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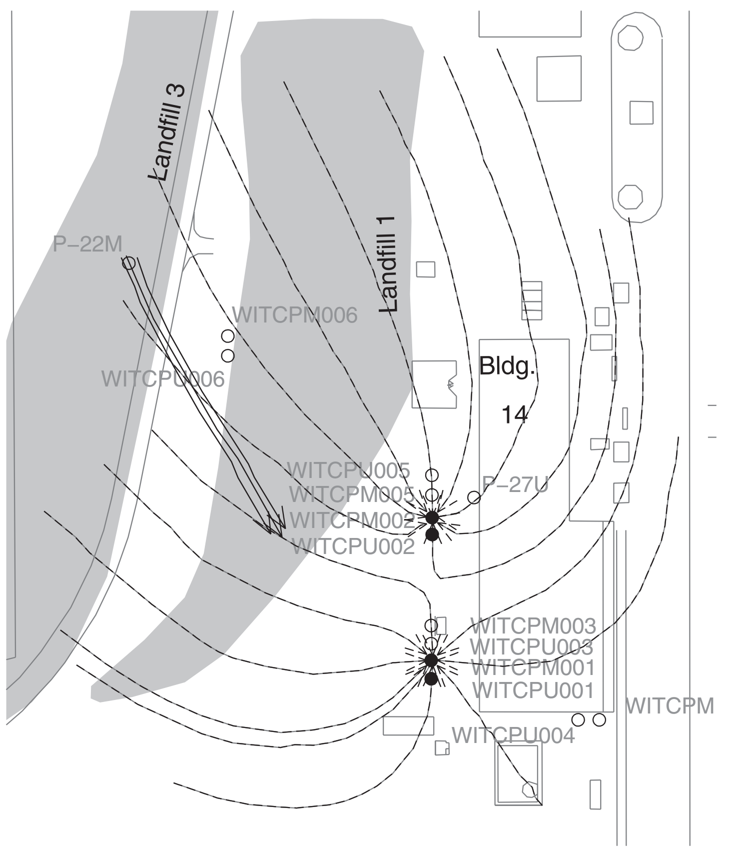
In cooperation with the
U.S. Air Force, Aeronautical Systems Center,
Environmental Management Directorate,
Wright-Patterson Air Force Base, Ohio

Hydrogeology and Simulation of Ground-Water Flow in the Paluxy Aquifer in the Vicinity of Landfills 1 and 3, U.S. Air Force Plant 4, Fort Worth, Texas

Water-Resources Investigations Report 98–4023



U.S. Department of the Interior
U.S. Geological Survey

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By Eve L. Kuniansky and Stanley T. Hamrick

U.S. GEOLOGICAL SURVEY

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Austin, Texas
1998

U.S. DEPARTMENT OF THE INTERIOR

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VERTICAL DATUM AND ABBREVIATIONS

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

Abbreviations:

cm/s, centimeter per second
°F, degree Fahrenheit
ft, foot
ft/d, foot per day
ft/ft, foot per foot
ft/mi, foot per mile
ft^2/d, foot squared per day
gal/d, gallon per day
gal/min, gallon per minute
(gal/min)/ft, gallon per minute per foot
in., inch
in/yr, inch per year
μg/L, microgram per liter

Hydrogeology and Simulation of Ground-Water Flow in the Paluxy Aquifer in the Vicinity of Landfills 1 and 3, U.S. Air Force Plant 4, Fort Worth, Texas

By Eve L. Kuniansky *and* Stanley T. Hamrick

Abstract

Ground-water contamination of the surficial terrace alluvial aquifer has occurred at U.S. Air Force Plant 4, a government-owned, contractor-operated facility, northwest of Fort Worth, Texas. A poorly constructed monitoring well, P–22M, open to the underlying middle zone of the Paluxy aquifer was installed at landfill 3, October 1987, allowing leakage of contaminated ground water to reach the Paluxy aquifer. This well was plugged and abandoned in November 1995. Additionally, volatile organic compounds have been detected in fractures in the Goodland-Walnut confining unit, the hydrogeologic unit separating the terrace alluvial aquifer from the underlying Paluxy aquifer, beneath the western part of landfill 1. Volatile organic compounds in concentrations near the analytical detection limit were detected in the upper Paluxy prior to the drilling of well P–22M.

The ground-water-flow simulation model described in this report was developed to examine the best logistically feasible location to install recovery wells to capture the low concentration (less than 100 micrograms per liter) trichloroethylene plume beneath landfills 1 and 3 (west Paluxy plume). Once the recovery wells were installed (1996), the simulation model was recalibrated with new data. This report documents the capture area of the installed recovery wells. Four geologic units are pertinent to this site-specific model. From oldest to youngest, these are the Glen Rose Formation, Paluxy Formation, Walnut Formation, and Goodland Limestone. The Glen Rose Formation is relatively impermeable in the study area and forms the confining unit underlying the Paluxy Formation. The Paluxy Formation forms the Paluxy aquifer, which is a public drinking water supply for the City of White Settlement. The Walnut Formation and Goodland Limestone form the Goodland-Walnut confining unit overlying the Paluxy aquifer. Near landfill 3, gamma-ray logs indicate three distinct zones of the Paluxy Formation; upper, middle, and lower. The formation is about 170-feet thick near landfill 3, and each zone is about 57-feet thick.

Two steady-state simulations using the computer program MODFLOW were analyzed using the particle-tracking computer program, MODPATH. One simulation is the calibration simulation using Paluxy aquifer water-level data for May 1993. The second simulation includes the installed recovery wells. A variably spaced grid was designed for the model. The smallest grid cells, 25 by 25 feet, are in the vicinity of landfills 1 and 3. The largest cells, 4,864.5 by 1,441.5 feet, are at the northwestern corner of the model grid near the Parker-Tarrant County line. The modeling was accomplished with three layers representing the upper, middle, and lower zones of the Paluxy aquifer. Particles, which represent contaminant molecules moving in solution with the ground water, were tracked from well P–22M and an area below landfill 1, at the top of the upper zone of the Paluxy aquifer, for 9 years (forward tracking). The forward tracking estimates where

contaminants might move by advection from 1987 to 1996. Analysis of backward tracking from the new recovery wells indicates that the simulated contributing area to the recovery wells intercepts the contaminant plume, minimizing off-site migration of the west Paluxy plume. To determine the effectiveness of the recovery wells, monitoring wells southeast of Building 14 have been installed (1996–97) for sampling.

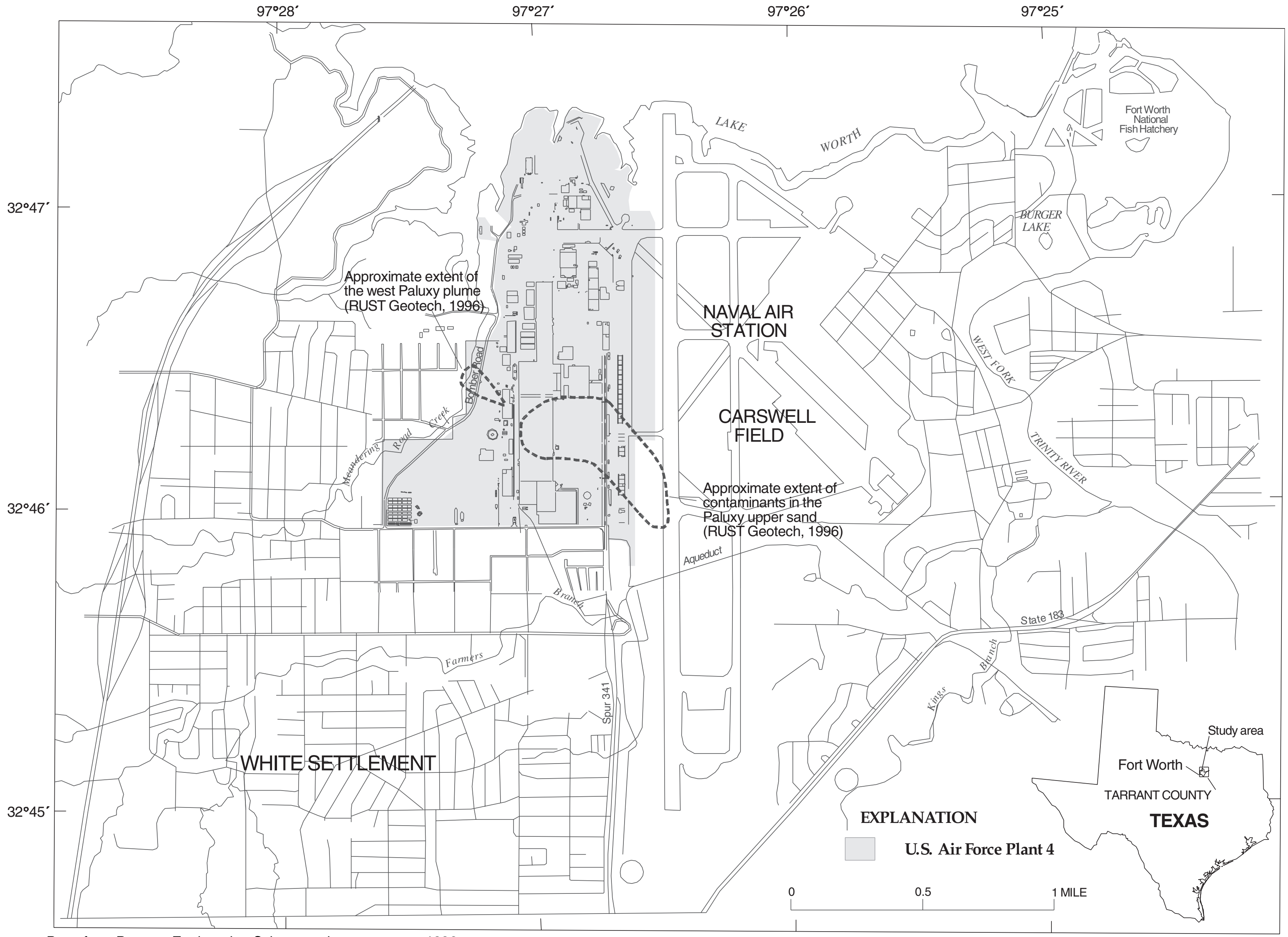
INTRODUCTION

U.S. Air Force Plant 4 (AFP4) has been in operation since 1942 when B–24 bombers were constructed for use in World War II (fig. 1). Subsequently, the government-owned contractor-operated 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 (NAS), Fort Worth, Joint Reserve Base, Carswell Field (formerly Carswell Air Force Base) (U.S. Army Corps of Engineers, 1986; Jacobs Engineering Group Inc., 1993, 1995; 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 Formation at two areas within the boundary of AFP4 (U.S. Air Force, Aeronautical Systems Center, Environmental Management Directorate, 1995). In August 1990, AFP4 was placed on the U.S. Environmental Protection Agency (USEPA) National Priorities List as a Superfund site. The Record of Decision (ROD) for remediation of environmental contamination at AFP4 (RUST Geotech, 1996) was signed July 9, 1996, by the Texas Natural Resource Conservation Commission (TNRCC); August 2, 1996, by the U.S. Air Force; and August 26, 1996, by the USEPA. Remediation of two areas where contaminants have leaked into the Paluxy Formation or Paluxy aquifer are required in the ROD. Ground-water contaminants of concern are the volatile organic compound trichloroethylene (TCE), a solvent used for degreasing metal parts, and the trace element chromium, used in plating metal parts. These contaminants were used and stored in the chemical processing facility in Building 181, and some of these contaminants might have been disposed of in landfills 1 and 3 (fig. 2).

The two areas where contaminants have entered the Paluxy Formation or Paluxy aquifer are distinct (U.S. Air Force, Aeronautical Systems Center, Environmental Management Directorate, 1995). One area is at the western side of AFP4 in landfill 3 where a low concentration plume (less than 100 µg/L of TCE) exists between landfill 3, west of Bomber Road, and former landfill 1, now covered by the west parking lot. In this area, low TCE concentrations have been detected in the upper and middle zones of the Paluxy aquifer adjacent to well P–22M. Well P–22M, installed in October 1987, had breached seals, allowing leakage of contaminated terrace alluvial water to migrate to the upper and middle zones of the Paluxy aquifer (Kuniansky and others, 1996, p. 25). Additionally, volatile organic compounds were detected within fractures in the Goodland-Walnut confining unit, the geologic unit that separates the terrace alluvial aquifer from the underlying Paluxy aquifer, beneath the western part of landfill 1 (Rick Wice, IT Corp., written commun., 1997). Volatile organic compounds in concentrations near the analytical detection limits were detected in the upper Paluxy aquifer prior to the drilling of well P–22M (Dan Schultz, Jacobs Engineering Group Inc., written commun., 1996). For clarity, this area will be called the west Paluxy plume.

The second area where contaminants have reached the Paluxy Formation is below the east parking lot of AFP4 and the flightline of NAS beneath the “window” area. The window is an area where the Goodland-Walnut confining unit is less than 5-ft thick (U.S. Air Force, Aeronautical Systems Center, Environmental Management Directorate, 1995; Kuniansky and others, 1996, fig. 2). In this area, small quantities of ground water contaminated with TCE leaked into an isolated sandstone lens, called the Paluxy “upper sand,” at the top of the Paluxy Formation. The Paluxy upper sand is of limited lateral extent and forms a perched zone of water with TCE concentrations ranging from 8,000 to 11,000 µg/L (Jacobs Engineering Group Inc., 1993). Beneath AFP4, the upper 20 to 35 ft of the Paluxy Formation is typically unsaturated or noted as dry in observation wells and on drillers’ logs. The Paluxy upper sand does not occur in the vicinity of landfills 1 and 3, where the top 30 ft of the Paluxy Formation is dry and the saturated upper zone of the Paluxy aquifer is confined by both the Goodland-Walnut confining unit and mudstone of the Paluxy Formation.



Base from Parsons Engineering Science, written commun., 1996
State Plane North-Central Zone 4202

Figure 1. Location of study area and approximate extent of contaminants in the Paluxy Formation.

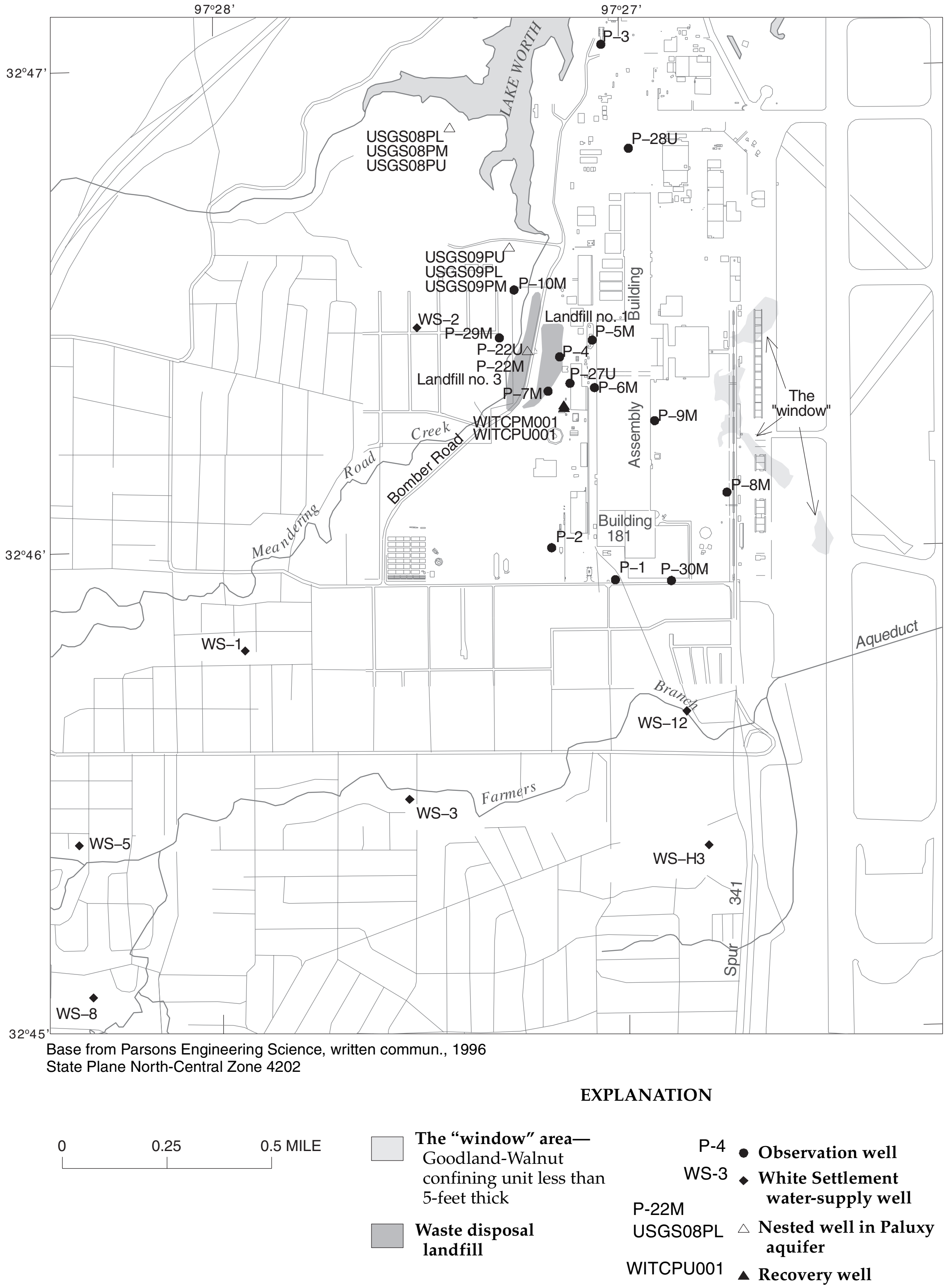


Figure 2. Location of landfills 1 and 3 and selected wells at Air Force Plant 4 and vicinity, Fort Worth, Texas.

The maximum contaminant level (MCL), the maximum permissible level of a contaminant in water delivered to any user of a public water system, is 5 µg/L for TCE (U.S. Environmental Protection Agency, 1976). Thus, recovery wells (installed in 1996) were mandated in the ROD to reduce concentrations of TCE to below the MCL at the west Paluxy plume. Additionally, local citizens are concerned that contaminants from AFP4 might enter nearby municipal wells that withdraw water from the lower and middle zones of the Paluxy aquifer (J.D. Doepker, Remediation Program Manager, U.S. Air Force, Aeronautical Systems Center, Environmental Management Directorate, oral commun., 1995). The City of White Settlement operates 5 to 7 municipal wells west and south of AFP4 (fig. 2).

At the request of the U.S. Air Force, Aeronautical Systems Center, Environmental Management Directorate (ASC/EM), the U.S. Geological Survey (USGS) reviewed data and reports of U.S. Air Force contractors, collected water-level data in Tarrant County (Rivers and others, 1996), installed monitoring wells (Williams and Kuniansky, 1996), defined lithology, collected water-quality data at domestic wells northwest of AFP4 (Kuniansky and others, 1996), and developed ground-water-flow models for site-specific use by the U.S. Air Force.

Purpose and Scope

This report describes an evaluation of the placement of newly installed (1996) recovery wells designed to capture the low concentration TCE plume in the vicinity of landfills 1 and 3—the west Paluxy plume (fig. 1). The report includes a discussion of the hydrogeology of the Paluxy aquifer and adjacent confining units at AFP4 and NAS, a description of the computer models (MODFLOW and MODPATH) used to simulate ground-water flow, the results of two model simulations of ground-water flow in the Paluxy aquifer in and near AFP4, and particle tracking of water indicating the capture area of the newly installed recovery wells. The data used in the development of the model are described in detail. Hydraulic properties, water levels, and simulated particle pathlines are described and mapped. Additionally, this report documents the calibration and sensitivity analysis for the model.

Two steady-state simulations using the computer program MODFLOW (MacDonald and Harbaugh, 1988; Harbaugh and MacDonald, 1996) were analyzed using the particle-tracking computer program MODPATH (Pollock, 1994). One simulation is the calibration simulation using Paluxy aquifer water-level data for May 1993. The second simulation includes the installed recovery wells. For many ground-water-flow modeling problems, the transport of dissolved contaminants is dominated by advection, and the processes of diffusion and dispersion provide minimal movement of the dissolved contaminants. Thus, particle tracking provides an estimate of contaminant migration. In some cases, where contaminants are sorbed onto the aquifer material or degrade or decay rapidly, particle tracking would be a worse case estimate of the transport of the contaminant. Particle tracking does not provide any information on concentrations of contaminants. The particle-tracking analysis does provide a useful estimate of the movement of the low concentration TCE from source areas and an estimate of the capture area of the recovery wells. The forward tracking represents a prediction of where contaminants would move by advection from 1987 to 1996. Backward tracking from the location of the new recovery wells was analyzed to determine if the contributing area to the recovery wells would intercept the contaminant plume, preventing off-site migration of the plume. For an understanding of MODFLOW and MODPATH, the ground-water-flow equation, and ground-water modeling refer to the above references.

Twenty-nine individual sites (4 landfills, 5 fire training areas, 3 chrome pits, 1 die yard pit, 3 fuel saturation areas, 1 fuel storage area, 6 underground storage tanks, and 6 additional sites) were examined as part of the Remedial Investigation and Feasibility Study for AFP4 (Chem-Nuclear Geotech, Inc., 1992; RUST Geotech, 1995a, b, c, d). These sites are not described in this report. The scope of this site-specific model is the simulation of ground-water movement and particle tracking in the Paluxy aquifer and the west Paluxy plume. This report does not address the window area and contaminants in the isolated sandstone lens, the Paluxy upper sand, below the east parking lot. The surficial terrace alluvial aquifer is discussed in Kuniansky and others (1996). Additionally, the Remedial Investigation and Feasibility Study addresses the chromium in surface soils at AFP4, which is not within the scope of this report as chromium has not been detected in the Paluxy Formation or Paluxy aquifer.

Description of Study Area

The study area is in north-central Texas in Tarrant County northwest of Fort Worth, Texas (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 draining AFP4 and NAS.

The plant was built on a 600-acre site, and NAS is on a 3,000-acre site adjacent to the southeastern 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 natural landscape of the area has some rolling hills but is relatively flat with a few limestone bluffs and hills. The 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. AFP4 was built on a topographic high that overlies a north-south trending bedrock high.

The climate is subhumid, with summers generally long and hot (average July temperatures of about 96 °F) and winters generally short and mild (average January temperatures of about 34 °F). The average annual temperature is 65 °F. The average annual precipitation in north-central Texas is 32 in., with most precipitation during spring and fall.

Previous Investigations

Winton and Adkins (1919) describe the geology of Tarrant County. Leggat (1957) provides one of the earliest reports on the geology and water resources of Tarrant County. Surface geology of the area is published by 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." Definitive studies of the Paluxy Formation by Caughey (1977) and Owen (1979) provide detailed descriptions of depositional systems and lithology. A report on the water resources in part of north-central Texas by Baker and others (1990) includes Tarrant County and information about the Paluxy aquifer. Nordstrum (1982) describes the occurrence, availability, and chemical quality of ground water in north-central Texas. Taylor (1976) developed ground-water-level maps and published ground-water-quality data for northeast Texas. Numerous site-specific reports by contractors to the U.S. Air Force are located in the White Settlement Public Library (8215 White Settlement Road, White Settlement, TX 76108), including three reports by the USGS about AFP4 and vicinity (Kuniansky and others, 1996; Rivers and others, 1996; and Williams and Kuniansky, 1996). The Remedial Investigation and Feasibility Study (Chem-Nuclear Geotech, Inc., 1992; RUST Geotech, 1995a, b, c, d) and other technical study reports are available for review at the White Settlement Public Library. These reports are part of the Administrative Record for this Superfund site, the supporting information and analysis used by ASC/EM, USEPA, TNRCC, and the Restoration Advisory Board (RAB) to determine the types of remediation used at AFP4. They were provided to the public for review, which enabled the public to participate on the RAB in development of the final Record of Decision for remediation of AFP4.

Acknowledgments

The USGS acknowledges the cooperation of Rick Wice and Robert Schoenewe of IT Corp. for providing specific-capacity data, lithologic data, and gamma-ray logs in the west Paluxy plume area at AFP4; Dan Schultz and Lynn Schuetter of Jacobs Engineering Group Inc., for collection of ground-water-level data and laboratory analysis of samples from wells at AFP4 and NAS during the comprehensive sampling of wells in May 1993 and October 1995; Ruben Martinez, Ph.D., of Parsons Engineering Science for his participation in detailed mapping of the site geology which was provided in both written and oral communications; Fred Holzmer of Intera Corp. for providing information on laboratory permeability of a core sample of the Walnut Formation; Surendra Joshi and John Doepker of ASC/EM for assistance in access to the facility and feedback on reports; and Luke Gilpin of Lockheed-Martin for sharing historical knowledge of the facility remediation history.

HYDROGEOLOGY

The formations that crop out in the vicinity of AFP4 (fig. 3) are the Paluxy Formation (part of which is an aquifer), Walnut Formation (a confining unit), and Goodland Limestone (a confining unit) of Cretaceous age. Beneath the Paluxy Formation is the Glen Rose Formation (a confining unit). At AFP4 and NAS, these

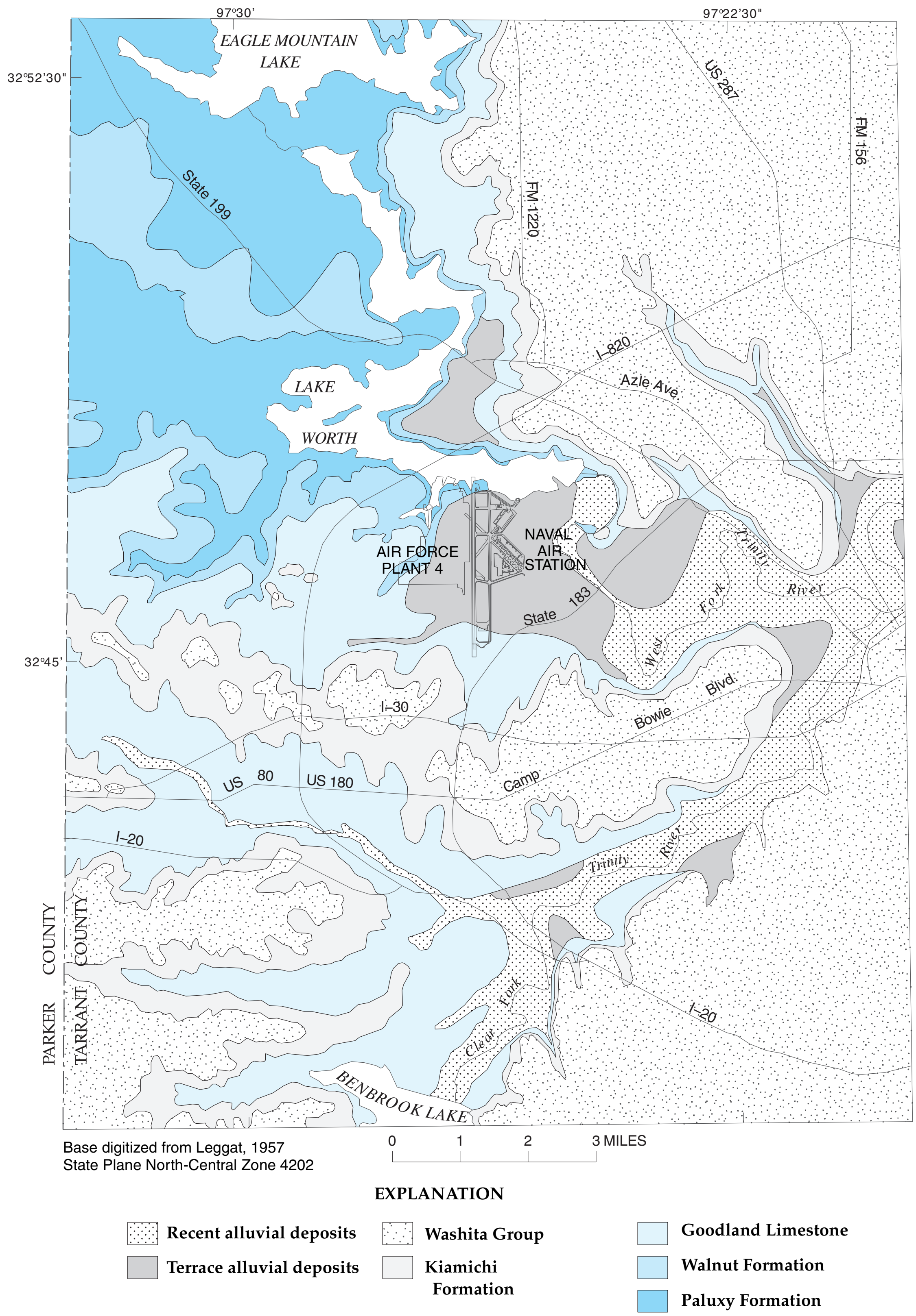


Figure 3. Surface geology in western Tarrant County, Texas (modified from Leggat, 1957; University of Texas, Bureau of Economic Geology, 1972).

and older Cretaceous rocks are overlain by Quaternary terrace alluvial deposits consisting of gravel, sand, silt, and clay. The geologic age of these formations (stratigraphic units), their lithologic characteristics, and most importantly, their general water-yielding properties are listed in table 1.

A generalized hydrogeologic cross section through AFP4 indicating the general dip of the formations from west to east and their relative thicknesses is shown in figure 4. The formations in the study area were deposited nearly horizontally. The formations dip about 20 to 30 ft/mi to the east-southeast near AFP4 (Owen, 1979). This cross section is drawn through the window area (fig. 2). The window is defined as an area just east of the assembly building and beneath the east parking lot and flightline where the Goodland-Walnut confining unit is less than 5-ft thick (Ruben Martinez, Ph.D., Parsons Engineering Science, written commun., 1995). This definition of the window area is more conservative than the ROD, which shows a smaller area (RUST Geotech, 1996, fig. 5–4) and assumes a thickness of 2 ft or less for the Goodland-Walnut confining unit.

Leakage between the surficial terrace alluvial aquifer and the Paluxy Formation is limited and occurs only at local areas where the Goodland-Walnut confining unit is breached by erosion, small fractures, or incompletely sealed wells. The upper part of the Paluxy Formation is dry beneath the Goodland-Walnut confining unit. Thus, the hydrogeologic units important for this report are the Goodland-Walnut confining unit, the Paluxy aquifer and the Glen Rose confining unit.

Goodland-Walnut Confining Unit

The Goodland-Walnut confining unit is composed of sediments of the Goodland Limestone and Walnut Formation. The Goodland Limestone consists of a very massive fossiliferous limestone interbedded with marl and shale beds. The Goodland is very resistant and can be about 90-ft thick in Tarrant County. At AFP4, the Goodland Limestone has largely been eroded, and only remnants of the Goodland overlie the Walnut. Thus, the Goodland ranges from 0- to 40-ft thick at the site. The Walnut consists equally of clay and limestone. Unlike the Goodland, the Walnut Formation contains more shale, clay, and shell conglomerates formed by ancient oyster beds. In general, the oyster beds of the Walnut Formation are cemented together forming an indurated rock composed of clay, shell conglomerate, and limestone. In Tarrant County, the maximum thickness of the Walnut Formation is about 30 ft. At AFP4, the Walnut ranges from 0.5- to 30-ft thick. The Goodland-Walnut confining unit forms the top of bedrock at AFP4 and NAS. The total thickness of the Goodland-Walnut confining unit ranges from 0.5 to 70 ft at the site. The Goodland-Walnut confining unit has very low permeability, which causes the top of the Paluxy Formation to be dry beneath areas where this confining unit is thick (fig. 4). Where the Goodland Limestone is completely eroded and the Walnut Formation is less than 5-ft thick, the confining unit might not prevent downward movement of water.

At landfill 1, the Goodland-Walnut confining unit is fractured and contains volatile organic compounds in the fractures near the western part of the landfill. Drilling information indicates the upper 20 to 35 ft of the Paluxy Formation are dry at landfill 1 and wells USGS08PL and USGS09PL (fig. 2), indicating no or limited transfer of water through the Goodland-Walnut confining unit despite these fractures (Kuniansky and others, 1996; Robert Schoenewe, IT Corp., written commun., 1996).

Two laboratory permeability tests were conducted on cores of the Goodland-Walnut confining unit. One test indicated a permeability of 10^{-10} cm/s or 10^{-7}ft/d (RUST Geotech, 1995a). The other test from a core in the window area indicated a permeability of 10^{-6} cm/s or 10^{-3} ft/d (Fred Holzmer, Intera Corp., oral commun., 1996).

Paluxy Aquifer

The lower two-thirds of the Paluxy Formation is considered an aquifer yielding small to moderate quantities of water. According to lithologic logs from AFP4 (Williams and Kuniansky, 1996; Robert Schoenewe, IT Corp., written commun., 1996) the formation is composed primarily of fine- to coarse-grained sandstone interbedded with mudstone. The lower part of the Paluxy Formation contains the coarsest sandstones. The upper part of the Paluxy Formation contains mudstone interbedded with fine-grained sandstone; some of the sandstone appears cemented with calcite. The sandstone within the Paluxy Formation can be well sorted, poorly cemented, and cross-bedded. The sandstone of

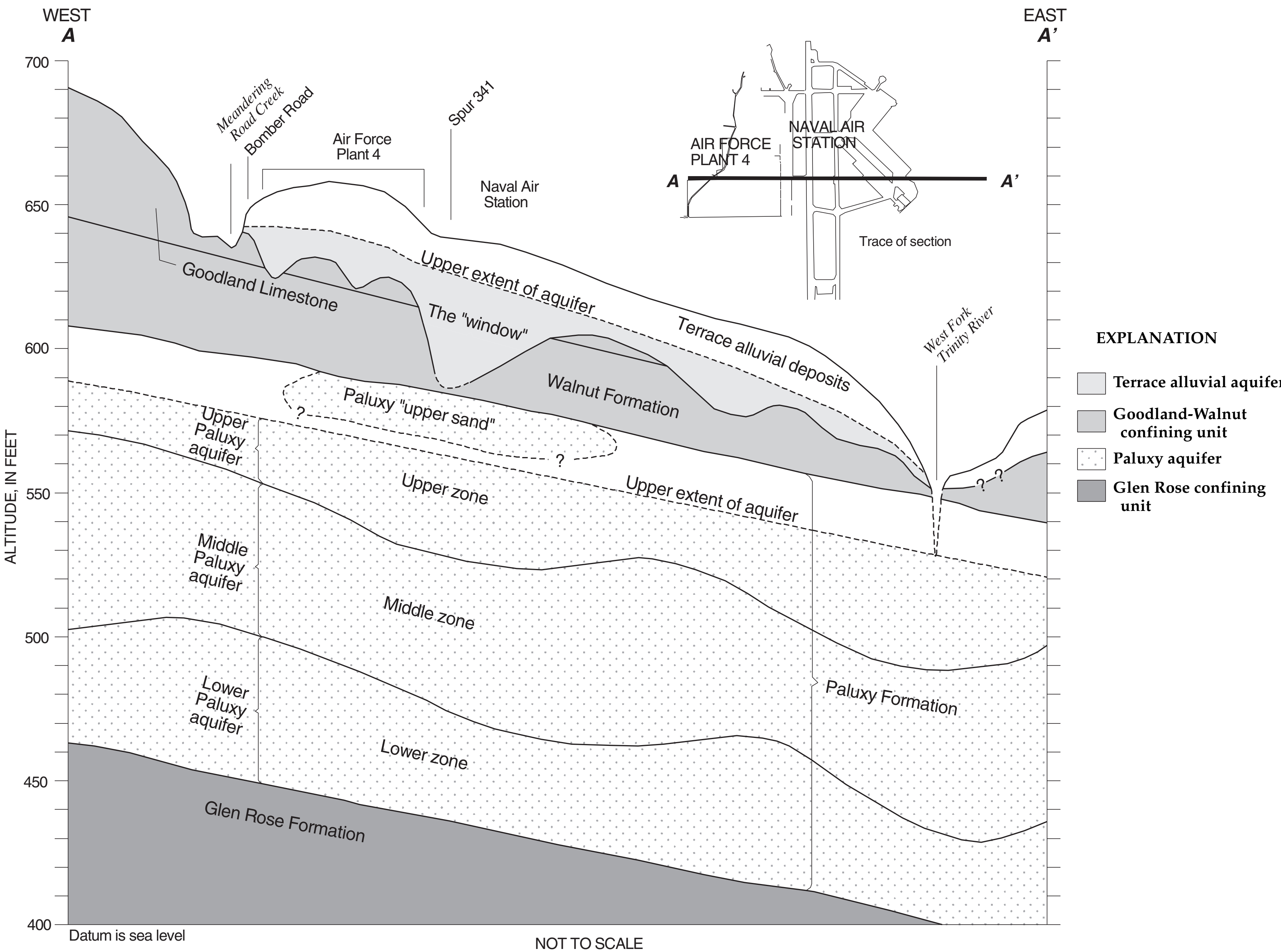


Figure 4. Generalized hydrogeologic section at Air Force Plant 4 and Naval Air Station, Fort Worth area, Texas.

Table 1. Stratigraphic units, lithology, and water-yielding characteristics of the units in the vicinity of Air Force Plant 4

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

Era	System	Series/group	Stratigraphic unit	Thickness (feet)[1]	Lithologic characteristics[2]	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	Absent or eroded and absent	--	--	--
		Paleocene/ Midway	Absent or eroded and absent	--	--	--
Mesozoic	Cretaceous (65 to 140 mya)	Gulfian	Absent or eroded and absent	--	--	--
		Comanchean/ Washita	Absent or eroded and absent	--	--	--
		Comanchean/ Fredericksburg	Kiamichi Formation	--	--	--
			Goodland Limestone	0–40	White, fossiliferous limestone, coarsely nodular, resistant, and dense—contains some marl and shale	Impermeable where not weathered—considered confining unit
			Walnut Formation	0.5–30	Medium- to dark-gray clay and limestone with shell conglomerate, fossiliferous, *Gryphaea* beds in top of formation 0.1- to 1-foot thick	Very low permeability—considered confining unit
		Comanchean/ Trinity	Paluxy Formation	130–175	Light-gray to greenish-gray sandstone, shale, mudstone, and limestone; sandstone fine to very fine grained, some coarse-grained sandstone at base	Lower two-thirds considered aquifer, yields small to moderate quantities of water
			Glen Rose Formation	150, range unknown at AFP4	Brownish-yellow and gray alternating limestone, clay, marl, and sand	Low permeability—considered confining unit in area of AFP4
			Twin Mountains Formation	200, range unknown at AFP4	Fine- to coarse-grained sandstone, red shale and claystone, basal gravel conglomerate	Coarse sandstones and parts of formation considered aquifer, yields moderate to large quantities of water

Absent or eroded and absent (shaded cells)

[1] Thickness determined from site logs, except for Glen Rose and Twin Mountains Formations (Baker and others, 1990, fig. 4).

[2] Lithologic characteristics determined 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; and field observations.

the Paluxy Formation often contains iron. For this reason, the Paluxy Formation might have a reddish-orange color in some beds. Generally, the Paluxy Formation is composed of gray sandstone beds. Lithologic changes between mudstone, poorly indurated clay, poorly indurated sandstone, and cemented sandstone occur over short distances in the upper Paluxy at landfill 1 (Rick Wice, IT Corp., written commun., 1997).

Although the total thickness of the Paluxy Formation ranges from 130 to 175 ft, the permeable sandstone units of the formation can be as little as 40-ft thick (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 are the lower Paluxy, middle Paluxy, and upper Paluxy (fig. 4). The Paluxy upper sand is a local, poorly indurated, sandstone lens of unknown lateral extent in the window area beneath the east parking lot at the top of the Paluxy Formation.

These zones of the Paluxy aquifer are separated by interbedded mudstone. 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 upper Paluxy Formation contain 2 or 3 fine-grained, sandstone beds less than 10-ft thick separated by mudstone beds 5- to 20-ft thick. The middle Paluxy Formation at these two wells is a fine-grained sandstone 40- to 50-ft thick separated from the lower Paluxy by an 8- to 12-ft-thick mudstone. The lower Paluxy Formation contains a sandstone unit 25- to 30-ft thick with interbedded sandstone and mudstone at the bottom 20 to 30 ft of the formation. The total thickness of the Paluxy Formation at these two wells is 170 ft.

Lithologic logs and gamma-ray logs of wells drilled by IT Corp. in the landfill 1 area indicate the upper 20 to 30 ft of the Paluxy Formation are predominantly mudstone, and the unit is dry. Additionally, the saturated part of the upper Paluxy is confined by the low permeability of the top 20 to 35 ft of the formation (Rick Wice, IT Corp., written commun., 1997).

The upper zone of the Paluxy aquifer (fig. 4) is a water-yielding unit that can supply small quantities of water (less than 5 gal/min). The upper Paluxy is artesian at AFP4 near Bomber Road. Near Lake Worth, the Paluxy Formation intersects the lake pool surface in the cove along Bomber Road.

The middle zone of the Paluxy aquifer is a water-yielding unit that can supply small quantities of water to wells (10 to 30 gal/min). The middle Paluxy at AFP4 has fewer interbedded mudstones than the upper Paluxy and thus, is more permeable than the upper Paluxy.

The lower zone of the Paluxy aquifer is the most permeable of the three zones. The sandstones in the lower Paluxy are coarse grained and can yield moderate quantities of water to wells (10 to 50 gal/min).

Domestic and public 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 Paluxy aquifer. Monitoring wells installed at AFP4 and NAS are screened in the Paluxy upper sand, the upper, middle, and lower zones of the Paluxy aquifer, and the Paluxy undifferentiated. Wells screened in the upper zone of the Paluxy aquifer are indicated by U in the well number (USGS08PU, P–28U, WITCPU001), in the middle zone are indicated by M (USGS08PM, P–9M, WITCPM003), and in the lower zone are indicated by L (USGS08PL).

Hydraulic Properties

Numerous aquifer pumping tests, slug tests, and specific-capacity tests have been conducted at AFP4 by different consultants. Results of aquifer pumping and slug tests conducted by Hargis & Associates, Inc. (1985) and RUST Geotech (1995a) are summarized in tables 2 and 3.

Additionally, IT Corp. (written commun., 1997) provided the raw data from the specific-capacity tests at the recovery wells. The specific-capacity data were analyzed using methods defined in Brown (1963) to determine transmissivity. At well WITCPU001, the specific capacity was 0.2 (gal/min)/ft, aquifer thickness was 20 ft, transmissivity was 50 ft^2/d, and hydraulic conductivity was 2.5 ft/d. At well WITCPM001, the specific capacity was 1.5 (gal/min)/ft, aquifer thickness was 30 ft, transmissivity was 500 ft^2/d, and hydraulic conductivity was 17 ft/d.

Vertical hydraulic conductivity (K_z) tests of core samples published by RUST Geotech (1995a) are summarized in table 4. Typical of most sedimentary rock, the Paluxy aquifer has substantially smaller permeability in the vertical direction than the horizontal direction. In general, differences in water levels between the upper, middle, and lower zones of the Paluxy aquifer are small, indicating hydraulic connection between zones at AFP4 (Kuniansky and others, 1996, p. 24).

Table 2. Hydraulic properties in the Paluxy aquifer estimated from aquifer pumping tests[1]

[ft, feet; ft^2/d, feet squared per day; ft/d, feet per day; cm/s, centimeters per second; --, not available; M, well screened in middle zone of the Paluxy aquifer]

Pumping well number (fig. 2)	Observation well number (fig. 2)	Saturated thickness (screen length) (ft)	Transmissivity		Average hydraulic conductivity	
			Drawdown (ft^2/d)	Recovery (ft^2/d)	(ft/d)	(cm/s)
P–1	P–1	60	4,011	3,209	60.2	2.1×10^{-2}
P–2	P–2	40	1,872	2,273	51.8	1.8×10^{-2}
P–3	P–3	70	--	1,110	15.8	5.6×10^{-3}
P–4	P–4	50	1,016	749	17.6	6.2×10^{-3}
P–5M	P–6M	40	2,139	1,110	40.6	1.4×10^{-2}
P–6M	P–5M	50	3,209	989	42.0	1.5×10^{-2}
P–7M	P–7M	40	--	535	13.4	4.7×10^{-3}
P–8M	P–9M	60	4,278	4,947	76.9	2.7×10^{-2}
P–9M	P–9M	40	936	1,110	25.6	9.0×10^{-3}
P–10M	P–10M	30	334	575	15.2	5.4×10^{-3}

[1] Hargis & Associates, Inc., 1985.

Table 3. Hydraulic conductivities in the Paluxy aquifer estimated from slug tests[1]

[K_h, horizontal hydraulic conductivity; ft/d, feet per day; cm/s, centimeters per second; U, well screened in upper zone of the Paluxy aquifer; M, well screened in middle zone of the Paluxy aquifer]

Well number (fig. 2)	K_h (ft/d)	K_h (cm/s)
P–27U	10.9	3.84×10^{-3}
P–28U	1.9	6.63×10^{-4}
P–29M	5.19	1.83×10^{-3}
P–30M	7.7	2.73×10^{-3}

[1] RUST Geotech, 1995a.

Table 4. Vertical hydraulic conductivity determined from laboratory triaxial cell tests on core samples obtained from the Paluxy aquifer[1]

[K_z, vertical hydraulic conductivity; ft/d, feet per day; cm/s, centimeters per second; U, well screened in upper zone of the Paluxy aquifer; M, well screened in middle zone of the Paluxy aquifer]

Well number (fig. 2)	K_z (ft/d)	K_z (cm/s)	Lithology of core samples
P–27U	9.4×10^{-7}	3.3×10^{-10}	Siltstone with some clay
P–28U	8.8×10^{-6}	3.1×10^{-9}	Calcareous, fine-grained sand
P–30M	3.4×10^{-2}	1.2×10^{-5}	Quartzose sandstone

[1] RUST Geotech, 1995a.

Table 5. Average daily production for White Settlement municipal supply wells completed in the Paluxy aquifer

[Data provided by City of White Settlement, written commun., 1989. gal/min, gallons per minute; gal/d, gallons per day; ft^3/d, cubic feet per day; ft, feet; --, not available]

White Settlement well number (fig. 2)	Average daily production			Depth of screened interval (ft)	Total depth (ft)
	(gal/min)	(gal/d)	(ft^3/d)		
WS–1	51	73,000	9,800	--	254
WS–2	39	56,000	7,500	--	200
WS–3	52	75,000	10,000	180–200	201
WS–H3	46	66,000	8,800	212–242	282
WS–5	57	83,000	11,000	175–305	305
WS–8	48	69,000	9,200	175–286	286
WS–12	43	62,000	8,300	--	195

Ground-Water Withdrawals

White Settlement water-supply wells are screened in the middle and lower zones of the Paluxy aquifer at depths ranging from 195 to 305 ft below land surface (City of White Settlement, written commun., 1995). Typical yields of these wells range from 30 to 90 gal/min. Average daily production of water from White Settlement water-supply wells is about 500,000 gal/d (table 5).

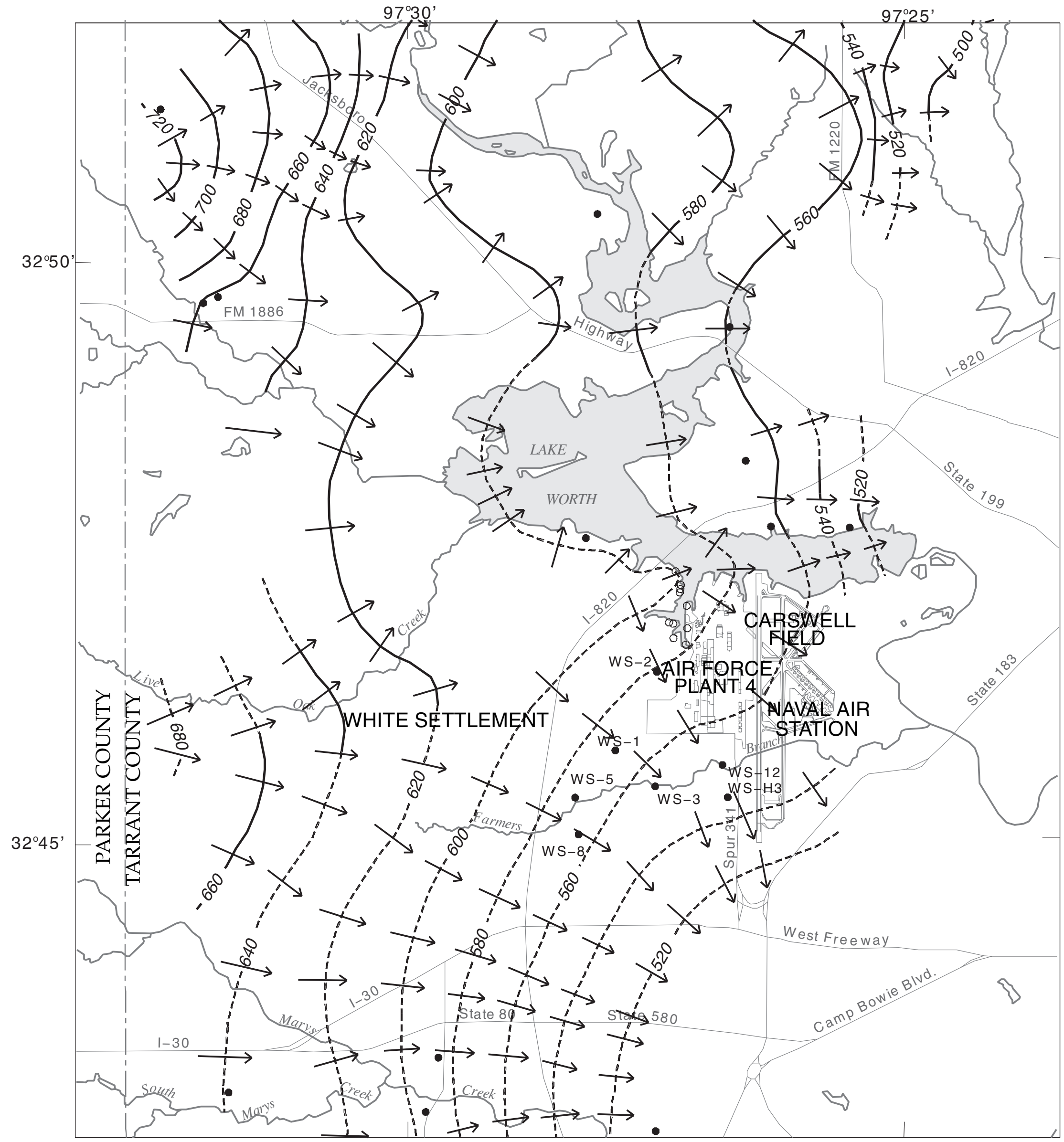
Numerous domestic wells completed in the Paluxy aquifer in the study area supply water to individual households. The USGS attempted to locate the domestic wells completed in the Paluxy aquifer and measure water levels. The locations of these domestic wells and the White Settlement water-supply wells are shown in figure 5. The estimated withdrawal of about 750 gal/d from each domestic well located is based on the assumption that each well supplies water for four people and is used for irrigation of yards and gardens.

Direction of Ground-Water Flow, May 1993

The potentiometric contours on figure 5 were determined from wells screened in the lower and middle zones of the Paluxy aquifer during May 1993. The potentiometric map represents the regional direction of ground-water flow. Arrows drawn on the map indicate the horizontal direction of flow in the aquifer. In general, the contours follow the dip of the formation to the east. Because the Paluxy aquifer is recharged by infiltration of precipitation over the Paluxy Formation outcrop area (fig. 3) in northwestern Tarrant County and Parker County (not shown), the highest water levels occur in the outcrop area. Water levels range from about 700 ft at the western edge of Tarrant County to about 520 ft at the eastern edge of NAS. This is an average gradient of about 0.005 ft/ft or 25 ft/mi from west to east. This horizontal gradient is consistent with the dip of the Paluxy Formation, which indicates that the water is entering the Paluxy aquifer in the outcrop area and flows horizontally downdip.

Hydraulic Connection With Lake Worth

The movement of water between the Paluxy aquifer and Lake Worth is complicated by the dip of the aquifer. The pool elevation of Lake Worth remains at about 590 ft above sea level. The aquifer discharges to Lake Worth near its western extent, where about one-half of 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. At the eastern 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



Base from 1:100,000 Digital Line Graphs
State Plane North-Central Zone 4202

0 1 2 MILES

EXPLANATION

620 — Water-level contour—Shows altitude at which water level would have stood in tightly cased well, 1993. Dashed where approximately located. Contour interval 20 feet. Datum is sea level

→ **Arrow**—Indicates direction of flow in the Paluxy aquifer

• **Water-supply well**

○ **Domestic well**

Figure 5. Regional potentiometric surface, flow directions, and location of water-supply wells and domestic wells completed in the Paluxy aquifer at Air Force Plant 4 and vicinity, Fort Worth, Texas, May 1993 (modified from Rivers and others, 1996).

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 that the upper 30 ft of the Paluxy Formation was dry and fairly impermeable. After drilling through the very hard, cemented sandstone and shale about 30 ft below the top of the Paluxy Formation, water rose above the top of the cemented sandstone 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 that Lake Worth recharges the Paluxy aquifer at the western side of AFP4.

Recharge

Recharge to the Paluxy aquifer occurs from the infiltration of precipitation over the Paluxy Formation outcrop area northwest of AFP4 in Tarrant County (fig. 3) and west in Parker County (not shown). The long-term average recharge rate is estimated to be 2 in/yr (RUST Geotech, 1995a). The amount of water recharging the aquifer from Lake Worth is unknown.

Glen Rose Confining Unit

The Glen Rose Formation, the confining unit underlying the Paluxy Formation, is composed of limestone, marl, clay, and very little sandstone. This confining unit has low permeability and is about 150-ft thick in Tarrant County. If the middle and lower zones of the Paluxy aquifer were to become contaminated from activities at AFP4, the Glen Rose confining unit might prevent the movement of contaminants to the underlying Twin Mountains aquifer.

SIMULATION OF GROUND-WATER FLOW IN THE PALUXY AQUIFER

The ground-water-flow model was used to evaluate placement of recovery wells designed to capture the west Paluxy plume. Two steady-state simulations were analyzed using the computer program MODFLOW in conjunction with the particle-tracking program, MODPATH. MODFLOW, solves the partial differential equation for ground-water flow by using a block-centered finite-difference algorithm (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). MODPATH, a computer program developed to use the ground-water-simulation files created by MODFLOW, is a particle-tracking program that identifies the paths that particles would move by advection alone (Pollock, 1994). Particle tracking is accomplished after a MODFLOW simulation by specifying the placement of particles in the model cells and computing where these particles would move over time. The recharge area or capture area of a well can be identified by backward-in-time particle tracking from the pumping well. For many ground-water-flow modeling problems, the transport of dissolved contaminants is dominated by advection, and the processes of diffusion and dispersion provide minimal movement of the dissolved contaminants. Thus, the movement of contaminants can be approximated by forward particle tracking from the source of the dissolved contaminant, such as the TCE plume beneath landfills 1 and 3.

Two steady-state simulations were analyzed. One simulation is the calibration simulation using Paluxy aquifer water-level data for May 1993 analyzed with forward particle tracking from contaminant source areas. The second simulation, which includes the data from the installed recovery wells, was analyzed with backward particle tracking from the wells.

Grid Design and Boundary Conditions

A variably spaced grid was designed for this model (fig. 6). The smallest grid cells, 25 by 25 ft, are located around observation well P–22M and landfills 1 and 3 (fig. 7). Well P–22M is in the center of row 58, column 48 of the finite-difference grid. The grid is designed to be site specific in the vicinity of landfills 1 and 3. The variable spacing allows the area simulated to be both regional and site specific. The grid extends west almost to the Parker-Tarrant County line. The largest cells, 4,864.5 by 1,441.5 ft, are at the northwestern corner of the model. Constant heads based on the May 1993 potentiometric contour map constructed for the Paluxy aquifer (Rivers and others, 1996) were applied to the western boundary. The western boundary is far enough from the site that small errors in the boundary conditions did not affect the area near the landfills. The grid extends far enough south to an area where the southern boundary is perpendicular to the potentiometric contours and is simulated as a no-flow

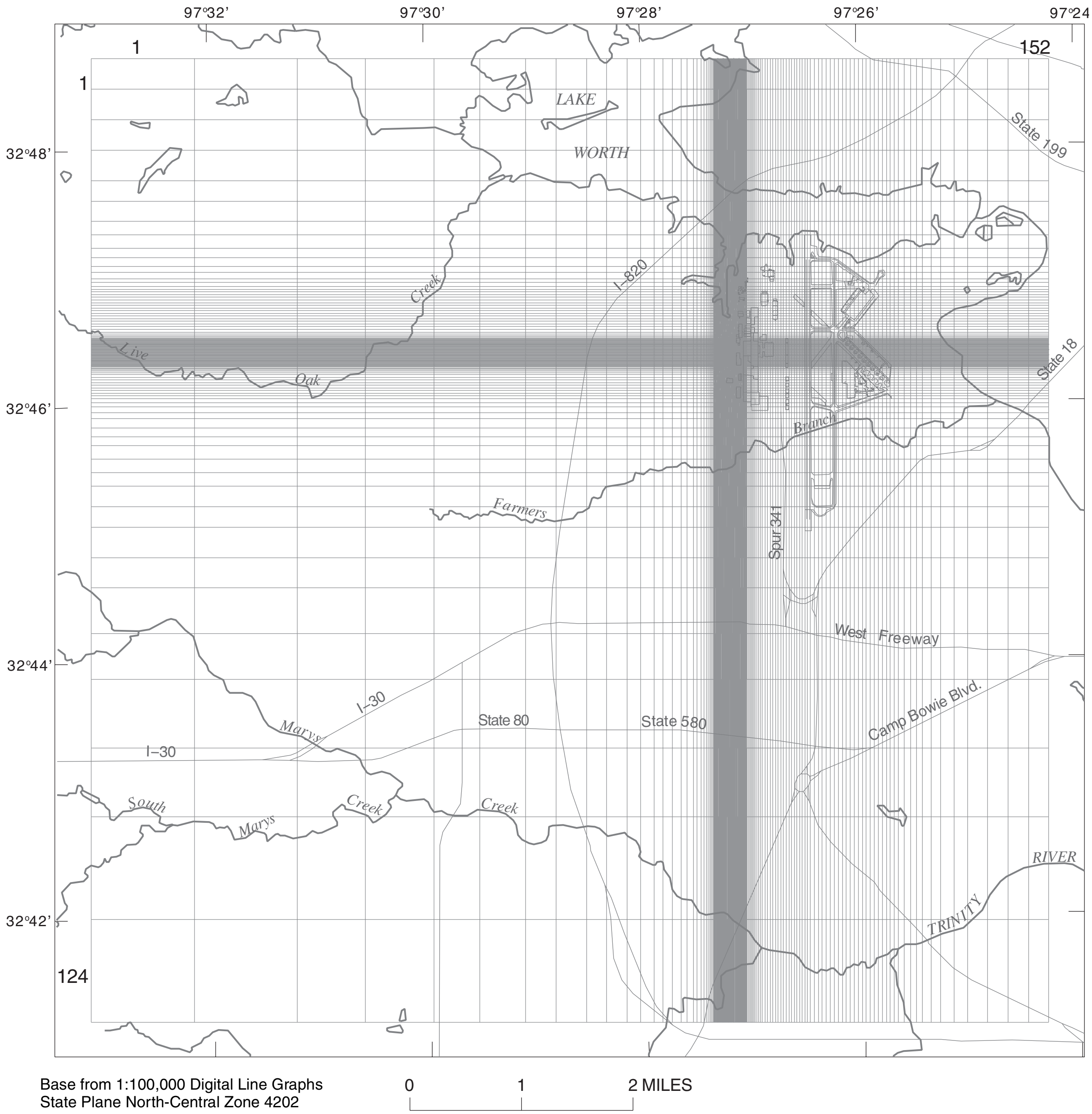


Figure 6. Model grid designed for simulation of the Paluxy aquifer at Air Force Plant 4 and vicinity, Fort Worth, Texas.

boundary. The northern boundary is simulated as a no-flow boundary and is partially in Lake Worth because the lake serves as an internal specified-head boundary. The easternmost boundary of the model is far enough from landfills 1 and 3 that it does not affect water levels at the landfills. The eastern boundary is defined by constant heads specified from the potentiometric map of the Paluxy aquifer (Rivers and others, 1996).

Internal Boundaries

Internally, the RIVER package (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) was

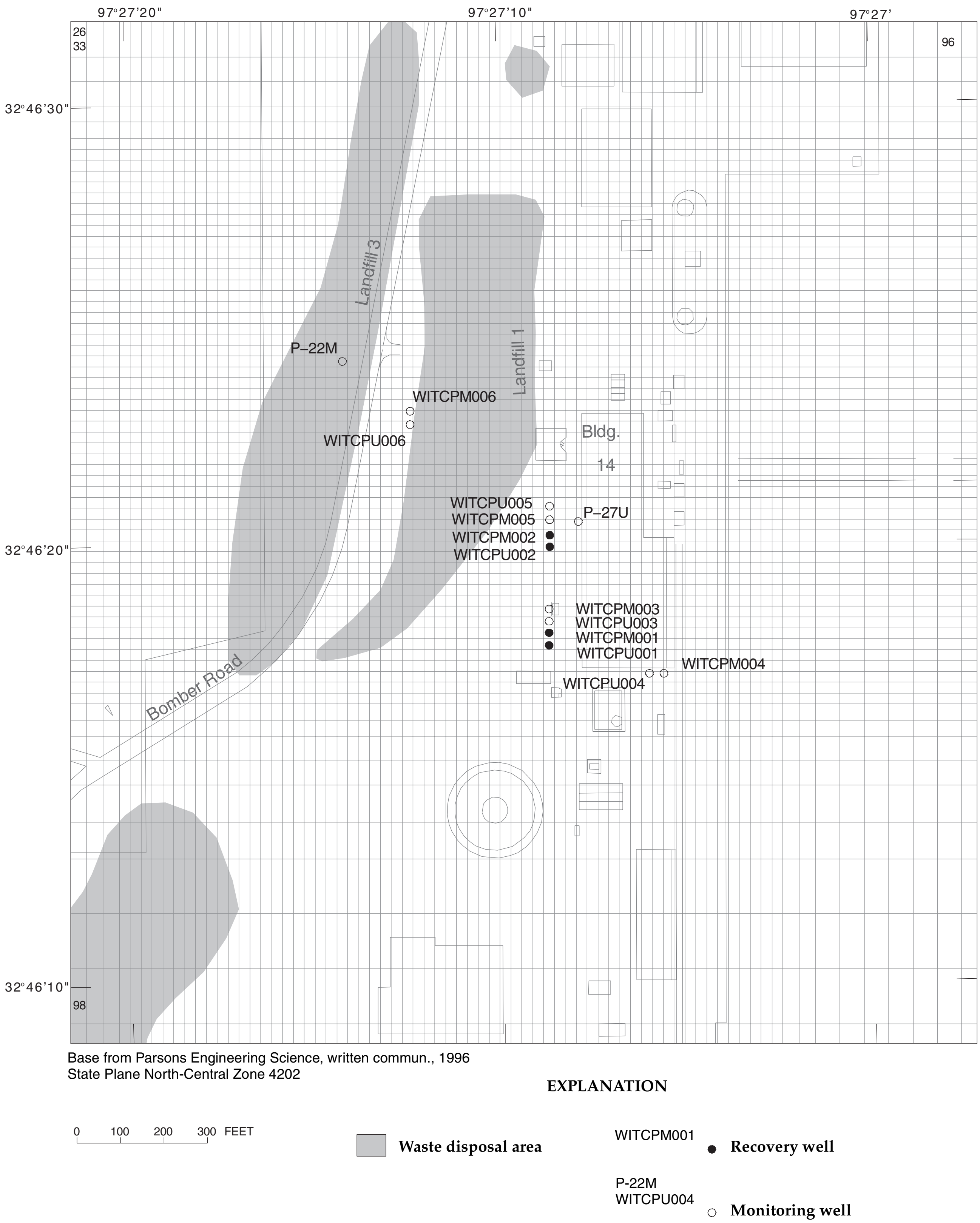


Figure 7. Detail of model grid in the vicinity of landfills 1 and 3 at Air Force Plant 4, Fort Worth, Texas.

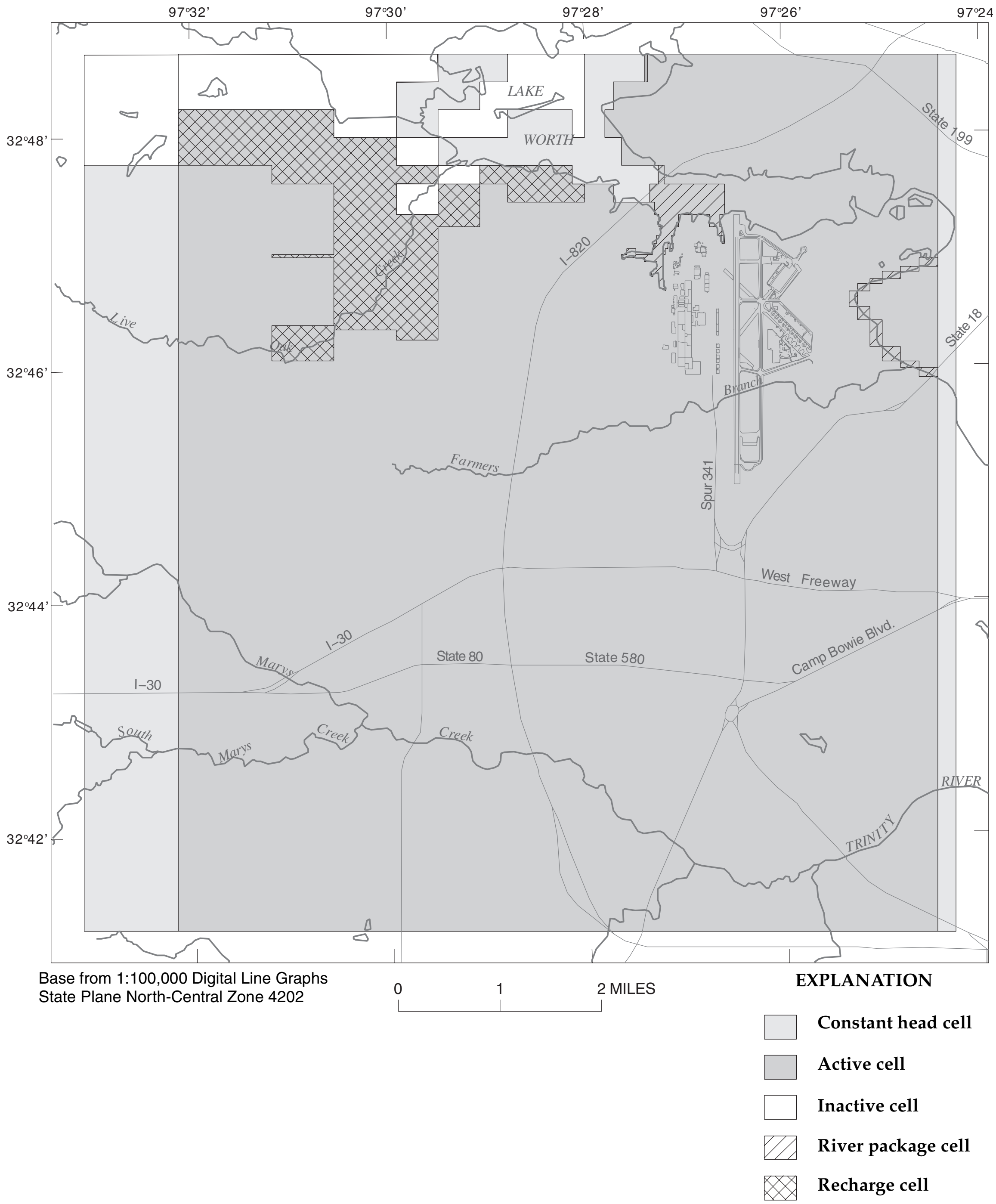


Figure 8. Location of constant head cells, active cells, and inactive cells in model layer 1, upper zone of the Paluxy aquifer at Air Force Plant 4 and vicinity, Fort Worth, Texas.

used to allow leakage to or from the aquifer along the West Fork Trinity River downstream of the spillway where the Walnut Formation has been eroded by the river and the river is incised into the Paluxy Formation (RUST Geotech, 1995e). The RIVER package also is used to simulate the interaction of Lake Worth, a constant pool lake, with the upper Paluxy near the middle of the lake by allowing leakage through the eroded Goodland-Walnut confining unit in finite difference cells beneath the lake (fig. 8).

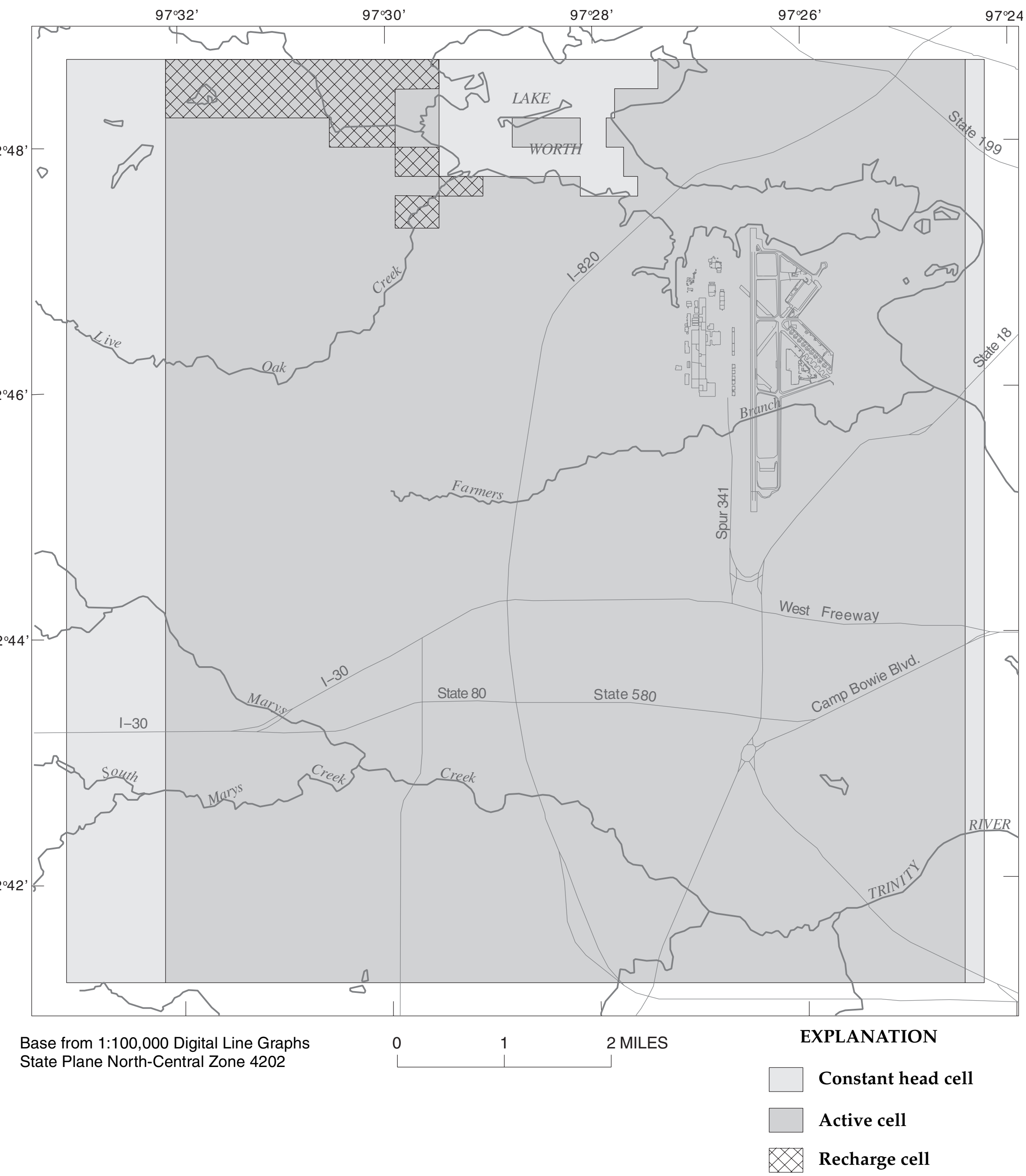


Figure 9. Location of constant head cells and active cells in model layer 2, middle zone of the Paluxy aquifer at Air Force Plant 4 and vicinity, Fort Worth, Texas.

Model Layers

The modeling was accomplished with three layers representing the upper, middle, and lower zones of the Paluxy aquifer. This model does not include the Paluxy upper sand, a local sandstone lens of unknown extent beneath the east parking lot and hydraulically separate from the rest of the upper Paluxy (Kuniansky and others, 1996). All three layers were simulated as confined aquifers. The location of constant head cells, active and inactive cells, recharge cells, or river cells in layers 1 and 2 are shown in figures 8 and 9. Layer 3 (not shown), the lower zone of the Paluxy aquifer, is active everywhere and has constant heads specified on the western and eastern boundaries that were selected from the regional potentiometric map (Rivers and others, 1996).

Because all layers are simulated as confined aquifers, transmissivity (defined as hydraulic conductivity of the aquifer multiplied by aquifer thickness; MacDonald and Harbaugh, 1988), in feet squared per day, was specified. Initially, constant transmissivity of 400 ft^2/d was used for layer 1, 1,000 ft^2/d was used for layer 2, and 1,200 ft^2/d was used for layer 3 (estimated from tables 2 and 3). These values were adjusted during calibration.

Simulated Recharge and Discharge

Recharge, net infiltration of precipitation, was applied to the topmost active model layer in the northwestern part of the model at a rate of 2 in/yr on the outcrop of the Paluxy aquifer northwest of Lake Worth (figs. 8 and 9). Six White Settlement water-supply wells were simulated with the average discharge rate divided between model layers 2 and 3. Additionally, all known domestic wells were incorporated into the model (fig. 5). Pumpage from water-supply wells was divided between layers 2 and 3. Newly installed recovery wells at AFP4 for remediation of the west Paluxy plume pump from layers 1 and 2.

Model Calibration

The model was calibrated to the May 1993 potentiometric surface and water-level data (Rivers and others, 1996). The 1993 potentiometric surface is similar to the potentiometric surface constructed by Leggat (1957), indicating that a steady-state simulation is adequate. The altitude at the top of well casings and the exact location of wells for water-level measurements outside AFP4 were not surveyed; thus, the accuracy of these water-level measurements is within 10 ft (the contour interval of the topographic map (1:24,000 scale) used to estimate land surface at the well).

The purpose of model calibration is to develop a set of parameters and stresses that result in a reasonable simulation of ground-water flow in the Paluxy aquifer. Calibration is accomplished by adjusting values of model parameters (transmissivity, vertical-leakage coefficient, and river-leakage coefficient) until there is a good fit between simulated and observed (measured) ground-water levels and known ground-water fluxes. The differences between the observed water levels (May 1993) and the simulated water levels are shown in figures 10a and 10b (a positive number indicates the observed water level is higher than the simulated water level). The mean difference of observed minus simulated water levels is 5 ft, which is considered acceptable on the basis of the accuracy of the water-level data. Another indication of the goodness of fit between the observed and simulated water levels is the root-mean-square error (RMSE). The RMSE is an approximation of the standard deviation, which means two-thirds of the errors between the observed and simulated water levels are less than the RMSE (16.75 ft for the calibration to May 1993).

Transmissivity was adjusted within the estimated ranges in table 2 and computed from the hydraulic conductivities in table 3 until a better fit to the regional potentiometric-surface map and water-level data was obtained. All aquifer pump test data obtained from contractors were then included; the final estimated transmissivities from model calibration are shown in figures 11–13.

Water-level and lithologic data indicate the Paluxy aquifer, while divided into zones, does not have a continuous confining unit between the upper and middle or middle and lower zones (Kuniansky and others, 1996). Thus, the vertical-leakage coefficient (computed as vertical hydraulic conductivity of the confining unit or aquifer divided by confining-unit thickness or thickness between cells; MacDonald and Harbaugh, 1988) between the layers is based on vertical hydraulic conductivity divided by 57 ft (the approximate distance between the midpoints of the cells). The estimated range for the vertical-leakage coefficient computed from data in table 4 is 10^{-4} to 10^{-8} day^{-1}. The vertical-leakage coefficient was held constant between layers 1 and 2 and layers 2 and 3 and adjusted during calibration. The vertical-leakage coefficient between the layers was 0.0006 day^{-1} in the final run, the highest estimated on the basis of the limited number of permeability tests.

The river-leakage coefficient (defined as the hydraulic conductance of the stream-aquifer interconnection, computed as the hydraulic conductivity of streambed material times the area of streambed in the model cell divided by the thickness of the streambed material; MacDonald and Harbaugh, 1988) is not well known and was estimated using the length of the river in a cell or the entire area of the cell if it was in Lake Worth.

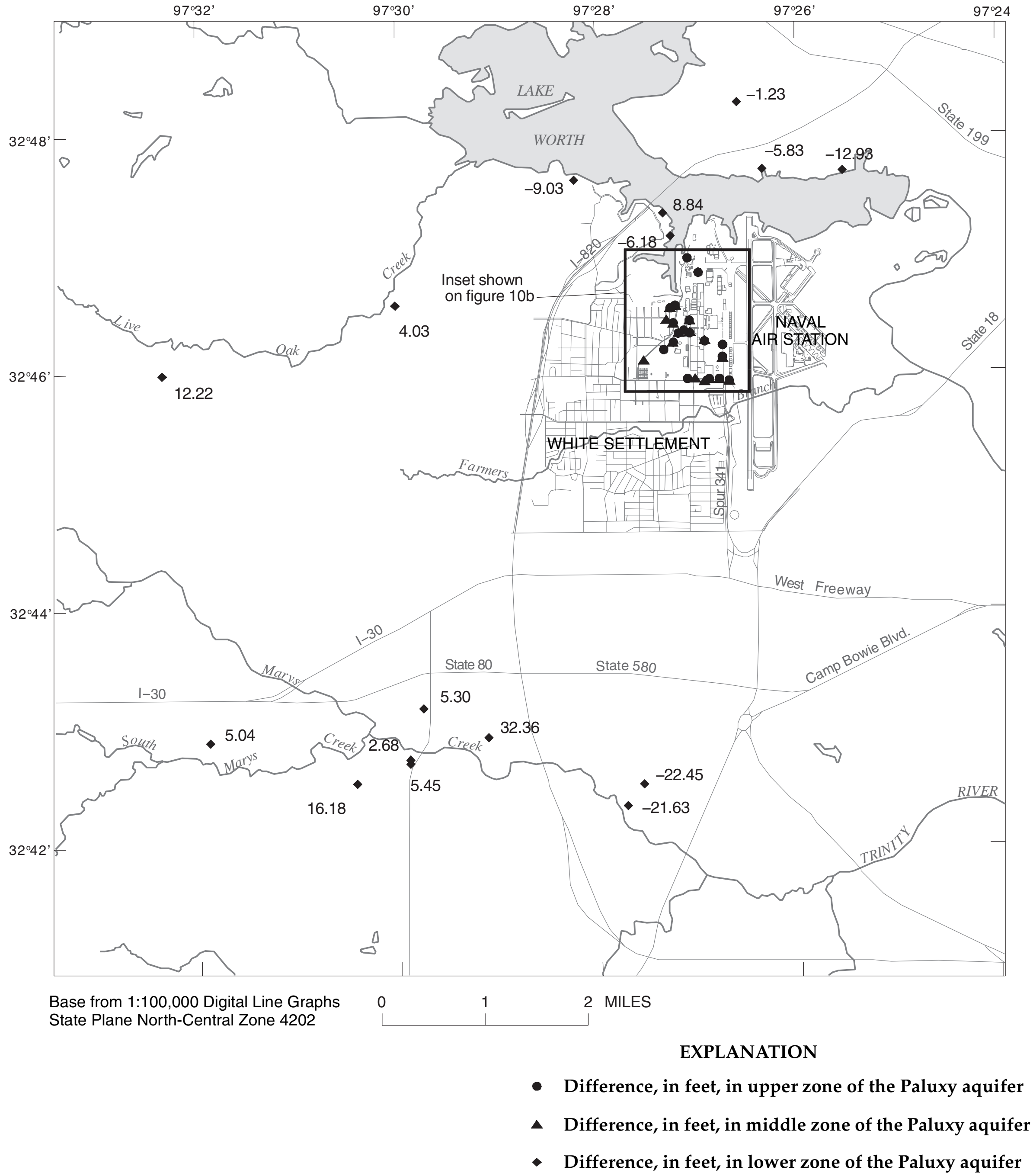
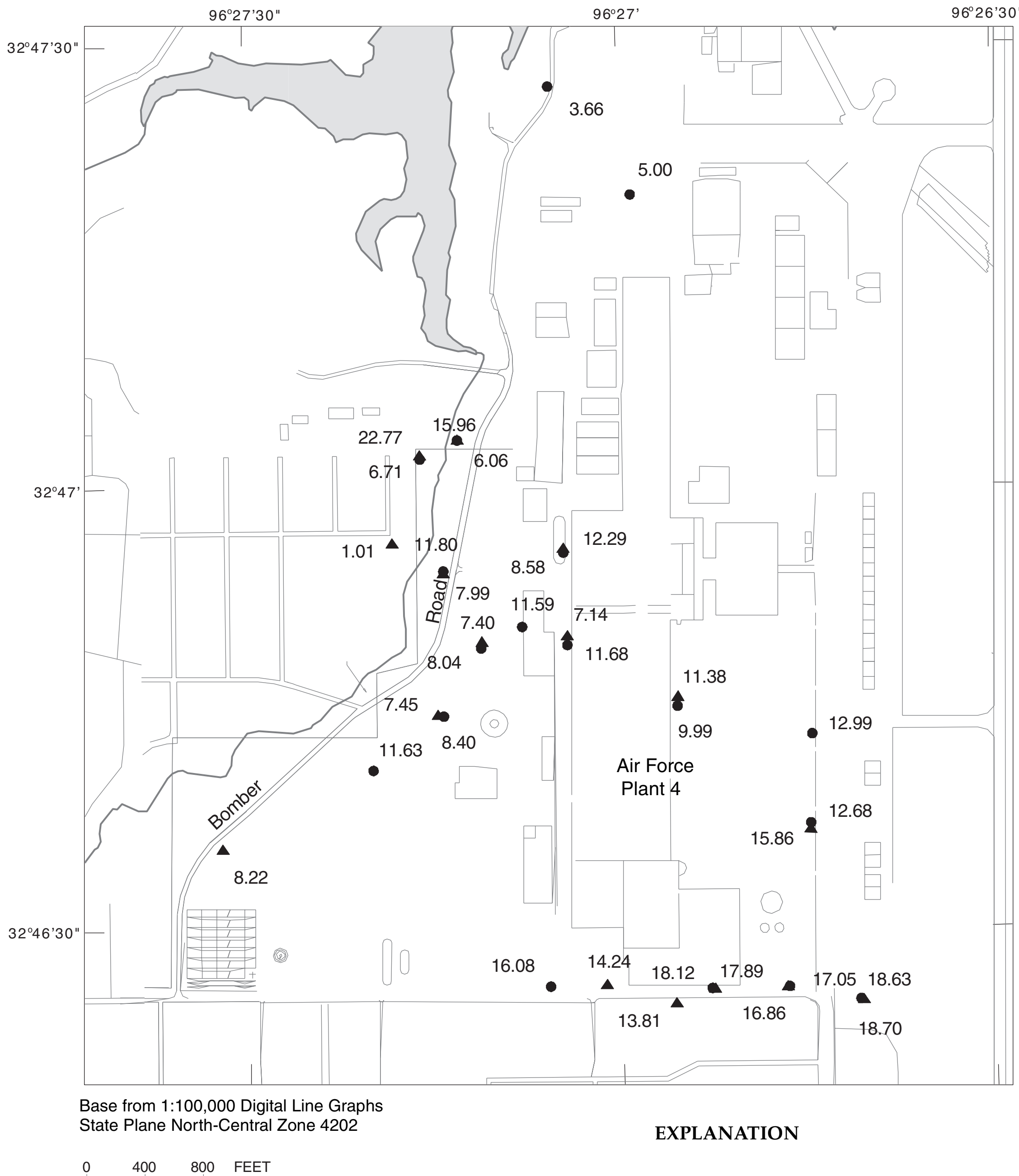


Figure 10a. Difference between observed and simulated ground-water levels in the Paluxy aquifer at Air Force Plant 4 and vicinity, Fort Worth, Texas.

Rates of pumpage and recharge were not adjusted during calibration as the rates were considered to be known. The main difference between the two steady-state simulations is the increased pumpage with the addition of the recovery wells as indicated by the water budgets for the two simulations. The increased pumpage is compensated by increased leakage from river cells in the simulation with the recovery wells. The water budget for the May 1993 simulation (table 6) had about a 0.9-percent error in mass balance, and the water budget for the steady-state simulation with the recovery wells (table 7) had about a 0.18-percent error.



EXPLANATION

Inset (from figure 10a)

● **Difference, in feet, in upper zone of the Paluxy aquifer**

▲ **Difference, in feet, in upper zone of the Paluxy aquifer**

Figure 10b. Difference between observed and simulated ground-water levels in the Paluxy aquifer at Air Force Plant 4, Fort Worth, Texas.

Simulated Water Levels

The simulated water levels with and without the recovery wells for model layers 1, 2, and 3 are shown in figures 14–16. The water levels between layers differ slightly where the aquifer is stressed either by recharge near Lake Worth or by pumping wells; otherwise, water levels between layers are similar.

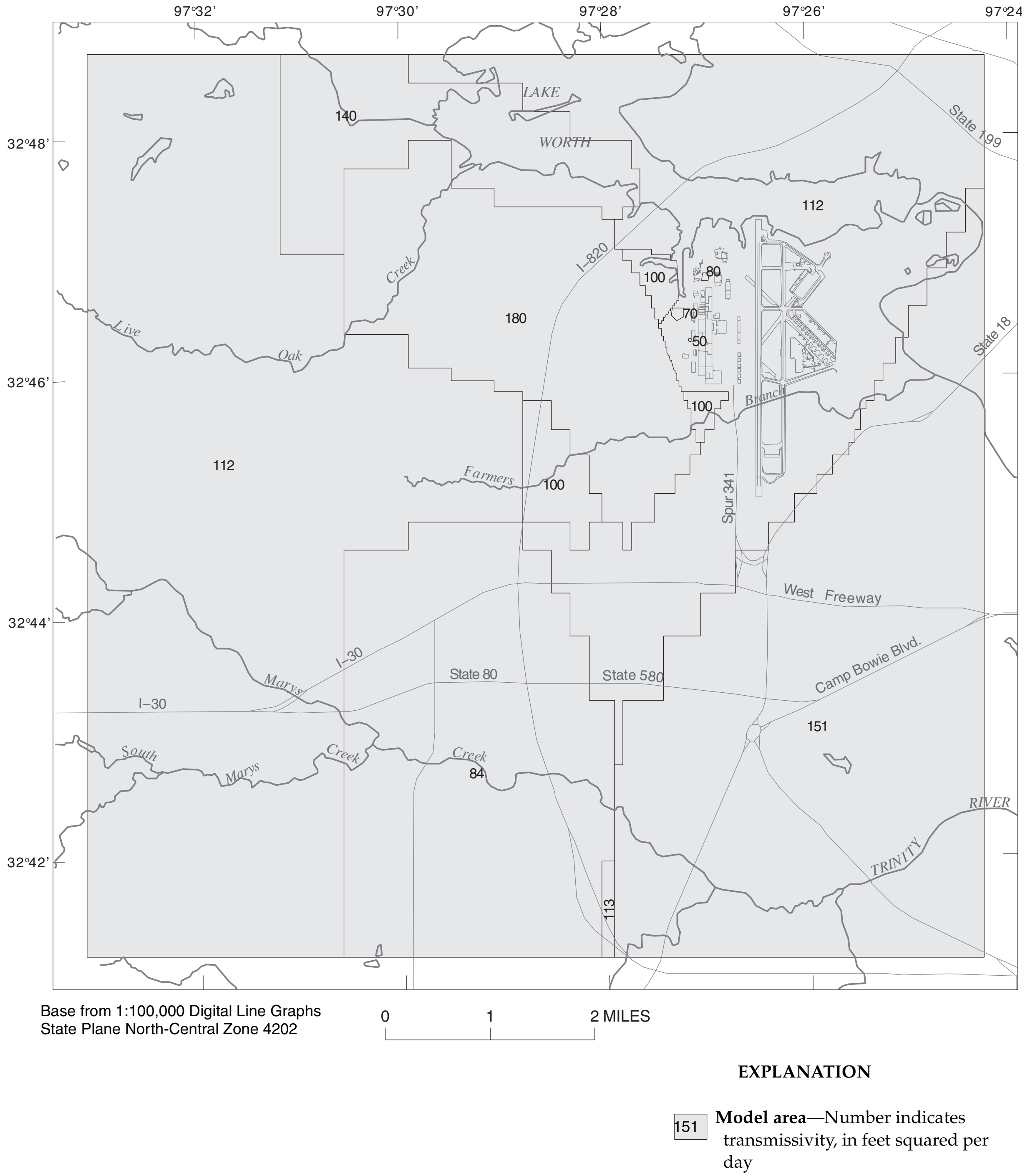


Figure 11. Model-estimated transmissivity for layer 1, upper zone of the Paluxy aquifer at Air Force Plant 4 and vicinity, Fort Worth, Texas.

Sensitivity Analysis

Sensitivity analysis provides an indication of how the set of model parameters and stresses affect the model response. For ground-water-flow models, the model response is the simulated water level and flow through the system. A model is considered sensitive to a parameter or stress when a small change (perturbation) of the parameter or stress causes a large change in the simulated water level. Sensitivity analysis is useful

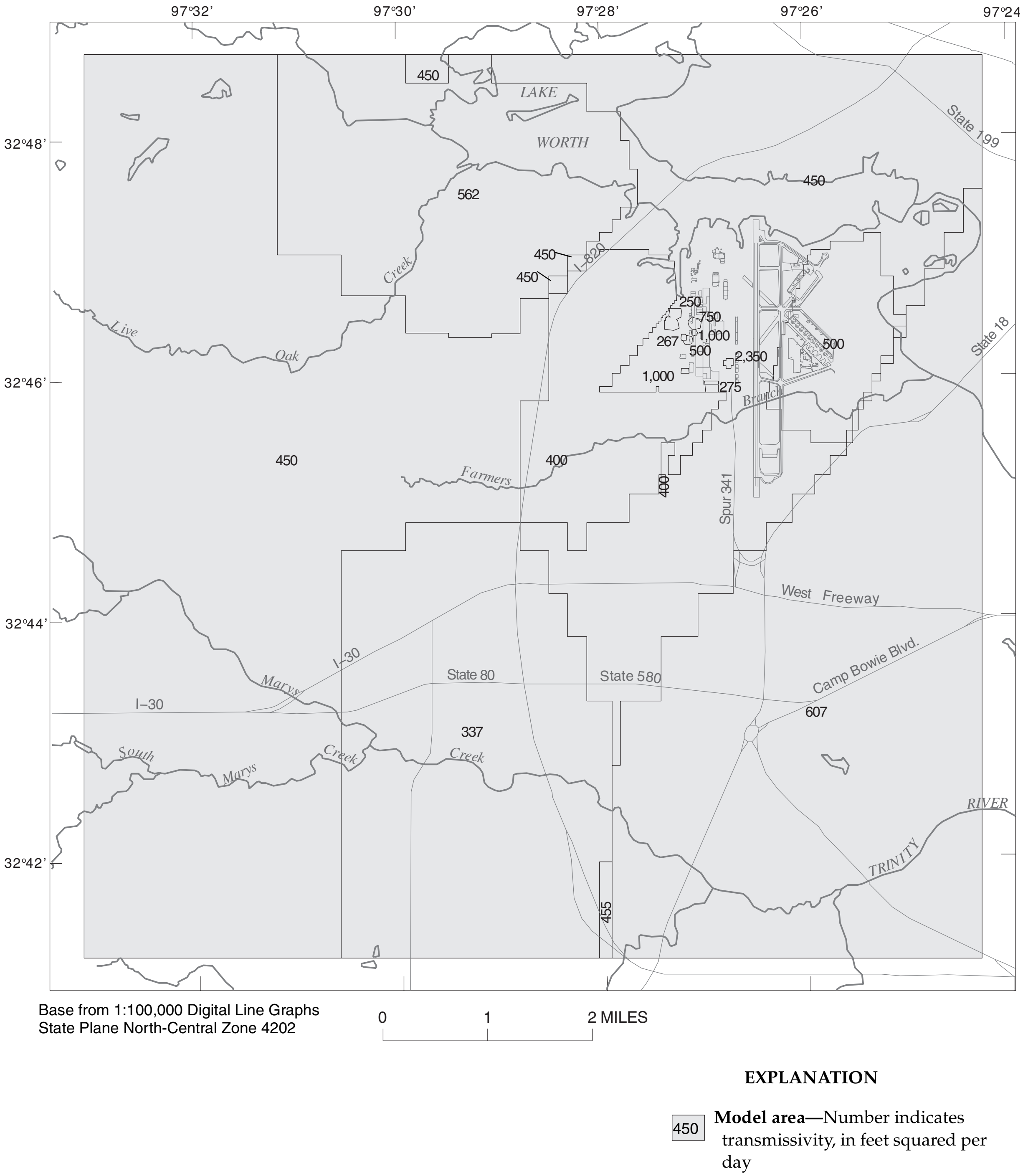


Figure 12. Model-estimated transmissivity for layer 2, middle zone of the Paluxy aquifer at Air Force Plant 4 and vicinity, Fort Worth, Texas.

for indicating areas where errors in the calibrated set of parameters and stresses are more likely. If the model is sensitive to changes in the parameter or stress, the calibrated value is more likely to be accurate or can be accurately estimated through simulation. If the model is insensitive to changes in a parameter or stress, then it is unknowable if the calibrated value is close to the actual value.

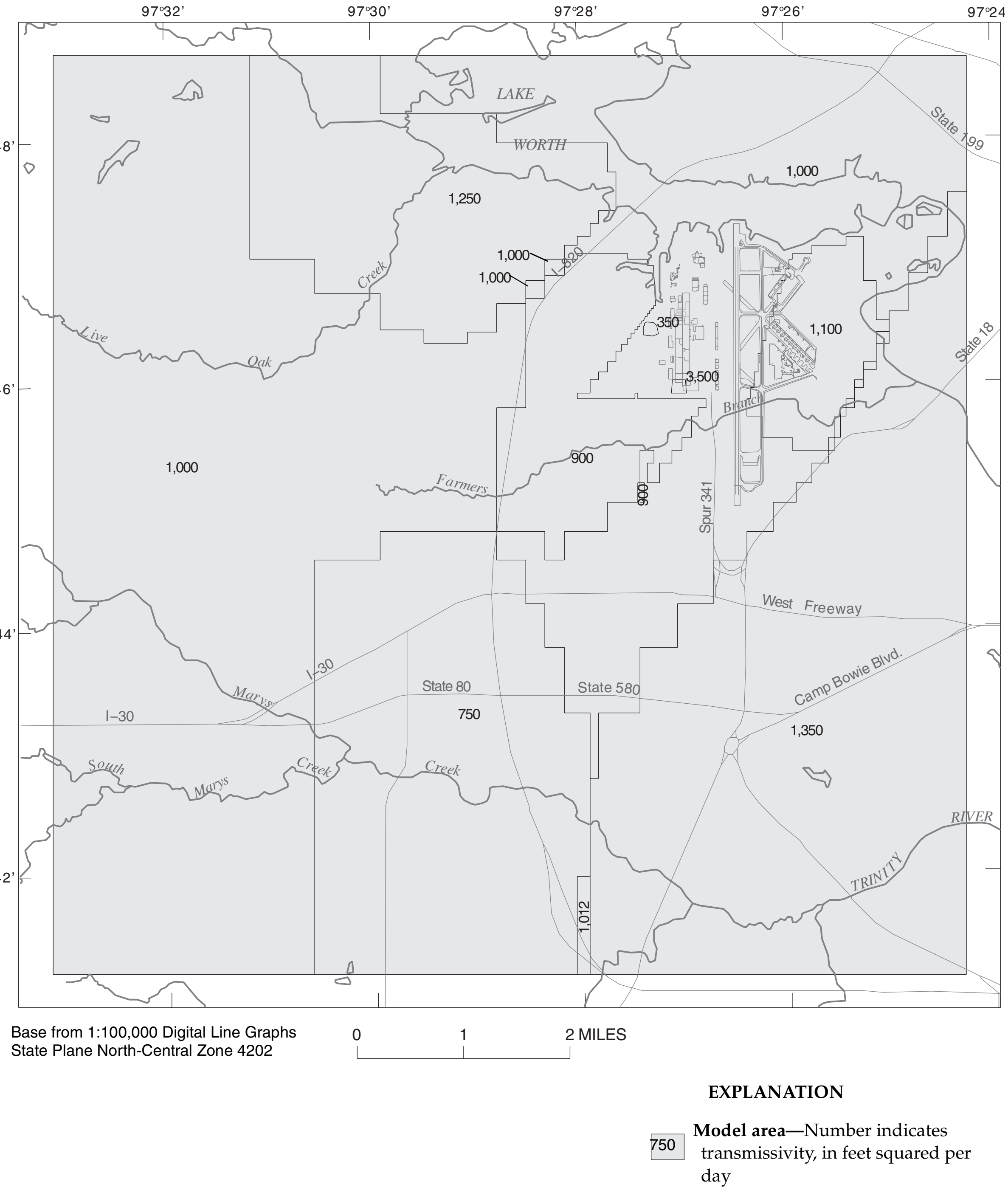


Figure 13. Model-estimated transmissivity for layer 3, lower zone of the Paluxy aquifer at Air Force Plant 4 and vicinity, Fort Worth, Texas.

Sensitivity analysis was done during calibration to help calibrate the flow model. The final sensitivity runs were accomplished systematically and represent the sensitivity of the calibrated model. One parameter or stress was changed using a multiplier (perturbing the parameter) and the RMSE computed. The multipliers used were 0.25, 0.5, 2.0 and 4.0. The RMSE then was plotted against the multiplication factor used to vary

Table 6. Water budget for steady-state simulation, May 1993

[ft^3/d, cubic feet per day]

Description	In (ft^3/d)	Out (ft^3/d)	In - out (ft^3/d)
Constant head	186,620	298,780	-112,160
Wells	0	58,946	-58,946
Recharge	66,323	0	66,323
River leakage	108,010	0	108,010
TOTALS	360,950	357,730	3,227

Table 7. Water budget for steady-state simulation with recovery wells

[ft^3/d, cubic feet per day]

Description	In (ft^3/d)	Out (ft^3/d)	In - out (ft^3/d)
Constant head	187,790	295,320	-107,530
Wells	0	71,651	-71,651
Recharge	66,323	0	66,323
River leakage	113,500	0	113,500
TOTALS	367,610	366,970	642

the parameter or stress. The RMSE for the calibrated model is indicated by a multiplication factor of 1.0 on figure 17.

The model of ground-water flow in the Paluxy aquifer is more sensitive to changes in transmissivity than in two other parameters, vertical-leakage coefficient and river-leakage coefficient (fig. 17). The model is fairly insensitive to changes in the recharge rate, possibly due to the small area to which recharge is applied. The model is more sensitive to changes in ground-water withdrawal than in recharge.

Particle-Tracking Analysis

MODPATH (Pollock, 1994) is a particle-tracking post-processing program for MODFLOW. MODPATH is used to compute where particles placed in or on the faces of the model finite-difference cells would travel on the basis of advective transport processes. The cell by cell budget produced by MODFLOW provides the Darcy velocity for the water. To determine the velocity of the water within the pore spaces, the Darcy velocity is divided by the porosity to determine the particle velocity. Sandstones typically have a porosity of 0.25. The porosity can range from 0.15 to 0.35 (Wolff, 1982). The velocity is inversely proportional to the porosity. Porosity data at the site were not available, so a porosity of 0.25 was assumed for the particle tracking. Because a lower porosity of 0.15 would be a worse case scenario (the TCE plume would travel farther in 9 years), some MODPATH simulations were done with the lower porosity for the particle tracking.

Forward tracking of particles from the cell that contained monitoring well P–22M (fig. 7; row 58, column 48), the abandoned poorly sealed well in landfill 3, was accomplished with the particles placed in layers 1 and 2, the upper and middle zones of the Paluxy aquifer, on the four horizontal faces of the finite-difference cell

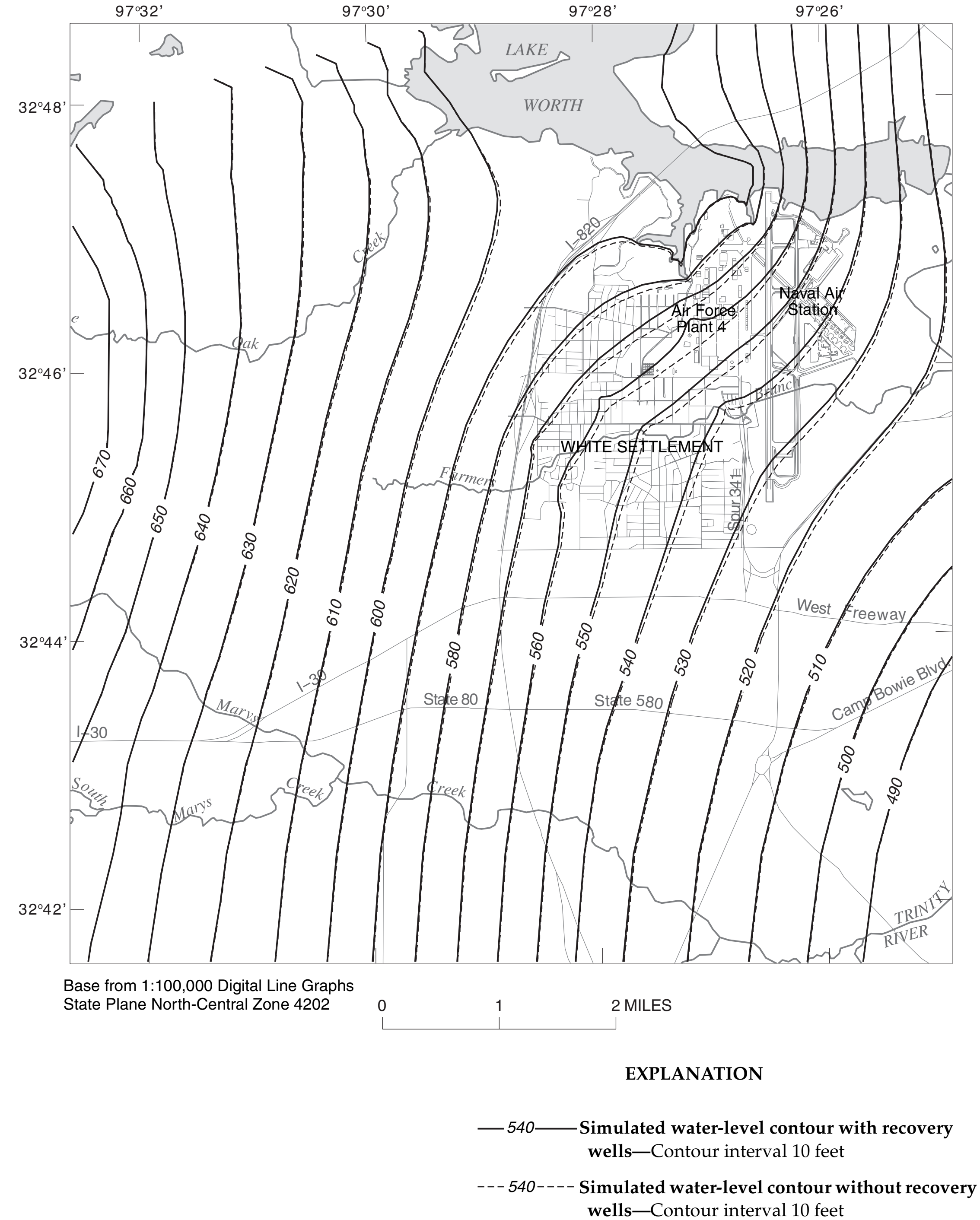


Figure 14. Simulated ground-water levels in layer 1, upper zone of the Paluxy aquifer, with and without recovery wells, at Air Force Plant 4 and vicinity, Fort Worth, Texas.

in each layer. Additionally, particles were placed at the top of layer 1, the upper Paluxy aquifer, in the vicinity of well WITCPU006, where some contaminants were detected in the Goodland-Walnut confining unit. The particles were tracked for 9 years (the length of time between installation and abandonment of well P–22M).

The results of particle-tracking analysis are shown in figure 18. With a porosity of 0.25, the

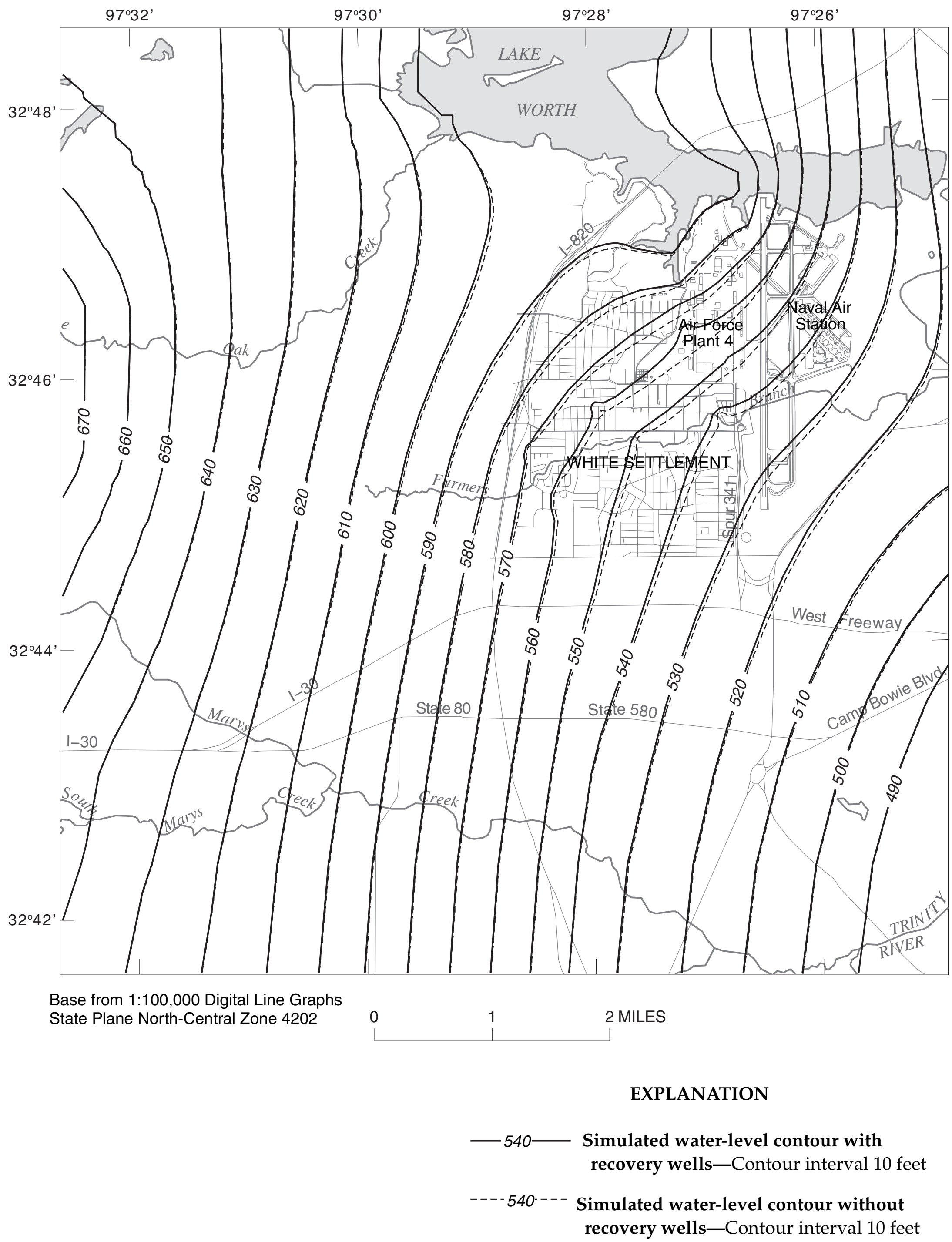


Figure 15. Simulated ground-water levels in layer 2, middle zone of the Paluxy aquifer, with and without recovery wells, at Air Force Plant 4 and vicinity, Fort Worth, Texas.

TCE plume could reach an area west of the middle of Building 14 in layer 2 southeast of well P–22M in 9 years. TCE has been detected in monitoring well P–27U at the middle of the western side of Building 14 (as labeled in the Management Action Plan, U.S. Air Force, Aeronautical Systems Center, Environmental Management Directorate, 1995). The particles move farther in layer 2 than in layer 1 as a result of higher transmissivity

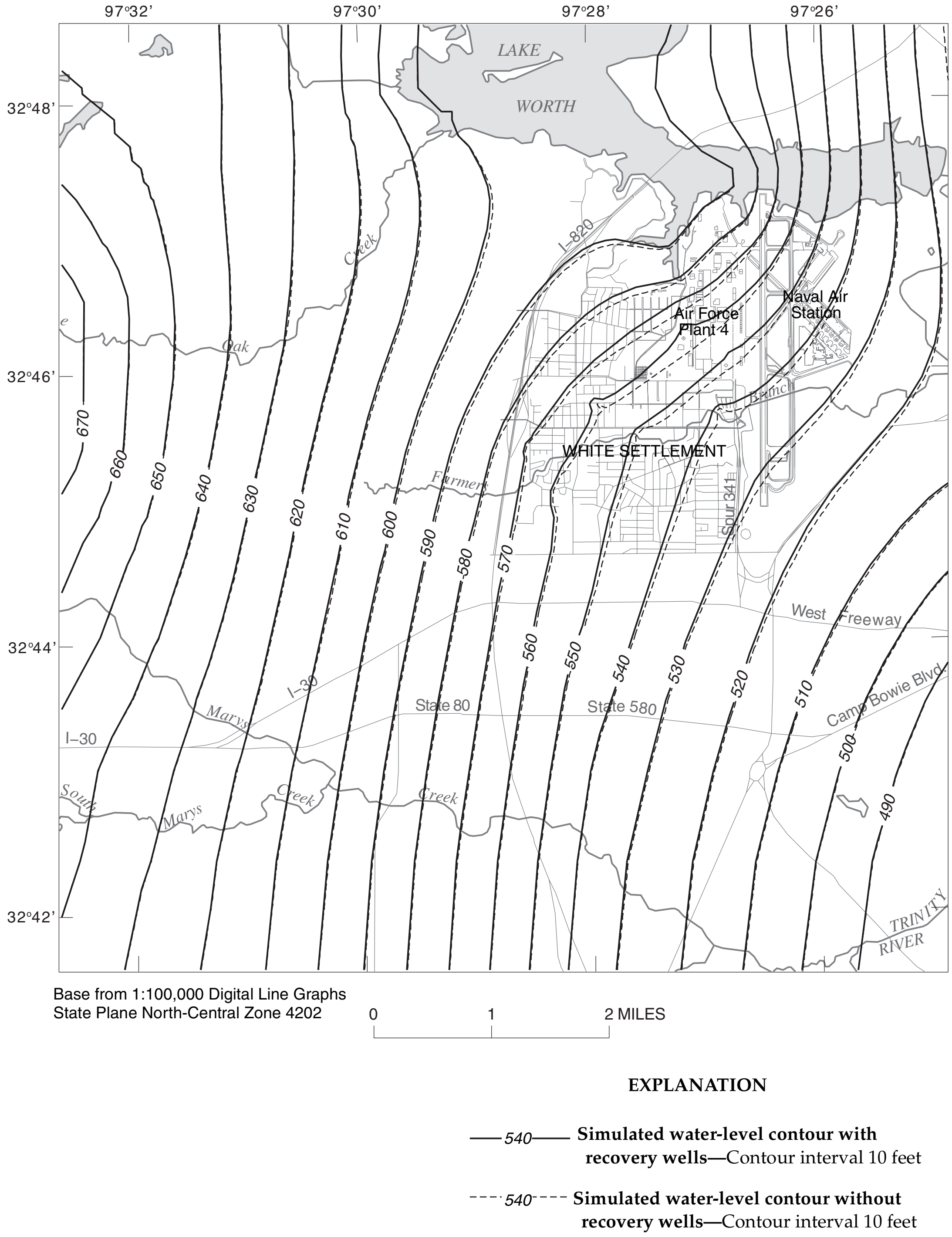
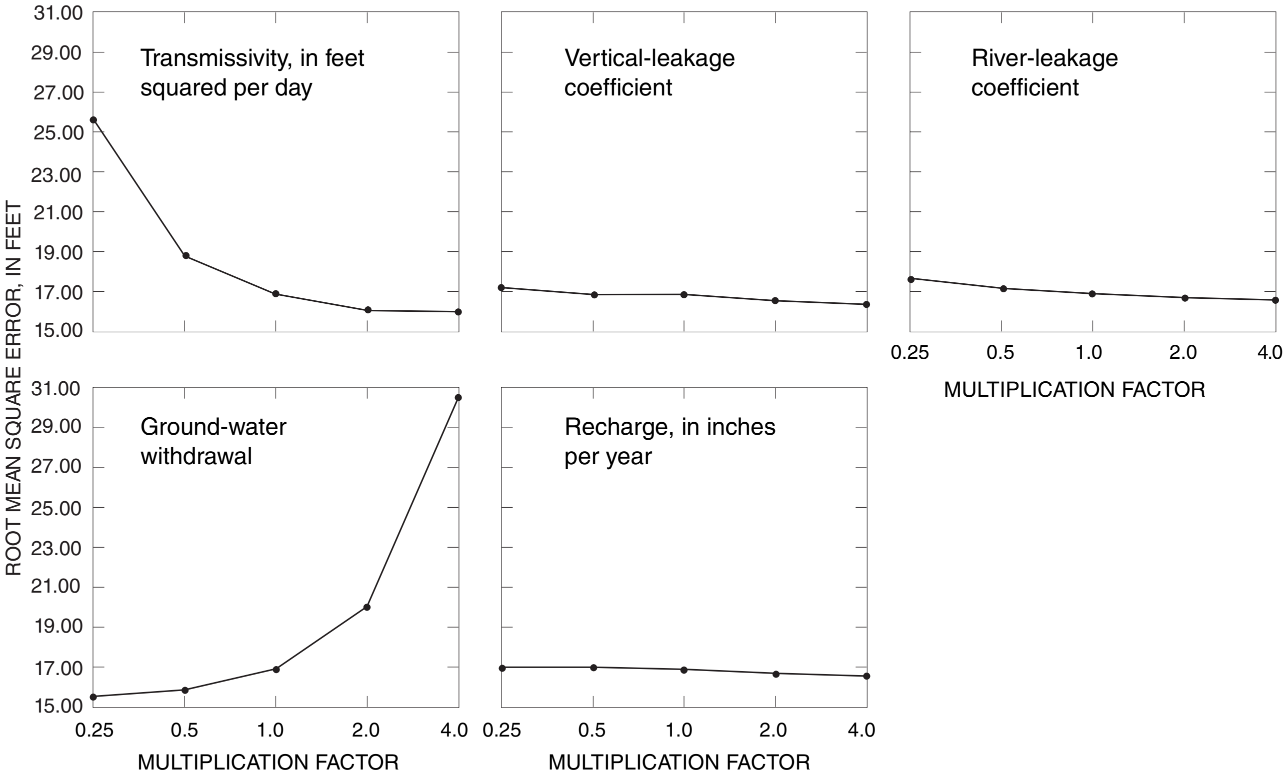


Figure 16. Simulated ground-water levels in layer 3, lower zone of the Paluxy aquifer, with and without recovery wells, at Air Force Plant 4 and vicinity, Fort Worth, Texas.

and possibly the pumping of White Settlement water-supply wells south of AFP4. No particles move from the upper zone to the middle zone of the Paluxy aquifer or from the middle zone to the lower zone of the Paluxy aquifer with the porosity simulated as 0.25. For the worse case scenario using a porosity of 0.15, the particles travel to the southern end of Building 14 in layer 2. No particles move from the upper zone to the middle



Root-mean-square error, in feet

Parameter	Multiplication factor				
	0.25	0.5	1.0	2.0	4.0
Transmissivity	25.58	18.74	16.85	16.04	15.99
Vertical-leakage coefficient	17.19	16.81	16.85	16.54	16.35
River-leakage coefficient	17.55	17.13	16.85	16.67	16.56
Ground-water withdrawals	15.43	15.78	16.85	20.00	30.51
Recharge	17.00	16.97	16.85	16.67	16.55

Figure 17. Sensitivity of the model to changes in parameters and stresses.

zone of the Paluxy aquifer or from the middle zone to the lower zone of the Paluxy aquifer with the porosity simulated as 0.15.

The backward tracking of particles is shown in figure 18. These pathlines were developed from the second steady-state simulation, which includes the installed recovery wells placed to capture the west Paluxy plume. Backward tracking indicates the direction that water would flow toward the recovery wells. From the specific-capacity data collected by IT Corp. (written commun., 1997), an assumption was made that the two recovery wells screened in the middle zone of the Paluxy aquifer would be able to sustain a yield of 30 gal/min. The recovery wells screened in the upper zone of the Paluxy aquifer would be able to sustain a yield of 3 gal/min. These were the pumping rates used in the second steady-state simulation. Several different locations were simulated with preliminary model simulations, but only the pathlines from the locations of the installed recovery wells are shown.

The particle-tracking results indicate that these four recovery wells provide adequate capture areas for minimizing off-site migration of the TCE plume in the upper and middle zones of the Paluxy aquifer beneath landfills 1 and 3. To determine the effectiveness of the recovery wells, monitoring wells southeast of Building 14 have been installed and will be sampled (IT Corp., written commun., 1997).

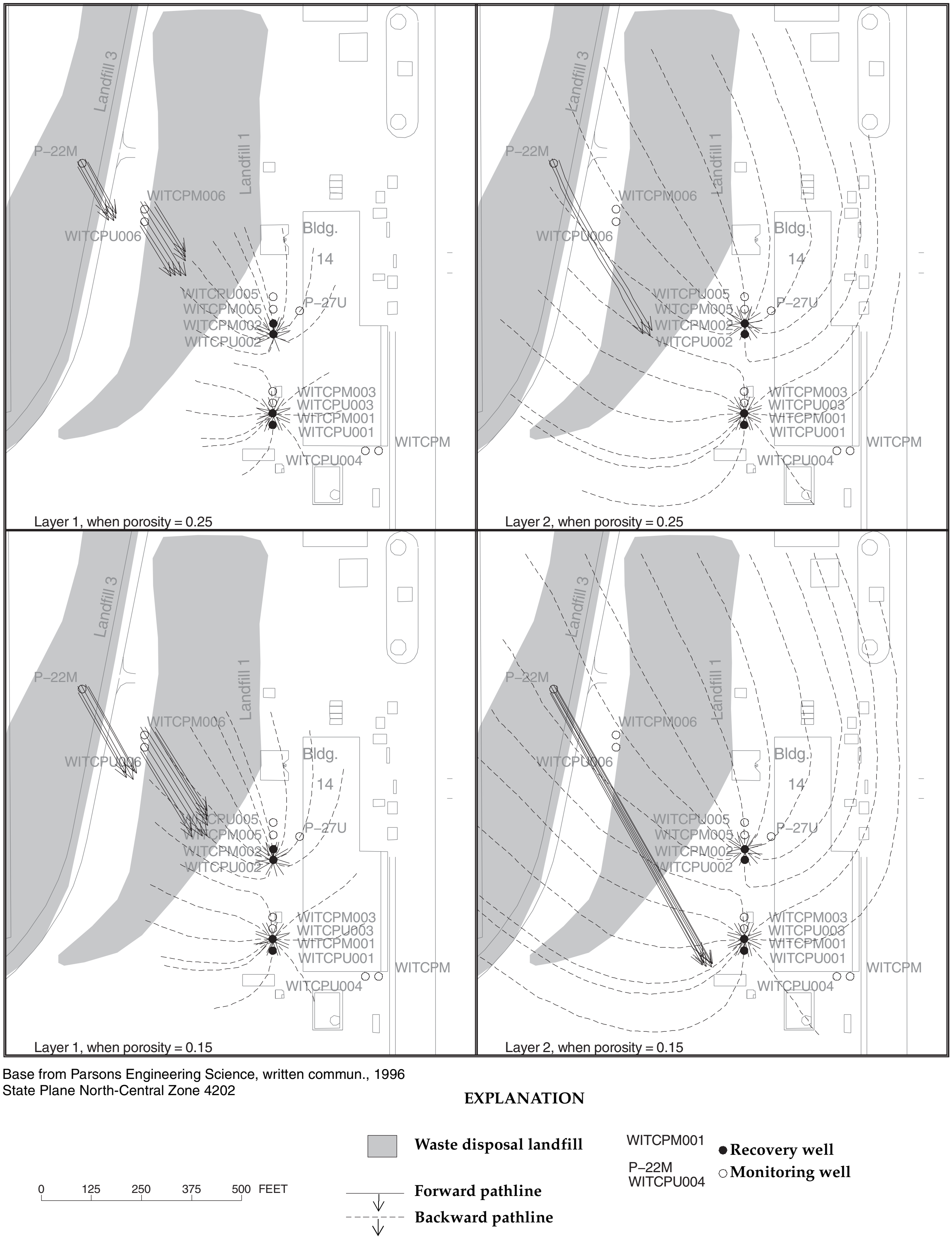


Figure 18. Location of forward and backward particle-tracking pathlines at Air Force Plant 4, Fort Worth, Texas.

SUMMARY

At the request of the U.S. Air Force, Aeronautical Systems Center, Environmental Management Directorate, the U.S. Geological Survey developed a ground-water-flow model for use by the U.S. Air Force. The model described in this report is a site-specific model of the Paluxy aquifer in the vicinity of landfills 1 and 3 at U.S. Air Force Plant 4. The model was developed to evaluate the best location for the installation of recovery wells to remediate a trichloroethylene (TCE) plume, the west Paluxy plume, as required in the Record of Decision, signed in 1996. The west Paluxy plume might be, in part, the result of leakage of ground water contaminated with dissolved TCE from the terrace alluvial aquifer down the annulus of a poorly sealed monitoring well, P–22M. Well P–22M was installed October 1987 and plugged and abandoned November 1995. Additionally, volatile organic compounds have been detected in fractures in the Goodland-Walnut confining unit, the hydrogeologic unit separating the terrace alluvial aquifer from the underlying Paluxy aquifer, beneath the western part of landfill 1. Volatile organic compounds in concentrations near the detection limit were detected in the upper zone of the Paluxy aquifer prior to the drilling of P–22M. TCE concentrations in the west Paluxy plume are less than 100 μg/L. The maximum contaminant level established by the U.S. Environmental Protection Agency for TCE is 5 μg/L.

Four geologic units are pertinent to this site-specific model. From oldest to youngest these are the Glen Rose Formation, Paluxy Formation, Walnut Formation, and Goodland Limestone. The Glen Rose Formation is relatively impermeable in the study area and forms the confining unit below the Paluxy Formation. The Paluxy Formation forms the Paluxy aquifer, which is a public drinking water supply for the City of White Settlement. The Walnut Formation and Goodland Limestone form the Goodland-Walnut confining unit overlying the Paluxy aquifer. Near landfill 3, gamma-ray logs indicate three distinct zones in the Paluxy aquifer; upper, middle, and lower. The aquifer is about 170-ft thick near landfill 3; each zone is about 57-ft thick.

Two steady-state ground-water-flow simulations using MODFLOW were analyzed using the particle-tracking software MODPATH. For many ground-water-flow modeling problems, the transport of dissolved contaminants is dominated by advection (dissolved solutes moving with the ground water), and the processes of diffusion and dispersion provide minimal movement of the dissolved contaminants. Thus, particle tracking provides an estimate of contaminant migration. In some cases, when contaminants sorb onto aquifer material or degrade or decay rapidly, particle tracking could be a worse case estimate of the transport of the contaminant. Particle tracking does not provide any information on concentrations of contaminants. The particle-tracking analysis does provide a useful estimate of the movement of the TCE plume from source areas and an estimate of the capture area of the recovery wells.

A variably spaced grid was designed for the model. The smallest grid cells, 25 by 25 ft, are in the vicinity of landfills 1 and 3. The largest cells, 4,864.5 by 1,441.5 ft, are at the northwestern corner of the model grid near the Parker-Tarrant County line. The modeling was accomplished with three layers representing the upper, middle, and lower zones of the Paluxy aquifer.

The first steady-state simulation was calibrated by matching simulated water levels to observed water levels in the Paluxy aquifer for May 1993. Forward tracking of particles from the cell that contained monitoring well P–22M (row 58, column 48), the abandoned poorly sealed well in landfill 3, was accomplished with the particles placed in layers 1 and 2 on the four horizontal faces of the finite-difference cell in each layer. Additionally, particles were placed at the top of the upper zone of the Paluxy aquifer near monitoring well WITCPU006, where contaminants have been detected in fractures in the Goodland-Walnut confining unit. The particles were tracked forward in time for 9 years using the calibrated model. Particle tracking indicated that ground water with dissolved TCE could reach an area west of the middle to southern end of Building 14 in 9 years.

The second steady-state simulation included the recovery wells installed to remediate the ground-water contamination beneath landfills 1 and 3, the west Paluxy plume. Backwards tracking from the recovery wells was used to define the capture area of the wells. The simulations indicate that the capture area of the four recovery wells is large enough to capture most of the ground water in the upper and middle zones of the Paluxy aquifer beneath landfills 1 and 3, minimizing off-site migration of the TCE plume. To determine the effectiveness of the recovery wells, monitoring wells southeast of Building 14 have been installed (1996–97) for sampling.

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