Shallow Aquifer Monitor Well MW-14

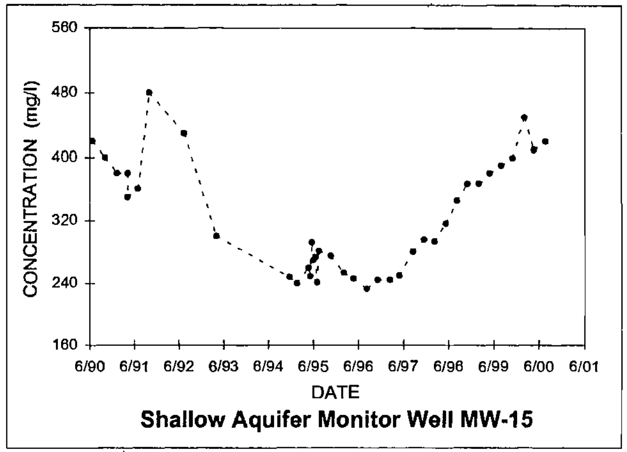


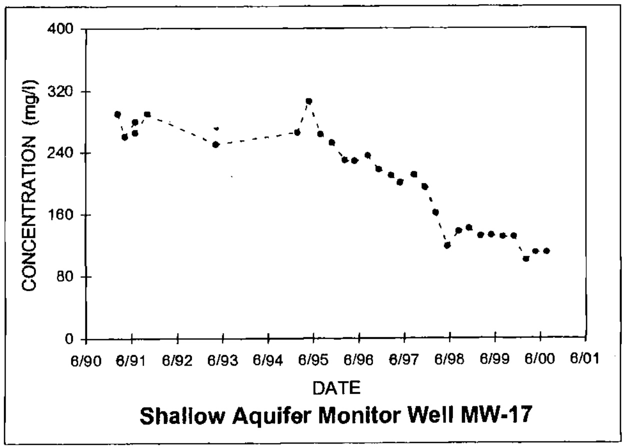
Shallow Aquifer Monitor Well MW-19

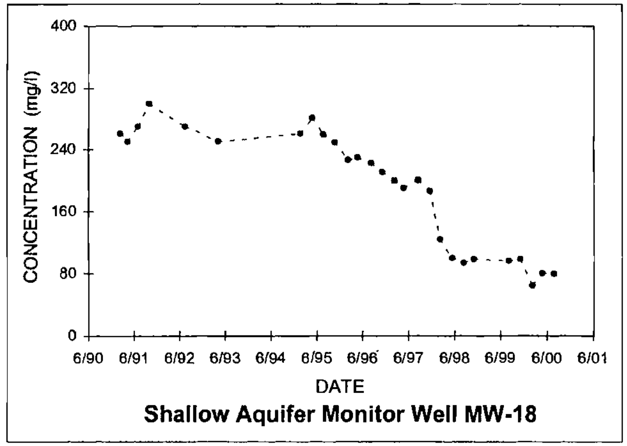
Note: see Figure D-8 for explanation of abbreviations and symbols

FIGURE D-3. WATER QUALITY HYDROGRAPHS FOR NO_3-N IN SHALLOW AQUIFER MONITOR WELLS MW-08, MW-11, MW-14, AND MW-19



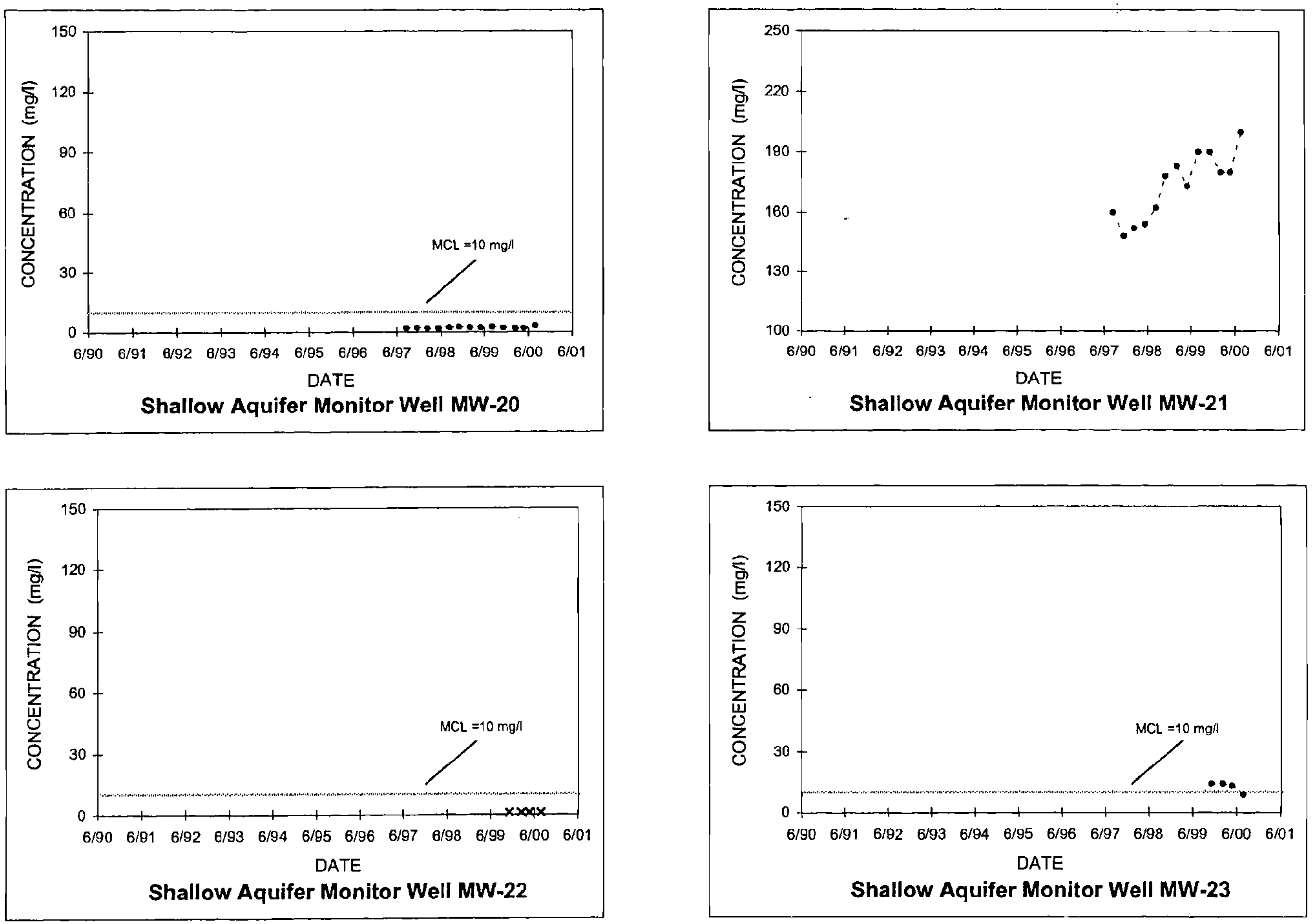






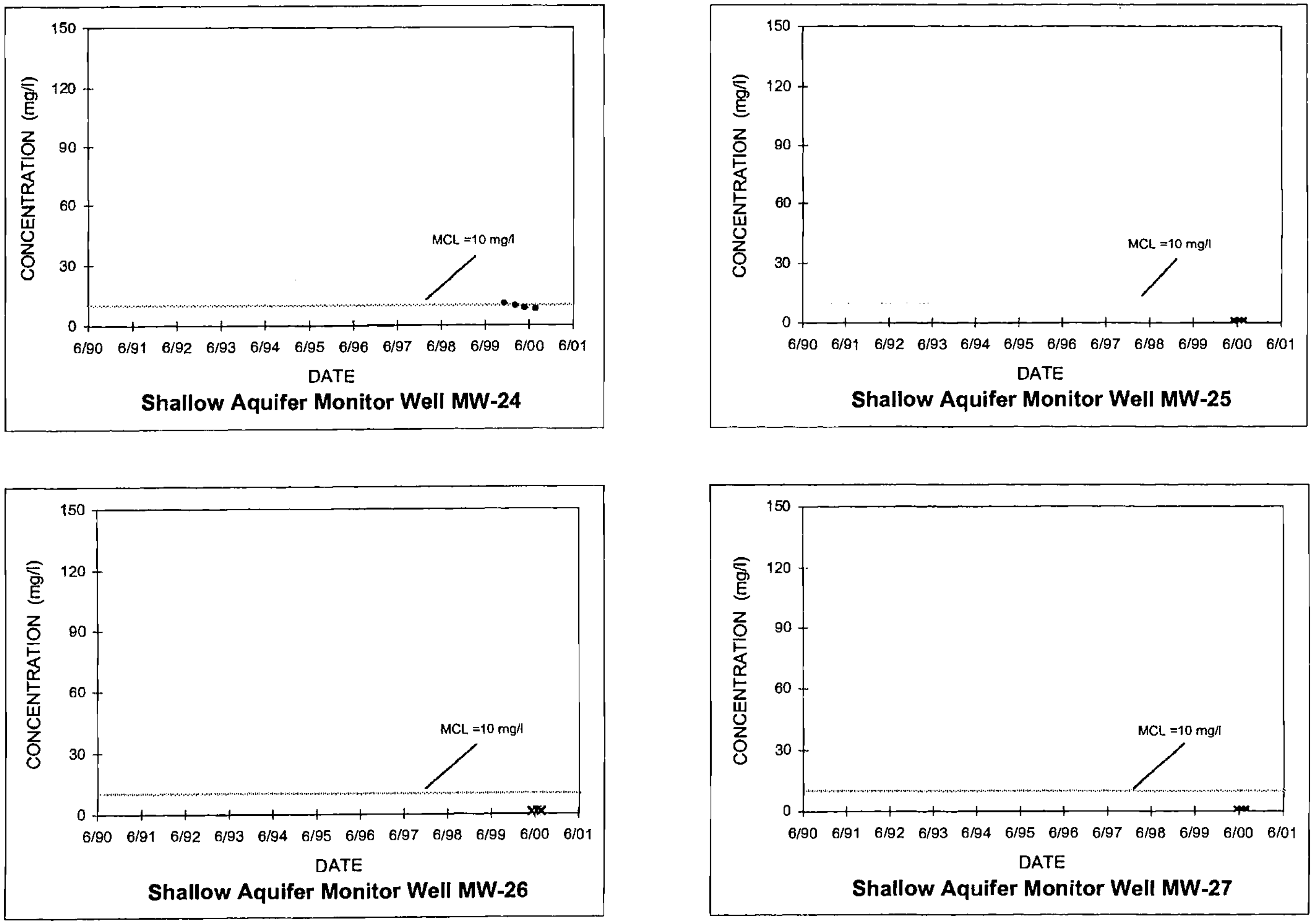
Note: see Figure D-8 for explanation of abbreviations and symbols

FIGURE D-4. WATER QUALITY HYDROGRAPHS FOR NO_3-N IN SHALLOW AQUIFER MONITOR WELLS MW-13, MW-15, MW-17, AND MW-18



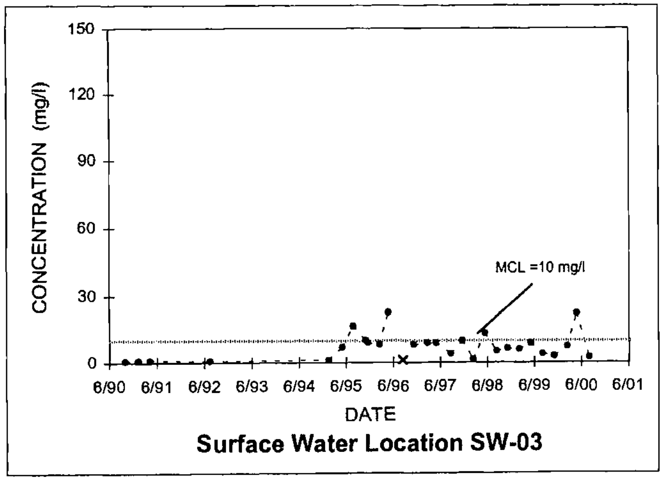
Note: see Figure D-8 for explanation of abbreviations and symbols

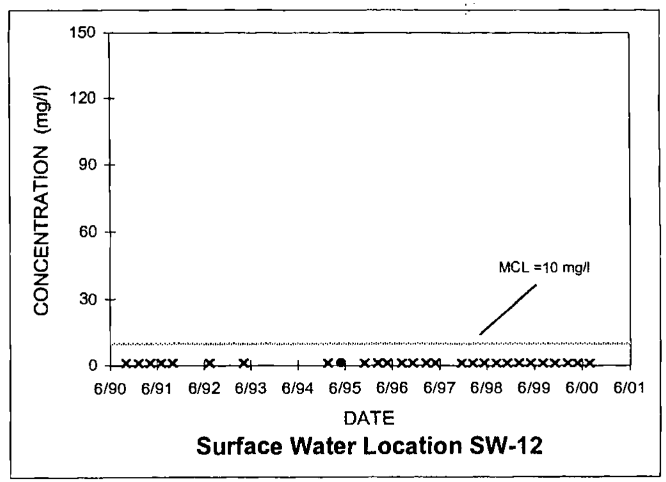
FIGURE D-5. WATER QUALITY HYDROGRAPHS FOR NO_3-N IN SHALLOW AQUIFER MONITOR WELLS MW-20, MW-21, MW-22 AND MW-23

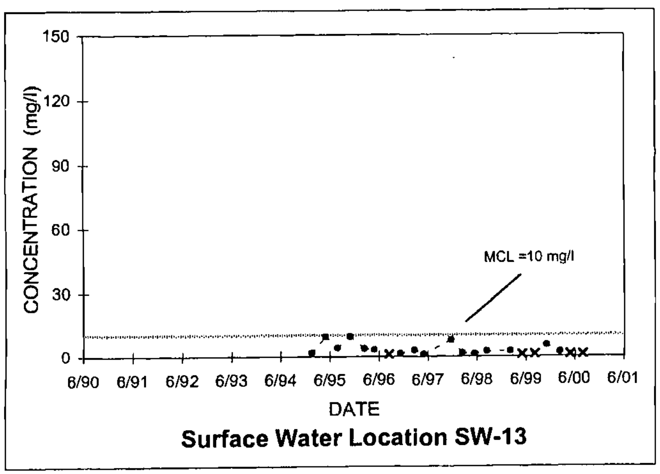


Note: see Figure D-8 for explanation of abbreviations and symbols

FIGURE D-6. WATER QUALITY HYDROGRAPHS FOR NO_3-N IN SHALLOW AQUIFER MONITOR WELLS MW-24, MW-25, MW-26 AND MW-27

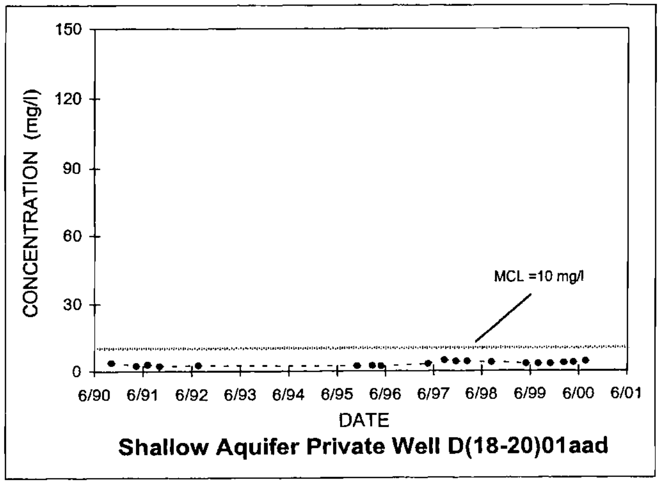






Note: see Figure D-8 for explanation of abbreviations and symbols

FIGURE D-7. WATER QUALITY HYDROGRAPH FOR NO3-N AT SURFACE WATER LOCATIONS SW-03, SW-12 AND SW-13



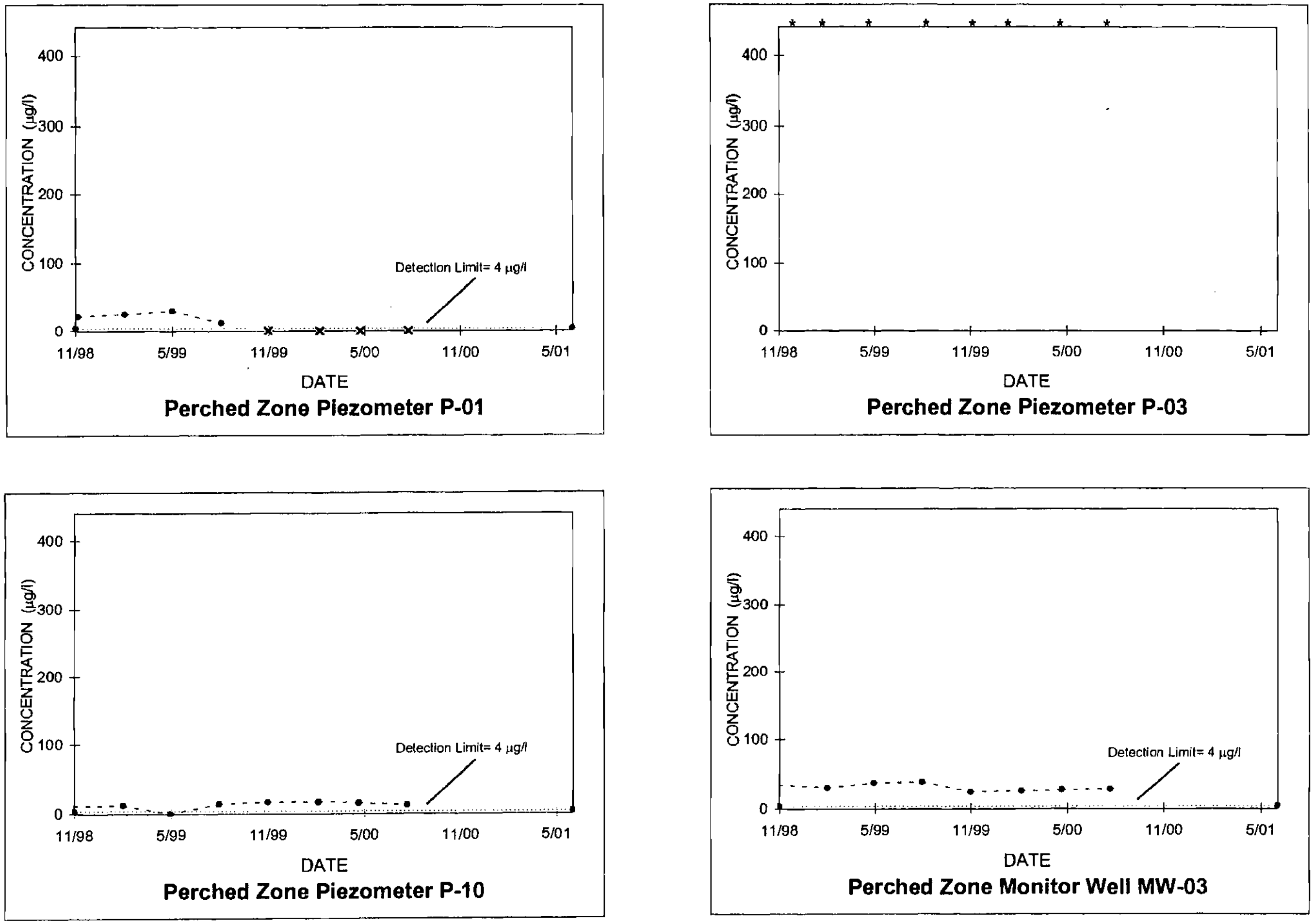
Notes:

DRY = Water level is below bottom of screen; No formation water is present
ft msl = Feet above mean sea level
INS = Less than 1 foot of formation water is present; Insufficient to collect representative sample
MCL = Federal Maximum Contaminant Level
mg/l = Milligrams per liter
X = Not detected; Numerical value is less than the method detection limit
NO_3-N = Nitrate as nitrogen
* = Value exceeds data range

FIGURE D-8. WATER QUALITY HYDROGRAPH FOR NO_3-N IN SHALLOW AQUIFER PRIVATE WELL D(18-20)01aad

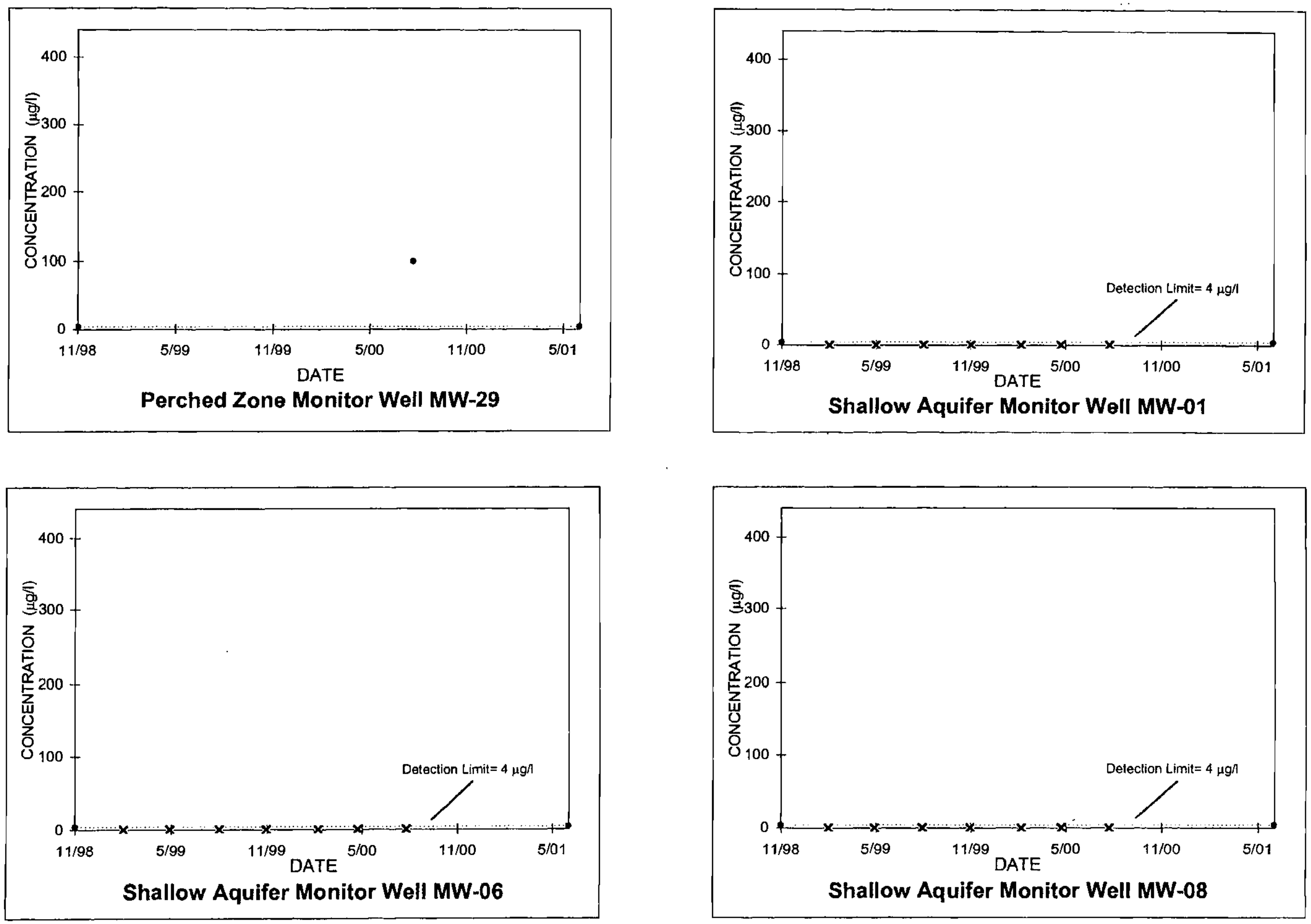
APPENDIX E

Perched Zone and Shallow Aquifer Perchlorate Hydrographs



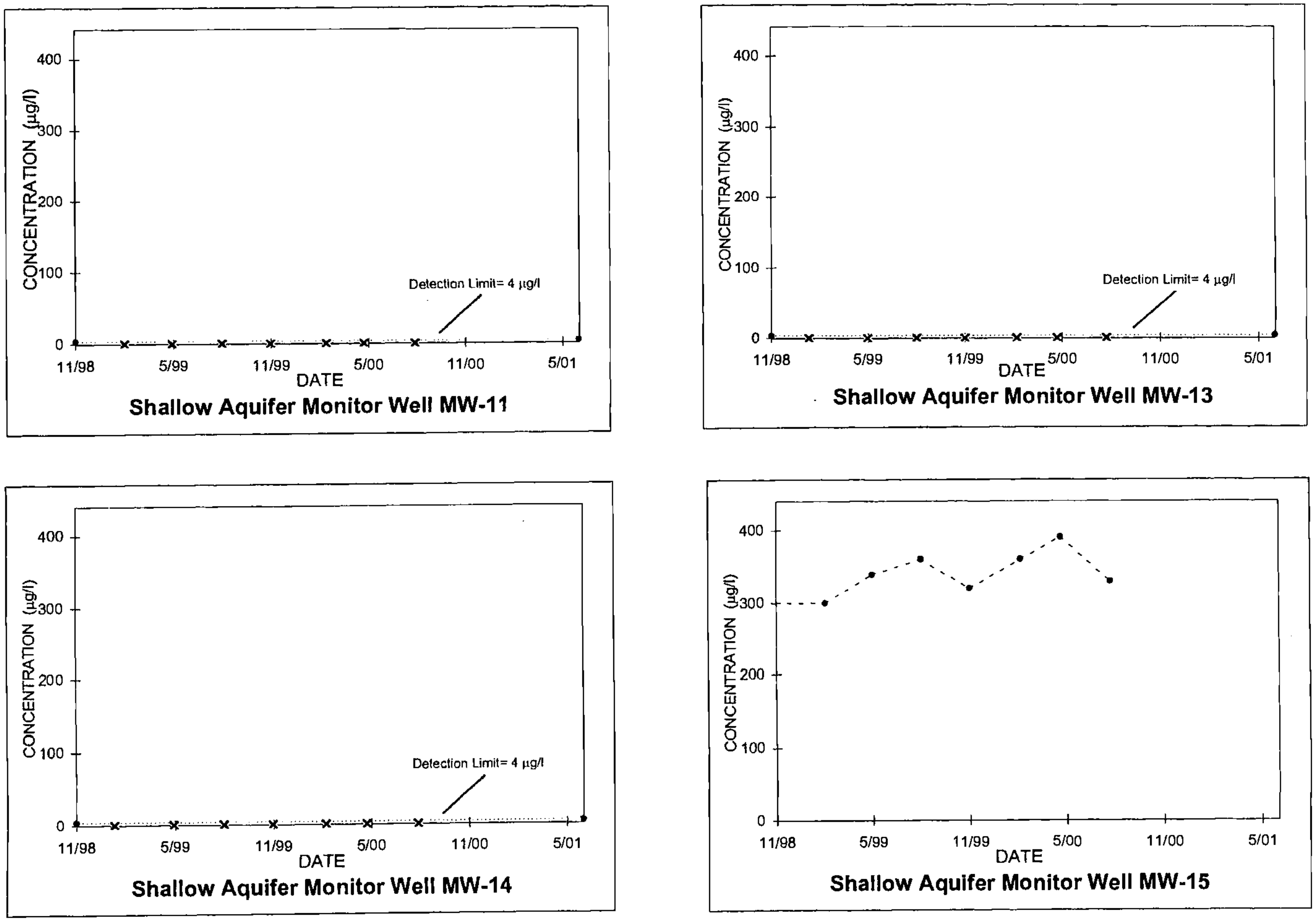
Note: see Figure E-8 for explanation of abbreviations and symbols

FIGURE E-1. WATER QUALITY HYDROGRAPHS FOR CLO4 IN
AND PERCHED ZONE PIEZOMETERS P-01, P-03 AND P-10 AND PERCHED ZONE MONITOR WELL MW-03



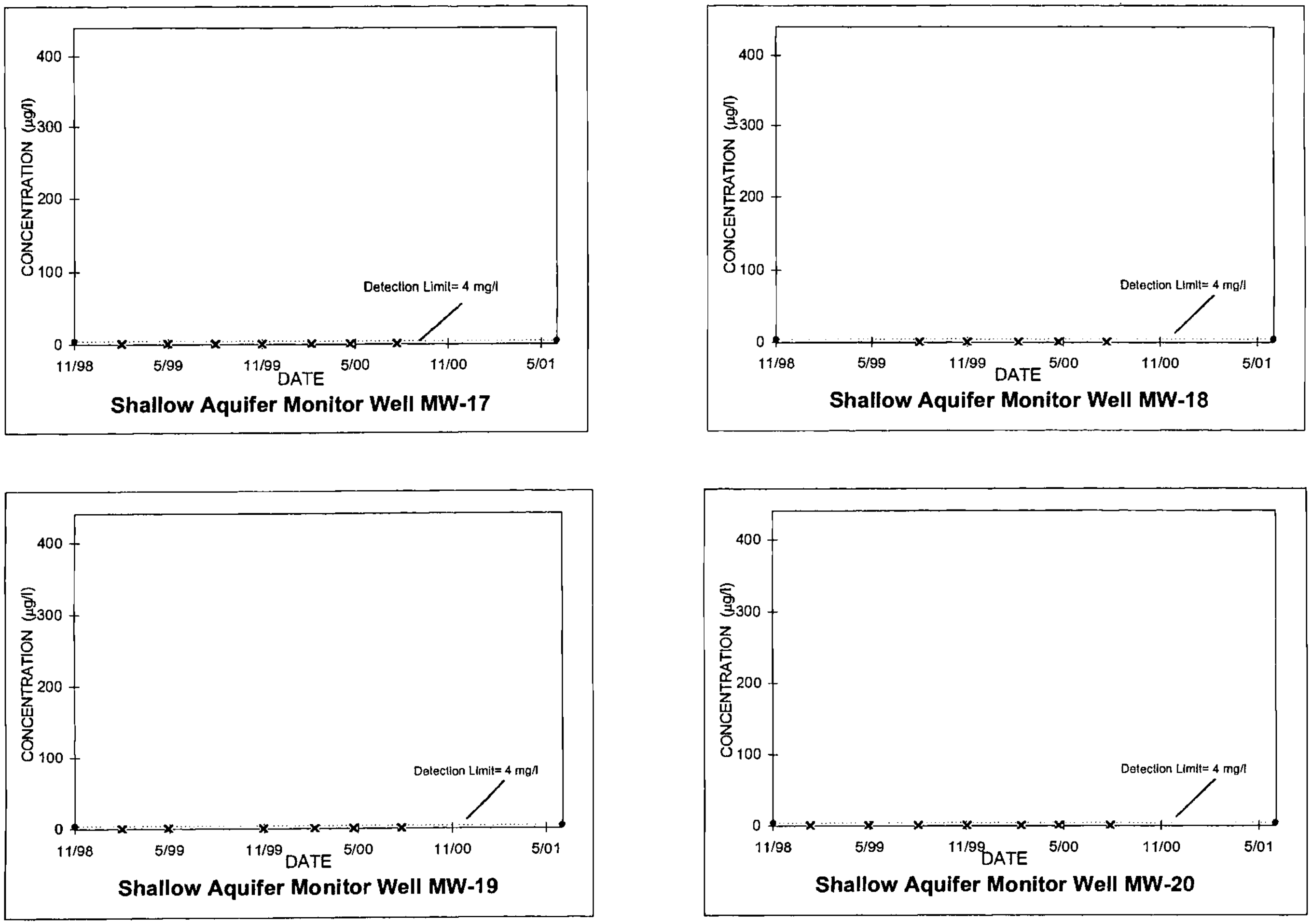
Note: see Figure E-8 for explanation of abbreviations and symbols

FIGURE E-2. WATER QUALITY HYDROGRAPHS FOR CLO4 IN PERCHED ZONE MONITOR WELL MW-29, SHALLOW AQUIFER MONITOR WELLS MW-01, MW-06 AND MW-08



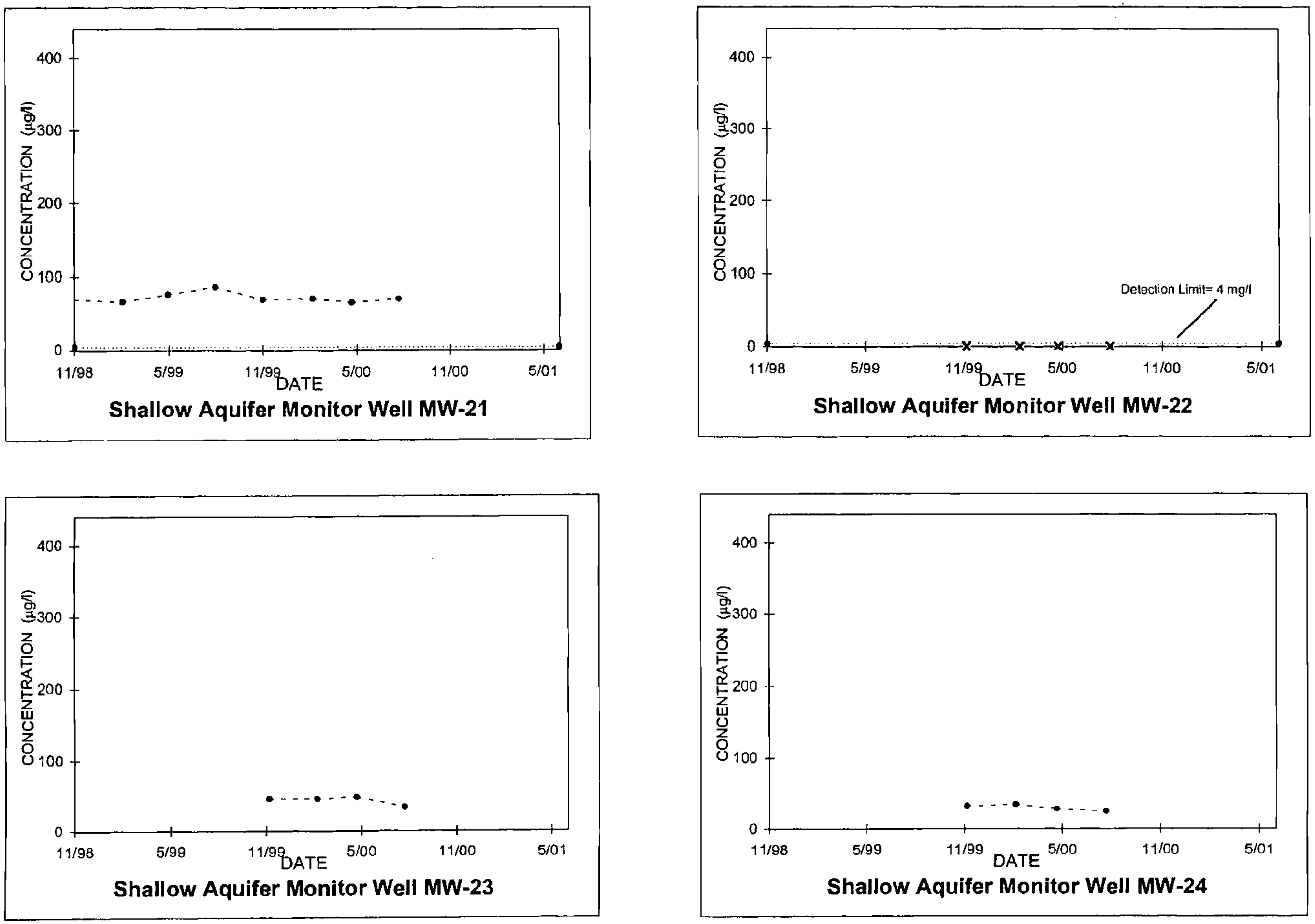
Note: see Figure E-8 for explanation of abbreviations and symbols

FIGURE E-3. WATER QUALITY HYDROGRAPHS FOR CLO4 IN SHALLOW AQUIFER MONITOR WELLS MW-11, MW-13, MW-14, AND MW-15



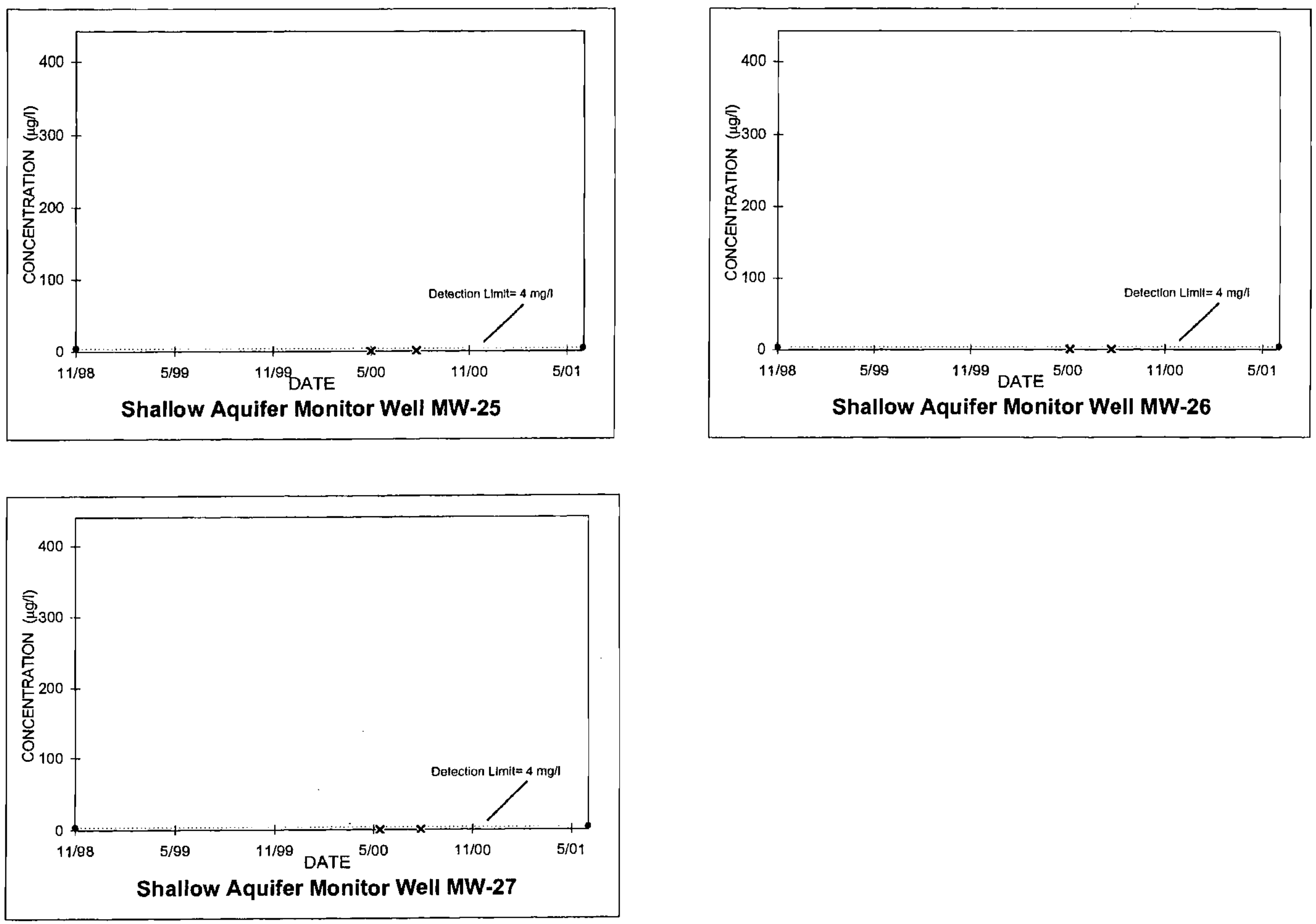
Note: see Figure E-8 for explanation of abbreviations and symbols

FIGURE E-4. WATER QUALITY HYDROGRAPHS FOR CLO4 IN SHALLOW AQUIFER MONITOR WELLS MW-17, MW-18, MW-19, AND MW-20



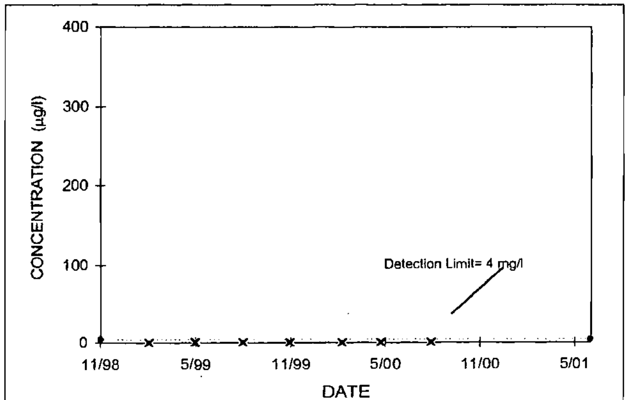
Note: see Figure E-8 for explanation of abbreviations and symbols

FIGURE E-5. WATER QUALITY HYDROGRAPHS FOR CLO4 IN SHALLOW AQUIFER MONITOR WELLS MW-21, MW-22, MW-23 AND MW-24

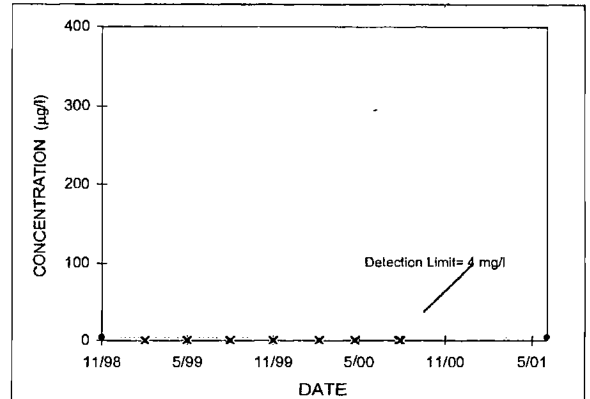


Note: see Figure E-8 for explanation of abbreviations and symbols

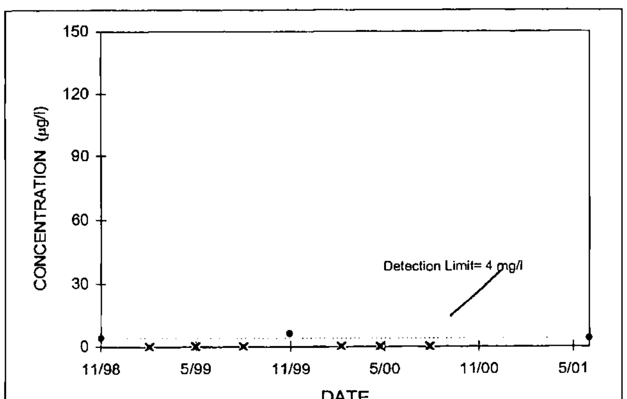
FIGURE E-6. WATER QUALITY HYDROGRAPHS FOR CLO4 IN SHALLOW AQUIFER MONITOR WELLS MW-25, MW-26 AND MW-27



Surface Water Location SW-03



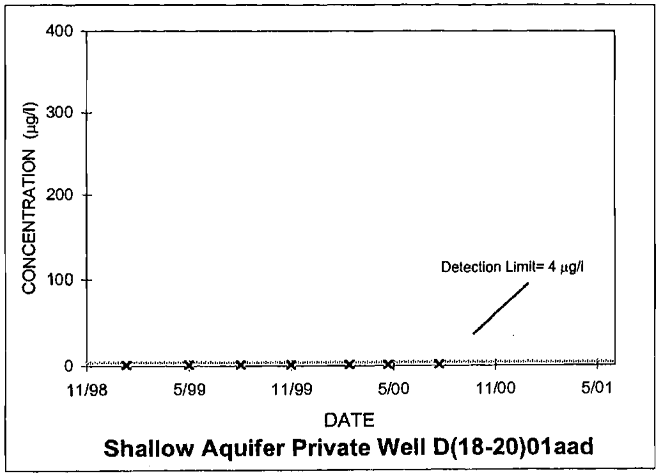
Surface Water Location SW-12



Surface Water Location SW-13

Note: see Figure E-8 for explanation of abbreviations and symbols

FIGURE E-7. WATER QUALITY HYDROGRAPH FOR CLO4 AT SURFACE WATER LOCATIONS SW-03, SW-12 AND SW-13



Notes:

DRY = Water level is below bottom of screen; No formation water is present
ft msl = Feet above mean sea level
INS = Less than 1 foot of formation water is present; Insufficient to collect representative sample
MCL = Federal Maximum Contaminant Level
µg/l Micrograms per liter
X = Not detected; Numerical value is less than the method detection limit
CLO4 = Perchlorate
* = Value exceeds data range

FIGURE E-8. WATER QUALITY HYDROGRAPH FOR CLO4 IN SHALLOW AQUIFER PRIVATE WELL D(18-20)01aad

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