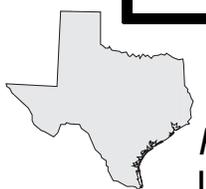
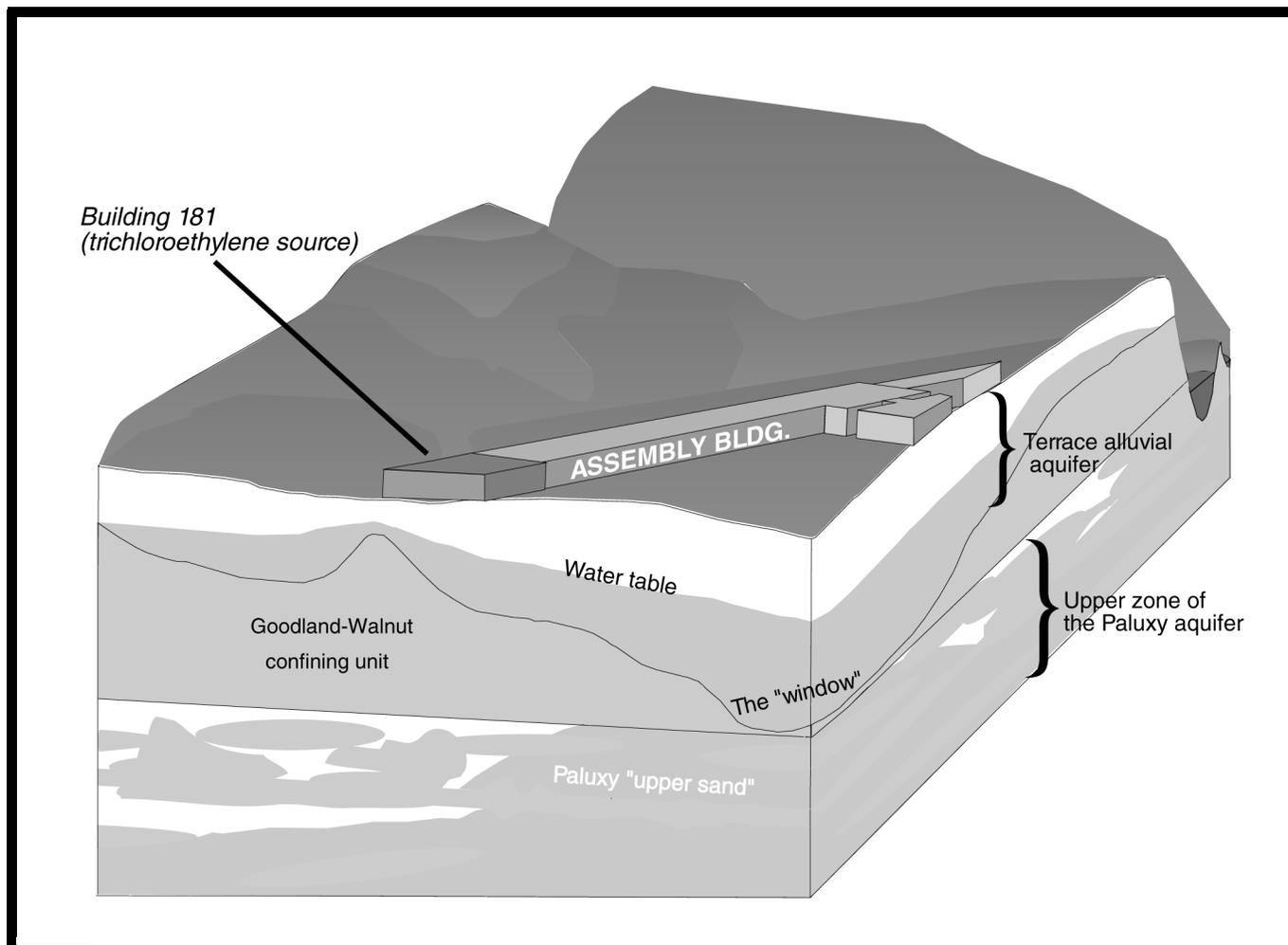


# HYDROGEOLOGY AT AIR FORCE PLANT 4 AND VICINITY AND WATER QUALITY OF THE PALUXY AQUIFER, FORT WORTH, TEXAS

U.S. GEOLOGICAL SURVEY  
Water-Resources Investigations Report 96-4091



*Prepared in cooperation with the*  
U.S. AIR FORCE AERONAUTICAL  
SYSTEMS CENTER, ENVIRONMENTAL  
MANAGEMENT DIRECTORATE



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**By E.L. Kuniansky, S.A. Jones, R.D. Brock, and M.D. Williams**

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U.S. AIR FORCE AERONAUTICAL  
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**Austin, Texas  
1996**

**U.S. DEPARTMENT OF THE INTERIOR**

**BRUCE BABBITT, Secretary**

U.S. GEOLOGICAL SURVEY

Gordon P. Eaton, Acting Director

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## VERTICAL DATUM AND ABBREVIATIONS

**Sea Level:** In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

### Abbreviations:

ft, foot  
ft/ft, foot per foot  
ft/mi, foot per mile  
°C, degree Celsius  
°F, degree Fahrenheit  
gal/d, gallon per day  
gal/min, gallon per minute  
in., inch  
µg/L, microgram per liter  
mg/d, milligram per day  
mg/L, milligram per liter

# Hydrogeology at Air Force Plant 4 and Vicinity and Water Quality of the Paluxy Aquifer, Fort Worth, Texas

By E.L. Kuniansky, S.A. Jones, R.D. Brock, and M.D. Williams

## Abstract

Ground water in the surficial terrace alluvial aquifer is contaminated at Air Force Plant 4, Fort Worth, Texas, and at the adjacent Naval Air Station. Some of the contaminated water has leaked from the terrace alluvial aquifer to an uppermost interval of the Paluxy Formation (the Paluxy "upper sand") beneath the east parking lot, east of the assembly building, and to the upper and middle zones of the Paluxy aquifer near Bomber Road, west of the assembly building. Citizens are concerned that contaminants from the plant, principally trichloroethylene and chromium might enter nearby municipal and domestic wells that pump water from the middle and lower zones of the Paluxy aquifer.

Geologic formations that crop out in the study area, from oldest to youngest, are the Paluxy Formation (aquifer), Walnut Formation (confining unit), and Goodland Limestone (confining unit). Beneath the Paluxy Formation is the Glen Rose Formation (confining unit) and Twin Mountains Formation (aquifer). The terrace alluvial deposits overlie these Cretaceous rocks.

The terrace alluvial aquifer, which is not used for municipal water supply, is separated from the Paluxy aquifer by the Goodland-Walnut confining unit. The confining unit restricts the flow of ground water between these aquifers in most places; however, downward leakage to the Paluxy aquifer might occur through the "window," where the confining unit is thin or absent.

The Paluxy aquifer is divided into upper, middle, and lower zones. The Paluxy "upper sand" underlying the "window" is an apparently isolated, mostly unsaturated, sandy lens within the uppermost part of the upper zone. The Paluxy aquifer is

recharged by leakage from Lake Worth and by precipitation on the outcrop area. Discharge from the aquifer primarily occurs as pumpage from municipal and domestic wells. The Paluxy aquifer is separated from the underlying Twin Mountains aquifer by the Glen Rose confining unit.

Water-level maps indicate that (1) ground water in the terrace alluvial aquifer appears to flow outward, away from Air Force Plant 4; (2) a ground-water mound, possibly caused by downward leakage from the terrace alluvial aquifer, is present in the Paluxy "upper sand" beneath the "window;" and (3) lateral ground-water flow in regionally extensive parts of the Paluxy aquifer is from west to east-southeast.

Trichloroethylene concentrations at Air Force Plant 4 have ranged from about 10,000 to about 100,000 micrograms per liter in the terrace alluvial aquifer, from 8,000 to 11,000 micrograms per liter in the Paluxy "upper sand," and from 2 to 50 micrograms per liter in the upper and middle zones of the Paluxy aquifer. Chromium concentrations at Air Force Plant 4 have ranged from 0 to 629 micrograms per liter in the terrace alluvial aquifer.

The seven municipal wells mostly west and south of Air Force Plant 4 are not along a flowpath for leakage of contaminants from the plant because ground-water flow in the Paluxy aquifer is toward the east-southeast. Furthermore, trichloroethylene was not detected in any of these wells in 1993 when all were sampled for water quality.

The results of water-quality sampling at 10 domestic wells northwest of the Air Force Plant 4 during April 1993 and April 1995 indicated that neither trichloroethylene nor chromium had migrated off-site to these wells.

## INTRODUCTION

Air Force Plant 4 (AFP4) in the Fort Worth area, Texas (fig. 1), has been in operation since 1942 when B-24 bombers were constructed for use in World War II. Subsequently, the facility has been used to manufacture B-36, B-58, F-111, and F-16 aircraft, radar units, missile components, and spare parts. The fabrication and assembly of aircraft and aircraft parts require various kinds of solvents, paints, metals, oils, fuels, and other toxic chemicals.

Ground-water contamination of the surficial terrace alluvial aquifer has occurred at AFP4 and at the adjacent Naval Air Station, Fort Worth, Joint Reserve Base, Carswell Field (NAS) (U.S. Army Corps of Engineers, 1986; Jacobs Engineering Group Inc., 1993; Geo-Marine, Inc., 1995; RUST Geotech, 1995a, b, c, d). Contaminated water from the terrace alluvial aquifer is known to have leaked into the Paluxy aquifer at two areas within the boundaries of AFP4 (U.S. Air Force, Aeronautical Systems Center, 1995). In August 1990, AFP4 was placed on the U.S. Environmental Protection Agency (USEPA) National Priorities List as a Superfund clean-up site. The ground-water contaminants of principal concern are: (1) trichloroethylene (TCE), a solvent used for degreasing metal parts during the manufacture of airplanes; and (2) chromium, a metal used in plating metal parts. These contaminants were used and stored in the chemical processing facility in building 181 (southwest corner of assembly building, fig. 2).

Citizens are concerned that contaminants from AFP4 might enter nearby municipal and domestic wells that withdraw water from the middle and lower zones of the Paluxy aquifer (J.D. Doepker, U.S. Air Force, oral commun., 1995). The City of White Settlement has seven municipal water-supply wells (fig. 2) west and south of AFP4. Additionally, domestic water-supply wells are located northwest of AFP4 (fig. 2).

At the request of the U.S. Air Force Aeronautical Systems Center, Environmental Management Directorate (ASC), the U.S. Geological Survey (USGS) reviewed data and reports of U.S. Air Force contractors, collected water-level data in Tarrant County, installed 16 monitoring wells, collected lithologic data, and collected water-quality data at domestic wells northwest of AFP4.

## Purpose and Scope

The purpose of this report is to (1) describe the hydrogeology at AFP4 and vicinity; and (2) assess the quality of water in the Paluxy aquifer northwest of AFP4 and determine if contaminants detected at AFP4 have migrated off-site to domestic wells or have the potential to migrate off-site to municipal water-supply wells in White Settlement. The hydrogeology of the Paluxy aquifer and adjacent aquifers (terrace alluvial and Twin Mountains aquifers) and confining units (Goodland-Walnut and Glen Rose confining units) in the vicinity of AFP4 is described. The horizontal direction of ground-water flow in the terrace alluvial aquifer and the potential for downward movement of contaminated ground water from the terrace alluvial aquifer to the Paluxy "upper sand" are evaluated. The vertical and horizontal directions of flow in the zones of the Paluxy aquifer are described. Analyses of water samples collected from domestic wells northwest of AFP4 and from nested monitoring wells adjacent to AFP4 are compiled to assess the water quality of the Paluxy aquifer.

## Description of Study Area

The study area is in north-central Texas in Tarrant County northwest of Fort Worth (fig. 1) within part of the Trinity River Basin. The study area is drained primarily by the West Fork Trinity River. Farmers Branch, Meandering Road Creek, and Kings Branch are small, intermittent tributaries to the West Fork Trinity River that drain AFP4 and NAS.

AFP4 was built on a 600-acre site and NAS is on a 3,000-acre site adjacent to the southeast shore of Lake Worth. AFP4 is bounded on the north by Lake Worth, on the east by NAS, on the south by White Settlement, and on the west by Bomber Road, just east of Meandering Road Creek. The land surface of the area has some rolling hills, but is relatively flat with a few limestone bluffs and hills. Land-surface altitudes range from 680 to 640 ft above sea level, from west to east along the southern boundary of AFP4, to about 600 ft above sea level along the northern boundary of AFP4, near Lake Worth. The assembly building at AFP4 was built upon a topographic high that overlies a north-south trending bedrock high.

The climate is subhumid, with summers generally long and hot (average July temperature about 96 °F) and winters generally short and mild (average January temperature about 34 °F). The average annual

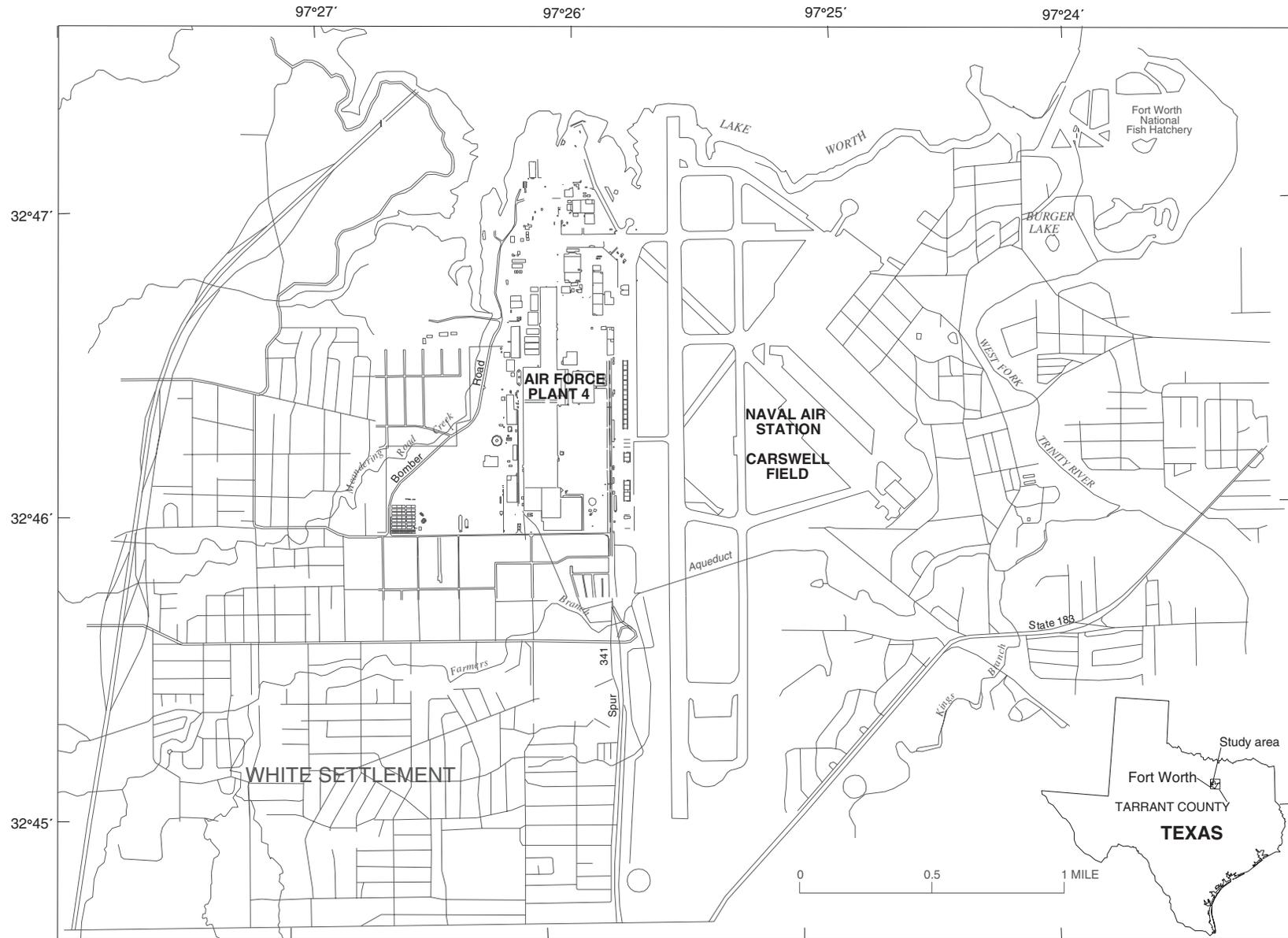


Figure 1. Location of study area.



temperature is 65 °F. The average annual precipitation in north-central Texas is 32 in., with most precipitation during the spring and fall.

## Previous Investigations

Winton and Adkins (1919) describe the geology of Tarrant County. Leggat (1957) provided one of the earliest reports on the geology and water resources of Tarrant County. Surface geology of the area is published in Leggat (1957) and as part of the Geologic Atlas of Texas, Dallas Sheet (University of Texas, Bureau of Economic Geology, 1972). Atlee (1962) describes the Paluxy "sand." Caughey (1977) and Owen (1979) conducted definitive studies of the Paluxy Formation that provide detailed descriptions of depositional systems and lithology. Baker and others (1990) published a report describing water resources in part of north-central Texas, including information about the Paluxy aquifer in Tarrant County. Nordstrum (1982) describes the occurrence, availability, and chemical quality of ground water in north-central Texas. Taylor (1976) developed ground-water-level maps and water-quality data for northeast Texas. Numerous site-specific reports by contractors to the U.S. Air Force are on file in the White Settlement Public Library, 8215 White Settlement Road, White Settlement, TX 76108. The Remedial Investigation and Feasibility Study (Chem-Nuclear Geotech, Inc., 1992; RUST Geotech, 1995a, b, c, d) and other technical study reports also are available for review at the White Settlement Public Library. These reports are part of the Administrative Record, the supporting information and analysis used by ASC, USEPA, and the Texas Natural Resource Conservation Commission to determine the remediation at AFP4. They are provided for public review so that citizens can participate in the development of the final Record of Decision for remediation of AFP4.

## Approach

A literature review of existing reports on the ground-water resources of Tarrant County and a review of technical reports on remedial investigations at AFP4 and NAS were conducted to develop a description of the hydrogeology of the study area and examine the extent of contamination at AFP4 and NAS.

Between November 1993 and January 1994, 16 monitoring wells were installed by the USGS (Rivers and others, 1996, pl. 1). Six wells completed in the terrace alluvial aquifer and four wells completed in the

upper and middle zones of the Paluxy aquifer were drilled on NAS property; and two sets of nested wells completed in different zones of the Paluxy aquifer were drilled off-site near the domestic water-supply wells northwest of AFP4. The wells were drilled mainly to provide additional ground-water sampling points for future monitoring by ASC, however, data collected during the installation of the wells were used to define hydrogeology.

Ten domestic water-supply wells northwest of AFP4 were sampled for water quality during April 1993 and April 1995. Well-completion data are not available for each of these wells. However, most domestic wells in the area are completed in the middle or lower zone of the Paluxy aquifer.

## Hydrogeology

Each of the two sets of nested wells, USGS08 and USGS09 (fig. 2), consists of three wells within 5 ft of each other screened in the upper, middle, and lower zones of the Paluxy aquifer (designated by PU, PM, and PL, respectively). Data from these nested wells were used to evaluate the directions of lateral flow and the patterns of vertical flow among the three zones of the Paluxy aquifer.

When the wells were drilled, lithologic logs describing the type of rocks from land surface to the total depth of the well were completed by geologists and recorded on a well logging form. Geophysical logs called natural gamma-ray logs were run in the deepest of the nested wells (USGS08PL and USGS09PL) and in 161 other wells at AFP4 and NAS. A gamma-ray log indicates the clay and shale content down the borehole of the well and is very useful, when interpreted with the lithologic log, for defining aquifers and confining units in the subsurface.

Field observations of streamflow and geology were made to determine recharge and discharge characteristics of the terrace alluvial aquifer and to evaluate the effects of the Goodland Limestone, Walnut Formation, and Paluxy Formation outcrops near the AFP4 and NAS. Data were collected during May 1993 and February 1994 to construct water-level maps for the terrace alluvial aquifer, Paluxy "upper sand," and regionally extensive parts of the Paluxy aquifer (Rivers and others, 1996). The May 1993 water-level maps for the terrace alluvial aquifer, Paluxy "upper" sand, and Paluxy aquifer are used in this report to describe the directions of ground-water flow.

**Table 1.** Well information for domestic water-supply wells sampled northwest of Air Force Plant 4, Fort Worth, Texas

[ft, foot; --, not available or unknown]

Well no. (fig. 2)	Well depth (ft)	Screened interval (ft)	Geologic unit of screened interval	Date drilled
32-13-8A	200	170-190	Lower Paluxy Formation	01-23-89
32-13-8B	200	160-200	Lower Paluxy Formation	07-08-85
32-13-8C	200	--	--	02-04-84
32-13-8D	--	--	--	--
32-13-8F	--	--	--	--
32-13-8I	190	150-190	Lower Paluxy Formation	09-24-82
32-13-8J	180	150-180	Lower Paluxy Formation	07-15-82
32-13-8K	222	160-222	Lower Paluxy Formation	12-02-91
32-13-8L	--	--	--	--
32-13-8N	--	--	--	--

Additional water-level data collected at AFP4 and NAS during 1994 and 1995 by the IT Corporation, Monroeville, Pa., were reviewed and analyzed to determine changes in water levels and the characteristics of ground-water flow among the terrace alluvial aquifer, the Paluxy "upper sand," and the upper, middle, and lower zones of the Paluxy aquifer.

### Water Quality

Water-quality sampling was conducted during April 1993 and April 1995 to determine if contaminants from activities at AFP4 were affecting the water quality of the Paluxy aquifer at the domestic water-supply wells northwest of AFP4. In April 1993, water samples from 10 domestic wells (table 1) were analyzed in the field using gas chromatography. A portable gas chromatograph (Brock, 1990) was calibrated with standards to detect selected volatile organic compounds (VOCs)—benzene, toluene, and trichloroethylene (TCE). Five of these wells were sampled for laboratory analysis of VOCs (using USEPA methods 524 and 8260), and three were sampled for laboratory analysis of total trace metals (using USEPA method 6010). In April 1995, the 10 wells were sampled and field-screened for benzene, dichloroethylene (DCE), tetrachloroethylene, toluene, TCE, and m-xylene. Ground water was sampled from five wells for laboratory analysis of VOCs and from all 10 wells for laboratory analysis of total trace metals and major anions.

Table 2 lists laboratory analyses performed during April 1993 and April 1995, and table 3 lists individual constituents analyzed for and laboratory reporting limits.

Water samples from four of the six USGS nested wells also were collected in April 1995 and field screened for VOCs and analyzed for VOCs, total petroleum hydrocarbons (TPHs), and oil and grease. Additionally, ASC has collected water samples from the White Settlement water-supply wells. All the ground water samples are used to describe the quality of water in the Paluxy aquifer and to determine if contaminants from AFP4 have migrated to these wells.

### Acknowledgments

The USGS acknowledges the cooperation of the citizens who allowed access to private domestic wells for data collection; the cooperation of Frank Grey and Alan Flolo of the U.S. Air Force Base Conversion Agency at Carswell Field for allowing access to wells at NAS; and Luke Gilpin of Lockheed Corporation for access to wells at AFP4. The USGS further acknowledges the collaboration of Jacobs Engineering Group Inc., for their collection of ground-water-level data and laboratory analysis of water samples from wells at AFP4 and NAS during the comprehensive sampling of wells in May 1993; IT Corporation for providing additional water-level data at AFP4 and NAS and their assistance in collection of gamma-ray logs; and Ruben

**Table 2.** Analyses performed for water-quality surveys of domestic water-supply wells northwest of Air Force Plant 4, Fort Worth, Texas, April 1993 and April 1995

[A complete list of constituents analyzed is shown in table 3. VOCs, volatile organic compounds; X, sampled; --, not sampled]

Well no. (fig. 2)	April 1993					April 1995					
	VOCs (priority pollutant 524)	VOCs (purgeable 8260)	Total trace metals	Field-screened VOCs <sup>1</sup>	Field-screened chromium	VOCs (priority pollutant 524)	VOCs (purgeable 8260)	Total trace metals	Major anions	Field-screened VOCs <sup>2</sup>	Field-screened chromium
32-13-8A	X	X	X	X	X	X	--	X	X	X	--
32-13-8B	--	--	--	X	X	X	--	X	X	X	--
32-13-8C	X	X	X	X	X	X	--	X	X	X	--
32-13-8D	--	--	--	X	X	--	--	X	X	X	--
32-13-8F	X	X	--	X	X	--	--	X	X	X	--
32-13-8I	X	X	X	X	X	X	--	X	X	X	--
32-13-8J	--	--	--	X	X	--	--	X	X	X	--
32-13-8K	X	X	--	X	X	X	--	X	X	X	--
32-13-8L	--	--	--	X	X	--	--	X	X	X	--
32-13-8N	--	--	--	X	X	--	--	X	X	X	--

<sup>1</sup> In 1993, all wells were sampled and analyzed in the field for the VOCs benzene, toluene, and trichloroethylene using gas chromatography.

<sup>2</sup> In 1995, all wells were sampled and analyzed in the field for the VOCs benzene, dichloroethylene, tetrachloroethylene, toluene, trichloroethylene, and m-xylene using gas chromatography.

**Table 3.** Constituents analyzed for and laboratory reporting limits

[Reporting limits provided by Quarterra Environmental Services. µg/L, micrograms per liter; mg/L, milligrams per liter; NR, nonrecoverable]

Volatile organic compounds (priority pollutant 524 <sup>1</sup> ), 1993 and 1995	Reporting limit <sup>2</sup> (µg/L)	Volatile organic compounds (purgeable 8260 <sup>1</sup> ), 1993	Reporting limit (µg/L)	Total trace metals, 1993 and 1995	Reporting limit (mg/L)	Major anions, 1995	Reporting limit (mg/L)
Chloromethane	2.0 (1.0)	Acetone	10	Aluminum	0.20	Alkalinity	5.0
Bromomethane	2.0 (1.0)	Benzene	1.0	Antimony	.20	Fluoride	.50
Vinyl chloride	2.0 (1.0)	Bromobenzene	1.0	Arsenic	.30	Chloride	.50
Chloroethane	2.0 (1.0)	Bromodichloromethane	1.0	Barium	.10	Nitrate	.50
Methylene chloride	1.0	Bromoform	1.0	Beryllium	.0020	Phosphate	.50
1,1-Dichloroethylene	1.0	Bromomethane	1.0	Cadmium	.0050	Sulfate	.50
1,1-Dichloroethane	1.0	2-Butanone (MEK)	10	Calcium	5.0		
1,2-Dichloroethene (cis/trans)	1.0	Carbon disulfide	1.0	Chromium	.030		
Chloroform	1.0	Carbon tetrachloride	1.0	Cobalt	.040		
1,2-Dichloroethane	1.0	Chlorobenzene	1.0	Copper	.030		
1,2,3-Trichlorobenzene	1.0	Chloroethane	1.0	Iron	.040		
1,2,4-Trichlorobenzene	1.0	2-Chloroethyl vinyl ether	1.0	Lead	.20		
1,1,1-Trichloroethane	1.0	Chloroform	.50	Magnesium	5.0		
Carbon tetrachloride	1.0	1-Chlorohexane	1.0	Manganese	.010		
Bromodichloromethane	1.0	Chloromethane	1.0	Molybdenum	.040		
1,2-Dichloropropane	1.0	Dibromochloromethane	1.0	Nickel	.040		
1,3-Dichloropropane	1.0	1,2-Dichlorobenzene	1.0	Potassium	5.0		
2,2-Dichloropropane	1.0	1,3-Dichlorobenzene	1.0	Selenium	.40		
1,1-Dichloropropene	1.0	1,4-Dichlorobenzene	.50	Silver	.030		
Trichloroethylene	1.0	1,1-Dichloroethane	1.0	Sodium	5.0		
Dibromochloromethane	1.0	1,2-Dichloroethylene (total)	1.0	Thallium	5.0		
cis-1,3-Dichloropropene	1.0	1,2-Dichloroethane	1.0	Vanadium	.040		
trans-1,3-Dichloropropene	1.0	1,1-Dichloroethylene	1.0	Zinc	.010		
1,1,2-Trichloroethane	1.0	1,2-Dichloropropane	1.0				
Benzene	1.0	cis-1,3-Dichloropropene	1.0				
Bromoform	1.0	trans-1,3-Dichloropropene	1.0				
1,1,1,2-Tetrachloroethane	1.0	EDB (1,2-Dibromoethane)	1.0				
1,1,2,2-Tetrachloroethane	1.0	Ethylbenzene	1.0				
Tetrachloroethylene	1.0	2-Hexanone	10				
Toluene	1.0	Methylene chloride	1.0				
Chlorobenzene	1.0	4-Methyl-2-pentanone (MIBK)	10				
Ethylbenzene	1.0	Styrene	1.0				
Styrene	1.0	1,1,1,2-Tetrachloroethane	1.0				
Xylenes (total)	1.0	1,1,2,2-Tetrachloroethane	1.0				
n-Propylbenzene	1.0	Tetrachloroethylene	1.0				
1-Methylethylbenzene (Cumene)	1.0	Toluene	1.0				
p-Isopropyltoluene (p-Cymene)	1.0	1,1,1-Trichloroethane	1.0				
1,2,4-Trimethylbenzene	1.0	1,1,2-Trichloroethane	1.0				
1,3,5-Trimethylbenzene	1.0	Trichloroethylene	1.0				
n-Butylbenzene	1.0	Trichlorofluoromethane	1.0				
tert-Butylbenzene	1.0	1,2,3-Trichloropropane	1.0				
sec-Butylbenzene	1.0	Vinyl acetate	10				
1,4-Dichlorobenzene	1.0	Vinyl chloride	1.0				
1,2-Dichlorobenzene	1.0	Xylenes (total)	1.0				
1,3-Dichlorobenzene	1.0	Ethyl ether	50				
2-Chlorotoluene	1.0	Acrolein	60				
4-Chlorotoluene	1.0	Acrylonitrile	25				
Bromobenzene	1.0	Dibromomethane	10				
Hexachlorobutadiene	1.0	Dichlorodifluoromethane	10				
Naphthalene	1.0	Ethanol	NR				
DBCP (1,2-Dibromo-3-chloropropane)	1.0	Ethyl methacrylate	10				
EDB (1,2-Dibromoethane)	2.0	Iodomethane	10				
Dibromomethane	1.0						
Dichlorodifluoromethane	1.0						
Trichlorofluoromethane	1.0						
1,2,3-Trichloropropane	1.0						
Bromochloromethane	1.0						

<sup>1</sup> U.S. Environmental Protection Agency analytical method for laboratory analysis.<sup>2</sup> Reporting limit for 1995 shown in parenthesis if different than reporting limit for 1993.

Martinez, Ph.D., of Parsons Engineering Science, for his participation in collection of gamma-ray logs.

## HYDROGEOLOGY

Hydrogeology is the study of subsurface water, specifically related to how water moves through the ground. It is a broad, multidisciplinary science involving knowledge of hydrology, geology, fluid mechanics, and water chemistry. Geologists define mappable beds of similar rock types as formations (also referred to as stratigraphic units). Formations can be composed of rocks with limited capacities to transmit and yield water (confining units) or rocks that readily transmit and yield ground water to wells or springs in sufficient quantities to be an economically feasible water supply (aquifers).

Permeability, or hydraulic conductivity, is a measure of a rock's capacity to transmit and yield water. During deposition, the individual particles of sediment settle into place, separated by voids of varying size and shape. If the voids within the resulting rock are connected—allowing water to move readily through a network of void space—the rock is permeable. Within many of the sedimentary rocks at AFP4 and NAS, gravity has helped pack the oval particles more tightly in the vertical direction, with their longer axes oriented horizontally. The tighter vertical packing of particles causes permeability to be appreciably larger in the horizontal direction than in the vertical direction. Furthermore, sedimentary rocks are laid down cyclically—as a series of horizontal layers, or beds, within which the permeability of vertically adjacent beds might differ substantially. Because sedimentary beds are thinner than they are wide, a typical sequence of sedimentary strata resembles a stack of pancakes. A single low-permeability bed can greatly restrict vertical groundwater flow over wide areas, while not affecting the horizontal flow through overlying and (or) underlying permeable beds. These conditions combine to greatly retard the vertical flow of water through the sedimentary rocks at AFP4 and NAS.

There are several kinds of sedimentary rocks at AFP4 and NAS, including alluvium, sandstone, limestone, shell conglomerate, shale, and claystone. The mostly unconsolidated alluvium and porous sandstone, which mainly compose aquifers, are characteristically more permeable than the limestone, shell conglomerate, shale, and claystone. The typically highly indurated limestone, shell conglomerate, shale, and claystone do not readily transmit ground water in either the horizon-

tal or vertical direction and, thus, mainly compose confining units.

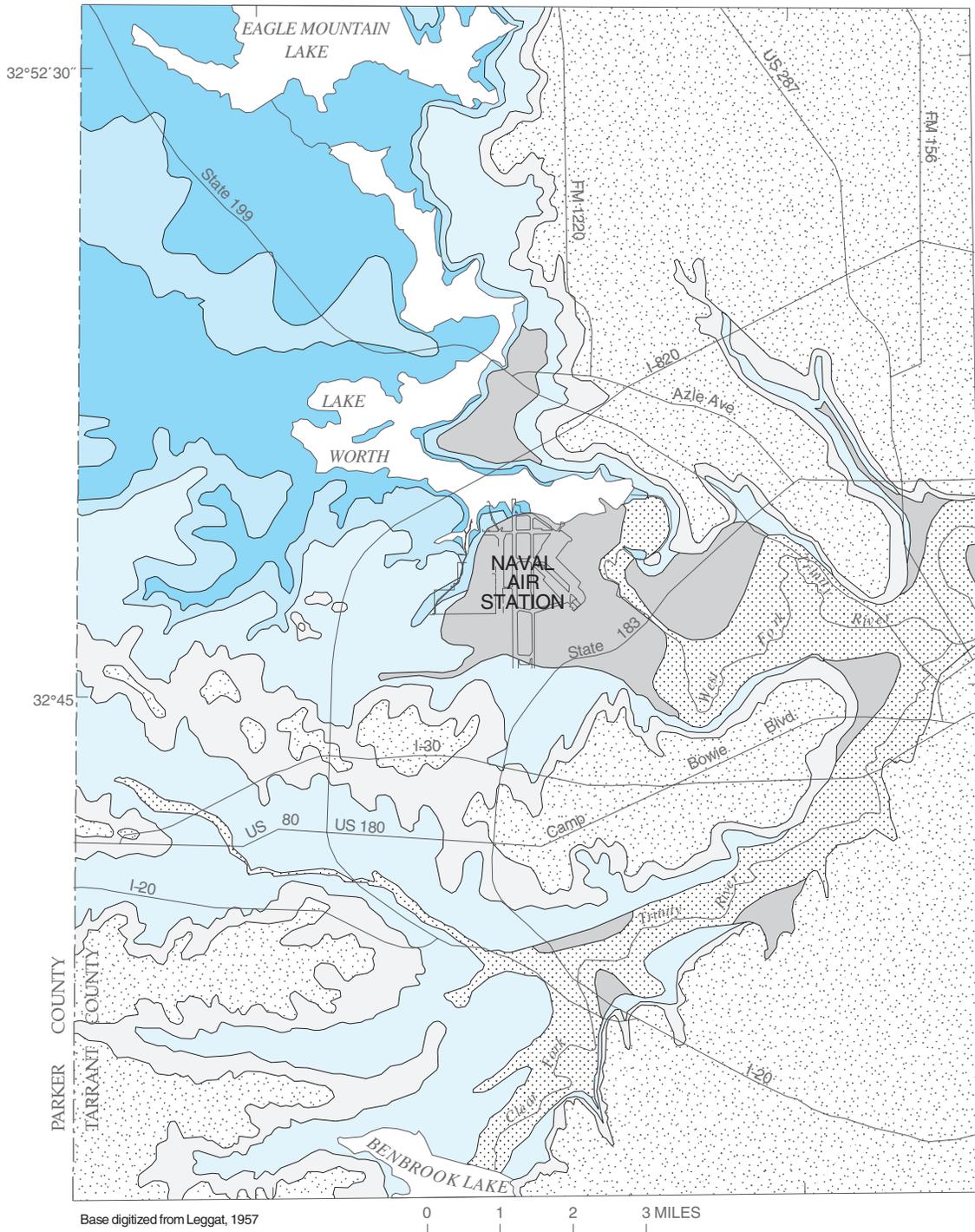
## Geology, Extent, and Water-Yielding Characteristics

From oldest to youngest, the Cretaceous rocks that crop out near AFP4 and NAS (fig. 3) are the Paluxy Formation (aquifer), Walnut Formation (confining unit), and Goodland Limestone (confining unit). The Twin Mountains Formation<sup>1</sup> (aquifer) underlies the Glen Rose Formation (confining unit), which underlies the Paluxy Formation. These older, Cretaceous rocks are overlain by Quaternary terrace alluvial deposits, consisting of gravel, sand, silt, and clay. Table 4 gives the geologic ages, thicknesses, and lithologic and water-yielding characteristics of these stratigraphic units.

Figure 4 shows the generalized hydrogeologic framework of the study area. Although the Cretaceous rocks in the study area were deposited horizontally, structural uplift in the west has tilted the bedding so that presently it dips about 20 to 30 ft/mi to the east-southeast beneath AFP4 (Owen, 1979). The hydrogeologic section is drawn through the "window," a buried bedrock channel below the east parking lot—just east of the assembly building (fig. 2)—where the Goodland-Walnut confining unit is less than 5-ft thick (Ruben Martinez, Ph.D., Parsons Engineering Science, written commun., 1995).

A generalized hydrogeologic diagram (fig. 5) shows the terrace alluvial aquifer and distinguishes between the Paluxy "upper sand" and the upper zone of the Paluxy aquifer. From the "window," near the center of the block, the left side of the block slices southwestward through an erosional paleochannel atop the Goodland-Walnut confining unit. The right side of the block starts at the "window" and slices northwestward through AFP4, across Bomber Road, and beyond the cove on Lake Worth. The configuration of the water table in the terrace alluvial aquifer approximates the land surface topography and (or) the top of the Goodland-Walnut confining unit. Building 181 of the assembly building at AFP4 (fig. 5) is located above a bedrock high in the Goodland-Walnut confining unit near an upgradient segment of the paleochannel. A leaking tank of TCE—believed the major source of TCE contamination in the terrace alluvial aquifer—was in

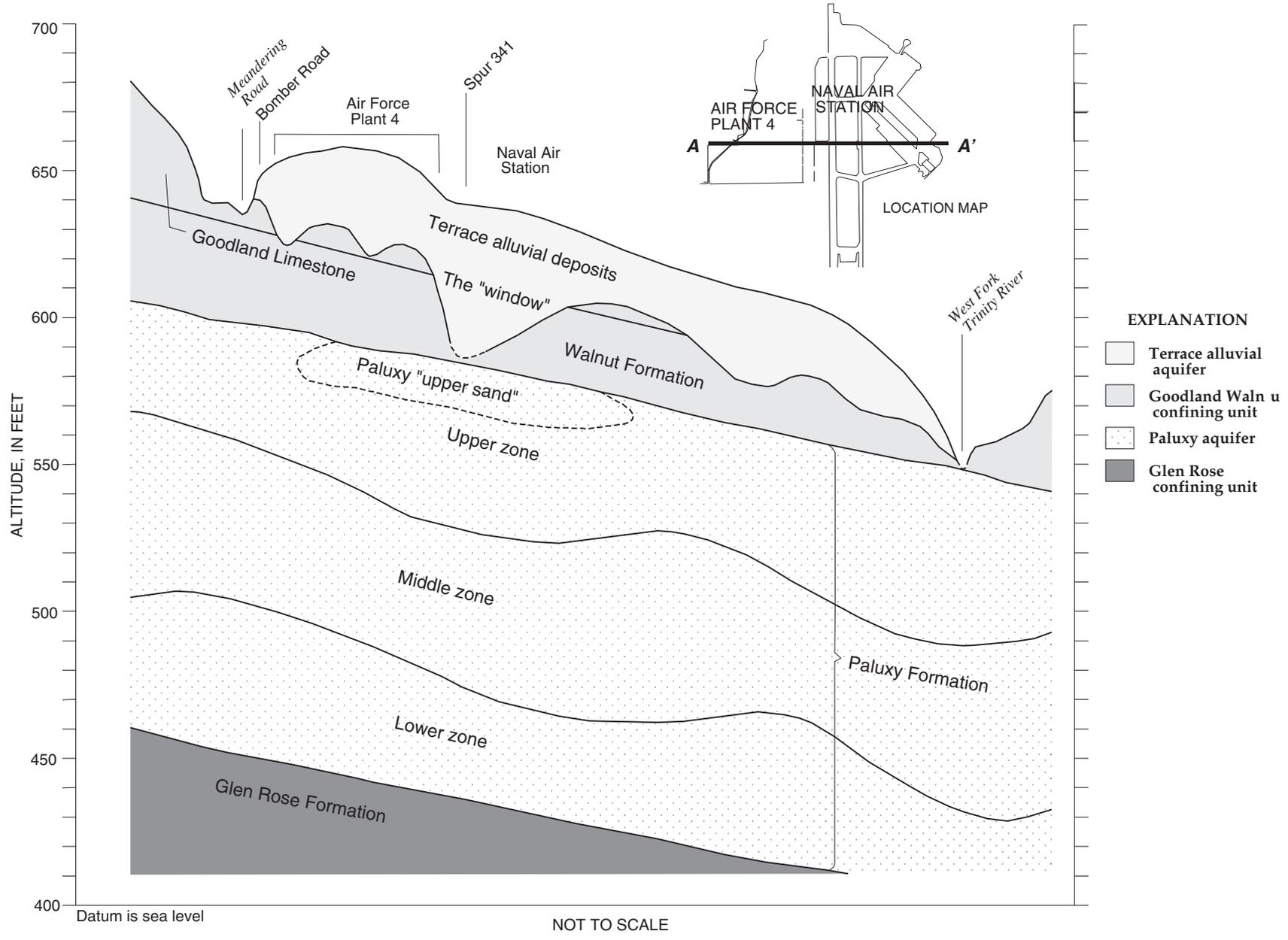
<sup>1</sup>This stratigraphic name does not conform to the usage of the U.S. Geological Survey.



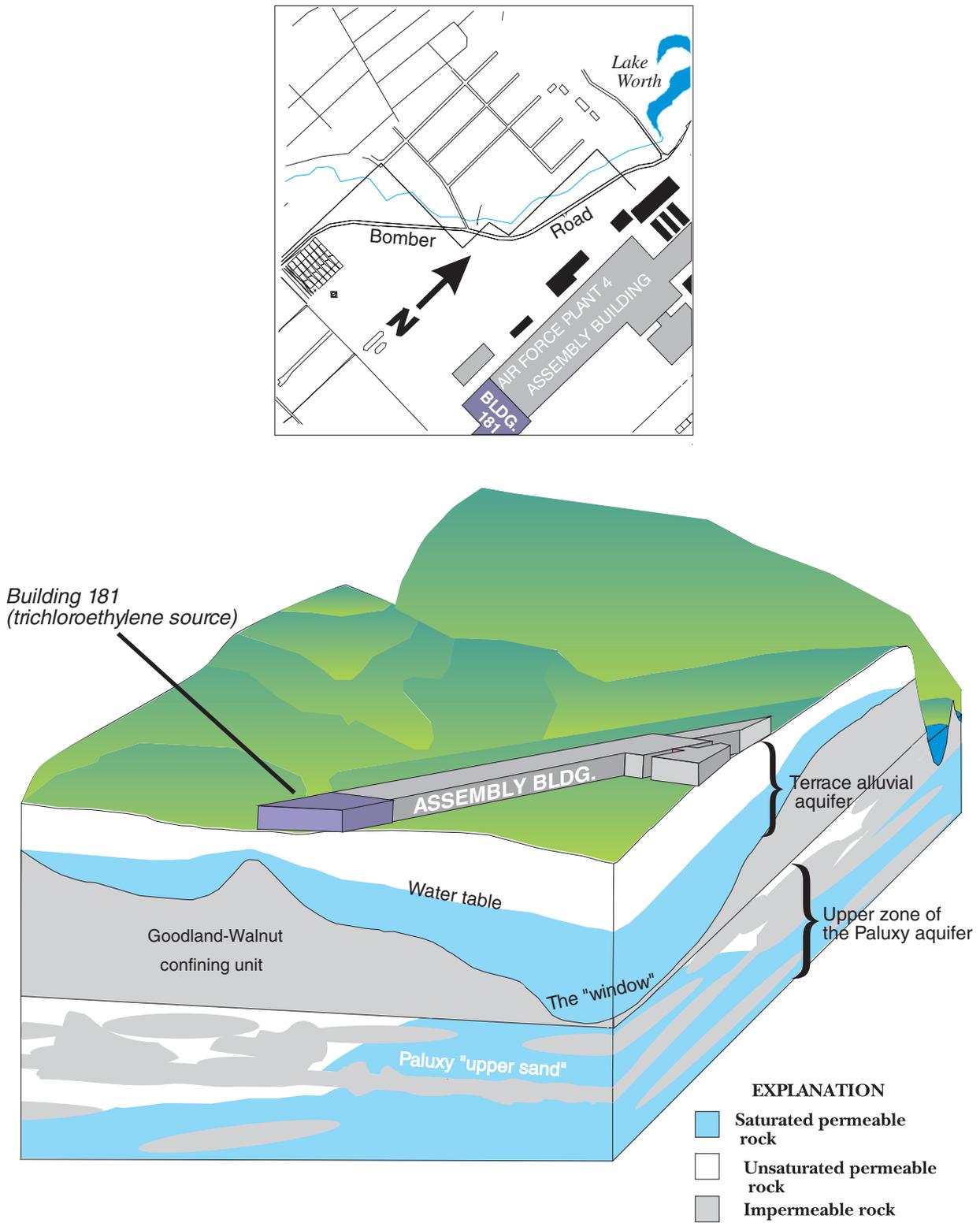
EXPLANATION

- |                           |                    |                    |
|---------------------------|--------------------|--------------------|
| Recent alluvial deposits  | Washita Group      | Goodland Limestone |
| Terrace alluvial deposits | Kiamichi Formation | Walnut Formation   |
|                           |                    | Paluxy Formation   |

**Figure 3.** Surface geology in western Tarrant County, Texas. (Modified from Leggat, 1957, and University of Texas, Bureau of Economic Geology, 1972.)



**Figure 4.** Generalized hydrogeologic section at Air Force Plant 4 and Naval Air Station, Fort Worth, Texas.



**Figure 5.** Generalized hydrogeologic diagram of the aquifer system underlying Air Force Plant 4, Fort Worth, Texas.

**Table 4.** Stratigraphic units at Air Force Plant 4 and Naval Air Station, Fort Worth, Texas

[mya, million years ago; --, not applicable; AFP4, Air Force Plant 4]

Era	System	Series/Group	Stratigraphic unit	Thickness (feet) <sup>1</sup>	Lithologic characteristics <sup>2</sup>	Water-yielding characteristics
Cenozoic	Quaternary (1.8 mya to present)	Holocene	Fill material	0–20	Construction debris	Permeability varies, gravels and sands permeable
			Recent alluvial deposits	0–50	Gravel, sand, silt, clay	
		Pleistocene	Terrace alluvial deposits	0–60	Gravel, sand, silt, clay	Permeability varies, gravels and sands permeable
	Tertiary (1.8 to 65 mya)	Eocene/Wilcox		--	--	--
Paleocene/Midway			--	--	--	
Mesozoic	Cretaceous (65 to 140 mya)	Gulfian		--	--	--
				--	--	--
				--	--	--
		Comanchean/Washita		--	--	--
				--	--	--
		Comanchean/Fredericksburg	Goodland Limestone	0–40	White, fossiliferous limestone, coarsely nodular, resistant, and dense—contains some marl	Impermeable where not weathered—considered confining unit
			Walnut Formation	0.5–30	Medium to dark grey clay and limestone with shell conglomerates, fossiliferous, <i>Gryphaea</i> beds	Very low permeability—considered confining unit
			Paluxy Formation	130–175	Light grey to greenish-grey sandstone and mudstone; fine-grained to coarse-grained sandstone	Considered aquifer, yields small to moderate quantities of water
Comanchean/Trinity	Glen Rose Formation	150, range unknown at AFP4	Brownish-yellow and gray alternating limestone, marl, shale, and sand	Low permeability—considered confining unit in area of AFP4		
	Twin Mountains Formation <sup>3</sup>	200, range unknown at AFP4	Fine- to coarse-grained sandstone, shale and claystone, basal gravel conglomerate	Coarse sandstones and parts of formation considered aquifer, yields moderate to large quantities of water		

<sup>1</sup> Thickness determined from site logs, except for Glen Rose Limestone and Twin Mountains Formation (Baker and others, 1990, fig. 4).

<sup>2</sup> Lithologic characteristics determined from field observations and from Winton and Adkins, 1919; University of Texas, Bureau of Economic Geology, 1972; U.S. Army Corps of Engineers, 1986; Baker and others, 1990; Environmental Science & Engineering, Inc., 1994.

<sup>3</sup> This stratigraphic name does not conform to the usage of the U.S. Geological Survey.

■ Absent or eroded and absent

building 181 (chemical processing facility), where chromium also was used. TCE has been detected in the Paluxy "upper sand." The Paluxy "upper sand" is saturated beneath the "window" (fig. 2) and is unsaturated away from the "window," beneath thick sequences of the Goodland-Walnut confining unit. The distributions of saturated and unsaturated sediments indicate some downward leakage through thin sequences of the Walnut Formation and (or) through incompletely grouted wells breaching the Goodland-Walnut confining unit.

The Paluxy "upper sand" is unsaturated at the nested wells (USGS08 and USGS09) south of the cove along Bomber Road (fig. 2), which indicates that the Paluxy "upper sand" is relatively impermeable or discontinuous and not recharged by Lake Worth in this area. The upper zone of the Paluxy aquifer is unsaturated near the southwestern boundary of AFP4 but is saturated near Lake Worth, with water levels above the base of the unsaturated, relatively impermeable Paluxy "upper sand" in this area.

### **Terrace Alluvial Aquifer**

The terrace alluvial aquifer comprises primarily terrace alluvial deposits; some recent alluvial deposits might be present in places. The terrace alluvial deposits form a thin blanket of gravel, sand, silt, and clay varying in thickness from 0 to 60 ft at AFP4 and NAS. The terrace alluvial deposits are very thin (5 to 30 ft) west of the assembly building; east of the assembly building, the deposits thicken to 60 ft along the erosional channel beneath the runway. The terrace alluvial deposits are absent southwest of the runway (fig. 3), where limestone of the Goodland Limestone forms the land surface. The terrace alluvial deposits consist primarily of clay with sand and gravel channel deposits that can be interconnected or interfingered along streams that existed during the time of deposition. The older stream channel (referred to as a paleochannel) can be defined by mapping the top of the eroded bedrock surface, the Goodland-Walnut confining unit (fig. 6). The sandy and gravelly deposits tend to be present along paleochannels and can readily transmit water in the subsurface.

The terrace alluvial aquifer, referred to as an upper-zone flow system (Chem-Nuclear Geotech, Inc., 1992; RUST Geotech, 1995a, b, c, d), is not used for water supply and is considered to be unconfined at AFP4. Recovery wells that have been installed for

pump-and-treat remediation of the TCE spill have yields ranging from less than 1 to 30 gal/min. (The treatment, called air stripping, removes TCE from the water by exposing the water to air and allowing the TCE to vaporize.)

The terrace alluvial aquifer is recharged locally by precipitation at the southwest corner of AFP4 where there are no buildings or pavement and by leaking water pipes beneath AFP4 and from buildings at AFP4. Leakage from sewers and pipelines at AFP4 is estimated to be about 300,000 gal/d (Chem-Nuclear Geotech, Inc., 1992). Ground water from the terrace alluvial aquifer is withdrawn by recovery wells and discharges naturally by evapotranspiration and by seepage to Lake Worth, Meandering Road Creek, Farmers Branch, and a few small tributaries along Farmers Branch. Because the terrace alluvial aquifer thickens east of the assembly building, most of the water leaking from sewers and pipelines can flow east toward the recovery wells and Farmers Branch. Natural discharge to the streams could be reduced by the recovery wells.

### **Goodland-Walnut Confining Unit**

The Goodland-Walnut confining unit, composed of the Goodland Limestone and (or) the Walnut Formation, directly underlies the terrace alluvial deposits at AFP4 and NAS. The Goodland Limestone is a white, fossiliferous, very massive limestone, which contains some marl and a few, mostly thin beds of clay. The Goodland is highly indurated and can be about 90-ft thick in other areas of Tarrant County. At AFP4, the Goodland Limestone mostly has been removed by erosion—only remnants (up to 40-ft thick) of the Goodland Limestone overlie the Walnut Formation in places. The Walnut Formation consists of nearly equal amounts of medium to dark grey clay and limestone. The Walnut Formation contains more shell conglomerates, clay, and shale than does the Goodland Limestone. A shell conglomerate is a mixture of pebbles, gravel, and fossil shell fragments bound together by clay and (or) limestone. Shell conglomerates in the Walnut Formation are formed of ancient oyster (*Gryphaea*) beds, which are gravelly in places. In general, the oyster beds in the Walnut Formation are bound within a clay and (or) limestone matrix. In Tarrant County, the maximum thickness of the Walnut Formation is 30 ft. At AFP4, the Walnut Formation ranges from 0.5- to 30-ft thick. The Goodland-Walnut confining unit forms the top of bedrock at AFP4 and

NAS (fig. 6). The total thickness of the Goodland-Walnut confining unit ranges from 0.5 to 70 ft at the site. The very low permeability of the Goodland-Walnut confining unit causes uppermost parts of the Paluxy aquifer to be unsaturated where they underlie thick sequences of this relatively impermeable unit (fig. 5). However, where erosion has completely removed the Goodland Limestone and all but a few feet of the Walnut Formation, the remaining thickness of low-permeability rock might not be sufficient to block the downward flow of ground water.

### **Paluxy Aquifer**

The Paluxy aquifer, comprised of the Paluxy Formation, yields small to moderate quantities of water to municipal and domestic water-supply wells. The unit is composed mostly of light grey to greenish-grey coarse- to fine-grained sandstone and dense mudstone; reddish-orange outcrops are common, as the result of oxidized iron sediment. The most permeable sequences typically are composed of well sorted, poorly cemented, and cross-bedded quartz-rich sand. The upper zone (shallowest, or top one-third) of the Paluxy aquifer is composed mostly of a fine-grained, highly indurated sandstone with interbeds of claystone and shale. The lower zone (deepest, or bottom one-third) of the aquifer contains the coarsest, most permeable sand.

Although the total thickness of the Paluxy Formation is between 130 and 175 ft, the permeable sandstone units of the formation can be as thin as 40 ft (Nordstrum, 1982, p. 14). At AFP4, the Paluxy aquifer has been divided into three zones. The three zones of the Paluxy might correspond to the Lake Merritt, Georges Creek, and Eagle Mountain members of the Paluxy Formation described by Owen (1979). From bottom to top (deepest to shallowest) the zones of the Paluxy aquifer are the lower, middle, and upper (fig. 4). The Paluxy "upper sand" (fig. 4) is a local sand lens of unknown lateral extent beneath AFP4 and is considered the uppermost interval of the upper zone of the Paluxy aquifer. The zones are isolated hydraulically by interbeds of highly indurated sandstone, shale, and (or) clay. Lithologic logs and gamma-ray logs from wells USGS08PL and USGS09PL (fig. 2) indicate the presence of these three distinct zones of the Paluxy Formation. The top 50 to 60 ft of the Paluxy Formation (upper zone of the Paluxy aquifer) contain 2 to 3 fine-grained, sandstone beds less than 10-ft thick separated by clay or shale beds 5- to 20-ft thick. The middle zone of the Paluxy aquifer at these

two wells is a fine-grained sandstone 40- to 50-ft thick separated from the lower zone of the Paluxy aquifer by 8- to 12-ft thick shale or clay. The lower zone of the Paluxy aquifer is a sandstone unit 25- to 30-ft thick with interbedded sandstone and shale. The total thickness of the Paluxy Formation at these two wells is 170 ft.

Municipal and domestic water-supply wells tend to be screened in the lower and middle zones of the Paluxy aquifer because of the poor water-yielding characteristics of the upper zone of the aquifer. Monitoring wells installed at AFP4 and NAS are screened in the Paluxy "upper sand;" in the upper, middle, and lower zones of the Paluxy aquifer; and in the Paluxy aquifer, undifferentiated.

#### **Paluxy "Upper Sand" and Upper Zone of the Paluxy Aquifer**

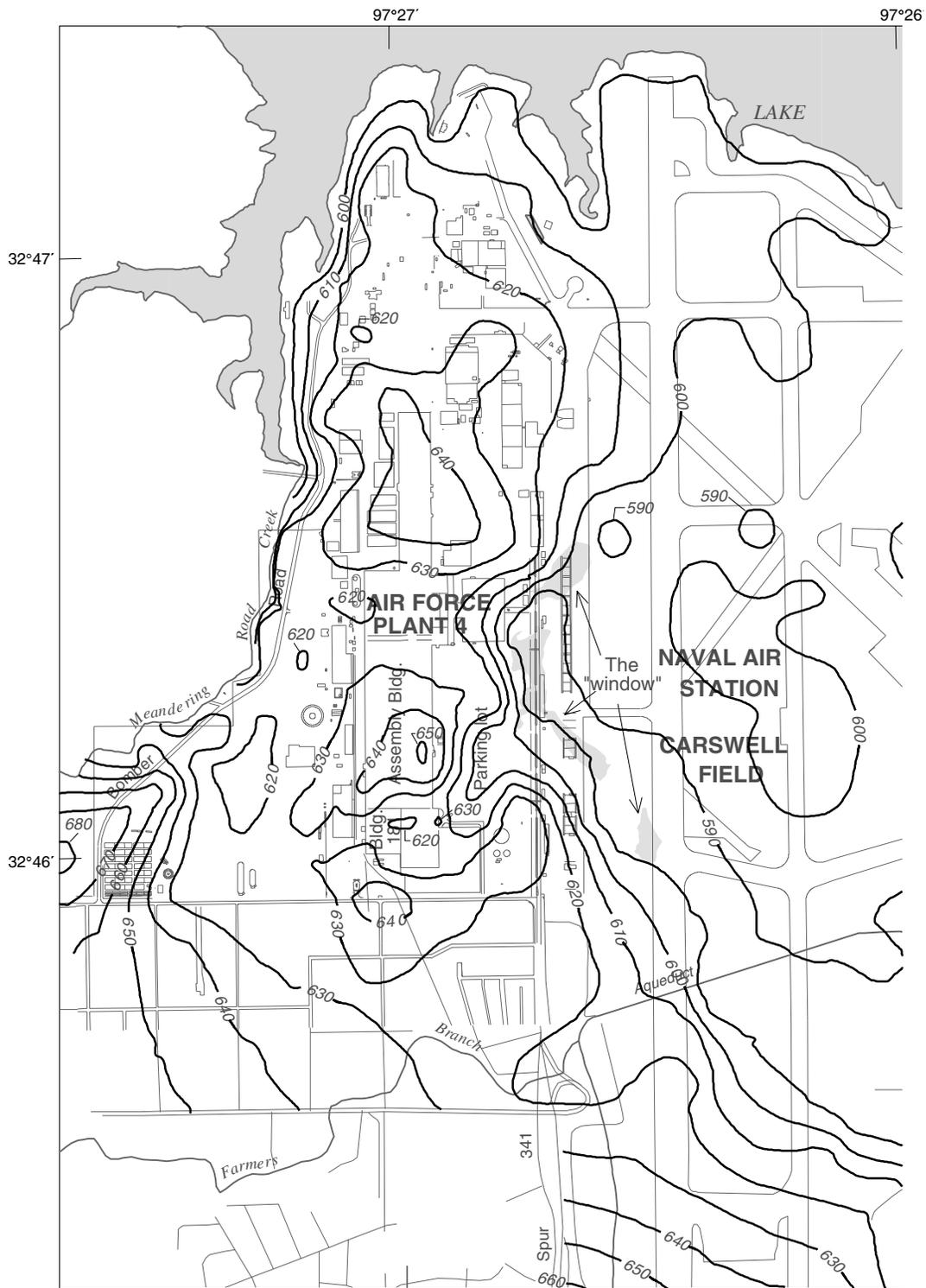
Although the Paluxy "upper sand" is physically part of the upper zone of the Paluxy aquifer, it appears to be hydraulically disconnected from the deeper, regionally extensive parts of the aquifer and is unsaturated, except directly below the "window." The lateral extent of the Paluxy "upper sand" is unknown; however, where observed, it is underlain by a strongly cemented, shaley, fine-grained sandstone that ranges from 5-in. to 10-ft thick. Because the Paluxy "upper sand" is unsaturated except beneath the east parking lot, it is concluded that the Paluxy "upper sand" must pinch out or is relatively impermeable near Lake Worth. The upper 5 ft of the Paluxy Formation crop out in the cove along Bomber Road (fig. 3). Here, the Paluxy Formation was observed to be very fine grained and highly indurated.

The upper zone of the Paluxy aquifer is composed of fine-grained sandstones. In places it is a water-yielding unit that can supply small quantities of water (less than 10 gal/min). The upper Paluxy is artesian at AFP4 near Bomber Road—that is, water will rise above the top of the aquifer in a well. Near Lake Worth, the Paluxy Formation intersects the lake in the cove along Bomber Road.

#### **Middle and Lower Zones of the Paluxy Aquifer**

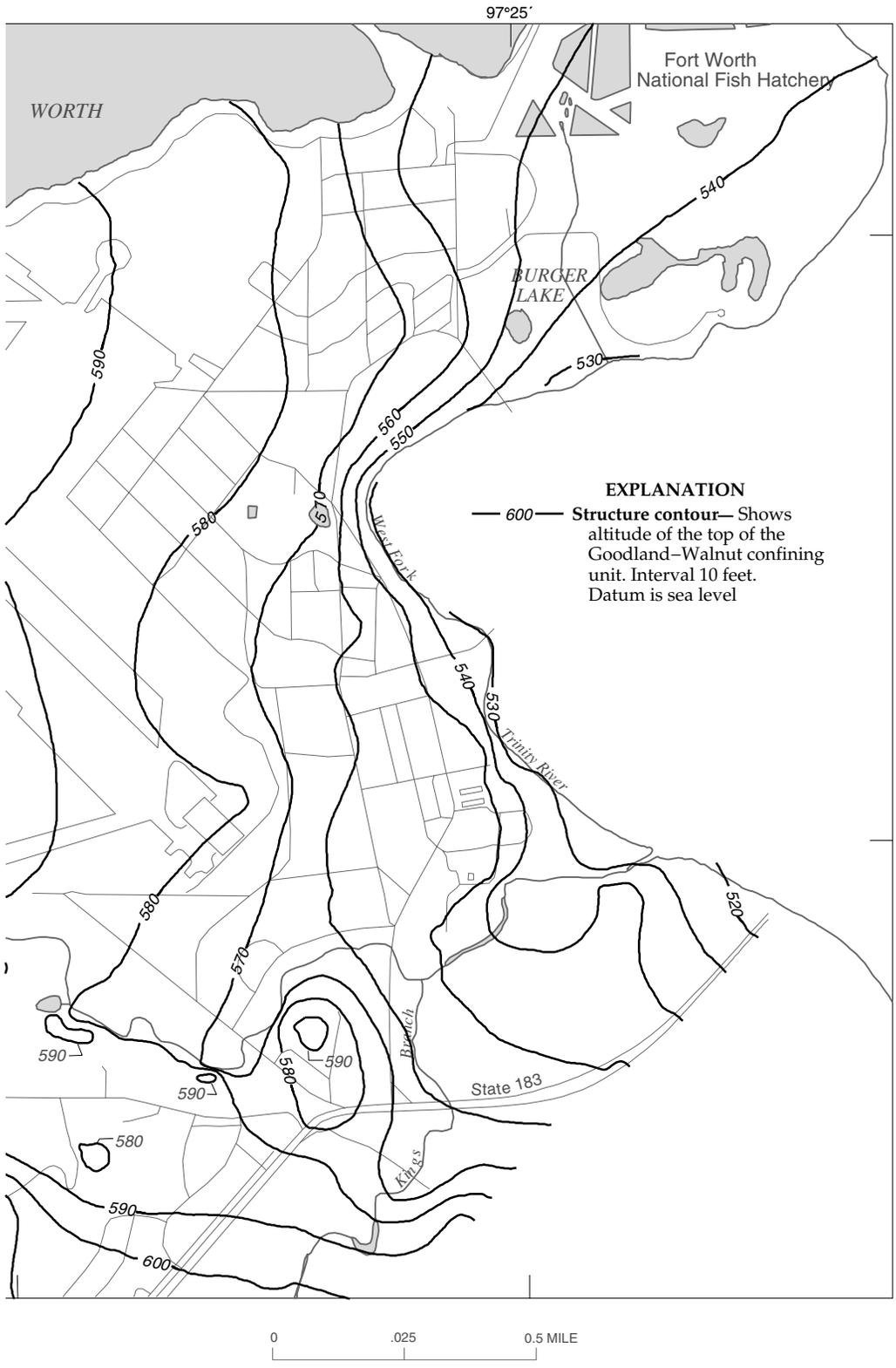
The middle zone of the Paluxy aquifer contains fine- to medium-grained sandstone. It is a water-yielding unit that can supply small quantities of water to wells. The middle Paluxy has fewer interbedded shale zones than the upper zone of the Paluxy at AFP4.

The lower zone of the Paluxy aquifer is the most permeable. The coarse-grained sandstone in the lower



Base from Chem-Nuclear Geotech, Inc.,  
written commun., 1993  
Universal Transverse Mercator projection  
Zone 14

**Figure 6.** Top of the Goodland-Walnut confining unit at Air Force Plant 4 and vicinity, Fort Worth, Texas. (From RUST Geotech, 1995b.)



**Figure 6.** Continued.

zone can yield moderate quantities of water to wells. The White Settlement water-supply wells are screened in the middle and lower zones of the Paluxy at depths ranging from 195 to 305 ft below land surface (City of White Settlement, written commun., 1995). Average production of water from all White Settlement water-supply wells is about 500,000 gal/d (RUST Geotech, 1995a).

### **Glen Rose Confining Unit**

The Glen Rose Formation, the confining unit below the Paluxy Formation, is composed of brownish-yellow and grey alternating limestone, marl, shale, and very little sand. It does not transmit water easily and is considered the confining unit between the Paluxy aquifer and Twin Mountains aquifer. The Glen Rose is about 150-ft thick at AFP4. If the middle and lower zones of the Paluxy aquifer were to become contaminated from activities at AFP4, the Glen Rose confining unit would restrict the movement of contaminants downward to the Twin Mountains aquifer.

### **Twin Mountains Aquifer**

The Twin Mountains Formation underlies the Glen Rose Formation and is considered an aquifer that can yield moderate to large quantities of water to wells (100 to greater than 1,000 gal/min). It is about 200-ft thick and composed of fine- to coarse-grained sandstone with a basal gravel conglomerate. Interbedded with the sandstone are shale and claystone. The Twin Mountains aquifer has greater permeability than the Paluxy aquifer. The Twin Mountains aquifer currently does not supply water for White Settlement because its depth is greater than 400 ft below land surface. However, the Twin Mountains aquifer might be a potential alternate water supply for White Settlement (Paul Bounds, City of White Settlement, oral commun., 1995).

### **Ground-Water Movement**

Ground water generally moves from areas of higher altitude to areas of lower altitude. A water-level map graphically shows the altitudes of the water surface in an aquifer, indicating the horizontal direction of ground-water movement. A water-level map is constructed by contouring water levels that are referenced to a common datum (sea level). The data for a water-level map are collected by measuring the depth to water in a well and subtracting this measurement from the

known land-surface altitude. The water-level map defines a surface that indicates the level water will rise to in a well. The water-level map is similar to a topographic map in that the contours indicate the slope of the water-level surface and the approximate direction of water movement downslope, from higher to lower altitudes. The slope of the water-level surface is called the hydraulic gradient (the difference between water levels for two contours divided by the distance between the contours).

As stated earlier, water can move more easily in the horizontal direction than in the vertical direction. Water levels of the terrace alluvial aquifer were mapped as one horizontal flow unit, and water levels in the middle and lower zones of the Paluxy aquifer were mapped as one horizontal flow unit. Water levels in the Paluxy "upper sand" were mapped separately from either the terrace alluvial aquifer or the rest of the Paluxy aquifer.

### **Terrace Alluvial Aquifer**

The water-level map of the terrace alluvial aquifer (fig. 7) indicates that ground water flows radially outward beneath AFP4. Ground water also moves by gravity flow along the bedrock surface. The mounding of water could be caused by water leaking into the aquifer from sewers and pipelines over a bedrock high beneath AFP4 (fig. 6). Thus, water moves toward Bomber Road and Meandering Road Creek to the west and toward the runways at NAS and West Fork Trinity River to the east (fig. 7). South of AFP4, Farmers Branch cuts through the terrace alluvial aquifer to the east of the aqueduct. Surface-water measurements and observations of seeps along Farmers Branch indicate that locally, water flows toward Farmers Branch and the aqueduct (fig. 7).

If the terrace alluvial aquifer is homogeneous (composed of the same material everywhere), ground water would move at uniform rates of flow in a direction perpendicular to the water-level contours. However, the terrace alluvial aquifer is not homogeneous. Thus, the approximate direction of ground-water flow can be determined from the water-level contour map, but the flow rates cannot be determined.

The water-level altitude ranges from about 615 to 620 ft above sea level in the terrace alluvial aquifer (fig. 7) above the "window" (where the Goodland-Walnut confining unit is less than 5-ft thick). The water-level high beneath the north and south ends of the

assembly building is 640 ft (fig. 7). West of the plant is a water-level high of 660 ft above sea level. In this area, the terrace alluvial aquifer is thin.

### **Goodland-Walnut Confining Unit**

Because the upper 40 ft of the Paluxy Formation, directly beneath the Goodland-Walnut confining unit, is unsaturated over large parts of the study area, the confining unit does not appear to readily transmit ground water. There appears to be little opportunity for water to move vertically through the confining unit, especially where it is 20-ft thick, or thicker. However, some vertical transmission of water between the terrace alluvial aquifer and the Paluxy aquifer might occur through the "window," where the confining unit is less than 5-ft thick.

The water-level map for the Paluxy "upper sand" (fig. 8) reveals a mound of ground water directly beneath the "window" in the Goodland-Walnut confining unit. Altitudes at the top of the mound range from about 605 to about 611 ft above sea level, or about 15 to 25 ft lower than water levels in the overlying terrace alluvial aquifer. Within small distances from the "window," water levels in the Paluxy "upper sand" are about 570 ft above sea level, or more than 40 ft lower than water levels in the overlying terrace alluvial aquifer. At farther distances from the "window," several wells screened in the Paluxy "upper sand" were dry during 1993 and 1994 (Rivers and others, 1996, figs. 4, 5). The decrease in hydraulic head across the Goodland-Walnut confining unit indicates a downward gradient between the terrace alluvial aquifer and upper parts of the Paluxy aquifer. The ground-water mound in the Paluxy "upper sand" indicates downward ground-water flow through the "window" in the Goodland-Walnut confining unit. The decrease in saturation away from the mound could indicate relatively small permeability for the Paluxy "upper sand."

### **Paluxy Aquifer**

The distribution of water levels in the Paluxy aquifer is affected by horizontal and vertical components of flow within and among the different zones of the aquifer. Water levels in the Paluxy "upper sand" differ approximately 50 ft from some water levels in the upper zone of the Paluxy aquifer (Rivers and others, 1996). The contours on figure 9 are based on water levels measured during May 1993 from wells screened

in the middle and lower zones of the Paluxy aquifer (Rivers and others, 1996).

### **Horizontal Movement**

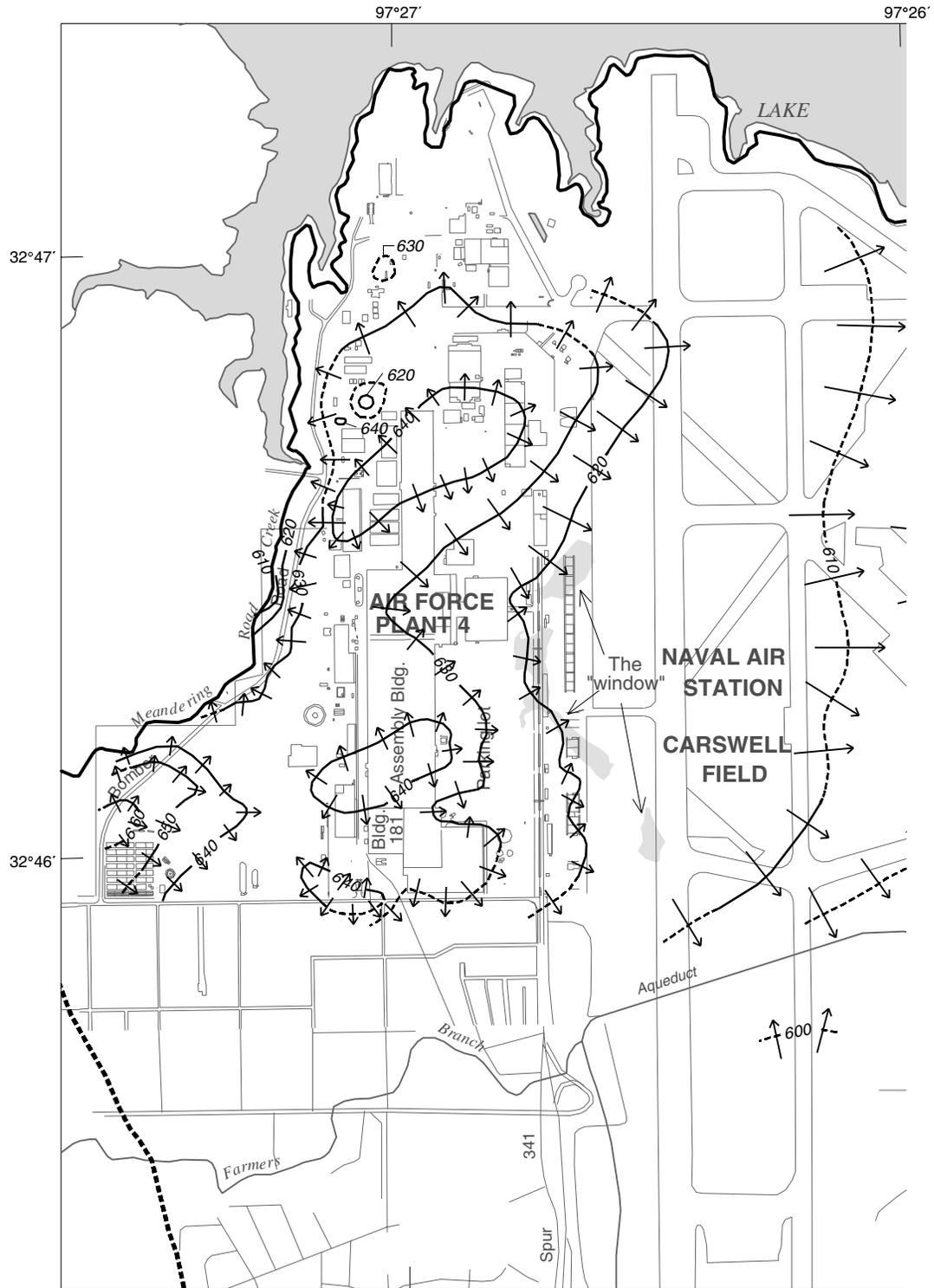
The horizontal movement of regional ground-water flow in the Paluxy aquifer, indicated by arrows in figure 9, is from west to east-southeast. In general, the water-level contours follow the dip of the formation to the east. Because the Paluxy aquifer is recharged from precipitation over its outcrop area in western Tarrant County (fig. 3) and Parker County (not shown), the highest water levels occur in the outcrop area. Water levels range from about 720 ft above sea level at the western edge of Tarrant County to about 520 ft above sea level at the eastern edge of NAS (fig. 9). This is an average gradient of about 0.005 ft/ft or about 25 ft/mi from west to east.

### **Vertical Movement**

The difference between the water levels measured in a set of nested monitoring wells divided by the vertical distance between the centers of the well screens is called the vertical hydraulic gradient. A large vertical hydraulic gradient does not equate with a large flow rate. It can indicate less flow because the gradient is the potential for water to flow. If there is a great resistance to water flowing, water pressure will rise upgradient of the resistant sediment and a large gradient (more than 1,000 ft/mi) will result.

The vertical hydraulic gradient at the nested well site near Lake Worth ranged from 0.070 to 0.118 ft/ft during February 1994 (table 5). This gradient is more than 10 times the horizontal hydraulic gradient in the regional Paluxy aquifer. The larger vertical gradient indicates that it is more difficult for water to move vertically in the Paluxy aquifer than horizontally as is typical of a sandstone aquifer. However, the vertical gradient is not so large as to indicate poor hydraulic connection between the upper, middle, and lower zones of the Paluxy aquifer.

Water levels were measured monthly by IT Corporation (for ASC) in wells at AFP4 and vicinity, including numerous sets of wells screened in different zones of the Paluxy aquifer (fig. 2). At three sites, the difference between the water levels of the Paluxy "upper sand" and the water levels of the upper or middle zones of the Paluxy aquifer ranged from 27 to 48 ft during December 1994 (IT Corporation, Monroeville, Pa., written commun., 1995). The direction of flow is down-



Base from Chem-Nuclear Geotech, Inc.,  
written commun., 1993  
Universal Transverse Mercator projection  
Zone 14

**Figure 7.** Water-level altitudes and flow direction in the terrace alluvial aquifer at Air Force Plant 4 and vicinity, Fort Worth, Texas, May 1993. (Modified from Rivers and others, 1996.)

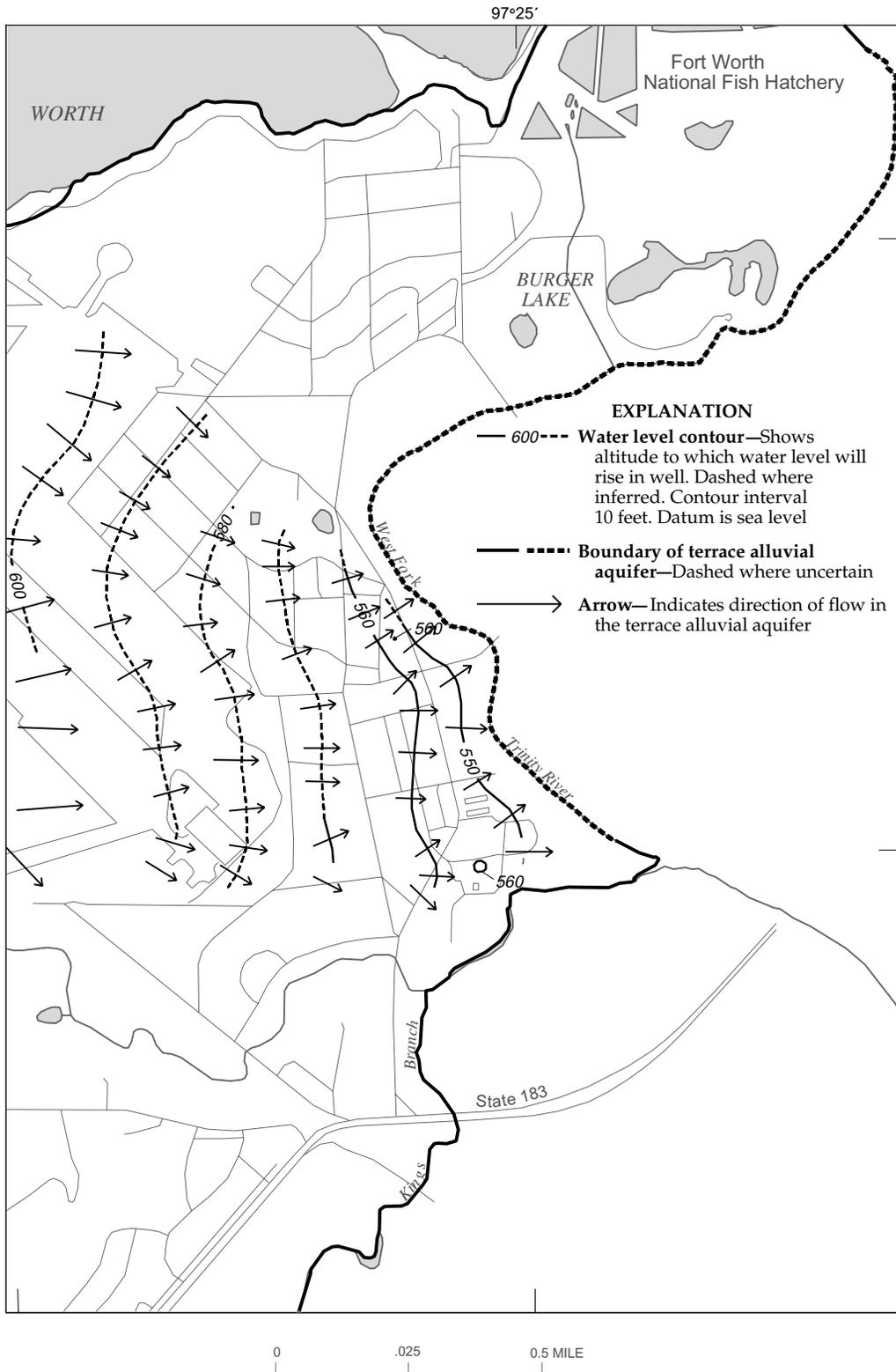
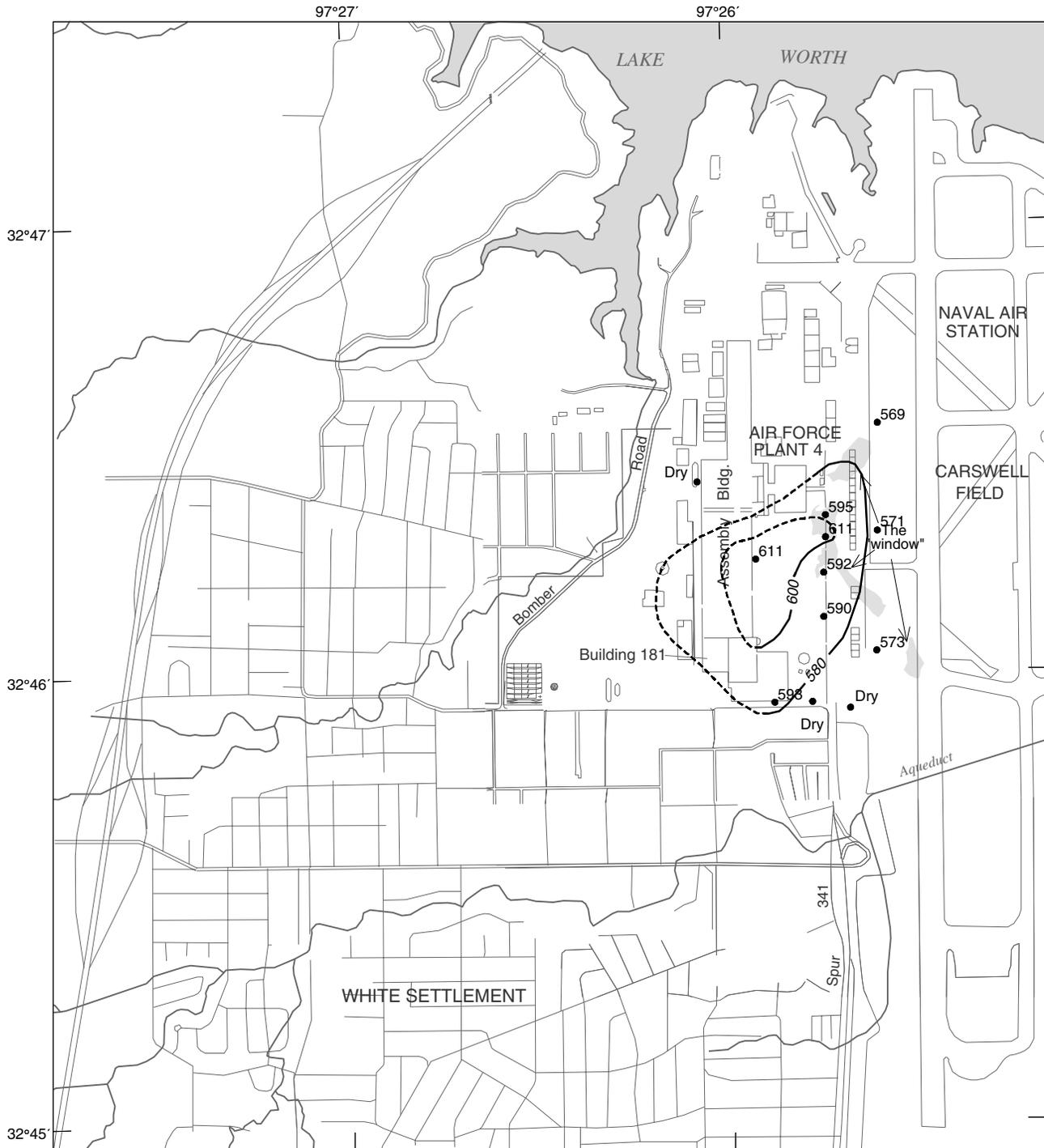


Figure 7. Continued.



Base from Chem-Nuclear Geotech, Inc.,  
written commun., 1993  
Universal Transverse Mercator projection  
Zone 14

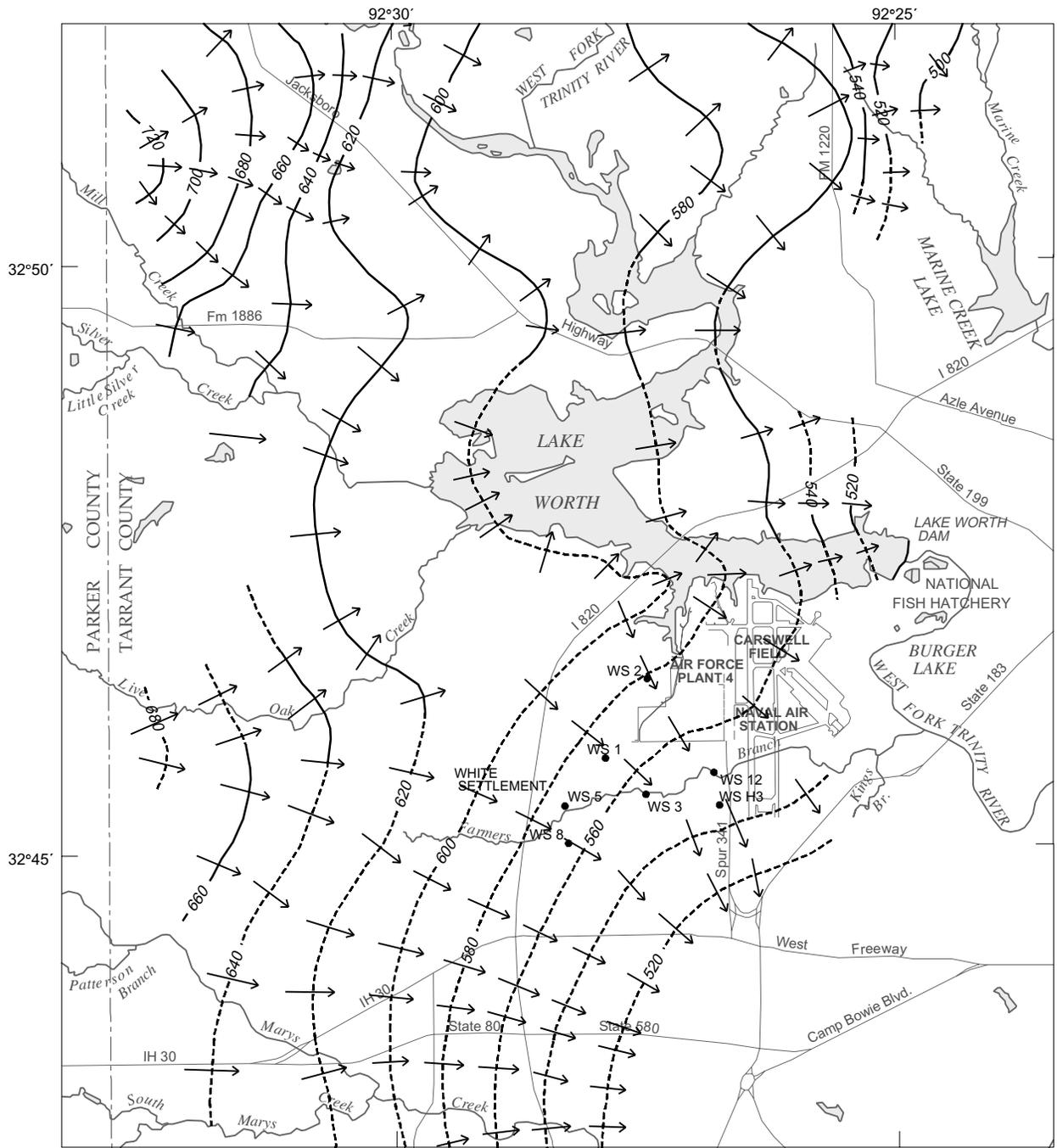
0 0.1 0.2 0.3 0.4 0.5 MILE

**EXPLANATION**

—580 - - - - - Water-level contour—Shows  
altitude to which water will  
rise in a well. Dashed where  
inferred. Contour interval  
20 feet. Datum is sea level

611 ● Well used for control—  
Number indicates altitude of  
water level, in feet. Datum is  
sea level. Water-level data  
from Jacobs Engineering Group  
Inc., written commun., 1993

**Figure 8.** Water-level altitudes in the Paluxy "upper sand" at Air Force Plant 4, Fort Worth, Texas, May 1993. (From Rivers and others, 1996.)



Base from RUST Geotech,  
written commun., 1993  
Universal Transverse Mercator projection  
Zone 14

0 1 2 MILES

**EXPLANATION**

- 620 ——— Water level contour—Shows altitude to which water level will rise in well  
Dashed where inferred. Contour interval 20 feet. Datum is sea level.
- Arrow—Indicates direction of flow in the Paluxy aquifer
- WS 5 • White Settlement water supply well

**Figure 9.** Regional water-level altitudes and flow direction in the Paluxy aquifer at Air Force Plant 4 and vicinity, Fort Worth, Texas, May 1993. (Modified from Rivers and others, 1996.)

**Table 5.** Water-level data for U.S. Geological Survey nested wells near Lake Worth, Fort Worth, Texas, February 1994

[ft, feet; ft/ft, foot per foot]

Well no. (fig. 2)	Aquifer unit	Depth to center of well screen, (ft)	Water level (ft above sea level)	Vertical hydraulic gradient (ft/ft)
USGS08PU	Upper zone of the Paluxy	59.5	593	0.070
USGS08PM	Middle zone of the Paluxy	116.5	589	.118
USGS08PL	Lower zone of the Paluxy	167.5	583	

ward. The vertical distance between the center of the well screen in the three wells screened in the Paluxy "upper sand" and the three wells screened in the upper zone of the Paluxy aquifer ranges from 22 to 35 ft. The downward gradients at the paired wells at the three sites near the "window" ranged from 1.23 to 1.37 ft/ft or 6,500 to 7,200 ft/mi. This extremely large vertical gradient indicates very poor hydraulic connection between the Paluxy "upper sand" and the upper zone of the Paluxy aquifer.

The difference between water levels in wells in the upper and middle zones of the Paluxy aquifer ranged from about 0 to 10 ft at AFP4 in December 1994, and the distance between well screens in the upper and middle Paluxy aquifers ranged from about 43 to 79 ft (IT Corporation, Monroeville, Pa., written commun., 1995). Thus, the downward gradient at AFP4 between the upper and middle zones of the Paluxy aquifer ranged from about 0 to 0.127 ft/ft or 0 to 670 ft/mi. The data indicate that in some places the upper and middle zones of the Paluxy aquifer are well connected hydraulically and that water can move easily between the two zones. In other places, the upper and middle zones of the Paluxy aquifer are not as well connected. Differences between water levels in the upper, middle, and lower zones of the Paluxy aquifer generally were less than 12 ft over a 135- to 170-ft distance. There was even less difference between water levels in the middle and lower Paluxy zones, thus, these were contoured together as one horizontal flow unit.

#### Hydraulic Connection with Lake Worth

The movement of water between the Paluxy aquifer and Lake Worth is complicated by the dip of the Paluxy aquifer. The pool elevation of Lake Worth

remains at about 594 ft above sea level. The Paluxy aquifer discharges to Lake Worth near its western extent, where about one-half the aquifer is above pool elevation. At the middle of the lake near Bomber Road, the top of the Paluxy aquifer is about 600 ft above sea level, placing the upper Paluxy in contact with Lake Worth. Thus, at Bomber Road the upper zone of the Paluxy aquifer is recharged by Lake Worth. At the east side of the lake, the top of the Paluxy aquifer is about 550 ft above sea level and beneath the lake, with part of the Walnut Formation separating the Paluxy aquifer from the lake. Water might not move between the Paluxy aquifer and the lake near the eastern extent of Lake Worth.

The nested wells USGS08 and USGS09 provide some insight pertinent to judging whether or not Lake Worth and the Paluxy aquifer are hydraulically connected. Drill cuttings revealed the Paluxy "upper sand" to be unsaturated at both locations. After drilling through the highly indurated sandstone and shale between the Paluxy "upper sand" and the remainder of the upper zone of the Paluxy aquifer, water rose above the top of the Paluxy "upper sand" to about the altitude of Lake Worth. Water levels in the completed nested wells decreased about 10 to 12 ft between the upper and lower zones of the Paluxy aquifer, indicating a downward gradient in that part of the Paluxy aquifer. It is concluded from this that Lake Worth recharges the Paluxy aquifer near AFP4.

#### WATER QUALITY OF THE PALUXY AQUIFER

Contaminants related to activities at AFP4 have not been detected in the Paluxy aquifer offsite, but contamination has been detected in the Paluxy aquifer

at two areas on AFP4 (U.S. Air Force, Aeronautical Systems Center, 1995). The ground-water contaminant detected was TCE, measured in mg/L and  $\mu\text{g/L}$ —1 mg/L can be thought of as one part contaminant by weight per million parts water by volume, and 1  $\mu\text{g/L}$  can be thought of as one part contaminant by weight per billion parts water by volume. In the dilute solutions of contaminants in ground water discussed in this report, mg/L and  $\mu\text{g/L}$  are equivalent to parts per million and parts per billion, respectively.

### Trichloroethylene and Other Volatile Organic Compounds

TCE is believed to enter the Paluxy aquifer at the "window," where the Goodland-Walnut confining unit is less than 5-ft thick and contaminants from the terrace alluvial aquifer could enter the Paluxy "upper sand." TCE is a VOC that is considered a dense nonaqueous phase liquid (DNAPL) because it is denser than water and does not dissolve easily in water (nonaqueous). Because pure TCE is dense, it tends to flow downward by gravity in the permeable parts of an aquifer and then flows horizontally along the top of the confining unit or clay (Goodland-Walnut confining unit). Part of the TCE will dissolve and move with the water (dissolved phase). The remainder (pure phase) can become trapped in pore spaces (residual DNAPL) with larger amounts collecting in low spots on the top of the confining unit (pooled DNAPL). When TCE moves through the soil, some TCE will stick to the soil grains. As TCE degrades, it loses chlorine atoms to form dichloroethylene (DCE) and then vinyl chloride (VC). DCE and VC also have been found in ground-water samples from wells at AFP4 (Jacobs Engineering Group Inc., 1993).

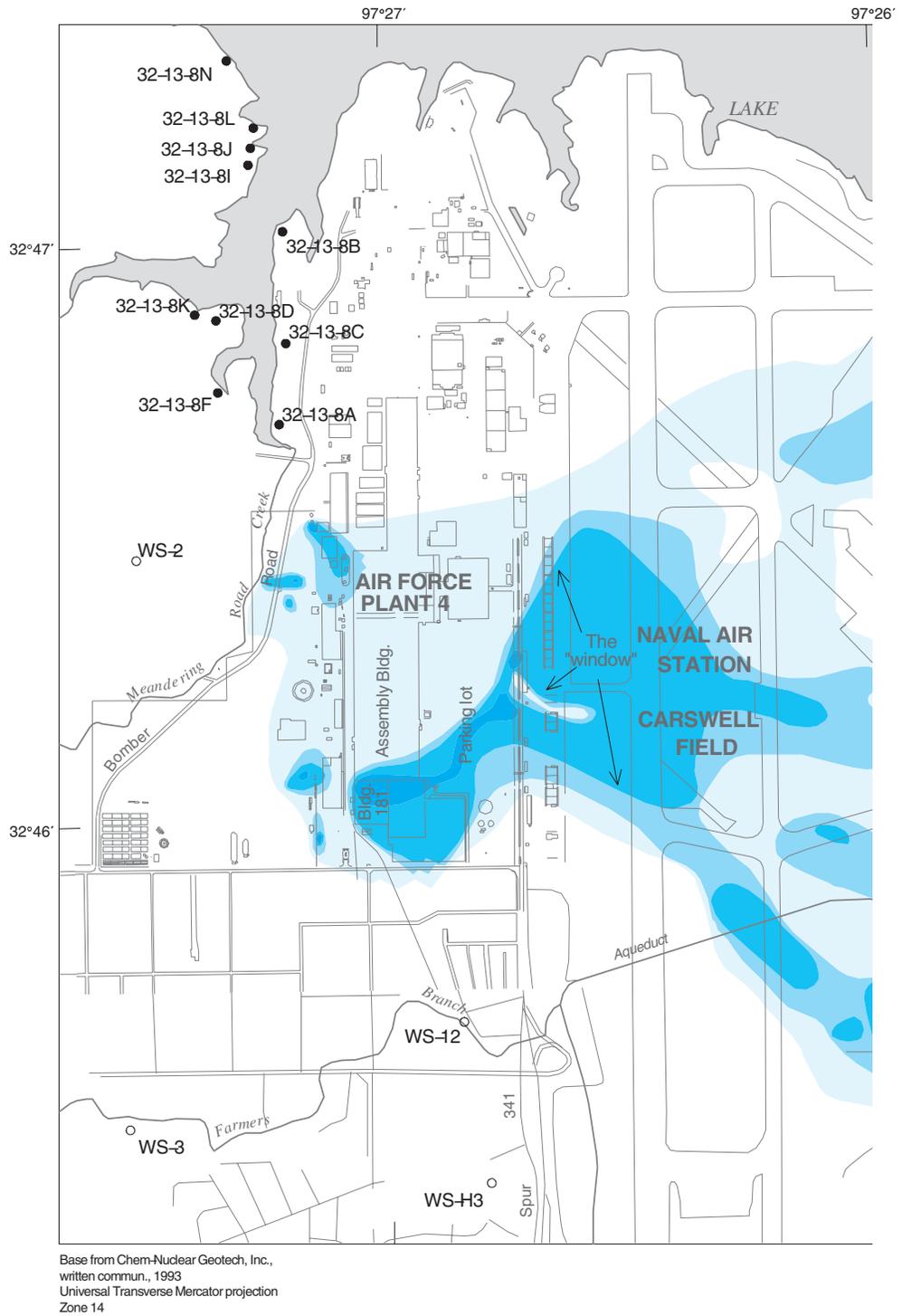
Concentrations of TCE in the terrace alluvial aquifer (fig. 10) indicate the extent of the TCE plume. This map originally was prepared by RUST Geotech (1995b)—from data collected by Jacobs Engineering Group Inc. (1993, 1995)—and by Geo-Marine, Inc. (1995). TCE concentrations of about 1,100 mg/L or 1,100,000  $\mu\text{g/L}$  indicate the possible presence of non-aqueous phase TCE, as this is the maximum amount of TCE that can dissolve in water (saturation concentration at 25 °C; Cohen and Mercer, 1993). Large concentrations of TCE (greater than 10,000 but less than 100,000  $\mu\text{g/L}$ ) were detected along the paleochannel beneath the assembly building and the east parking lot (fig. 10). These concentrations are less than 10-percent total saturation, but might indicate that some pure phase TCE is

present. Concentrations greater than 100,000  $\mu\text{g/L}$  occur in the terrace alluvial aquifer beneath building 181 of the assembly building.

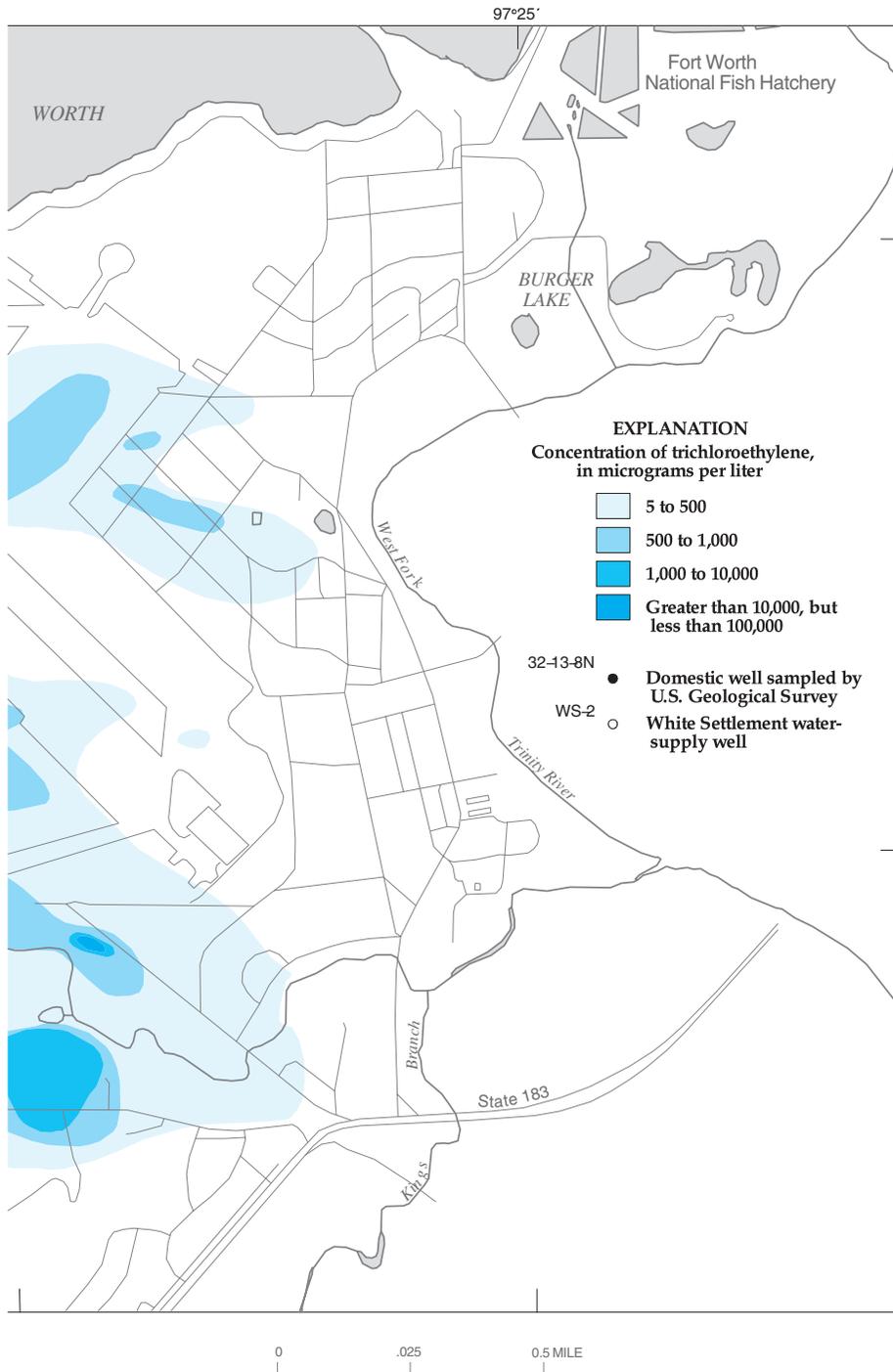
TCE has been detected in the Paluxy "upper sand" beneath the east parking lot at AFP4 ("window" area) in concentrations ranging from 8,000 to 11,000  $\mu\text{g/L}$  (Jacobs Engineering Group Inc., 1993). TCE also has been detected in small concentrations (2 to 50  $\mu\text{g/L}$ ) in two nested wells (P-22U and P-22M, fig. 2) in the upper and middle zones of the Paluxy aquifer (Jacobs Engineering Group Inc., 1993). One of these wells (P-22M) had no seal between the outer casing and the terrace alluvial aquifer and no seal between the well and the outer casing; and therefore could have been the pathway for leakage of contaminated water from the terrace alluvial aquifer. Well P-22M has been abandoned and plugged to prevent any further possibility of contamination from the terrace alluvial aquifer moving downward to the Paluxy aquifer along the well annulus. P-22U and P-22M are less than 1,500 ft east of White Settlement water-supply well WS-2 (fig. 2). Because the regional direction of flow is east-southeast, well WS-2 cannot be contaminated by migration from AFP4 unless the natural direction of ground-water flow is reversed by increased pumping. White Settlement has taken WS-2 out of production as a precautionary measure even though no contaminants have been detected in water samples from this well (Paul Bounds, City of White Settlement, oral commun., 1995).

White Settlement has seven water-supply wells adjacent to AFP4. Four of the seven water-supply wells are west of AFP4 (fig. 2), where the regional direction of flow in the Paluxy aquifer is east-southeast. The three remaining wells are south of AFP4 (fig. 2). The easternmost well, WS-12, is within 2,000 ft of the plant boundary. The regional direction of ground-water flow in the Paluxy aquifer is toward WS-12 across AFP4 (fig. 9). Thus, WS-12 has the greatest potential to be affected by contaminants in the ground water beneath AFP4. TCE was not detected in any White Settlement wells when all were sampled in 1993 (Jacobs Engineering Group Inc., 1993).

To determine if contaminants from AFP4 were migrating off-site, the USGS sampled 10 domestic wells northwest of AFP4 (fig. 2) in April 1993 and April 1995. TCE or its degradation products (DCE, VC) were not detected in any of the field or laboratory samples collected. However, two VOCs, chloromethane and bromomethane, were detected in laboratory samples col-



**Figure 10.** Trichloroethylene concentrations in the terrace alluvial aquifer at Air Force Plant 4 and vicinity, Fort Worth, Texas. (Modified from Geo-Marine, Inc., 1995; RUST Geotech, 1995b.)



**Figure 10.** Continued.

lected in 1993. No other VOCs were detected above the reporting limit in any samples.

Chloromethane and bromomethane are classified as unregulated contaminants (U.S. Environmental Protection Agency, 1995). The Lifetime Health Advisory (HA) designated by the USEPA for chloromethane is 3  $\mu\text{g/L}$  (U.S. Environmental Protection Agency, 1976). "The Lifetime HA represents that portion of an individual's total exposure that is attributed to drinking water and is considered protective of noncarcinogenic adverse health effects over a lifetime exposure" (U.S. Environmental Protection Agency, 1986). The Lifetime HA for bromomethane is 50  $\mu\text{g/L}$  (U.S. Environmental Protection Agency, 1989).

During April 1993 water samples were collected for laboratory analysis of VOCs from wells 32-13-8A, 32-13-8C, 32-13-8F, 32-13-8I, and 32-13-8K. The sample collected at well 32-13-8K and analyzed for priority pollutant VOCs contained concentrations of chloromethane and bromomethane of 5.7 and 2.5  $\mu\text{g/L}$ , respectively (table 6 at end of report). Samples collected at wells 32-13-8C and 32-13-8K and analyzed for purgeable VOCs contained concentrations of chloromethane of 2.3 and 1.5  $\mu\text{g/L}$ , respectively. The differences between concentrations of chloromethane and between concentrations of bromomethane using USEPA methods—priority pollutant (524) and purgeable (8260)—are considered to be within acceptable limits. These methods produce comparable results because they employ the same analytical techniques, but the samples should not be considered to be duplicates because they were not analyzed at the same time. The analytical results for chloromethane and for bromomethane were in good agreement because these compounds were detected at or near the method reporting level where the uncertainty of the data can approach or exceed the reported value.

During April 1995 water samples were collected for laboratory analysis of VOCs from wells 32-13-8A, 32-13-8B, 32-13-8C, 32-13-8I, and 32-13-8K. Well 32-13-8B was sampled instead of 32-13-8F (1993) because the gas chromatograph indicated an unknown organic compound in well 32-13-8B. VOCs, including DCE, TCE, VC, chloromethane, and bromomethane, were not detected in the five wells sampled. The results of the April 1995 sampling are listed in table 7 (at end of report). The April 1993 laboratory samples were analyzed for two lists of VOCs—priority pollutant and purgeable. Because most of the VOCs were duplicated by these two lists and because results of the April 1993

sampling indicated VOCs were not elevated in the study area, purgeable VOCs were not analyzed in April 1995.

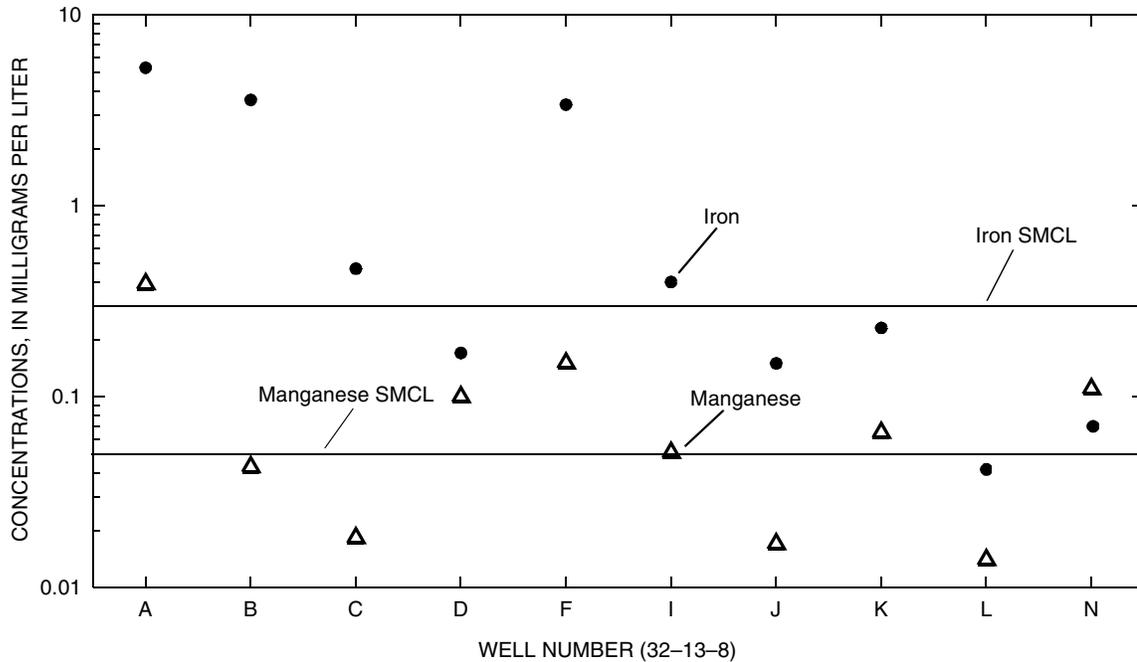
Four USGS wells at two nested sites, USGS08PL, USGS09PU, USGS09PM, and USGS09PL (fig. 2), were sampled in April 1995 for VOCs, TPHs, and oil and grease. Wells USGS08PU and USGS08PM could not be sampled in April 1995 because of mechanical problems with the pump. All these wells previously had been sampled by Jacobs Engineering Group Inc. (1994). VOCs, TPHs, and oil and grease were not detected in any of these wells.

## Chromium

Chromium is used in a metal plating facility at AFP4 and has been detected in the terrace alluvial aquifer at AFP4 near building 181 (RUST Geotech, 1995a, b, c, d). The distribution of chromium at AFP4 is similar to the distribution of TCE (fig. 10), but not as widespread. However, chromium concentrations in the terrace alluvial aquifer range from 0 to 629  $\mu\text{g/L}$  (RUST Geotech, 1995b, fig. II-18), while TCE concentrations range from 0 to 10,000  $\mu\text{g/L}$  and higher (Geo-Marine, Inc., 1995; RUST Geotech, 1995b). The primary maximum contaminant level (MCL) for chromium is 0.1  $\text{mg/L}$  (U.S. Environmental Protection Agency, 1995). Chromium was not detected in the Paluxy aquifer prior to this study (Jacobs Engineering Group Inc., 1993) and also was not detected in any of the laboratory samples from domestic water-supply wells northwest of AFP4 collected during April 1993 and April 1995 (tables 6, 7).

## Iron and Manganese

Iron and manganese are naturally occurring minerals that often are present in ground water. Elevated levels of iron in ground water can be caused by dissolution of aquifer rock, absence of oxygen, or corrosion of plumbing pipes. Iron is an essential trace metal required by plants and animals. The average human intake of iron is 16  $\text{mg/d}$  (U.S. Environmental Protection Agency, 1976). The secondary maximum contaminant level (SMCL) for iron (0.3  $\text{mg/L}$ ) is established for aesthetic purposes to prevent objectionable taste and discoloration of clothes and plumbing fixtures (U.S. Environmental Protection Agency, 1995); the SMCL constitutes a small fraction of the iron normally consumed by humans. A Public Health Service study indicated that humans can taste iron in spring water at



**Figure 11.** Concentrations of iron and manganese, and the corresponding secondary maximum contaminant level (SMCL), at domestic water-supply wells northwest of Air Force Plant 4, Fort Worth, Texas, April 1995.

concentrations of 1.8 mg/L and in distilled water at concentrations of 3.4 mg/L (U.S. Environmental Protection Agency, 1976). Manganese is a vital micronutrient for plants and animals. The average human intake of manganese is 10 mg/d (U.S. Environmental Protection Agency, 1976). The SMCL for manganese is 0.05 mg/L (U.S. Environmental Protection Agency, 1995).

In 1993, the sample from well 32-13-8A had iron and manganese concentrations above the SMCL—4.3 and 0.36 mg/L, respectively (table 6). The sample from well 32-13-8C had an iron concentration of 0.62 mg/L. These concentrations represent the total concentrations of these trace metals in water because samples were not filtered prior to analysis.

In 1995, samples from 8 of the 10 domestic water-supply wells had concentrations of iron or manganese or both that equaled or were greater than the SMCL—well 32-13-8A (iron, 5.3 mg/L, and manganese, 0.39 mg/L); well 32-13-8B (iron, 3.6 mg/L); well 32-13-8C (iron, 0.47 mg/L); well 32-13-8D (manganese, 0.10 mg/L); well 32-13-8F (iron, 3.4 mg/L, and manganese, 0.15 mg/L); well 32-13-8I (iron, 0.40 mg/L, and manganese, 0.05 mg/L); well 32-13-8K (manganese, 0.07 mg/L); well 32-13-8N (manganese, 0.11 mg/L) (fig. 11, table 7). These elevated iron and manganese concen-

trations probably are caused by natural geochemical conditions in the aquifer.

### Other Trace Metals

Many trace metals are normal constituents of drinking water. The USEPA has established an MCL and SMCL for some trace metals (U.S. Environmental Protection Agency, 1995). However, many of the metals analyzed for this investigation do not have a defined MCL or SMCL.

Water samples were collected for laboratory analysis of trace metals at 3 of the wells, 32-13-8A, 32-13-8C, and 32-13-8I, in April 1993 (table 6) and at all 10 wells in April 1995 (table 7). Some of the metals concentrations are below the laboratory reporting limit. This indicates that the concentration is an estimate. The same metals are listed for each well for consistency. The trace metal of principal interest in this report, chromium, was not detected in any wells. Lead concentrations were detected only in 1995 in samples from wells 32-12-8J (0.04 mg/L) and 32-13-8N (0.04 mg/L). These concentrations are below the laboratory reporting limit of 0.20 mg/L.

## CONCLUSIONS

Ground water in the surficial terrace alluvial aquifer is contaminated at AFP4 and at the adjacent NAS. Some of the contaminated water has leaked from the terrace alluvial aquifer to an uppermost interval of the Paluxy Formation (the Paluxy "upper sand") beneath the east parking lot, east of the assembly building, and to the upper and middle zones of the Paluxy aquifer near Bomber Road, west of the assembly building. AFP4 was placed on the USEPA National Priorities List as a Superfund site in August 1990. Citizens are concerned that contaminants from the plant might enter nearby municipal and domestic water-supply wells that pump water from the middle and lower zones of the Paluxy aquifer. The ground-water contaminants of principal concern are trichloroethylene, used for degreasing metal parts, and chromium, used in plating metal parts.

Geologic formations that crop out in the study area, from oldest to youngest, are the Paluxy Formation (aquifer), Walnut Formation (confining unit), and Goodland Limestone (confining unit). Beneath the Paluxy Formation is the Glen Rose Formation (confining unit) and Twin Mountains Formation (aquifer). The terrace alluvial deposits overlie these Cretaceous rocks.

The terrace alluvial aquifer (0- to 60-ft thick) is not used for municipal water supply. The aquifer is recharged by precipitation and by leaking water pipes at AFP4. The aquifer is discharged by evapotranspiration and seepage to Lake Worth, Meandering Road Creek, and Farmers Branch, and is possibly discharged by downward leakage to the Paluxy "upper sand" through the "window," an elongated, erosional channel in the Goodland-Walnut confining unit.

The Goodland-Walnut confining unit (0.5- to 70-ft thick) separates the terrace alluvial aquifer from the Paluxy aquifer and restricts the flow of ground water between these aquifers in most places. However, the downward leakage of water from the terrace alluvial aquifer to the Paluxy aquifer might occur where this confining unit is nearly breached by the "window."

The Paluxy aquifer (130- to 175-ft thick) is divided into upper, middle, and lower zones. The Paluxy "upper sand" is an apparently isolated, mostly unsaturated, sandy lens within the uppermost part of the upper zone of the aquifer that underlies the "window." The Paluxy aquifer is recharged primarily by leakage from Lake Worth and by precipitation on the outcrop area west of the study area. Discharge from the

Paluxy aquifer in the study area primarily occurs as pumpage from municipal and domestic water-supply wells.

The Glen Rose confining unit (about 150-ft thick) separates the Paluxy aquifer from the underlying Twin Mountains aquifer (about 200-ft thick). The Twin Mountains aquifer might be considered an alternate water supply for municipal purposes.

Ground water in the terrace alluvial aquifer appears to flow outward, away from AFP4. Water levels in the terrace alluvial aquifer are higher than water levels in the Paluxy "upper sand." The water-level map for the Paluxy "upper sand" reveals a ground-water mound in this characteristically unsaturated, uppermost interval of the Paluxy aquifer. The mound has formed beneath the "window" in the overlying Goodland-Walnut confining unit. Thus, the Paluxy "upper sand" probably is recharged by downward leakage through the "window," from the terrace alluvial aquifer.

The water-level map for regionally extensive parts of the Paluxy aquifer indicates that the highest water levels coincide with the outcrop area, northwest of Lake Worth. The prevailing direction of lateral ground-water flow in the Paluxy aquifer is from west to east-southeast. The observed hydraulic gradients between the different zones of the Paluxy aquifer indicate a greater potential for downward leakage from the upper zone to the middle zone of the Paluxy aquifer, than from the Paluxy "upper sand" to the upper zone.

The terrace alluvial aquifer at AFP4 is contaminated with trichloroethylene and chromium. Trichloroethylene concentrations greater than 10,000, but less than 100,000  $\mu\text{g/L}$ , are present beneath the assembly building and east parking lot. Concentrations of trichloroethylene greater than 100,000  $\mu\text{g/L}$  occur beneath building 181 of the assembly building. The distribution of chromium in the terrace alluvial aquifer, where concentrations range from 0 to 629  $\mu\text{g/L}$ , is not as widespread as that of trichloroethylene.

Trichloroethylene concentrations ranging from 8,000 to 11,000  $\mu\text{g/L}$  were present in the Paluxy "upper sand" below the "window," where downward leakage of contaminated water from the terrace alluvial aquifer is greatest. Water samples from two nested wells (P-22U and P-22M, screened in the upper and middle zones of the Paluxy aquifer) west of the assembly building had trichloroethylene concentrations ranging from 2 to 50  $\mu\text{g/L}$ . Well P-22M, the most likely path of leakage to the Paluxy aquifer, has been plugged.

Seven wells adjacent to AFP4 provide water for the city of White Settlement. Because the wells mostly are west and south of the areas of known trichloroethylene contamination and because the regional direction of ground-water flow in the Paluxy aquifer is toward the east-southeast, leakage of contaminated water to these wells is unlikely. Municipal well WS-2, about 1,500 ft west of well P-22M, has been taken out of production as a precautionary measure. Although ground water is flowing toward well WS-12 (the municipal well with the greatest potential for contamination) trichloroethylene was not detected in any White Settlement wells sampled for water quality during 1993.

The results of water-quality sampling at 10 domestic wells northwest of the plant during April 1993 and April 1995 indicated that neither trichloroethylene nor chromium had migrated off-site to these wells. The only volatile organic compounds detected during the 1993 or 1995 sampling activities were chloromethane (during 1993, in water from two wells) and bromomethane (during 1993, in water from one well).

Water samples from four of six wells drilled by the U.S. Geological Survey northwest of AFP4 were collected during April 1995. No detections were found of volatile organic compounds, total petroleum hydrocarbons, and oil and grease constituents.

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**Table 6.** Selected results of laboratory analyses for volatile organic compounds, total trace metals, and field-measured properties for domestic water-supply wells sampled northwest of Air Force Plant 4, Fort Worth, Texas, April 1993<sup>1</sup>

[µg/L, micrograms per liter; mg/L, milligrams per liter; µS/cm microsiemens per centimeter at 25 °C; °C, degrees Celsius; ND, nondetect; --, not sampled]

Well no. (fig. 2)	Volatile organic compounds (priority pollutant 524 <sup>2</sup> )	Con- cen- tration (µg/L)	Report- ing limit (µg/L)	Volatile organic compounds (purgeable 8260 <sup>2</sup> )	Con- cen- tration (µg/L)	Report- ing limit (µg/L)	Total trace metals	Con- cen- tration (mg/L)	Report- ing limit (mg/L)	Field measurements		
										pH (standard units)	Specific conduct- ance (µS/cm)	Temper- ature (°C)
32-13-8A	Chloromethane	ND	2.0	Chloromethane	ND	1.0	Barium	0.12	0.10	7.5	526	22.0
	Bromomethane	ND	2.0	Bromomethane	ND	1.0	Calcium	62	5.0			
	Dichloroethylene	ND	1.0	Dichloroethylene	ND	1.0	Chromium	ND	.030			
	Trichloroethylene	ND	1.0	Trichloroethylene	ND	1.0	Copper	.97	.030			
	Vinyl chloride	ND	2.0	Vinyl chloride	ND	1.0	Iron	4.3	.040			
							Lead	ND	.20			
							Magnesium	9.7	5.0			
							Manganese	.36	.010			
							Sodium	22	5.0			
							Zinc	.36	.010			
32-13-8B	--			--			--			7.6	594	21.5
32-13-8C	Chloromethane	ND	2.0	Chloromethane	2.3	1.0	Barium	.12	.10	7.6	521	21.5
	Bromomethane	ND	2.0	Bromomethane	ND	1.0	Calcium	63	5.0			
	Dichloroethylene	ND	1.0	Dichloroethylene	ND	1.0	Chromium	ND	.030			
	Trichloroethylene	ND	1.0	Trichloroethylene	ND	1.0	Copper	ND	.030			
	Vinyl chloride	ND	2.0	Vinyl chloride	ND	1.0	Iron	.62	.040			
							Lead	ND	.20			
							Magnesium	14	5.0			
							Manganese	.01	.010			
							Sodium	18	5.0			
							Zinc	.03	.010			
32-13-8D	--			--			--			7.1	654	21.5

**Table 6.** Selected results of laboratory analyses for volatile organic compounds, total trace metals, and field-measured properties for domestic water-supply wells sampled northwest of Air Force Plant 4, Fort Worth, Texas, April 1993<sup>1</sup>—Continued

Well no. (fig. 2)	Volatile organic compounds (priority pollutant 524 <sup>2</sup> )	Con- cen- tration (µg/L)	Report- ing limit (µg/L)	Volatile organic compounds (purgeable 8260 <sup>2</sup> )	Con- cen- tration (µg/L)	Report- ing limit (µg/L)	Total trace metals	Con- cen- tration (mg/L)	Report- ing limit (mg/L)	Field measurements		
										pH (standard units)	Specific conduct- ance (µS/cm)	Temper- ature (°C)
32-13-8F	Chloromethane	ND	2.0	Chloromethane	ND	1.0	--			7.6	602	21.5
	Bromomethane	ND	2.0	Bromomethane	ND	1.0						
	Dichloroethylene	ND	1.0	Dichloroethylene	ND	1.0						
	Trichloroethylene	ND	1.0	Trichloroethylene	ND	1.0						
	Vinyl chloride	ND	2.0	Vinyl chloride	ND	1.0						
32-13-8I	Chloromethane	ND	2.0	Chloromethane	ND	1.0	Barium	ND	0.10	7.4	836	21.0
	Bromomethane	ND	2.0	Bromomethane	ND	1.0	Calcium	110	5.0			
	Dichloroethylene	ND	1.0	Dichloroethylene	ND	1.0	Chromium	ND	.030			
	Trichloroethylene	ND	1.0	Trichloroethylene	ND	1.0	Copper	.35	.030			
	Vinyl chloride	ND	2.0	Vinyl chloride	ND	1.0	Iron	.25	.040			
							Lead	ND	.20			
							Magnesium	23	5.0			
							Manganese	.04	.010			
							Sodium	28	5.0			
							Zinc	.03	.010			
32-13-8J	--			--			--			7.4	698	20.5
32-13-8K	Chloromethane	5.7	2.0	Chloromethane	1.5	1.0	--			7.5	586	20.5
	Bromomethane	2.5	2.0	Bromomethane	ND	1.0						
	Dichloroethylene	ND	1.0	Dichloroethylene	ND	1.0						
	Trichloroethylene	ND	1.0	Trichloroethylene	ND	1.0						
	Vinyl chloride	ND	2.0	Vinyl chloride	ND	1.0						
32-13-8L	--			--			--			7.6	651	20.5
32-13-8N	--			--			--			7.0	803	21.0

<sup>1</sup> All wells were field screened for benzene, toluene, and trichloroethylene—none detected.<sup>2</sup> U.S. Environmental Protection Agency analytical method for laboratory analysis.

**Table 7.** Selected results of laboratory analyses for volatile organic compounds, total trace metals, major anions, and field-measured properties for domestic water-supply wells sampled northwest of Air Force Plant 4, Fort Worth, Texas, April 1995<sup>1</sup>

[µg/L, micrograms per liter; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 °C; °C, degrees Celsius; NA, not applicable; ND, nondetect; --, not sampled]

Well no. (fig. 2)	Volatile organic compounds (priority pollutant 524 <sup>2</sup> )	Concen- tration (µg/L)	Report- ing limit (µg/L)	Total trace metals	Concen- tration (mg/L)	Report- ing limit (mg/L)	Major anions	Concen- tration (mg/L)	Report- ing limit (mg/L)	Field measurements		
										pH (stand- ard units)	Specific conduct- ance (µS/cm)	Temper- ature (°C)
32-13-8A	Chloromethane	ND	1.0	Barium	0.12	0.10	Field alkalinity as HCO <sub>3</sub>	264	NA	7.6	538	19.5
	Bromomethane	ND	1.0	Calcium	68	5.0	Fluoride	ND	.50			
	Dichloroethylene	ND	1.0	Chromium	ND	.030	Chloride	37	.50			
	Trichloroethylene	ND	1.0	Copper	.01	.030	Nitrate as N	ND	.50			
	Vinyl chloride	ND	1.0	Iron	5.3	.040	Orthophosphate as P	ND	.50			
				Lead	ND	.20	Sulfate	.98	.50			
				Magnesium	10	5.0						
				Manganese	.39	.010						
				Potassium	2.7	5.0						
				Sodium	25	5.0						
32-13-8B	Chloromethane	ND	1.0	Barium	.08	.10	Field alkalinity as HCO <sub>3</sub>	278	NA	7.7	565	19.5
	Bromomethane	ND	1.0	Calcium	54	5.0	Fluoride	ND	.50			
	Dichloroethylene	ND	1.0	Chromium	ND	.030	Chloride	26	.50			
	Trichloroethylene	ND	1.0	Copper	.01	.030	Nitrate as N	ND	.50			
	Vinyl chloride	ND	1.0	Iron	3.6	.040	Orthophosphate as P	ND	.50			
				Lead	ND	.20	Sulfate	23	.50			
				Magnesium	18	5.0						
				Manganese	.04	.010						
				Potassium	3.7	5.0						
				Sodium	34	5.0						
			Zinc	.02	.010							

Footnotes at end of table.

**Table 7.** Selected results of laboratory analyses for volatile organic compounds, total trace metals, major anions, and field-measured properties for domestic water-supply wells sampled northwest of Air Force Plant 4, Fort Worth, Texas, April 1995<sup>1</sup>—Continued

Well no. (fig. 2)	Volatile organic compounds (priority pollutant 524 <sup>2</sup> )	Concen- tration (µg/L)	Report- ing limit (µg/L)	Total trace metals	Concen- tration (mg/L)	Report- ing limit (mg/L)	Major anions	Concen- tration (mg/L)	Report- ing limit (mg/L)	Field measurements		
										pH (stand- ard units)	Specific conduct- ance (µS/cm)	Temper- ature (°C)
32-13-8C	Chloromethane	ND	1.0	Barium	0.13	0.10	Field alkalinity as HCO <sub>3</sub>	268	5.0	7.7	527	19.0
	Bromomethane	ND	1.0	Calcium	72	5.0	Fluoride	ND	.50			
	Dichloroethylene	ND	1.0	Chromium	ND	.030	Chloride	33	.50			
	Trichloroethylene	ND	1.0	Copper	.01	.030	Nitrate as N	ND	.50			
	Vinyl chloride	ND	1.0	Iron	.47	.040	Orthophosphate as P	ND	.50			
				Lead	ND	.20	Sulfate	.89	.50			
				Magnesium	14	5.0						
				Manganese	.02	.010						
				Potassium	2.0	5.0						
				Sodium	20	5.0						
32-13-8D	--			Zinc	.05	.010				7.3	703	19.6
				Barium	.04	.10	Field alkalinity as HCO <sub>3</sub>	261	5.0			
				Calcium	120	5.0	Fluoride	ND	.50			
				Chromium	ND	.030	Chloride	39	.50			
				Copper	.01	.030	Nitrate as N	ND	.50			
				Iron	.17	.040	Orthophosphate as P	ND	.50			
				Lead	ND	.20	Sulfate	93	.50			
				Magnesium	5.20	5.0						
				Manganese	.10	.010						
				Potassium	2.6	5.0						
			Sodium	22	5.0							
			Zinc	.58	.010							

Footnotes at end of table.

**Table 7.** Selected results of laboratory analyses for volatile organic compounds, total trace metals, major anions, and field-measured properties for domestic water-supply wells sampled northwest of Air Force Plant 4, Fort Worth, Texas, April 1995<sup>1</sup>—Continued

Well no. (fig. 2)	Volatile organic compounds (priority pollutant 524 <sup>2</sup> )	Concen- tration (µg/L)	Report- ing limit (µg/L)	Total trace metals	Concen- tration (mg/L)	Report- ing limit (mg/L)	Major anions	Concen- tration (mg/L)	Report- ing limit (mg/L)	Field measurements		
										pH (stand- ard units)	Specific conduct- ance (µS/cm)	Temper- ature (°C)
32-13-8F	--			Barium	0.05	0.10	Field alkalinity as HCO <sub>3</sub>	294	5.0	7.6	610	20.3
				Calcium	61	5.0	Fluoride	ND	.50			
				Chromium	ND	.030	Chloride	11	.50			
				Copper	.01	.030	Nitrate as N	ND	.50			
				Iron	3.4	.040	Orthophosphate as P	ND	.50			
				Lead	ND	.20	Sulfate	59	.50			
				Magnesium	16	5.0						
				Manganese	.15	.010						
				Potassium	4.2	5.0						
				Sodium	46	5.0						
				Zinc	.03	.010						
32-13-8I	Chloromethane	ND	1.0	Barium	.07	.10	Field alkalinity as HCO <sub>3</sub>	404	5.0	7.2	906	19.1
	Bromomethane	ND	1.0	Calcium	130	5.0	Fluoride	ND	.50			
	Dichloroethylene	ND	1.0	Chromium	ND	.030	Chloride	53	.50			
	Trichloroethylene	ND	1.0	Copper	.01	.030	Nitrate as N	ND	.50			
	Vinyl chloride	ND	1.0	Iron	.40	.040	Orthophosphate as P	ND	.50			
				Lead	ND	.20	Sulfate	68	.50			
				Magnesium	23	5.0						
				Manganese	.05	.010						
				Potassium	3.7	5.0						
				Sodium	37	5.0						
				Zinc	.07	.010						

Footnotes at end of table.

**Table 7.** Selected results of laboratory analyses for volatile organic compounds, total trace metals, major anions, and field-measured properties for domestic water-supply wells sampled northwest of Air Force Plant 4, Fort Worth, Texas, April 1995<sup>1</sup>—Continued

Well no. (fig. 2)	Volatile organic compounds (priority pollutant 524 <sup>2</sup> )	Concen- tration (µg/L)	Report- ing limit (µg/L)	Total trace metals	Concen- tration (mg/L)	Report- ing limit (mg/L)	Major anions	Concen- tration (mg/L)	Report- ing limit (mg/L)	Field measurements		
										pH (stand- ard units)	Specific conduct- ance (µS/cm)	Temper- ature (°C)
32-13-8J	--			Barium	0.08	0.10	Field alkalinity as HCO <sub>3</sub>	337	5.0	7.8	681	18.5
				Calcium	40	5.0	Fluoride	ND	.50			
				Chromium	ND	.030	Chloride	13	.50			
				Copper	.01	.030	Nitrate as N	ND	.50			
				Iron	.15	.040	Orthophosphate as P	ND	.50			
				Lead	.04	.20	Sulfate	64	.50			
				Magnesium	20	5.0						
				Manganese	.02	.010						
				Potassium	4.9	5.0						
				Sodium	83	5.0						
				Zinc	.08	.010						
32-13-8K	Chloromethane Bromomethane Dichloroethylene Trichloroethylene Vinyl chloride	ND	1.0	Barium	.07	.10	Field alkalinity as HCO <sub>3</sub>	296	5.0	7.6	601	19
				Calcium	72	5.0	Fluoride	ND	.50			
				Chromium	ND	.030	Chloride	38	.50			
				Copper	.03	.030	Nitrate as N	ND	.50			
				Iron	.23	.040	Orthophosphate as P	ND	.50			
				Lead	ND	.20	Sulfate	22	.50			
				Magnesium	19	5.0						
				Manganese	.07	.010						
				Potassium	3.4	5.0						
				Sodium	22	5.0						
				Zinc	.02	.010						

Footnotes at end of table.

**Table 7.** Selected results of laboratory analyses for volatile organic compounds, total trace metals, major anions, and field-measured properties for domestic water-supply wells sampled northwest of Air Force Plant 4, Fort Worth, Texas, April 1995<sup>1</sup>—Continued

Well no. (fig. 2)	Volatile organic compounds (priority pollutant 524 <sup>2</sup> )	Concen- tration (µg/L)	Report- ing limit (µg/L)	Total trace metals	Concen- tration (mg/L)	Report- ing limit (mg/L)	Major anions	Concen- tration (mg/L)	Report- ing limit (mg/L)	Field measurements		
										pH (stand- ard units)	Specific conduct- ance (µS/cm)	Temper- ature (°C)
32-13-8L	--			Barium	0.09	0.10	Field alkalinity as HCO <sub>3</sub>	321	5.0	7.8	647	18.5
				Calcium	38	5.0	Fluoride	ND	.50			
				Chromium	ND	.030	Chloride	11	.50			
				Copper	.02	.030	Nitrate as N	ND	.50			
				Iron	.04	.040	Orthophosphate as P	ND	.50			
				Lead	ND	.20	Sulfate	57	.50			
				Magnesium	20	5.0						
				Manganese	.01	.010						
				Potassium	4.7	5.0						
				Sodium	72	5.0						
				Zinc	.01	.010						
32-13-8N	--			Barium	.13	.10	Field alkalinity as HCO <sub>3</sub>	346	5.0	7.2	812	18.5
				Calcium	130	5.0	Fluoride	ND	.50			
				Chromium	ND	.030	Chloride	57	.50			
				Copper	.03	.030	Nitrate as N	ND	.50			
				Iron	.07	.040	Orthophosphate as P	ND	.50			
				Lead	.04	.20	Sulfate	48	.50			
				Magnesium	11	5.0						
				Manganese	.11	.010						
				Potassium	3.6	5.0						
				Sodium	25	5.0						
				Zinc	.02	.010						

<sup>1</sup> All wells were field screened for benzene, dichloroethylene, tetrachloroethylene, toluene, trichloroethylene, and m-xylene—none detected.

<sup>2</sup> U.S. Environmental Protection Agency analytical method for laboratory analysis.

## GLOSSARY OF COMMON HYDROGEOLOGIC AND CHEMICAL TERMS

- Alluvial terrace** - A stream deposit of unconsolidated sediments (including gravel, sand, silt, and clay) produced when a stream downcuts a flood plain or valley floor
- Alluvium** - A general term for gravel, sand, silt, and clay, or similar unconsolidated detrital sediments deposited during comparatively recent geologic time by a stream or other body of running water.
- Anion** - Negative ion—atom or molecule which has gained one or more electrons in an electrolyte, and is therefore attracted to an anode, the positive electrode.
- Anisotropy** - The condition of having different properties in different directions. For example, the permeability of a sedimentary rock that is more permeable in the horizontal direction than the vertical direction.
- Aquifer** - A body of rock or sediment that is porous enough to transmit ground water and to yield significant quantities of water to wells and springs.
- Bedrock** - The rock encountered beneath the soil zone and unconsolidated sediment zone.
- Cation** - Positive ion—atom or molecule which has lost one or more electrons and therefore is attracted to the negative electrode.
- Clay** - A fine-textured, sedimentary deposit consisting of hydrated silicates of aluminium mixed with various impurities. In the mechanical analysis of soil, according to international classification, clay has a grain size less than 0.002 millimeter.
- Cone of depression** - A depression in the potentiometric surface or water-table surface of a body of ground water that has the shape of an inverted cone and develops around a well from which water is being withdrawn. It defines the area of effect (area of influence) of a well.
- Confined aquifer** - An aquifer contained between two beds that retard but do not necessarily prevent the flow of water to or from an adjacent aquifer. Confined aquifers may be under pressure greater than atmospheric pressure.
- Confining unit** - A body of impermeable or distinctly less permeable material adjacent to one or more aquifers.
- Cretaceous** - The final period of the Mesozoic Era (after the Jurassic and before the Tertiary Period of the Cenozoic Era), thought to have covered the span of time between 65 and 140 million years ago; also, the corresponding system of rocks.
- Detrital** - Adjective referring to rock fragments or organic material that result from disintegration or weathering.
- Dense nonaqueous phase liquid (DNAPL)** - A liquid that is denser than water and does not dissolve easily in water.
- Dip** - The angle that a bedding or fault plane makes with the horizontal.
- Fluvial** - Pertaining to a river or rivers; produced by the action of a stream or river.
- Fluvial deposit** - A sedimentary deposit consisting of material transported by, suspended in, or laid down by a stream.
- Glauconite** - A green mineral common in sedimentary rock. It is an indicator of very slow sedimentation rates.
- Head** - The height above a standard datum (such as sea level) of the surface of a column of water that can be supported by the pressure at a given point in the column.
- Hydraulic gradient** - In an aquifer, the change in head per unit of distance in a given direction; if not specified, the direction is that of the maximum rate of decrease in head.
- Hydraulic conductivity** - The property or capacity of a porous rock, sediment, or soil to transmit water. It is a measure of the relative ease of water flow under unequal head.
- Hydrogeology** - The study of subsurface water, specifically related to how water moves through the ground. It is a broad, multidisciplinary science involving knowledge of hydrology, geology, fluid mechanics, and water chemistry.
- Indurated** - Characteristic of rock or soil hardened or consolidated by pressure, cementation, or heat.
- Limestone** - A sedimentary rock consisting chiefly of the calcium carbonate mineral calcite ( $\text{CaCO}_3$ ); specifically a carbonate sedimentary rock containing more than 95 percent calcite and less than 5 percent dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ).
- Marl** - Crumbling unconsolidated deposits consisting chiefly of a mixture of clay and calcium carbonate in varying proportions formed under either marine or freshwater conditions.
- Maximum contaminant level (MCL)** - Maximum permissible level of a contaminant in water which is delivered to any user of a public water system as established by the U.S. Environmental Protection Agency (USEPA, 1995).
- Microgram per liter ( $\mu\text{g/L}$ )** - Generally used for chemical concentrations; in a dilute solution represents one part constituent per billion parts water.
- Milliequivalent** - The concentration in milligrams per liter of an ion divided by its formula weight divided by its charge.
- Milligram per liter ( $\text{mg/L}$ )** - Generally used for chemical concentrations; in a dilute solution represents one part constituent per million parts water.
- National Priorities List (NPL)** - The USEPA list of the most serious uncontrolled or abandoned hazardous waste sites identified for possible long-term remedial

action under the Superfund Act (USEPA, 1994). A site must be on the NPL to receive money from the Trust Fund for remedial action. The list is based primarily on the score a site receives from the Hazard Ranking System. USEPA is required to update the NPL at least once a year.

**Outcrop** - That part of a geologic formation or structure that appears at the surface of the Earth; also, bedrock that is covered only by surficial deposits such as alluvium.

**Paleochannel** - Older stream channel that has been filled with recent alluvium.

**Permeability** - The property or capacity of a porous rock, sediment, or soil to transmit a fluid. It is a measure of the relative ease of fluid flow under a head gradient.

**Phase** - A discrete homogeneous part of a material system that is mechanically separable from the rest, such as steam from water. For example, water has three phases, solid, liquid, and gas. In discussions about trichloroethylene there can be three phases, pure phase—the pure solvent not mixed with water, dissolved phase, and vapor phase.

**Plume** - A three-dimensional zone of contaminants in an aquifer or soil. A plume may extend downgradient for some distance depending on site hydrogeologic and geochemical conditions. At Air Force Plant 4 the plume discussed is the dissolved phase of trichloroethylene.

**Porosity** - The ratio of the volume of void space in a rock divided by the volume of rock. A rock with a large porosity may have a large permeability or hydraulic conductivity.

**Potentiometric surface** - An imaginary surface representing the level to which water will rise in a well. The surface is constructed by contouring water levels that are referenced to a common elevation, sea level. For a confined aquifer, the potentiometric surface represents the head within the aquifer. The water table is a potentiometric surface of an unconfined aquifer. The potentiometric or

water-table surface represents the potential for water to move downgradient.

**Reporting limit** - The lower limit of detection (expressed in units of concentration) as established by the laboratory method and procedures.

**Secondary Maximum Contaminant Level (SMCL)** -

Contaminants that affect the aesthetic quality of drinking water. At high concentrations, health implications as well as aesthetic degradation also can exist. SMCLs are not federally enforceable but are intended as a guideline for the states (USEPA, 1995).

**Shale** - A fine-grained detrital sedimentary rock, formed by the consolidation (especially by compression) of clay, silt, or mud.

**Surficial** - Pertaining to, or occurring on, a surface, especially the surface of the Earth.

**Terrace alluvium** - See alluvial terrace.

**Trichloroethylene (TCE)** - A chemical solvent used for degreasing and cleaning—considered a DNAPL that vaporizes easily when exposed to air.

**Unconfined aquifer** - An aquifer that has a water table.

**Volatile organic compounds (VOCs)** - Organic chemicals that vaporize easily. Gasoline, benzene, toluene, TCE, and xylene are common organic chemicals considered to be VOCs.

**Water-level map** - A map of contours of equal water levels, referenced to a common datum (sea level), which defines an imaginary surface that indicates the level to which water will rise in a well. The water-level map is similar to a topographic map in that the contours indicate the slope of the water-level surface and the approximate direction of water movement downslope, from higher to lower altitudes.

**Water table** - The surface in an unconfined aquifer at which the pressure is atmospheric. It is defined by the levels at which water stands in wells that penetrate the aquifer just far enough to contain standing water.

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