

DISTRIBUTION AND MOVEMENT OF TRICHLOROETHYLENE
IN GROUND WATER IN THE TUCSON AREA, ARIZONA

By S. A. Leake and R. T. Hanson

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CONVERSION FACTORS

For readers who prefer to use metric (International System) units, the conversion factors for the inch-pound units used in this report are listed below:

<u>Multiply inch-pound unit</u>	<u>By</u>	<u>To obtain metric unit</u>
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
square mile (mi ²)	2.590	square kilometer (km ²)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
micromho per centimeter at 25° Celsius (μ mho/cm at 25°C)	1.00	microsiemens per centimeter at 25° Celsius (μ S/cm at 25°C)
degree Fahrenheit (°F)	$^{\circ}\text{C} = 5/9 (^{\circ}\text{F}-32)$	degree Celsius (°C)

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ABSTRACT

In 1981, investigations of ground-water quality around Tucson International Airport revealed a number of wells that pumped water contaminated by trichloroethylene. Subsequent investigations have resulted in the delineation of three distinct areas of contamination, the largest of which encompasses about 5 square miles of aquifer surface area. Most of the contamination is within the uppermost 100 feet of the saturated ground-water flow system. A fine-grained confining layer that is present in much of the contaminated area significantly limits the vertical movement of the contaminated ground water. Within the contaminated area, measured trichloroethylene concentrations were as high as 3,100 micrograms per liter in 1984. Measured concentrations are highly variable vertically as well as horizontally. Future quantitative studies of contaminant movement may benefit from additional data collection and experiments to determine which contaminant-transport and ground-water flow equations are most appropriate.

INTRODUCTION

In 1981, the U.S. Environmental Protection Agency, Arizona Department of Health Services, and city of Tucson conducted field investigations of ground-water quality around Tucson International Airport (fig. 1). Water samples were collected from municipal and private wells and analyzed to determine the concentrations of various pollutants including volatile organic compounds. Ground water from a substantial number of wells was found to be contaminated by trichloroethylene (TCE), a volatile organic compound used in various industrial applications. As a result of the investigations, seven municipal wells were removed from service and the need for further studies of the extent of the contamination problem was established.

Purpose and Scope

The purpose of this report is to present a summary of the hydrologic conditions relating to the extent and movement of trichloroethylene in ground water in the study area (fig. 2). Besides TCE, other

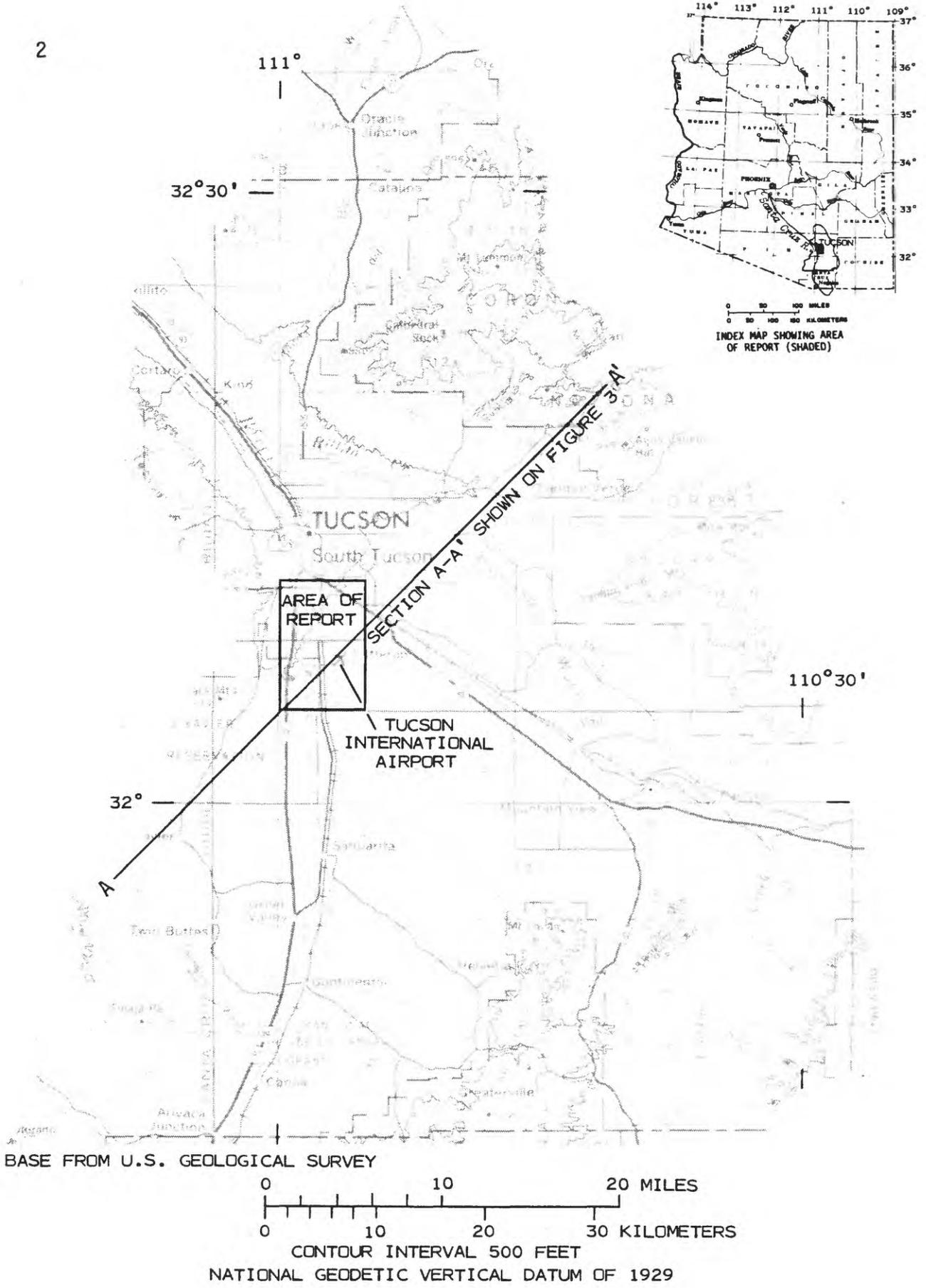


Figure 1.--Area of report.

volatile organic compounds and chromium have been identified as contaminants in ground water in the study area. This study does not address the distribution and movement of contaminants other than TCE. The conceptual framework of the ground-water flow system in the study area is given on the basis of data collected through December 1984. The data were collected by private consulting firms, the city of Tucson, the Arizona Department of Health Services, the Arizona Department of Water Resources, and the U.S. Geological Survey. The report also identifies data needs and considerations for future quantitative analyses of contaminant movement in the study area and of the processes involved in the movement of TCE with ground water.

Extent and Nature of Contamination

Studies conducted after the initial investigations in 1981 have further delineated areas of TCE contamination in the Tucson Airport area. These studies revealed an area of contamination on the south and west sides of the airport and extending northwest of the airport and two small separate areas north and east of the airport (fig. 2). As of 1984, ground-water contamination encompassed about 5 mi² of aquifer surface area with a length of about 35,500 ft and width of about 4,000 ft. Most of the TCE contamination is in the upper several hundred feet of saturated alluvium.

The areal distribution of TCE may be a result of contamination from several source areas rather than from a single source. Several studies have dealt with identifying source areas (Eberhardt, 1983; JRB Associates, 1983, Hargis and Montgomery, Inc., 1984; and Rampe, 1985). Many of the source areas were identified as "suspected" TCE disposal areas. The extent of ground-water contamination associated with the various suspected source areas is not easily quantified. For information relating to locations of suspected source areas, the reader is referred to Rampe (1985).

Characteristics of Trichloroethylene

TCE ($\text{CHCl}=\text{CCl}_2$, 1,1,2--trichloroethylene) is a colorless, sweet-smelling, volatile liquid. This powerful industrial solvent of both natural and synthetic organic compounds is used mainly for degreasing and dry cleaning. The liquid form is about 1.5 times heavier than water, and the vapor form is about 4.5 times heavier than air. For standard pressure and temperature conditions, TCE has a boiling point of 86.7 °C, a surface tension of 29 dynes per centimeter, and a viscosity of 0.58 centipoise (Kirk and Othmer, 1978). TCE is miscible with a number of organic compounds and is made stable by the addition (less than 1 percent by weight) of an antioxidant. Many combinations of stabilizers also are organic toxins. The solubility of TCE in water is 1,100 mg/L (Kirk and Othmer, 1978). TCE is moderately toxic and has some narcotic

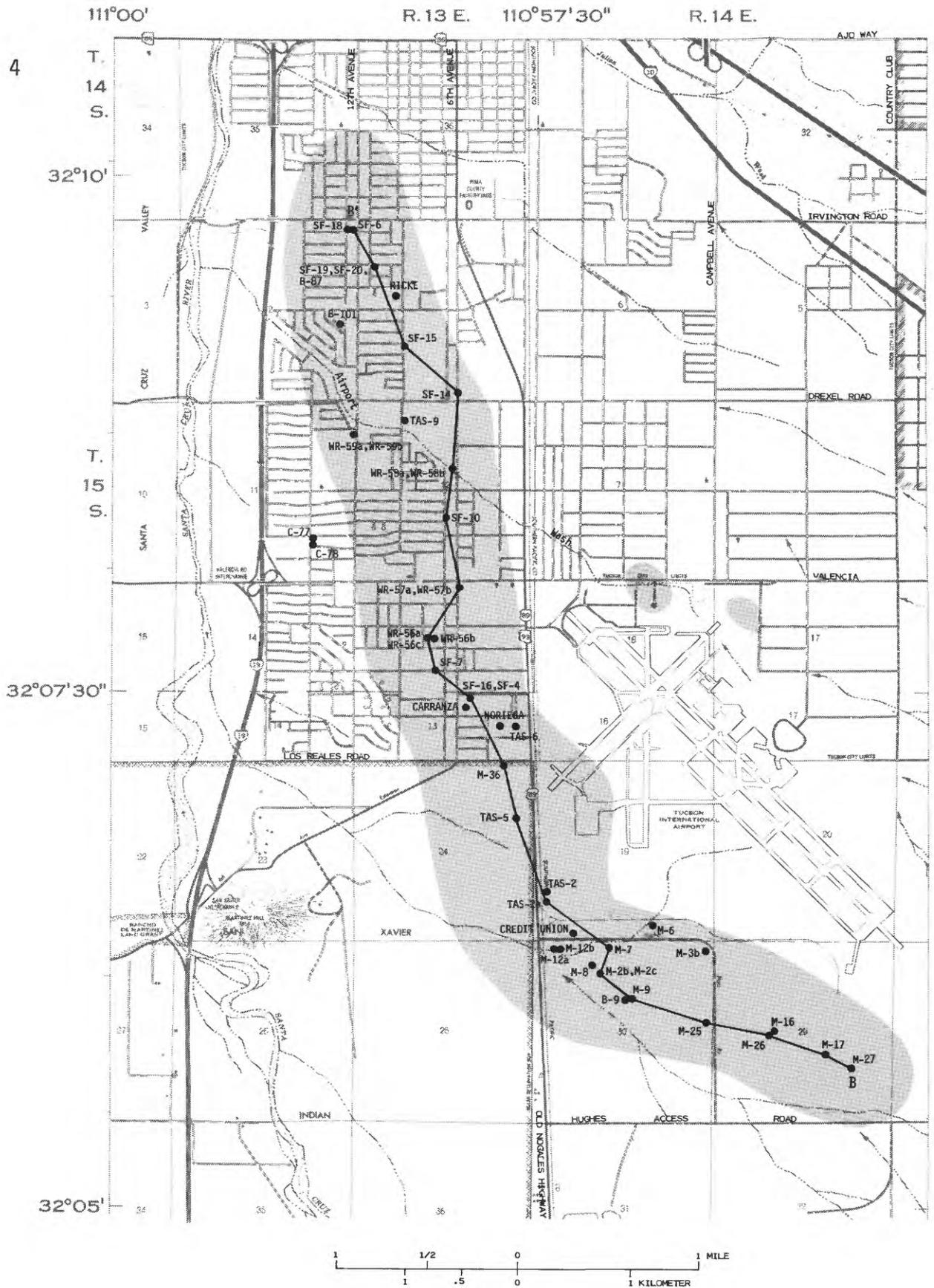


Figure 2.--Approximate area of trichloroethylene contamination in ground water in 1984 and location of selected wells.

E X P L A N A T I O N



APPROXIMATE AREA OF TRICHLOROETHYLENE
CONTAMINATION IN GROUND WATER

TAS-5 WELL—Identifier, TAS-5, is well name

B———B' TRACE OF SECTION

Figure 2

properties (Kirk and Othmer, 1978). An octanol/water partition coefficient for TCE of 2.29 reported by the U.S. Environmental Protection Agency (1978) indicates that TCE may bioaccumulate. For humans, TCE is specifically damaging to kidneys and liver (Kirk and Othmer, 1978). TCE was classified as a B2 carcinogen and a mutagenic compound (U.S. Environmental Protection Agency, 1985). The Environmental Protection Agency maximum contamination level is 5 µg/L and the recommended maximum contamination level is 0 (U.S. Environmental Protection Agency, 1985). In Arizona the maximum contamination level for TCE was set at 5 µg/L (Arizona Department of Health Services, 1985).

TCE appears to be chemically and physically stable in the laboratory and in water-table aquifers but is susceptible to biodegradation. Dilling and others (1975) report an experimental half-life of 10.7 months for an aerated, dilute solution of TCE and water when kept in darkness. Pearson and McConnell (1975) estimate a half-life of 2.5 years for TCE in seawater. For laboratory experiments, Bouwer and others (1981) report no appreciable degradation of TCE in dilute solutions in an anaerobic environment in the presence of methanogenic bacteria or in an aerobic environment in the presence of primary sewage bacterial cultures. Wilson and others (1983) also report no significant rate of degradation in the presence of bacteria indigenous to a shallow water-table aquifer composed of flood-plain alluvium. More recent studies (Parsons and others, 1984, and Kleopfer and others, 1985), however, have reported significant biodegradation of TCE to 1, 2-dichloroethlyene in soils and mucks extracted from field sites. With the addition of stabilizers, TCE is stable in the presence of air, light, moisture, aqueous ammonia, hydrochloric acid, and nitric acid. TCE breaks down to form monochloroacetic acid (CH₂ClCOOH) in the presence of concentrated sulfuric acid (Kirk and Othmer, 1978). Dilling and others (1975) report that TCE resists hydrolysis to temperatures as high as 100 °C.

Dilling and others (1975) observed that 10 percent of the diluted mixtures of chlorinated hydrocarbons exposed to dry granular material were adsorbed by clay and 50 to 90 percent by dolomitic limestone. Selectivity over the type of chlorinated compound adsorbed was not observed, and addition of silica sand had no additional effect on adsorption. A literature search for this study did not reveal publications that quantified the effects of adsorption on the mass of TCE in solution in alluvial aquifers such as that of the study area.

Other Investigations

A number of State, county, municipal, and university studies have focused on different aspects of the geohydrologic framework of the Tucson basin. The U.S. Geological Survey has published papers on geohydrology and water resources (Davidson, 1973), chemical quality of water (Laney, 1972), streamflow characteristics (Condes de la Torre, 1970; Burkham, 1970), and simulation of ground-water flow (Anderson, 1972) within the Tucson basin.

As of September 1984, several investigations of the distribution and movement of TCE in the study area were being done. A study funded by the U.S. Environmental Protection Agency was carried out in cooperation with the Arizona Department of Health Services, the Arizona Department of Water Resources, and the city of Tucson. Phase I of the investigation, referred to as the "EPA Superfund Study," included:

1. Installation of monitor wells and development of a monitoring program.
2. Definition of geohydrologic conditions relating to contaminant movement north of Los Reales Road (fig. 2).
3. Identification of source areas and estimation of contaminant quantities associated with various source areas.
4. Development of a data base of information relating to ground-water contamination and geohydrology of the contaminated area.
5. Development of a solute-transport model for at least part of the contaminated ground-water flow system north and south of Los Reales Road.
6. Identification of features of the contamination for which further study is needed.
7. Recommendations of remedial action.

Results of phase I of the EPA Superfund Study are published in Schmidt (1985), Mock and others (1985), and Rampe (1985).

The U.S. Air Force and a private contractor, Hughes Aircraft Company, have completed detailed studies of ground-water contamination by TCE and other contaminants in the part of the study area south of Los Reales Road (Hargis and Montgomery Inc., 1982a, b, c; 1983b, c). Those studies included tasks similar to the EPA Superfund Study including development of a solute-transport model of part of the contaminated ground-water flow system.

The distribution and movement of TCE in the soil gas above the contaminated ground water were addressed by several studies. A study funded by the U.S. Environmental Protection Agency and carried out by the Hydrology Department of the University of Arizona focused on the relations of TCE concentrations in soil gas with those in the underlying ground water (Marrin, 1984a). Another soil-gas study by the Water Resource Research Center of the University of Arizona included analyses of the temporal variations of TCE in the soil gas at a particular site (D. K. Kraemer, formerly of the University of Arizona, written commun., 1985).

Acknowledgments

Most of the data presented in this report were provided by the organizations involved in studies of TCE contamination in the study area. Formal and informal meetings of hydrologists of the organizations resulted in the sharing of hypotheses relating to the geohydrology of the contaminated area. This exchange of ideas advanced the understanding of the contamination problem. In particular, G. L. Hix and J. A. Babcock, city of Tucson; J. R. Angell and J. J. Rampe, formerly of Arizona Department of Health Services; and P. A. Mock and B. C. Travers, formerly of Arizona Department of Water Resources provided help and information relating to the development of a conceptual model of the geohydrologic system in the study area.

GEOHYDROLOGIC FRAMEWORK

Location, Physiographic Setting, and Climate

The study area (fig. 1) includes about 40 mi² within the Tucson basin, which is located in the northwestern part of the upper Santa Cruz River drainage basin (Davidson, 1973, p. 2-4). The Tucson basin encompasses about 1,000 mi² and is bounded on the east and north by the Santa Rita, Empire, Rincon, Tanque Verde, and Santa Catalina Mountains and on the west by the Sierrita, Black, and Tucson Mountains. Natural surface-water and ground-water outflow from the Tucson basin occurs between the Tortolita and Tucson Mountains. The Santa Cruz River and a minor tributary, Airport Wash, are the main ephemeral streams in the study area.

Mean annual precipitation is about 15.5 in. for the upper Santa Cruz River drainage basin. The lowlands receive between 11 and 16 in./yr, and the mountains on the east and north, which are at altitudes of 6,000 to 9,400 ft above sea level, receive between 16 and 30 in./yr. The eastern mountains receive more precipitation than the western mountains, which are at altitudes of 3,000 to 6,000 ft. Most recharge to the ground-water flow system in the alluvial aquifer is derived from infiltration along the major stream channels and from mountain-front recharge. Annual underflow and direct infiltration are less than 1 percent of the total volume of ground water in storage in the upper Santa Cruz River basin (Freethey and others, in press).

Stratigraphy and Structure

The mountains surrounding the Tucson basin are composed of various types of bedrock. Davidson (1973, p. 13-15) gives a brief

summary of bedrock types and water-bearing properties. The bedrock generally is treated as impermeable for most water-resource problems related to the alluvial aquifer because of the high permeability contrast between the bedrock and the alluvial fill.

The basin fill was divided into three separate units by Davidson (1973). These units are partly overlain by thin, discontinuous surficial deposits that range from stream alluvium to alluvial fans and sheetflow deposits. The generalized geologic section shown in figure 3 shows the relations of stratigraphy and structure. The pre-Basin and Range sediments form a layer called the Pantano Formation of middle Tertiary age (Finnell, 1970) that predominantly consists of weakly to strongly cemented, reddish-brown silty sandstone to gravel. The Tinaja beds, which unconformably overlie the Pantano Formation (Davidson, 1973), are the oldest locally derived basin-fill deposits. The Tinaja beds are composed of interbedded sands and gravels along the basin margin that grade into clayey silt and mudstone toward the center of the basin. The Fort Lowell Formation of Quaternary age, which unconformably overlies the Tinaja beds (Davidson, 1973), is the youngest basin-fill deposit. The Tinaja beds are thousands of feet thick near the center of the basin, and the Fort Lowell Formation ranges from 300 to 400 ft thick in most of the basin (fig. 3). Distribution of coarse- and fine-grained sediments of the Tinaja beds and Fort Lowell Formation appear to be areally coincident in many areas (S. R. Anderson, hydrologist, U.S. Geological Survey, written commun., 1984), and the sediments of the Fort Lowell Formation are slightly coarser than the underlying Tinaja beds at most locations. The Fort Lowell Formation and upper part of the Tinaja beds generally are fine grained east of the Santa Cruz fault and coarse grained west of the fault (fig. 3).

The pre-Basin-and-Range sediments—the Pantano Formation—and the older basin-fill deposits—lower to middle Tinaja beds—are offset by high-angle normal faults throughout the basin. The center of the basin is a dissected graben structure where massive accumulations of fine-grained sediments and evaporites are present. The fault system on the west side of the graben traverses the middle of the study area and is in part represented by offset segments of the Santa Cruz fault (Davidson, 1973, pl. 1). The areal coincidence of the distribution of coarse- and fine-grained sediments within the upper Tinaja beds and Fort Lowell Formation indicates that the location of the ancestral drainage system and related provenance was fairly constant since the onset of intermittent through-flowing drainage (S. R. Anderson, written commun., 1984). In addition, the facies have lateral boundaries coincident with and adjacent to the trace of the Santa Cruz fault segments within the study area (S. R. Anderson, written commun., 1984). Only drill cuttings and borehole-geophysical logs were available for interpreting subsurface stratigraphy; therefore, differentiation between facies changes and minor fault offsets within the younger basin-fill deposits was not possible. No evidence, such as shallow seismic traverses or long-term aquifer tests, are available to indicate that these Basin-and-Range faults dissect the younger Tinaja beds and Fort Lowell Formation.

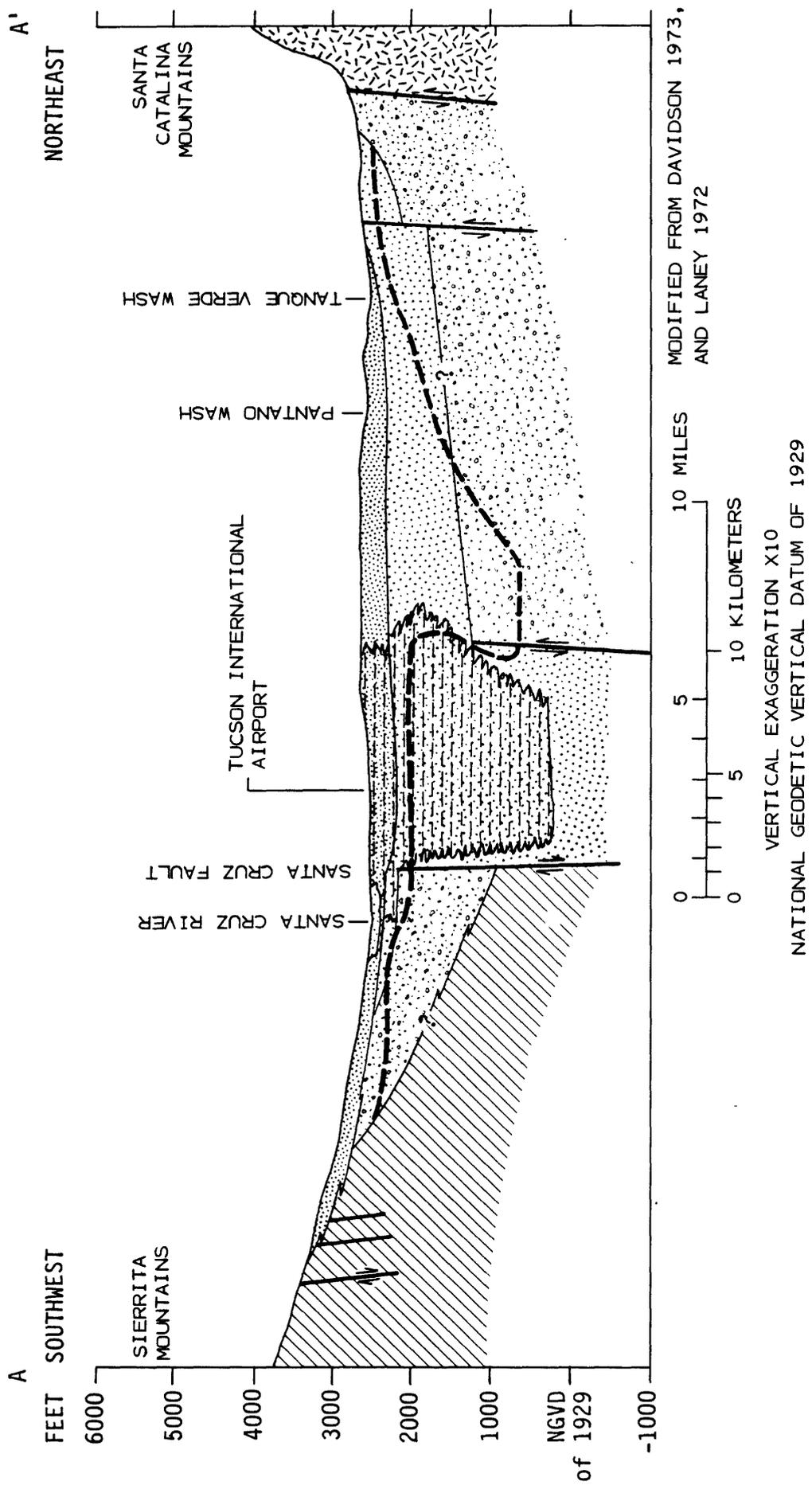


Figure 3.--Generalized geologic section of the upper Santa Cruz basin.

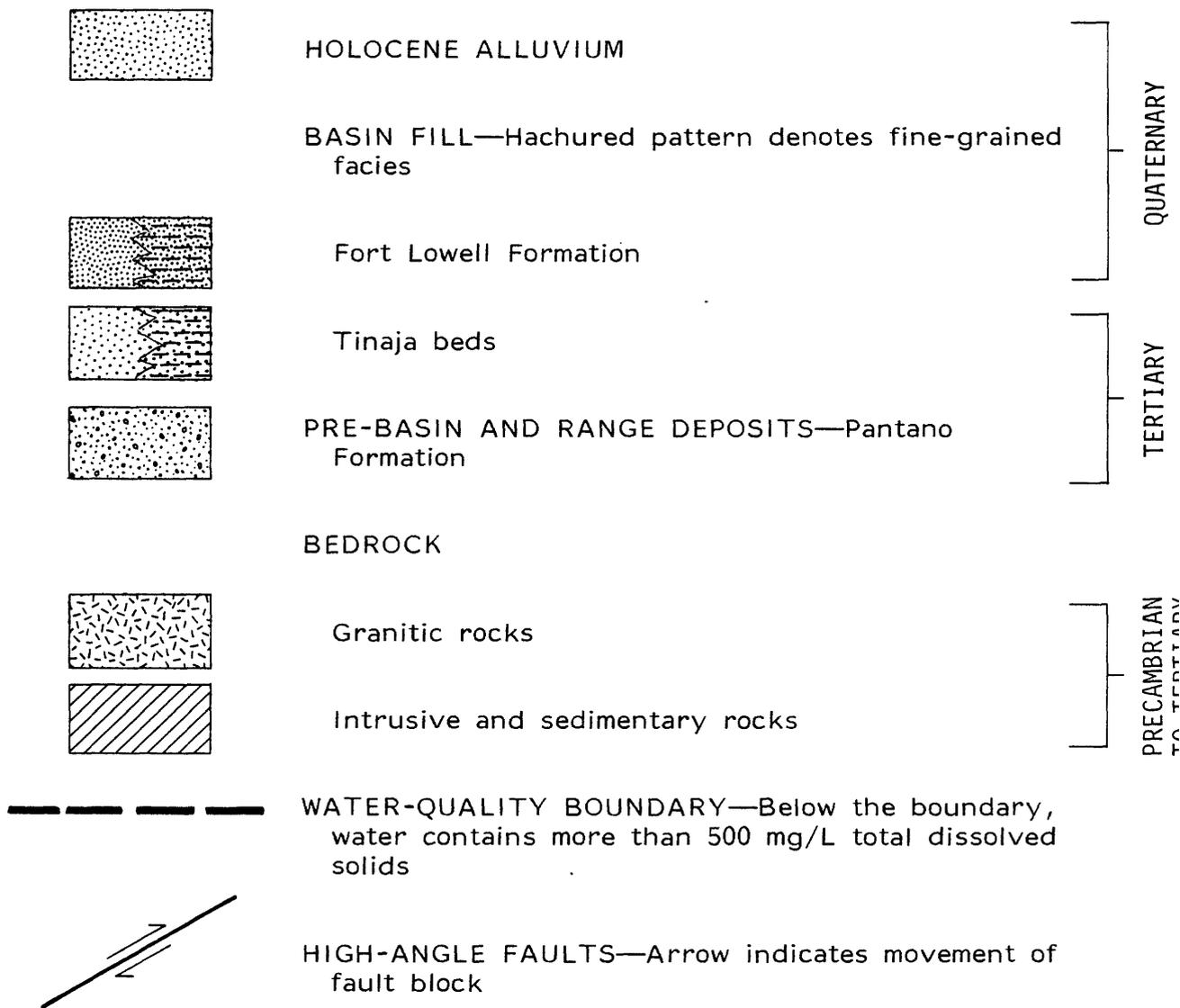


Figure 3

The stratigraphy along the northwest-trending geologic section B-B' located within the study area (fig. 2) is illustrated on the upper section of plate 1. Formational boundaries as interpreted from data from nearby wells (Davidson, 1973; S. R. Anderson, written commun., 1984) were used for stratigraphic control. The uppermost unit indicated on the section is the Quaternary sediments and the Fort Lowell Formation, undifferentiated. This unit is composed of extensive fine-grained layers with interbedded sand and gravel beds. This unit ranges from 90 to 240 ft thick along section B-B', is coincident with the upper aquifer zone identified by Hargis and Montgomery, Inc. (1982b), and disconformably overlies the Tinaja beds. Collectively, the Quaternary sediments and the Fort Lowell Formation become progressively thicker, are more fine grained, and show thicker individual layers toward the southeast end of section B-B'.

The Tinaja beds were subdivided by Davidson (1973) into upper and lower beds. The lower Tinaja beds (Davidson, 1973) were further divided into middle and lower beds by S. R. Anderson, (written commun., 1984). The fine-grained facies of the upper Tinaja beds will be herein referred to as "the confining layer." This layer is confining with respect to hydraulic head in the units underlying it along the western margin of the basin and ranges from 10 to 170 ft in thickness along section B-B'. Calcareous clays and caliche layers are present throughout this unit and especially near the top, which may indicate remnants of an indurated erosional surface.

The lower unit shown on section B-B' (pl. 1) represents lower and middle Tinaja beds and Pantano Formation and was designated as Tinaja beds and Pantano Formation, undifferentiated. Cuttings from several wells, such as WR-57, SF-4, and TAS-2a, indicate the presence of calcareous deposits near the top of this unit (Hix and Brumbaugh, 1984d; Ecology and Environment, 1982). These deposits may be an artifact of the erosional surface along the top of either the Tinaja beds or Pantano Formation.

Aquifer Zones

For the purposes of studying contaminant movement in the study area, definition of local geohydrologic units is warranted. In a study of ground-water contamination in and around secs. 29 and 30, T. 15 S., R. 14 E., Hargis and Montgomery, Inc. (1982b) divided the regional aquifer system into an upper aquifer zone and a lower aquifer zone separated by an extensive clay confining layer. Data collected outside of those sections indicate that the concept of an upper aquifer zone underlain by a confining layer and a lower aquifer zone is valid in much of the study area. The vertical relation of the aquifer zones and confining layer is shown on the lower section of plate 1. The upper and lower limits of the upper aquifer zone are the water table and the top of the confining layer, respectively. The upper limit of the lower aquifer zone is the base of the confining layer. The lower limit of the lower aquifer zone cannot be defined without additional data.

Because the presence of the confining layer is the primary basis for defining vertical limits of zones within the regional aquifer, the areal extent of the upper and lower aquifer zones is coincident with the areal extent of the confining layer. In a detailed study of subsurface geology in and around the study area, Mock and others (1985) mapped the areal extent of the confining layer (fig. 4). In general, the confining layer covers most of the east half of the study area. The part of the ground-water flow system where the confining layer is not present is referred to as the regional undivided aquifer or undivided aquifer by other investigators (Mock and others, 1985; Schmidt, 1985).

Hargis and Montgomery, Inc. (1982a, b) identified a perched aquifer zone in the north half of sec. 30, T. 15 S., R. 14 E. Their mapped area of the perched zone covered about 100 acres, and the saturated thickness ranged from less than 1 ft to as much as 5 ft. For a detailed description of the geohydrology of the perched ground water in the southern part of the contaminated area, the reader is referred to Hargis and Montgomery, Inc. (1982a, b). Mock and others (1985) identified an additional perched water-table system overlying the regional undivided aquifer in parts of secs. 1, 2, and 11, T. 15 S., R. 13 E.

The terms in this report—upper aquifer zone, lower aquifer zone, and regional undivided aquifer—will be used as previously defined. Division of the aquifer into zones, however, does not imply a lack of hydraulic continuity between the zones.

Hydraulic Head and Direction of Ground-Water Movement

In many ground-water flow systems, horizontal directions of ground-water movement can be determined from the distribution of hydraulic head. Horizontal directions of ground-water movement are normal to lines of equal hydraulic head if head does not vary significantly with depth and the aquifer is isotropic with respect to transmissivity. In the study area, the upper and lower aquifer zones probably are isotropic with respect to transmissivity because the sediments were deposited as interbedded horizontal layers with few geologic features that would lead to preferential horizontal flow in any given direction. Furthermore, in the central and western parts of the study area, vertical variations in head are small within the upper aquifer zone. Small variation in vertical head is evidenced by a general consistency of water levels in wells near each other yet open to different intervals of the upper aquifer zone. A specific example of this consistency is seen in water levels at monitor wells WR-56c and WR-56b, which are at the same site and are open to the aquifer at altitudes of 2,396 to 2,417 ft and 2,350 to 2,370 ft, respectively. The difference in the water levels in the two wells is less than 1 ft (Hix and Brumbaugh, 1984b). In the fine-grained sediments in the eastern part of the study area, vertical distribution of head may be less uniform than the distribution in the coarse sediments of the upper aquifer zone to the west. Water levels in wells near each other yet open

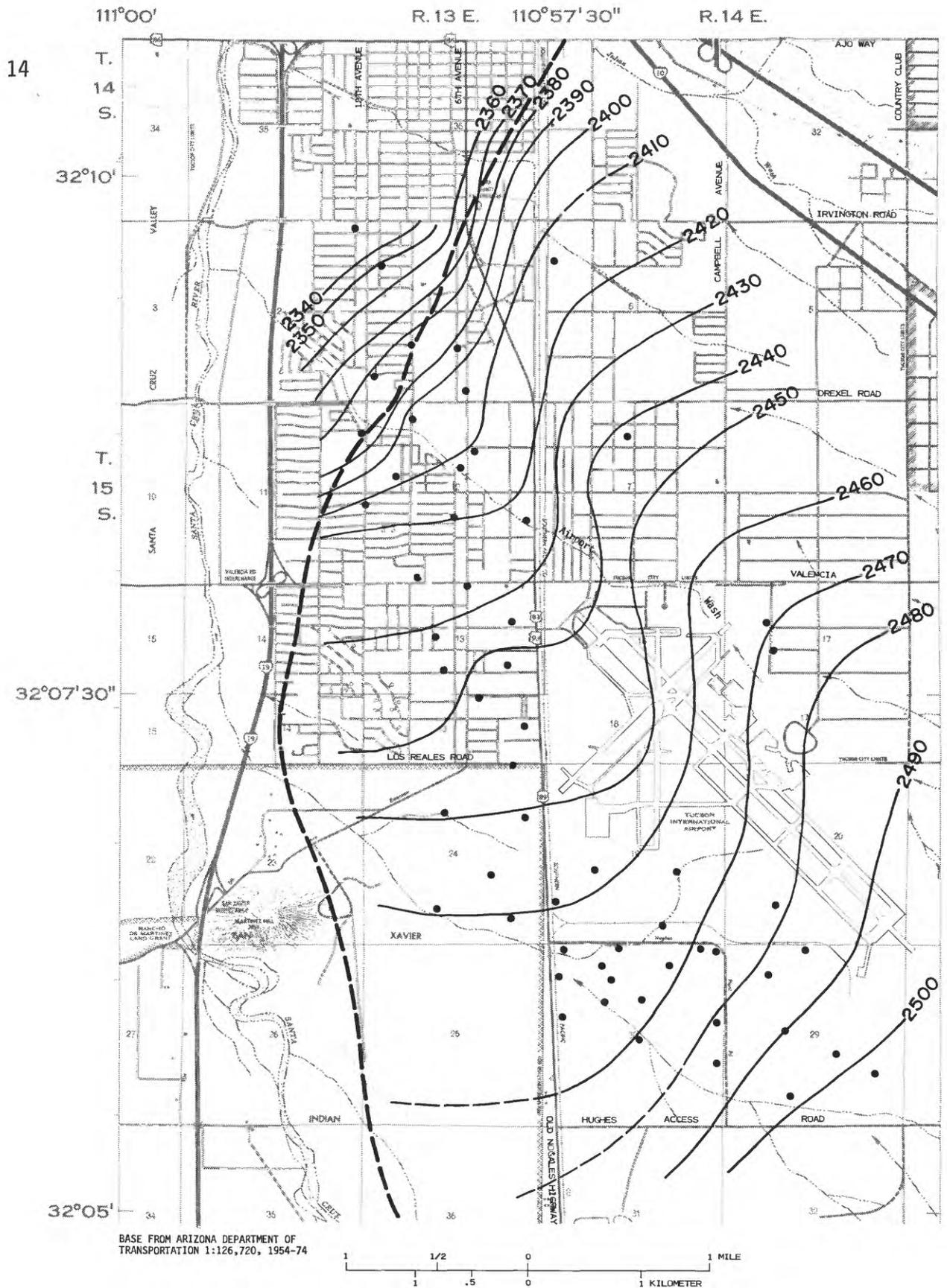
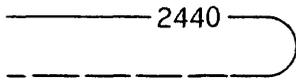


Figure 4.--Hydraulic head in the upper aquifer zone and part of the regional undivided aquifer, 1984.



HYDRAULIC-HEAD CONTOUR—Shows line of equal hydraulic head. Dashed where inferred. Contour interval 10 feet. National Geodetic Vertical Datum of 1929



WELL IN WHICH HEAD WAS MEASURED



WEST EDGE OF CONFINING LAYER—Divides upper and lower aquifer zones. Mapped by Mock and others (1985)

Figure 4

to different intervals may be significantly different. Vertical variations in head are caused by beds of fine-grained sediments that inhibit the vertical movement of ground water.

Lines of equal hydraulic head in the upper aquifer zone for 1984 (fig. 4) indicate that ground water flowed to the northwest in the eastern and northern parts of the study area and to the north in the central and western parts. Additionally, gradients of hydraulic head are steepest in the east where sediments are predominantly fine grained. Toward the north, head gradients steepen where the fine-grained confining beds that separate the aquifer zones become discontinuous or nonexistent. In this area, vertical-flow components may be significant as ground water moves from the upper zone to the unconfined part of the regional undivided aquifer where hydraulic heads are lower.

The spatial distribution of hydraulic head in the lower aquifer zone is poorly defined on the basis of existing water-level data. Water levels from monitor wells along section B-B' (pl. 1) are above the bottom of the confining layer where the confining layer is present. Horizontal gradients of water level in the lower aquifer zone steepen at the southeast end of the section. At the northwest end of the section, water levels in wells SF-6 and SF-18 were about the same in 1984. Vertical-flow components at that point in the regional undivided aquifer therefore were small. At wells SF-19 and SF-20, water levels differed by about 30 ft; the higher water level was in the shallower well. That difference indicates that significant vertical-flow components may have been present as water moved downward from the upper aquifer zone to the regional undivided aquifer.

Long-term variations of head with time in the upper aquifer zone are small in comparison to variations in other parts of the ground-water flow system. At well C-77, which is open to the upper aquifer zone, the head decline from the early 1950's to the early 1980's is about 10 ft (fig. 5). Similar head declines are evident in shallow wells in the eastern part of the study area, although declines are more variable laterally and vertically. The temporal variations in water level for well C-78 (fig. 5) are typical of variations measured in other wells open to the lower aquifer zone. The differences in the water-level trends of wells C-77 and C-78 undoubtedly reflect differences in past ground-water withdrawal rates as well as in hydraulic properties of the two aquifer zones. Long-term head declines throughout the ground-water system can be accounted for by withdrawal by pumping. Production wells that supply the city of Tucson generally are open to the upper aquifer zone, or both the upper and lower aquifer zones, or the regional undivided aquifer. Water levels in wells that tap both the upper and lower aquifer zones generally are significantly lower than water levels in wells that tap only the upper zone. In many of these wells, cascading water is present. Withdrawal from the upper zone by wells that tap both zones probably is limited to gravity drainage within the well bores. In addition to the city production wells, many domestic wells withdraw water from the upper aquifer zone.

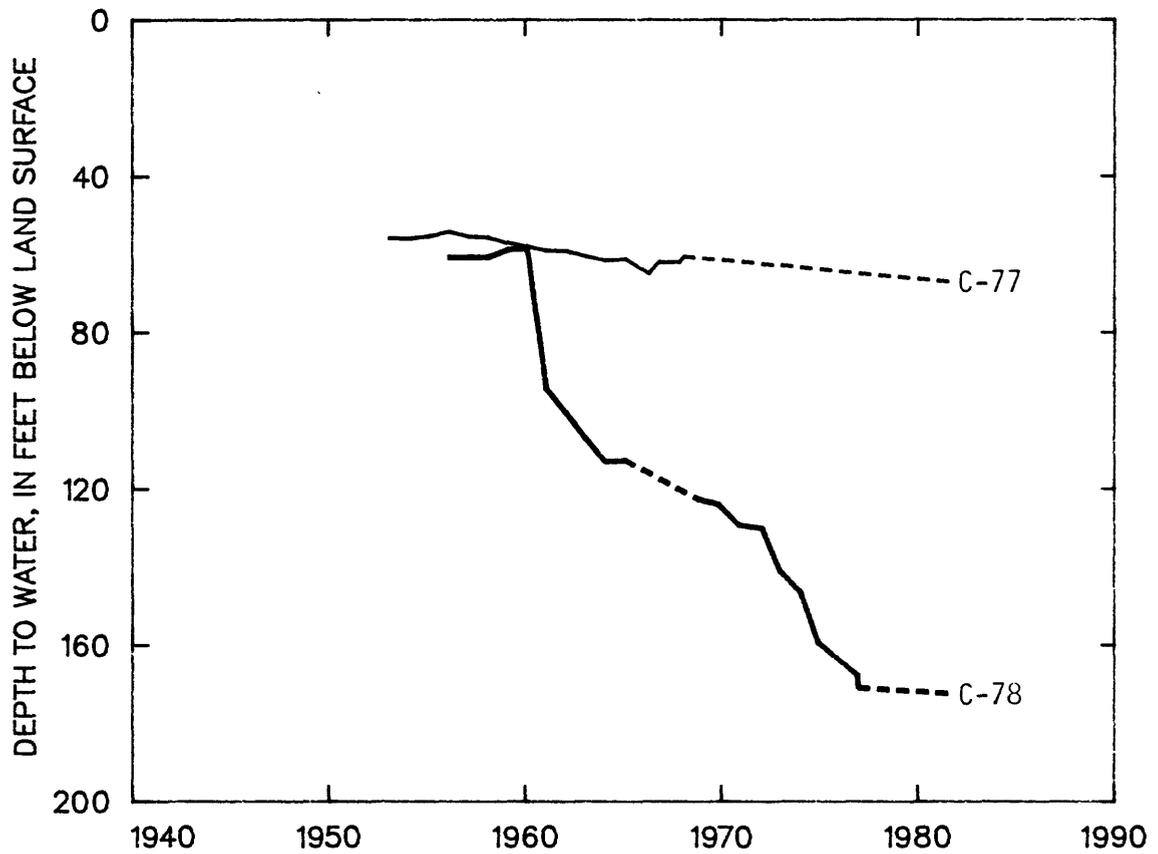


Figure 5.--Water levels in adjacent wells open to different vertical intervals. Well C-77 taps the upper aquifer zone to a depth of 150 feet below the land surface. Well C-78 taps the upper and lower aquifer zones to a depth of 230 feet below the land surface.

Data from monitor wells drilled since 1981 indicate that water levels are rising throughout most of the ground-water system in the study area. The rises in water levels probably are due to reductions in ground-water pumpage in the study area since 1981.

Aquifer Hydraulic Characteristics

Hydraulic characteristics of interest in quantitative studies of contaminant movement in ground water are transmissivity, hydraulic conductivity, saturated thickness, porosity, specific yield, and specific storage. Reliable knowledge of spatial and temporal distributions of these properties in the study area is not available and perhaps is not directly obtainable.

The best-defined hydraulic characteristic is saturated thickness of the upper aquifer zone. The difference between the 1984 water-surface profile and the top of the confining layer shown on section B-B' is the saturated thickness of the upper aquifer zone. The saturated thickness of the upper aquifer zone decreases toward the north where the confining layer becomes discontinuous. In the western and central parts of the study area where the upper aquifer zone is present, saturated thicknesses are similar to those shown on section B-B'. The top of the upper aquifer zone is the water table; therefore, temporal variations in water-table altitude also are variations in saturated thickness.

Estimates of other hydraulic properties, such as transmissivity, hydraulic conductivity, specific yield, and specific storage, commonly are obtained from the analysis of aquifer tests. Aquifer tests have been performed using many monitor wells and a few larger production wells pumping exclusively from the upper aquifer zone. Most of the tests that use monitor wells were conducted by pumping at a constant discharge rate for a 3- to 12-hour period and measuring drawdown and recovery in the pumped well. The monitor wells commonly tap from 20 to 100 ft of the upper aquifer zone and pump from a few gallons per minute to as much as 114 gal/min.

For aquifer tests that involve a single pumped well and no observation wells, storage properties of the aquifer cannot be determined because the effective radius of the well is unknown. The degree of reliability to which transmissivity and hydraulic conductivity can be estimated is in part dependent on the degree to which the ground-water hydraulics of the flow systems established by the pumping stresses can be approximated with mathematical models available for test analysis.

Mock and others (1985, table 1) presented results of analyses of 45 monitor-well tests from the upper aquifer zone and regional undivided aquifer in the study area. Of the 53 reported hydraulic-conductivity values, the minimum is 2 (gal/d)/ft² (0.27 ft/d) and the maximum is 2,000 (gal/d)/ft² (270 ft/d). The average of the values is

520 (gal/d)/ft² (70 ft/d) and the coefficient of variation is 0.85. A well-defined areal distribution of hydraulic conductivity cannot be inferred from the estimated values. Apparent high areal variability may be due in part to a high spatial (areal as well as vertical) variability in the actual hydraulic conductivity distribution. Also, uncertainty or error in individual estimated hydraulic conductivity values may result in apparent high areal variability. In general, the monitor-well tests are not ideal for estimating aquifer characteristics in the study area.

In addition to the specific information on aquifer characteristics that may be derived from aquifer tests, some general information can be inferred from the distribution of hydraulic head in the ground-water flow system and from geologists' logs of wells in the area. The variations in head gradients and direction of ground-water movement in the study area may, in part, be caused by variations in hydraulic properties. Steeper gradients on the east than on the west are indicative of lower hydraulic conductivity on the east. The change in flow direction in the central part of the study area also indicates an increase in hydraulic conductivity in the downgradient direction. This major change in hydraulic conductivity is supported by geologists' logs, which indicate more fine-grained material on the east than on the west. Throughout the area, fine-grained beds are present; however, on the east, fine-grained beds are a large percentage of the aquifer thickness.

EXTENT OF MOVEMENT OF TRICHLOROETHYLENE

The alluvial aquifer of the Tucson basin was designated as the sole-source water supply for the municipalities of the Tucson basin (U.S. Environmental Protection Agency, 1984). The city of Tucson relies exclusively on ground water for its water supply. The quality of water from the alluvial aquifer naturally varies areally and with depth. Laney (1972) grouped ground-water types in the aquifer into shallow—less than 700-foot depth—and deep—greater than 700-foot depth—hydrochemical zones on the basis of water quality. The water in the deep zone is soft (0-60 mg/L of CaCO₃). The deep-zone water varies between a sodium bicarbonate type—less than 500 milligrams per liter (mg/L) dissolved solids—and a sodium sulfate type—greater than 500 mg/L dissolved solids—and may contain fluoride in excess of 1.4 mg/L. The ground water in the shallow zone varies between a calcium bicarbonate and calcium sodium bicarbonate type with less than 500 mg/L dissolved solids, and a calcium sulfate to calcium sodium sulfate type with greater than 500 mg/L dissolved solids. The shallow-zone water ranges from hard to moderately hard (60-180 mg/L of CaCO₃) and contain less than 1.0 mg/L of fluoride. The depth of water that contains less than 500 mg/L total dissolved solids is shown by the water-quality boundary on the geologic section A-A' (fig. 3). Good-quality water occurs in both hydrochemical zones of Laney (1972) and extends to depths as great as 2,000 ft along the east side of the basin where recharge is greatest. The water-quality boundary then abruptly rises to less than 500 ft in depth within the fine-grained deposits of the central graben.

The shallow hydrochemical zone of Laney (1972) was subdivided areally into four subregions on the basis of dissolved-solids concentration intervals of (1) less than 300 mg/L; (2) between 300 and 500 mg/L; (3) between 500 and 1,000 mg/L; and (4) greater than 1,000 mg/L. For the shallow hydrochemical zone, Laney (1972, pl. 2) delineated areas of poor water quality adjacent to the Santa Cruz River, along the Santa Cruz Fault, and adjacent to Black Mountain. Within the uppermost 700 ft of saturated sediments, total dissolved solids in the ground water decreases slightly in areas where the predominant texture is coarser than silt and clay (Laney, 1972, p. 20) and the calcium sodium ratio generally decreases (Laney, 1972, fig. 4) with increasing depth.

Areal and depth variations in water quality are spatially coincident with facies changes, which in turn reflect changes in sediment composition and texture (Laney, 1972, pl. 1-4). Laney (1972, p. 40) stated that differing mineralogy due to provenance and not dominant particle size controls the natural water quality. Most ground water in the shallow zone contains less than 300 mg/L dissolved solids, and over 75 percent of the shallow ground water contains less than 500 mg/L dissolved solids. The poor quality water adjacent to the Santa Cruz River and the Santa Cruz Fault contains large proportions of calcium, sulfate, and chloride (Laney, 1972, p.19). The TCE contamination occurs in the upper part of the shallow hydrochemical zone. The largest contaminated area occurs in waters that are predominantly a calcium bicarbonate to calcium sodium bicarbonate type with 300 to 500 mg/L total dissolved solids.

Areal Distribution

Areas where ground water in the upper aquifer zone and regional undivided aquifer may contain TCE concentrations of more than 5 µg/L, which is the Environmental Protection Agency and State of Arizona maximum contamination level, are shown in figure 6. The areas were delineated on the basis of TCE concentrations in water samples from wells penetrating the upper aquifer zone or upper part of regional undivided aquifer. The concentrations shown in figure 6 are from samples collected between January and November 1984. TCE concentrations in water samples from about 90 wells ranged from not detected to 3,100 µg/L within the upper zone and from not detected to 92 µg/L within the lower zone.

Placement of monitor wells used to delineate the extent of TCE contamination was primarily guided by geohydrologic data and previously drilled monitor wells and a need to identify both the areas of highest concentration and the perimeter of the contaminated area. Using those guidelines resulted in a relatively biased areal distribution of data points (fig. 6), which in turn makes statistical analysis of the data of limited value in describing the nature of the contaminant distribution. One measure of intrinsic sample variation is the percentage difference between

duplicate samples from the same location and pumping event. The difference in TCE concentration between duplicate samples ranges from 0 to 56 percent depending on concentration levels and the laboratories doing the analysis. Thus, the intrinsic sample variation could be in excess of 50 percent for some locations. Because of this intrinsic sample variation at sample locations and the complex spatial distribution of the contaminant that undoubtedly exists, estimation of TCE concentrations at points away from sample locations involves considerable uncertainty.

On the basis of the present (1984) data for the upper aquifer zone, three distinct areas of TCE contamination were delineated (fig. 6). Two small areas are located adjacent to the municipal airport and industrial facilities in T. 15. S., R. 14 E., secs. 7, 18, and 17. The major area of TCE contamination is north of the Hughes Access Road and south of Ajo Way and trends N. 75° W. in R. 14 E. and N. 13° W. in R. 13 E. The major area of contamination is more than 35,500 ft long and is spread over about 5 mi². The elongated shape of the major contaminated area (fig. 6) has an average width of 4,000 ft.

Distinct areas of contamination were not delineated for the lower aquifer zone because of the sparsity of data. Existing data, however, indicate that little TCE has reached the lower aquifer zone. Water samples that contain 5 µg/L of TCE or more were obtained from four monitor wells—SF-19, M-3b, M-12b, and M-26—that penetrate the lower aquifer zone and are near water-supply wells open to both aquifer zones. Ground water near these monitor wells may be contaminated from downward movement of contaminated water within the supply wells. As of 1984, seven municipal and five private water-supply wells were discontinued from production because TCE concentrations were in excess of 5 µg/L.

Vertical Distribution

An example of the vertical distribution of TCE is shown on plate 1. The hydrologic section B-B' is subparallel to the present (1984) hydraulic gradient and illustrates both the vertical distribution and flow-path distribution of TCE in shallow ground water along the major contaminated area. Concentrations of TCE along this section range from 0.8 to 3,100 µg/L in the upper aquifer zone and from not detected to 38 µg/L in the lower aquifer zone. The lower zone, however, contains little TCE along section B-B'. The nonzero concentration at well SF-19 may be attributed to cascading water in nearby municipal wells B-87 and B-101 (fig. 6).

Vertical stratification of TCE was identified in adjacent pairs of wells in the southeastern part of the contaminated area in secs. 29 and 30 of T. 15 S., R. 14 E. and was also identified at the Carranza site by Thompson and Thomson (1983). The large difference in concentration between the Carranza domestic supply well and the nearby SF-16 monitor well (fig. 6) may be in part related to sampling from different vertical

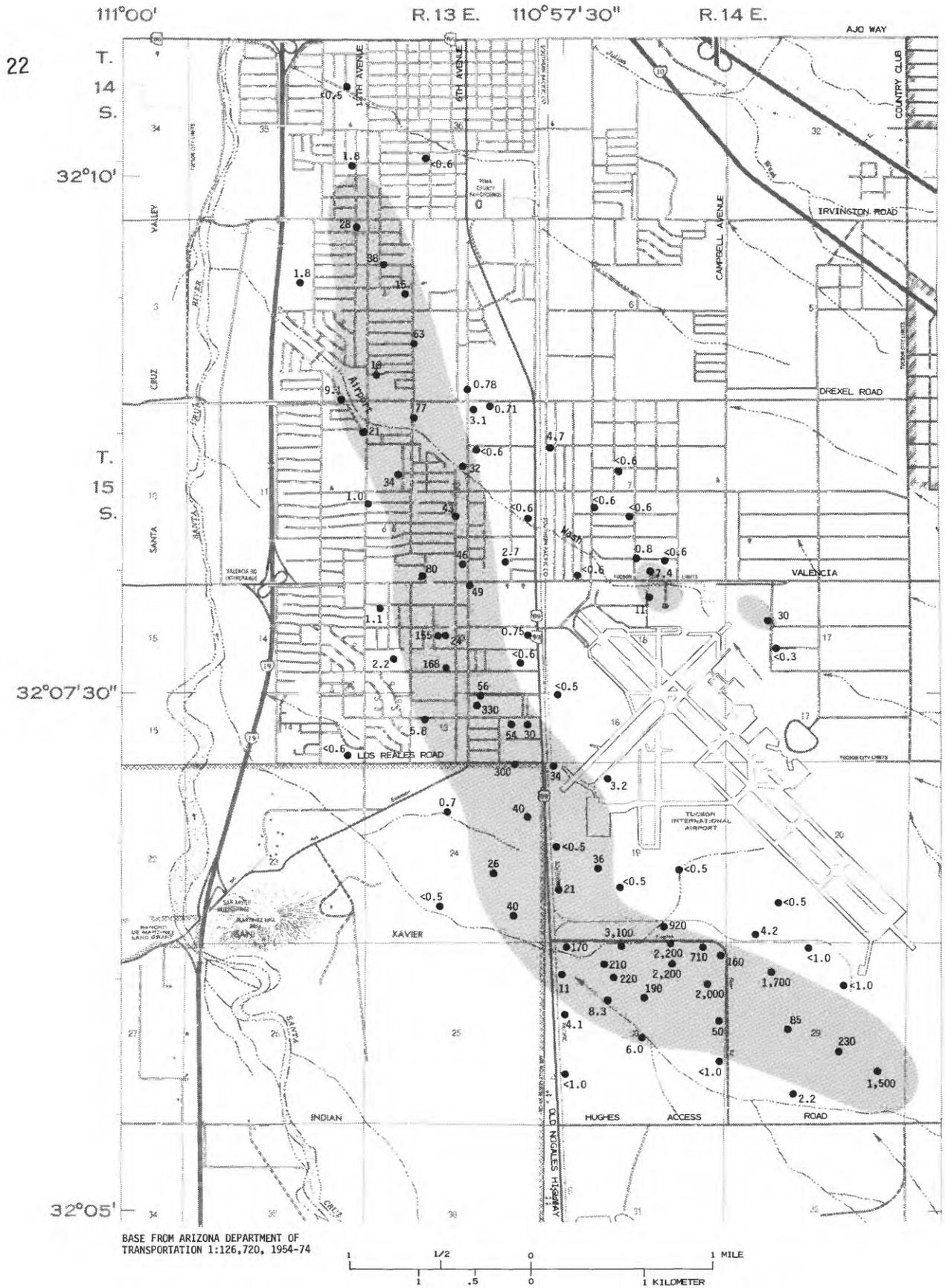


Figure 6.--Trichloroethylene concentrations in the upper aquifer zone and regional undivided aquifer from samples collected between January and November 1984. Samples were collected from wells open to various vertical intervals.



- 1700

APPROXIMATE AREA OF TRICHLOROETHYLENE
CONCENTRATION IN GROUND WATER GREATER
THAN 5 MICROGRAMS PER LITER

WELL—Number, 1700, is sampled trichloroethylene
concentration, in micrograms per liter

Figure 6

intervals. The Carranza well samples are from the uppermost 8 ft of the upper aquifer zone whereas SF-16 samples are from about 40 ft of saturated thickness near the top of the upper aquifer zone. The ratio of TCE concentrations in the Carranza well to that of SF-16 is 5.9:1, and the ratio of saturated contributing intervals is 0.2:1. If most of the TCE is near the water table, some of the difference may be accounted for by dilution from water of lower concentration. This dilution is a feature common to areally applied pollutants such as nitrates (Robertson, 1979). The wells are about 300 ft apart; therefore, some of the difference in concentration may also be related to areal variations in concentrations within the upper aquifer zone. Samples from adjacent monitoring wells, WR-56b and WR-56c, also exemplify the vertical variation of TCE in the central part of the contaminated area. Both wells have 20 ft of contributing interval; the deeper well, WR-56b, yields samples with higher TCE levels (pl. 1). These samples indicate vertical variation across a fine-grained layer within the upper aquifer zone.

Temporal Distribution

The temporal distribution of TCE in time frames of less than a day are much more difficult to assess than the spatial distribution of TCE. Almost all samples taken by the Task Force and consultants were obtained from pumping wells that were discharging for various elapsed-time intervals (10 to about 720 minutes) at a substantial range in discharge rates (as much as 114 gal/min). This procedure resulted in a wide range of sampling volumes. For wells that were sampled more than once, the concentrations shown in figure 6 and on plate 1 are from the longest elapsed pumping times sampled.

Many wells were sampled for TCE two or more times during a pumping interval. In general, the concentrations of TCE during these short tests were relatively constant regardless of contributing-interval size, magnitude of TCE concentration, or aquifer zones sampled. Some decrease in concentration occurred in many wells within the first 100 minutes and then remained at a nearly constant value between 400 and 720 minutes. Stratified water-chemistry samples with flowmeter and temperature logs from unpumped wells and composite samples from wells pumped for long-term aquifer tests may help identify the locations and proportions of mixing. These types of samples and geophysical logs may also help characterize the general vertical distribution within the more transmissive portions of the upper aquifer zone.

Temporal distribution of TCE concentrations in samples that span months or years were analyzed for wells in various parts of the main contaminated area. In the northwestern or downgradient part of the contaminated area, TAS-9, Ricke, WR-58b, WR-59b, are referred to as group 2 wells. Noriega and TAS-6 in the central part of the contaminated area are referred to as group 1 wells. B-9, Credit Union, and M-7 in the southeastern part of the contaminated area are referred

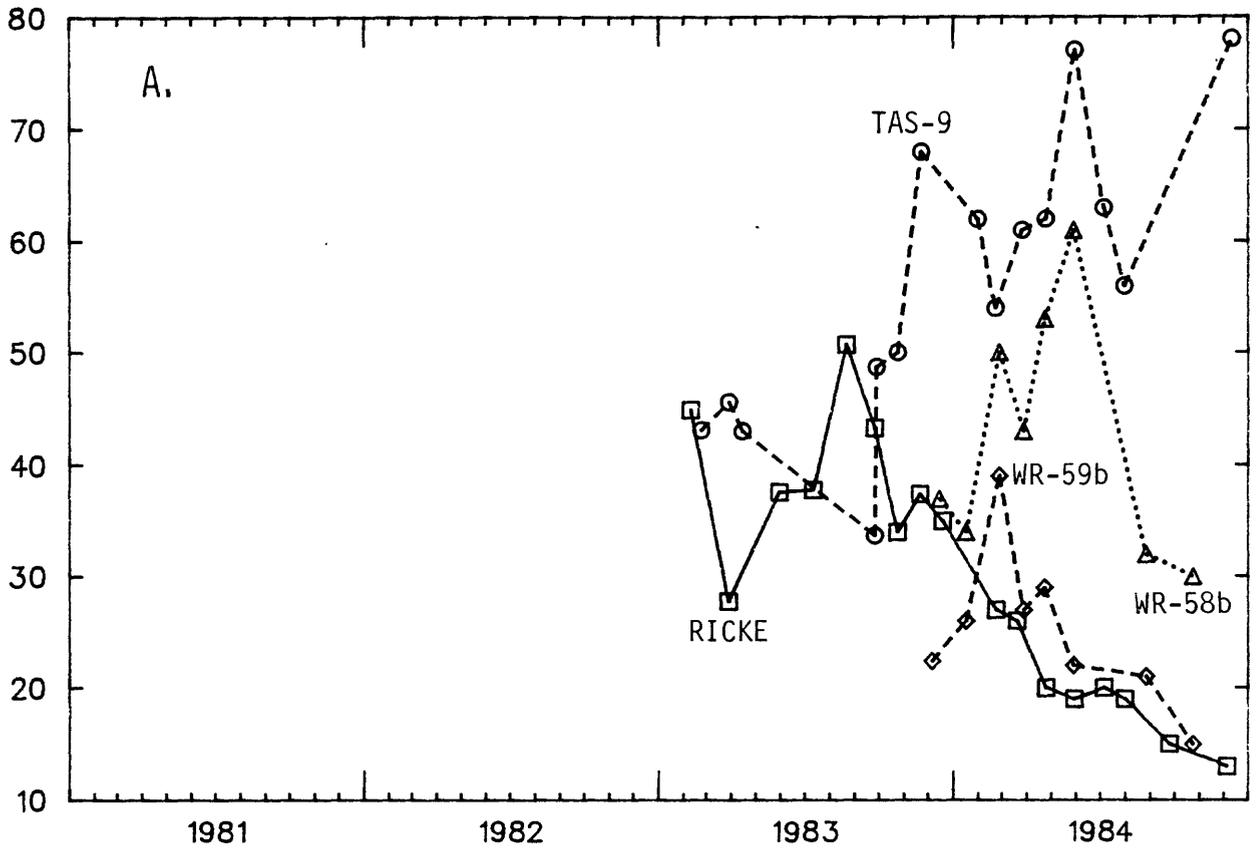
to as group 3a wells. M-8, M-9, and M-2b are near group 3a wells but contain significantly lower levels of contamination and are referred to as group 3b wells. Wells were selected on the basis of the number of samples available for temporal analysis.

If the temporal distribution of TCE is viewed over periods longer than a day, the data are still insufficient for determining changes in concentration with time in the contaminated area. The distribution of TCE concentration for group 1 and group 2 well samples are shown in figure 7. Water levels generally are constant over the 23-month time span covered by the TCE samples. The wells in group 1 are in an area where other data indicate that vertical concentration gradients may exist. The monitor well, TAS-6, has a greater contributing interval than the adjacent Noriega domestic well and contained about 60 percent of the TCE concentrations of the Noriega well samples (table 1). Samples from both wells show a slightly decreasing trend in TCE concentration with time during the last 12 months of record (fig. 7). On the basis of seven samples, no significant correlation was indicated between TCE concentrations in the Noriega well and TAS-6. Wells in group 2 are more than a mile down the present (1984) flowpath from the group 1 wells, yet the range of TCE concentrations is comparable. Samples from group 2 wells generally show smaller temporal variations in TCE concentration than group 1 wells. TCE generally has increased with time at TAS-9 and generally has decreased with time at Ricke. TCE in samples from WR-58b generally has increased with time; but the last two samples contained TCE concentrations less than that of initial samples. TCE in samples from WR-59b generally has decreased with time. Samples from two wells—TAS-9 and WR-58b, which are adjacent to and down hydraulic gradient from Airport Wash—show a similar pattern of concentrations with time. The other two wells—WR-59b and Ricke—have samples with smaller variations in TCE concentrations that are not aligned with TCE variations at TAS-9 or WR-58b. The causes of these variations and groupings of variations may include domestic well pumping in the upper aquifer zone and infiltration of runoff along Airport Wash.

Table 1.--Summary of trichlorethylene concentrations at selected wells

Sample group number	Well name	Time span of samples, in months	Number of samples	Mean, in micrograms per liter	Standard deviation, in micrograms per liter	Coefficient of variation
1	Noriega	23	17	52	13	0.25
	TAS-6	23	18	33	8	.24
2	Ricke	23	17	30	11	.37
	TAS-9	23	15	56	13	.23
	WR-58b	11	8	43	11	.26
	WR-59b	11	8	25	7	.28
3a	Credit Union	41	34	1,699	1,455	.86
	M-7	38	24	2,919	1,219	.42
	B-9	42	17	1,173	285	.24
3b	M-9	38	15	384	198	.52
	M-8	38	13	190	34	.18
	M-2b	41	17	190	76	.40

CONCENTRATION, IN MICROGRAMS PER LITER



CONCENTRATION, IN MICROGRAMS PER LITER

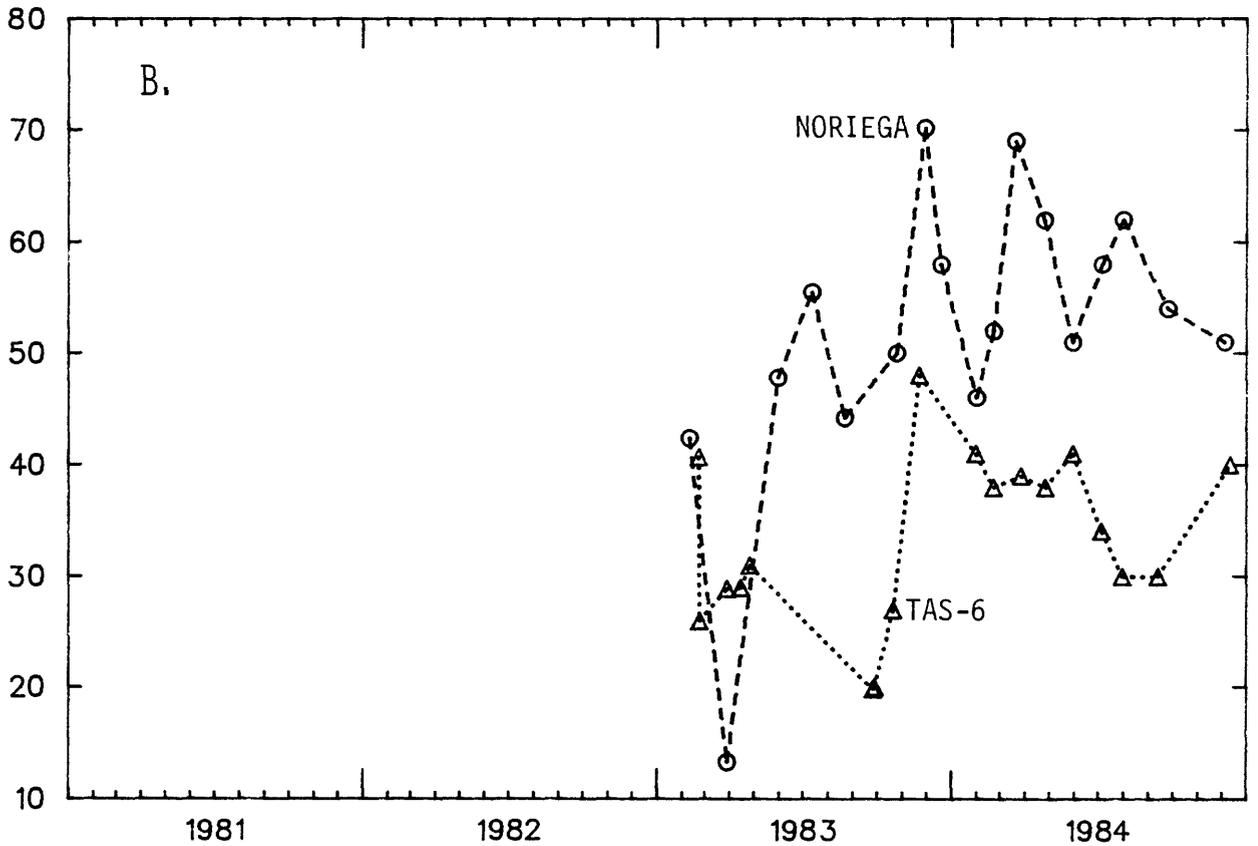


Figure 7.--Temporal distributions of trichloroethylene concentration in ground water from selected wells north of Los Reales Road. A, Group 2 wells. B, Group 1 wells.

Temporal variations in TCE concentrations were large in the southern part of the contaminated area, group 3a and 3b wells (fig. 8 and table 1). The TCE concentration at well B-9 (completed in the perched aquifer zone) is about twice that at well M-9 (completed in the upper aquifer zone) within a vertical interval of less than 100 ft. On the basis of six samples, significant correlation was not indicated for TCE concentrations or water-level altitudes between these two wells. TCE concentrations at B-9 remained generally constant while TCE concentrations at M-9 declined within this 42-month period. During this interval, TCE concentrations tended to increase with increasing head at B-9 and decrease with increasing head at M-9.

Wells M-2b and M-9 shown on section B-B' have contributing intervals of 40 and 75 ft (a ratio of 0.53:1), respectively, within the upper aquifer zone and a mean TCE concentration ratio of 0.53:1, which may indicate a direct relation of TCE and size of contributing intervals near these wells. The direct relation between TCE and contributing interval is the opposite from SF-16 and the Carranza well, or TAS-6 and the Noriega well in the central part of the contaminated area. The differing relations between contributing interval and concentration of TCE in the southern part of the contaminated area may be, in part, due to a complex spatial distribution of TCE in wells completed beneath the perched aquifer zone. Samples from these two wells indicate opposing trends of concentration with time until February 1984. Concentrations at M-9 ranged from more than twice the concentrations at M-2b from February 1982 samples to almost comparable concentrations between February and December 1984 samples. M-8 is just down the present (1984) hydraulic gradient from M-2b and has a comparable contributing-interval altitude. In contrast to M-9, the patterns of TCE concentrations are similar for samples from M-8 and M-2b. M-2b and M-8 show an increase in TCE with increase in head. The sample correlation coefficient for TCE between these two wells is 0.84 (at the 99 percent significance level for 10 samples).

M-7 is farther down the general flow path of section B-B' and northeast of M-8, M-9, and M-2b. M-7 is completed over an altitude interval comparable to M-9, and samples from M-7 show large variations in TCE and increasing TCE concentrations with time (fig. 8). Significant correlation for TCE between M-7 and M-8 was not indicated on the basis of seven samples. The increase in TCE with increase in head at M-7 is about 18 times greater than that at M-8 or M-2b. The higher TCE concentrations, increasing time trend, and higher sensitivity of TCE to head changes at well M-7 versus the temporal behavior at wells M-9, M-8, and M-2b may be due in part to the large concentration gradients perpendicular to the hydraulic gradient in this southern part of the main contaminated area (fig. 6).

TCE concentrations from the Credit Union well and M-7 display similar temporal variations and time trends at comparably high levels of TCE (fig. 8). The sample correlation coefficient for TCE between these two wells is 0.89 (at the 99 percent significance level for 12 samples).

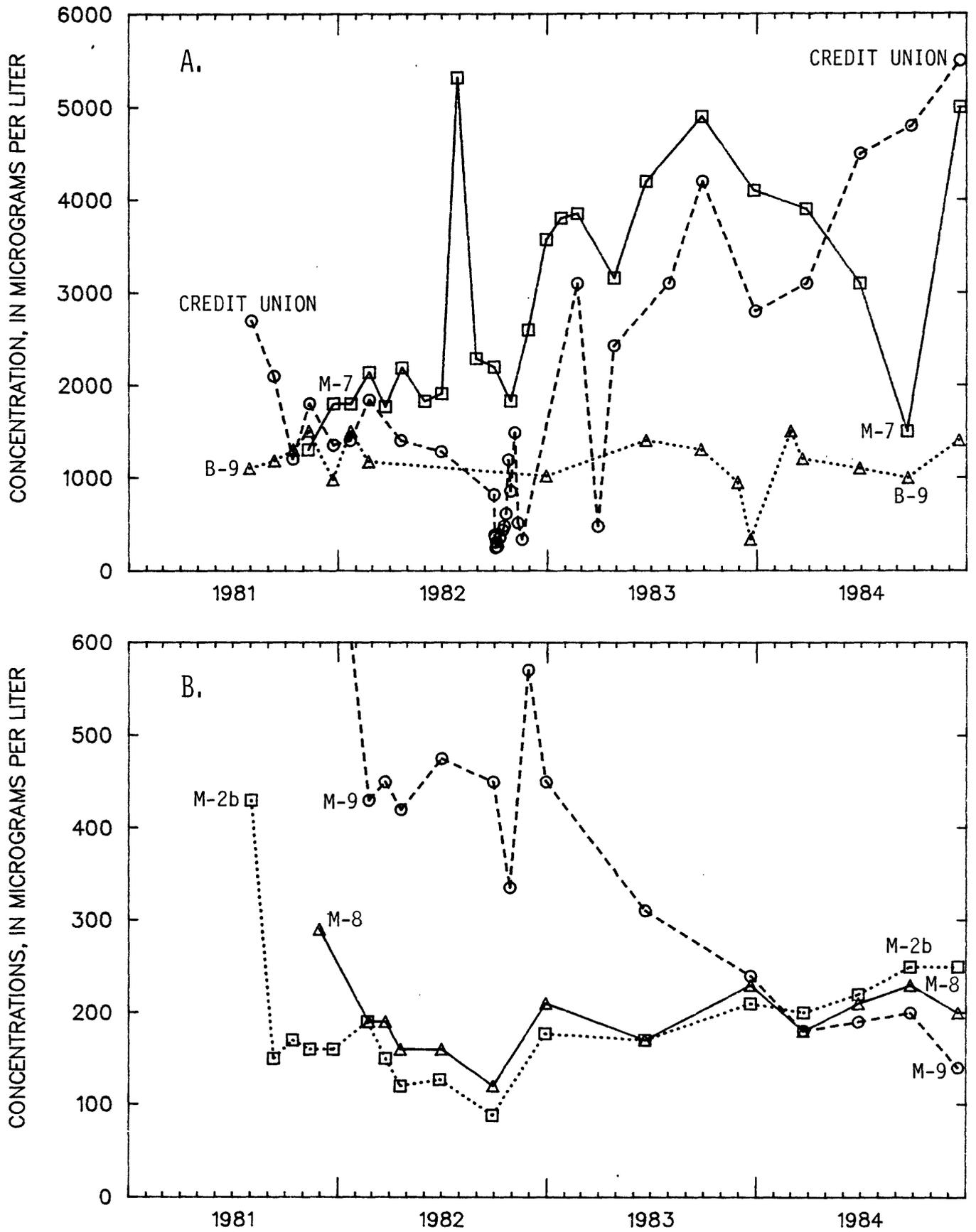


Figure 8.--Temporal distributions of trichloroethylene concentration in ground water from selected wells south of Los Reales Road. A, Group 3a wells. B, Group 3b wells.

TCE at M-7 and the Credit Union Well are increasing in time at a comparable rate. When head increases, TCE concentrations decrease at the Credit Union well while increasing at M-7. These relations demonstrate the importance of sealing off supply wells that were completed over large contributing intervals, as they can serve as conduits for pollution to enter water supplies and lower aquifer zones that are under less hydraulic head than the contaminated aquifer zones (pl. 1). A higher frequency of sampling for the Credit Union well between September and November 1982 show concentration variations over time periods shorter than a month.

Contaminant Movement

The present (1984) distribution of TCE contamination is the result of more than 30 years of introducing TCE (Rampe, 1985) into the ground-water flow system from one or more locations. The distribution of TCE is also controlled by the distribution of pumping and hydrogeologic conditions. Most suspected sources of TCE were from application at the land surface. Such application probably resulted in complex flow paths through the unsaturated zone and perched aquifer zone down to the upper aquifer zone. The contaminated study area is in the western part of the Tucson basin beneath south-central metropolitan Tucson. Most of the TCE occurs in the upper aquifer zone. Small amounts of TCE have also moved down to the lower aquifer zone through borehole mixing in water-supply wells completed over large contributing intervals.

Small amounts of TCE are also volatilizing from the water table into the unsaturated zone. A high correlation between soil-gas and ground-water TCE concentrations was established in the southwestern part of sec. 19, T. 15 S., R. 14 E. (Marrin, 1984b). Marrin (1984b) estimated a vapor flux of 2×10^{10} ($\mu\text{g}/\text{mi}^2$)/yr from a 0.2 mi^2 site. The lowest rate estimated for part of Marrin's study site was 9×10^7 ($\mu\text{g}/\text{mi}^2$)/yr.

The movement of TCE to the water table may be a tortuous path in the southern part of the contaminated area. D. K. Kreamer (written commun., 1985) found a negative correlation between TCE concentration in soil gas and cumulative precipitation. Several of the TCE time distributions show peaks that coincide with major precipitation events. These peak concentrations may indicate that TCE is redissolved or remobilized during infiltration through the unsaturated zone in the contaminated area. On the basis of low TCE concentrations from soil-gas samples below the small arroyo adjacent to M-6, Marrin (1984b) also suggest that a small depletion of contaminated soil gas and ground water occurs from localized recharge along these small arroyos.

The highest values of TCE reported for the perched zone and upper aquifer zone indicate that the TCE concentrations have not exceeded 1 percent of the reported solubility limit. Unless TCE is concentrating on the top of fine-grained layers, TCE, based on data from

pumped wells, is generally acting as a dissolved constituent in the ground-water flow system. The percentage increase in density of the ground water from TCE contamination appears to be insignificant.

Movement of TCE in the upper aquifer zone is areally coincident with the higher permeability sediments along the west margin of the study area. The main contaminated area is bounded on the east-northeast by the refracted head contours that hinge along the edge of the central-basin fine-grained facies. The vertical distribution is probably nonuniform over most of the contaminated area because of the complex lithology and location and pumpage of wells that are completed over large contributing intervals that tap both the upper and lower aquifer zones, and resultant ground-water velocity distribution. The rate of TCE movement is difficult to estimate on the basis of the temporal and spatial distribution of the contaminant as defined by existing contaminant-concentration data. Estimates of contaminant movement based on ground-water velocities may also be difficult due to the variable spatial distribution of permeability and hydraulic gradients.

CONSIDERATIONS FOR DETAILED QUANTITATIVE STUDIES OF CONTAMINANT MOVEMENT

At least two previous studies have developed numerical models of transport of TCE in part of the contaminated ground-water flow system. One of the models was developed by Hargis and Montgomery (1982c) and another was developed by Mock and others (1985). Both models simulate areal, two-dimensional ground-water flow and contaminant transport. Mock and others (1985, p. 34) recognized that a two-dimensional model may be inappropriate for simulation of contaminant movement from the upper aquifer zone into the regional undivided aquifer. Their model was used to determine a range of transport parameters and to determine the extent of contamination under different source distributions. The transport model developed by Hargis and Montgomery (1982c) was used to determine transport parameters and to determine the extent of contamination from sources in the southern part of the contaminated area. Both model studies were completed during the period of initial basic-data acquisition and recommended periodic updates and refinements made on the basis of new geologic and hydrologic information.

Future studies that incorporate new information in more detailed transport simulations may include the following objectives:

1. To determine which physical properties are most significant in the complex geohydrologic environment of the study area and to determine the degree to which they can be quantified as input parameters.

2. To estimate spatial and temporal distributions of contaminant inflow and ground-water flow that could result in the contamination distribution observed in the aquifer.
3. To estimate potential rates of future contaminant movement assuming future pumping stresses in the aquifer system.

Quantitative methods or approaches to simulation of transport developed for future analyses may most appropriately be thought of as tools to help understand the transport processes rather than as precise simulators of past and future contaminant movement.

For most simulations of contaminant movement, average velocities are computed with equations describing ground-water flow. The velocities are used in equations that describe contaminant transport. A general advection-dispersion equation for three-dimensional contaminant transport is given by Konikow and Grove (1977, p. 15, eq. 38) as

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i} \left(D_{ij} \frac{\partial C}{\partial x_j} \right) - \frac{\partial}{\partial x_i} (C V_i) + \frac{C' W^*}{\varepsilon} + \sum_{k=1}^s R_k ,$$

where

- C = concentration,
- t = time,
- x_i = cartesian coordinates, $i = 1, 2, 3$,
- D_{ij} = components of coefficient of dispersion tensor,
 $i, j = 1, 2, 3$,
- V_i = components of seepage velocity, $i = 1, 2, 3$
- C' = concentration of solute in source or sink fluid,
- W^* = volume flux of recharge or discharge per unit volume,
- ε = effective porosity,
- s = number of reactions removing or adding solute,
- R_k = rate of production of solute for reaction k.

Konikow and Grove (1977, p. 23) also derive an equation for two-dimensional horizontal transport of a solute. They point out that if vertical variations in head or concentrations are significant, the equation does not precisely describe areal solute transport. That observation could be extended to say that the two-dimensional equation does not precisely describe areal solute transport if vertical variations in velocity are significant, regardless of whether or not head varies vertically.

The actual distribution of ground-water velocity in the study area is undoubtedly complex. To apply any numerical-modeling technique, some averaging is necessary for velocity as well as for concentrations and hydraulic and dispersive characteristics of the aquifer. For example, if the problem of contaminant transport in the upper aquifer zone is to be treated as being strictly horizontal, the horizontal components of the velocity vector and concentration must be averaged over the vertical dimension. In the three-dimensional advection-dispersion equation, components of velocity and concentration appear as products. The average or expected value along a vertical for the product of velocity and concentration is not equal to the product of the average values unless one or both are constant along the vertical or unless the covariance of the two distributions is zero. Because the sediments in the study area include interbedded fine- and coarse-grained units and concentrations are known to vary with depth, there is reason to carefully consider the uncertainties in using a two-dimensional transport equation. Insight into the applicability of various approaches to averaging could be gained by conducting numerical experiments with two- and three-dimensional contaminant-transport models or by comparison of areal and cross-sectional simulations from a two-dimensional model. In the experiments, hypothetical horizontal and vertical transport could be simulated. The results could be compared with results from corresponding horizontal simulations using vertical averaging. Experiments such as these could lead to insight into the way in which the transport-simulation problem should be approached.

Although determination of an optimum approach to modeling contaminant transport may require additional research, some general considerations for future modeling studies can be presented on the basis of the current knowledge of the ground-water flow system. The considerations relate to description of lateral model boundaries, selection of ground-water flow equations, selection of solute-transport equations, and collection of additional data.

Lateral boundaries of a model ideally should correspond to real boundaries of the flow system, which are low-permeability rocks of mountain ranges that bound the basin. Models that consider flow in the entire basin, however, cannot practically provide sufficiently detailed velocity distributions for studies of the movement of the contaminant. An alternative approach would be to construct a detailed model of the flow system with artificial boundaries. These boundaries delineate a flow region within which past, present, and future movement of the contaminant is of interest. These boundaries can be used if the head distribution is known along the boundary, or if the distribution of flux normal to the boundary is known. Because flow in the system is transient, conditions at the lateral boundaries must be known for the past, present, and future. In other words, the boundaries must initially describe the flow system for predevelopment steady-state conditions and then incorporate the effects that later stresses, inside and outside the modeled region, have on the flow system at the locations of the artificial boundaries.

The description of the flow system at the location of the boundaries is a complex problem that may be approached with a larger scale model of ground-water flow in the Tucson basin. At least two such models exist or are currently (1984) under development. A model of ground-water flow in the Tucson basin is under development by the U.S. Geological Survey (T. W. Anderson, hydrologist, U.S. Geological Survey, written commun., 1984). Travers and Mock (1984) developed a regional ground-water flow model that included the upper Santa Cruz basin. Ideally, the regional-flow model used to study boundary conditions should have the same vertical discretization as the flow model used to compute velocity distributions in the contaminated region. The model developed by Travers and Mock (1984) incorporates the entire saturated flow system into one model layer in which flow is horizontal. The model being developed by the Survey discretizes the flow system into two layers; the upper layer corresponds to the Holocene alluvium and Fort Lowell Formation and the lower layer corresponds to the Tinaja beds and Pantano Formation. Regardless of which regional-flow models are available for future studies, the specification of boundary conditions will undoubtedly require serious consideration and careful evaluation of the flow system beyond the contaminated region.

Another important consideration in future studies of contaminant movement is selection of ground-water flow equations. In the upper aquifer zone where most of the contamination is present, vertical components of ground-water flow probably are small. Wells at the same location that are open to different vertical intervals in the upper aquifer zone have approximately equal water levels. Significant vertical-flow components probably exist at the edge of the confining layer that separates the upper aquifer zone from the lower aquifer zone. Because the ground-water contamination extends from the upper aquifer zone across the edge of the confining layer and into the regional undivided aquifer, the problem of determining vertical-flow components must be addressed. Flow that moves horizontally in the upper aquifer zone with vertical components where the confining layer ends can be studied with a ground-water model that solves equations describing three-dimensional flow. The model must be capable of simulating the effects of a moving free surface at the water table. Additionally, the model must be capable of treating aquifer storage as a function of space as well as a function of hydraulic head.

For future studies, selection of solute-transport equations may require testing some assumptions. Numerical experiments can be conducted to gain insight into which solute-transport equations are most appropriate. In many models of contaminant movement, equations include a term to describe increases or decreases in the amount of contaminant in the system from various reactions. In modeling the movement of TCE in the study area, Hargis and Montgomery, Inc. (1983c) treated the contaminant as a nonreactive tracer. No known published scientific literature presents evidence that suggests that adsorption or other chemical reactions significantly affect the mass of TCE in solution in aquifers such as the one in the study area. TCE is a volatile organic compound, however, and studies by the University of Arizona indicate

that some of the contaminant may be leaving the system by gaseous diffusion through the unsaturated zone overlying the contaminated area (Marrin, 1984b). Although estimates of mass flux by volatilization are relatively small, additional studies relating this mass flux to that of ground water transport are warranted. Until more is known about how reactions of any type affect transport of TCE in ground water, treatment of TCE as a conservative tracer may be the most appropriate.

Collection of additional data may be warranted during and after future model studies. Reliability of models generally increases with decreasing numbers of unknown characteristics. Data on past water levels, past withdrawal rates, and past contaminant-inflow rates cannot be obtained in the present. Additional information that would lead to an improved understanding of how contaminants move in the system, however, can be obtained. Future detailed quantitative studies would benefit from continued or additional collection of data relating to the following spatial distributions: (1) Contaminant concentration in the aquifer with emphasis on determining vertical distributions in the aquifer zones; (2) the effects of degradation of volatile organic compounds on transport and spatial distribution; (3) head in the aquifer system, particularly in the regional undivided aquifer where definition is poor; (4) pumping rates; and (5) physical and hydraulic characteristics of the aquifer, such as storage coefficient, hydraulic conductivity, saturated thickness, porosity, and dispersivity. Insight into some physical and hydraulic properties as well as ground-water and contaminant-movement velocities could be obtained by conducting multiple-well tracer tests. Future studies would benefit particularly from additional data collected in the area where the confining layer ends and the contaminant is moving into the regional undivided aquifer.

SUMMARY

Investigations since 1981 have revealed three distinct areas of ground water contaminated by TCE near Tucson International Airport. The largest of the three areas is about 35,500 ft long and 4,000 ft wide. That area of contamination is elongated in the direction of ground-water movement as indicated by contours of hydraulic head in the upper part of the flow system. Most of the TCE contamination occurs in the upper 100 ft of saturated alluvium. Downward movement of the contaminated ground water is restricted in some areas by poorly permeable layers.

Areal, vertical, and temporal variations in TCE concentration generally are high within the major area of contamination. In 1984, measured concentrations were as high as 3,100 micrograms per liter. Concentrations of TCE from samples taken at different times follow distinct trends at some locations, but temporal trends in concentration are highly variable within relatively short distances.

For future studies of contaminant movement, vertical movement of contaminated ground water may be an important consideration.

Numerical experiments may be of value in determining which solute-transport equations are appropriate for simulation of contaminant movement in the study area. Future studies also may benefit from collection of additional TCE concentration and head data, particularly in areas where contaminated ground water moves vertically as well as horizontally.

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