Contamination of Ground Water at the Tucson International Airport Area Superfund Site, Tucson, Arizona—Overview of Hydrogeologic Considerations, Conditions as of 1995, and Cleanup Efforts

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CONVERSION FACTORS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
pound (lb)	0.4536	kilogram
gallon (gal)	3.785	liter

In this report, temperature is reported in degrees Fahrenheit (°F), which can be converted to degrees Celsius (°C) by using the following equation:

$$°C = (°F-32)/1.8$$

UNITS OF CHEMICAL CONCENTRATIONS

The metric units milligrams per liter (mg/L) and micrograms per liter (µg/L) are used to express concentrations of chemicals dissolved in water. These units express concentrations in terms of the mass (milligram or microgram) of dissolved chemical per unit volume (liter) of water. An ordinary paper clip has a mass of about 1 gram. A milligram is equal to one-thousandth of a gram and is about equal to the weight of six grains of common table salt. A microgram is 1,000 times smaller than a milligram. A liter is slightly more than a quart. In this report, concentrations of organic chemicals and heavy metals dissolved in water are given in micrograms per liter. In other documents, parts per million (ppm) and parts per billion (ppb) often are used to express concentrations of chemicals dissolved in water. The units microgram per liter (μg/L) and parts per billion (ppb) essentially are equivalent, as are the units milligrams per liter (mg/L) and parts per million (ppm) at concentrations of less than 7,000 mg/L.

VERTICAL DATUM

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.

DEFINITION OF TERMS

Terms used in this report are listed below.

Aquifer—A unit of saturated unconsolidated sediments, such as sand or gravel, or consolidated rocks that will yield water in significant quantities to wells and springs and allow the water to move from one location to another.

Capillary fringe—A zone of sediments that overlies the water table in which some or all of the spaces between sediment particles are filled with water and held against the pull of gravity by suction.

Capillary suction—A force that draws water into the small spaces between sediment particles and holds it against the pull of gravity similar to the process by which a spill is picked up with a paper towel.

Confining unit—A layer of geologic material, such as clay, that slows the vertical movement of water in an aquifer or between two aquifers. A confining unit is sometimes referred to as an aquitard.

Dense nonaqueous-phase liquids (DNAPLs)—A liquid chemical, such as TCE, that is heavier than water and does not readily mix with or dissolve in water.

Drawdown cone—A depression in the water table created by the removal of water from the aquifer by pumping from a well; also may be referred to as a cone of depression.

Dual-phase extraction (DPE)—A ground-water cleanup system in which ground water is extracted from the aquifer for treatment at the same time as soil vapor is removed from the unsaturated zone.

Geographic-information system (GIS)—A computerized information storage-and-retrieval system for data that have a geographic component.

Gravel pack—Well-sorted, coarse-grained sediment that is installed in the annular space surrounding a well screen.

Heterogeneity—Not the same everywhere; having nonuniform properties.

pH—A measure of the acidity of water. A neutral water has a pH of 7.0, an alkaline water has a pH of more than 7.0, and an acidic water has a pH of less than 7.0.

Perched ground water —Water found in pockets of saturated sediments underlain by unsaturated sediments.

Permeability—A measure of the ability of rocks or sediments to transmit water or other fluids.

Porosity—The property of rocks and sediments of having openings or void spaces between the solid particles; usually expressed quantitatively as a ratio or percentage.

Preferential flow—Movement of water and dissolved chemicals along distinct pathways rather than as uniform flow. Flow may follow interconnected cracks or zones having high permeability. Preferential flow is also referred to as bypass flow.

Pump and treat—A ground-water cleanup technique in which water is removed from an aquifer using extraction wells. The water is treated to remove contaminants and then recharged to the aquifer or used for water-supply purposes.

Rebound—An increase in contaminant concentrations in ground water after a period of decreasing or constant concentrations and after an extraction well is shut off.

Recharge area—A place where water enters the ground and percolates down to the aquifer.

Screened interval—The length of well casing that is perforated or slotted to receive water from the aquifer.

Soil-vapor extraction (SVE)—A cleanup technique by which VOC's, such as TCE, are removed from the unsaturated zone.

Sorption—Sorption occurs when contaminants adhere to soil particles.

Tailing—A leveling off in the rate of decline of contaminant concentrations, and may indicate that sources of contaminant are continuing to be dissolved in ground water or that removal is being limited by other factors.

Tucson Airport Remediation Project (TARP)—A ground-water cleanup system north of the main area of ground-water contamination at the Tucson International Airport Area Superfund Site.

Unsaturated zone—A shallow subsurface zone that contains both water and air; also may be called the vadose zone.

Volatile organic compound (VOC)—An organic compound, such as TCE, that readily changes from a liquid to a gas or vapor.

Water table—A surface beneath the ground defined by the levels at which water stands in wells that are completed in the upper part of an aquifer. The water table defines the upper boundary of the aquifer.

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By D.D. Graham *and* J.E. Monical

Abstract

Organic contaminants in ground water from parts of the sole-source regional aquifer underlying the City of Tucson in Pima County, southeastern Arizona, have been an issue of public concern for many years. Characterization studies done subsequent to studies in the early 1980's have provided much additional information about the extent of contamination at the Tucson International Airport Area Superfund Site. Cleanup activities have been initiated at many locations at the site. The principal contaminant in ground water is trichloroethylene (commonly referred to as TCE), which is a volatile organic compound that was widely used as an industrial solvent at several locations in the study area. Other volatile organic compounds, including trichloroethane, dichloroethylene, chloroform, and xylene, are in ground water at the site at much lower concentrations. Heavy metals, such as lead, cadmium, nickel, and chromium, released as components of an industrial waste stream, also are contaminants of concern. Heavy metals generally were immobilized at shallow depths in the unsaturated zone and have not been found in ground water. Chromium in the form of hexavalent chromium is the exception.

Monitoring of concentrations of TCE and other organic and inorganic compounds in ground water is done throughout the site. Data provided by industries and government agencies involved with monitoring and cleanup efforts at the site were used to create a unified geographic-information system data base. Data for concentrations of TCE for December 1995 were plotted using this storage-and-retrieval system. Areas with wells that yield water with concentrations of TCE that exceed 5 micrograms per liter were delineated. The main area of contaminated ground water is similar in overall shape and extent to the area delineated in a study done in 1987 using data for 1984. South of the airport, a small reduction in the width of the main area of contaminated ground water is evident, and concentrations of TCE in the discharge of several wells within the delineated area have declined. Two smaller areas of contaminated ground water are immediately north and northeast of the airport as in 1984. Data for 1995 suggest an increase in size of the contaminated area immediately north of Tucson International Airport. The apparent increase in size may be because additional wells were completed to better define the area of contaminated ground water. Recently completed characterization studies indicate concentrations of TCE in ground water as large as 74,000 micrograms per liter in samples taken from a layer of fine-grained sediments at the uppermost part of the aquifer in an area on the west side of Tucson

International Airport immediately north of Los Reales Road. As of 1995, this area has the largest concentrations of TCE in ground water.

Many potential sources of contaminants have been identified throughout the Tucson International Airport area, and cleanup techniques were put into operation at some locations. For the area of ground-water contamination south of Los Reales Road, cleanup efforts were initiated in 1987 that were designed to contain the movement of contaminated ground water, extract contaminated ground water, remove contaminants, and recharge the treated water. Cleanup efforts resulted in the treatment of over 13 billion gallons of ground water and the removal of an estimated 17,000 pounds of volatile organic compounds, mainly TCE, by the end of 1995. Near historical disposal areas, cleanup efforts also focused on removing contaminants from the sediments that overlie the upper zone of the regional aquifer. For example, by the end of 1995, about 29,000 pounds of volatile organic compounds, mainly TCE, was removed from the sediments that overlie the upper zone of the aquifer in an area south of the airport.

Although the size of the area where ground water has been contaminated with TCE has not increased and concentrations of TCE in water from many wells have declined, indications are that permanent aquifer restoration may be more difficult and time consuming than originally anticipated. The heterogeneity of the sediments in the regional aquifer and overlying capillary fringe and unsaturated zone hinders cleanup efforts. Near disposal areas, large concentrations of TCE commonly are associated with fine-grained sediments that have high porosity and low permeability. Slow dispersal from these sediments may limit cleanup efforts as may the tendency of undissolved TCE to become entrapped or to sorb to sediment particles. Continuation of a strategy of containment probably will remain important because of the difficulty of removing all traces of contaminants from the subsurface.

The purpose of this report is to provide an overview as of 1995 of the extent of ground-water contamination at the site and summarize technical information relevant to cleanup efforts. To make the report useful to a broad audience, a "Definition of Terms" has been provided at the front of the report, and many technical terms are explained in the text.

INTRODUCTION

Contaminants in ground water in parts of the regional aquifer, which underlie the City of Tucson in Pima County, southeastern Arizona (fig. 1), have been an issue of public concern for many years. Initial indications of ground-water contamination in southwest Tucson date back to the 1950's, when water from a municipal well was found to have large concentrations of chromium. Also, people living near Tucson International Airport complained that water from their private wells had a foul odor (U.S. Environmental Protection Agency, 1995). In early 1981, the U.S. Environmental Protection Agency (USEPA) and the Arizona Department of Health Services (ADHS) identified contaminants in ground water from the upper several hundred feet of the regional aquifer near Tucson International Airport (U.S. Environmental Protection Agency, 1988, p. 2). The primary contaminant detected was trichloroethylene (TCE), an industrial solvent in common use by electronics and aerospace industries. Historically, TCE has been used for degreasing metals, dry-cleaning operations, refrigerants, and as a component of septic-tank cleaning fluids. Several private and municipal wells were removed from service when concentrations of TCE in excess of drinking-water standards were detected. A number of potential sources were identified by the USEPA and ADHS at the airport and in the adjacent industrial area. Industrial activities that resulted in the contamination of ground water with TCE near Tucson International Airport began in the early 1940's. At that time, the common practice was to

Figure 1 goes here.

dispose of liquid wastes including used solvents, such as TCE, by dumping them directly on the ground without any form of treatment (U.S. Environmental Protection Agency, 1992, p. 1).

In 1982, the USEPA identified the boundaries of the Tucson International Airport Area Superfund Site, hereafter referred to as the Airport Area Site. In early 1983, the site was included on the National Priorities List. The site is bounded on the west by the ephemeral Santa Cruz River, on the east by Alvernon Way, on the north by Ajo Way, and on the south by Hughes Access Road (fig. 2). The site includes industrial, commercial, residential, and undeveloped areas (U.S. Environmental Protection Agency, 1988, p. 1).

Initial investigations determined that several contaminants were in the ground water. Principal contaminants included volatile organic compounds (VOC's), primarily TCE, with lesser amounts of trichloroethane (TCA), dichloroethylene (DCE), chloroform, benzene, and xylene. Dissolved chromium, a heavy metal in the form of hexavalent chromium, also was found in ground water in concentrations that exceeded drinking-water standards (U.S. Environmental Protection Agency, 1988, p. 3). Several potential sources of contaminants were identified and included solvent-disposal areas, firefighting-training areas, unlined wastewater evaporation ponds and ditches, and metal-sludge beds. Leake and Hanson (1987) summarized the results of these and several other investigations of ground-water contamination in the area around Tucson International Airport. Leake and Hanson (1987) delineated one large and two small areas of contaminated ground water in which concentrations of TCE exceeded the USEPA maximum contaminant level (MCL) and the Arizona State Action Level of 5 μg/L. The largest of the areas of ground-water contamination was about 5 mi^2 in surface area, was about 35,500 ft long, and about 4,000 ft wide.

Since 1987, additional areas that were thought to be contributing to contamination of ground water by organic solvents have been identified, and much additional work has been directed to site characterization, installation of additional monitor wells, collection of water-quality data, and selection of cleanup procedures. Cleanup has been initiated in many areas of the site, and data relevant in the assessment of results of these procedures are being collected. A vast amount of information has been released, in various forms, to regulatory agencies and the public.

Public interest in the effect of releases of organic solvents and other contaminants on ground-water quality in the area has remained high in the years succeeding the initial contamination studies. The large amount and technical nature of the information released to the public have made it difficult for the public to stay current and develop an understanding of technical issues relevant to cleanup efforts and progress being made to resolve them.

Regulatory oversight for cleanup efforts at the airport site is the responsibility of the USEPA, Region 9. The cleanup efforts for the part of the Superfund site that is south of Los Reales Road is being overseen by the U.S. Air Force as the lead agency. Oversight is provided by USEPA, Region 9; Arizona Department of Environmental Quality (ADEQ); and Arizona Department of Water Resources (ADWR).

Because Tucson is in a desert region, ground water is a valuable resource. Alternative sources of water are distant, expensive to transport to the area, and may require extensive treatment to be used for water-supply purposes. As of 1995, ground water from the regional aquifer, which underlies the Tucson Basin, and from nearby Avra Valley provides all of the water being used for municipal, private, and industrial supplies by the City of Tucson, the City of South Tucson, nearby tribal lands of the Tohono O'odham Nation, and in adjacent areas of Pima County. The regional aquifer of the Tucson Basin was designated as a sole-source water supply (U.S. Environmental Protection Agency, 1984). This report, the product of compilation, review, summary, and interpretation of existing hydrologic and geologic data from many sources, has been prepared by the USGS in cooperation with the U.S. Air Force.

Purpose and Scope

The purpose of this report is to provide a succinct, updated overview of the extent of ground-water contamination at the site and summarize technical information relevant to cleanup efforts. In this report, discussion is limited

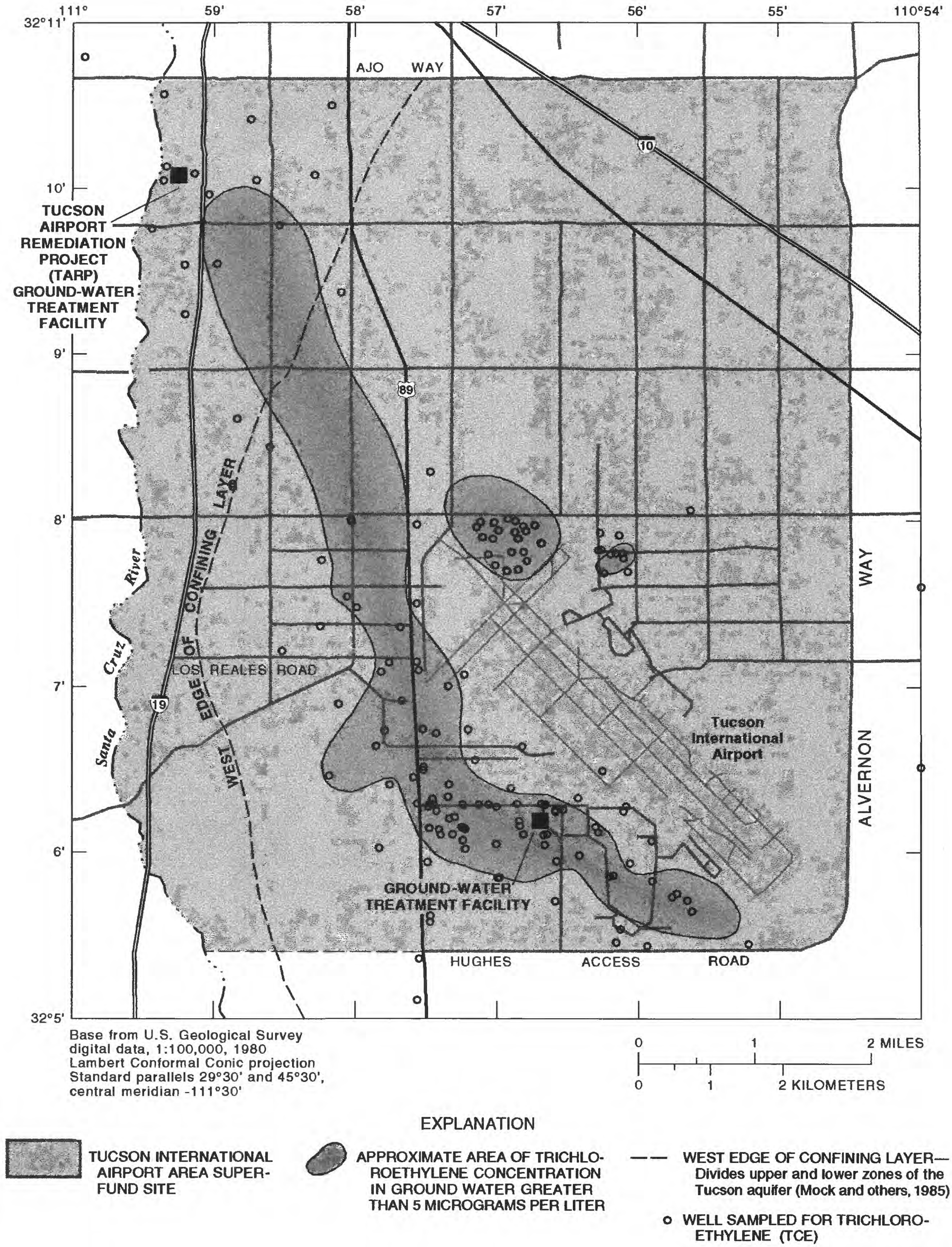

Figure 2. Approximate area of trichloroethylene contamination in ground water, December 1995, and western edge of confining layer that divides the upper and lower zones of the regional aquifer.

to a general summary and interpretation of the processes that allowed contaminants to enter the subsurface, to be transported to the underlying aquifer, and to spread in the aquifer to distant areas. An attempt has been made to minimize the use of unexplained technical terms in this report. The section "Definition of Terms" is provided at the beginning of the report.

Additional Sources of Information

Because it is difficult for a report to be both succinct and comprehensive, priority has been given to informing readers of sources of additional information by including a listing of site-related documents at the back of this report that are available to the public at the TCE Superfund Library in Tucson. Characterization, cleanup, and monitoring activities continue at locations throughout the Tucson International Airport Area Superfund Site and additional site-related information is continually being made available to the public. A TCE Superfund Information Library, funded by the USEPA, has been established in Tucson to serve as a repository for information about the Tucson International Airport Area Superfund Site. Representatives of government agencies involved with site restoration also can be contacted for current information about activities at the site.

The TCE Superfund Information Library was established in order to facilitate public access to documents about the characterization and cleanup of environmental contamination at the Tucson International Airport Area Superfund Site. The library also provides access to documents from public health agencies and other health studies about the potential effects of TCE and other site-related contaminants. The library provides for the distribution of fact sheets about the affected area. In addition to technical and legal documents, the library also maintains a "Community Relations File" that contains fact sheets, memos, meeting notices, letters, newspaper clippings, and other items regarding the site. Minutes of meetings of the Unified Community Advisory Board (UCAB), which is a panel of local citizens and representatives of various government agencies involved with cleanup efforts at the site are included in the file. Audiotapes of some of the UCAB meetings are available at the library. The library is in Tucson at the El Pueblo Neighborhood Center.

Site-specific documents, including those that were reviewed, summarized, and interpreted for the preparation of this report, generally are available for inspection, copying, or loan at the TCE Superfund Information Library. A shelf list provided by staff of the library is included at the back of this report. In addition to the documents listed, other site-related documents are available on microfilm at the library. The reader is encouraged to contact the staff of the library directly for more information.

TCE Superfund Information Library
101 W. Irvington Road, Bldg. B-2
Tucson, AZ 85714-3099
(520) 889-9194, FAX (520) 741-8818

Several government agencies involved with cleanup efforts at the Tucson International Airport Area Superfund Site provide information about the extent of environmental contamination at the site and the status of cleanup efforts.

United States Environmental Protection Agency, Region 9
Mr. Craig Cooper
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75 Hawthorne Street (Mailcode SFD7-1)
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Air National Guard
Base Environmental Coordinator
162nd Fighter Wing
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Arizona Department of Environmental Quality
Mr. Richard Olm
Arizona Department of Environmental Quality
3033 N. Central Avenue
Phoenix, AZ 85012
(800) 234-5677 (Arizona only)
(602) 207-4130

Physical Setting

The Airport Area Site is in the central part of the Tucson Basin in the Santa Cruz River drainage basin in southeastern Arizona (fig. 1). Tucson Basin is a broad, downfaulted, sediment-filled depression surrounded by mountains. The surrounding mountain ranges are the Santa Catalina Mountains to the north, Tucson Mountains to the west, Rincon Mountains to the east, and Santa Rita Mountains to the south. Maximum elevations range from 6,000 to more than 9,000 ft above sea level. Tucson Basin is 15 to 20 mi wide in the southern and central parts, about 4 mi wide at the northwest outlet, and about 50 mi long. In the central part of the basin, the terrain generally is flat, and the average elevation is 2,600 ft above sea level near the Airport Area Site. The Santa Cruz River and its major tributaries—Rillito Creek and Cañada del Oro—drain the Tucson Basin to the northwest. At present, all major surface drainages in the Tucson area are ephemeral except for reaches where discharge of treated effluent maintains streamflow. The major streams generally are dry more than 300 days each year, and flows that result from precipitation within the basin generally last 3 days or less (Condes de la Torre, 1970, p. 16).

Tucson Basin is in the Sonoran desert, which extends from central Arizona into northwestern Mexico. Long hot summers include an average of 41 days with maximum temperatures exceeding 100°F. Mean annual precipitation is 11 to 12 in. in the central part of Tucson Basin. Mount Lemmon, which is about 20 mi from Tucson, is at an altitude of about 9,200 ft and has more than 30 in./yr of precipitation (Sellers and others, 1985). From July through September, most precipitation in Tucson Basin occurs as intense, localized thunderstorms. From December through March, frontal storms produce widespread precipitation that generally is less intense and of longer duration than summer precipitation.

HYDROGEOLOGIC SETTING

The sediments that fill the Tucson Basin are derived from the weathering and erosion of rocks in surrounding areas. Sediments, such as clay, silt, sand, and gravel, were transported into the basin by streams and then deposited over millions of years in layers of varying thickness and composition. This process of weathering, erosion, transport, and deposition continues to the present with stream sediments being transported into the Tucson Basin. These sediments are derived from the mountains that lie along the perimeter of the basin. Interbedded with some of the deeper, older sediments are rocks of volcanic origin. The volcanic rocks and the deeper, older sediments are unrelated to the mountains that now surround the basin. A generalized geologic section of the basin near Tucson International Airport is shown in figure 3. Anderson (1987) provides a thorough review of the geologic history of the Tucson Basin.

Regional Aquifer, Capillary Fringe, and Unsaturated Zone

The water-bearing materials that make up the regional aquifer consist mainly of unconsolidated to semiconsolidated layered sediments and rocks. These layered sediments and rocks are at least 20,000 ft in thickness in the center of the Tucson Basin and form a single, hydraulically continuous regional-aquifer system. The deposits consist of geologic formations that range in age from middle Tertiary to Quaternary, and deposition occurred from about 35 million years ago to the present (table 1). Information about the lithology and water-bearing properties of the sediments and sedimentary rocks that fill and surround Tucson Basin are given by Davidson (1973).

The main source of recharge to the regional aquifer is streamflow that infiltrates along the major channels. When streams are flowing, water

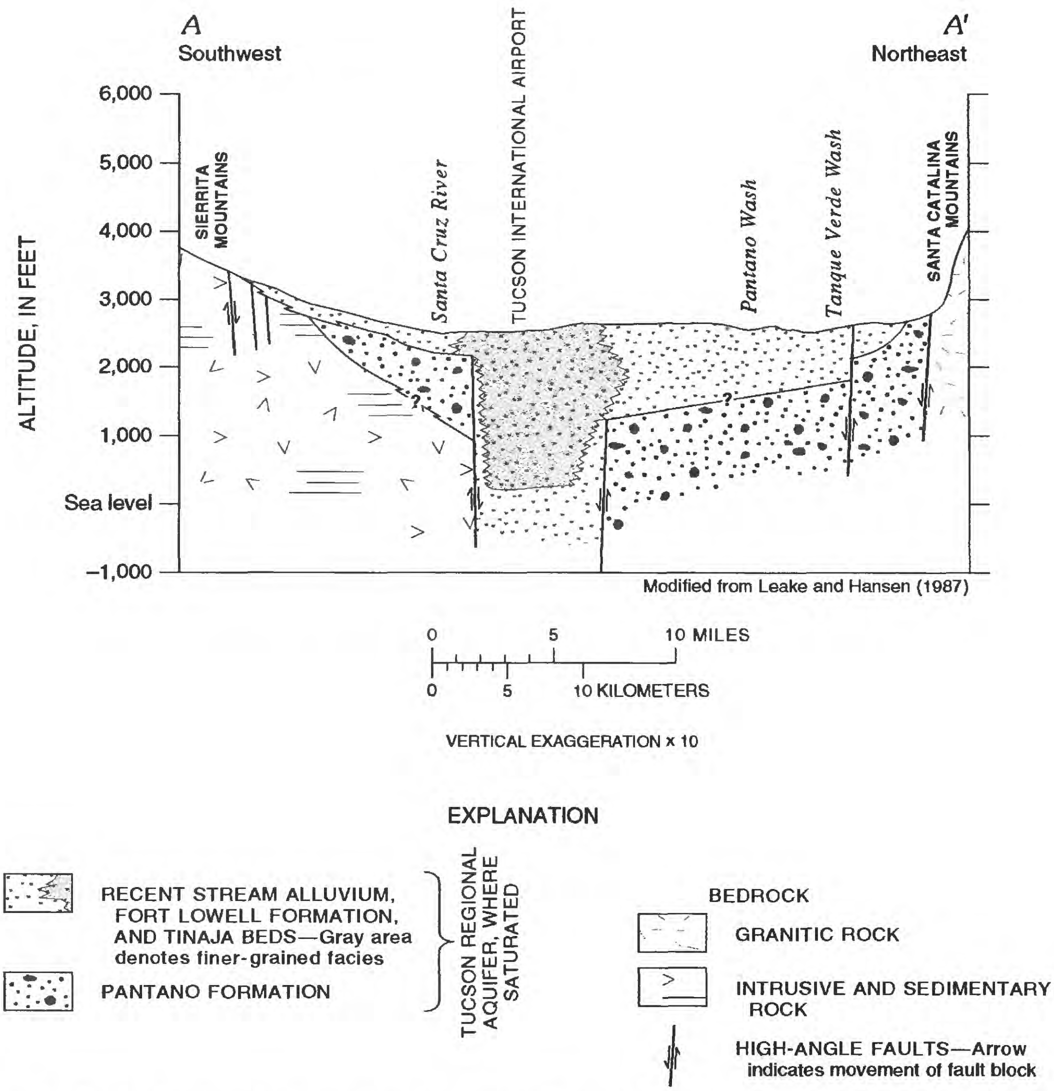

Figure 3. Generalized geologic section of the upper Santa Cruz Basin near the Tucson International Airport Area Superfund Site, Tucson, Arizona.

moves by gravity down through the sediments to recharge the aquifer. Another major source of recharge is water entering the aquifer margins along the mountain fronts as infiltrated water from many small stream channels and directly from cracks in the rocks of the mountains. Another substantial source of recharge to the regional aquifer is derived from the subsurface flow of water into the Tucson Basin from Cañada del Oro and the Santa Cruz River through the permeable deposits that underlie these streams. Other sources include water returned to the aquifer after having been used for public supply, agriculture, mining, or industrial uses.

Sediments and rocks near the land surface are composed of solids and voids. The voids are usually either pore spaces in materials such as sand and gravel or cracks in otherwise solid rocks. Water that fills the voids between sediment particles and cracks in rocks constitutes the ground-water resource (fig. 4).

In Tucson Basin, the main ground-water supply comes from coarse-grained, water-saturated sediments such as sand and gravel.

The levels at which water stands in wells that are completed in the upper part of the water-saturated sediments reveal the location of the water table that delineates the upper boundary

Table 1. Geologic units and components of the Tucson regional-aquifer system and their environmental significance at the Tucson International Airport Area Superfund Site

[Modified from Anderson, 1987]

Era	Geologic age	Stratigraphic units	Components of the Tucson regional-aquifer system and their environmental significance
QUATERNARY	Holocene	Alluvium of the University, Cemetery, and Jaynes terraces Unconformity	*Unsaturated zone*—Water only partially fills the voids between sediment particles. Consists principally of alluvial stream and flood-plain deposits. In many places, sediments of the Fort Lowell Formation constitute part of the unsaturated zone. Beneath and near stream channels, the alluvial deposits may be saturated with water and constitute the capillary fringe and upper part of the regional aquifer. Locally, contaminants originating at the land surface may reside in the unsaturated zone.
	Pleistocene	Fort Lowell Formation Unconformity	
TERTIARY	Pliocene	Upper Tinaja beds Unconformity	*Capillary fringe*—Water held by capillary forces fills the voids between sediment particles immediately above the water table. Thickest where sediments are fine grained and where recharge occurs. Thinnest where sediments are coarse grained or where no recharge occurs. Contaminants trapped in fine-grained sediments in the capillary fringe may be particularly resistant to removal. *Regional aquifer*—Upper limit is the water table. Lower limit and horizontal boundaries are the bottom and edges of the Tucson Basin, respectively, In the central part of the Tucson Basin, the regional aquifer may be subdivided into upper and lower aquifer zones, which are separated by a *confining unit* consisting of clayey silt to sandy clay of the upper Tinaja beds. The confining unit, where present, slows water movement between the upper and lower aquifer zones. The confining unit is present throughout the southeastern part of the Tucson International Airport Area Superfund Site, where suspected sources of TCE contamination are located. In the western to northwestern parts of the Tucson International Airport Area Superfund Site, the aquifer is undivided. Sediments that make up the aquifer become progressively more consolidated with depth. Well yields tend to decrease with increasing depth below land surface; generally only the upper 1,000 feet of the aquifer is used as a water source. At greater depths, water quality is commonly less suitable for potable uses.
	Miocene	Unconformity Middle Tinaja beds Unconformity Lower Tinaja beds Unconformity	
	Oligocene	Pantano Formation Unconformity	
	Eocene and older	Pre-Oligocene igneous, metamorphic, and sedimentary rocks	*Confining unit*—Restricts flow of ground water into or out of the Tucson aquifer.

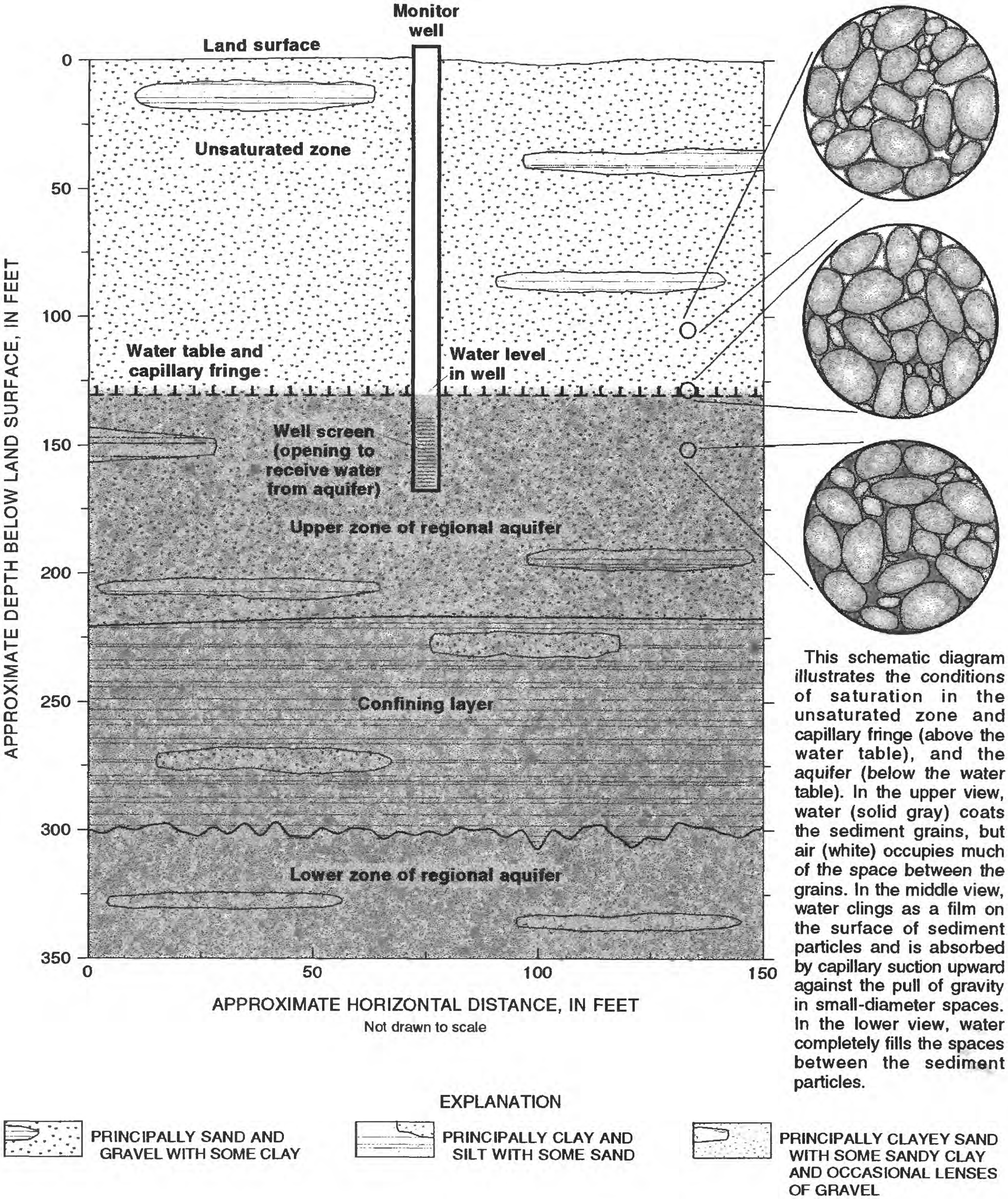

Figure 4. Generalized features of the regional-aquifer system in part of the Tucson International Airport Area Superfund Site. Where the confining layer is absent, the aquifer is not divided into upper and lower zones.

of the aquifer (fig. 4). The shape of the water table generally is similar in configuration to the contours of the land surface except where it has been reshaped by the drawdown effects of water being pumped from wells. The water table also may be temporarily elevated near sources of recharge, such as streams and washes, or other places where water collects on the land surface and percolates down to the aquifer. Aquifer recharge commonly occurs after intense or prolonged periods of precipitation. Fluctuations in the depth to the water table occur seasonally and over shorter time intervals with changes in the quantity and distribution of water that is recharging or being withdrawn from the aquifer.

A water-saturated capillary fringe in which water is held in the sediments by the action of capillary suction of small pore spaces between sediment particles overlies the water table (fig. 4). Capillary suction exerts a strong attraction that counteracts gravity drainage to the water table below. The pore spaces between particles of fine-grained sediments are smaller than those of coarse-grained sediments. As the size of the pore spaces decreases, the force of capillary suction increases. Thus, the capillary fringe generally is thicker in areas where fine-grained sediments overlie the water table. The thickness of the capillary fringe that overlies the regional aquifer varies widely and depends on type of sediments, fluctuations in the altitude of the water table, and occurrence and frequency of local recharge. The capillary fringe is likely to be thickest where the water table is in fine-grained sediments and where frequent or sustained recharge percolates down from the land surface and creates a mound of slow-draining sediments. The capillary fringe is likely to be thinnest where the water table is in coarse-grained sediments and little or no recharge occurs.

Between the capillary fringe and the land surface is the unsaturated zone where some water clings as a film to the surface of rock particles but does not completely saturate the voids between the particles (fig. 4). In Tucson Basin, thickness of the unsaturated zone ranges from less than 25 to more than 700 ft. Deposits in the unsaturated zone are similar to those in the upper zone of the regional aquifer and consist mainly of layers of unconsolidated sand, silt, gravel, clay, and mixtures of these sediments. Caliche (a hard soil layer cemented by calcium carbonate) also is in the unsaturated zone in some locations. The unsaturated zone is thinnest in low-lying areas, particularly where aquifer recharge occurs, such as at the mountain fronts and beneath and near stream channels or other depressions in the land surface where water collects in large quantities or over a prolonged period of time. The unsaturated zone generally is thickest in the southeastern part of Tucson Basin. Throughout most of the Tucson Basin, the thickness of the unsaturated zone exceeds 100 ft. Near the Airport Area Site, the thickness of the unsaturated zone ranges from about 110 to about 140 ft as of 1995.

The air in the void spaces of the unsaturated zone contains water vapor and, where contaminated by industrial activity, may contain VOC's in gaseous form. VOC's in their liquid form also may occupy some of the spaces between particles. The unsaturated zone is important because it is the link between the land surface where contaminants commonly originate and the underlying aquifer. Because the configuration of the water table is continually changing in response to changes in ground-water withdrawals and recharge to the aquifer, the boundaries between aquifer, capillary fringe, and unsaturated zone also are continually changing.

Recharge to the aquifer occurs most readily where the unsaturated zone is thin, such as along major streams, but may occur anywhere that substantial amounts of water are applied or collect naturally on a regular basis. The aquifer is potentially vulnerable to contamination wherever recharge occurs.

Near the Airport Area Site, drainage of runoff that results from precipitation consists of ephemeral streams, drainage channels, and subsurface storm drains. Large amounts of surface flow occur only during and immediately after moderate to heavy rainfall. Surface water leaving the site drains toward the normally dry Santa Cruz River. Surface water may recharge the aquifer in areas where it collects and infiltrates in large quantities such as along the ephemeral streams and unlined sections of drainage channels.

In areas where water recharges the aquifer, pockets of water-saturated or perched sediments may exist within the unsaturated zone. Often this is a temporary condition that occurs after a period of recharge or a sudden lowering of the water table because of water being pumped from nearby wells. Ordinarily, water in the perched layers eventually drains to the aquifer below or is lost to evaporation. The layers of sediment that intercept downward moving water and cause perching to occur may cause the intercepted water to spread laterally beneath recharge areas. Eventually, water leaks down through or around these layers and may recharge a substantial area of the underlying aquifer (U.S. Environmental Protection Agency, 1986, p. 6; Wilson, 1971). In some documents and publications referring to specific parts of the Airport Area Site, the uppermost water-saturated layer of the regional aquifer and overlying capillary fringe has been variously referred to as the perched zone and the shallow ground-water zone.

Although the sediments and sedimentary rocks that fill Tucson Basin are hydraulically interconnected, thus constituting a single regional aquifer, only the upper part of the thick water-saturated sequence is used for water-supply purposes. Well yields tend to decrease with increasing depth below land surface. For practical considerations, such as the cost of drilling wells and the expense of pumping water from great depths, only the upper 1,000 ft or so is utilized as a water source. At greater depths, the sediments that constitute the aquifer become progressively more consolidated and yield less water to wells. Also, the water quality at greater depths is often less suitable for potable uses. The quality of water in the aquifer varies with location and with depth. Wells completed in some sediment types within the aquifer, such as mudstone, generally yield water with large concentrations of constituents such as sulfate and fluoride (Laney, 1972, p. 15). The mountains surrounding the Tucson Basin are composed of various types of bedrock that yield little or no water and are not considered part of the regional aquifer.

The upper layers of the aquifer used for water-supply purposes are composed mainly of sand and gravel and often contain a considerable amount of fine-grained sediments such as silt and clay. Because of the nature of the processes by which these alluvial sediments were deposited in the Tucson Basin, layers rarely are uniform in grain size. Discontinuous layers of silt and clay are common within the aquifer. Lenses of silt and clay often are interbedded with gravel. The sediments vary in the degree to which they are compacted and cemented with depth and location within the basin. Similarly, the layers of sediment vary in their ability to store and transmit water with depth and location within the basin. Locally, such as in the southeastern part of the Airport Area Site, a thick sequence of sediments consisting mainly of discontinuous sandy clay and clayey sand lenses acts as a confining layer that restricts vertical movement of water within the aquifer (fig. 4). Ground water flows through the confining layer as well as through the coarse-grained layers; however, flow through the confining layer occurs at a substantially reduced velocity and flow rate. Where the confining layer is present, the aquifer is considered to be subdivided into upper and lower zones by the confining layer. Where the confining layer is absent, thin, or indistinct, the aquifer is considered to be undivided. In general, the confining layer is in most of the southeastern part of the site (fig. 2).

At the Airport Area Site, the upper zone of the aquifer is about 70 to 100 ft thick and extends from the water table to a depth of 200 to 220 ft below the land surface. The upper zone consists of sand and gravel layers along with thin, discontinuous layers of clayey sediments that transmit water less readily. Where present, in the southeastern part of the site, the confining layer generally is about 100 ft thick. In many documents and publications, including older reports of the USGS, the confining layer is sometimes referred to as an aquitard, aquitard unit, or confining clay. The top of the lower zone of the regional aquifer is beneath the confining layer at a depth of about 300 to 350 ft below land surface. Sediments in the lower zone consist of clayey sand, sandy clay, and occasional thin layers of gravel or sand. The sediments of the lower zone store and transmit water less readily because they contain more clay, are more poorly sorted, and are more heavily cemented than in the upper zone (Davidson, 1973).

Locally, the upper and lower zones of the aquifer, where separated by the confining layer, and the undivided aquifer contain discontinuous fine-grained layers. In general, the aquifer contains more fine-grained sediments in the southeastern part of the site than in the northwestern part. In some parts of the Airport Area Site, the upper zone of the aquifer appears to be further subdivided because of layers of fine-grained sediments; however, these layers are continuous only for short distances. Similarly, the confining layer may contain layers of coarse-grained sediments that are continuous only for short distances. The layered, interlaced nature of the sedimentary deposits of the aquifer, particularly where the confining layer is present, does have a distinct effect on the way water moves through the water-saturated sediments. Horizontal water movement occurs much more readily than vertical water movement.

How Water Moves in the Aquifer

Ground water moves in response to gravity and moves laterally from areas where the water table is high to areas where it is low. Often this is in the direction of the overlying surface drainage such as along streams and washes. Where pumped wells have lowered the water table and created localized depressions, water moves from surrounding areas toward the centers of the depressions. A depression in the water table created by a pumped well is referred to in this report as a drawdown cone (fig. 5).

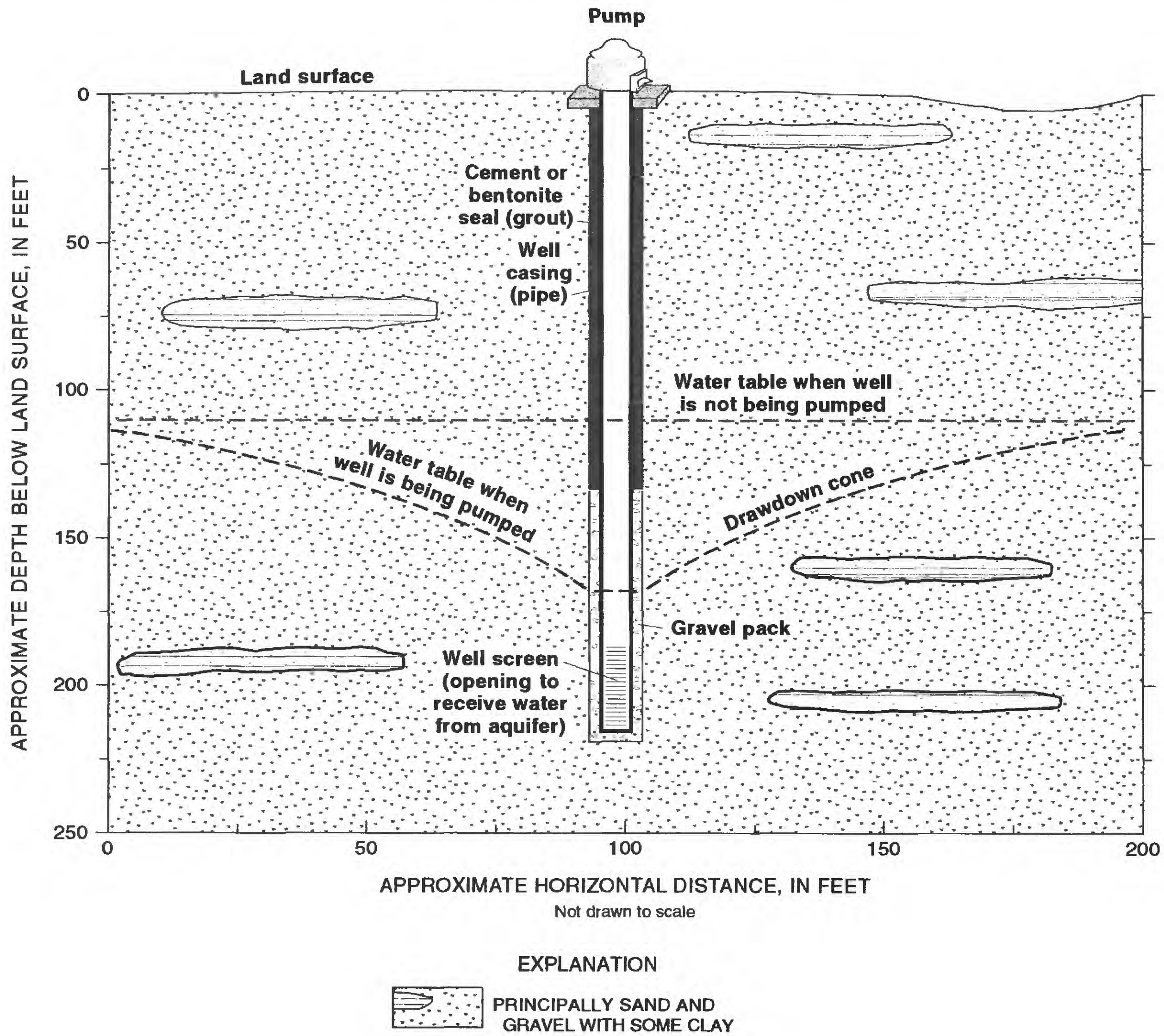

Figure 5. Drawdown cone and general features of a typical extraction well. When water is removed from the aquifer, the water table is lowered and a drawdown cone is created.

Near the Airport Area Site, the water table slopes gently to the northwest except where pumping has created localized drawdown cones or where injection wells that are operated for purposes of cleanup have created recharge mounds. The configuration of the water table in areas where drawdown cones and recharge mounds have been created by cleanup efforts is continually changing in response to changes made to the distribution of water removal and reinjection to the aquifer. Local variations in the direction of ground-water flow are common. South of Los Reales Road, extraction wells that are operated for cleanup purposes have created several steep, and sometimes overlapping drawdown cones (Groundwater Resources Consultants, Inc., 1996, fig. 4). The configuration, depth, and lateral extent of these drawdown cones varies continually with changes in the distribution and withdrawal rates of the extraction wells. North of Los Reales Road, the overall lateral direction of ground-water movement also is toward the northwest (City of Tucson, 1996a, plate 2) except where drawdown cones are created by extraction wells that are operated for cleanup purposes and municipal supply.

Ground water also has a vertical component of flow. If water levels are higher in wells screened in the upper part of the aquifer than in nearby wells screened in a lower part of the aquifer, then there is potential for downward water movement (fig. 6). Conversely, if water levels are lower in wells screened in the upper part of the aquifer than in nearby wells screened in a lower part of the aquifer, then there is potential for upward movement of water. More vertical water movement through the confining layer is likely where the differences in water levels between the upper and lower zones are larger and the fine-grained sediments are absent, thin, or discontinuous. Throughout the Airport Area Site, potential for downward movement of ground water exists in the upper and lower zones of the regional aquifer and in the undivided regional aquifer. Locally, where injection wells are operated for cleanup purposes, upward movement of ground water is possible.

Knowing the magnitude and depth relations of water-level differences for wells screened at different depths and locations allows predictions to be made about the general direction of water movement in the aquifer. The movement of contaminants and the bulk movement of ground water, however, may not necessarily coincide, and this is especially true for chemicals that have a different density than water, such as gasoline or TCE. In concentrated liquid form, gasoline is lighter than water and tends to float on the water surface at the top of the aquifer, although some components of gasoline may dissolve and move with the bulk flow of ground water. TCE in concentrated liquid form, on the other hand, is denser than water and tends to sink through the water column unless other factors, such as entrapment between sediment particles or sorption to sediment particles inhibit downward movement. TCE and other heavier-than-water organic chemicals are often referred to as dense nonaqueous phase liquids (DNAPLs). When heavier-than-water chemicals move down through layered sediments at the Airport Area Site, the liquid contaminant may spread into thin layers immediately above layers of fine-grained sediments. The layers of liquid contaminant may be only a fraction of an inch thick and difficult to detect.

Effect of Aquifer Irregularities on the Movement of Ground Water

An aquifer consisting of materials whose hydrologic properties vary with location is said to be heterogeneous, and all aquifers are heterogeneous to some extent. The aquifer, which consists largely of layers of sand, gravel, silt, clay, and mixtures of these sediments, has a high degree of heterogeneity. Variations in the type of sediments occur vertically and horizontally over short distances. The different sediments have vastly different properties, and these differences affect the movement of water in the aquifer and the behavior of contaminants within the aquifer. The effects occur under natural-flow conditions and during altered-flow conditions created by cleanup efforts. Aquifer properties vary with the direction of water movement. In particular, the volume of water that sediments can transmit in a given length of time is much larger in the horizontal direction than in the vertical direction. This difference in the capacity to transmit water depending on the direction of water movement is typical of unconsolidated alluvial sediments. The effects of heterogeneity are often

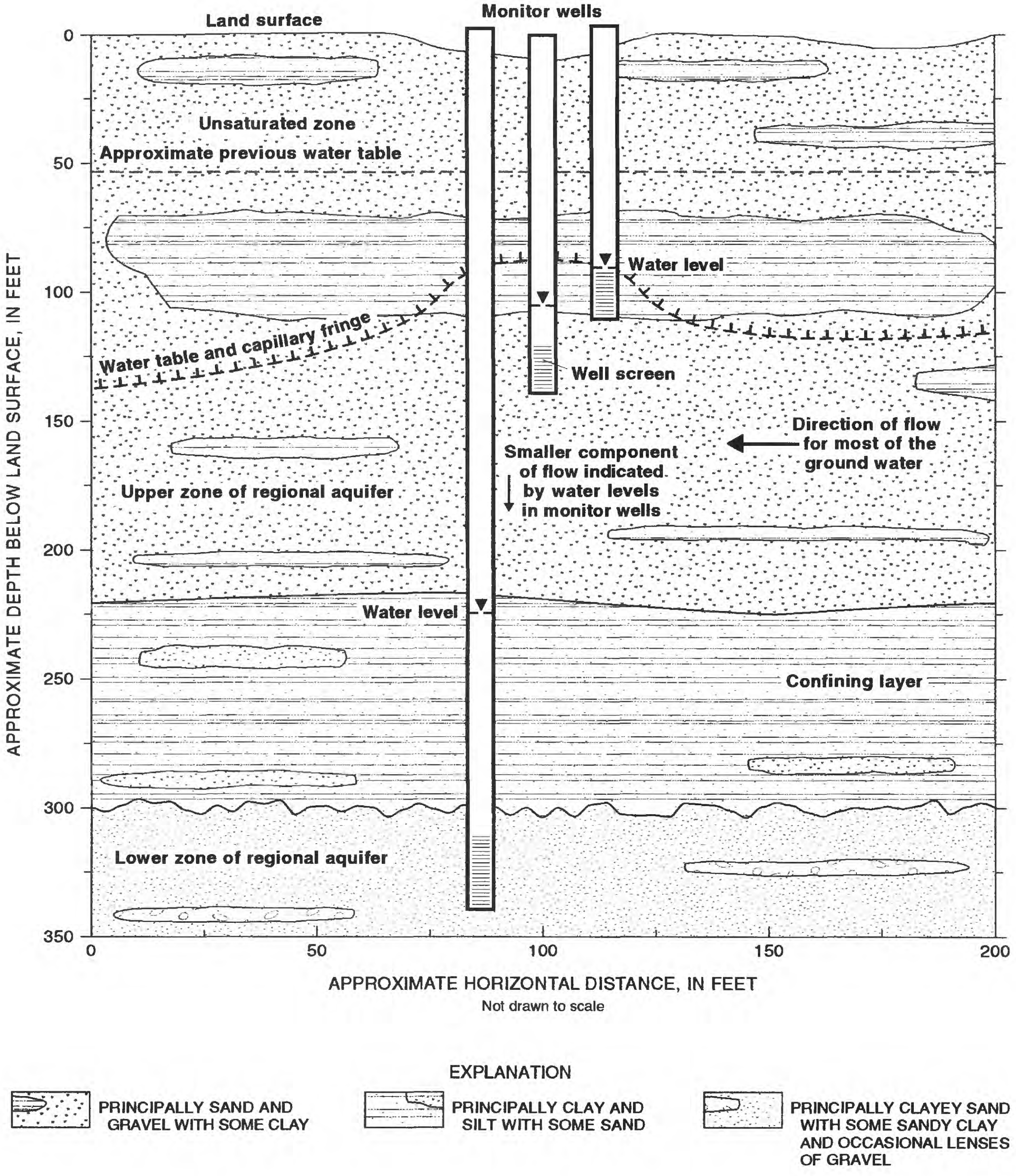

Figure 6. Vertical component of ground-water flow indicated by water levels in monitor wells completed at different depths in the aquifer, Tucson International Airport Area Superfund Site, Tucson, Arizona. Although most ground water moves laterally towards the northwest, some ground water may also move downward.

difficult to predict at the scale of investigations at the Airport Area Site. The effects are hard to predict, in part, because of the difficulty of completely characterizing the highly discontinuous layered sediments in the subsurface in many locations.

BEHAVIOR OF CONTAMINANTS BENEATH THE LAND SURFACE

Potential ground-water contaminants commonly originate at the land surface and move downward to the water table; therefore, developing an understanding of their distribution and behavior above the water table is necessary for understanding the potential threat they pose to the ground water and for identifying appropriate cleanup procedures. The movement and fate of contaminants beneath the land surface is determined, to a large degree, by interactions among the contaminants, air, water, and sediment particles. The interactions may take place in the unsaturated zone, capillary fringe, or aquifer. Contaminants, such as TCE, introduced into the subsurface environment as a component of a waste stream, for example, may volatilize (become a gas) into the air filling the voids in the unsaturated zone, remain undissolved, dissolve in water, or become sorbed to sediment particles. In most instances, all four of these processes will occur, and the movement and fate of the contaminant depends largely on location in the subsurface and degree to which each process occurs. Interaction between contaminants and biological organisms also can play an important role in determining the fate of contaminants beneath the land surface in some instances.

Contaminants, such as TCE and other VOC's found in the subsurface at the Airport Area Site, which have infiltrated from the land surface may be in the aquifer, the capillary fringe, or in the unsaturated zone. The bulk of ground water containing concentrations of VOC's in excess of drinking-water standards is found in the upper zone of the regional aquifer. Near historical disposal areas, large quantities of ground-water contaminants may be in sediments that overlie the water table. Characterization studies so far have detected only VOC's in their gaseous form or dissolved in water; however, these chemicals also may be in their undissolved concentrated form (Brusseau and others, 1996a, p. 1).

Physical and chemical properties of the contaminant, such as volatility, density, and solubility, are important factors in determining if contaminants released at the land surface will reach the water table and subsequently will be distributed by ground-water movement beneath the site of release. Other important factors influencing the movement of contaminants below the land surface include the mineralogy and grain-size distribution of sediments that contaminants are passing through and the amount of contaminants and water percolating through the sediments.

Two major types of contaminants found at the Airport Area Site are VOC's and heavy metals. VOC's found at the site include TCE, DCE, and TCA. Localized occurrences of other organic chemicals, such as 1,2-dichloropropane, methylene chloride, benzene, and chloroform, have been found in ground water near the top of the aquifer during the continuing process of site characterization. Localized occurrences of polychlorinated biphenyls (PCB's), which are a class of organic chemicals having different properties from those of the VOC's, also have been found at the land surface but did not penetrate far into the subsurface or cause ground-water contamination (Daniel B. Stephens and Associates, 1995a). Heavy metals found at the site include lead, cadmium, nickel, and chromium. The two major types of contaminants found at the site have different properties; thus their behavior beneath the land surface is different (fig. 7). VOC's, such as TCE, the principal contaminant of concern, readily change from liquid to vapor at low temperatures. Liquid TCE is 1.5 times heavier than water. The vapor form of TCE is about 4.5 times heavier than air. TCE is only slightly soluble in water. At standard laboratory conditions of temperature and atmospheric pressure, only 1,100 mg of liquid TCE will dissolve in 1 L of water. If more than 1,100 mg of TCE is added to the water, the TCE will remain undissolved and sink to the bottom of the water column. Each of these properties has played an important role in determining the distribution and fate of TCE released into the environment at the Airport Area Site.

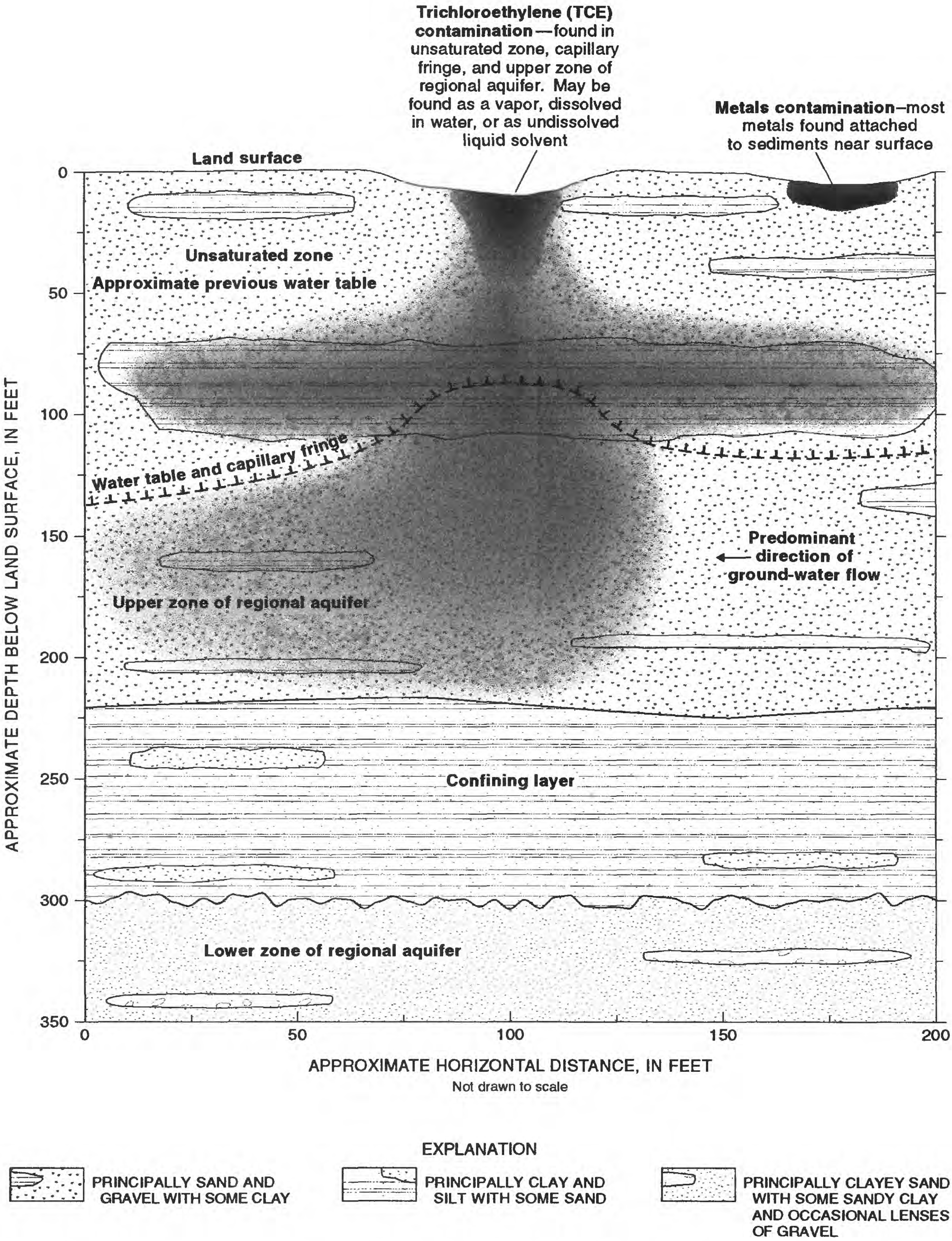

Figure 7. Generalized distribution of trichloroethylene (TCE) and heavy metals beneath the land surface.

Because undissolved TCE is denser than water and the vapor is denser than air, the contaminant tends to move downward through the sediments except where it is entrapped or sorbed to sediments. This characteristic increases the importance of removing contaminants that remains beneath historical disposal areas to avoid continued downward migration to the aquifer.

Probably the most important characteristic of heavy metals released at the site is the strong tendency to sorb to sediment particles. Heavy metals were dissolved in water when released into the environment at the Airport Area Site. The solubility of heavy metals in water depends, in part, on the pH of the water. Generally, heavy metals are more soluble in acidic water. At the pH of native ground water, which ranges from about 7.0 to 8.0 at depths of less than 1,000 ft, most heavy metals tend to become sorbed to soil particles and thus are not very mobile. Heavy metals released at the site tend to be found near the land surface. Historically, acidic wastewater containing heavy metals was released into unlined detention basins at locations south of Tucson International Airport. At these locations, heavy metals mainly are found sorbed to soil particles in the unsaturated zone. Chromium is more mobile than most heavy metals and has been found above and below the water table (Earth Technology Corporation, 1994). Unlike organic contaminants, some of the heavy metals in sediments are natural constituents at varying concentrations. Thus, it is difficult to distinguish between natural and man-made sources.

HOW THE AQUIFER BECAME CONTAMINATED

Many areas have been identified as possible contaminant sites in the southwestern part of the Airport Area Site and in areas immediately north and northeast of Tucson International Airport. Detailed investigations characterized these sites, evaluated the environmental risk, and identified appropriate cleanup procedures. In this report, discussion is limited to a general summary and interpretation of the processes that allowed contaminants to enter the subsurface, to be transported to the underlying aquifer, and to spread in the aquifer to distant areas.

In general, substances that contaminate ground water at the Airport Area Site were used for industrial purposes and were released at or near the land surface. The vulnerability of aquifers to contamination was less understood when the contaminants were released into the environment than at present. In some instances, contaminants may have been dumped directly on the land surface. Contaminants also may have been buried in landfills or released into unlined detention basins, ditches, or washes.

When TCE was initially disposed of near the land surface, much of it volatilized into the atmosphere. TCE that did not volatilize seeped into the unsaturated zone and moved downward to the aquifer. Some of it may have become entrapped between particles of sediment or sorbed to the sediment particles and may remain in the sediments above the water table. Some of it reached the aquifer and remains there either as undissolved TCE or is dissolved in the ground water. Undissolved TCE, if present, is most likely to remain near sites of disposal. The TCE that dissolved in water was distributed as it moved in the direction of ground-water flow. Much of the areal extent of ground-water contamination at the site consists of the TCE that dissolved in water and was slowly distributed in a northwesterly direction (fig. 2). Although there are strong indications of the possible presence of undissolved TCE in the aquifer, there has been no direct confirmation of this to date.

A large portion of the contaminants probably volatilized at the land surface, and some of the liquid contaminant seeped into shallow depths of the unsaturated zone. A large portion of the contaminants that seeped into the unsaturated zone remains in some locations. The likelihood of contaminants percolating through the sediments above the water table to the aquifer is greater where large amounts of liquid contaminant were released, where releases occurred in low-lying areas in which water collects naturally after rainfall, or where a waste stream that had a large volume of water was discharged.

At other locations, contaminants were released as part of an industrial waste stream into unlined detention basins, ditches, or washes at the Airport Area Site. Movement of water from the detention basin, ditch, or wash through the unsaturated zone and capillary fringe to the water table carried dissolved contaminants to the upper zone of the aquifer in some locations (fig. 7). Because the principal contaminants found at the Airport Area Site tend to become entrapped or sorbed to sediment particles, much of the contamination may reside in the sediments that overlie the aquifer, especially in locations where fine-grained sediments overlie the aquifer or where the volume of water available to transport the contaminants to the underlying aquifer was limited. Where fine-grained sediments are above the aquifer in areas where recharge occurs, a thick capillary fringe or recharge mound is likely. Areas where contaminants have been found in fine-grained sediments near the top of the upper zone of the regional aquifer have been identified on the west and south sides of Tucson International Airport (Daniel B. Stephens and Associates, Inc., 1995a; Hargis and Associates, Inc., 1996). In these areas, the water table historically was higher than at present, and contaminants may have diffused into the fine-grained sediments in a greater thickness than is presently saturated. Removal of residual organic contaminants from the fine-grained layer in these areas probably is difficult because of the high water-retention ability and slow drainage of the clay and clayey-sand sediments. Two basic sediment properties—porosity and permeability—are responsible for much of the difficulty associated with cleanup of these areas. The porosity of deposits of unconsolidated sediments is simply its property of having openings (void spaces) between the rock particles that make up the sediment. The porosity of deposits of unconsolidated sediments depends on the range in grain size (degree of sorting) and on the shape of the rock particles but not on their size. Fine-grained sediments tend to be better sorted and, thus, tend to have the largest porosities. The permeability of a deposit of unconsolidated sediment is a measure of its ability to transmit fluid, such as water or air. Permeability is not only different in different types of deposits of unconsolidated sediment but also may be different from place to place in the same layer of unconsolidated sediment. The ability to transmit fluids also is commonly different in different directions. Deposits of unconsolidated sediments transmit fluids more readily in the horizontal direction than in the vertical direction (Heath, 1983, p. 13). Some of the contaminated sediments in the areas on the west and south sides of Tucson International Airport have high porosity and can retain a large amount of water. Low permeability to water and air make it difficult to remove contaminants from sediments by passing water or air through them.

Where recharge occurs, dissolved constituents and liquid contaminants may flow along distinct pathways, rather than as a uniform wetting front that pushes out water previously stored in the spaces between the sediment particles. Preferential or bypass flow allows contaminants that originate at the land surface to move more quickly through the unsaturated zone to the water table than would occur if flow was uniform. Bypass flow may have been the process by which chemicals released at the Airport Area Site penetrated a fairly thick unsaturated zone and contaminated the upper part of the regional aquifer.

When TCE and other VOC's were initially released into the environment at the Airport Area Site, the water table was higher than in 1995. Contaminants moved through the unsaturated zone and spread through the sediments at the top of the aquifer. As the water table declined in response to removal of water from the aquifer, contaminants may have been left behind in fine-grained sediments in the unsaturated zone and capillary fringe. Contaminants remaining in these sediments may be largely bypassed by recharge water moving along preferential pathways. Most of the water and contaminants that remain in the fine-grained sediments above the water table does not mix with recharge water when preferential flow prevails. Recharge water bypasses much of the sediments and the fluids contained in the sediments. Recharge through parts of the unsaturated zone and capillary fringe may allow a minor amount of a soluble contaminant to wash into the underlying aquifer. Recharge is sporadic at the Airport Area Site because of intermittent precipitation. Preferential flow, therefore, may create the possibility of continued, long-term recontamination of the aquifer by intermittent recharge if contaminants remain in the sediments overlying the water table in stream channels and washes. Preferential flow in the unsaturated zone is difficult to predict and detect in field situations. Stratification (layering), especially where fine-grained layers overlie coarse-grained layers, and high rates of water application are factors that may cause preferential flow in the unsaturated zone (Graham, 1989, p. 21).

The tendency of organic chemicals, such as TCE, to adhere to sediments slows but does not completely prevent the eventual movement of contaminants through the unsaturated zone to the aquifer. The entrapment and sorption of TCE to the sediments is not a one-way process. As more water flows through the sediments, TCE adhering to the sediments is slowly released. Near disposal areas, recharge water passing through the sediments above the water table could dissolve and transport enough TCE to cause continued contamination of the aquifer because even small amounts of TCE dissolved in water can cause ground-water contamination above the MCL (5 μg/L). Studies have been initiated to characterize and quantify interactions between TCE and the sediments found at the Airport Area Site (Brusseau and others, 1996a). Because TCE in vapor form is denser than air, downward movement through unsaturated sediments above the water table also may contribute to ground-water contamination near disposal areas.

In general, most metals released as part of an industrial waste stream at the Airport Area Site were immobilized at shallow depths in the unsaturated zone and did not cause ground-water contamination. Chromium, however, is more mobile than other metals released at the Airport Area Site, and wastewater containing dissolved chromium in the form of hexavalent chromium may have been recharged to the aquifer in a limited area (Groundwater Resources Consultants, 1996, fig. 12).

CONDITIONS AS OF 1995

Cleanup efforts have focused largely on containing ground water contaminated with TCE, removal of TCE from ground water, and removal of TCE from sediments above the water table near historical disposal sites. Other VOC's are in ground water in lesser quantities, and their removal occurs concurrently with the removal of TCE. Hexavalent chromium, another contaminant of concern in ground water, was found to be localized, and cleanup efforts have been successful at bringing concentrations of chromium in ground water to less than the MCL (100 μg/L; Groundwater Resources Consultants, 1996, p. 19).

Distribution of Trichloroethylene (TCE) in Ground Water

Data provided by industries and government agencies involved with the monitoring and cleanup efforts at the Airport Area Site were used to create a unified geographic-information system (GIS) data base, which utilizes ARC/INFO software. Information stored in this data base includes well identifiers, concentrations of TCE, dates of sampling, and geographic locations.

The GIS system was used to plot data for TCE so that the approximate limits of ground-water contamination as of December 1995 could be delineated (fig. 2). South of Los Reales Road, data from wells in the upper zone of the regional aquifer, including wells completed in the fine-grained unit near the top of the aquifer, were used to delineate the area where concentrations of TCE in ground water exceeded the MCL (5 μg/L) as of 1995. North of Los Reales Road, some of the data are from wells completed in the upper part of the undivided aquifer. In instances where data for December 1995 were not available for a well in the data base, the most recent data collected prior to December 1995 were used as supplemental control for delineating the areas of contaminated ground water. Within the area delineated as having concentrations of TCE larger than 5 μg/L, a few wells yield water with no detectable TCE, and other wells yield water with concentrations of TCE less than 5 μg/L. The highly variable distribution of TCE in the aquifer may be largely a result of aquifer heterogeneity. In some instances, samples from wells that are close together have widely different concentrations of TCE. In these instances, wells having larger concentrations were favored in the delineation process.

The areas of contaminated ground water for 1995 were delineated using the MCL (5 μg/L) for TCE, as was done in 1984 by Leake and Hanson (1987). As of December 1995, the largest area of contamination was about 35,500 ft long and about 3,900 to 4,700 ft wide. On the basis of concentrations of TCE in samples from wells that were included in the data base, the main area of contamination near Tucson International Airport (fig. 2) is similar in overall shape to the area of contamination delineated in 1984 (Leake and Hanson, 1987, fig. 2). South of the airport, some reduction in the apparent areal extent of contamination has occurred since 1984 although large concentrations of TCE are still in the water discharged from some wells. Two small separate areas of ground-water contamination north and northeast of Tucson International Airport also are present on the basis of data for 1995. The data for 1995 indicate that the area of contamination immediately north of the airport is larger than was indicated by the data in 1984. The apparent increase in size may be largely the result of additional wells having been installed to better define the area of contaminated ground water. The area of contamination immediately northeast of the airport is similar to the area shown by Leake and Hanson (1987).

The largest reported concentration of TCE in samples of ground water taken from wells included in the data base for December 1995 was 5,600 μg/L from a well south of Tucson International Airport. More detailed maps of concentrations of TCE in ground water for the area south and west of Tucson International Airport are shown by Groundwater Resources Consultants (1996, figs. 9 and 15). Maps of concentrations of TCE shown in Groundwater Resources Consultants (1996, figs. 8 and 9) indicate considerable reduction in concentrations of TCE in the discharge of many of the wells in this area since cleanup efforts began in 1987. Some of the minor differences between the map of concentrations of TCE in ground water from the upper zone of the regional aquifer shown by Groundwater Resources Consultants (1996) and figure 2 in this report may be a result of inclusion in figure 2 of concentration data for wells completed in the uppermost part of the regional aquifer. These data are shown on a separate map of concentrations of TCE in a unit of the aquifer designated as the "shallow ground-water zone" by Groundwater Resources Consultants (1996).

Characterization studies indicate concentrations of TCE of as much as 74,000 μg/L in ground water in the uppermost part of the aquifer in an area on the west side of Tucson International Airport, immediately north of Los Reales Road (Daniel B. Stephens and Associates, Inc., 1995a, b). To date, ground-water cleanup efforts have not been initiated at this location. This area, thus, has the largest concentrations of TCE in ground water as of 1995. Concentrations this large are a strong indication of undissolved TCE that is acting as a continuing source of ground-water contamination.

Limitations of Map Showing Distribution of Trichloroethylene (TCE) in Ground Water

Where the regional aquifer is divided at the Airport Area Site, TCE in ground water is found mainly in the upper zone of the aquifer. Where the confining layer is absent, TCE in ground water is found mainly in the upper part of the undivided regional aquifer. Where detailed vertical sampling for TCE in ground water has been done, concentrations of TCE are found to be distributed unevenly throughout the upper part of the aquifer. Nonuniform vertical distribution of concentrations of TCE in ground water probably is common throughout much of the site; thus, plumes of contaminated ground water are distinctly three dimensional. Concentrations of TCE vary vertically as well as horizontally. Because of the nonuniform vertical distribution of contaminants in the aquifer, concentrations of TCE within the aquifer cannot be accurately portrayed with an ordinary map, which shows only the horizontal distribution of TCE on the basis of the distribution and construction of wells sampled. Vertical variations in TCE are not shown because different sampling procedures or wells that draw water from isolated vertical intervals are needed to accurately define them.

The representativeness of data for TCE used to construct the map portraying the distribution of wells that yield contaminated ground water has limitations related to methods of sample collection. One such limitation is caused by characteristics of wells from which samples are collected. The length of well casing that is perforated or slotted to receive water from the aquifer is referred to as the screened interval (fig. 5). The length and placement of the screened interval affects the contaminant concentration in a sample when a well is in an area where there is a nonuniform vertical distribution of the contaminant. Unless special measures are taken to restrict the water entering a well, the water brought to the surface by the well pump is a composite of water that enters the well in different zones within the screened interval. If the screened interval spans zones of the aquifer containing highly contaminated water and zones containing less contaminated water, for example, the concentration of the contaminant in the discharge of the well will have an intermediate value. Also, because the flow of water into a well along the length of the screened interval may not be uniform especially where the aquifer consists of a mix of fine-grained and coarse-grained sediments, much of the water that enters a well may be coming from short intervals along the length of the screened interval. These short intervals may not span zones where the concentrations of TCE are representative of the entire screened interval. The vertical distribution of concentrations of TCE is not uniform at some places at the Airport Area Site, and often the largest concentrations are found in association with fine-grained sediments near the top and bottom of the zone in which wells are completed (Brusseau and others, 1996a, p. 1). Data are not representative of the differences that exist along the length of the screened interval in these instances.

Often, when a hole has been drilled to construct a well, the annular space surrounding the screened interval of a well is backfilled with a clean, well-sorted, coarse-grained sediment that creates a gravel pack (fig. 5). This well-construction practice was used for many of the wells at the Airport Area Site. Unfortunately, because some wells have a long screened interval, water may migrate readily from one depth to another through the gravel pack so that water samples taken from the well may not always represent a particular depth in the aquifer.

Many of the extraction wells and some of the monitor wells sampled at the Airport Area Site are screened and gravel packed over intervals that may be too long for one value of contaminant concentration to be representative particularly near disposal sites where large vertical variations in contaminant concentration are likely to occur. Unfortunately, information on the vertical distribution of contaminants throughout the site is insufficient for a three-dimensional portrayal of the plumes of contaminated ground water.

In some cases, methods and circumstances of sampling may have an influence on the concentrations of contaminants in water samples from wells at the Airport Area Site because of the nonuniform distribution of contaminants in the subsurface and other factors. Preliminary results of studies being done at the site (Brusseau and others, 1996a, b) suggest that discharge rate of the sampling pump, length of time that the well has been pumped or shut down before a sample is taken, and proximity of the sampled well to other extraction or injection wells are among the factors that can influence the representativeness of samples taken from a well. The influence of factors such as these on the representativeness of data for the Airport Area Site probably is greatest on samples taken from wells that are close to historical disposal areas because of the nonuniform distribution of the dissolved contaminant in the subsurface in these areas, the possibility of undissolved TCE remaining in the subsurface, and slow desorption and dispersal of the contaminant from fine-grained sediments.

In constructing a map that depicts the distribution of a dissolved contaminant in an aquifer, concentration values for locations between data points are assumed to be intermediate between those of the data points. This assumption may not be valid throughout the Airport Area Site because of highly irregular vertical and horizontal distribution of concentrations caused by aquifer heterogeneity and other factors. The spacing and screen lengths of wells from which samples are taken may not always be suitable to characterize the irregularity of contaminant distribution throughout the boundaries of the site. For these reasons, the boundaries that delineate areas of contamination (fig. 2) should be regarded as highly generalized. Within the delineated areas, some wells yield water that is uncontaminated or has concentrations of TCE below 5 μg/L.

CLEANUP EFFORTS

In recent years, much effort and expense have been directed to minimizing the adverse environmental consequences of historical disposal practices and cleaning up ground-water contamination at the Airport Area Site. Permanent aquifer restoration requires that contaminants be removed from the sediments above the water table as well as from the aquifer. Major cleanup efforts initiated at the Airport Area Site include the following activities:

- Characterization studies to identify potential sources of contamination and facilitate selection of appropriate cleanup procedures.
- Construction and use of a facility for treating water from municipal wells north and west of Tucson International Airport where concentrations of VOC's in water generally are small.
- Construction and operation of a network of extraction and recharge wells along with a large-scale treatment facility for the part of the site south of Los Reales Road where large concentrations of VOC's in ground water are found in some locations.
- Removal of VOC's from sediments above the water table near disposal areas.
- Excavation and disposal of soils contaminated with heavy metals and removal of hexavalent chromium from ground water.

In general, VOC's that are dissolved in ground water are removed by extracting water from the aquifer and aerating it to allow the VOC's to escape into the air. VOC's then are recaptured by passing the air through an absorbing material such as activated carbon. Chromium dissolved in ground water is removed by extracting water from the aquifer and passing it through ion-exchange columns. Removal of VOC's from the capillary fringe and the upper part of the aquifer is being attempted by using a combination of techniques that include extraction of contaminated water and air and possibly the addition of substances to encourage biological activity that degrades the VOC's into harmless compounds such as carbon dioxide. Removal of VOC's from the unsaturated zone is accomplished by pumping out air containing VOC's in the vapor phase. Heavy metals are removed from the land surface by excavation.

Characterization Studies

Characterization studies are done at locations throughout the Airport Area Site to understand the distribution and behavior of contaminants and to identify cleanup procedures. Documents containing information obtained from completed and ongoing characterization studies for many specific locations within the site boundaries are listed at the back of this report. Many studies have been initiated throughout the site to gain information about sources of ground-water contamination resulting from historical disposal practices, to assist in the selection of cleanup procedures, and to evaluate changes after implementation. Results of many of these studies have been reviewed, interpreted, and generalized in the preparation of this report.

Removal of Volatile Organic Compounds (VOC's) from Ground Water

A water-treatment facility—Tucson Airport Remediation Project (TARP)—was completed in 1994 and began treatment of water from extraction wells near the north end of the main area of ground-water contamination (fig. 2). In this part of the site, ground water contains low concentrations of dissolved TCE and other VOC's. Water is pumped from the aquifer and VOC's are removed from the ground water at the treatment facility. This type of cleanup activity is often referred to as pump and treat. Treatment of ground water supplied by nine extraction wells consists of passing the water through air-stripping towers where VOC's are removed from the water and then recaptured by passing the air stream containing the vapors through canisters of activated carbon or other suitable materials. After treatment, water from the facility is distributed for public supply. On the basis of community concerns about the capability of the treatment facility to provide drinking water to residents, USEPA established a 1.5 μg/L standard for concentrations of TCE in the treated water. Samples are collected weekly and analyzed for VOC's. Additional samples are collected monthly by USEPA personnel and members of the local community during unannounced inspections and analyzed for quality-assurance purposes. As of July 1996 and after about 2 years of operation of the facility, all samples have met drinking-water standards. Except for two samples, concentrations of TCE have been below the detection level (0.5 μg/L). These two samples had concentrations of TCE of 0.6 and 1.1 μg/L, respectively (City of Tucson, 1996b). The extraction wells that provide water to the treatment facility were placed to keep water that has been contaminated with TCE from spreading farther to the northwest where municipal-supply wells currently yield water with no detectable concentrations of TCE.

South of Los Reales Road, a network of extraction and recharge wells and a ground-water treatment facility were put into operation in 1987 (fig. 2) to contain the spread of the contaminant plume and treat contaminated ground water. A network of 24 wells is used to extract contaminated ground water, which is then processed at the treatment facility and recharged to the aquifer through a network of 19 injection wells at the periphery of the southeastern part of the contaminant plume. By the end of 1995, the total volume of water treated at the facility was about 13.4 billion gallons, including 12.7 billion gallons of water removed from the upper zone of the regional aquifer, and 711 million gallons of ground water removed from the lower zone of the regional aquifer. An estimated 17,000 pounds of VOC's, mainly TCE, have been removed from ground water at the facility. About 13.2 billion gallons of treated ground water was recharged to the regional aquifer by the end of 1995 (Groundwater Resources Consultants, 1996, p. 6).

Ongoing or recently completed characterization and remedial investigations are being used to formulate cleanup strategies for other areas of environmental contamination within the boundaries of the Airport Area Site. Treatment systems for removing dissolved VOC's from ground water, which are similar to but less extensive than the system that is in use south of Los Reales Road, also are being used to clean up two smaller areas of ground-water contamination immediately north and northeast of Tucson International Airport (ERM-West, 1996; EMCON, 1996).

Removal of Volatile Organic Compounds (VOC's) from the Capillary Fringe and Unsaturated Zone

South of Tucson International Airport, VOC's are being removed from the unsaturated zone and capillary fringe in conjunction with removal of VOC's from the underlying aquifer. In August 1994, cleanup of several areas south of Los Reales Road that were contaminated with TCE and other solvents was initiated using a dual-phase extraction (DPE) system, which is an enhancement to the existing pump-and-treat system. The DPE system is to simultaneously remove dissolved VOC's from ground water and VOC's as vapors from overlying sediments (fig. 8). The system is to be used with existing wells in some locations and with wells that are planned in other locations. The DPE system has been connected to several wells screened in the upper zone of the aquifer that are part of the pump-and-treat system in use south of Los Reales Road (Groundwater Resources Consultants, Inc., 1996). Ground water is extracted from the well and sent to the ground-water treatment facility for removal of VOC's, and at the same time, soil vapor is removed from the unsaturated zone near the well and directed through on-site canisters of granular activated carbon for removal of VOC's. A blower is used to create a vacuum in the well pipe for removal of soil vapor. Soil vapor is extracted through openings in the well screen that are above the water table in the drawdown cone that is created when water is extracted from the well.

The DPE system has been used to remove large quantities of the VOC's from the subsurface of parts of the Airport Area Site. VOC's have been removed from the unsaturated zone at rates that average as high as 30.6 lbs/hr using the DPE system. In one well where the system was used, a maximum monthly rate of VOC removal of about 6,000 lbs was achieved. By the end of 1995, about 29,000 lbs of VOC's, mainly TCE, were removed from the unsaturated zone south of Tucson International Airport using the DPE system (Groundwater Resources Consultants, Inc., Appendix I). Thus, in less than 2 years of operation, more VOC's were removed from the subsurface with the DPE system than have been removed from ground water with the pump-and-treat system in 8 years of operation. The DPE system, however, is mainly of use where large amounts of VOC's remain in sediments above the water table near historical disposal areas.

On the basis of a recent remedial investigation (Daniel B. Stephens and Associates, Inc., 1995b), a plan is being formulated for cleanup of the uppermost part of the regional aquifer and overlying sediments in an area immediately north of Los Reales Road and west of Tucson

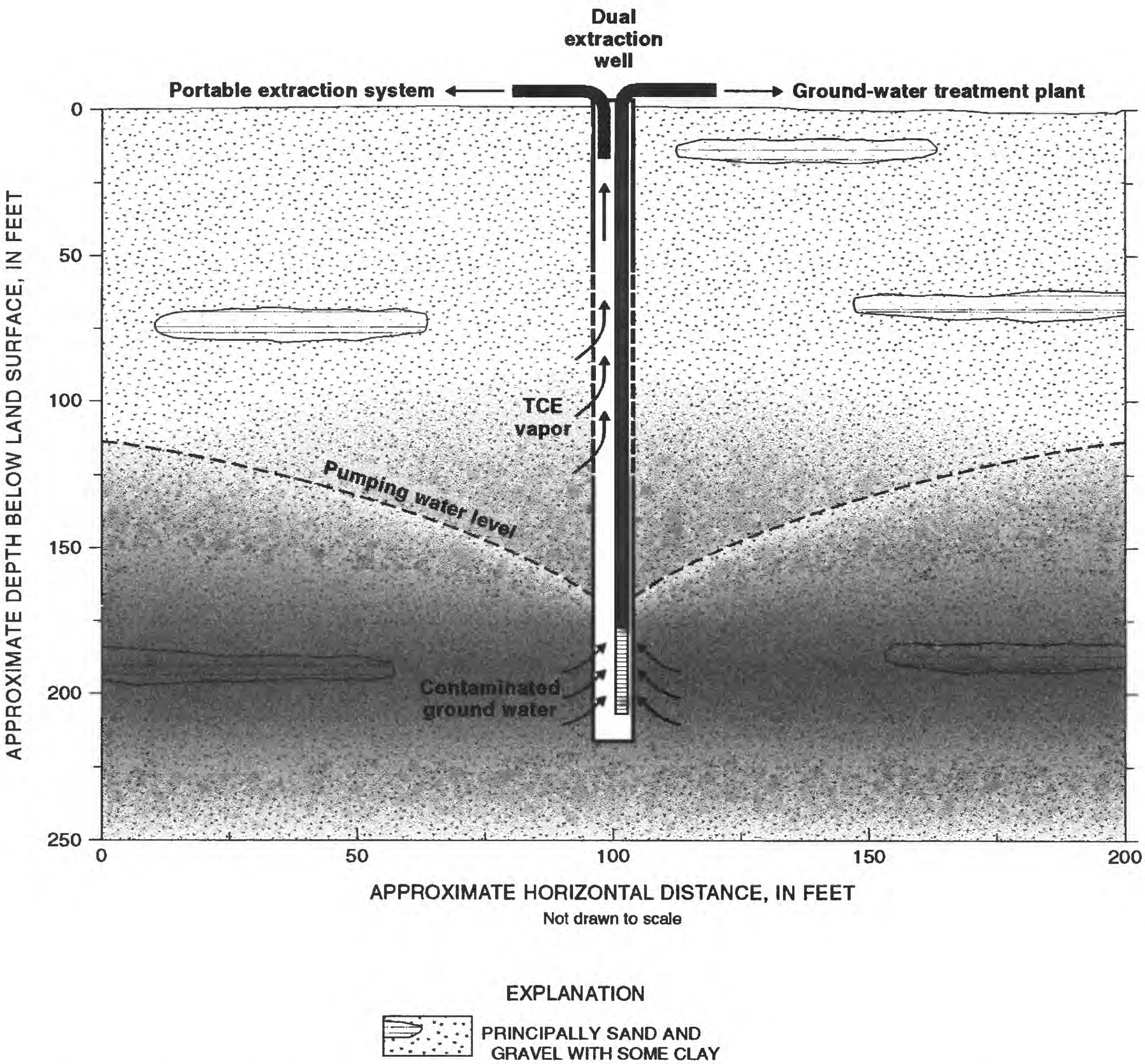

Figure 8. Features of the dual-phase extraction (DPE) system for simultaneous removal of volatile organic compounds in the vapor phase from the unsaturated zone and contaminated ground water from the aquifer.

International Airport (Conestoga-Rovers and Associates, 1996). In this area, concentrations of TCE as large as 74,000 μg/L and smaller concentrations of other VOC's have been found in a fine-grained layer of sediment at the top of the upper zone of the regional aquifer. The large concentrations of TCE in ground water suggest the possibility of undissolved TCE at this location. In addition to the pump-and-treat technique and soil-vapor extraction (SVE), the use of techniques designed to enhance biological activity to degrade the VOC's is being explored to clean up this area.

TCE and other VOC's in vapor form are being removed from the unsaturated zone by means of SVE. Air containing VOC's in the vapor phase is being pumped from hundreds of shallow wells completed in the unsaturated zone near disposal areas. At each well site, contaminants are removed by passing the evacuated air stream through canisters containing absorbing material such as activated carbon.

Removal of Heavy Metals from the Unsaturated Zone and Hexavalent Chromium from Ground Water

In historical disposal areas south of Tucson International Airport, the upper few feet of soil in the unsaturated zone was contaminated with heavy metals. These areas are not considered to pose a threat to ground-water quality. Cleanup procedures, however, were initiated because soil that contains large concentrations of heavy metals could be dispersed by wind. In areas south of Tucson International Airport, contaminated soil is removed by excavation of the affected areas. As of March 1996, 36,600 tons of contaminated soil have been excavated and shipped by rail to an out-of-state disposal facility. This amount is estimated to represent about 40 percent of the total volume of soils to be removed (U.S. Air Force, 1996, p. 2).

Ground water removed from some areas of the upper zone of the aquifer south of Los Reales Road also has been treated for removal of hexavalent chromium at the facility south of Tucson International Airport. An ion-exchange system at the facility was used to remove chromium from ground water. The ion-exchange system was deactivated in November 1994 when concentrations of chromium in water from all extraction wells were determined to be less than 100 µg/L (Groundwater Resources Consultants, Inc., 1996, p. 3).

POTENTIAL LIMITATIONS FOR AQUIFER RESTORATION

Although the apparent size of the area of ground water contaminated with TCE at the Airport Area Site has not increased since delineated by Leake and Hanson (1987), concentrations of TCE in the discharge of many wells have declined. A reduction in the rate of decline of concentrations of TCE in ground water and an increase in concentrations of TCE when wells are shut off, however, indicate that aquifer restoration may be more difficult and time-consuming than anticipated. Several factors have been identified that limit the effectiveness of cleanup efforts.

Historical disposal practices led to situations where solvents or wastewater containing solvents seeped into the ground and slowly diffused into or sorbed to fine-grained and coarse-grained sediments in the unsaturated zone, capillary fringe, and upper zone of the aquifer (fig. 7). Below the water table, slow dispersal of TCE from fine-grained sediments may hinder aquifer restoration. Complete removal of contaminants from the aquifer is complicated by differences in the rates of water movement in mixed sediments having different hydraulic properties and by the tendency of TCE and similar organic solvents to sorb, reversibly, to the sediment particles or become entrapped between sediment particles in the form of globules of undissolved compound. Complete and permanent restoration of the aquifer also is complicated by the possibility that residual contaminants in sediments overlying the aquifer may act as sources of recontamination. Complete removal of VOC's from sediments overlying the aquifer may be hindered by the low air permeability of fine-grained sediments in some areas.

Tailing

Concentrations of TCE in water from the extraction-well network entering the treatment facility south of the airport showed a rapid decline, from slightly more than 300 µg/L in late 1987, when operation commenced, to about 100 µg/L in late 1990. Since that time, however, average monthly concentrations of TCE from the extraction-well network have declined only slightly even though hundreds-to-thousands of pounds of TCE continue to be removed from the aquifer and overlying sediments each month. The trend of concentration decline for DCE, another VOC found at the site, is similar (fig. 9). A similar leveling of concentrations of TCE and DCE in an individual monitor well was measured during a short-term tracer experiment near the ground-water treatment facility (Brusseau and others, 1996a). A leveling off in the rate of decline of contaminant concentrations is called tailing. Tailing may indicate that sources of these contaminants are continuing to become dissolved in ground water or that removal is being limited by other factors.

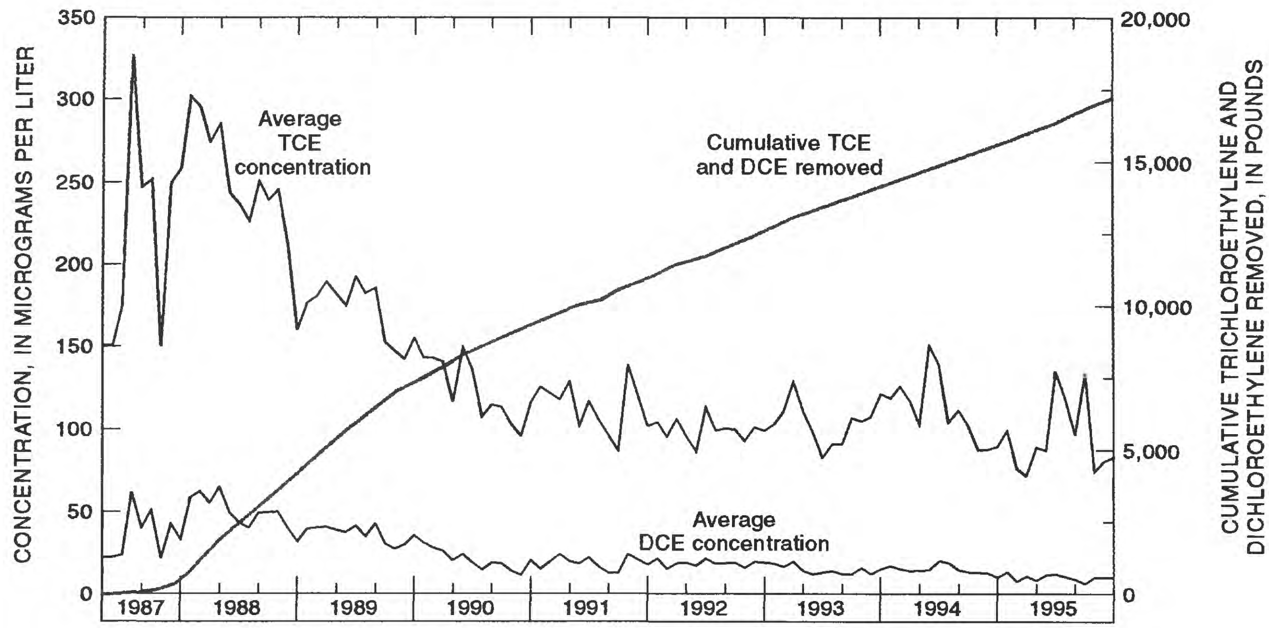

Figure 9. Concentrations of trichloroethylene (TCE) and dichloroethylene (DCE) entering the ground-water treatment facility south of Tucson International Airport and cumulative amounts of TCE and DCE removed. (Graph supplied by Hughes Missile Systems Company, Tucson, Arizona.)

Rebound

Tracer experiments were done near the ground-water treatment facility south of Tucson International Airport (Brusseau and others, 1996a). As a component of these studies, an extraction well was operated for 61 days then shut off for 20 days. Samples of ground water were taken over the 81-day period from the extraction well and from a newly installed multilevel monitor well 12 ft away. The monitor well was directly between the extraction well and an injection well. Concentrations of TCE in samples taken from the monitor well declined when the extraction well was operating. Soon after the well was shut off, however, concentrations began to rebound (fig. 10).

Brusseau and others (1996a, b) observed that concentrations of TCE in water samples from a depth of 140 ft below land surface in the monitor well increased from an initial concentration of 2,029 to about 3,600 μg/L. Concentrations of TCE in water samples from the monitor well gradually declined to less than 100 μg/L after 61 days of pumping. When the extraction well was shut off, concentrations of TCE in water samples began to increase significantly. Concentrations of TCE in water samples from a depth of 140 ft increased from about 100 μg/L when pumping ceased to 3,493 μg/L 20 days later. Concentrations of TCE in water samples taken from a depth of 156 ft below land surface in the same monitor well followed a similar pattern (Brusseau and others, 1996b, fig. 7.3–2). In samples taken from the discharge of the extraction well, concentrations declined rapidly in the first 2 days of operation, then remained constant for the remainder of the 61-day pumping period. When the pump was restarted 20 days later, a water sample was taken, and rebound was not indicated. Rebound may not be noticeable at the extraction well because sampling is done at a higher discharge rate than at the monitor well. At the higher discharge rate, most of the water entering the well may be coming from less contaminated, coarse-grained sediments. Alternatively, rebound may not be observed at rapid pumping rates because TCE is desorbing slowly from the sediment particles. These and other factors may be influencing the rebound behavior and may hinder efficient removal of contaminants from the aquifer. Other aspects of the characterization studies that

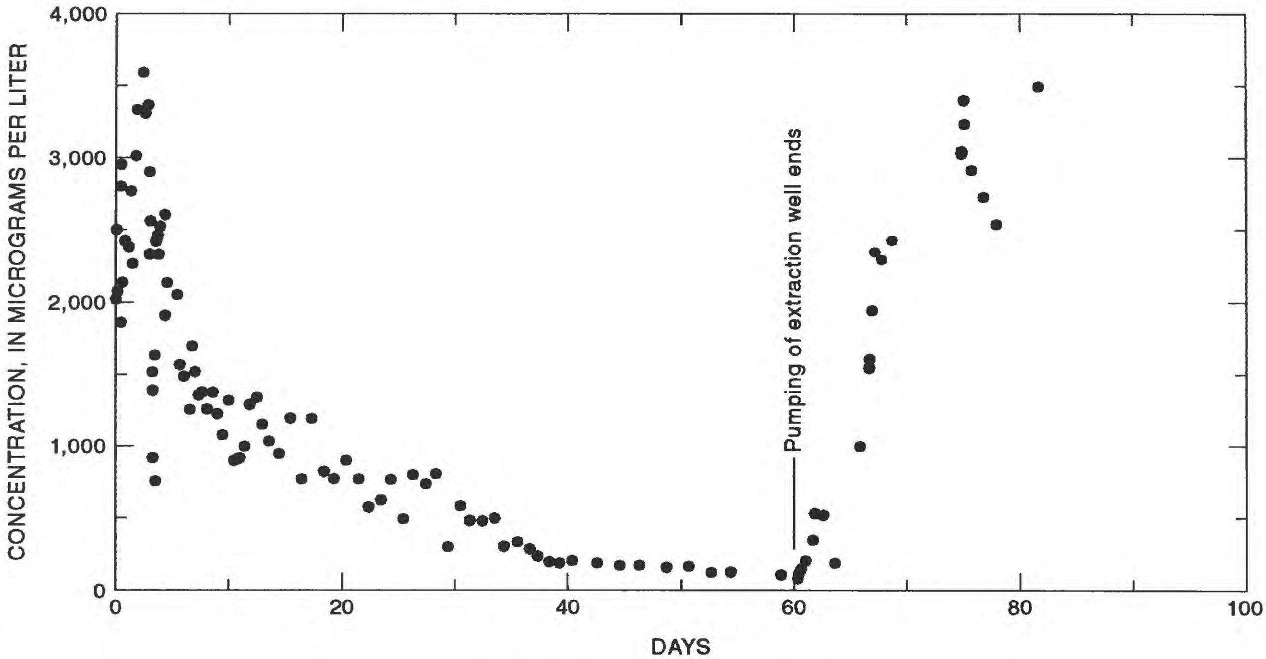

Figure 10. Decline of concentrations of trichloroethylene (TCE) in monitor well as extraction well 12 feet away is pumping and rebound of concentrations after cessation of pumping (from Brusseau and others, 1996b).

are not yet completed, such as the introduction of chemical tracers and mathematical modeling, may help to explain the observed rebound behavior (Brusseau and others, 1996a).

Solubility of Trichloroethylene (TCE) Compared with the Maximum Contaminant Level (MCL)

Although TCE is considered to be only slightly soluble in water, the solubility is high compared with the targeted cleanup concentration. The solubility of TCE in water is 1,100 mg/L. The maximum contaminant level (MCL) of USEPA and the action level of the State of Arizona is 5 µg/L. These figures suggest that, if mixing were thorough, 1 L of water (slightly more than a quart) saturated with TCE could contaminate about 60,000 gallons of ground water to the MCL (5 µg/L). If complete mixing occurred, one gallon of pure TCE is sufficient to contaminate about 300 million gallons of ground water to the MCL. In actuality, the assumption of complete mixing is unrealistic because water containing large concentrations of dissolved TCE that is not totally isolated may eventually mix with uncontaminated water. Small amounts of undissolved TCE or water having large concentrations of dissolved TCE remaining in areas that are not totally isolated from the aquifer can cause extensive ground-water contamination above the MCL (5 µg/L). If TCE were highly soluble in water and did not have a tendency to sorb to or become entrapped between sediment particles, it would be largely or totally dissolved in water and removing and treating the contaminated water would remove the TCE from the aquifer. Because TCE is only slightly soluble, some TCE may remain undissolved and continue to contaminate ground water for many years. Also, TCE and other VOC's that have adhered temporarily to sediments may be released slowly as water continues to flow through the sediments and can cause continual recontamination of ground water.

Heterogeneity and Dead-End Zones

The heterogeneity of the aquifer may limit the effectiveness of pump-and-treat as a cleanup technique. The aquifer consists of discontinuous layers of coarse-grained sediments interbedded with layers of fine-grained sediments. The interlaced nature of the deposits may allow for dead-end zones of stagnation to occur when water is pumped for cleanup. Water movement, in response to pumping stress, occurs much more readily along pathways of interconnected lenses of coarse-grained sediments, such as gravel. A fine-grained sediment, such as clay, has high porosity but low permeability; thus, these sediments have a lot of pore space that contains a large amount of water but do not transmit water readily. If the water contained in the fine-grained sediments is contaminated, it probably will take a long time for all of the contaminant to be removed by pumping water from the sediments or by attempting to flush contaminants from the sediments with uncontaminated water.

At the Airport Area Site, large concentrations of TCE commonly are found in association with fine-grained sediments, particularly clay. Thus, when wells are pumped for cleanup, water movement occurs preferentially along coarse-grained pathways that are less contaminated. Water containing dissolved TCE can be removed easily from the coarse-grained layers. Whenever pumping is temporarily halted, however, small amounts of contaminated water that has dispersed from the fine-grained layers may mix with the water that moves into the coarse-grained layers to take the place of the extracted water. Contaminants will need to be removed from fine-grained sediments and zones of the aquifer that are partially cut off from preferred flow paths or these fine-grained sediments may continue to act as secondary sources of contamination to the coarser units. The slow transfer of contaminants from the fine-grained sediments where there is little water movement to the coarse-grained sediments where active flow occurs when wells are pumped may require that exceedingly large quantities of water must be removed over many years before permanent cleanup to regulatory standards can be achieved. These effects are likely to be most pronounced near disposal areas where water containing large concentrations of dissolved solvents has diffused into the fine-grained sediments.

Delayed Drainage in Drawdown Cones

Another effect that may limit the effectiveness of the pump-and-treat technique for permanent aquifer restoration involves lowering the water table and creating unsaturated drawdown cones when wells are pumped. This effect, however, also can be used to advantage using the DPE system. Near some disposal areas, layers of slow-draining, fine-grained sediments are close to the water table. The layers may contain water with dissolved TCE and other VOC's. When a drawdown cone forms and the water table declines because water is being withdrawn from the aquifer, some of these sediments are then at or above the water table. Drainage from the fine-grained layers probably will be delayed and incomplete because contaminants remain in areas not affected by pumping. When the pump in a well is temporarily shut off, water levels recover and sediments within the drawdown cone are rewetted. Water may then become recontaminated with VOC's that remained in the fine-grained sediments previously above the water table. This effect might be partially overcome by alternating pumping and recovery periods between adjacent wells to minimize the extent of drawdown cones and periodically resaturate the sediments within the drawdown cones. The coupled problems created by the slow transfer of TCE from the fine-grained layers to the coarse-grained layers and the presence of dead-end zones of stagnation created by the interlaced layers of sediment, however, are again potential limiting factors for the complete removal of VOC's from the sediments in the drawdown cones. In general, extraction well fields are operated in such a manner that large drawdown cones are not created, so this effect may be less of a limiting factor than the pathways of preferential flow created by aquifer heterogeneity.

The DPE system, implemented at some locations south of Tucson International Airport, makes use of the drawdown cones and lowered water table created by ground-water extraction to remove TCE and other solvents in their vapor phase from the exposed sediments. The DPE system has dramatically increased the rate of recovery of solvents. The vapor-extraction component of the DPE system, however, also has limitations. Many cycles of pumping and recovery, over many years, or other enhancements to the pump-and-treat technique probably will be needed to flush contaminants from the fine-grained sediments in the drawdown cones of extraction wells if they are heavily contaminated.

Slow Removal from Capillary Fringe

Contaminants held in the capillary fringe that overlies the natural water table and the lowered water table created by subsequent pumping are held tightly by capillary suction and tend not to respond quickly to ground-water movement created by pumping water from the underlying aquifer. Near historical disposal areas, if fine-grained sediments are at the natural water table or at the depth of the lowered water table created by pumping, the capillary fringe probably is thick and difficult to clean up, especially if globules of undissolved TCE are present. Because undissolved TCE is denser than water and moves downward because of the influence of gravity, the possibility of recontamination of the aquifer is strong if undissolved TCE is not removed from the capillary fringe. The depth and thickness of the capillary fringe varies as the water table moves up and down in response to changes in pumping, and measured rates of removal at some locations suggest that this fluctuation is beneficial for removal of TCE.

Nonuniform Flow to a Well and Nonuniform Vertical Distribution of Contaminants

Rarely is the flow of water uniform in the entire length of the screened interval of a well especially where the aquifer consists of a mix of fine-grained and coarse-grained sediments (fig. 11). Nonuniform flow, in itself, creates a problem even if contaminants were evenly distributed vertically. Much more water would enter the well from some depths than from other depths; therefore, more water would ultimately need to be removed to achieve the same degree of contaminant removal. The problem is further complicated when the vertical distribution of contaminants is not uniform as is the case in the upper zone of the regional aquifer. Characterization studies for an area south of Tucson International Airport have indicated that in some instances contaminant concentrations are largest near the top and bottom of the upper part of the aquifer and in lenses of fine-grained sediments that do not transmit water as readily as coarse-grained sediments (Brusseau and others, 1996a). Thus, along the screened interval, much more water may enter the well at depths where concentrations of contaminants are small than at depths where concentrations are large and may limit the efficiency of the system in that additional water must be extracted, treated, and recharged. Unfortunately, the vertical distribution of contaminants is unknown in much of the area; therefore, specific contaminant zones cannot be easily targeted for cleanup.

ATTEMPTS TO IMPROVE CLEANUP EFFORTS

As of 1995, studies are underway to find ways to improve the efficiency of pump-and-treat operations near historical disposal areas south of Tucson International Airport (Brusseau and others, 1996a). One strategy to maximize contaminant removal from the aquifer and minimize pumping costs includes the adjustment of pumping rates to minimize drawdown and alteration of drawdown and recovery periods. Minimizing the extent of extraction-well drawdown cones may minimize the problem of delayed drainage. A decrease in the rate of water extraction may allow more contaminated water to slowly disperse from the fine-grained sediments for removal and may result in a short-term decrease in the rate of solvent removal and an increased efficiency in the cleanup effort in the long term.

Alteration of drawdown and recovery periods allows for rewetting of sediments within the drawdown cones created by pumping and allows for the redistribution of contaminated water from zones of inactive flow to areas of active flow beneath the water table. Alternatively, recovery may be more effective if drawdown is maximized in areas where a DPE system can be used effectively to remove solvents in their vapor phase from the dewatered areas.

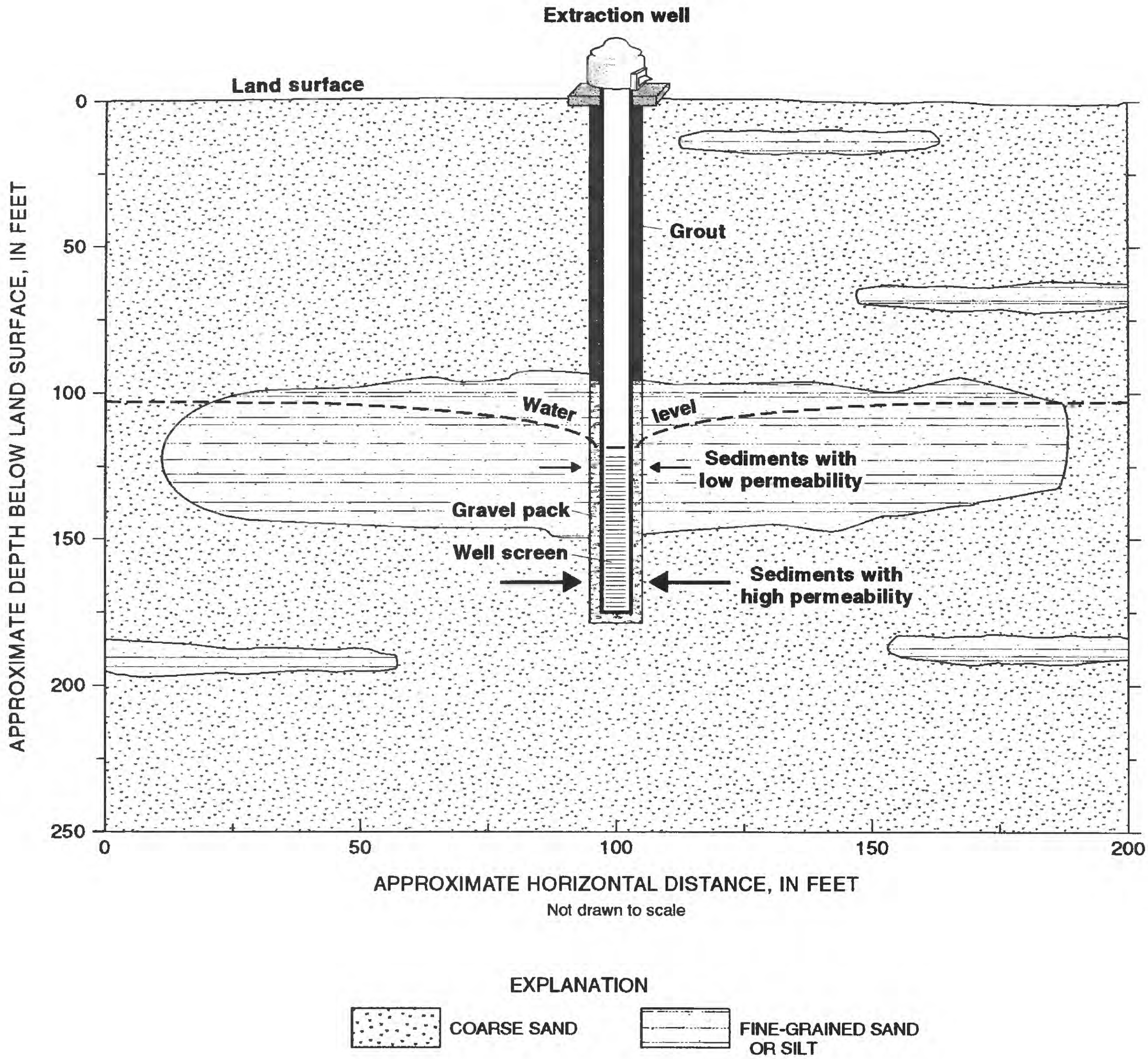

Figure 11. Extraction well completed in mixed sediments. More water enters the screened interval of the extraction well where the sediments have high permeability.

Additional characterization studies near disposal areas to locate zones of large concentrations of contaminants will allow more precise targeting of cleanup efforts. Identifying and pumping selectively from zones of highest ground-water contamination speeds removal of undissolved TCE and the most highly contaminated water. To achieve the same amount of contaminant removal, less water needs to be removed if water is removed mainly from zones having the largest concentrations. Selective pumping from zones with the largest concentrations of contaminants also may minimize the spreading effects brought about by removing water from less contaminated zones. Nevertheless, permanent cleanup to a target concentration of less than 5 μg/L probably will be difficult using the pump-and-treat technique. Development of an optimal pumping strategy for VOC removal probably will continue to include trial-and-error testing as it may be exceedingly difficult, or prohibitively expensive, to quantify all of the subsurface factors that may be affecting flow to the wells and contaminant removal from the aquifer throughout the entire Airport Area Site.

CONTAINMENT AND PREVENTION OF GROUND-WATER CONTAMINATION

To date, the network of extraction and recharge wells installed for cleanup purposes south of Los Reales Road appears to have been successful in containing the spread of contaminated ground water from historical disposal areas, as shown by the similarity in shape and extent of the delineated area of ground-water contamination (fig. 2, this report; Leake and Hanson, 1987, fig. 6) and the reduction of the concentrations of dissolved TCE in water from many wells. As it may prove to be more difficult than originally anticipated to remove all traces of contaminants from the subsurface in these areas, continued success with a containment strategy is important for avoiding potential recontamination of the aquifer in areas currently thought to be cleaned up.

Practices for the management and disposal of potentially hazardous materials have undergone much change as understanding of the vulnerability of aquifers to contamination has improved. In the past, the moderately thick unsaturated zone near Tucson International Airport was thought to afford sufficient protection to the aquifer so that casual disposal practices would not result in ground-water contamination. Much greater emphasis is now placed on prevention of ground-water contamination. As is the case nationwide, the expense and difficulty of restoring a contaminated aquifer have created economic incentive for local industries using potentially hazardous materials to adopt practices that assure protection of the ground-water resource.

Ground water being used for municipal supply continues to be tested regularly for compliance with State and Federal standards, and efforts have been made to ensure that no water exceeding these standards is delivered to the public. In addition, a study by the USEPA and Pima County concluded that no known private well users near the site are drinking contaminated ground water as of 1995 (U.S. Environmental Protection Agency, 1995).

SUMMARY

Investigations initiated in the early 1980's identified areas near Tucson International Airport where wells yield ground water contaminated with various VOC's and hexavalent chromium. Ground water contaminated with TCE, the principal contaminant of concern, was found to be largely confined to the upper zone of the regional aquifer. Leake and Hanson (1987) summarized the results of the investigations of ground-water contamination, and on the basis of data collected in 1984, they delineated one large and two small areas where concentrations of TCE exceeded the MCL of 5 μg/L. The largest of the areas is about 5 mi^2. Since 1984, much effort has been directed to additional site characterization and selection and implementation of cleanup procedures.

Monitoring of concentrations of TCE and other organic and inorganic constituents in ground water is being done throughout the site. Data provided by industries and government agencies involved with monitoring and cleanup efforts at the site were put into a unified GIS data base. Data were plotted using the GIS data base, and areas with wells that yield water with concentrations of TCE that exceed 5 μg/L were delineated. As of December 1995, the main area of contaminated ground water south and west of Tucson International Airport is similar in overall shape and dimensions to the area mapped by Leake and Hanson (1987) for 1984. South of the airport, a small reduction in the width of the main area of contaminated ground water is evident, and concentrations of TCE in several wells within the delineated area have declined. Two small areas where wells yield water containing concentrations of TCE that exceed 5 μg/L are immediately north and northeast of the airport as in 1984. Concentrations of TCE in ground water as large as 74,000 μg/L have been reported in samples taken from a layer of fine-grained saturated sediments at the uppermost part of the aquifer in an area on the west side of Tucson International Airport, immediately north of Los Reales Road. This area has the highest concentrations of TCE in ground water as of 1995.

At disposal sites throughout the airport area, TCE and other VOC's moved from the land surface into the unsaturated zone. At some locations, contaminants moved through the sediments overlying the water table to the upper zone of the regional aquifer where water containing dissolved TCE spread in the direction of prevailing ground-water movement. Near disposal areas, VOC's may remain in the unsaturated zone, capillary fringe, and upper zone of the regional aquifer. Where aquifer recharge occurs near historical disposal areas, VOC's in the sediments overlying the aquifer may dissolve and wash into the aquifer and cause continual, long-term recontamination of ground water. The tendency of TCE to become entrapped or sorbed to sediment particles slows, but does not completely prevent, eventual migration through the unsaturated zone to the aquifer, particularly where aquifer recharge occurs. TCE in vapor form is considerably denser than air and also may move downward through unsaturated sediments beneath disposal areas to cause continual recontamination of ground water.

Tucson Airport Remediation Project was completed in 1994 and was constructed to remove VOC's from ground water supplied by a network of extraction wells north of Los Reales Road where contaminant concentrations are low. The treated water then is distributed for municipal supply. Another network of extraction wells, south of Los Reales Road, provides water to a water-treatment facility south of Tucson International Airport. After removal of VOC's at this facility, treated water is supplied to a network of injection wells situated to contain the spread of contaminated ground water through the aquifer. By the end of 1995, an estimated 17,000 lbs of TCE were removed from about 13.4 billion gallons of ground water at this facility. Similar systems are to be used for cleanup purposes in the two smaller areas of contaminated ground water that are north and northeast of the airport.

Near historical disposal sites, efforts have been directed to remove the VOC's from the aquifer and overlying sediments by simultaneously extracting ground water from the aquifer and air from the overlying unsaturated sediments. At some locations near disposal areas, large quantities of VOC's have been removed from unsaturated sediments above the drawdown cones of extraction wells using this technique. In less than 2 years of operation, more than 29,000 lbs of VOC's, mainly TCE, were removed from the unsaturated zone south of the airport.

Although the size of the area where ground water has been contaminated with TCE has not increased and concentrations of TCE in the discharge of many wells have declined, permanent aquifer restoration will be more difficult and time consuming than originally anticipated. Initially, average concentrations of TCE in water from the extraction-well network that enters the treatment facility south of the airport declined rapidly from slightly more than 300 μg/L in late 1987 to about 100 μg/L in late 1990. Since 1990, concentrations have declined only slightly even though hundreds-to-thousands of pounds of TCE are being removed from the aquifer and overlying sediments each month. This indicates that there are factors limiting efficient removal of contaminants from the aquifer or that ground water continues to receive additional dissolved contaminants. Permanent reduction of concentrations of TCE in ground water to less than 5 μg/L will be difficult to achieve if this is the case.

Heterogeneity of the aquifer and overlying sediments hinders cleanup efforts. Large concentrations of TCE are commonly associated with fine-grained sediments that have high porosity and low permeability, which makes it difficult to remove contaminants by passing air or water through them. Slow dispersal of TCE from these fine-grained sediments may limit cleanup efforts. The tendency of TCE to become entrapped between sediment particles or sorb to fine-grained sediments also may be factors limiting cleanup attempts. Complete and permanent restoration of the aquifer is complicated by the possibility that near historical disposal areas residual contaminants in the capillary fringe and unsaturated zone may recontaminate the underlying ground water.

Additional characterization studies near disposal areas directed to delineating zones with the largest contaminant concentrations will allow for more precise targeting of cleanup efforts. Continuation of a strategy of containment probably will be important because of the difficulty of removing all traces of contaminants from the subsurface near disposal areas. A better understanding of the vulnerability of aquifers to contamination and the expense and difficulty of restoring a contaminated aquifer has caused much greater emphasis to be placed on prevention of ground-water contamination.

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