POTENTIAL FOR GROUND-WATER CONTAMINATION FROM MOVEMENT OF WASTEWATER THROUGH THE UNSATURATED ZONE, UPPER MOJAVE RIVER BASIN, CALIFORNIA

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By Amjad M.J. Umari, Peter Martin, Roy A. Schroeder,

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U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 93-4137

Prepared in cooperation with the

CALIFORNIA REGIONAL WATER QUALITY

CONTROL BOARD—LAHONTAN REGION

7208-13

Sacramento, California

1993

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Conversion Factors, Vertical Datum, Abbreviations, and Well-Numbering System

Multiply	By	To obtain
acre	0.4047	hectare
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per year (acre-ft/y)	0.001233	cubic hectometer per year
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon per day (gal/d)	0.003785	cubic meter per day
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	259.0	hectare
square mile (mi^2)	2.590	square kilometer

Temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation:

$$°F = 1.8(°C) + 32.$$

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

ABBREVIATIONS

CFU/g:	Colony-forming units per gram
CFU/100 mL:	Colony-forming units per 100 milliliters
g:	gram
mL:	milliliter
mg/kg:	milligram per kilogram
µg/kg:	microgram per kilogram
mg/L:	milligram per liter
µg/L:	microgram per liter
µS/cm:	microsiemen per centimeter at 25 degrees Celsius

Wells are numbered according to their location in the rectangular system for subdivision of public lands in California. For example, in well number 4N/3W-15C1, the part of the number preceding the hyphen indicates the township (T. 4 N.) and range (R. 3 W.); the number following the hyphen indicates the section (sec. 15); and the letter (C) following the section number indicates the 40-acre subdivision. Within the 40-acre subdivision, wells are sequentially numbered in the order in which they are inventoried (1). The area covered by this report lies in the northwest quadrant of the San Bernardino base line and meridian.
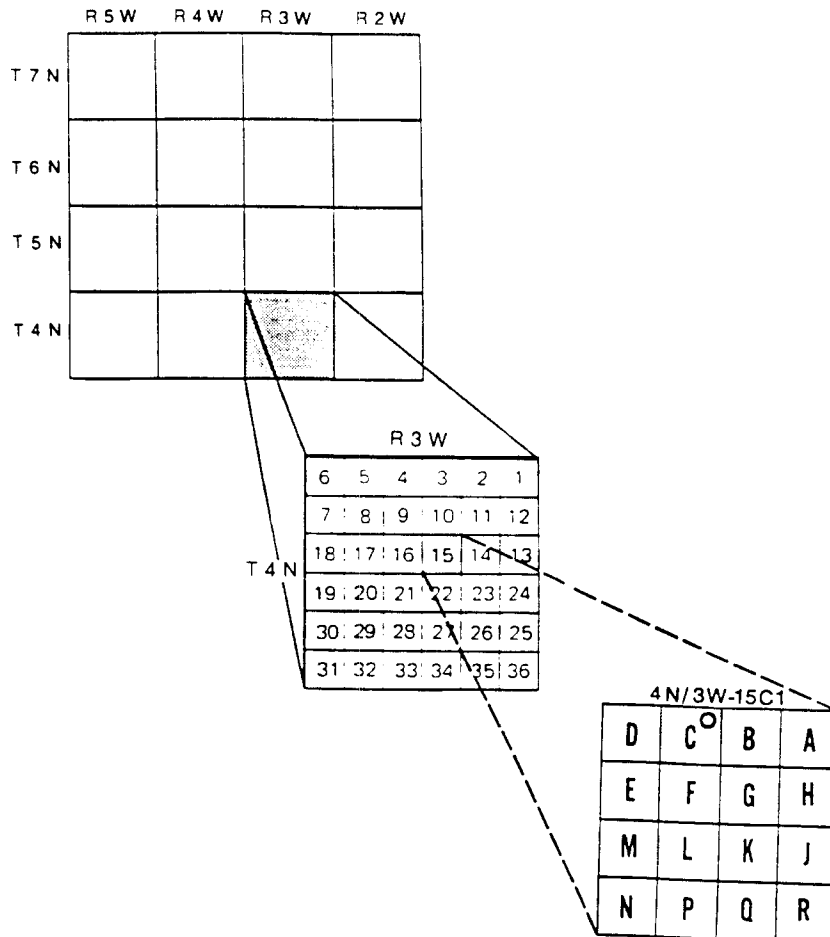
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ABSTRACT

Septic-tank wastewater disposed in 30-foot-deep seepage pits (dry wells) at 46,000 residences is estimated to equal 18 percent of the natural recharge to the sole-source aquifer in the rapidly developing upper Mojave River Basin (Victor Valley) in the high desert northeast of Los Angeles. Vertical rates of movement of the wastewater-wetting front through the unsaturated zone at three newly occupied residences ranged from 0.07 to 1.0 foot per day. These rates translate to traveltimes of several months to several years for the wastewater-wetting front to reach the water table and imply that wastewater from many disposal systems already has reached the water table, which averages about 150 feet below land surface in the Victor Valley.

Dilution by vertical mixing in the saturated zone and retention of the wastewater in the unsaturated zone could also explain the observed low nitrate concentrations in the ground water. Results of a single-cell mixing model that allows nitrate from wastewater to be mixed instantaneously with the underlying ground water suggest that measurable increases in nitrate concentration should be expected within 5 to 10 years after wastewater reaches the water table if the mixing depth is less than 100 feet.

As wastewater percolates from seepage pits into the adjacent unsaturated zone, the nitrogen present in reduced form is rapidly converted to nitrate. Analyses on soil-core extracts and soil moisture from suction lysimeters installed beneath the seepage pits at eight residences showed that nitrate concentrations and nitrate/chloride ratios generally become lower with increasing depth. The intervals of greatest decline seemed to coincide with finer soil texture or were near the water table. Nitrate-reducing bacteria were tested for and found to be present in soil cores from two residences. Sparse nitrogen-15 data from suction lysimeters at one of these residences, where the nitrate concentration decreased by about one-half at a depth of 200 feet, indicate that the nitrate decline was accompanied by nitrogen-15 enrichment in the residual nitrate with an isotope-separation factor of about -10 permil.

Despite the potential input of abundant nitrogen with the domestic wastewater recharge, nitrate concentrations in the area's ground water are generally low. The absence of high nitrate concentrations in the ground water is consistent with the existence of denitrification, a microbial nitrogen-removal mechanism, as wastewater moves through the thick unsaturated zone and mixes with the ground water.

Although high fecal coliform densities were measured in wastewater from septic tanks and seepage pits, removal of these enteric bacteria in the unsaturated zone is very effective, as was indicated by their absence in soil only a few feet from the seepage pits. In testing for organic priority pollutants in wastewater, 17 of 85 compounds were detected. Most compounds detected were present in low concentrations, except at one residence where the concentration of three compounds exceeded 100 micrograms per liter. These high concentrations may be a consequence of disposal practices unique to this residence. Extractable organic priority pollutants were not found in any soil cores taken adjacent to seepage pits and, therefore, are not of concern.

INTRODUCTION

About one-quarter of all inhabitants of the United States dispose of sewage by means of onsite septic systems (Brown and others, 1979) that have the potential to contaminate the receiving waters (Boyle and Otis, 1979). The main cause of failure of these systems has been variously reported to be poor operation and maintenance (Viraraghavan, 1986), unsuitable soils (Duda and Cromartie, 1982), and excessive septic-tank density (Yates, 1985). These conditions exist locally at some residences and regionally in some parts of the upper Mojave River Basin.

Disposal of domestic wastewater from 46,000 residences in the upper Mojave River Basin (Frank Merrill, Al-Desert Septic Systems, Inc., written commun., 1991) is predominantly by discharge of septic-tank effluent to seepage pits (dry wells) from which the wastewater percolates into the unsaturated zone. Rapid population growth in this high-desert area northeast of Los Angeles has led to concern, particularly because alternative public-water supplies are not currently available, that these wastewater-disposal practices could contaminate or pose an increasing threat of contamination to the sole-source aquifer that underlies the area.

To respond to this concern, the U.S. Geological Survey, in cooperation with the California Regional Water Quality Control Board—Lahontan Region, began a study in 1988 that had the following objectives:
1. To determine the rate of movement of wastewater through the unsaturated zone and whether wastewater reaches the water table.
2. To determine whether constituents in the wastewater, primarily nitrogen and fecal coliform bacteria, reach the water table.
3. To evaluate the current and potential effects of wastewater contaminants, particularly nitrate, on ground-water quality in the upper Mojave River Basin.

Purpose and Scope

This report presents results of a study on the movement of septic-tank wastewater and associated contaminants through the unsaturated zone at eight sites chosen to represent a range in (1) geohydrologic conditions, (2) years of seepage-pit operation, and (3) sewage-effluent loading as represented by six single-family and two multiple-family residences. The vertical rates of wastewater movement were estimated from neutron-probe data. Water-quality data in the unsaturated zone were obtained from soil cores and from suction lysimeters. Ground-water-quality data were obtained from suction lysimeters

(where they were installed below the water table) and from shallow monitoring wells installed in a part of the study area containing numerous residences that dispose of wastewater in seepage pits. Available ground-water-quality data from 20 wells in the study area also are presented in this report.

The last samples collected as part of the original agreement under which this study was funded were taken in January 1990. Data from additional sampling of lysimeters at three sites (Cajon, Vasquez, and Cheyenne-I) were obtained after September 1991 with the financial support of the U.S. Geological Survey's Regional Aquifer-System Analysis study in southern California desert and coastal basins, and selected results are included in this report. Additional data and discussion of results from the ongoing sampling at the Cajon site are published in Schroeder and others (1993).

Acknowledgments

Holes drilled at the eight wastewater-disposal sites were on private residences, and thus the authors are indebted to the homeowners. The authors also thank the members of a Technical Advisory Committee consisting of local citizens, business owners, and government officials for helpful guidance, and especially the Apple Valley Ranchos Water Company and Hi-Desert Septic Systems for providing space to store drilling equipment and supplies and providing buildings for use as field laboratories.

DESCRIPTION OF STUDY AREA

General Features

The upper Mojave River Basin is in the Mojave Desert region of southern California, about 80 miles northeast of Los Angeles (fig. 1). The study area includes the part of the upper Mojave River Basin adjacent to the Mojave River that locally is referred to as the Victor Valley. The approximately 180-mi^2 study area includes the communities of Victorville, Apple Valley, and Hesperia.

The Mojave River, which bisects the study area, originates in the foothills of the San Bernardino Mountains and flows northward toward Victorville. In the upper Mojave River Basin, perennial streamflow occurs only in the mountains and near Victorville where a basin constriction created by shallow bedrock, locally referred to as the "Narrows," causes ground water to discharge to the river. An aerial photograph of the dry river channel near the study area is shown in figure 2.

The climate of the upper Mojave River Basin is typical of the arid high-desert region of southern California. It is characterized by low precipitation, low humidity, high summer temperatures, and strong winds at certain times of the year (Hardt, 1971, p. 5). Average annual precipitation at Victorville is 5.1 inches (National Oceanic and Atmospheric Administration, 1989).

Land use in the study area is predominantly residential (fig. 3). Most of this residential development occurred in the 1980's, reflecting the inland growth of the Los Angeles megalopolis. In 1990, the population of the upper

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Mojave River Basin was about 200,000 (California Regional Water Quality Control Board, written commun., 1991). Prior to the 1980's, most of the study area was undeveloped. Earlier, development of agricultural and residential areas occurred primarily along the Mojave River (California Department of Water Resources, 1967, p. 9).

Ground water historically has been the sole source of water in the upper Mojave River Basin. In the study area, water for municipal and industrial use is supplied by large-capacity supply wells. Water from these wells is delivered to individual residences and industrial sites by a series of pipelines. Only a few domestic wells exist in the study area.

Most of the study area is unsewered (fig. 3). The use of shallow leach fields to dissipate wastewater from septic tanks is not possible because of the presence of low-permeability caliche layers in most of the study area. Instead, the wastewater from septic tanks is discharged into deep seepage pits (dry wells). The seepage pits are typically about 5 ft in diameter, about 30 ft deep, and are lined with bricks or blocks with unmortared joints that allow rapid percolation of the wastewater into the unsaturated zone. A photograph of a newly constructed septic tank and seepage pit is shown in figure 4.

Geohydrology

Geologic Units

The geologic units in the study area are grouped into two broad categories according to their water-bearing characteristics: non-water-bearing and water-bearing formations (California Department of Water Resources, 1967, p. 18). The outcrop pattern of the geologic units is shown in figure 5, and stratigraphic and structural relations are shown in a geologic section in figure 6.

The non-water-bearing (basement complex) formations include metamorphic and igneous rocks of pre-Tertiary age and sedimentary continental rocks of Tertiary age. These formations underlie the basin and form the surrounding mountains and hills. The Tertiary sedimentary rocks include some water-bearing units; however, yields from wells generally are low, and most of the water is of poor quality (California Department of Water Resources, 1967, p. 26).

The water-bearing formations of the upper Mojave River Basin resulted primarily from erosion of the surrounding mountains. These formations consist of gravel- to clay-size material and generally become more consolidated and less permeable with increasing depth. The water-bearing formations include younger alluvium of Holocene age, and old lake and lakeshore deposits, older alluvium, older fan deposits, landslide breccia, Shoemaker Gravel, and the Harold Formation of Pleistocene age (California Department of Water Resources, 1967).

The younger alluvium, as used in this report, includes the river deposits, dune sand, younger alluvium, and younger fan deposits mapped by the California Department of Water Resources (1967). These deposits generally are the most permeable of all the geologic units and, where saturated, yield large quantities of water to wells. In the study area, the younger alluvium is

saturated only beneath the Mojave River channel (fig. 6). Throughout the remainder of the study area, the younger alluvium is only a veneer overlying older materials.

Old lake and lakeshore deposits are exposed in several places east and west of the Mojave River near Victorville (fig. 5). The old lake deposits consist predominantly of silt and clay and are generally less than 75 ft thick. Where saturated, the old lake deposits yield little water to wells, and where unsaturated, percolation rates are very low. The lakeshore deposits are remnants of sand and gravel bars of Late Pleistocene lakes (California Department of Water Resources, 1967, p. 23) and are generally permeable.

The older alluvium underlies most of the study area and ranges in thickness from a few feet to more than 250 ft beneath the Mojave River channel (fig. 6). The deposits consist of unconsolidated to consolidated gravel, sand, silt, and clay. In the Hesperia area these deposits yield water freely to wells; however, in parts of Apple Valley the water-yielding characteristics of these deposits are poor. Caliche deposits near land surface in much of the area prevent the percolation of rainfall, and deep seepage pits extending below the caliche deposits must be constructed to discharge wastewater from septic tanks.

The older fan deposits are exposed along the flanks of the highland areas (fig. 5). These partly consolidated deposits consist of poorly sorted gravel, sand, silt, and clay. Reported well yields from the older fan deposits are variable but generally are low (California Department of Water Resources, 1967, p. 24). As in the areas of older alluvium, the older fan deposits in places are cemented with caliche near land surface, requiring the installation of seepage pits to discharge wastewater from septic tanks.

The other water-bearing formations are well below the water table in the study area and have no effect on the movement of wastewater.

Recharge and Discharge

The principal source of natural recharge in the upper Mojave River Basin is precipitation in the San Bernardino Mountains south of the study area. Most of this recharge occurs as percolation of floodflows in the Mojave River mountain front and is estimated to average 40,000 acre-ft/yr for the period 1931-92 (G.C. Lines, U.S. Geological Survey, written commun., 1993). Smaller sources of recharge to the upper Mojave River Basin are runoff from the San Gabriel Mountains (9,300 acre-ft/yr) and subsurface inflow from Lucerne Valley (250 acre-ft/yr) (Hardt, 1971). Direct infiltration of precipitation on the basin floor is considered negligible because, in most places, potential evapotranspiration greatly exceeds annual precipitation. In addition, the presence of shallow caliche deposits throughout much of the basin impedes the percolation of precipitation.

Discharge occurs naturally from the basin as evapotranspiration, streamflow (base flow), and subsurface outflow at the "Narrows" near Victorville, where a basin constriction caused by shallow bedrock forces ground water to the surface. Natural ground-water discharge, however, is significantly less than municipal and agricultural pumpage. Total pumpage from the upper Mojave River Basin in 1990 is estimated to have been 124,000 acre-ft

(Jack Clark, Apple Ranchos Water District, written commun., 1991).
Historically, most of the pumpage was from the younger alluvium along the
Mojave River channel. As development in the area has expanded, pumpage from
the older deposits has increased. Part of the pumped water returns to the
basin as irrigation return flows and septic-tank wastewater. Evapo-
transpiration is estimated to be 9,000 acre-ft/yr (Hardt, 1971, p. 43). Base
flow was about 8,000 acre-ft/yr in 1990 (G.C. Lines, U.S. Geological Survey,
written commun., 1992), and subsurface outflow at the "Narrows" is estimated
to be 350 acre-ft/yr (Slichter, 1905, p. 63).

Recharge		Discharge	
Mojave River	40,000	Pumpage	124,000
Mountain front runoff	9,300	Evapotranspiration	9,000
Subsurface inflow	250	Base flow	8,000
		Subsurface outflow	350
	49,550		141,350

Net loss = 91,800 acre-ft/yr if pumping return flows are ignored.

As stated above, septic-tank wastewater discharged to seepage pits
installed to depths below the shallow caliche deposits decreases the net
pumpage (total pumpage-returns) from the basin. In 1990, there were
approximately 46,000 septic-tank systems in use in the upper Mojave River
Basin area (Frank Merrill, Hi-Desert Septic Systems, Inc., written commun.,
1991). Assuming an average septic-tank discharge of 70 (gal/d)/person
(Bookman-Edmonston Engineering, 1991), and 2.5 people per household, annual
septic-tank wastewater discharge is estimated to have been 9,000 acre-ft/yr in
1990, equal to about 18 percent of the estimated natural recharge to the
basin.

Ground-Water Levels and Movement

In general, ground water adjacent to the Mojave River flows from south
to north. East and west of the Mojave River, ground water flows toward the
river. Pumping in Apple Valley has resulted in local water-level depressions
(John S. Murk Engineering, Inc., and LeRoy Crandall and Associates, 1985,
p. 3-11).

Depth to ground water generally increases from the center of the basin
toward the surrounding mountain ranges and their upward-sloping alluvial fans.
Depth to water in the study area ranges from less than 50 ft beneath the
Mojave River to more than 400 ft below land surface at Hesperia, west of the
river (fig. 6). In Apple Valley the depth to water ranges from 100 to 150 ft
north of Bear Valley Cutoff and from 150 to more than 400 ft south of Bear
Valley Cutoff (Subsurface Surveys, Inc., 1990, pl. 4).

Ground-water pumpage exceeds natural recharge to the basin, and water levels are declining throughout the study area (fig. 7). The water-level declines have been largest in the Apple Valley area (fig. 7), where water levels have declined by almost 50 ft since the early 1950's. Most of the observed water-level decline in the Apple Valley area has occurred since the rapid increase in residential development during the 1980's.

Ground-Water Quality

The chemical character of water from selected wells (on the basis of available data collected during 1978-90) is shown in figure 8. The water-quality diagrams in figure 8 depict the concentrations of major cations and anions, and give an approximate indication of total-ion content. The dissolved-solids concentration of samples from the wells shown in figure 8 is given in table 1.

Samples from wells adjacent to and west of the Mojave River generally have dissolved-solids concentrations less than 200 mg/L. Dissolved-solids concentration of samples from wells east of the river is dramatically higher, ranging from 113 mg/L (4N/3W-07P01), within 0.5 mi of the river, to 1,030 mg/L (4N/3W-15C01), more than 3 mi from the river (fig. 8 and table 1). The water-quality diagrams indicate that composition of the water also differs significantly. Most of the samples from wells east of the river contain much higher concentrations of chloride than do samples from wells adjacent to and west of the river. The distributions of dissolved-solids concentration and water composition are similar to those shown by California Department of Water Resources (1967, pl. 6) for 1967. This earlier study was completed prior to most of the development in the area and suggests that the source of the high dissolved-solids concentrations is geologic, rather than anthropogenic.

A gravity survey of the study area (Subsurface Surveys, Inc., 1990, pl. 3) indicates that the basement complex rises sharply toward land surface east of the Mojave River (fig. 6), underlying areas where dissolved-solids concentrations are observed to be high. The rapid rise in altitude of the basement complex suggests the presence of a fault that has uplifted the basement complex east of the Mojave River (fig. 6). In any case, the depth to the basement complex and the overlying continental deposits of Tertiary age (where they have not been removed by erosion) decreases rapidly east of the river. Therefore, wells east of the river could penetrate the low-permeability continental deposits at shallower depths than wells west of the river. This observation is supported by Hardt (1971, fig. 8), who showed that transmissivity decreases sharply toward the mountains east of the Mojave River. As stated previously, the continental deposits contain water of poor quality and are presumed to be the source of the high dissolved-solids concentrations east of the Mojave River.

Available nitrate data obtained from wells during 1978-90 are given in table 1 as nitrite plus nitrate as nitrogen (NO_2+NO_3-N). Nitrate-N concentrations generally are less than 2 mg/L throughout the study area-- considerably less than the U.S. Environmental Protection Agency (1976) maximum contaminant level of 10 mg/L for drinking water. Because nitrite concentrations generally are negligible, the concentrations given in table 1 are virtually the same as nitrate concentrations.

The low nitrate concentrations in the upper Mojave River Basin are of particular interest because ground-water nitrate concentrations commonly are high in areas where wastewater is discharged from septic-tank systems (Bouwer, 1978). The movement of nitrate from the septic tank through the unsaturated zone to the underlying ground water and its effect on nitrate concentrations in the ground water will be addressed in subsequent sections of this report.

SAMPLING AND ANALYSIS

Site Selection

Test holes for studies in the unsaturated zone were drilled at eight sites (fig. 9) chosen to represent a range in geohydrologic conditions, years of seepage-pit operation, and residential density. All sites are located away from areas of either current or historical agricultural land use (fig. 3). Residential density, date of seepage-pit construction, surface geology, and other pertinent characteristics of each of these sites are given in table 2.

At four of the eight sites (Cheyenne-I and -II, Choctaw, and Cajon), sampling devices were installed below the water table to determine possible effects of wastewater on ground-water quality. In addition, two multiple-well monitoring sites (fig. 9) were installed--one upgradient (Apple Ranchos) and one downgradient (Rincon) of a group of mostly older residences that dispose of wastewater in seepage pits--to determine the importance of dilution by vertical mixing in the saturated zone. Construction specifications of all ground-water-sampling devices and monitoring wells are given in table 3.

Test Drilling and Instrumentation of Study Sites

Test holes for installation of suction lysimeters and neutron-probe access tubes were drilled using a 9.75-inch-diameter hollow-stem auger at seven of the eight sites and using the ODEX drilling method at the Cajon site because of the greater depth (more than 250 ft) to the water table. Cores were taken from each of the test holes using an 18-inch stainless steel split-spoon core barrel driven into the undisturbed material ahead of the drill or auger bits.

The ODEX method is a reverse-air drilling system that allows a casing to follow the bit as the hole is drilled. When completion depth is reached, the drill stem and bit are pulled through the casing and the casing then is pulled from the borehole. However, during the process of pulling the casing at the Cajon site, the 6-inch steel casing ruptured, leaving the hole cased from 184 to 262 ft below land surface (on the basis of caliper measurements). The entire length of this unrecovered casing was perforated in place, at 3-inch intervals with eight 1 1/2-inch by 3/16-inch vertical slots spaced equidistant around the casing. These perforations, which constitute slightly less than 2 percent of the casing's surface area, allow for the exchange of moisture between the unsaturated zone and the three lysimeters installed within the casing at depths of 199, 243, and 257 ft.

Suction lysimeters were installed at several depths in at least one test hole (lysimeter hole) at each of the eight residential sites to monitor the movement and quality of wastewater in the unsaturated zone (table 4). At six

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of the eight sites, lysimeter holes were drilled within about 5 ft of the seepage pits. At two of the new-residence sites (Toltec and Vasquez), the hole was drilled through the bottom of the (as-yet-unused) seepage pit. At Cheyenne-I and Choctaw, a second test hole for installation of suction lysimeters was drilled 25 and 50 ft, respectively, from the seepage pit to ascertain possible lateral movement of wastewater. The suction lysimeters within each test hole were isolated from one another by backfilling the annulus with alternating layers of native material and bentonite powder. The suction lysimeter's porous ceramic cup was encased in silica flour to provide a clean transmission medium for soil water entering the porous cup, to enhance hydraulic contact between the adjoining soil and the cup, and to help prevent clogging of the porous cup by colloids, organic matter, or soil particles (Parizek and Lane, 1970). Typical suction lysimeters and their installation are shown in figure 10A,B.

Suction lysimeters consist of a porous ceramic cup that is attached to a polyvinyl chloride pipe that is connected to land surface by two access tubes (fig. 10C). Two types of suction lysimeters, each about 2 ft long, 1.9 in. in diameter, and having a nominal pore size of 1.4 μm were used for this study: (1) single chamber (for installation depths less than 50 ft below land surface) and (2) double chamber (for installation depths greater than 50 ft). Many of the single-chamber lysimeters, as indicated in table 4, were damaged before the study was completed. A possible explanation for the high failure rate of the single-chamber lysimeters is that excess pressure was applied to the access tubes during sampling, resulting in separation of the tubes from the lysimeter.

At four of the sites (Toltec, Vasquez, Little Beaver, and Cheyenne-II), a test hole (neutron-logging hole) was drilled within 5 ft of the seepage pit for installation of a 2-inch galvanized-steel access tube, which was used for measuring moisture content by neutron logging. The annular space was backfilled with native material and with a 2- to 3-foot plug of bentonite powder opposite clay-rich zones.

A summary of monitoring devices installed and analyses completed at each study site is given in table 5.

Analysis of Soil Cores and Pore Water

Core material from the upper part of the split-spoon core barrel was placed in a plastic bag, air-dried for several days, then stored for later analysis of grain size. Material from the lower part of the split-spoon core barrel was taken for determination of moisture content and for selected chemical and bacterial analyses.

Physical Analyses

Color, lithology, and qualitative indications of moisture content were determined by field inspection as the cores were recovered. Subsamples were dried and placed in ziplock plastic bags for later analysis of grain size. Grain-size analyses were done according to methods described by American Society for Testing and Materials (1988, p. 87-93). Sieves were used for the sand and gravel fractions, and hydrometers were used for the clay and silt

fractions. Results of these grain-size analyses for the eight residential sites (which are shown graphically in figures 12 and 13 later in this report) are given in table 6.

Gravimetric moisture content of core material was determined by comparing the original weight of the sample (approximately 100 grams) with its dry weight (dried to a constant weight at 100 to 105°C for 12 to 18 hours). Measured moisture contents, expressed in percent of wet sample weight, are given in table 7. Variability in determinations of moisture-content results from natural inhomogeneity and from moisture loss in the field, even during brief exposure of the core material to the high winds and very low humidity common in the study area, prior to weighing the soil (especially for those samples with very low moisture content). Five subsamples of a core collected from 67 to 69 ft in the neutron hole at Vasquez demonstrate this variability: Measured moisture contents range from 12.1 to 16.5 percent (the mean value of 15.5 percent is given in table 7).

Chemical Analyses

Core extracts for determination of pore-water (or interstitial water) chemistry were prepared by adding 300-mL of deionized water to approximately 100 g wet weight of core material. The relative proportion of water and soil used in the extraction was a compromise between use of enough water to permit processing and chemical analysis, but not so much water as to cause detection problems from excessive dilution. This soil-and-water mixture was placed in a polypropylene centrifuge tube with screw-top cap and agitated vigorously on a wrist-action shaker for about 30 minutes, then centrifuged for 1 hour at 5,000 revolutions per minute (producing a centrifugal force of 5,000 times gravity). The resulting liquid "extract" contains diluted pore water plus any soluble salts (minerals) and exchangeable cations extracted (leached) from the solid phase.

The extract was analyzed for specific conductance and pH in the field laboratory and for ammonia (NH_3), nitrate (NO_3), chloride (Cl), boron (B), and total alkalinity (Alk) at the USGS National Water-Quality Laboratory in Arvada, Colorado, using methods described by Fishman and Friedman (1989). The results of these analyses are given as computed pore-water concentration in table 7 (and in fig. 13 presented later). Pore-water concentrations are computed from the measured concentrations in the extracts using the equation:

$$C_p = C_e \frac{W + W_p}{W_p},$$

(1)

where
    C_p is the computed concentration in the pore water,
    W is the weight of deionized water used in extraction,
    W_p is the weight of pore water held by the soil sample, and
    C_e is the measured concentration in the extract solution.

The large dilution that results during extraction leads to substantial uncertainty in computed pore-water concentrations, especially for those samples with very low moisture content. Additional sources of error are in the

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measurement of soil moisture and chemical analyses, along with natural inhomogeneity between subsamples (discussed previously). (See Feltz and others, 1985, and Fishman and Friedman, 1989, for general information on analytical precision and detection limits.) A quantitative assessment of precision in computed pore-water concentrations was not attempted for this study, and the precision is likely to be quite variable (depending on soil texture, soil moisture, and chemical concentrations). However, semi-quantitative evaluation of the sources listed above, and qualitative comparison to data obtained from lysimeters and from core extracts at adjacent depths, yields an overall uncertainty estimated to range from about 30 to about 50 percent.

In addition to the dilution errors, there is some ambiguity in interpretation of pore-water concentrations for sparingly soluble constituents. Highly soluble constituents, such as NO_3^-, Cl^-, and probably B, are not affected by such considerations. However, NH_4^+ is strongly sorbed, especially by ion-exchange on clays. Specific-conductance data from one core sample extracted with varying soil-to-water proportions (range was from 2:1 to 1:4) revealed the additional dissolution of sparingly soluble minerals and (or) a shift in the relative proportion of major cations in the extract at the greater dilutions. Although alkalinity is presumed to be similarly affected, values of pH varied less than 0.1 pH unit over this entire range of dilution.

Data for nitrate that are given in this report include the analysis of nitrate plus nitrite; however, because nitrite (a transient form of nitrogen that generally undergoes rapid biological transformation in nature) is present in quantities that are much less than the quantities of nitrate, results are referred to throughout this report simply as "nitrate."

Microbiological Analyses

All microbiological analyses of core material and wastewater were done in the field laboratory, which was equipped with an autoclave, refrigerator, incubators, filtration apparatus, and microscope. Analyses included total heterotrophic bacteria (standard plate count), fecal coliform, and nitrifying and nitrate-respiring (including denitrifying) bacteria. Standard methods of analysis described by Britton and Greeson (1987) were used.

The stainless steel split-spoon core barrel was flame-sterilized prior to collection of each core. Exterior parts of the core that were in contact with the liner were removed with a sterile spatula, and a small quantity of soil from the interior was excised and placed in a sterile "whirl-pak" plastic bag. The bag was stored on ice or refrigerated until analyses were begun (usually within 6 hours of sample collection).

The membrane filtration (MF) method was used for analysis of total bacteria (standard plate count) and fecal coliform. Ten grams (wet weight) of soil was dispersed into 90 mL of sterile phosphate (with peptone) buffer. Six successive decimal (10x) dilutions (total dilution factor of 10^{-7}) were prepared from the mixture to produce ideal plate counts. Aliquots of each dilution were assayed in triplicate. Cellulose acetate nitrate, 0.45-μm membrane filters were incubated for enumeration of total bacteria on Standard Methods agar (extract of tryptone glucose yeast) [manufactured by BBL Microbiology Systems, Cockeysville, Maryland] at 30°C for 24 hours. Filters

for fecal coliform were incubated on M-FC agar [manufactured by Millipore Corp., Bedford, Massachusetts] at 44.5°C for 24 hours. Total-bacteria and coliform counts are reported as CFU (colony-forming units) per gram of wet soil in table 8. The data indicate widespread presence of heterotrophic bacteria but complete absence of fecal coliform in the soil beneath the seepage pits.

The presence of nitrifying and nitrate-respiring (a group of nitrate reducers that includes denitrifiers) bacteria was determined for core samples from two test holes, at Cheyenne-I and Cajon. A three-tube MPN (most probable number) method was used with five order-of-magnitude dilution aliquots inoculated. An ammonium calcium carbonate medium and a nitrite calcium carbonate medium were used for the *Nitrosomonas* and *Nitrobacter* groups of nitrifying bacteria, respectively. Nitrate-broth medium was used for the nitrate-respiring bacterial group. Ten grams of wet soil was dispersed in a dilution blank containing 95-mL of deionized water and glass beads, and from this mixture successive decimal dilutions (to a dilution factor of 10^{-6}) were prepared with deionized water. Culture tubes containing appropriate media were inoculated with an aliquot from each dilution series, and an additional tube of medium was set aside as a control. Results are reported in table 9 as MPN per gram of wet soil with 95-percent confidence interval based on positive and negative results from three 1-, three 0.1-, and three 0.01-milliliter dilutions from each dilution series.

In Situ Monitoring in the Unsaturated Zone

Soil-Moisture Content

Periodic monitoring of soil-moisture content beneath the seepage pits at four sites was done using a neutron-logging instrument. The instrument measures the attenuation of neutrons by hydrogen atoms in water as a neutron source is lowered down the access tube. Moisture content can be determined from neutron logging by calibration to known field soil-moisture contents or, as was done in this study, by using the manufacturer's calibration. Manufacturer's calibration was adequate for this study because the results were used only qualitatively to estimate the rate of vertical wastewater movement. Theory, operation, and calibration of neutron logging are described by Troxler Electronic Laboratories, Inc, (1983).

Weekly monitoring was done at the three new residences (Toltec, Vasquez, and Little Beaver sites) to accurately characterize the initial movement of wastewater. Frequency of monitoring was later reduced to monthly, as was done at the established 2-year-old site at Cheyenne-II. The profiles of soil-moisture content over time are presented (in figure 12) later in this report.

Pore-Water Quality

Time-series water-quality data from the unsaturated zone beneath the seepage pits at all eight residential sites were acquired by frequent sampling of suction lysimeters. Suction lysimeters were sampled by applying a vacuum (about 60 centibars, equal to 40 centibars absolute pressure) greater than soil suction to the interior of a buried porous cup, which induces water to flow from the unsaturated material into the lysimeter. The sampled soil water,

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which is presumed to have been effectively filtered by its passage through the silica flour and ceramic cup, then was forced to land surface by applying nitrogen gas pressure to one tube of the two-tube system (fig. 10C). Although sampling characteristics varied considerably from one lysimeter to another, about 2 to 4 weeks between the evacuation and subsequent application of nitrogen pressure was found to be necessary for maximum accumulation of water within most lysimeter cups. Shorter periods resulted in incomplete recovery and longer periods apparently result in partial loss of the sample through leakage back into the soil.

Following installation, the lysimeters initially were sampled several times (although few of these samples were analyzed) to establish hydraulic contact between the soil moisture and ceramic cup, to remove contaminants associated with the installation process, and to observe the wastewater plume's rapid initial movement through the unsaturated zone. Monitoring was reduced to once a month or less frequently, at both new and established residences, after this short initial period. Determination of specific conductance and pH was done in the field immediately after sample collection. Aliquots were sent in polyethylene bottles to the USGS National Water Quality Laboratory in Arvada, Colorado, for analysis of NO_3^-, NH_4^+, Cl^-, B, and alkalinity (and other constituents in a few samples). Bottles for analysis of nutrients (nitrogen species) were chilled, and mercuric chloride was added as a biocide. Water-quality data from the suction lysimeters are presented in table 10.

Suction lysimeters provide the only practical means for obtaining an in situ water sample from the deep unsaturated zone. However, some investigators have questioned whether the chemical quality of lysimeter samples is representative of the soil water. Possible problems include contamination of the sample by lysimeter materials, variability of intake rates of the lysimeters, inability to collect sufficient sample volume, inhomogeneities in the flow regime, and the effects of chemical disequilibrium conditions. A study by Peters and Healy (1988) demonstrated that for non-dilute solutions, samples from suction lysimeters that measured major cation and anion concentrations were representative of the natural soil water; however, trace-metal concentrations could be significantly altered by this collection procedure at low concentrations. It was found in this study of the upper Mojave River Basin that once the lysimeter system had been thoroughly flushed by collection of several samples, chemical composition, especially as measured by specific conductance, approached a steady-state value. Unfortunately, the approximately 1-year period for which monitoring was originally budgeted for this study is shorter than ideal, and the frequency of sample collection and analysis may have been too low. The much greater constancy in data acquired after monitoring was resumed at the Cajon site in 1991, as well as the long time required for downward movement of the wastewater (Schroeder and others, 1993), indicates that monitoring should proceed for a few years. It is also probable that the lower variability in concentrations within the wastewater zone is partly due to sample collection by a single individual when monitoring was resumed in 1991 as opposed to collection by several individuals before then.

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Analysis of Tapwater and Wastewater

Water quality was determined in the tapwater (collected from outdoor taps) supplied to the eight residences. The results, given in table 11, can be used to quantify water-quality changes as the water is used and disposed. The wide range in specific conductance of tapwater, from about 200 μS/cm at Toltec, Vasquez, Choctaw, and Cajon to more than 700 μS/cm at Cheyenne-I and -II, reflects areal variations in ground-water quality in the study area that are discussed in the "Ground-Water Quality" section and portrayed in figure 9. Note that nitrate concentration is very low (0.4 to 1.22 mg/L as N) at all sites. Data for a few of the minor (or trace) constituents at the new residences--for example, zinc at Toltec--likely were influenced by leaching from new pipes at the time of sample collection.

Wastewater quality was determined on samples from septic tanks and(or) seepage pits at five of the residential sites (table 12). Access to the disposal systems was achieved by removing about 3 ft of dirt and lifting off the concrete covers. Samples were collected by dipping a glass jar into the wastewater. Access to the seepage pit at Vasquez was through a tube extended to land surface, and sampling was accomplished by lowering a bottom-filling glass bailer with glass-ball check valve. At the time of sample collection at Vasquez, the residence had been occupied for only a short time and the seepage pit contained only a few inches of wastewater. For wastewater samples analyzed for inorganic constituents and organic carbon, solids were removed by centrifugation. Specific organic compound (priority pollutant) analyses were on raw (uncentrifuged) samples, and these results are presented in a later section of this report.

Results of analyses for total bacteria and fecal coliform in wastewater from septic tanks at four residences and from seepage pits at Vasquez and Cheyenne-II are presented in table 13. Methods of analysis were similar to those used for soil samples, and results are expressed in colony-forming units (CFU) per 100 mL of wastewater.

Analysis of Shallow-Ground-Water Quality

Results of ground-water-quality analyses from the multiple-well monitoring sites are given in table 14. These sites consist of three to four 2-inch PVC monitoring wells installed at different depths in the same hole. Perforated intervals of the wells are isolated from one another by low-permeability bentonite grout. A typical multiple-well monitoring site is depicted in figure 11.

Ground water from just below the water table at four of the residential sites also was analyzed. Samples were obtained from a well point attached to the bottom of the neutron-access tube at Cheyenne-II (119 to 123 ft); from suction lysimeters at Cheyenne-I (113 ft), Choctaw (131 ft), and Cajon (257 ft); and from a core recovered during drilling at Cheyenne-I (124 ft). Although data from the ground-water sample recovered during drilling at Cheyenne-I are included in table 13, it is noted that a sample obtained in this manner is less reliable than one obtained from a permanent well or suction lysimeter because the drill auger mixed soil and water in varying proportions from over a fairly broad depth zone.

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MOVEMENT OF WASTEWATER THROUGH THE UNSATURATED ZONE

In order to establish the effect of septic-tank wastewater on ground-water quality of the area, it was important to determine how fast wastewater is moving from seepage pits to the water table. It was thought that low-nitrate concentrations in ground water throughout the area (table 1) indicated that wastewater from septic tanks installed during the 1970's and 80's (the period when most development occurred) had not yet reached the water table. In this study, the movement of the wastewater-wetting front in the unsaturated zone was determined using moisture-content profiles developed from analysis of soil cores, neutron logs, and suction-lysimeter data.

Several studies (Warrick and others, 1971; Ghuman and Prihar, 1980; and Young and others, 1992) have shown that wetting fronts move through the unsaturated zone at rates much raster than the solutes associated with the wetting front. Young and others (1992) theorized that the observed difference was caused by the displacement of pre-existing soil moisture by the applied water. They observed, in field experiments, that the difference between the arrival of the wetting front and the solute front was directly proportional to the water content of the unsaturated zone; larger differences (lags) were observed where the unsaturated zone had a higher pre-existing water content. The rates of wastewater movement presented in this section of the report are representative of the wastewater-wetting front; the movement of the actual wastewater will be much slower.

Moisture-Content Profiles

Moisture content of the unsaturated zone was expected to be very low in areas unaffected by wastewater. A near-surface caliche layer present throughout most of the study area impedes percolation of the scant precipitation that occurs. This hypothesis was tested by selecting a new residence (Toltec) as the initial site to investigate. Field inspection of the soil cores collected at this site indicated that the unsaturated zone beneath the seepage pit indeed was very dry. Laboratory analyses indicate that nearly all the cores had moisture contents of less than about 5 percent, and about half had moisture contents of less than 2 percent (table 7). Therefore, the vertical extent of the wastewater-wetting front can be determined qualitatively by ascertaining whether soil cores beneath an active seepage pit are comparatively wet or dry. This distinction is made with relative ease at new sites, especially in upper parts of the unsaturated zone; however, it is less readily made in lower parts of the unsaturated zone, especially near the water table where moisture content would normally be higher even in the absence of any wastewater. In addition, the water table has declined by almost 50 ft (fig. 7) in some areas, leaving a residual moisture in the unsaturated zone beneath the earlier water table. Further complicating assignments based solely on soil-moisture content is the wide range in grain-size distributions that exists throughout the study area and with depth at individual sites.

Moisture-content profiles were prepared from analyses of soil cores collected between land surface and the water table at five sites (Cheyenne-I, Choctaw, Kiowa, Cheyenne-II, and Cajon) where seepage pits had been in operation for at least 2 years. The profiles are illustrated graphically in figures 12 and 13 presented later in this report. At all five sites, both field and laboratory determinations indicate that the entire unsaturated zone

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beneath the seepage pits was moist. Moisture contents in most soil cores exceeded 10 percent, except in cores containing predominantly sand and gravel (table 7). The presence of comparatively high moisture contents throughout the profiles suggests that the wastewater wetting front had reached the water table at all five selected sites. Chemical analyses of samples from the Cajon site collected after 1991 indicate, however, that wastewater had reached a depth of at least 199 ft, but it had not yet reached the water table, which was at least 260 ft below land surface in 1991. Preliminary results from the resumption of water-quality monitoring after June, 1993, at the Cheyenne-I site also suggest that wastewater may not yet have arrived at the three lowermost lysimeters (equal or deeper than 92.5 ft) in 1988 and (or) that these lysimeters are near or beneath a recently declining water table. A minimum value for the rate of vertical movement of the wastewater-wetting front can be estimated at each site by dividing thickness of the unsaturated zone beneath the seepage pit by length of time that the seepage pit had been in service. These calculated minimum vertical flow rates of the wastewater-wetting front, shown below, served as this study's earliest estimates.

Residential study site	Thickness of unsaturated zone (ft)	Age of septic tank as of April 1988 (years)	Vertical flow rate (ft/d)
Cheyenne-I	87	• 5	0.05
Choctaw	99	10	.03
Kiowa	125	9	.04
Cheyenne-II	92	1.2	.21
Cajon	213	10	.06

Rates determined later with greater precision, using methods that followed movement of the wastewater (neutron logs and lysimeter samples), confirmed that actual rates generally were greater.

The finding of wastewater (comparatively high moisture content) in soil cores collected from holes drilled about 5 to 7 ft from the center of the seepage pit at established sites was the first indication in this study that there may be substantial lateral movement of wastewater as well as vertical movement. The extent of this lateral wastewater movement was further delineated by drilling an additional hole 25 ft from the seepage pit at the Cheyenne-I site and 50 ft from the seepage pit at the Choctaw site. Moisture content of soil cores from both holes was similar to moisture contents of cores from holes adjacent to the respective seepage pits (table 4). Water-quality analyses of soil cores from the Cheyenne-I lateral hole (table 7) and of one suction-lysimeter sample from the Choctaw site (table 10) also are similar to analyses from holes adjacent to the seepage pits. This confirms that wastewater can move laterally 50 ft or more from seepage pits in some locations. Additional discussion of lateral movement based on wastewater discharge and constraints from mass-balance calculations at the Cajon site is given in Schroeder and others (1993).

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Lateral flow can occur in the unsaturated zone wherever a coarse-textured layer of high permeability overlies a finer textured layer of low permeability. With continued infiltration, ponding (a perched water table) occurs just above the boundary of the impeding finer layer (Hillel, 1971, p. 143). Lateral flow also can take place where fine-textured soil overlies a layer of coarse-textured soil (Hillel, 1971, p. 143). Any discontinuities in texture can result in the development of preferential flow paths in the unsaturated zone (Steenhuis and others, 1991); the discontinuities, by implication, could be a major source of variability among water-quality data obtained from suction lysimeters. Finally, low-permeability caliche layers and other cemented layers also can cause lateral movement of wastewater.

Neutron Moisture Logs

Moisture-content profiles were obtained from neutron moisture logs in order to more directly calculate rates of vertical movement of the wastewater wetting front. This approach involved collecting numerous neutron moisture logs from the three new sites (Toltec, Vasquez, and Little Beaver) and one established site (Cheyenne-II). Selected moisture-content profiles that were obtained are shown in figure 12. Vertical movement of the wastewater wetting front is inferred from changes in successive moisture-content profiles. As previously stated, moisture content of the unsaturated zone is very low in areas unaffected by wastewater. Therefore, increasing moisture content in more recent profiles indicates vertical movement of the wastewater wetting front.

The vertical rate of movement of the wastewater wetting front is calculated by dividing the distance the wetting front has moved by the elapsed time (traveltime) between consecutive neutron moisture logs (table 15). Estimated rates range from 0.09 ft/d for the fine-grained consolidated soil between 48 and 67 ft at Little Beaver to 0.79 ft/d for the coarse-grained unconsolidated soil between 35 and 59 ft at Vasquez. In most cases, the estimated rates decrease with increasing depth. In fact, during the period of neutron moisture logging between April 1988 and June 1989, little if any increase in moisture content was measured at depths below about 70 ft at Little Beaver (fig. 12). Inspection of the geologic log for this site indicates that the soils are cemented (consolidated) from this depth to the bottom of the hole. The presence of these cemented soils would be expected to impede vertical movement of the wastewater.

As discussed previously, temporal changes in the moisture-content profiles indicate that vertical movement of the wastewater wetting front initially is transient. However, movement of the wastewater wetting front seems to approach steady-state conditions after the seepage pits have been used for some time, as indicated by very little change in successive moisture-content profiles. A steady-state condition is approached within the upper 80 ft at all the recently occupied sites in less than 1 year (fig. 12). Moisture-content profiles at the established site (Cheyenne-II) also reflect steady-state conditions. (Some changes in the Cheyenne-II profile are believed to be due to rewetting of the backfill that was placed around the neutron-access tube during its installation; this rewetting is most evident (fig. 12) at depths at which bentonite was used as a seal.). Steady-state conditions are established rapidly beneath seepage pits because wastewater discharge to the seepage pits remains nearly constant on a daily basis.

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Suction Lysimeters

Sampling of suction lysimeters provides yet another estimate for the vertical rate of movement of the wastewater wetting front. The approach involved measurements from the periodic sampling for water quality in the suction lysimeters installed at multiple depths beneath the three recently constructed seepage pits (Toltec, Vasquez, and Little Beaver). Very little, if any, water could be extracted from the suction lysimeters prior to arrival of the wastewater wetting front. The vertical rate of movement of the wastewater wetting front is calculated by dividing the vertical distance between suction lysimeters at successive depths by the elapsed time between the first yield of water from suction lysimeters at successive depths. The estimated rates for the different sites are compared (table 15) with rates obtained from neutron moisture logs.

The vertical rate of movement of the wastewater wetting front estimated using the suction-lysimeter data ranged from 0.07 to 1.00 ft/d; this range is similar to the range (0.09 to 0.79 ft/d) estimated from neutron moisture logs (table 15). The lowest rate determined using either method is 0.07 ft/d for the moderately consolidated to consolidated, poorly sorted older alluvium at Toltec and Little Beaver. The highest rate is 1.0 ft/d for unconsolidated silty sand and gravel of the old lake and lakeshore deposits at Vasquez. If these are considered the minimum and maximum rates, respectively, for the movement of the wastewater wetting front in the study area, then the length of time for the wastewater wetting front to travel 150 ft (the average depth to ground water in the study area) ranges from almost 6 months to almost 6 years. These results indicate that the wastewater wetting front from nearly all seepage pits constructed prior to the mid-1980's is likely to have reached the water table, where it is shallower than the average depth of 150 ft, by the end of this study in 1990.

In summary, moisture-content profiles, neutron moisture logs, and suction-lysimeter data all indicate that the wetting fronts resulting from wastewater discharge to seepage pits in the study area reach the underlying water table. Estimated rates for the movement of the wastewater wetting front range from a low of 0.03 ft/d (a minimum estimate based on profiles obtained from direct measurement of soil-moisture content) to a high of 1.0 ft/d (estimate based on suction-lysimeter method). Actual vertical rates of wastewater (solute) movement probably are significantly less than these estimates.

CONCENTRATIONS OF SELECTED WASTEWATER CONSTITUENTS IN THE UNSATURATED ZONE

Septic-tank wastewater is a major potential source of ground-water contamination in the study area. A septic tank separates floating and settleable solids (sludge) from wastewater while discharging the clarified wastewater into a drainfield or seepage pit. The sludge that accumulates at the bottom of the septic tank is decomposed by bacteria. The resulting wastewater contains high concentrations of nitrogen, bacteria, and organic carbon. As the wastewater moves through the unsaturated zone, the concentrations of these constituents--and thus the severity of ground-water contamination--can be greatly affected by physical, chemical, and biological processes. In this study, the concentration and changes in concentration of

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selected wastewater constituents (including nitrogen, total bacteria, fecal coliform, and selected organic compounds) were investigated as wastewater moved from the septic tank to the underlying water table at eight sites.

Nitrogen

Septic-tank wastewater is known to contain high concentrations (40 to 80 mg/L) of nitrogen, (Bouwer, 1978, p. 413). As wastewater moves from the septic tank to a drainfield or seepage pit, and subsequently through the underlying unsaturated zone, both concentration and chemical form (speciation) of nitrogen in the wastewater change. The nitrogen species are interrelated by a complicated series of reactions that collectively constitute the nitrogen cycle. This section of the report includes a discussion of some of the more important reactions of the nitrogen cycle, changes in concentrations of the various nitrogen species as wastewater moves from the septic tank through the unsaturated zone, and possible reasons for the observed changes.

Nitrogen Cycle

Because of the importance of nitrogen to the biological cycle, numerous reports discuss the nitrogen cycle in great detail (Bartholomew and Clark, 1965; and National Research Council, 1978, for example). This section of the report emphasizes the processes of the nitrogen cycle that are important to an understanding of the accumulation of nitrogen and its transformation in wastewater as the wastewater moves from the septic tank through the unsaturated zone. The reader is referred to the references that are given above for a more detailed explanation of the complete nitrogen cycle.

Nitrogen in septic-tank wastewater is predominantly in the form of ammonia (NH_3) and organic nitrogen. (In this report, the term "ammonia" is used for the gaseous form of ammonia (NH_3) and, collectively, for the cationic form (NH_4^+) plus NH_3 when there is no need or intention to distinguish between these forms. "Ammonium" is used specifically to indicate the cationic form.) Under aerobic (oxic) conditions, organic nitrogen in wastewater is converted to ammonia, which, along with ammonia already present in the wastewater, can be oxidized to nitrate (NO_3^-). The conversion is a two-step biological process known as mineralization. The first step (conversion of organic nitrogen to ammonia) is referred to as ammonification and can be accomplished both by aerobic bacteria, which exist in the presence of oxygen, and anaerobic bacteria, which exist in the absence of oxygen.

The second step (conversion of ammonia to nitrate) is referred to as nitrification and is carried out by several different groups of aerobic microorganisms. Nitrification also is a two-step process: the first group of bacteria, predominantly *Nitrosomonas*, oxidize ammonia to nitrite (NO_2^-), and the second group, predominantly *Nitrobacter*, oxidize the nitrite to nitrate (National Research Council, 1978, p. 33). Nitrite usually does not accumulate during nitrification because it is oxidized as rapidly as it is formed.

Nitrogen can be removed from wastewater by sorption and ion exchange, ammonia volatilization, incorporation into cell biomass, plant-root uptake, and denitrification. As wastewater moves through the unsaturated zone, ammonium can be removed by adsorption (including ion exchange) onto soil

particles. If the wastewater is sufficiently alkaline (that is, has high pH), some ammonia may be lost to the atmosphere by volatilization of the gas. This process is more likely to occur in the seepage pit than in soil beneath the pit. Organic nitrogen may be immobilized in soils by adsorption and by incorporation into cell biomass as a result of biological activity. In most soil environments, nitrogen also is removed by plant-root uptake. In this study, however, plant-root uptake is not a significant factor because wastewater is discharged by seepage pits below the root zone.

Denitrification apparently is the main process for the removal of nitrogen from wastewater in the study area. Denitrification is the biochemical reduction of nitrate and nitrite to gaseous nitrogen in the form of molecular nitrogen and (or) nitrogen oxides. This process is carried out under anoxic conditions by many types of soil bacteria that can use the oxidized form of nitrogen as a terminal electron acceptor for respiration where oxygen has been depleted. Denitrification occurs rapidly and completely in soils in which conditions are anaerobic (anoxic) and organic matter is readily available (National Research Council, 1978, p. 44). Continual but slow loss of nitrogen also may occur in moist, fine-textured soils in which conditions generally are oxidizing but anoxic microenvironments are present (Broadbent and Clark, 1965).

Septic-Tank Wastewater

The use of water within residences results in an increase in dissolved concentrations of nitrogen and many other chemical constituents in the wastewater. The magnitude of the increase was calculated by subtracting concentrations in tapwater from concentrations in wastewater sampled from the septic tank or seepage pit at six of the sites (table 16). The calculated differences show a rather large variability, particularly for some of the major ions and boron, among residences. For comparison, calculated differences between wastewater and tapwater concentrations from 3 years of monitoring at a rural residence near Fresno, California (Nightingale and McCormick, 1985), also are included in table 16.

The small range observed in the concentrations of nitrogen, for which the coefficient of variation is 10 percent, and other chemicals during a long period of monitoring at the Fresno residence suggests a relatively constant pattern of water usage among bath, kitchen, laundry, and toilet facilities. Some rather large site-to-site differences observed in this study are believed to be caused primarily by differences in the relative contribution from each of these household uses. For example, the large increase in boron in wastewater at Cheyenne-I and Cheyenne-II suggests greater use of laundry detergents (softeners) in these residences where the dissolved-solids and alkaline-earth (hardness) concentrations of the tapwater are comparatively high.

For dissolved nitrogen, the chemical constituent of greatest interest in this study, site-to-site differences are much smaller than for other constituents (table 16). Increases in total-nitrogen concentrations range from 21 mg/L at Kiowa to 62 mg/L at Cajon (table 16). Because total nitrogen concentrations generally were less than 1 mg/L in the tapwater, the calculated increases are almost the same as the septic-tank wastewater concentrations, which ranged from 22 mg/L at Kiowa to 63 mg/L at Cajon. For the five sites at

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which wastewater from the septic tank was sampled (Cheyenne-I, Choctaw, Kiowa, Cheyenne-II, and Cajon), dissolved-nitrogen concentrations average 47 mg/L (table 17).

Almost all the dissolved nitrogen in the septic-tank and seepage-pit wastewater was in the form of organic nitrogen and ammonia (tables 11 and 17), and little or no nitrate is present in any of the samples. These results are consistent with the absence of oxygen. In addition, methanethiol concentrations ranging from 2 to 11 μg/L were found in wastewater samples during analysis for purgeable (volatile) organic compounds. The presence of methanethiol, which implies not only absence of oxygen but also presence of hydrogen sulfide, indicates that the wastewater is strongly reducing. Although wastewater samples were collected only once, the wide variation among sites in relative proportion of organic nitrogen and ammonia (tables 12 and 17) is consistent with rapid conversion of organic nitrogen to ammonia (ammonification) by bacteria (Cantor and Knox, 1985, p. 75-76; and Khanbilvardi and Long, 1985).

Nitrogen Concentrations and Transformations

This section of the report documents changes in nitrogen concentration and the transformation among different species of nitrogen as domestic wastewater moves from the septic tank through the underlying unsaturated zone. Nitrogen concentrations were determined in pore water (soil-core extracts) (table 7) and suction-lysimeter samples (table 10) collected at eight study sites to document the changes. The nitrate-N concentrations of soil-core extracts and suction-lysimeter samples collected at the eight study sites are shown graphically in figure 13. Also shown are grain-size distributions, soil-moisture content, chloride concentrations of soil-core extracts and suction-lysimeter samples, and numbers of nitrate-reducing bacteria present in soil cores for selected sites. Chloride concentrations are included because chloride is present in septic-tank wastewater and it is physically conservative and biologically unreactive, thereby making it a useful tracer of wastewater movement and transformations in the unsaturated zone. Median concentrations of the different nitrogen species found in the suction-lysimeter samples are given in table 17. Ideally, the last sample collected would be anticipated to be the most representative of actual concentrations in the unsaturated zone; however, median values are chosen instead to minimize any biases resulting from a single anomalous result or from failure of the earliest data to yet reflect steady-state conditions as noted previously in the "Pore-Water Quality" section.

As septic-tank effluent is discharged to a new seepage pit, it percolates readily through the base of the pit into the surrounding soil, leaving behind only a small quantity of wastewater in the seepage pit. However, after operation of the disposal system for a period of time, microbial activity in the anaerobic environment that prevails in the wastewater quickly results in biological clogging of the cinder blocks and soil immediately adjacent to the pit's wall (Stewart and others, 1979, and references therein). Progressive clogging causes the wastewater level to rise in the seepage pit until it reaches a zone of sufficiently high permeability that it can't be sealed by microbial activity, and most of the wastewater then percolates through the rapid-flow pathway at this level (Sinton, 1986). For the purposes of this study, this level is referred to as the active discharge

level of the seepage pit. This active discharge level ranges from the bottom of the seepage pit at new residences such as Vasquez (about 35 ft below land surface) to about 20 ft below land surface at the established sites. The unsaturated zone above the active discharge level is unaffected by septic-tank wastewater. This zone contains high concentrations of nitrate and chloride in soil moisture (table 7 and fig. 13) that probably are related to the caliche layer present in most of the study area. The high nitrate and chloride concentrations in this shallow zone are characteristic of shallow desert soils where there has been minimal leaching.

With the exception of samples collected directly beneath the seepage pits, dissolved nitrogen in the unsaturated zone is almost entirely in the form of nitrate (tables 7, 10, and 17). This indicates that reduced nitrogen (ammonia and organic nitrogen) present in the septic-tank wastewater is rapidly nitrified by microorganisms in soil near the seepage pit. Nitrification is an aerobic process that requires oxic conditions. Measured oxygen concentrations of about 19 volume percent (air is 21 percent) in soil gas from the unsaturated zone at Cheyenne-I and the general observation of brown coloration (as opposed to gray or olive coloration) of nearly all the cores recovered at all sites suggests that the unsaturated zone is well aerated. The main bacterial species responsible for nitrification (*Nitrosomonas* and *Nitrobacter*) were sought but were not detected in core samples (table 9), possibly because the reaction takes place in such a narrow zone that appropriate samples close enough to the seepage pit were not obtained.

Careful measurement of pH on selected core extracts provides additional indirect evidence for nitrification. The overall stoichiometric reaction represented by

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O \tag{2}$$
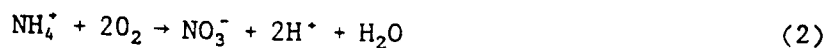
indicates that nitrification is accompanied by the release of hydrogen ions (acidity). Accurate measurement of pH in the deionized-water extracts of core material was difficult to achieve because of poor buffering in the low-ionic-strength solutions, (voltage) drift of the electrode, and the potential for carbon dioxide exchange with the atmosphere. Improved reliability was obtained after deionized water equilibrated with atmospheric carbon dioxide (pH = 5.6 - 5.7) was used as a secondary standard to calibrate the pH electrode. For the purpose of distinguishing those core extracts in which this more exacting procedure was followed, as opposed to those in which only commercial pH standards were used, the more reliable pH data are listed to hundredths, rather than tenths, in table 7. Results show that pH in the extract from 13-15 ft at Choctaw, 17-19 ft at Kiowa, and 27-29 ft at Cheyenne-II is about 1 unit less than average pH below these depths. The decrease in pH persists over only a narrow depth interval because of rapid neutralization by reaction with the soil. On the basis of estimated wastewater movement rates of 0.07 to 1 ft/d (from table 15), it is apparent that nitrification and subsequent neutralization of the acid generated must take no longer than a few weeks.

At all the sites, total-nitrogen concentrations were lower in samples from suction lysimeters emplaced beneath the seepage pit than in septic-tank

wastewater (table 17). For the five established sites (Cheyenne-I, Choctaw, Kiowa, Cheyenne-II, and Cajon), the dissolved-nitrogen concentration for the suction lysimeters closest to the bottom of the seepage pit averaged 27 mg/L, about 42 percent less than the average nitrogen concentration of 47 mg/L in septic-tank wastewater at the same sites (table 17). Wastewater sampling was not sufficiently frequent and lysimeters were not spaced sufficiently close to permit a precise mass-balance estimate of nitrification extent. Studies elsewhere, however, suggest that virtually all the dissolved ammonia present in the septic-tank wastewater is ultimately transformed to nitrate (Stewart and others, 1979, and references therein). For example, Walker and others (1973a,b) found that the concentration of nitrate in a sandy drainfield below a biologically encrusted sublayer was approximately equal to that of total nitrogen in the septic-tank wastewater and, also, that the oxygen content of the soil gas was 19 percent, as in this study. In these other studies, septic-tank wastewater was discharged to drainfields, rather than into seepage pits. The results of this study suggest that significant nitrogen is removed in the seepage pit and (or) in the soil immediately adjacent to the seepage pit. Possible mechanisms for nitrogen reduction are partial denitrification, physical loss of nitrogen in the reduced form, volatilization of ammonia (from the seepage pit), incorporation in organic matter deposited on the walls and floor of the seepage pit, sorption of ammonium and organic nitrogen on the soil, and ion exchange of ammonium on clays.

As the septic-tank wastewater moves from the seepage pit through the unsaturated zone, nitrification seems to continue, at least for some depth, as indicated by some increase in nitrate concentration with increasing depth at most of the sites (tables 7 and 17, fig. 13). However, this trend is suddenly reversed above the water table at the Choctaw, Kiowa, and Cajon sites and opposite moist fine-grained deposits at the Cheyenne-I and -II sites (fig. 13). At all these sites, nitrate-N concentrations decreased to less than 10 mg/L in both soil-core and suction-lysimeter samples (tables 7 and 17). At Choctaw, Kiowa, and Cajon, nitrate-N concentrations were about 1 mg/L near the water table (tables 7 and 17), although more recent evidence discussed later attributes the very low nitrate concentration at depths below 200 ft at Cajon to the absence of wastewater below this depth. Although monitoring has only recently resumed at the Cheyenne-I site, scant data obtained so far also suggest a similar possible explanation, and (or) dilution with ground water, for the nitrate-concentration profile there as well.

Three explanations for the observed decrease in nitrate concentration are (1) microbial nitrate reduction, (2) mixing of the wastewater with low-nitrate ground water in the capillary fringe, and (3) the wastewater-wetting front has reached the water table, but the actual wastewater has yet to arrive. If microbial nitrate reduction were responsible for the reduced nitrate concentrations, chloride concentrations would remain unchanged (because chloride is biologically unreactive) and the nitrate-to-chloride ratio would decrease. Shallow ground water at Cheyenne-I and Choctaw had higher chloride concentrations than did wastewater in the unsaturated zone (table 17). Therefore, if mixing with ground water were solely responsible for the reduced nitrate concentrations, nitrate-to-chloride ratios would decrease and chloride concentrations would increase. (Although the principle is the same, the pattern differs at Cajon because the chloride concentration is much lower in ground water than in the wastewater.)

Inspection of available data (tables 7 and 17, fig. 13) indicates that chloride concentrations remain relatively unchanged; whereas, nitrate-to-chloride ratios decrease dramatically opposite the zones where nitrogen concentrations also decrease. Thus, these data suggest that microbial nitrate reduction might be partly responsible for the observed decrease in nitrate concentrations. The presence of high numbers of nitrate-reducing bacteria opposite zones where nitrate concentrations also decrease at the two sites where bacterial analyses were performed (Cheyenne-I and Cajon) (fig. 13, table 9) lend further support to this inference. It should be noted, however, that the presence of these bacteria indicates only that the potential for nitrate reduction exists. The numbers found cannot be used to infer in situ activity--that is, the degree to which possible nitrate removal proceeds.

The fact that nitrate concentrations decreased a significant distance above the water table at the Cheyenne-I and -II sites (fig. 13) would seem to preclude the possibility of ground-water mixing at these sites. However, the results of ongoing monitoring at Cajon since 1991 described by Schroeder and others (1993) do raise the possibility of a similar or related explanation for the low nitrate concentrations at depth at the Cheyenne sites. The soil surface is commonly soaked with tapwater from the local residence prior to drilling a hole for installation of a seepage pit. Any residual soil moisture (prior to discharge of wastewater) plus this added water would be "pushed" ahead (piston flow) of the advancing wastewater front, as the results at Cajon have shown. If this was the source of water in the lysimeters at 92.5 and 106 ft (the lysimeter at 113 ft was below the water table in 1988-89) at Cheyenne-I, analyses in table 7 indicate that this soil moisture should be lower in chloride than is local ground water, as was found to be the case. There is a substantial increase in nitrate in the last samples collected in July and August 1989 for analysis from the lysimeters at 92.5 and 106 ft, respectively (table 10). Unfortunately, sample collection then was terminated at Cheyenne-I and it was not resumed until June 1993. Preliminary results from the resumed monitoring have confirmed the existence of high nitrate concentrations in the lysimeters from 92.5 and 106 ft, as well as in the lysimeter from 113 ft (the water table had subsequently declined below 113 ft). Sampling is continuing at Cheyenne-I for analysis of nitrate and nitrogen isotopes as well as a number of chemical constituents.

Denitrification

As stated above, denitrification may be partly responsible for the decrease in nitrate concentration as wastewater moves through the unsaturated zone in the study area. Results of standard plate counts in table 8 show an abundance of aerobic, heterotrophic bacteria in the unsaturated zone. Degradation of organic carbon by these microorganisms probably is the main source of increased carbon dioxide, whose content is 2.94 volume percent in soil gas from 47 ft at Cheyenne-I (air is 0.03 percent). As long as molecular oxygen is present, the bacteria will use it as a terminal electron acceptor. In the absence of oxygen, a large and diverse group of nitrate-respiring heterotrophs, including *Pseudomonas*, can use nitrogen instead of oxygen as the terminal electron acceptor. The pathway for denitrification can be represented by a series of steps as follows:

$$NO_3^- \rightarrow NO_2^- \rightarrow \underset{\text{oxide}}{\underset{\text{nitric}}{NO}} \rightarrow \underset{\text{oxide}}{\underset{\text{nitrous}}{N_2O}} \rightarrow \underset{\text{dinitrogen}}{N_2.} \qquad (3)$$

$$\underset{\text{nitrate}}{NO_3^-} \rightarrow \underset{\text{nitrite}}{NO_2^-}$$
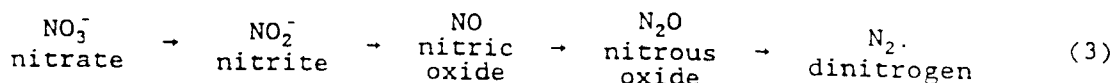
Although the multiple steps in this process are carried out by separate bacteria, and denitrification refers only to those later steps that produce the gaseous end products (NO, N_2O, and N_2), the term denitrification commonly is loosely applied to the entire process of nitrate reduction, except when the end product is ammonium.

Although there are nitrate-respiring microorganisms capable of reducing nitrate to ammonium, ground-water studies in other areas suggest that this reaction is either unlikely or of very minor importance in this study. Smith and Duff (1988) initially reported denitrification only, with no evidence of dissimilatory nitrate reduction to ammonium, in a shallow sand and gravel aquifer in Cape Cod, Massachusetts. There, the aquifer was contaminated by secondary-treated wastewater in which nitrate-N was 13 mg/L and organic carbon was 12 mg/L. Subsequent ^{15}N studies on dissolved ammonium in the same aquifer confirmed dissimilatory nitrate reduction but concluded that it seemed to be only a minor sink for nitrate (Smith and others, 1991). At low organic carbon-to-nitrate ratios, denitrification is favored over dissimilatory nitrate reduction to ammonium (Tiedje and others, 1982). In fact, an important consideration is whether sufficient degradable carbon even exists in the wastewater at the study site to effect complete denitrification.

Experiments elsewhere indicate that soil organic matter is an ineffective long-term energy source to effect complete denitrification (Stewart and others, 1979). This is why addition of an organic carbon source to soils fertilized with inorganic nitrogen aids denitrification (Adelman and Spalding, 1988). Addition of natural and synthetic organic carbon to wastewater also has been shown to increase denitrification (Lance and Whisler, 1976; Lance and others, 1980; Rice and Bouwer, 1984; and Lance, 1986). From the results of soil-column experiments, Stewart and others (1979) concluded that wastewater is only slowly available to degradation by denitrification. However, such slow rates may not necessarily be a hindrance to denitrification at the study sites, where wastewater-transit velocities in the unsaturated zone are estimated to be 0.07-1 ft/d (table 15) and times to reach the water table at 150 ft range from almost 6 months to almost 6 years.

Experimental data indicate that an organic carbon-to-nitrate-N ratio close to 1 is needed to effect denitrification (McCarty and others, 1969; Stewart and others, 1979). This matches closely the stoichiometry of model reactions for denitrification of methanol (CH_3OH) and sugars ($(CH_2O)_n$):

$$6NO_3^- + 5CH_3OH + H^+ \rightarrow 3N_2 + 8H_2O + 5HCO_3^- \qquad (4)$$

$$4NO_3^- + 5(CH_2O) \rightarrow 2N_2 + H_2CO_3 + 2H_2O + 4HCO_3^- . \tag{5}$$
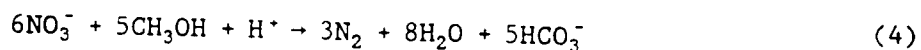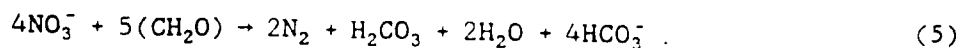
The average organic carbon-to-nitrogen mass ratio in wastewater calculated from data (tables 12 and 17) at four sites (Vasquez, Choctaw, Kiowa, and Cheyenne-II) is 0.65 (equivalent to a stoichiometric ratio of 0.76). The data suggest that wastewater at the study sites is at least somewhat deficient in the organic carbon needed for complete denitrification. The organic carbon deficit is even greater if analyses of samples from lysimeters can be considered to be reliable indicators of bioavailable carbon. The few data available (table 10), principally from lysimeters at Cheyenne-I and Cajon, show that aqueous organic carbon concentrations at all depths are much lower than the dissolved organic carbon concentrations in wastewater itself (table 12). Furthermore, no depth-related trend in concentration can be discerned. The result is that organic carbon-to-nitrate-N ratios are as low as 0.1 at relatively shallow depths where nitrate concentration is still high. However, caution is necessary in interpreting the significance of this result as it is not known whether a large fraction of the available organic carbon may be retained on particle surfaces or even on the ceramic lysimeter cup itself. At the Cape Cod aquifer contaminated by secondary wastewater cited earlier, denitrification was found to occur despite a decrease in dissolved organic carbon from 12 mg/L in the wastewater effluent to less than 2.5 mg/L in the contaminated ground water (Smith and Duff, 1988). Model calculations yielded 0.77 carbon atoms mineralized (oxidized to inorganic carbon) for each nitrate ion reduced by denitrification (Smith and others, 1991).

Whether sufficient organic carbon is available to effect complete denitrification becomes less important if chemlithotrophs (autotrophs) capable of using inorganic elements, rather than organic carbon, as an energy source (electron donor) are present. Mariotti and others (1988) and Böttcher and others (1990) cite evidence for denitrification in an aquifer mediated by the chemlithotrophic bacterium *Thiobacillus denitrificans* using sulfur in pyrite (FeS_2) as the electron donor according to the reaction:

$$14NO_3^- + 5FeS_2 + 4H^+ \rightarrow 7N_2 + 10SO_4^{2-} + 5Fe^{2+} + 2H_2O. \tag{6}$$
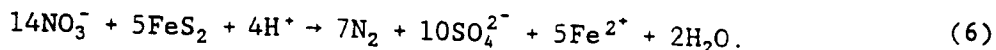
If both iron and sulfur act as electron donors, the reaction is represented by:

$$6NO_3^- + 2FeS_2 + 2H_2O \rightarrow 3N_2 + 2FeOOH + 4SO_4^{2-} + 2H^+ . \tag{7}$$
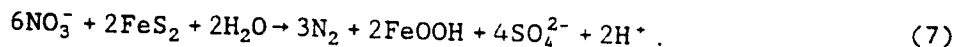
A comprehensive review of both heterotrophic and autotrophic denitrification in ground water (Korom, 1992) recently has been published.

In this study, abundant nitrate-reducing bacteria in the unsaturated zone at the Cheyenne-I and Cajon sites (table 9) and high oxygen levels (in soil gas at Cheyenne-I and in soil moisture at Cajon) were found despite experimental evidence that denitrification does not occur above even a very

low oxygen threshold (Nakajimi and others, 1984, and Rönner and Sörensson, 1985). These results suggest the existence of microenvironments where oxygen is absent and denitrification can occur. The brownish coloration of nearly all recovered cores indicates a general absence of anaerobic (sulfidic) layers. However, a few exceptions--such as several feet of clay-rich, olive-gray soil near the water table at Cheyenne-I and -II--were encountered, and these could be zones where denitrification, perhaps by chemlithotrophs, might occur.

Additional, indirect evidence for denitrification was sought from measurements of nitrogen-15-to-nitrogen-14 ratios in nitrate. Applications and limitations of the method have been reviewed by Hübner (1986) and Mariotti (1986). Isotope ratios are expressed in the commonly used delta (δ) notation (Fritz and Fontes, 1980):

$$\delta^{15}N = [(R_{sample}/R_{standard}) - 1] \times 1,000, \qquad (8)$$

where R is the nitrogen-15-to-nitrogen-14 ratio in the sample and standard, and the standard is air (atmospheric nitrogen). Although denitrification is a complex multi-step reaction, isotopic fractionation accompanying denitrification has been found to follow the simple kinetics of a first-order, irreversible reaction (Mariotti and others, 1982) for which the approximate equation of a Rayleigh process is (Fritz and Fontes, 1980, and Létolle, 1980):

$$\delta^{15}N = \delta^{15}N_0 + \epsilon \ln[NO_3^-]/[NO_3^-]_0. \qquad (9)$$

This equation expresses the relation between isotopic composition of the residual nitrate ($\delta^{15}N$) and nitrate concentration $[NO_3]$ at any time. The subscript "0" refers to the initial (time = 0) isotope ratio and nitrate concentration, and the constant ϵ is the isotopic-separation (enrichment) factor.

Isotopic fractionation during denitrification varies with environmental conditions and the type of bacterium. The largest value of ϵ reported for denitrification in a ground-water system is -30±6 permil in the Kalahari desert (Vogel and others, 1981, and Heaton and others, 1983). Böttcher and others (1990) measured an ϵ value of -15.9 permil in ground water beneath arable land where denitrification was carried out by chemlithotrophic bacteria, and an enrichment value of about -30 permil can be inferred from data for shallow ground water beneath an irrigated field in the middle of the Imperial Valley (Schroeder and others, 1991). Denitrification, with an ϵ value of -13.9 permil, was reported in ground water from the shallow sand-and-gravel aquifer in Cape Cod (Smith and others, 1991), a site that has some important similarities to, as well as differences from, the Victor Valley study area. Disposal of secondary-treated sewage effluent having a nitrate-N concentration of 13 mg/L and a dissolved organic carbon concentration of 12 mg/L onto sand infiltration beds for more than 50 years has produced an extensive plume of contaminated ground water at the Cape Cod site. Despite these comparatively large enrichment factors, in most ground-water studies where denitrification has been proven, ϵ is reported to be only about -5 permil, which is much less than values measured in the laboratory (Mariotti and others, 1988) and in the few ground-water studies cited above. Some possible explanations for the low

isotopic enrichment usually observed in nature are discussed by Mariotti and others (1988).

All nitrogen-isotope data initially obtained for this study from suction lysimeters (table 10) and monitoring wells (table 14) are reproduced in table 18. To ascertain isotopic evidence for denitrification, samples representing low nitrate concentrations were sought from the unsaturated zone. No completely unambiguous data were obtained, partly because of the difficulty in collecting a sufficiently large sample for analysis and partly because no samples were collected in which wastewater was known to be present but at reduced concentrations. Ideally, the laboratory requires 5 mg nitrate as nitrogen; and, although isotopic analysis can be done on smaller quantities, the risk of contamination by atmospheric nitrogen during preparation of the sample for analysis increases. Composite samples were collected over a period as long as a month. All five samples from depths between 37 and 92.5 ft at Cheyenne-I had a $\delta^{15}N$ of about 8 permil. All these samples also contained high nitrate concentrations, and thus little or no shift in isotopic composition would be expected. In fact, these isotope ratios for nitrate are only a few permil less than published ratios for nitrogen in septic-tank wastewater itself (Martin, 1980, and Mariotti and others, 1988), a result that is consistent with fairly complete nitrification of wastewater in the unsaturated zone. Partial nitrification would lead to much greater depletion of ^{15}N in the nitrate (Delwich and Steyn, 1970).

On the basis of data obtained during the previous 13 months (table 10), it was expected that the July 1989 composite sample from the lysimeter at 92.5 ft at Cheyenne-I would contain low but sufficient nitrate for isotopic analysis. However, because the nitrate concentration was found to be anomalously high in comparison with previously collected samples from this depth, a sample from the lysimeter at 243 ft at the Cajon site was collected the following year for isotope analysis. Although the nitrate-N concentration of 0.8 mg/L is low, the sample shows no enrichment in ^{15}N ($\delta^{15}N = 7.1$ permil). If the decrease in concentration were due to denitrification, even the smallest published values for isotopic enrichment would predict a $\delta^{15}N$ of at least 20 permil. The apparent lack of ^{15}N enrichment may indicate that this sample is from a depth that may have been below the water table (at least at times) although at the time of collection in June 1990 it was above the water table. If the sample from 243 ft at Cajon does, in fact, represent soil moisture derived from regional ground water rather than wastewater, it would not be a surprise that its isotopic composition is similar to that of ground-water samples from Apple Ranchos and Rincon (table 18). Whatever the source of the water in this lysimeter may be, it is clear from ongoing monitoring that it was not wastewater because wastewater had not yet reached this depth by 1993 (Schroeder and others, 1993).

One possible explanation for the nitrogen-isotope values observed in the study area is that the isotopic composition of nitrate is nearly the same in undenitrified wastewater from the unsaturated zone and in ground water where the nitrate is from natural sources (prior to development). It then would be impossible to distinguish, on the basis of isotopes alone, between discharge to the ground water of completely denitrified wastewater (dilution of ground-water nitrate) or of undenitrified wastewater (mixing into low-nitrate ground water). If there were only partial denitrification, followed by the mixing of partially denitrified wastewater and ground water, both theory

and the example discussed by Mariotti and others (1988) suggest that isotopic evidence for denitrification should exist.

Additional sampling is continuing, on a limited basis, to test for isotopic evidence of denitrification in the study area (table 19). Unfortunately, some lysimeters no longer operate (table 4) and some of the more important sites, such as Cheyenne-I, were subsequently covered by a concrete driveway. Samples are being collected from lysimeters at Cajon where the water table as of late 1991, when monitoring resumed, had declined below the piezometer at 266 ft (table 3) that lies beneath the series of eight lysimeters at this site (table 4). Although the coarseness of the soils at the Cajon site would seem to make it a less favorable environment for denitrification to occur than many other parts of Victor Valley, preliminary data on samples from the uppermost six lysimeters between 35 and 199 ft indicated isotopic enrichment with an ϵ value of about -10 permil on the basis of a $\delta^{15}N$ of 14.8 permil at the 199-ft lysimeter (Schroeder and Martin, 1992). The ^{15}N enrichment is accompanied by a large increase in iron, sulfate, and free hydrogen ion (pH approximately 4) at this depth (Schroeder and others, 1993). These chemical changes seem to be similar to those from an example (Postma and others, 1991) and model (Engesgaard and Kipp, 1992) of aqueous chemical effects due to nitrate removal by pyrite oxidation in a ground-water system (denitrification by chemlithotrophs).

The changes that have occurred in specific conductance at the Cajon site between initial monitoring (1988-90) and the more recent monitoring (after 1991) provide ample evidence for the importance of maintaining monitoring in the unsaturated zone for a period perhaps as long as several years. The relative constancy in specific conductance for successive samples above 199 ft during the current sampling period (table 19) in comparison with the earlier period (table 7) that immediately followed installation of the lysimeter are notable. The lysimeters were sampled as many as 11 times between November 5, 1991, and March 29, 1993. Selected data are given in table 19; additional data are given by Schroeder and others (1993). During this period, specific conductance showed no trend (average unsigned difference of 4 percent between successive samples) in the five lysimeters above 199 ft and within the wastewater zone, and also showed no trend (average unsigned difference of 10 percent between successive samples) in the two lysimeters below 199 ft and beneath the advancing wastewater front. Concurrently, the specific conductance increased monotonically by almost 40 percent in the lysimeter at 199 ft during the same 1.5-year period as lower-conductance soil moisture was being displaced by higher-conductance wastewater (Schroeder and others, 1993).

The fact that the effect of sampling "artifacts" is much more pronounced and persists much longer for major ions than for nitrate strongly suggests that leaching of material used to backfill the drilled holes is the main source of contamination in early samples. With time, equilibration between the soil moisture (wastewater) and minerals that surround the suction-lysimeter cup is reestablished as the readily soluble salts are leached from the backfill material. Monitoring is continuing at the Cajon site to determine when (if) the advancing wastewater reaches the lysimeter at 243 ft. The concrete driveway was removed and monitoring resumed at the Cheyenne-I site in June 1993 to determine whether wastewater had reached the lowermost lysimeters at this site when monitoring was initially stopped in 1989. It is hoped that comparison of nitrogen-isotope data from both sites and

in ground water will indicate whether isotope ratios can be used to distinguish wastewater nitrate from natural nitrate in the ground water.

Total Bacteria and Fecal Coliforms

Wastewater contains a wide variety of pathogenic bacteria, viruses, protozoa, and worms. One published average biological characteristic for domestic wastewater is: total bacteria - 5.6-8×10^7 CFU (colony-forming units)/100 mL, total coliform - 2×10^6 MPN/100 mL, fecal coliform and fecal streptococci - 3×10^4 MPN/100 mL, and enteric viruses - 32-$7,000$ PFU (plaque-forming colonies)/L (Viraraghavan, 1976, and Siegrist, 1977). Other values for average total-bacteria and fecal-coliform densities that exceed the above values by a factor of about 10 also have been reported (Siegrist, 1977; Canter and Knox, 1985). These published values can be compared with measured ranges of 1.2×10^8 to 9.4×10^8 CFU/100 mL for total (heterotrophic) bacteria and 5.2×10^4 to 3.9×10^5 CFU/100 mL for fecal coliform in wastewater at five residences in the study area (table 8).

For this study, fecal coliforms were the only enteric microorganisms analyzed. Historically, fecal coliforms have been widely used as a reliable indicator of fecal contamination (Clark and Kabler, 1964). Persistence of other microorganisms in ground water, in comparison with *Escherichia coli*, has been reported to range from 0.02 to 3 times longer for seven common pathogenic bacteria and from 1.3 to 6 times longer for four viruses (Matthess and others, 1988). On the basis of these comparisons, the disappearance of fecal coliforms from soils only a short distance from the seepage pits in Victor Valley suggests that other pathogenic microorganisms also would be unlikely to reach the water table given the long distance and traveltimes, although additional study on the movement and attenuation of viruses is needed.

Sinton (1986) found significant movement of fecal coliforms from seepage pits to ground water in a system with an experimental design similar to that of this study. However, the water table at that study site was only 3.5 m (11.5 ft) below the bottom of a seepage pit in a gravel aquifer in which downward percolation velocities exceeded 5 m/h (16 ft/h). Wherever silt and clay are present, as in this study area, removal of non-native bacteria and viruses generally requires less than 1 m (3 ft) of bulk soil that is free of channels or cracks (Brown and others, 1979, and Lance and Gerba, 1984). Physical straining (filtration) and adsorption (Canter and Knox, 1985) probably are the most important mechanisms of fecal coliform removal in the soils at Victor Valley. Additional factors that might favor rapid attenuation are competition with native bacteria for nutrients, antagonism from actinomycetes and other groups of bacteria such as *Pseudomonas* and *Bacillus* (Matthess and others, 1988), and an unsaturated (as opposed to saturated) flow regime below the seepage pits (Hagedorn and others, 1978, and Reneau, 1978).

Bacterial analyses were done on soils, rather than on water, because of the overwhelming predilection of bacteria for attachment to the solid rather than the aqueous phase in aquifers that contain even a smaller proportion of fine material (Harvey and others, 1984, and Smith and Duff, 1988) than is present in Victor Valley. Although percolating wastewater provides the medium for bacterial transport through the unsaturated zone, direct collection of aqueous samples for reliable analysis of bacteria is not possible because passage of the water through the small pore openings of the lysimeter's

ceramic cup results in bacterial removal factors of 10^2-10^6 (Dazzo and Rothwell, 1974).

Total-bacteria densities as high as 10^4 CFU/g were measured in core samples (table 8), but the significance of these findings to disposal of wastewater in Victor Valley is uncertain because the measurement does not distinguish between native and wastewater populations. The high numbers may be due to the growth of native bacteria on wastewater organic carbon. However, the general occurrence of high counts near the base of the seepage pits does suggest a wastewater component, and, if so, the nearly universal absence of measurable heterotrophic bacteria (assuming the standard-methods agar or broth used is appropriate to support growth in the laboratory) at greater depths (except below the water table at Cheyenne-I) implies their effective removal in the unsaturated zone.

Other Contaminants in Wastewater

Beginning about 1980, it was recognized that synthetic organic chemicals might exist in septic-tank effluent, and a few analyses have been done (Viraraghavan and Hashem, 1986, and references therein). Volatile (or purgeable) priority pollutants, which are commonly used solvents, and acid-extractable priority pollutants, such as phenols, have chemical properties that are favorable for their transport, making them the trace organic constituents of greatest concern (Viraraghavan and Hashem, 1986). For this study, extractable organic compounds were analyzed on core samples and purgeable-plus-extractable organic compounds were analyzed on wastewater samples from five residential sites using gas chromatographic/mass spectrometric methods described by Wershaw and others (1987). The core samples analyzed were from 97 to 99 ft at Toltec, 22 to 24 ft at Cheyenne-I, 28 to 30 ft at Choctaw, 27 to 29 ft at Kiowa, and 32 to 34 ft at Cheyenne-II. With the exception of the background sample at Toltec, the depths selected for analysis are near the bottom of the seepage pit and therefore would be most likely to contain organic contaminants if they were present. The detection limit for most extractable priority pollutants was 200 μg/kg, and none were found in any of the five core samples.

The detection limit was 0.2 μg/L for most purgeable organic priority pollutants and 5 μg/L for most extractable organic priority pollutants analyzed in wastewater. Of 85 priority pollutants analyzed, 17 were detected in at least one of the six samples from five residential sites; however, their concentrations were generally low--except at Cheyenne-II, where wastewater from both the seepage pit and septic tank was analyzed (table 20). It is likely that the synthetic organic chemical concentrations in domestic wastewater are generally low, as was reported by Viraraghavan and Hashem (1986) from their analysis of 11 purgeable priority pollutants. Where comparatively high concentrations do occur in this study, they seem to be associated with inappropriate disposal practices that were unique to a particular site (Cheyenne-II).

In addition to the priority pollutants, other organic compounds were tentatively identified in wastewater from Choctaw and Cheyenne-II. Identification was by comparison of spectrums corresponding to gas-chromatographic peak maximums against a computerized library containing more than 70,000 reference spectrums. A number of nonspecific acids and alcohols

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that probably are microbial degradation products of precursors commonly present in domestic wastewater were found. Concentrations of some specific compounds are given in table 21. Note the similarity of septic-tank and seepage-pit results at Cheyenne-II.

POTENTIAL FOR GROUND-WATER CONTAMINATION

As stated previously, there were more than 46,000 septic-tank systems in use in the study area in 1990. Wastewater discharge from these systems was estimated to be 9,000 acre-ft/yr, equal to about 18 percent of the natural recharge to the upper Mojave River Basin (see "Recharge and Discharge" section of this report). Because of the high concentrations of nitrogen and bacteria in septic-tank wastewater, recharge of the wastewater was expected to degrade the quality of the underlying ground water. This study showed that nitrogen and bacteria are attenuated in the unsaturated zone. In addition, the low nitrate concentrations found in samples from shallow and deep ground water (tables 1 and 14) indicate the absence of widespread ground-water-quality degradation. In general, nitrate-N concentrations in ground water were less than 2 mg/L.

Shallow ground water was sampled just below the water table at three of the established sites (Cheyenne-I, Choctaw, and Cajon). With the exception of one sample, nitrate-N concentrations were less than 3.1 mg/L, and most of the samples had concentrations less than 1 mg/L (table 14). The only sample that had a high (13 mg/L) nitrate-N concentration was collected from the suction lysimeter at 257 ft at the Cajon site on April 12, 1989 (table 14). All prior and subsequent samples from this suction lysimeter had low nitrate-N concentrations (less than 3.1 mg/L). Other chemical constituents in the April 12, 1989, sample also were anomalous. This strongly suggests that this sample was mislabeled when collected and thus was from a different suction lysimeter than the one identified.

To further investigate the effect of septic-tank wastewater on ground-water quality, two multiple-well monitoring sites were installed in the Apple Valley area (fig. 7). The first site (Apple Ranchos) was constructed in the center of Apple Valley in an area that is sewered (figs. 5 and 7). The second site (Rincon) was constructed about 2 mi west of the Apple Ranchos site, downgradient of numerous residences that use seepage pits to discharge septic-tank wastewater (figs. 5 and 7). The general direction of ground-water flow is from the Apple Ranchos site toward the Rincon site. Each site includes three or four monitoring wells that enable sampling at depths between about 5 and 100 ft below the water table (table 3). The objective in sampling at several depths was to determine the importance of dilution by vertical mixing in the saturated zone. The two sites are in a part of Apple Valley where most of the houses were constructed in the early 1960's and where depth to the water table was 150 to 175 ft at the time of the study (1988-90). On the basis of wastewater-movement rates determined for this study (0.07-1.0 ft/d, table 14), wastewater discharged to seepage pits in this area should have reached the water table many years ago. Both sites also are east of and sufficiently far from the Mojave River to receive little if any recharge from the river. The absence of river recharge is confirmed by differences in water chemistry between these wells and other wells near the river (fig. 9; table 1). Therefore, septic-tank wastewater is believed to constitute a significant source of recharge in this part of the study area.

Water-quality data collected from the multiple-well monitoring sites are presented in table 14. If undenitrified septic-tank wastewater were recharging the shallow ground-water system, one would expect higher nitrate concentrations in samples from wells closest to the water table and at the downgradient site (Rincon). Inspection of table 14 indicates that at both Apple Ranchos and Rincon, the nitrate-N concentrations of samples from the shallowest wells were less than or equal to the concentrations in samples from the deeper wells. Samples from the shallowest well at each site had nitrate-N concentrations less than 0.2 mg/L, and the highest nitrate-N concentrations, 2.0 to 4.1 mg/L, were in samples from the second-deepest well (199 feet) at the Apple Ranchos site. All nitrate-N concentrations in samples from the Rincon site were less than or equal to 1.0 mg/L, indicating no increase in nitrate concentration in a downgradient direction. The data collected from these sites indicate that either (1) a substantial fraction of the nitrogen in septic-tank wastewater is being removed in the unsaturated zone or in the saturated zone near the water table, (2) substantial dilution is occurring over a thick saturated zone, (3) the quantity of wastewater is small in comparison with the quantity of underlying ground water, or (4) the wastewater has not yet reached the water table near the monitoring sites.

A single-cell model that considers the main sources of water and nitrate to a part of the ground-water system was used to further evaluate the importance of dilution by vertical mixing with low-nitrate ground water. This approach is similar to that used by Bauman and Schafer (1985), in which mass-balance equations are developed for the water and nitrate in the system. Assumptions include an isotropic and homogeneous water-table aquifer, steady-state ground-water flow, and instantaneous mixing of nitrate. The purpose of the model is to illustrate the relative importance of differences in aquifer properties and nitrogen loading to changes in nitrate concentration in the ground-water system with time.

The region modeled is a 2-mile-long by 1-mile-wide block of the aquifer extending from the Apple Ranchos multiple-well monitoring site along a ground-water flow line toward the Mojave River. The total volume of ground water in the model block at any time, Q_{tot}, is calculated by multiplying the surface area of the block by the aquifer thickness and the porosity of the aquifer. For the purpose of this model, the aquifer thickness is assumed to equal the depth of vertical mixing of the septic-tank wastewater in the aquifer. Because of stratification in the aquifer system, the depth of vertical mixing will be much less than the aquifer thickness in most places. A vertical-mixing depth of 50 ft was chosen for most model simulations. Porosity was assumed to be 30 percent, a value which probably is high for the entire aquifer as a whole and which therefore has the effect of understating the influence of wastewater on the ground water (overestimating dilution with ground water). A value of 2.0 mg/L was chosen to represent the initial nitrate-N concentration prior to any mixing with septic-tank wastewater (see table 1).

Ground-water inflow enters the model block through the upgradient boundary, and inflow through the lateral boundaries of the model block was assumed to be zero because the model block lies along parallel ground-water flow lines. Septic-tank wastewater is the only other source of recharge, and ground-water inflow and septic-tank wastewater are assumed to mix instantaneously with the ground water in the aquifer. Ground-water outflow through the downgradient end of the model block is the only output from the system. Ground water removed from the system by pumping is assumed to be

balanced by septic-tank wastewater recharge (consumptive use is considered negligible). Therefore, the nitrate concentration of the ground-water outflow consists of a mixture of the ground-water inflow, the septic-tank wastewater, and the underlying ground water.

The quantity of ground-water inflow at the upgradient boundary (Q_{in}) can be estimated using the following form of Darcy's law:

$$Q_{in} = K \cdot b \cdot \frac{dh}{dl} \cdot w \cdot t ,$$

(10)

where
Q_{in} — quantity of ground-water inflow [L^3];
K — hydraulic conductivity [L/T];
b — aquifer thickness of vertical mixing depth [L];
dh/dl — hydraulic gradient [L/L];
w — width of the model block [L];
t — time period [T] .

K was estimated by dividing the reported transmissivity of the aquifer (20,000 ft^2/d) (Hardt, 1971, fig. 8) by the saturated thickness of the Quaternary and Tertiary deposits (1,000 ft) (fig. 6). The estimated value of K, 20 ft/d, probably is less than the actual values in the upper part of the saturated deposits and greater than actual values in the lower part of the aquifer. Therefore, model simulations were done using different chosen values of K (2, 20, and 200 ft/d) to evaluate the influence of this parameter on predicted nitrate concentrations. As stated previously, the vertical mixing depth (b) was assumed to be 50 ft for most of the model simulations. Model simulations also were made with smaller and greater mixing depths (10, 100, and 1,000 ft) to evaluate the influence of mixing depth on predicted nitrate concentrations. The hydraulic gradient was determined to be 0.0012 ft/ft on the basis of water-level measurements in the vicinity of the Apple Ranchos multiple-well monitoring site. The width of the aquifer block was previously defined as 5,280 ft. The time period (step) was set equal to 1 year (365.25 d). Nitrate-N concentrations for the ground-water inflow (N_{in}) were assumed, on the basis of available information, to be 2 mg/L (table 1).

The quantity of septic-tank wastewater (Q_{st}) mixing into the underlying ground water during any given time period was estimated--by assuming an average septic-tank discharge of 70(gal/d)/person (Bookman-Edmonston Engineering, 1991) and 2.5 persons per household--to be 175 gal/d or 23 ft^3/d per household. In most of the Victor Valley area, residential density ranges from 1 to 4 houses per acre. To evaluate the influence of housing density, densities of 1,2, and 4 houses per acre were simulated in the model.

The nitrate-N concentration of the septic-tank wastewater (N_{st}) was chosen to be 50 mg/L, slightly higher than the 47 mg/L average dissolved-nitrogen concentration for wastewater from the five sites sampled for this study (table 17). It is assumed that there are no losses of nitrogen after wastewater leaves the septic tank, and that all the nitrogen is entirely converted to nitrate. To evaluate the influence of lower nitrate concentrations in the wastewater and (or) denitrification of the wastewater,

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different concentrations of wastewater nitrate-N (50, 25, and 10 mg/L) were simulated in the model.

The quantity of underlying ground water (Q_{gw}) in the model block during any time period can be determined by subtracting Q_{in} and Q_{st} from Q_{tot}. As stated previously, the background nitrate-N concentration of the underlying ground water prior to mixing with septic-tank wastewater (N_{gw}) was assumed to be 2 mg/L. The nitrate-N concentration of the ground water after mixing with the septic-tank wastewater is determined in the model on a yearly basis for 100 years using the following equation:

$$N_{gw}^{n+1} = \frac{1}{Q_{tot}}(Q_{in}*N_{in} + Q_{st}*N_{st} + Q_{gw}*N_{gw}^{n}) \quad n=0,1,2,\ldots,99 ,$$ (11)

where

n is the time step, in years, and all values of N and Q are in consistent units.

N_{gw} on the right side of the equation is updated with the computed N_{gw} for the previous time step (the left side of the equation) for each successive yearly time step. Model results for each of the different simulations are presented in figure 14. The parameters used in the model, unless otherwise noted, are the same as those shown in table 22. The computed nitrate-N concentrations should be considered only as crude estimates, given the simplifying assumptions of the model.

The influence of changing porosity on the model-computed nitrate concentration is shown in figure 14A. Higher values of porosity result in lower computed nitrate concentrations during the early years before the concentrations reach a steady state. Model-computed concentrations are lower when the aquifer porosity is greater because initially a larger quantity of low-nitrate ground water is present in the underlying aquifer to dilute the septic-tank wastewater. Nevertheless, even the highest value of porosity simulated (30 percent) resulted in computed nitrate-N concentrations in excess of 10 mg/L in less than 20 years.

The influence of hydraulic conductivity and hydraulic gradient on model-computed nitrate concentrations is shown in figure 14B. Higher values of K result in increased ground-water inflow (see eq. 10) and therefore in lower computed concentrations. Increasing the hydraulic gradient would have the same effect as increasing K (see eq. 10); that is, greater dilution with low-nitrate ground water. Again, the predicted nitrate-N concentration was in excess of 10 mg/L in less than 20 years, even when the effect of dilution was maximized by selecting a high value for K (200 ft/d).

The influence of different housing densities on model-computed nitrate concentrations is shown in figure 14C. Increasing the housing density results in a proportional increase in the quantity of septic-tank wastewater that recharges the underlying ground water. Even at 1 house per acre (the lowest housing density simulated), computed nitrate-N concentrations would exceed 10 mg/L in less than 20 years.

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The influence of vertical-mixing depth is shown in figure 14D. Increases in the vertical-mixing depth result in lower model-computed nitrate concentrations because (1) the quantity of ground-water inflow increases directly with increases in the vertical-mixing depth (eq. 1), and (2) the quantity of ground water initially available to mix with septic-tank wastewater increases directly with the vertical-mixing depth. When a vertical-mixing depth equal to the total saturated thickness of the aquifer (1,000 ft) was chosen, computed nitrate-N concentrations did not exceed 10 mg/L during the entire 100-year simulation period. However, for more realistic vertical-mixing depths of 100 ft and less, the computed nitrate-N concentrations exceeded 10 mg/L in less than 30 years, and measurable increases are simulated within 5 to 10 years.

The effect of reducing the septic-tank wastewater nitrate concentration is shown in figure 14E. The previous simulations all used a nitrate-N concentration of 50 mg/L for the septic-tank wastewater. In all these simulations, except when the mixing-zone depth was in excess of 100 ft, the predicted nitrate-N concentrations exceeded 10 mg/L in less than 30 years. When the nitrate-N concentration of the wastewater is reduced to 25 mg/L (a 50-percent reduction), model-simulated nitrate-N concentrations do not exceed 10 mg/L for more than 30 years, assuming the best-estimate parameter values given in table 22. Reducing the nitrate-N concentration of the wastewater to 10 mg/L (an 80-percent reduction) obviously results in predicted nitrate-N concentrations that do not exceed 10 mg/L during the entire simulation period.

The results of these model simulations indicate that if the vertical-mixing depth is 100 ft or less and if the values used for the other model parameters are reasonable (table 22), then the nitrate concentration of ground water in the Victor Valley area should be increasing at a readily discernible rate. The low nitrate concentrations measured in samples of ground water from the Victor Valley suggest that either nitrogen is being removed from the septic-tank wastewater, the vertical-mixing depth must be substantially greater than 100 ft, or a large percentage of the septic-tank wastewater has not yet reached the water table. Differences in several water-quality characteristics with depth at the Apple Ranchos and Rincon multiple-well monitoring sites (table 14) indicate that the vertical-mixing depth is less than 100 ft and thus support the contention that some nitrogen is being removed in the unsaturated zone or in the saturated zone near the water table in the study area.

In addition to providing indirect support for the existence of a nitrogen-removal process, the model simulations also imply that any temporal trends in ground-water degradation would be sufficiently slow that continued monitoring, especially in multiple-depth piezometers distributed locally beneath seepage pits as well as regionally near the water table, can provide adequate early indication of possible degradation. Continued monitoring also is important to any further decisions on the need for sewering given the highly variable distribution of environments that favor denitrification and the absence of knowledge on their capacity to sustain denitrification and the uncertainty, therefore, inherent in quantifying wastewater-nitrate loading to the ground water on either a local or a regional scale.

The nitrate concentrations present in ground water underlying the study area are much lower than the concentrations that have been measured in other areas with high septic-tank densities: for example, Long Island, New York (Ku and Sulam, 1976); Delaware (Miller, 1975); southern Florida (Pitt and others, 1975); Fresno, California (Schmidt, 1972); and Tucson, Arizona (Martin, 1980). A possible explanation for the low nitrate concentrations in this study area is that the unsaturated zone is much thicker than in most of those areas and wastewater movement is sufficiently slow to allow greater opportunity for attenuation of nitrogen in the unsaturated zone. If the unsaturated zone were thinner and (or) more permeable, wastewater-transit times through the unsaturated zone might be so rapid that attenuation would not occur. Another explanation for the observed low nitrate concentrations is that there are few domestic wells in the area at which possible faulty well construction could allow the septic-tank wastewater to "short circuit" the thick unsaturated zone and enter the aquifer. An unusual aspect of the upper Mojave River Basin, as a septic-tank area, is that virtually all the area is serviced by several principal water purveyors. These water purveyors distribute ground water pumped from large municipal supply wells by pipelines to individual residences. In most other septic-tank areas, there commonly is one well for each septic tank. The wells usually are small domestic wells that do not have to meet the same stringent construction standards that are applied to large municipal supply wells. Therefore, there are many more chances (in most other septic-tank areas) for faulty well construction (inadequate sanitary seals) or failed wells (corroded casings or leaking seals) to short circuit septic-tank wastewater directly to the water table.

In summary, the data collected for this study indicate that when the study was completed (except for limited continued monitoring) in 1990, septic-tank wastewater had not degraded ground-water quality in the upper Mojave River Basin. Septic-tank wastewater is a significant source of recharge to the ground-water system in the basin. If the entire area were sewered, this wastewater would be treated at a regional wastewater treatment plant and then likely would be discharged to the Mojave River east of the "Narrows" downgradient of the upper Mojave River Basin. This source of recharge then would be exported from the study area, creating a larger imbalance between recharge and discharge; this imbalance would result in water-level declines that are greater than would otherwise occur. Of course, if wastewater were no longer discharged from seepage pits, any contaminants in wastewater still present in the unsaturated zone would simply remain there and would no longer be transported to the water table.

SUMMARY AND CONCLUSIONS

Septic-tank wastewater disposed in seepage pits at 46,000 residences in the rapidly developing upper Mojave River Basin (Victor Valley) northeast of Los Angeles is estimated to equal about 18 percent of the natural recharge to the underlying aquifer. However, this wastewater-disposal practice has led to concern about possible contamination, especially by nitrate, of the sole-source aquifer that underlies the area. To respond to this concern, the U.S. Geological Survey began a study in 1988 to (1) determine vertical rate of wastewater movement through the unsaturated zone, (2) determine whether constituents in wastewater reach the water table, and (3) evaluate the current and potential effects of wastewater discharge on ground-water quality. The study entailed monitoring wastewater movement and water-quality changes in the

unsaturated zone at eight residences and determining regional ground-water quality in multiple-depth piezometers near the water table at two locations.

Disposal of domestic wastewater is achieved by discharge of septic-tank effluent to seepage pits (30-foot-deep dry wells) from which the wastewater percolates into the unsaturated zone below a near-surface caliche layer that extends throughout most of the Victor Valley. Movement of the wastewater was observed by means of periodic neutron logging and periodic sampling of suction lysimeters beneath the seepage pits. Water-quality changes in the unsaturated zone were determined by analysis of suction-lysimeter samples and by extraction of soil cores. Bacteria in the unsaturated zone were analyzed from soil cores. The eight residential sites that were studied were selected to represent the range in geohydrologic environments that prevail in the Victor Valley. The sites included three newly occupied residences as well as other residences whose disposal systems had been in use for as long as 10 years. Six were single-family residences and two were multiple-family residences. The interpretation of results from this study area was less complicated than for many other published investigations of septic-tank effects because of (1) the absence of other nitrogen sources in this desert environment (agricultural areas adjacent to the Mojave River channel were avoided) where landscaping is minimal, and (2) the presence of only a few large municipal-supply wells rather than numerous individual-homeowner wells.

The measured vertical rate of the wastewater wetting front ranged from 0.07 to 1.0 ft/d, indicating that the wastewater wetting front reaches the water table, at an average depth of 150 ft in the study area, in about 6 years and about 6 months, respectively. The time for the wastewater to reach the water table would be longer. Although there is evidence of lateral wastewater movement, these vertical rates imply that wastewater from many of the disposal systems in Victor Valley already has reached the water table. Therefore, the absence of widespread high nitrate concentrations in ground water near the water table indicates that either a significant fraction of the nitrogen present in wastewater is no longer present when it mixes into the ground water, or the nitrate is confined to shallow depths below the water table that have not been sampled. Denitrification in the unsaturated zone and (or) at the water table beneath disposal systems seems to be a possible mechanism of nitrogen removal. Another mechanism is dilution by vertical mixing with low-nitrate ground water in a thick unsaturated zone.

Total dissolved nitrogen concentrations in wastewater ranged from 22 to 63 mg/L. The nitrogen was present in reduced form as ammonium and as organic nitrogen. Dissolved organic carbon concentrations in wastewater ranged from 10 to 63 mg/L. All concentrations are within the expected range for domestic wastewater, and the differences between residences probably are related to the way its occupants use the water and to the quantities they use.

The reduced nitrogen present in wastewater is oxidized, presumably by nitrifying bacteria, in the soil zone close to the seepage pit. Accordingly, maximum median nitrate-N concentration in lysimeter samples ranged from 6.4 to 43 mg/L, and the highest concentrations usually occurred in a shallow lysimeter only a short distance below the seepage pit. Further declines in nitrate concentration and nitrate-to-chloride ratios were observed with increasing depth, and these decreases seemed to coincide with the presence of finer soils and with the presence of nitrate-respiring bacteria identified in soils from the two sites where these bacterial analyses were done. However,

more recent results suggest the possibility that low nitrate concentrations in deeper parts of the unsaturated zone could be due to the fact that wastewater had not yet arrived at these depths during the initial period of monitoring before 1990 at the Cheyenne-I and Cajon sites. Monitoring is continuing at both sites.

The precise reduction in nitrate concentration of wastewater as it recharges at the water table is difficult to ascertain because of variability in concentration among multiple sample collections; a temporal trend toward steady-state conditions only after numerous successive samplings; nonideal selection of depth for installation of the deepest lysimeter (which can be related to uncertainty and fluctuations in depth to water table); and the inherent limitations on obtaining representative water-quality samples from an unsaturated zone using suction lysimeters. At one of the residential study sites, Cajon, a decrease of approximately 50 percent in nitrate concentration was found at the deepest in a series of six lysimeters between 35 and 199 ft, the deepest of which still is well above a declining water table that was at least 266 ft below land surface in late 1991. Incomplete results from ongoing sampling of the lysimeters at this site indicate that the reduction in nitrate concentration is accompanied by an apparent isotopic fractionation (enrichment of ^{15}N at the lower nitrate concentration at 199 ft) factor of about -10 permil and that the reaction may be mediated by autotrophs (chemlithotrophs). Enrichment in ^{15}N in the residual nitrate, and absence of widespread high levels of nitrate in the regional ground water and in ground water near the water table provide evidence for at least partial removal of nitrogen in wastewater recharge by denitrification. However, the significance of this reaction throughout the study area, and the capacity to sustain the reaction for a long period of time, cannot be evaluated.

Although fecal coliform densities ranged from 5×10^4 to 4×10^5 CFU/100 mL in the wastewater itself, fecal coliforms never were detected in any soil samples analyzed, including those only a few feet away from the seepage pits. Comparison of published transport properties for other microorganisms with those of fecal coliform suggests that various other pathogenic bacteria and viruses that might be present in domestic wastewater also are unlikely to persist a great distance from the seepage pits.

Of 85 organic priority pollutants analyzed, 17 were detected in domestic wastewater, mostly at low concentrations. At one site, concentrations were high--but the high concentrations are believed to be a consequence of disposal practices unique to this particular residence. Concentrations of toluene, tetrachloroethylene, and 1,2-dichlorobenzene approached or exceeded 100 μg/L in both the septic tank and the seepage pit at this site. No extractable priority pollutants were detected in soils adjacent to the seepage pit at this site or at three other sites.

About one-quarter of all inhabitants of the United States dispose of sewage by means of onsite septic systems that have the potential to contaminate the receiving waters. The major cause of failure of these systems has been variously reported to be poor operation and maintenance, unsuitable soils, and excessive septic-tank density. Although these conditions exist locally at some residences and regionally in some parts of the upper Mojave River Basin, this study shows that current onsite domestic-wastewater disposal practices pose little immediate threat to the local ground-water resource.

Continued monitoring in the unsaturated zone and in wells perforated just below the water table could provide adequate warning of any future ground-water degradation, which model simulations indicate can occur only over a period of many years. Although discontinuance of current domestic-disposal practices in favor of a municipal treatment plant would eliminate any further transport of contaminants through the unsaturated zone, it also would result in greater water-level declines if this source of recharge were exported from the area.

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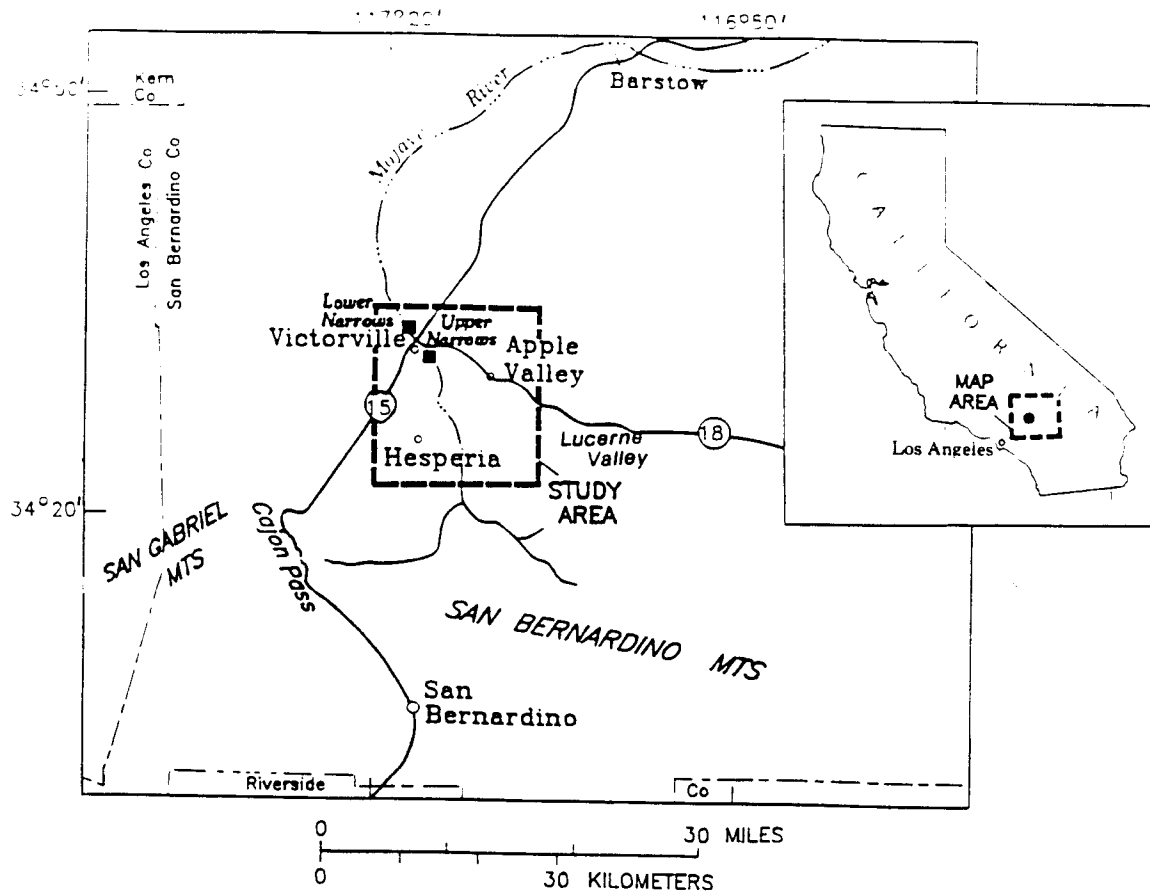
Figure 1. Location of study area.
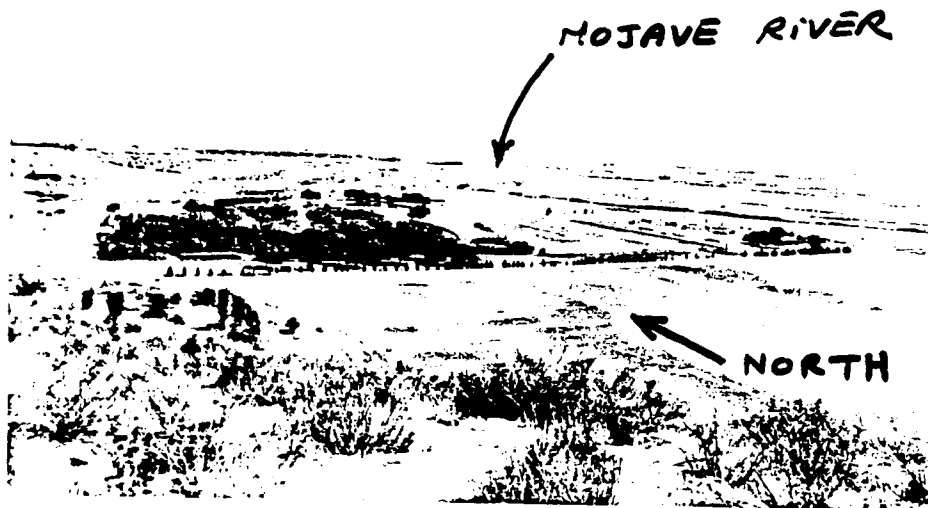
Figure 2. Mojave River channel, looking north toward study area.

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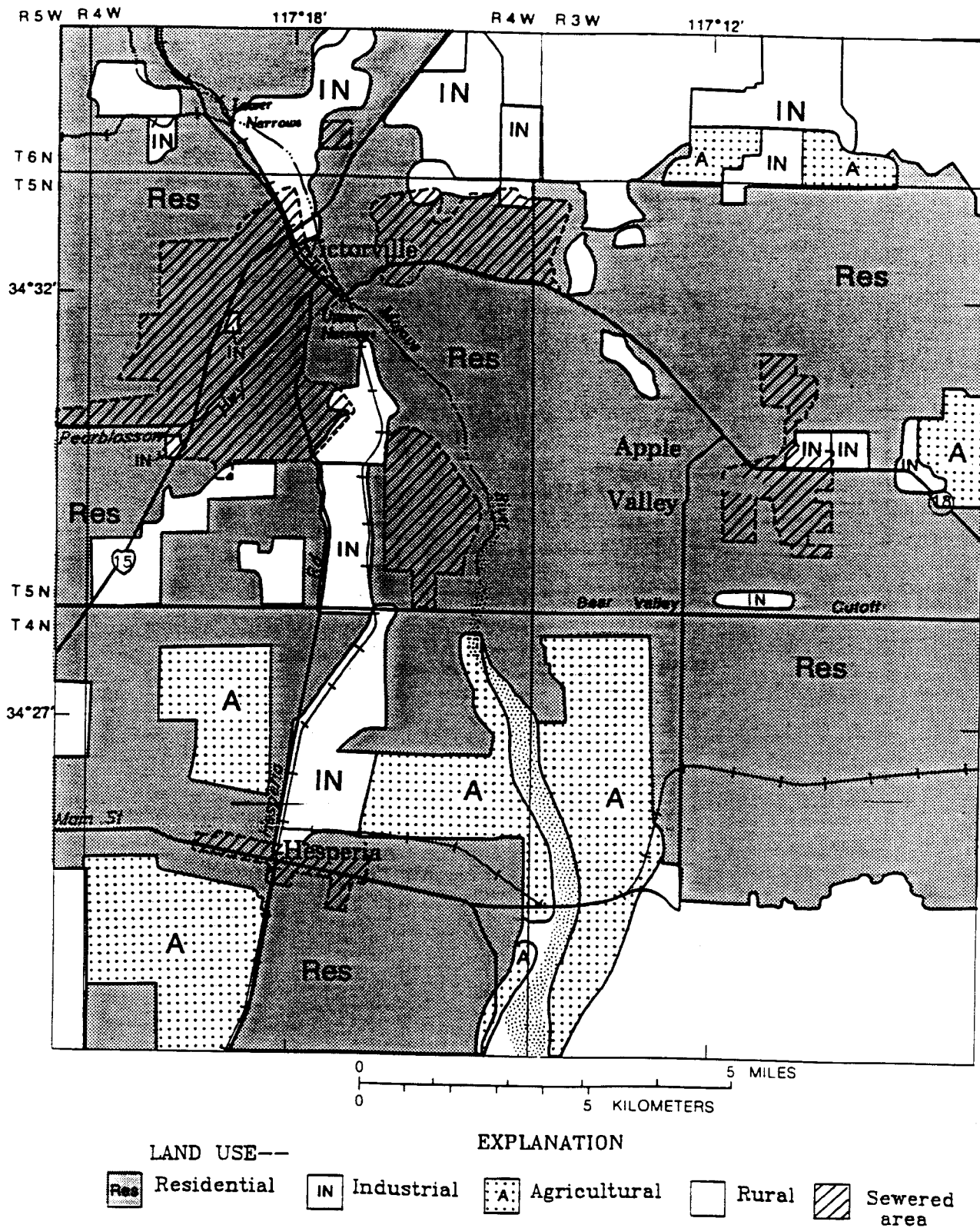
Figure 3. Major land uses (San Bernardino County Planning Department, 1979) and sewered parts (California Regional Water Quality Control Board, written commun., 1988) of study area.
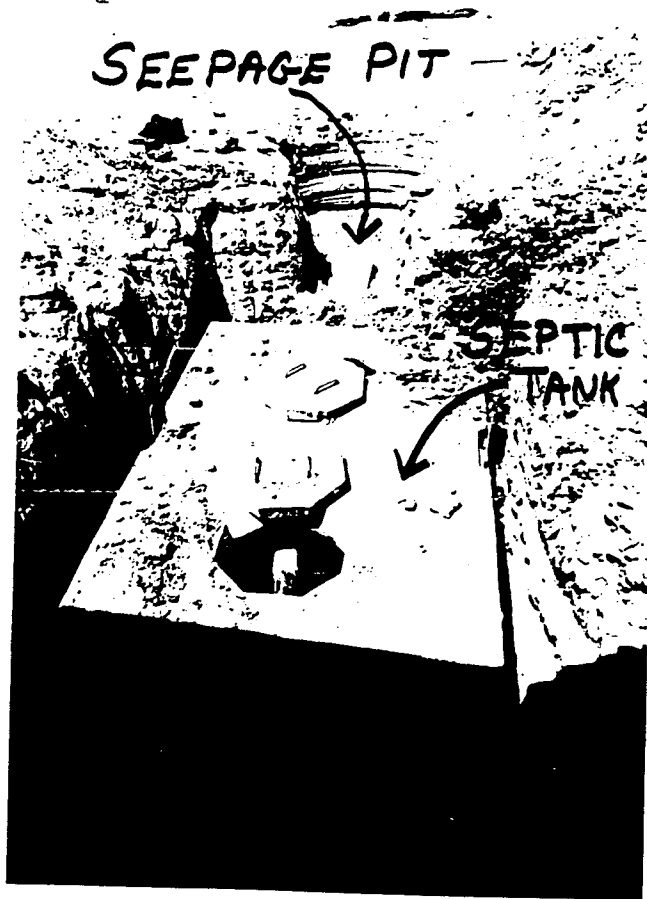
Figure 4. A newly constructed septic tank and seepage pit.
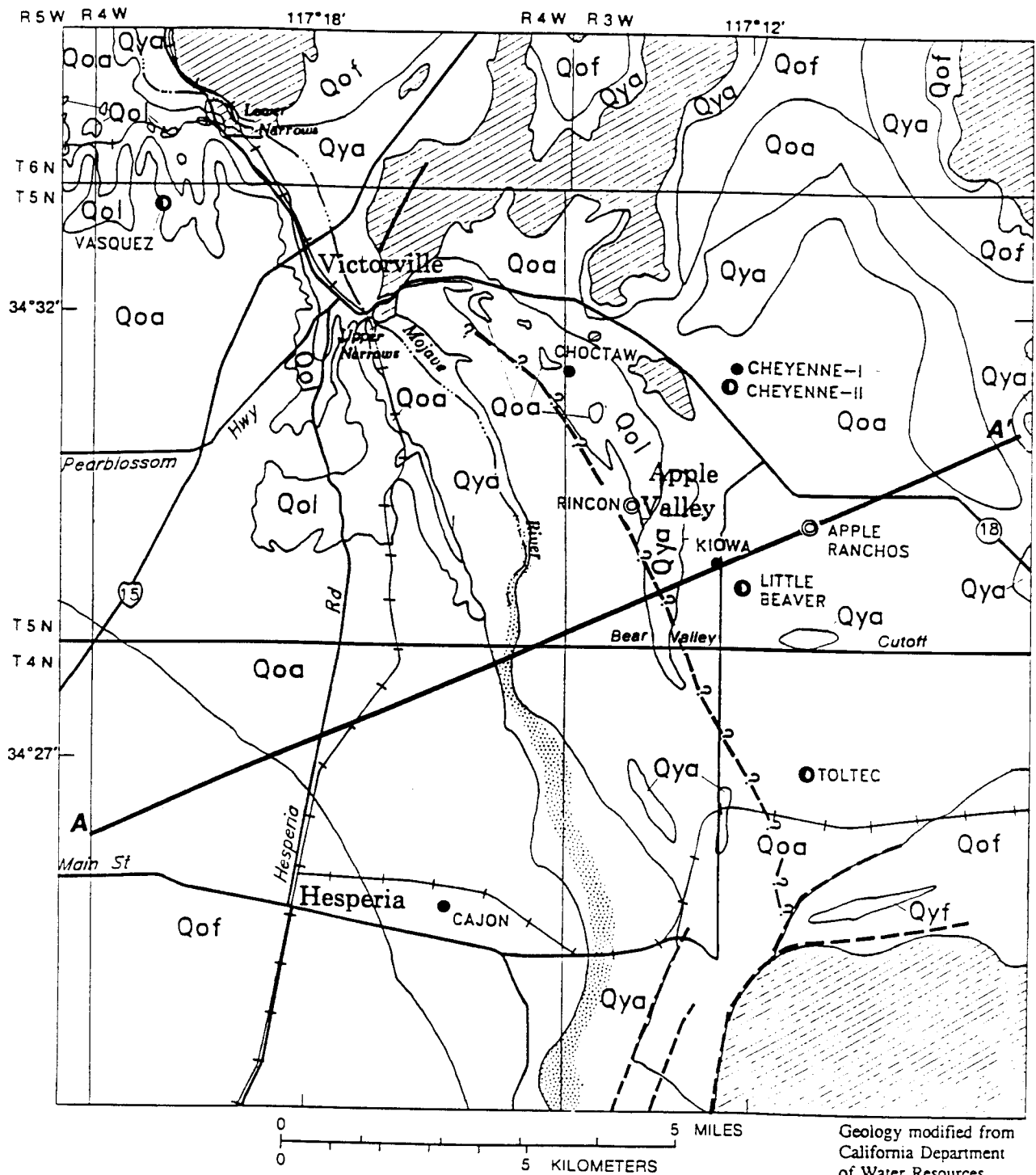
Figure 5. Geology of study area.

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EXPLANATION

GEOLOGIC UNITS
UNCONSOLIDATED DEPOSITS-- (Quaternary)

Qya	Younger alluvium
Qoa	Older alluvium
Qof	Older fan deposits
Qh	Harold Formation

CONSOLIDATED ROCKS--

Tc	Continental rocks (Tertiary)
Bc	Basement complex (Pre-Tertiary) Igneous and metamorphic rocks (Depth of basement complex from Subsurface Surveys, Inc., 1990, plate III

———?— CONTACT--Dashed and queried where uncertain

FAULT--Dashed where uncertain; queried where doubtful. Arrows show relative vertical movement

KIOWA TEST HOLE AND NAME --Drilled for this study
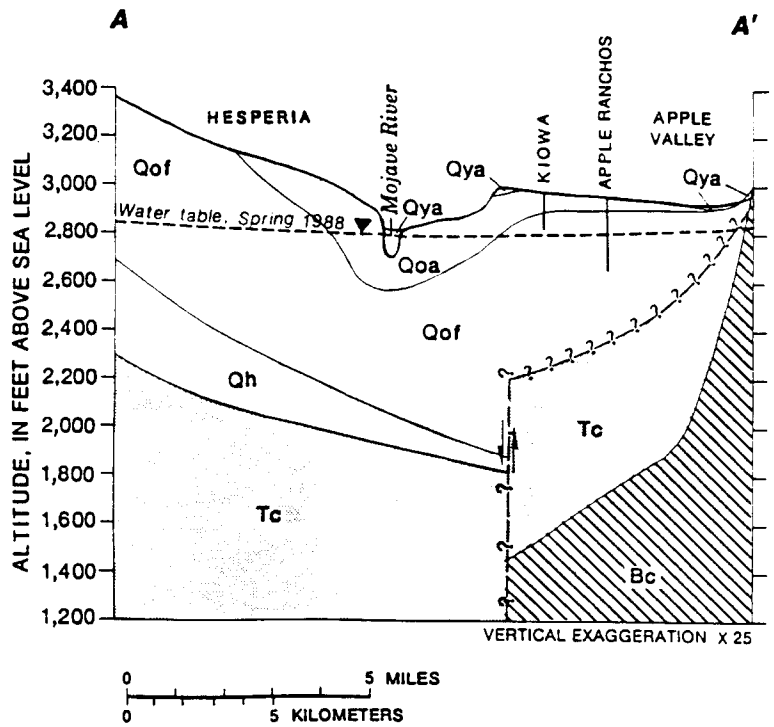
Figure 6. Geologic section through study area.

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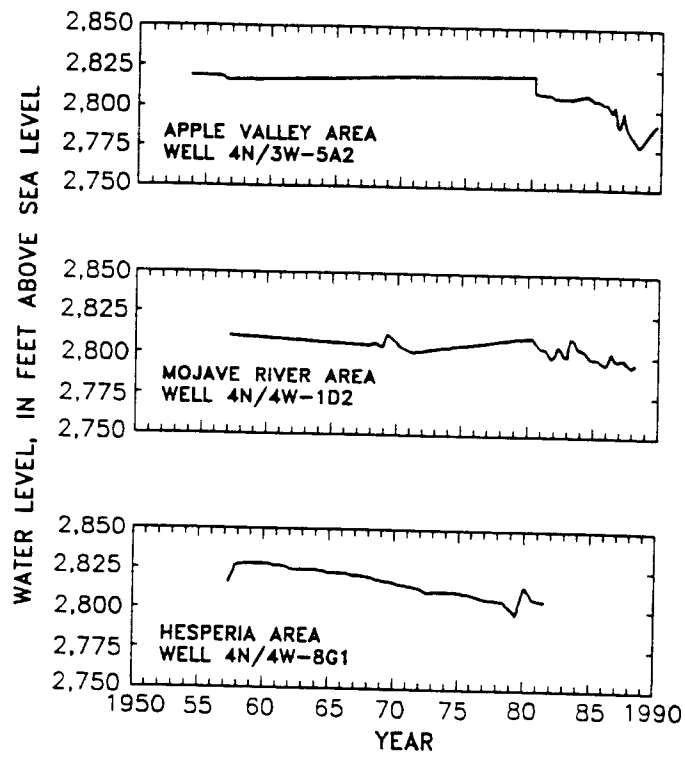
Figure 7. Water-level altitude of selected wells.
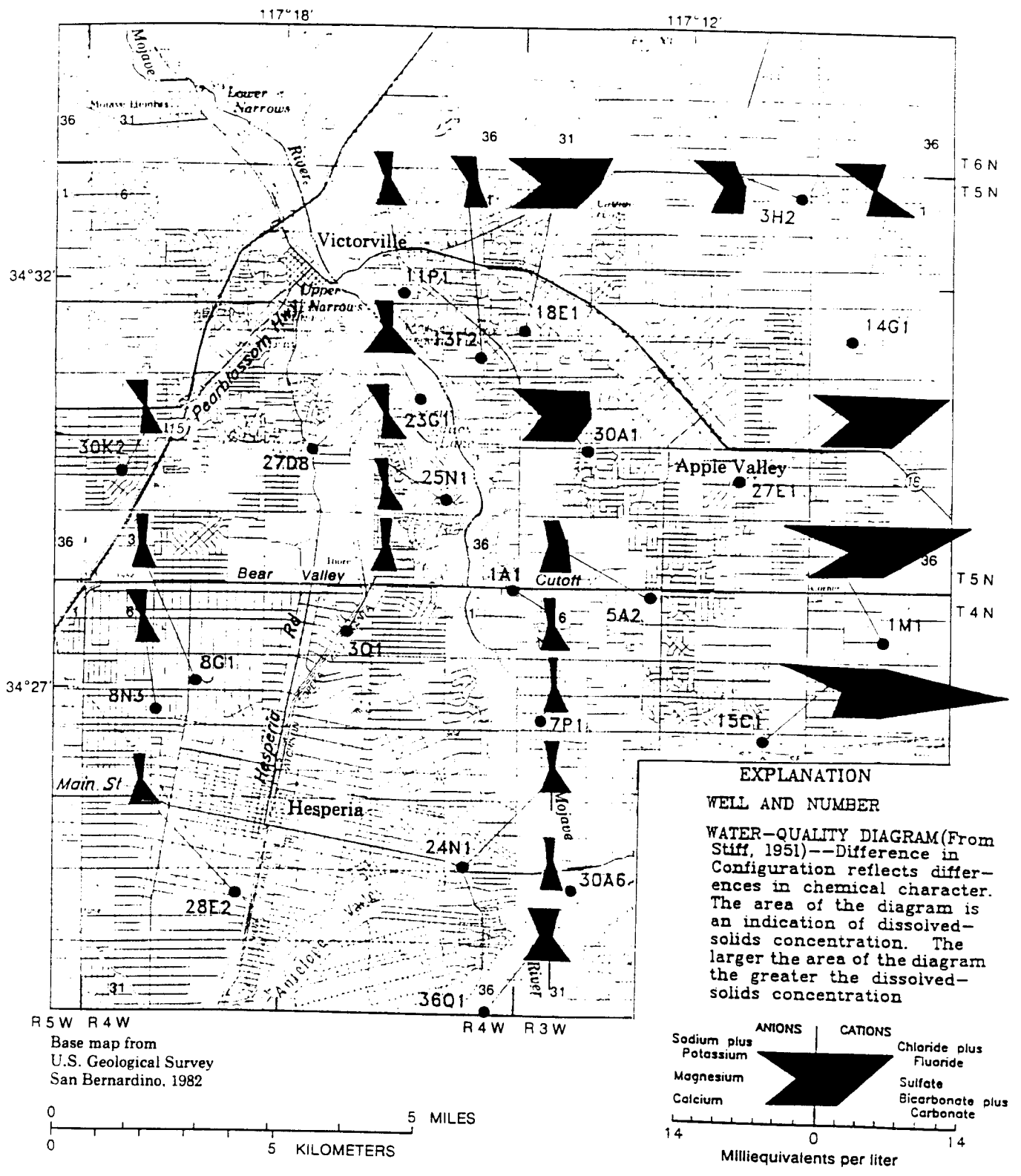
Figure 8. Chemical character of water from selected wells.
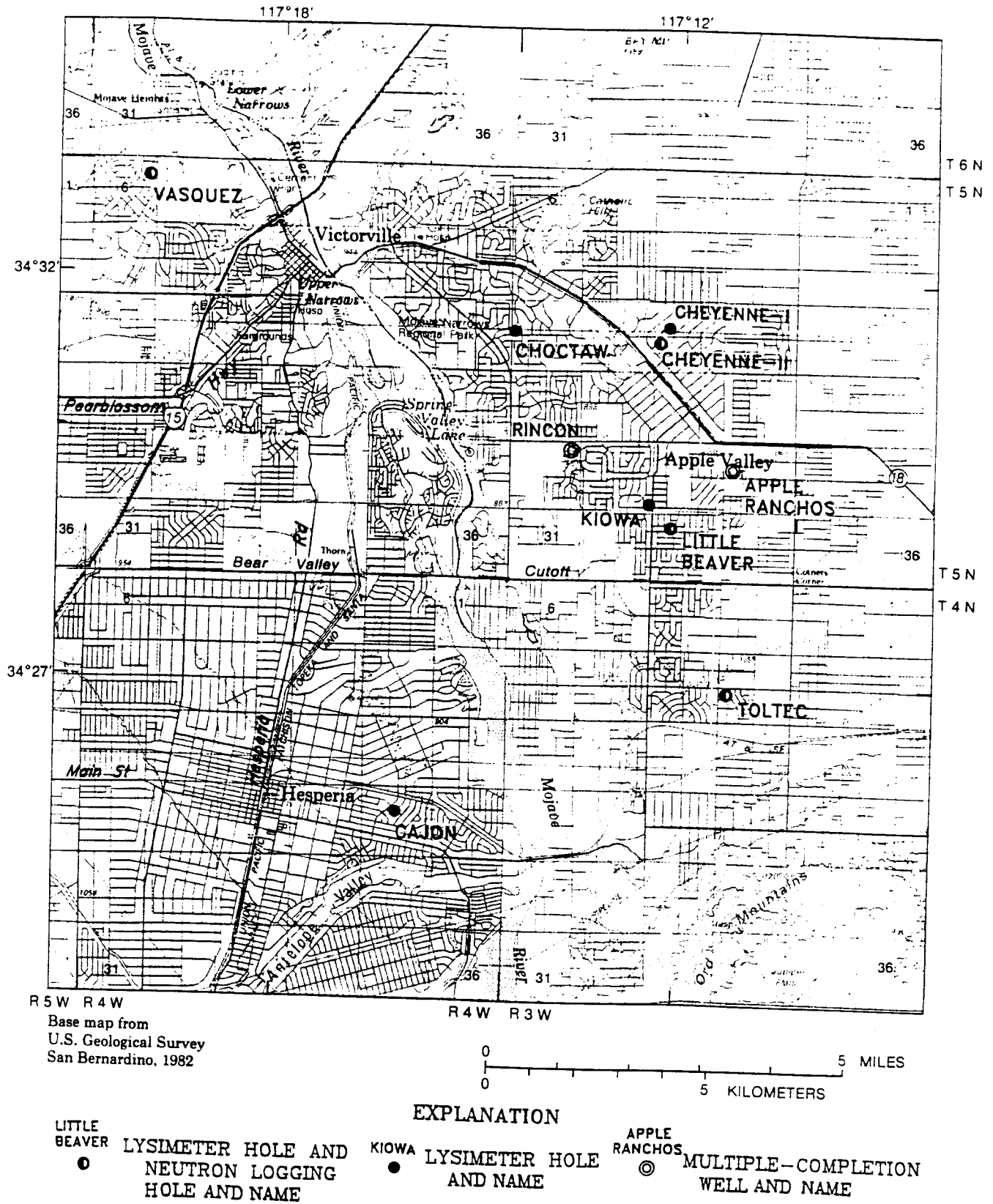
Figure 9. Location of monitoring sites.

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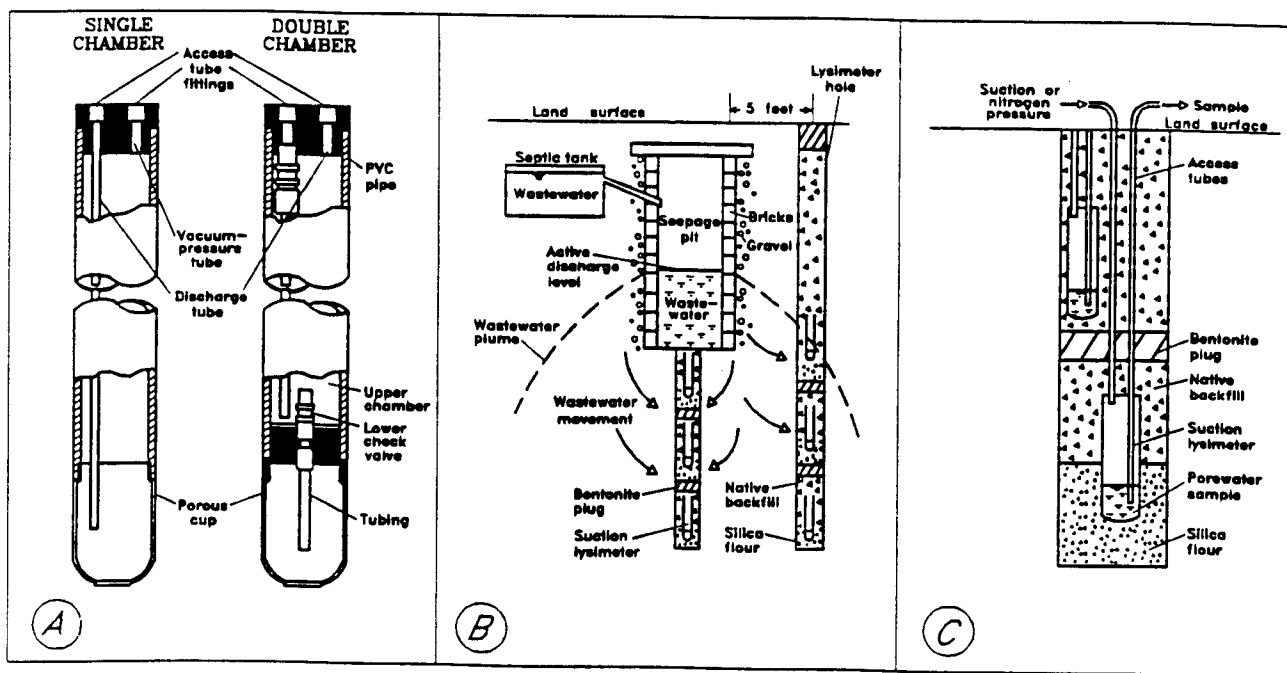
Figure 10. Typical suction lysimeters, installation, and sampling method.
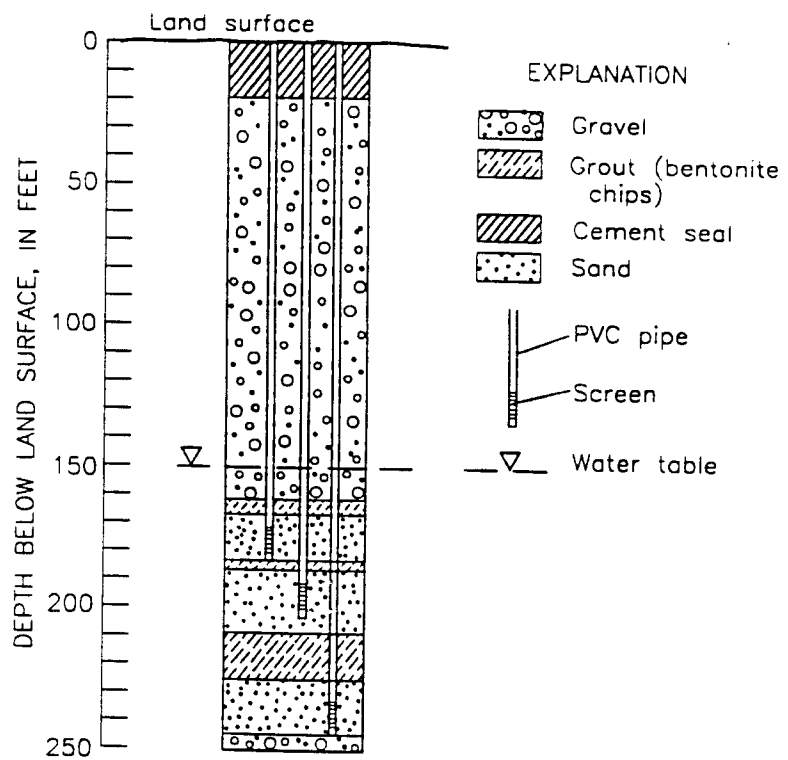
Figure 11. Construction of a typical multiple-well monitoring site.

Figure 12. Temporal changes in soil-moisture content (determined from neutron-probe measurement), and vertical variation in grain size at selected residential sites.

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Figure 12. Temporal changes in soil-moisture content (determined from neutron-probe measurement), and vertical variation in grain size at selected residential sites--Continued.

Figure 12. Temporal changes in soil-moisture content (determined from neutron-probe measurement), and vertical variation in grain size at selected residential sites--Continued.

Figure 12. Temporal changes in soil-moisture content (determined from neutron-probe measurement), and vertical variation in grain size at selected residential sites--Continued.

TOLTEC SITE

DEPTH BELOW LAND SURFACE, IN FEET

GRAIN-SIZE
DISTRIBUTION,
IN PERCENT

MOISTURE CONTENT,
IN PERCENT OF
WET WEIGHT

CHLORIDE CONCENTRATION, IN MILLIGRAMS PER LITER

NITRATE-NITROGEN CONCENTRATION, IN MILLIGRAMS PER LITER

NITRATE/CHLORIDE RATIO,
MULTIPLIED BY 100

EXPLANATION

GRAIN SIZE-
Gravel
Coarse sand
Fine sand
Silt/Clay
Not determined

Note:
Absence of shading pattern in grain-
size distribution of a soil horizon
indicates incomplete analysis. Grain-
size distribution within each soil horizon
shown is extrapolated from 1.5-ft core
centered at middle of horizon

☐   DATA FROM SOIL CORES

■   MEDIAN OF LYSIMETER DATA
      AT INDICATED DEPTHS

— —   BOTTOM OF NEUTRON
         LOGGING HOLE

Figure 13. Vertical variation in selected physical properties and in concentrations of selected
chemical and biological constituents at residential sites.

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CHEYENNE-1 SITE
(First lysimeter hole and lateral-hole core data)

EXPLANATION

GRAIN SIZE—   NOTE:
Gravel   Grain-size- distribution
Coarse sand   within each soil horizon
Fine sand   shown is extrapolated
Silt/clay   from 1.5 ft core centered
                     at middle of horizon

DATA FROM SOIL CORES—
□   First lysimeter hole
— — —   Lateral flow hole

— —   BOTTOM OF FIRST
           LYSIMETER HOLE
▽   WATER TABLE

GRAIN-SIZE
DISTRIBUTION,
IN PERCENT

MOISTURE CONTENT,
IN PERCENT OF
WET WEIGHT

CHLORIDE CONCENTRATION, IN MILLIGRAMS PER LITER

NITRATE-NITROGEN CONCENTRATION,
IN MILLIGRAMS PER LITER

NITRATE/CHLORIDE
RATIO,MULTIPLIED
BY 100

Figure 13. Vertical variation in selected physical properties and in concentrations of selected chemical and biological constituents at residential sites--Continued.

Figure 13. Vertical variation in selected physical properties and in concentrations of selected chemical and biological constituents at residential sites--Continued.

VASQUEZ SITE

Figure 13. Vertical variation in selected physical properties and in concentrations of selected chemical and biological constituents at residential sites--Continued.

CHOCTAW SITE

GRAIN-SIZE DISTRIBUTION, IN PERCENT

MOISTURE CONTENT, IN PERCENT OF WET WEIGHT

CHLORIDE CONCENTRATION, IN MILLIGRAMS PER LITER

NITRATE-NITROGEN CONCENTRATION, IN MILLIGRAMS PER LITER

NITRATE/CHLORIDE RATIO, MULTIPLIED BY 100

DEPTH BELOW LAND SURFACE, IN FEET

EXPLANATION

GRAIN SIZE—
Gravel
Coarse sand
Fine sand
Silt/Clay

NOTE:
 Grain-size distribution within each
soil horizon shown is extrapolated
from 1.5-ft core centered at
middle of horizon

DATA FROM SOIL CORES—
Lysimeter hole
Lateral-flow hole
MEDIAN OF LYSIMETER DATA AT INDICATED DEPTHS
BOTTOM OF LYSIMETER HOLE
∇   WATER TABLE

Figure 13. Vertical variation in selected physical properties and in concentrations of selected chemical and biological constituents at residential sites--Continued.

LITTLE BEAVER SITE

GRAIN—SIZE
DISTRIBUTION,
IN PERCENT

MOISTURE CONTENT,
IN PERCENT OF
WET WEIGHT

CHLORIDE CONCENTRATION,
IN MILLIGRAMS PER LITER

NITRATE—NITROGEN
CONCENTRATION, IN
MILLIGRAMS PER LITER

NITRATE/CHLORIDE
RATIO, MULTIPLIED
BY 100

EXPLANATION

GRAIN SIZE—
Gravel
Coarse sand
Fine sand
Silt/Clay

NOTE:
Grain—size distribution
within each soil horizon
shown is extrapolated from
1.5—ft core centered at
middle of horizon

□   DATA FROM SOIL CORES
■   MEDIAN OF LYSIMETER DATA
     AT INDICATED DEPTHS
——   BOTTOM OF NEUTRON
     LOGGING HOLE

Figure 13. Vertical variation in selected physical properties and in concentrations of selected chemical and biological constituents at residential sites--Continued.

KIOWA SITE

Figure 13. Vertical variation in selected physical properties and in concentrations of selected chemical and biological constituents at residential sites--Continued.

Figure 13. Vertical variation in selected physical properties and in concentrations of selected chemical and biological constituents at residential sites--Continued.

Figure 13. Vertical variation in selected physical properties and in concentrations of selected chemical and biological constituents at residential sites--Continued.

Figure 14. Influence of selected parameters on model-computed nitrate concentrations in ground water.
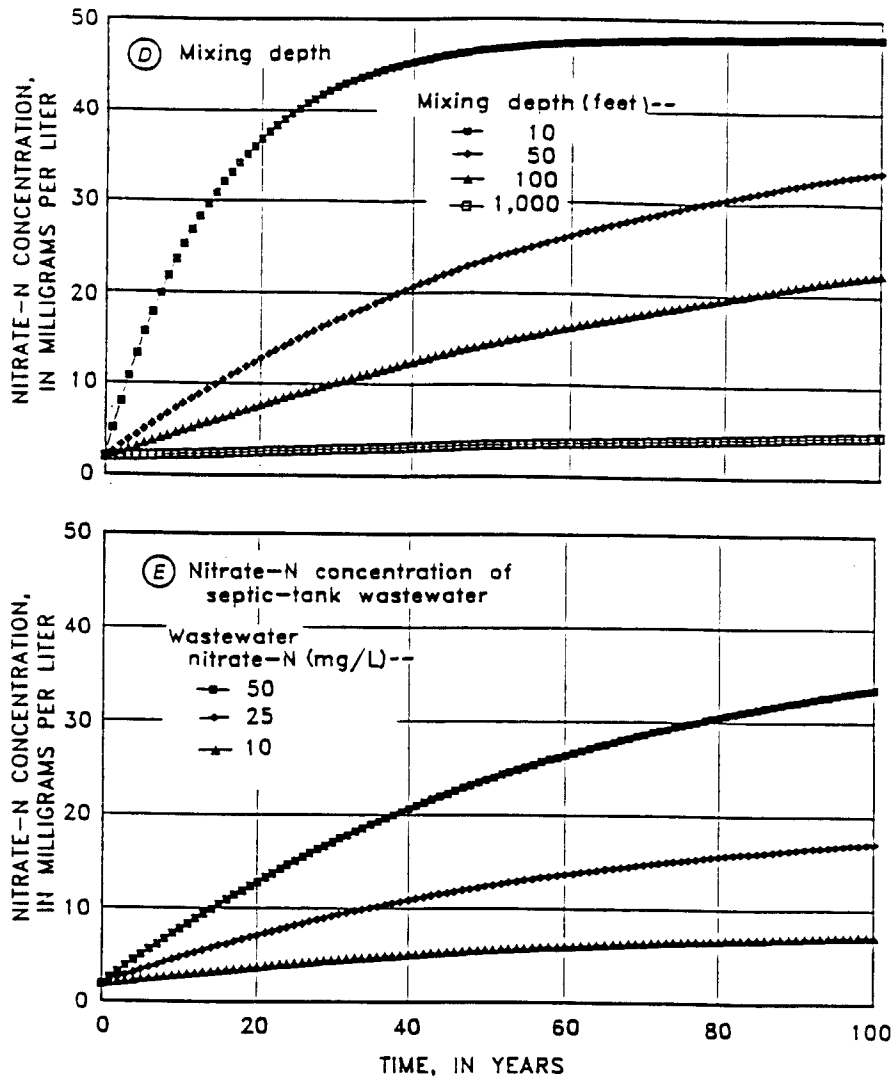
Figure 14. Influence of selected parameters on model-computed nitrate concentrations in ground water--Continued

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Table 1. Dissolved-solids and nitrate concentrations in samples from selected wells in the study area

[Well No: See "Well-Numbering System" in text. ft, foot; mg/L, milligram per liter; --, no data]

Well No.	Date of sample	Well depth (ft)	Dissolved solids, calculated sum of constituents (mg/L)	Nitrogen, $NO_2 + NO_3$ dissolved (mg/L as N)
4N/3W-01M01	4-07-80	--	990	1.60
-05A02	6-24-87	300	213	.580
-07P01	5-27-87	415	113	.610
-15C01	6-08-89	390	1,030	.320
-30A06	5-22-90	120	118	.300
4N/4W-01A01	5-27-88	275	140	2.30
-03Q01	6-08-89	400	125	.330
-08G01	4-08-89	610	106	.960
-08N03	6-06-89	900	135	2.20
-24N01	4-08-80	452	133	2.50
-28E02	4-08-80	593	143	.770
-36Q01	5-27-87	--	274	4.90
5N/3W-03H02	6-07-89	223	329	2.10
-14G01	7-11-78	226	253	.090
-18E01[1]	8-23-89	131	703	.730
-27E01[2]	8-22-89	240	814	1.70
-30A01[3]	8-23-89	285	542	.890
5N/4W-11P01	5-22-90	--	148	.900
-13F02	5-22-90	260	170	.400
-23G01	5-27-87	63	217	.490
-25N01	5-24-90	400	122	.500
-27D08	6-07-89	520	137	1.90
-30K02	6-07-89	650	127	.310

[1] Choctaw site--suction lysimeter at 131 ft.
[2] Apple Ranchos multiple-completion well.
[3] Rincon multiple-completion well.

Table 2. Location and characteristics of residential wastewater-disposal study sites

[Residential density: single family, 1/2 acre per lot; multiple family, duplex or triplex. Geologic units penetrated: Qoa, older alluvium; Qof, older fan deposits; Qol, old lake and lakeshore deposits; gal/d, gallon per day; mo/yr, month and year; ft, foot; --, no neutron access tube]

Site name	Community	Residential density	Winter water usage, 1989 (gal/d)	Date seepage pit was constructed (mo-yr)	Altitude of land surface (ft)	Lysimeters installed	Depth of neutron access tube (ft)	Lateral-flow hole	Depth to water table, 1988-89 (ft)	Geologic units penetrated
Toltec	Apple Valley	Single family	388	4-88	3,030	4	99	No	[1]220	Qoa, Qof
Cheyenne-I	Apple Valley	Single Family	750	11-83	2,923	7	--	Yes	112	Qoa, Qof
Vasquez	Victorville	Single family	250	4-88	2,840	4	89	No	[1]85	Qol
Choctaw	Apple Valley	Single family	625	4-78	2,920	4	--	Yes	124	Qol, Qoa
Little Beaver	Apple Valley	Multiple family	875	4-88	2,970	4	121.5	No	[1]150	Qoa, Qof
Kiowa	Apple Valley	Multiple family	812	9-79	2,975	3	--	No	[1]150	Qoa, Qof
Cheyenne-II	Apple Valley	Single family	338	3-87	2,927	3	119	No	117	Qoa, Qof
Cajon	Hesperia	Single family	260	12-77	3,060	8	--	No	252	Qoa, Qof

[1]Water table not reached by drilling; depth based on estimate from Subsurface Surveys, Inc., (1990, pl. 4).

Table 3. Location and characteristics of ground-water monitoring sites

[Well No: See "Well-Numbering System" in text (LYS at end of well number indicates lysimeter). Altitude in feet above sea level. Depths and sampling interval in feet below land surface]

Site name	Well No.	Altitude of land surface	Type of monitoring device	Depth of monitoring device	Sampling interval	Depth to water table	Date of measurement	Remarks
Cheyenne-I	5N/3W-16E01LYS	2,923	Suction lysimeter below water table	113	112.5–113	112	4-9-88	Water level measured when hole drilled
Choctaw	5N/3W-18E01LYS	2,920	Suction lysimeter below water table	131	130.5–131	124	4-13-88	Water level measured when hole drilled
Cheyenne-II	5N/3W-16M01	2,927	Neutron access tube	123	119–123	Min. 117.3 Max. 120.70	9-12-88 6-9-88	Well point attached to neutron access tube
Cajon	4N/4W-23F01LYS	3,060	Lysimeter below water table	257	256.5–257	Min. 253.2 Max. 254.3	12-9-89 1-11-90	
	4N/4W-23F09	3,060	Piezometer	266	254–260.8	Min. 253.2 Max. 254.3	12-9-89 1-11-90	1.5-inch pipe
Apple Ranchos	5N/3W-27E03	2,950	Multiple-completion well	240	232–236.5	Min. 153.69 Max. 170.09	2-6-89 8-22-89	Upgradient multiple-well monitoring site
	-27E04	2,950	do.	199	189–194	Min. 152.74 Max. 163.48	2-6-89 8-22-89	
	-27E05	2,950	do.	173	163–168	Min. 151.62 Max. 158.99	12-15-88 8-22-89	
	-27E06	2,950	do.	152	143–148	Min. 145.73 Max. 147.04	6-2-88 ([1])	
Rincon	5N/3W-30A01	2,960	Multiple-completion well	285	270–280	Min. 175.74 Max. 185.99	3-7-89 8-13-89	Downgradient multiple-well monitoring site
	-30A02	2,960	do.	233	218–228	Min. 177.22 Max. 182.92	3-7-89 8-23-89	
	-30A03	2,960	do.	200	185–195	Min. 177.14 Max. 181.14	3-7-89 4-12-89	

[1]147.04 feet is depth from land surface to bottom of perforation; depth to water level exceeded this on 6-7-88, 7-23-88, 8-9-88, 9-13-88, 10-14-88, and 8-22-89.

Table 4. Suction-lysimeter depth and lateral distance from seepage pit

[USGS site identification No.: A unique number for each site based on the latitude and longitude of the site. The first six digits are latitude, the next seven digits are longitude, and the final two digits are a sequence number to uniquely identify test holes and (or) depth of monitoring device at each residential site. ft, foot]

Site name	USGS site identification No.	Depth of suction lysimeter (ft)	Lateral distance from seepage pit (ft)	Remarks
Toltec	342655117111401	73	0	Destroyed 5-4-90.
	02	50	0	Do.
	03	40	0	Do.
	04	33	0	Do.
Cheyenne-I	343125117121501	113	5	First hole, drilled 4-9-88; destroyed 1-11-90.
	08	106	5	Second hole, drilled 12-6-88; destroyed 1-11-90.
	02	92.5	5	First hole
	09	73	5	Second hole
	10	63	5	Do.
	04	48	25	Lateral flow hole; no water; destroyed 1-11-90.
	11	42	5	Second hole
	03	37	5	First hole
Vasquez	343314117195201	71	0	
	02	51	0	No water after 6-8-88; damaged.
	03	43	0	
	04	35	*0	No water after 8-23-89.
Choctaw	343124117143001	131	5	
	02	80	5	
	03	48	5	No water after 10-14-88; damaged.
	04	33	5	No water after 1-27-89; damaged.
	05	48	50	Lateral-flow hole; never made water.
Little Beaver	342857117120604	77	5	Suction lysimeter in hole with neutron-probe access tube; only made water last time sampled (1-11-90).
	05	67	5	Suction lysimeter in hole with neutron-probe access tube; only made water once.
	01	40	5	
	02	31.5	5	
Kiowa	342917117122601	149	5	Sample volumes small.
	02	107.5	5	
	03	67.5	5	No water after 10-14-88; damaged.
	04	32	5	No water after 3-6-89; possibly damaged.
Cheyenne-II	343114117122302	98	5	Never produced water; damaged on installation.
	03	67	5	
	04	10	5	Above active water level in seepage pit; never produced water.
Cajon	342518117160601	257	5	Only two samples.
	02	243	5	
	03	199	5	Only two samples.
	04	160	5	Only one sample (1-11-90).
	05	130	5	
	06	97.5	5	Only two samples.
	07	70	5	
	08	35	5	No water after 3-6-89.

Table 5. Summary of monitoring devices installed and analyses completed at each study site

[Site: T, Toltec; C-I, Cheyenne-I; V, Vasquez; Ch, Choctaw; LB, Little Beaver; K, Kiowa; C-II, Cheyenne-II; Ca, Cajon; AR, Apple Ranchos; Ri, Rincon]

	T	C-I	V	Ch	LB	K	C-II	Ca	AR	Ri
Monitoring devices										
Lysimeter at seepage pit	X	X	X	X	X	X	X	X		
Lateral-flow lysimeter		X		X						
Piezometer		(1)		(1)			(1)	(2)	X	X
Neutron-access tube	X			X	X		X			
Analyses										
Grain-size distribution in soil cores	X	X	X	X	X	X	X	X		
Moisture content in soil cores	X	X	X	X	X	X	X	X		
Fecal coliform in soil		X						X		
Nitrifying bacteria in soil		X						X		
Nitrate-reducing bacteria in soil		X						X		
Total bacteria in soil	X	X		X		X	X			
Soil extract, inorganic, chemical constituents	X	X	X	X	X	X	X	X		
Soil, organic priority pollutants	X	X		X		X	X			
Wastewater, inorganic, chemical constituents		X	X	X		X	X	X		
Wastewater, organic priority pollutants		X	X	X		X	X			
Wastewater, bacteria		X	X	X		X	X			
Nitrogen isotopes		X						X	X	X
Tapwater, chemical constituents	X	X	X	X	X	X	X	X		

[1]Bottom lysimeter below water table.
[2]Piezometer above declining water table after late 1991.

Table 6. Grain-size distribution for core samples at study sites

[ft, foot; --, no data; <, actual value is less than value shown. Particle-size descriptions are based on Wentworth scale]

Depth interval (ft)	Percent finer than size, in millimeters, indicated					
	Coarse sand	Medium sand	Fine sand	Silt	Clay	
	2	0.5	0.25	0.0625	0.002	0.0014
Toltec site (lysimeter hole)--April 7, 1988						
33.5-34	93	63	45	31	6	3
34-34.6	100	74	52	25	7	2
37.3-37.7	100	65	46	27	7	3
37.7-38	100	41	21	13	4	2
37.8-38.6	100	40	21	12	3	1
41.8-42.5	100	47	27	15	5	3
42.5-43	70	--	9	--	4	3
46.7-48.3	77	--	17	--	5	4
48.4-49	80	--	11	--	3	3
72.5-73.5	83	--	7	--	1	1
Toltec site (neutron-access hole)--April 7-8, 1988						
32-33	91	71	55	34	10	6
57-58.5	64	24	14	7	2	<1
67-68	78	34	19	8	1	<1
77-78	71	33	25	20	2	<1
87-88	67	30	18	7	2	<1
97-99	100	88	45	7	2	<1
Cheyenne-I site (first lysimeter hole)--April 9, 1988						
7-9	100	82	58	19	<1	<1
12-14	94	73	43	8	1	<1
17-19	90	40	17	3	1	<1
22-24	100	90	77	29	3	2
27-28	100	87	60	15	4	2
32-34	98	80	54	9	2	<1
37-39	87	84	78	50	7	6
42-44	100	89	63	23	5	4
47-49	85	69	57	38	12	7
57-59	78	30	11	3	<1	<1
67-69	81	32	15	6	1	<1
77-79	99	98	81	54	13	1
87-89	84	33	13	4	<1	<1
97-99	96	72	53	32	10	4

Table 6. Grain-size distribution for core samples at study sites--Continued

Depth interval (ft)	Percent finer than size, in millimeters, indicated					
	Coarse sand	Medium sand	Fine sand	Silt	Clay	
	2	0.5	0	0.0625	0.002	0.0014
Cheyenne-I site (first lysimeter hole)--April 9, 1988--(continued)						
107–109	100	87	78	49	11	3
118–120	100	49	28	12	2	<1
124	100	78	43	8	1	<1
Cheyenne-I site (lateral-flow hole)--April 10, 1988						
27–29	99	94	82	33	4	2
37–39	99	98	96	62	12	8
47–49	99	82	68	48	7	5
Vasquez site (lysimeter hole)--April 11, 1988						
36–38	55	22	10	7	2	<1
41–43	94	49	20	4	2	<1
46–48	92	56	19	8	3	<1
51–53	94	64	45	30	7	4
61–63	89	50	35	22	6	3
71–73	99	92	81	48	12	7
Vasquez site (neutron hole)--April 12, 1988						
7–9	98	89	76	39	6	3
17–19	89	34	11	3	2	<1
27–29	100	98	95	64	4	2
37–39	64	19	9	6	3	<1
47–49	98	84	50	7	<1	<1
57–59	98	76	67	53	5	3
67–69	98	78	56	37	4	2
77–78	98	83	69	41	2	1
87–89	89	39	18	7	1	<1
Little Beaver site (lysimeter hole)--April 23, 1988						
17–19	82	34	14	6	2	2
27–29	95	93	90	37	3	<1
37–39	91	89	86	51	4	2
47–49	92	82	74	45	14	3
57–59	91	74	59	32	13	4
77–79	100	100	97	58	3	2
97–99	91	81	71	39	6	3

Table 6. Grain-size distribution for core samples at study sites--Continued

Depth interval (ft)	Percent finer than size, in millimeters, indicated					
	Coarse sand 2	Medium sand 0.5	Fine sand 0	Silt 0.0625	Clay 0.002	Clay 0.0014
Kiowa site (lysimeter hole)--April 25, 1988						
7-9	58	26	14	7	3	<1
12-14	77	35	14	4	2	<1
17-19	99	93	65	14	2	<1
22-24	100	99	96	34	3	<1
27-29	100	97	90	53	4	2
32-34	99	87	55	19	3	<1
37-39	87	52	37	15	2	<1
42-44	95	66	45	23	4	<1
47-49	100	94	78	24	4	<1
57-59	100	100	97	44	3	<1
67-69	98	86	78	64	13	7
77-79	93	74	• 62	19	2	<1
87-89	77	39	22	10	5	<1
97-99	97	82	69	46	7	4
117-119	96	89	84	63	14	7
127-129	94	76	65	31	5	2
137-139	96	82	64	31	17	4
147-149	90	50	23	9	2	<1
Cheyenne-II site (neutron-access hole)--April 27, 1988						
7-9	100	88	61	14	2	2
17-19	85	60	47	22	2	2
22-24	94	87	80	22	5	4
27-29	96	39	17	3	2	<1
32-34	92	29	11	3	1	<1
37-39	100	98	94	37	7	3
42-44	91	78	42	9	3	1
47-49	100	97	94	63	11	7
57-59	95	73	58	41	13	9
67-69	100	95	79	39	8	5
77-79	80	32	23	8	4	3
87-89	99	92	82	44	6	4
97-99	79	41	30	14	4	3

Table 6. Grain-size distribution for core samples at study sites--Continued

| Depth interval (ft) | Percent finer than size, in millimeters, indicated | | | | | |
| | Coarse sand | Medium sand | Fine sand | Silt | Clay | |
	2	0.5	0	0.0625	0.002	0.0014
Cajon site (lysimeter hole)--November 29, 1988						
82–84	93	46	27	13	5	<1
101–103	86	56	36	18	8	7
121–123	100	91	47	20	8	7
140.5–142.5	98	78	52	19	8	8
160.5–162.5	92	43	24	9	3	<1
180.5–182.5	78	35	19	7	<1	<1
200.5–202.5	62	36	23	9	4	1
220–222	81	54	36	14	4	3
240–242	83	40	22	8	3	3

Table 7. Moisture content and pore-water chemical concentration determined from cores at residential study sites

[Chemical concentrations calculated from analyses on deionized-water extracts using known quantities of core material, except pH reported from extract analyses directly; mg/L, milligram per liter; μS/cm, microsiemen per centimeter at 25 degrees Celsius; <, less than reporting limit; ND, not detected; --, not analyzed]

Core depth interval (in feet below land surface	Moisture content (weight percent)	Nitrate/ chloride (weight ratio)	pH (standard units)	Specific conductance (μS/cm)	Ammonia NH_3-N (mg/L)	Nitrate NO_3-N (mg/L)	Chloride (mg/L)	Boron (mg/L)	Total alkalinity, as $CaCO_3$ (mg/L)
Toltec site (neutron-access hole)--April 7-8, 1988									
5-7	1.85	0.017	7.9	18,000	1	40	2,400	4	3,000
23-24	4.15	.10	7.0	13,000	ND	270	2,700	2	300
32-33	5.73	.12	7.3	3,900	ND	89	750	1	400
42-43	3.38	.062	7.5	2,100	ND	36	580	2	600
57-58.5	1.58	.037	7.7	2,100	--	14	380	2	1,100
67-68	2.23	.034	7.9	1,500	ND	11	320	3	900
77-78	1.22	.049	7.8	2,400	7	17	340	2	1,400
87-88	1.94	.038	7.6	2,000	--	8.9	240	3	1,000
97-99	5.96	.049	7.7	610	--	5.6	110	1	300
Cheyenne-I site (first lysimeter hole)--April 9, 1988									
7-9	6.81	0.0024	9.0	22,000	1	11	4,800	9	2,700
12-14	3.58	.0088	7.3	17,000	5	33	3,700	6	400
17-19	2.92	--	7.9	4,200	--	88	--	--	--
22-24	9.60	.28	7.4	1,500	.6	58	210	10	300
27-28	12.10	.025	9.0	2,200	--	4.6	180	10	800
32-34	8.15	--	7.2	2,100	3	52	--	--	--
37-39	23.70	.24	8.4	1,900	--	29	120	13	600
42-44	13.70	--	8.4	1,400	--	40	--	--	--
47-49	14.80	--	8.9	2,900	ND	44	--	--	--
57-59	3.30	--	8.7	2,600	--	56	--	--	--
67-69	5.02	.099	9.7	5,600	ND	55	550	18	2,500
77-79	22.30	.16	8.6	2,900	ND	31	190	2	600
87-89	2.78	--	7.3	2,600	ND	19	--	--	--
97-99	23.00	--	7.9	1,600	2	.73	--	--	--
107-109	18.40	--	8.9	2,700	.3	.82	--	--	--
118-120	17.50	.011	7.7	1,400	.5	2.0	180	.5	150
Cheyenne-I site (lateral-flow hole)--April 10, 1988									
27-29	14.0	0.11	8.4	4,500	--	31	290	7	400
27-29	14.0	.11	8.7	4,800	--	32	280	7	600
37-39	30.7	.28	8.4	4,300	ND	35	130	4	500
47-49	12.3	.19	8.5	2,400	--	31	160	3	500
49-49.2	15.3	.18	8.7	2,500	--	33	180	4	600
Cheyenne-I site (second lysimeter hole)--December 6, 1988									
17-19	12.7	0.11	--	3,900	2	24	220	6	1,000
22-24	13.1	.18	--	1,700	.3	33	180	6	400
27-29	13.2	.26	--	1,500	.7	52	200	9	300
32-34	3.87	.12	--	2,000	5	34	290	12	600
37-39	32.8	.21	--	1,600	ND	22	100	8	500
42-44	10.0	.13	--	1,500	.09	27	200	11	300
47-49	12.4	.12	--	1,600	1	25	210	15	300
52-53	3.04	.11	--	2,000	1	36	350	14	600
62-64	14.3	.10	--	1,500	1	22	220	12	400

Table 7. Moisture content and pore-water chemical concentration determined from cores at residential study sites--Continued

Core depth interval (in feet below land surface	Moisture content (weight percent)	Nitrate/ chloride (weight ratio)	pH (standard units)	Specific conductance (μS/cm)	Ammonia NH₃-N (mg/L)	Nitrate NO₃-N (mg/L)	Chloride (mg/L)	Boron (mg/L)	Total alkalinity, as CaCO₃ (mg/L)
Cheyenne-I site (second lysimeter hole)--December 6, 1988--(Continued)									
67–69	9.02	.19	--	1,500	.5	36	180	12	300
72–74	14.2	.1	--	1,700	.08	33	180	8	400
77–79	17.6	.22	--	1,600	.04	35	160	3	300
82–84	8.04	.033	--	1,900	.9	10	310	.7	200
87–89	1.90	.031	--	400	.5	2.1	68	.3	100
92–94	13.1	.067	--	2,700	.7	15	230	.6	500
97–99	12.4	.086	--	1,700	2	18	210	.8	200
Vasquez site (lysimeter hole)--April 11, 1988									
36–38	4.21	--	--	--	--	--	--	--	--
41–43	6.94	--	--	--	--	--	--	--	--
46–48	6.14	--	--	--	--	--	--	--	--
51–53	11.4	--	--	--	--	--	--	--	--
61–63	10.4	--	--	--	--	--	--	--	--
71–73	20.0	--	--	--	--	--	--	--	--
Vasquez site (neutron hole)--April 12, 1988									
7–9	11.9	--	--	--	--	--	--	--	--
17–19	1.00	--	--	--	--	--	--	--	--
27–29	11.9	--	--	--	--	--	--	--	--
37–39	3.81	--	--	--	--	--	--	--	--
47–49	7.05	--	--	--	--	--	--	--	--
57–59	10.3	--	--	--	--	--	--	--	--
67–69	15.5	--	--	--	--	--	--	--	--
77–78	16.1	--	--	--	--	--	--	--	--
87–89	5.21	--	--	--	--	--	--	--	--
Choctaw site (lysimeter hole)--April 13, 1988									
3–5	6.99	0.051	9.67	5,600	2	7.3	140	2	4,400
8–10	9.37	.38	8.72	2,900	.6	40	110	.8	1,200
13–15	5.07	.63	7.02	1,100	ND	40	63	1	200
18–20	12.4	.026	7.50	820	.7	2.2	82	.7	300
23–25	17.2	.60	8.22	2,000	ND	22	37	.4	900
28–30	15.9	.032	7.63	750	3	5.3	170	1	300
28–30	15.9	.11	7.64	660	7	6.0	53	.9	200
28–30	15.9	.049	7.56	700	12	6.6	130	1	200
33–45	7.31	.0037	7.80	1,200	--	.49	130	1	600
38–40	12.3	.0079	7.95	1,400	--	.65	83	2	700
43–45	2.97	.014	7.46	2,700	3	2.7	200	3	700
48–50	13.5	.084	7.78	1,000	.2	9.9	120	2	400
53–55	10.4	.12	9.11	2,500	.5	15	120	3	1,400
63–65	6.92	.064	7.99	980	--	7.4	110	7	400
73–75	9.26	.12	7.53	920	.6	21	170	6	300
83–85	12.1	--	7.40	890	--	20	--	3	300
93–95	4.24	.10	7.45	1,400	--	19	190	11	600
103–105	5.14	.15	7.19	1,000	2	16	110	4	400
113–115	3.31	.18	7.25	1,200	2	19	110	1	400
123–125	19.8	.0054	8.51	2,600	.1	.88	160	.9	580

Table 7. Moisture content and pore-water chemical concentration determined from cores at residential study sites--Continued

Core depth interval (in feet below land surface)	Moisture content (weight percent)	Nitrate/ chloride (weight ratio)	pH (standard units)	Specific conductance (μS/cm)	Ammonia NH₃-N (mg/L)	Nitrate NO₃-N (mg/L)	Chloride (mg/L)	Boron (mg/L)	Total alkalinity, as CaCO₃ (mg/L)
Little Beaver site (lysimeter hole)--April 23, 1988--(Continued)									
17-19	2.57	--	--	--	--	--	--	--	--
27-29	8.54	--	--	--	--	--	--	--	--
37-39	8.25	--	--	--	--	--	--	--	--
47-49	3.88	--	--	--	--	--	--	--	--
57-59	11.8	--	--	--	--	--	--	--	--
67-69	6.13	--	--	--	--	--	--	--	--
Little Beaver site (neutron hole)--April 24, 1988									
77-79	6.86	--	--	--	--	--	--	--	--
88-89	15.1	--	--	--	--	--	--	--	--
97-99	6.87	--	--	--	--	--	--	--	--
Kiowa site (lysimeter hole)--April 25, 1988									
7-9	4.35	0.082	7.51	120,000	5	34	420	4	1,200
12-14	3.52	.049	9.37	9,400	ND	36	730	2	3,100
17-19	12.4	.28	6.44	760	1	20	72	.6	200
22-24	13.5	--	6.90	1,200	--	11	--	.4	100
27-29	15.5	--	7.29	1,600	.7	33	--	.6	200
32-34	17.0	1.1	7.47	950	.3	42	38	.7	200
37-39	7.26	--	7.21	820	--	3.6	--	1	300
42-44	9.90	.29	7.17	830	ND	23	--	.8	200
47-49	12.9	--	7.95	1,500	--	26	--	.9	500
57-59	18.7	--	7.60	1,100	--	19	--	.7	300
67-69	18.8	--	7.84	510	--	7.5	--	2	200
77-79	14.5	--	7.84	880	--	15	--	.5	300
87-89	7.95	--	7.38	750	1	16	--	.3	300
97-99	11.6	.35	7.71	940	--	22	62	.4	400
107-109	13.8	.0037	8.51	1,500	--	.73	200	.8	100
117-119	15.7	--	7.61	690	--	20	--	1	300
127-129	14.3	--	7.37	570	--	--	--	--	--
137-139	12.6	--	8.64	2,500	3	27	--	.9	1,100
148-149	4.27	--	8.17	1,300	--	1	--	2	600
Cheyenne-II site (neutron-access hole)--April 27, 1988									
7-9	0.98	0.0096	8.25	44,000	ND	51	5,300	39	4,200
12-14	3.6	.0037	8.28	33,000	ND	22	6,000	14	1,900
17-19	8.41	.021	8.4	15,000	ND	43	2,100	6	1,400
22-24	11.1	.24	8.7	4,400	ND	31	130	1	1,100
27-29	5.62	.17	6.87	1,400	.5	45	260	.9	200
32-34	5.86	.12	7.13	1,400	.9	38	330	--	300
37-39	24.6	.45	7.87	1,600	.2	52	120	.9	300
42-44	8.35	.37	8.76	1,900	.7	92	250	1	600
47-49	20.1	--	7.84	1,500	.1	41	--	1	400
57-59	15.6	--	7.61	1,800	--	--	160	1	300
67-69	19.2	.040	7.59	1,500	.1	6.9	170	.3	200
77-79	2.77	.0023	6.96	2,200	4	1.3	570	ND	500

Table 7. Moisture content and pore-water chemical concentration determined from cores at residential study sites--Continued

Core depth interval (in feet below land surface)	Moisture content (weight percent)	Nitrate/chloride (weight ratio)	pH (standard units)	Specific conductance (µS/cm)	Ammonia NH₃-N (mg/L)	Nitrate NO₃-N (mg/L)	Chloride (mg/L)	Boron (mg/L)	Total alkalinity, as CaCO₃ (mg/L)
Cheyenne-II site (neutron-access hole)--April 27, 1988 (Continued)									
87–89	14.5	--	7.38	1,600	--	.85	--	--	--
97–99	7.11	.0031	7.22	2,000	.8	1.1	360	1	200
107–109	11.0	.48	7.23	1,600	ND	24	50	.5	700
117–119	13.3	.036	7.44	1,900	2	9	250	.8	200
Cheyenne-II site (lysimeter hole)--April 28, 1988									
27–29	5.56	--	7.32	1,700	4	59	--	1	300
42–43	19.3	0.30	8.58	2,000	ND	39	130	.8	500
43–44	16.4	.10	8.71	1,800	ND	20	200	.7	500
67–69	19.9	.055	7.96	2,100	ND	12	220	.4	300
97–99	13.0	.0043	7.87	1,400	.6	.79	180	.9	200
Cajon site (lysimeter hole)--November 29, 1988									
21–23	9.62	0.41	--	280	4	48	120	ND	200
82–84	7.72	.14	--	890	6	25	180	ND	200
101–103	6.89	.25	--	1,100	4	29	110	0.4	200
121–123	11.6	.33	--	710	1	27	81	ND	100
140.5–142.5	12.3	.24	--	710	2	32	130	.2	100
160.5–162.5	5.14	.22	--	1,300	3	24	110	ND	300
200.5–202.5	7.44	.13	--	870	1	25	200	ND	200
220–222	6.69	.0078	--	900	3	.99	130	ND	300
240–242	3.74	.031	--	1,900	6	3.9	130	ND	400

Table 8. Fecal coliform and total bacteria (from standard plate count) for core samples at study sites

[Fecal coliform and total bacteria colony count (colony-forming units) are per gram of wet soil; ft, foot]

Sample depth (ft)	Date	Colony count	
		Fecal coliform	Total bacteria
Toltec site (neutron hole)			
5-7	4-7-88	0	4,200
23-24	4-7-88	0	0
32-33	4-8-88	0	0
42-43	4-8-88	0	0
57-58	4-8-88	0	0
77-78	4-8-88	0	200
97-99	4-8-88	0	0
Cheyenne-I site (lysimeter hole)			
12-13	4-9-88	0	0
22-24	4-9-88	0	13,000
27-38	4-10-88	0	0
37-39	4-9-88	0	0
67-69	4-9-88	0	250
77-79	4-10-88	0	0
118-120	4-10-88	0	[1]120
124	4-9-88	0	560
Cheyenne-I site (lateral-flow hole)			
27-29	4-11-88	0	0
37-39	4-11-88	0	0
47-49	4-11-88	0	0
Choctaw site (lysimeter hole)			
23-25	4-13-88	0	0
28-30	4-13-88	0	[1]190
43-45	4-13-88	0	0
53-55	4-13-88	0	0
73-75	4-14-88	0	0
113-115	4-14-88	0	0
Kiowa site (lysimeter hole)			
17-19	4-25-88	0	[1]160
22-24	4-25-88	0	0
27-29	4-25-88	0	0
32-34	4-25-88	0	[1]290
37-39	4-26-88	0	25,000
42-44	4-26-88	0	[1]13,000
47-49	4-26-88	0	0
77-79	4-26-88	0	0
Cheyenne-II site (neutron hole)			
12-14	4-27-88	0	0
27-29	4-27-88	0	1,200
32-34	4-27-88	0	[1]1,800
42-44	4-27-88	0	0
67-69	4-27-88	0	0
77-79	4-28-88	0	0
97-99	4-27-88	0	0
117-119	4-28-88	0	0
Cheyenne-II site (lysimeter hole)			
27-29	4-28-88	0	0
43-44	4-28-88	0	0

[1]Estimate based on non-ideal colony count.

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Table 9. Nitrifying and nitrate-reducing bacteria for core samples from Cheyenne-I and Cajon sites

[ft, foot; <, actual value is less than value shown; --, confidence limit cannot be calculated]

Sample depth (ft)	Most probable number (MPN) of nitrifying bacteria per gram of wet soil	Most probable number (MPN) of nitrate-reducing bacteria per gram of wet soil	95-percent confidence limits	
			Lower	Upper
Cheyenne-I site Samples collected December 6-7, 1988				
19	0	4,300	700	21,000
24	0	200	70	890
29	0	23,000	4,000	120,000
39	0	4,300	700	21,000
49	0	150	30	440
53	0	90	10	360
64	0	90	10	360
69	0	40	<5	200
74	0	140	30	370
79	0	2,300	400	12,000
89	0	30	<5	90
94	0	<30	--	--
99	0	90	10	360
109	0	<30	--	--
Cajon site Samples collected November 29-December 2, 1988				
84	0	93,000	15,000	380,000
123	0	930	150	3,800
182	0	230	40	1,200
242	0	<30	--	--

Table 10. Chemical analyses of samples from suction lysimeters

[USGS Site Identification No. is explained in headnote for table 4. ft, foot; mg/L, milligram per liter; µS/cm, microsiemen per centimeter at 25 degrees Celsius; °C, degree Celsius; <, less than indicated reporting limit; --, no data]

USGS site identification No. (lysimeter depth)	Date	Temper-ature, water (°C)	Specific conduct-ance (µS/cm)	Nitro-gen (mg/L as N)	Nitro-gen, organic (mg/L as N)	Nitro-gen, ammonia (mg/L as N)	Nitro-gen, NO2+NO3 (mg/L as N)	Carbon, organic total (mg/L as C)	Calcium (mg/L)
Toltec site									
342655117111401 (73 ft)	8-23-89	21.5	735	15	1.2	0.04	14	--	54
	12-09-89	23.0	685	14	.77	.03	13	--	--
342655117111402 (50 ft)	9-12-88	26.0	740	3.0	.29	.01	2.7	--	--
	10-14-88	26.0	690	--	--	.07	7.3	--	--
	3-06-89	21.0	700	18	1.4	.06	17	--	--
	4-10-89	20.0	820	22	1.7	.04	20	--	--
	5-22-89	20.0	850	27	2.6	.01	24	--	--
	8-23-89	22.0	770	18	.68	.02	17	--	--
	12-09-89	23.0	770	18	--	<.01	17	--	--
342655117111403 (40 ft)	6-02-88	--	--	1.9	.38	.02	1.5	--	25
	6-08-88	--	--	4.2	.82	.08	3.3	--	28
	6-09-88	--	--	8.3	.56	.04	7.7	--	--
	7-13-88	24.0	650	6.8	--	<.01	6.4	--	41
	8-09-88	28.0	670	--	--	.03	4.8	--	45
	9-12-88	26.5	730	3.0	.56	.04	2.4	--	55
	10-14-88	26.0	635	--	--	.02	8.3	--	--
	2-06-89	11.0	715	11	1.3	.04	9.9	--	--
	3-06-89	24.0	810	20	1.0	.10	19	--	--
	4-10-89	20.0	750	7.3	1.8	.07	5.4	--	--
	5-22-89	20.0	810	27	1.9	.02	25	--	--
	7-08-89	--	--	22	1.6	.03	20	--	--
	8-23-89	22.0	660	19	.87	.03	18	--	--
	12-09-89	23.0	690	16	.79	.01	15	--	--
342655117111404 (33 ft)	6-02-88	--	--	2.8	.57	.03	2.2	--	24
	6-08-88	--	--	7.2	1.2	.05	5.9	--	32
	6-09-88	--	--	7.5	--	<.01	6.5	--	--
	7-13-88	24.0	490	7.3	.80	3.9	2.6	--	41
	8-09-88	28.0	620	--	1.0	11	<.10	--	35
	9-12-88	26.0	700	--	12	1.5	<.10	--	40
	10-14-88	26.0	615	--	--	22	.10	--	--
	2-06-89	14.0	685	9.5	1.1	7.8	.57	--	29
	3-06-89	25.0	710	24	21	1.6	.53	--	--
	4-10-89	20.5	740	30	8.0	22	.26	--	--
	5-22-89	21.0	750	22	<.10	22	.30	--	28
	7-08-89	--	--	--	<.10	23	<.10	--	--
	8-23-89	25.0	610	29	9.0	20	.17	--	31
	12-09-89	23.0	995	--	51	1.6	<.10	--	42
Cheyenne-I site									
343125117121501 (hole 1, 113 ft)	5-13-88	--	--	--	--	0.02	0.71	--	200
	6-02-88	--	--	0.50	0.35	.05	.10	--	260
	6-08-88	--	--	--	.40	.10	<.10	--	300
	7-13-88	25.0	3,100	--	.42	.08	<.10	--	--

USGS site identification No. (lysimeter depth)	Magne-sium (mg/L)	Sodium (mg/L)	Potas-sium (mg/L)	Chloride (mg/L)	Sulfate (mg/L as SO_4)	Silica (mg/L)	Boron (μg/L)	$^{15}N/^{14}N$ stable-isotope ratio (permil)	Alkalinity, lab (mg/L as $CaCO_3$)
Toltec site--Continued									
342655117111401	12	79	2.9	54	68	84	100	--	158
(73 ft)	--	--	--	28	50	86	90	--	199
342655117111402	--	--	--	--	--	--	--	--	--
(50 ft)	--	--	--	--	--	--	--	--	--
	--	--	--	--	--	--	--	--	--
	--	--	--	--	--	--	--	--	--
	--	--	--	--	--	--	--	--	--
	--	--	--	23	31	100	490	--	263
	--	--	--	--	--	--	--	--	--
342655117111403	4.2	60	3.0	12	45	88	100	--	162
(40 ft)	6.1	74	2.9	11	63	93	90	--	173
	--	--	--	12	--	--	--	--	--
	9.8	70	4.2	16	63	87	80	--	190
	12	64	8.0	24	31	79	70	--	244
	15	77	7.1	29	27	91	80	--	289
	--	--	--	20	--	--	110	--	289
	--	--	--	20	27	98	300	--	276
	--	--	--	25	21	98	780	--	273
	--	--	--	38	17	97	890	--	250
	--	--	--	23	18	91	610	--	225
	--	--	--	20	14	90	390	--	218
	--	--	--	18	18	92	180	--	205
	--	--	--	24	15	88	190	--	213
342655117111404	5.6	43	2.9	9.6	21	27	70	--	142
(33 ft)	7.4	31	4.6	9.5	25	29	40	--	136
	--	--	--	--	--	--	--	--	--
	9.0	34	16	17	14	31	50	--	171
	8.7	47	33	27	7.2	37	50	--	226
	10	52	17	24	5.0	40	110	--	173
	--	--	--	20	--	--	180	--	294
	7.9	91	13	25	11	38	760	--	322
	--	--	--	43	9.0	43	680	--	345
	--	--	--	29	3.0	39	220	--	305
	7.6	62	12	22	2.0	39	80	--	266
	--	--	--	21	3.0	38	60	--	272
	8.0	57	11	23	2.0	38	150	--	244
	10	83	11	34	1.0	41	710	--	126
Cheyenne-I site--Continued									
343125117121501	51	270	7.9	660	360	33	600	--	103
(hole 1, 113 ft)	60	320	8.2	820	370	34	690	--	97
	67	320	8.4	820	380	32	780	--	97
	--	--	--	830	380	33	740	--	100

USGS site identification No. (lysimeter depth)	Date	Temperature, water (°C)	Specific conductance (µS/cm)	Nitrogen (mg/L as N)	Nitrogen, organic (mg/L as N)	Nitrogen, ammonia (mg/L as N)	Nitrogen, $NO_2 + NO_3$ (mg/L as N)	Carbon, organic, total (mg/L as C)	Calcium (mg/L)
Cheyenne-I site--Continued									
343125117121501 (hole 1, 113 ft)-- Continued	8-09-88	25.0	3,100	0.42	0.22	0.08	0.12	--	260
	9-12-88	30.0	3,200	.75	.35	.05	.35	--	--
	10-14-88	26.0	2,800	--	--	.07	.95	--	--
	1-27-89	26.0	2,750	1.4	.54	.16	.66	--	--
	3-06-89	22.0	2,600	2.1	.53	.07	1.5	--	--
	4-10-89	19.0	2,300	1.9	.34	.06	1.5	3.8	160
	7-08-89	--	--	3.9	2.7	.06	1.1	--	--
	8-23-89	24.5	2,200	1.6	.43	.07	1.1	--	140
	1-11-90	24.5	1,990	--	--	--	--	10	--
343125117121508 (hole 2, 106 ft)	3-07-89	--	--	2.6	.66	.84	1.1	--	--
	4-10-89	21.0	1,160	8.5	1.6	.04	6.9	--	--
	5-22-89	20.0	1,110	6.3	1.2	.03	5.1	--	--
	7-08-89	--	--	7.3	.57	.03	6.7	--	--
	8-23-89	25.0	1,480	19	.57	.03	18	--	--
	12-10-89	25.0	1,420	--	--	--	--	4.0	--
343125117121502 (hole 1, 92.5 ft)	6-02-88	--	--	3.7	2.0	.05	1.7	--	--
	6-08-88	--	--	5.2	1.3	.07	3.8	--	--
	8-09-88	--	2,100	--	--	--	--	--	--
	9-12-88	--	2,250	--	--	--	--	--	--
	10-14-88	26.0	2,160	--	--	--	--	--	--
	1-27-89	24.0	2,030	--	--	.10	5.8	--	--
	7-20-89	--	1,740	--	--	.05	32	--	--
343125117121509 (hole 2, 73 ft)	1-27-89	24.0	2,210	14	1.3	.04	13	--	--
	3-07-89	23.0	1,900	2.5	.58	.82	1.1	--	--
	4-10-89	21.0	2,440	32	.77	.13	31	--	--
	5-22-89	20.0	2,300	41	.96	.14	40	--	--
	7-08-89	--	--	42	1.2	.07	41	--	--
	7-21-89	--	2,060	--	--	.06	35	--	--
	12-10-89	25.0	1,640	--	--	--	--	4.1	--
343125117121510 (hole 2, 63 ft)	4-10-89	21.0	1,240	31	1.7	.05	29	--	--
	5-22-89	20.0	1,260	37	.88	.02	36	--	--
	7-08-89	--	--	35	.77	.03	34	--	--
	7-20-89	--	1,370	--	--	.01	31	--	--
	8-23-89	25.0	1,250	32	.68	.02	31	--	--
	12-10-89	25.0	1,160	33	1.2	.05	32	2.5	54
343125117121511 (hole 2, 42 ft)	4-10-89	20.0	2,500	30	2.0	.05	28	--	--
	5-22-89	20.0	2,400	31	.95	.05	30	--	--
	7-23-89	--	2,200	--	--	.02	38	--	--
	12-10-89	25.0	1,860	--	--	--	--	5.4	--
343125117121503 (hole 1, 37 ft)	6-02-88	--	--	60	.94	.06	59	--	140
	6-08-88	--	--	64	1.0	.07	63	--	220
	7-13-88	25.0	2,250	63	--	.07	62	--	220
	8-09-88	25.0	2,300	58	--	<.01	62	--	220
	9-12-88	27.0	2,320	43	1.2	.06	57	--	210
					1.1	.03	42	--	190

USGS site identification No. (lysimeter depth)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Chloride (mg/L)	Sulfate (mg/L as SO_4)	Silica (mg/L)	Boron (μg/L)	$^{15}N/^{14}N$ stable-isotope ratio (permil)	Alkalinity, lab (mg/L as $CaCO_3$)
Cheyenne-I site--Continued									
343125117121501 (hole 1, 113 ft) Continued	62	320	7.3	780	370	33	770	--	92
	--	--	--	750	350	32	850	--	105
	--	--	--	690	--	--	880	--	113
	--	--	--	670	340	33	800	--	113
	--	--	--	570	320	35	800	--	121
	41	270	6.6	110	310	34	830	--	122
	--	--	--	--	--	--	--	--	--
	36	240	6.4	450	280	33	800	--	134
	--	--	--	--	--	--	--	--	--
343125117121508 (hole 2, 106 ft)	--	--	--	--	--	--	--	--	--
	--	--	--	--	--	--	--	--	--
	--	--	--	280	210	31	610	--	120
	--	--	--	--	--	--	--	--	--
	--	--	--	--	--	--	--	--	--
	--	--	--	--	--	--	--	--	--
343125117121502 (hole 1, 92.5 ft)	--	--	--	--	--	--	--	--	--
	--	--	--	--	--	--	--	--	--
	--	--	--	--	--	--	--	--	----
	--	--	--	--	--	--	--	--	--
	--	--	--	--	--	--	--	--	--
	--	--	--	--	--	--	--	--	--
	--	--	--	--	--	--	--	7.80	--
343125117121509 (hole 2, 73 ft)	--	--	--	--	--	--	--	--	--
	--	--	--	370	150	3.1	270	--	23
	--	--	--	99	790	24	2,600	--	197
	--	--	--	280	430	24	4,800	--	284
	--	--	--	200	310	23	5,900	--	255
	--	--	--	--	--	--	--	8.30	--
	--	--	--	--	--	--	--	--	--
343125117121510 (hole 2, 63 ft)	--	--	--	200	73	76	7,900	--	353
	--	--	--	160	49	49	7,300	--	315
	--	--	--	130	43	46	6,700	--	295
	--	--	--	--	--	--	--	8.70	--
	15	180	3.0	88	54	44	6,700	--	306
	--	--	--	--	--	--	--	--	--
343125117121511 (hole 2, 42 ft)	--	--	--	290	590	94	3,900	--	365
	--	--	--	230	430	94	5,100	--	314
	--	--	--	--	--	--	--	7.90	--
	--	--	--	--	--	--	--	--	--
343125117121503 (hole 1, 37 ft)	44	260	10	320	390	92	5,300	--	291
	44	230	10	300	420	98	5,200	--	274
	45	240	9.2	280	410	90	5,500	--	266
	42	230	8.4	260	410	95	5,800	--	257
	37	230	7.8	240	390	90	6,800	--	254

USGS site identification No. (lysimeter depth)	Date	Temper-ature, water (°C)	Specific conduct-ance (µS/cm)	Nitro-gen (mg/L as N)	Nitro-gen, organic (mg/L as N)	Nitro-gen, ammonia (mg/L as N)	Nitro-gen, NO_2+NO_3 (mg/L as N)	Carbon, organic, total (mg/L as C)	Calcium (mg/L)
Cheyenne-I site--Continued									
343125117121503 (hole 1, 37 ft)--Continued	10-14-88	26.0	2,110	--	--	0.06	11	--	--
	1-27-89	25.0	1,940	40	1.7	.02	38	--	--
	3-06-89	22.0	2,050	52	.75	.05	51	--	--
	4-10-89	19.5	1,660	35	1.0	.06	34	3.1	150
	7-08-89	--	--	42	.57	.03	41	--	--
	7-20-89	--	1,920	--	--	.03	32	--	--
	8-23-89	25.0	1,650	38	.68	.02	37	--	130
	1-11-90	25.0	1,610	40	.68	.02	39	4.0	--
Vasquez site									
343314117195201 (71 ft)	6-22-88	--	700	6.4	1.1	0.02	5.3	--	--
	7-12-88	24.5	720	7.2	--	<.01	6.5	--	32
	8-08-88	28.0	800	6.9	.67	.03	6.2	--	--
	9-12-88	--	--	5.3	--	<.01	4.4	--	--
	10-14-88	24.0	820	--	--	.04	5.4	--	--
	2-06-89	9.0	840	4.3	.75	.05	3.5	--	--
	3-06-89	21.0	850	4.6	.37	.03	4.2	--	--
	4-10-89	20.0	860	4.1	.17	.03	3.9	--	--
	5-22-89	20.0	840	4.1	.37	.03	3.7	--	--
	1-11-90	23.0	950	3.3	.79	.31	2.2	--	--
343314117195202 (51 ft)	6-02-88	29.5	900	6.4	.39	.01	6.0	--	52
	6-08-88	--	--	7.6	.78	.02	6.8	--	--
343314117195203 (43 ft)	5-19-88	--	--	6.7	--	<.01	6.2	--	59
	6-02-88	30.0	1,850	--	--	--	--	--	20
	6-08-88	--	--	--	--	--	--	--	12
	7-13-88	25.0	930	--	--	<.01	<.10	--	11
	8-08-88	28.0	1,600	--	.76	.04	<.10	--	17
	9-12-88	--	1,300	--	--	<.01	<.10	--	17
	10-14-88	24.0	1,220	--	--	.27	<.10	--	--
	2-06-89	13.0	860	--	.50	2.8	<.10	--	--
	3-06-89	21.0	1,100	4.0	.40	3.2	.35	--	--
	4-10-89	20.0	940	--	1.5	3.6	<.10	--	20
	5-22-89	20.0	960	--	.40	5.2	<.10	--	--
	8-23-89	22.0	850	--	<.10	7.7	<.10	--	16
343314117195204 (35 ft)	5-19-88	--	--	--	--	<.01	11	--	25
	6-02-88	29.0	1,550	6.3	.49	.01	5.8	--	48
	6-08-88	--	--	6.5	.67	.03	5.8	--	44
	7-13-88	25.0	1,550	5.9	--	<.01	4.9	--	51
	8-08-88	28.0	1,550	5.7	--	<.01	4.7	--	39
	9-12-88	27.0	1,240	6.1	--	<.01	5.1	--	40
	10-14-88	24.0	1,120	--	--	.03	5.0	--	--
	2-06-89	12.0	805	1.5	1.2	.07	.17	--	--
	3-06-89	21.0	1,150	1.8	.77	.03	1.0	--	--
	4-10-89	20.0	870	2.8	.77	.03	2.0	--	--
	8-23-89	22.0	890	11	1.1	.03	10	--	64

USGS site identification No. (lysimeter depth)	Date	Temper-ature, water (°C)	Specific conduct-ance (µS/cm)	Nitro-gen (mg/L as N)	Nitro-gen, organic (mg/L as N)	Nitro-gen, ammonia (mg/L as N)	Nitro-gen, NO_2+NO_3 (mg/L as N)	Carbon, organic, total (mg/L as C)	Calcium (mg/L)
				Choctaw site					
343124117143001 (131 ft) [within saturated zone]	6-02-88	--	--	1.1	0.58	0.02	0.47	--	90
	6-08-88	--	--	1.5	.47	.03	1.0	--	75
	7-13-88	24.0	1,120	1.3	--	<.01	.89	--	92
	8-08-88	--	1,400	1.2	.48	.02	.67	--	89
	9-13-88	27.0	1,150	.88	--	<.01	.58	--	91
	10-14-88	26.0	1,130	--	--	.02	.73	--	--
	1-27-89	20.0	1,170	.88	.36	.04	.48	--	--
	3-06-89	22.0	1,160	.89	.28	.02	.59	--	--
	4-10-89	21.0	1,050	1.0	.26	.04	.70	--	94
	7-08-89	--	--	.79	.27	.03	.49	--	89
	8-23-89	22.0	1,050	1.2	.48	.02	.73	--	91
	1-11-90	24.0	1,040	.52	.39	.01	.12	--	--
343124117143002 (80 ft)	6-02-88	--	--	--	--	--	--	--	--
	6-08-88	--	--	--	--	--	--	--	--
	7-13-88	25.0	1,100	19	--	<.01	17	--	--
	8-08-88	--	1,160	--	--	--	--	--	--
	9-13-88	27.0	990	14 *	--	<.01	13	--	--
	10-14-88	26.0	920	--	--	.04	20	--	--
	1-27-89	20.0	970	14	1.7	.31	12	--	--
	3-06-89	22.0	1,100	22	1.2	.02	21	--	--
	4-10-89	21.0	950	24	1.3	.04	23	--	--
	7-08-89	--	--	24	2.0	.05	22	--	--
	8-23-89	22.5	1,100	25	.53	.07	24	--	--
	1-11-90	24.0	1,010	26	1.4	.06	24	--	--
343124117143003 (48 ft)	5-19-88	--	--	--	--	<.01	18	--	86
	6-08-88	--	--	11	1.2	.05	10	--	--
	8-08-88	--	1,750	15	1.5	.01	13	--	--
	9-13-88	27.0	1,560	9.8	--	<.01	8.8	--	--
	10-14-88	26.0	1,460	--	--	.05	14	--	--
343124117143004 (33 ft)	5-19-88	--	--	8.9	1.0	.05	7.8	--	--
	6-02-88	--	--	7.1	.62	.08	6.4	--	--
	6-08-88	--	--	7.2	.93	.07	6.2	--	160
	7-13-88	25.0	1,620	6.4	--	<.01	5.6	--	160
	8-08-88	--	1,750	6.2	.44	.06	5.7	--	130
	9-13-88	--	--	--	--	--	--	--	130
	10-14-88	26.0	1,380	--	--	.03	8.3	--	130
	1-27-89	17.0	1,480	12	.78	.02	11	--	--
343124117143005 (lateral-flow hole, 48 ft)	5-19-88	--	--	7.7	1.1	.04	6.6	--	200

USGS site identification No. (lysimeter depth)	Magne-sium (mg/L)	Sodium (mg/L)	Potas-sium (mg/L)	Chloride (mg/L)	Sulfate (mg/L as SO$_4$)	Silica (mg/L)	Boron (μg/L)	^{15}N/^{14}N stable-isotope ratio (permil)	Alkalinity, lab (mg/L as CaCO$_3$)
				Choctaw site--Continued					
343123117143001 (131 ft) [within saturated zone]	20	110	4.1	190	200	32	470	--	86
	20	110	4.1	190	210	33	480	--	85
	20	110	3.6	180	210	34	470	--	274
	20	110	3.5	190	190	33	460	--	87
	21	110	3.4	190	200	34	500	--	86
	--	--	--	180	--	--	490	--	88
	--	--	--	190	210	36	460	--	88
	--	--	--	180	210	38	450	--	88
	21	120	3.6	190	200	36	490	--	87
	19	110	7.4	180	210	34	480	--	89
	19	110	3.7	190	200	34	450	--	86
	--	--	--	180	200	35	480	--	87
343124117143002 (80 ft)	--	--	--	120	170	98	2,100	--	242
	--	--	--	110	160	95	1,100	--	226
	--	--	--	100	160	160	2,600	--	235
	--	--	--	75	120	23	2,800	--	229
	--	--	--	64	120	98	3,300	--	229
	--	--	--	56	--	--	3,500	--	226
	--	--	--	--	--	--	--	--	--
	--	--	--	50	160	100	3,700	--	215
	--	--	--	50	170	98	4,000	--	211
	--	--	--	--	--	--	--	--	--
	--	--	--	49	210	96	3,700	--	210
	--	--	--	--	--	--	--	--	--
343123117143003 (48 ft)	16	150	6.7	120	160	94	2,000	--	240
	--	--	--	120	250	93	640	--	405
	--	--	--	--	--	--	--	--	--
	--	--	--	100	290	98	760	--	351
	--	--	--	--	--	--	--	--	--
343124117143004 (33 ft)	--	--	--	--	--	--	--	--	--
	27	280	13	150	400	100	740	--	544
	26	240	10	120	330	97	800	--	496
	25	210	10	100	290	95	820	--	560
	25	200	8.8	88	260	96	840	--	489
	26	180	8.1	74	230	96	930	--	473
	--	--	--	66	--	--	980	--	462
	--	--	--	62	270	100	910	--	454
343124117143005 (lateral-flow hole, 48 ft)	36	320	11	190	570	98	680	--	347

Table 10. Chemical analyses of samples from suction lysimeters--Continued

USGS site identification No. (lysimeter depth)	Date	Temperature, water (°C)	Specific conductance (μS/cm)	Nitrogen (mg/L as N)	Nitrogen, organic (mg/L as N)	Nitrogen, ammonia (mg/L as N)	Nitrogen, NO_2+NO_3 (mg/L as N)	Carbon, organic, total (mg/L as C)	Calcium (mg/L)
Little Beaver site									
342857117120604 (hole 2, 77 ft)	1-11-90	24.0	2,600	24	3.4	0.22	20	--	--
342857117120605 (hole 2, 67 ft)	8-23-89	24.0	980	21	.67	.03	20	--	--
342857117120601 (hole 1, 40 ft)	9-12-88	28.0	1,130	3.4	--	<.01	3.0	--	--
	10-14-88	27.0	1,180	--	--	.03	11	--	--
	2-06-89	15.0	1,080	11	.76	.14	9.9	--	--
	3-06-89	21.0	1,100	5.1	.48	.02	4.6	--	--
	4-10-89	21.0	880	4.0	1.6	.03	2.4	--	--
	5-22-89	20.0	910	1.6	.37	.03	1.2	--	--
	7-08-89	--	--	3.2	.37	.03	2.8	--	--
	8-23-89	26.5	1,170	5.9	.39	.01	5.5	--	--
	1-11-90	23.5	1,100	8.7	.89	.01	7.8	--	78
342857117120602 (hole 1, 31.5 ft)	6-08-88	--	--	23	2.0	.13	21	--	--
	6-09-88	--	--	12	1.3	.12	11	--	--
	7-13-88	25.5	1,660	13 •	1.2	.03	12	--	--
	8-09-88	28.0	1,120	9.3	.86	.04	8.4	--	130
	9-12-88	28.0	2,300	16	.64	.06	15	--	--
	10-14-88	27.0	2,600	--	--	.23	28	--	--
	2-06-89	15.0	1,080	11	.76	.14	9.9	--	--
	03-06-89	21.0	1,100	5.1	.48	.02	4.6	--	--
	4-10-89	21.0	2,600	25	.73	.07	24	--	--
	5-22-89	20.0	2,500	22	.73	.07	21	--	--
	7-08-89	--	--	21	1.3	.06	20	--	--
	8-23-89	26.5	2,500	--	--	.05	14	--	--
	1-11-90	23.5	2,450	13	.98	.02	12	--	--
Kiowa site									
342917117122601 (149 ft)	6-08-88	--	--	6.3	1.4	0.06	4.8	--	--
	8-09-88	28.0	1,300	4.2	--	<.01	3.1	--	--
	9-12-88	--	--	1.7	--	<.01	1.3	--	--
	10-14-88	25.0	825	--	--	.04	1.3	--	--
	5-22-89	20.0	800	4.3	3.8	.09	.42	--	--
342917117122602 (107.5 ft)	6-02-88	--	--	12	1.1	.09	11	--	--
	6-08-88	--	--	16	1.2	.07	15	--	--
	8-09-88	28.0	1,340	18	2.3	.04	16	--	--
	9-12-88	27.0	1,240	15	1.8	.03	13	--	--
	10-14-88	25.0	1,210	--	--	.36	20	--	--
	2-06-89	14.0	1,110	24	6.1	2.9	15	--	--
	3-06-89	21.0	1,220	18	1.7	.08	16	--	--
	4-10-89	21.0	760	20	.97	.13	19	8.3	82
342917117122603 (67.5 ft)	9-12-88	27.0	840	15	--	<.01	14	--	--
	10-14-88	25.0	820	--	--	.04	17	--	--
342917117122604 (32 ft)	10-14-88	25.0	1,380	--	--	.03	11	--	--
	2-06-89	14.0	1,290	10	.77	.03	9.6	--	--
	3-06-89	21.0	1,190	7.7	.67	.03	7.0	--	--

USGS site identification No. (lysimeter depth)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Chloride (mg/L)	Sulfate (mg/L as SO_4)	Silica (mg/L)	Boron (μg/L)	$^{15}N/^{14}N$ stable-isotope ratio (permil)	Alkalinity, lab (mg/L as $CaCO_3$)
Little Beaver site--Continued									
342857117120604 (hole 2, 77 ft)	--	--	--	--	--	--	--	--	--
342857117120605 (hole 2 67 ft)	--	--	--	81	35	91	800	--	238
342857117120601 (hole 1, 40 ft)	--	--	--	--	--	--	--	--	--
	--	--	--	90	--	--	1,100	--	371
	--	--	--	71	95	93	1,100	--	377
	--	--	--	47	37	95	1,000	--	419
	--	--	--	44	17	92	950	--	424
	--	--	--	79	13	89	890	--	413
	--	--	--	85	13	94	1,000	--	407
	--	--	--	95	13	99	1,600	--	413
	19	130	2.0	82	12	91	1,500	--	418
342857117120602 (hole 1, 31.5 ft)	--	--	--	--	--	--	--	--	--
	--	--	--	310	--	--	--	--	--
	--	--	--	270	200	94	150	--	221
	37	50	3.8	130	190	97	160	--	198
	--	--	--	130	750	100	210	--	215
	--	--	--	130	--	--	440	--	251
	--	--	--	--	--	--	--	--	--
	--	--	--	75	1,500	110	830	--	296
	--	--	--	56	1,200	110	910	--	344
	--	--	--	51	980	110	890	--	372
	--	--	--	68	880	110	860	--	--
	--	--	--	84	750	110	860	--	280
	--	--	--	89	470	110	1,200	--	501
Kiowa site--Continued									
342917117122601 (149 ft)	--	--	--	170	430	100	190	--	117
	--	--	--	--	--	--	--	--	--
	--	--	--	83	210	110	260	--	117
	--	--	--	73	--	--	280	--	115
	--	--	--	--	--	--	--	--	--
342917117122602 (107.5 ft)	--	--	--	--	--	--	--	--	--
	--	--	--	130	220	100	230	--	220
	--	--	--	--	--	--	--	--	--
	--	--	--	92	--	--	260	--	204
	--	--	--	--	--	--	--	--	--
	--	--	--	41	40	79	220	--	245
	17	50	2.9	38	15	73	230	--	247
342917117122603 (67.5 ft)	--	--	--	42	47	99	270	--	259
	--	--	--	53	--	--	310	--	265
342917117122604 (32 ft)	--	--	--	78	--	--	350	--	436
	--	--	--	78	150	87	620	--	427
	--	--	--	--	--	--	--	--	--

Table 10. Chemical analyses of samples from suction lysimeters--Continued

USGS site identification No. (lysimeter depth)	Date	Temperature, water (°C)	Specific conductance (µS/cm)	Nitrogen (mg/L as N)	Nitrogen, organic (mg/L as N)	Nitrogen, ammonia (mg/L as N)	Nitrogen, NO_2+NO_3 (mg/L as N)	Carbon, organic, total (mg/L as C)	Calcium (mg/L)
Cheyenne-II site									
343114117122303 (67 ft)	5-13-88	--	--	34	1.9	0.06	32	--	--
	6-02-88	--	--	35	3.2	.06	32	--	230
	6-08-88	--	--	43	1.0	.06	42	--	190
	6-09-88	--	--	42	1.0	.06	41	--	--
	7-13-88	24.5	1,700	46	--	<.01	45	--	170
	8-08-88	34.0	1,600	45	1.1	.08	44	--	150
	9-12-88	28.0	1,790	--	--	<.01	31	--	160
	10-14-88	25.0	1,590	--	--	.03	45	--	--
	1-27-89	24.0	1,500	37	1.9	.03	35	--	--
	3-06-89	23.0	1,460	46	1.4	.04	45	--	--
	4-10-89	21.0	1,550	49	1.4	.05	48	--	--
	5-22-89	20.0	1,500	54	1.5	.06	52	--	--
Cajon site									
342518117160601 (257 ft) [within saturated zone]	2-06-89	10.0	660	4.3	0.75	0.55	3	--	--
	3-07-89	20.0	710	4.5	.20	1.2	3.1	--	--
	4-12-89	21.0	1,500	14	1.0	.18	13	--	--
	8-22-89	22.0	490	3.0	.10	1.8	1.1	--	--
	1-11-90	23.0	510	--	--	--	--	15	--
342518117160602 (243 ft)	8-22-89	22.0	2,250	3.1	.88	.62	1.6	--	--
	1-11-90	23.0	2,300	1.9	.81	.19	.93	6.1	--
	5-04-90	--	--	--	--	.17	1.8	--	--
	5-18-90	--	--	--	--	.17	1.1	--	--
	6-12-90	--	--	--	--	.21	.8	--	--
342518117160603 (199 ft)	8-22-89	22.0	550	16	.53	.07	15	--	--
	1-11-90	23.0	610	16	.66	.14	15	4.0	--
342518117160604 (160 ft)	1-11-90	23.0	1,200	37	1.3	.44	35	7.6	--
342518117160605 (130 ft)	4-10-89	20.0	760	35	.87	.33	34	--	--
	7-08-89	--	--	38	1.2	.92	36	--	--
	8-22-89	22.0	660	34	1.1	.31	33	--	--
	1-11-90	23.0	710	--	--	--	--	15	--
342518117160606 (97.5 ft)	4-10-89	21.0	520	31	1.6	.20	29	7.7	26
	7-08-89	--	--	35	1.4	.44	33	--	28
	8-22-89	22.0	530	32	.52	.18	31	--	--
	1-11-90	23.0	580	36	1.3	.40	34	5.6	56
342518117160607 (70 ft)	4-10-89	20.0	750	32	1.6	.03	30	--	--
	7-08-89	--	--	32	1.2	.57	30	--	--
	8-22-89	22.0	720	30	1.2	.37	28	--	--
	1-11-90	23.0	710	6.7	1.3	.09	5.3	3.9	--
342518117160608 (35 ft)	2-06-89	10.0	980	27	1.9	.05	25	--	--
	3-07-89	20.0	1,110	39	1.4	.06	37	--	76

USGS site identification No. (lysimeter	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Chloride (mg/L)	Sulfate (mg/L as SO_4)	Silica (mg/L)	Boron (µg/L)	$^{15}N/^{14}N$ stable-isotope ratio (permil)	Alkalinity, lab (mg/L as $CaCO_3$)
				Cheyenne-II site--Continued					
343114117122303 (67 ft)	--	--	--	380	390	88	<10	--	148
	62	160	8.3	370	430	90	490	--	157
	59	140	6.7	240	340	92	760	--	230
	--	--	--	190	--	--	--	--	--
	50	120	5.3	180	230	94	930	--	506
	46	100	4.3	150	160	89	880	--	274
	52	120	4.0	180	160	80	870	--	131
	--	--	--	170	--	--	840	--	300
	--	--	--	170	96	85	770	--	294
	--	--	--	190	86	85	730	--	323
	--	--	--	190	83	81	800	--	311
	--	--	--	200	120	74	780	--	259
				Cajon site--Continued					
342518117160601 (257 ft) [within saturated zone]	--	--	--	130	55	12	60	--	63
	--	--	--	--	51	16	20	--	88
	--	--	--	380	150	29	190	--	89
	--	--	--	69	39	14	20	--	89
	--	--	--	--	--	--	--	--	--
342518117160602 (243 ft)	--	--	--	370	260	74	130	--	318
	--	--	--	71	130	78	40	--	87
	--	--	--	--	--	--	--	--	--
	--	--	--	--	--	--	--	--	--
	--	--	--	--	--	--	--	7.10	--
342518117160603 (199 ft)	--	--	--	53	49	91	40	--	52
	--	--	--	46	42	85	40	--	44
342518117160604 (160 ft)	--	--	--	--	--	--	--	--	--
342518117160605 (130 ft)	--	--	--	40	74	94	40	--	95
	--	--	--	35	92	90	20	--	59
	--	--	--	33	66	86	30	--	45
	--	--	--	--	--	--	--	--	--
34251811716060c (97.5 ft)	7.3	54	1.8	32	22	54	80	--	30
	8.1	52	1.5	32	16	55	90	--	26
	--	--	--	34	17	58	90	--	26
	15	95	4.3	37	16	81	90	--	30
342518117160607 (70 ft)	--	--	--	35	82	98	70	--	116
	--	--	--	35	120	87	70	--	59
	--	--	--	33	110	89	80	--	55
	--	--	--	46	88	82	80	--	52
342518117160608 (35 ft)	--	--	--	50	150	110	110	--	258
	16	160	4.3	87	230	85	60	--	156

Table 11. Chemical analyses of tapwater at residential study sites

[mg/L, milligram per liter; μg/L, microgram per liter, μS/cm, microsiemen per centimeter at 25 degrees Celsius; <, less than indicated reporting limit; --, not analyzed]

Site name	Date	Specific conductance (μS/cm)	pH (standard units)	Nitrogen, nitrite, dissolved (mg/L as N)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	Nitrogen, ammonia, dissolved (mg/L as N)	Nitrogen, ammonia + organic, dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Alkalinity, lab (mg/L as $CaCO_3$)
Toltec	4-22-88	181	8.0	--	0.57	<0.01	<0.20	0.02	13	7.7	12	1.6	76
Cheyenne-I	4-22-88	780	8.2	<0.01	1.3	<.01	<.20	.01	57	14	75	3.3	84
Vasquez	4-22-88	202	9.1	--	1.1	<.01	<.20	.01	4.6	.42	40	1.1	84
Choctaw	4-22-88	212	8.6	--	.44	.01	<.20	.04	13	1.5	30	1.2	76
Little Beaver	4-24-88	345	8.1	--	.74	<.01	<.20	.02	26	9.3	32	2.4	80
Kiowa	4-25-88	402	8.1	--	.79	<.01	<.20	.02	29	10	40	2.4	83
Cheyenne-II	4-27-88	736	8.2	--	1.2	<.01	<.20	.02	55	13	72	3.1	84
Cajon	3-17-89	222	--	<.01	.89	.03	<.20	.03	21	2.9	24	1.4	89

Site name	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Boron, dissolved (μg/L as B)	Chromium, dissolved (μg/L as Cr)	Copper, dissolved (μg/L as Cu)	Iron, dissolved (μg/L as Fe)	Lead, dissolved (μg/L as Pb)	Lithium, dissolved (μg/L as Li)	Manganese, dissolved (μg/L as Mn)	Nickel, dissolved (μg/L as Ni)	Strontium, dissolved (μg/L as Sr)	Zinc, dissolved (μg/L as Zn)	Carbon, organic, dissolved (mg/L as C)
Toltec	9.1	4.6	0.3	29	20	--	--	110	--	9	2	--	79	160	--
Cheyenne-I	140	100	.5	26	570	--	--	4	--	16	<1	--	890	3	--
Vasquez	4.9	7.7	.3	16	10	--	--	<3	--	9	<1	--	140	<3	--
Choctaw	22	8.2	.6	18	120	--	--	7	--	10	<1	--	220	<3	--
Little Beaver	80	14	.5	28	210	--	--	13	--	11	<1	--	200	19	--
Kiowa	80	28	.5	27	340	--	--	7	--	12	<1	--	250	<3	--
Cheyenne II	140	98	.5	25	560	--	--	30	--	16	<1	--	840	5	--
Cajon	12	6.8	.5	27	20	2	9	3	<5	<4	<1	<1	220	<3	0.6

Table 12. Chemical analyses of wastewater at residential study sites

[mg/L, milligram per liter; µg/L, microgram per liter; µS/cm, microsiemen per centimeter at 25 degrees Celsius; <, less than indicated reporting limit; --, not analyzed]

Site name (source of sample)	Date	Specific conductance (µS/cm)	pH (standard units)	Nitrogen, nitrite, dissolved (mg/L as N)	Nitrogen, NO₂+NO₃, dissolved (mg/L as N)	Nitrogen, ammonia, dissolved (mg/L as N)	Nitrogen, ammonia + organic, dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)
Cheyenne-I (septic tank)	4-22-88	1,690	7.9	--	--	--	53	7.2	59	17	200	13
Vasquez (seepage pit)	6-08-88	696	--	--	3.9	30	30	18	18	2.2	94	11
	3-17-89	947	--	--	--	27	18	--	--	--	--	--
Choctaw (septic tank)	6-08-88	735	--	0.07	.26	6.1	46	1.2	26	4.3	70	14
Kiowa (septic tank)	6-08-88	645	--	.03	.20	18	22	4.9	37	10	57	7.3
Cheyenne-II (septic tank)	6-08-88	1,910	--	--	--	31	50	6.7	78	19	230	13
Cheyenne-II (seepage pit)	6-08-88	1,890	--	--	<.10	8.9	60	1.2	86	19	230	15
Cajon (septic tank)	3-07-89	750	7.4	--	--	44	63	--	--	--	--	--
Cajon (seepage pit)	3-07-89	747	7.6	--	--	41	40	--	--	--	--	--

Site name (source of sample)	Alkalinity, lab, (mg/L as CaCO₃)	Sulfate, dissolved (mg/L as SO₄)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO₂)	Boron, dissolved (µg/L as B)	Iron, dissolved (µg/L as Fe)	Lithium, dissolved (µg/L as Li)	Manganese, dissolved (µg/L as Mn)	Strontium, dissolved (µg/L as Sr)	Zinc, dissolved (µg/L as Zn)	Carbon, organic, dissolved (mg/L as C)
Cheyenne-I (septic tank)	457	140	180	0.5	30	1,300	69	30	21	870	11	--
Vasquez (seepage pit)	246	25	30	.5	26	40	62	5	38	230	3	17
	--	--	--	--	--	--	--	--	--	--	--	32
Choctaw (septic tank)	274	58	39	.8	24	320	400	8	39	300	50	42
Kiowa (septic tank)	180	70	37	.6	30	320	280	9	20	280	22	10
Cheyenne-II (septic tank)	492	270	160	.7	41	1,400	210	22	31	1,200	22	40
Cheyenne-II (seepage pit)	238	170	160	.6	43	1,500	530	23	40	1,200	31	37
Cajon (septic tank)	--	--	--	--	--	--	--	--	--	--	--	63
Cajon (seepage pit)	--	--	--	--	--	--	--	--	--	--	--	43

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Table 13. Fecal coliform and total bacteria (from standard plate count) in wastewater from septic tanks and seepage pits

[CFU/100 mL, colony-forming units per 100 milliliters wastewater]

Site name	Sample date	Fecal coliform (CFU/100 mL)	Total bacteria (CFU/100 mL)
Cheyenne-I (septic tank)	4-22-88	2.5×10^5	9.4×10^8
Choctaw (septic tank)	6-8-88	6.8×10^4	1.2×10^8
Kiowa (septic tank)	6-8-88	3.9×10^5	3.7×10^8
Cheyenne-II (septic tank)	6-8-88	3.3×10^5	4.1×10^8
Cheyenne-II (seepage pit)	6-8-88	2.8×10^5	8.1×10^8
Vasquez (seepage pit)	6-8-88	5.2×10^4	5.5×10^8

Table 14. Chemical analyses of ground water from selected residential study sites and multiple-well monitoring sites

[ft, foot; mg/L, milligram per liter; µg/L, microgram per liter; µS/cm, microsiemen per centimeter at 25 degrees Celsius; °C, degrees Celsius. <, less than indicated reporting limit]

Site name (source of sample)	Depth (ft)	Date	Temperature, water (°C)	Specific conductance (µS/cm)	pH (standard units)	Nitrogen, organic, dissolved (mg/L as N)	Nitrogen, ammonia, dissolved (mg/L as N)	Nitrogen, NO$_2$+NO$_3$, dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)
Cheyenne-I (suction lysimeter)	113	5-13-88	--	--	--	--	0.02	0.71	--
		6-02-88	--	--	--	0.35	.05	.10	--
		6-08-88	--	--	--	.40	.10	<.10	--
		7-13-88	25.0	3,100	--	.42	.08	<.10	--
		8-09-88	25.0	3,100	--	.22	.08	.12	--
		9-12-88	30.0	3,200	--	.35	.05	.35	--
		10-14-88	26.0	2,800	--	--	.07	.95	--
		1-27-89	26.0	2,750	--	.54	.16	.66	--
		3-06-89	22.0	2,600	--	.53	.07	1.5	--
		4-10-89	19.0	2,300	--	.34	.06	1.5	--
		7-08-89	--	--	--	2.7	.06	1.1	--
		8-23-89	24.5	2,200	--	.43	.07	1.1	--
		1-11-90	24.5	1,990	--	--	--	--	--
Cheyenne-I (soil core)	124	4-09-88	--	--	--	0.19	0.11	2.3	0.02
Choctaw (suction lysimeter)	131	6-02-88	--	--	--	0.58	0.02	0.47	--
		6-08-88	--	--	--	.47	.03	1.0	--
		7-13-88	24.0	1,120	--	--	<.01	.89	--
		8-08-88	--	1,400	--	.48	.02	.67	--
		9-13-88	27.0	1,150	--	--	<.01	.58	--
		10-14-88	26.0	1,130	--	--	.02	.73	--
		1-27-89	20.0	1,170	--	.36	.04	.48	--
		3-06-89	22.0	1,160	--	.28	.02	.59	--
		4-10-89	21.0	1,050	--	.26	.04	.70	--
		7-08-89	--	--	--	.27	.03	.49	--
		8-23-89	22.0	1,050	--	.48	.02	.73	--
		1-11-90	24.0	1,040	--	.39	.01	.12	--
Cheyenne-II (neutron-access tube)	119	7-13-88	25.0	1,000	--	0.70	1.3	--	--
Cajon (suction lysimeter)	257	2-06-89	10.0	660	--	0.75	0.55	3.0	--
		3-07-89	20.0	710	--	.20	1.2	3.1	--
		4-12-89	21.0	1,500	--	1.0	.18	13	--
		8-22-89	22.0	490	7.4	.10	1.8	1.1	--
		1-11-90	23.0	510	--	--	--	--	--

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Table 14. Chemical analyses of ground water from selected residential study sites and multiple-well monitoring sites—Continued

Site name (source of sample)	Depth (ft)	Date	Carbon, organic, total (mg/L as C)	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Potassium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Sulfate, dissolved (mg/L as SO₄)	Fluoride, dissolved (mg/L)	Silica, dissolved (mg/L)
Cheyenne-I (suction lysimeter)	113	5-13-88	—	54	51	270	7.9	660	360	—	33
		6-02-88	—	—	60	320	8.2	820	370	—	34
		6-08-88	—	—	67	320	8.4	820	380	—	32
		7-13-88	—	—	—	—	—	830	380	—	33
		8-09-88	—	—	62	320	7.3	780	370	—	33
		9-12-88	—	—	—	—	—	750	350	—	32
		10-14-88	—	—	—	—	—	690	—	—	—
		1-27-89	—	—	—	—	—	670	340	—	33
		3-06-89	—	—	—	—	—	570	320	—	35
		4-10-89	—	—	41	270	6.6	110	310	—	34
		7-08-89	—	—	—	—	—	—	—	—	—
		8-23-89	—	—	36	240	6.4	450	280	—	33
		1-11-90	—	—	—	—	—	—	—	—	—
Cheyenne-I (soil core)	124	4-09-88	—	82	21	110	5.4	150	180	1.1	31
Choctaw (suction lysimeter)	131	6-02-88	—	90	20	110	4.1	190	200	—	32
		6-08-88	—	75	20	110	4.1	190	210	—	33
		7-13-88	—	92	20	110	3.6	180	210	—	34
		8-08-88	—	89	20	110	3.5	190	190	—	33
		9-13-88	—	91	21	110	3.4	190	200	—	34
		10-14-88	—	—	—	—	—	180	—	—	—
		1-27-89	—	—	—	—	—	190	210	—	36
		3-06-89	—	—	—	—	—	180	210	—	38
		4-10-89	—	94	21	120	3.6	190	200	—	36
		7-08-89	—	89	19	110	7.4	180	210	—	34
		8-23-89	—	91	19	110	3.7	190	200	—	34
		1-11-90	—	—	—	—	—	180	200	—	35
Cheyenne-II (neutron-access tube)	119	7-13-88	—	—	—	—	—	—	—	—	—
Cajon (suction lysimeter)	257	2-06-89	—	—	—	—	—	130	55	—	12
		3-07-89	—	—	—	—	—	—	51	—	16
		4-12-89	—	—	—	—	—	380	150	—	29
		8-22-89	—	—	—	—	—	69	39	—	14
		1-11-90	15	—	—	—	—	—	—	—	—

USGS identification No. (lysimeter depth)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Chloride (mg/L)	Sulfate (mg/L as SO$_4$)	Silica (mg/L)	Boron (μg/L)	^{15}N/^{14}N stable-isotope ratio (permil)	Alkalinity, lab (mg/L as CaCO$_3$)
Cheyenne-I site--Continued									
343125117121503 (hole 1, 37 ft)-- Continued	--	--	--	230	--	--	7,100	--	258
	--	--	--	210	360	98	6,500	--	253
	--	--	--	210	330	100	6,500	--	255
	32	200	5.9	200	300	95	6,700	--	259
	--	--	--	170	230	97	6,600	--	291
	--	--	--	--	--	--	--	8.70	--
	25	200	5.6	150	190	96	6,000	--	328
	--	--	--	130	160	96	6,200	--	325
Vasquez site--Continued									
343314117195201 (71 ft)	--	--	--	--	--	--	--	--	--
	12	100	5.6	37	37	97	170	--	265
	--	--	--	33	55	25	170	--	263
	--	--	--	--	--	--	--	--	--
	--	--	--	--	--	--	--	--	--
	--	--	--	--	--	--	--	--	--
	--	--	--	30	280	110	120	--	146
	--	--	--	28	290	110	120	--	139
	--	--	--	25	270	100	130	--	125
	--	--	--	--	--	--	--	--	--
343314117195202 (51 ft)	15	77	3.1	36	49	93	150	--	250
	--	--	--	35	40	100	140	--	261
343314117195203 (43 ft)	15	74	3.5	46	70	95	180	--	225
	5.6	350	4.9	67	400	21	190	--	326
	3.3	240	3.8	45	170	22	150	--	343
	3.1	210	3.3	41	100	25	130	--	352
	4.7	300	4.3	44	260	23	180	--	409
	5.0	270	3.3	38	190	22	190	--	420
	--	--	--	30	--	--	190	--	409
	--	--	--	27	130	22	150	--	412
	--	--	--	26	72	25	130	--	430
	5.6	190	5.6	26	48	24	120	--	457
	--	--	--	24	41	25	110	--	437
	4.6	160	6.7	26	20	26	120	--	382
343314117195204 (35 ft)	6.4	400	5.5	83	540	23	190	--	259
	14	240	7.0	160	170	100	350	--	268
	14	250	7.8	180	180	100	380	--	293
	17	260	8.0	200	210	99	420	--	294
	15	230	7.9	130	170	100	420	--	351
	16	210	7.4	71	130	100	400	--	386
	--	--	--	41	--	--	340	--	411
	--	--	--	26	63	110	220	--	424
	--	--	--	26	45	110	160	--	428
	--	--	--	25	32	110	150	--	443
	15	140	4.3	25	18	110	140	--	415

Table 14. Chemical analyses of ground water from selected residential study sites and multiple-well monitoring sites—Continued

Site name (source of sample)	Depth (ft)	Boron, dissolved (μg/L)	Iron, dissolved (μg/L)	Manganese, dissolved (μg/L)	Strontium, dissolved (μg/L)	Zinc, dissolved (μg/L)	Lithium, dissolved (μg/L)	$^{15}N/^{14}N$, stable-isotope ratio (per mil)	Alkalinity, lab (mg/L as $CaCO_3$)
Cheyenne-I (suction lysimeter)	113	600	--	--	--	--	--	--	
		690	--	--	--	--	--	--	103
		780	--	--	--	--	--	--	97
		740	--	--	--	--	--	--	97
		770	--	--	--	--	--	--	100
		850	--	--	--	--	--	--	92
		880	--	--	--	--	--	--	105
		800	--	--	--	--	--	--	113
		800	--	--	--	--	--	--	113
		830	--	--	--	--	--	--	121
		--	--	--	--	--	--	--	122
		800	--	--	--	--	--	--	--
		--	--	--	--	--	--	--	134
								--	--
Cheyenne-I (soil core)	124	460	240	340	1,000	21	30	--	115
Choctaw (suction lysimeter)	131	470	--	--	--	--	--	--	
		480	--	--	--	--	--	--	86
		470	--	--	--	--	--	--	85
		460	--	--	--	--	--	--	274
		500	--	--	--	--	--	--	87
		490	--	--	--	--	--	--	86
		460	--	--	--	--	--	--	88
		450	--	--	--	--	--	--	88
		490	--	--	--	--	--	--	88
		480	--	--	--	--	--	--	87
		450	--	--	--	--	--	--	89
		480	--	--	--	--	--	--	86
								--	87
Cheyenne-II (neutron-access tube)	119	--	--	--	1,100	87,000	28	--	--
Cajon (suction lysimeter)	257	60	--	--	--	--	--	--	
		20	--	--	--	--	--	--	63
		190	--	--	--	--	--	--	88
		20	--	--	--	--	--	--	89
		--	--	--	--	--	--	--	89
								--	--

Table 14. Chemical analyses of ground water from selected residential study sites and multiple-well monitoring sites-- Continued

Site name (source of sample)	Depth (ft)	Date	Temperature, water (°C)	Specific conductance (µS/cm)	pH (standard units)	Nitrogen, organic, dissolved (mg/L as N)	Nitrogen, ammonia, dissolved (mg/L as N)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)
Apple Ranchos (multiple-well monitoring site)	240	6-03-88	24.5	1,370	6.2	0.35	0.05	1.5	<0.01
		4-12-89	23.0	1,340	--	--	.21	1.7	<.01
		8-22-89	23.0	1,410	7.8	--	.01	1.7	.01
	199	6-02-88	24.0	1,280	--	.26	.04	2.0	<.01
		4-12-89	23.0	1,360	--	.36	.04	2.9	<.01
		8-22-89	22.5	1,240	7.7	--	<.01	4.1	.01
	173	6-03-88	24.5	1,180	5.8	.29	.01	1.1	<.01
		4-12-89	23.5	1,240	--	--	.04	1.9	.04
		8-23-89	21.5	1,180	7.7	--	.03	2.7	.03
	152	6-03-88	25.0	1,290	--	.33	.17	<.10	--
Rincon (multiple-well monitoring site)	285	4-12-89	22.5	530	--	--	0.010	<0.10	0.02
		8-23-89	23.5	895	7.9	--	<.010	.89	.02
	233	4-12-89	23.0	660	--	0.38	.020	<.10	.29
		8-23-89	23.0	720	8.0	.29	.010	1.0	.03
	200	4-12-89	23.0	930	--	--	.030	<.10	.11
		8-23-89	22.0	810	7.8	.24	.060	.18	.05

Table 14. Chemical analyses of ground water from selected residential study sites and multiple-well monitoring sites--Continued

Site name (source of sample)	Depth (ft)	Carbon, organic, total (mg/L as C)	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Potassium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Sulfate, dissolved (mg/L as SO$_4$)	Fluoride, dissolved (mg/L)	Silica, dissolved (mg/L)
Apple Ranchos (multiple-well monitoring site)	240	—	100	28	130	4.5	250	210	0.5	30
		1.4	100	28	130	4.2	260	210	.5	30
		—	100	27	130	4.7	250	210	.5	30
	199	—	100	27	110	4.4	220	190	.6	30
		1.3	93	25	100	4.4	210	190	.5	29
		—	97	25	110	4.4	210	190	.5	30
	173	—	61	22	140	6.5	180	180	.7	27
		3.5	86	26	100	5.6	180	180	.6	31
		—	91	25	100	4.9	190	190	.7	32
	152	—	—	—	—	—	—	—	—	—
Rincon (multiple-well monitoring site)	285	—	29	5.7	44	3.4	23	40	0.6	22
		—	59	15	93	3.3	110	170	.8	27
	233	15	16	4.2	110	4.5	42	67	.9	22
		—	46	13	76	3.6	51	150	.8	29
	200	34	19	5.8	130	4.9	78	93	.9	23
		—	34	10	120	4.8	60	120	.8	24

Table 14. Chemical analyses of ground water from selected residential study sites and multiple-well monitoring sites—Continued

Site name (source of sample)	Depth (ft)	Date	Boron, dissolved (µg/L)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)	Strontium, dissolved (µg/L)	Zinc, dissolved (µg/L)	Lithium, dissolved (µg/L)	$^{15}N/^{14}N$, stable-isotope ratio (per mil)	Alkalinity, lab (mg/L as $CaCO_3$)
Apple Ranchos (multiple-well monitoring site)	240	6-03-88	660	27	21	1,300	8	31	--	88
		4-12-89	670	27	4	--	--	--	--	87
		8-22-89	680	5	<1	--	--	--	--	87
	199	6-02-88	590	9	220	1,200	5	29	--	95
		4-12-89	620	48	3	--	--	--	--	91
		8-22-89	590	5	<1	--	--	--	8.10	93
	173	6-03-88	590	7	780	870	4	24	--	116
		4-12-89	590	90	8	--	--	--	--	100
		8-23-89	580	7	83	--	--	--	--	96
	152	6-03-88	--	--	--	--	--	--	--	--
Rincon (multiple-well monitoring site)	285	4-12-89	250	51	42	--	--	--	--	119
		8-23-89	750	3	<1	--	--	--	--	94
	233	4-12-89	450	90	130	--	--	--	--	180
		8-23-89	600	5	48	--	--	--	5.30	118
	200	4-12-89	390	240	240	--	--	--	--	175
		8-23-89	490	19	350	--	--	--	--	187

Table 15. Comparison of wastewater vertical-movement rates determined from neutron moisture logs and from suction lysimeters

[Geologic unit: Qoa, older alluvium; Qof, older fan deposits; Qol, old lake and lakeshore deposits. ft, foot; ft/d, foot per day]

Site name	Geologic unit	Lithologic description	Degree of consolidation	Data from neutron moisture logs				Data from suction lysimeters			
				Depth of interval monitored (ft)	Vertical distance traveled (ft)	Travel ime (days)	Rate of vertical movement (ft/d)	Depth of interval monitored (ft)	Vertical distance traveled (ft)	Travel ime (days)	Rate of vertical movement (ft/d)
Toltec	Qoa	Gravelly sand with some silt and trace of clay.	Consolidated								
			Unconsolidated	44-64	20	28	0.71	40-50	10	92	0.11
								50-73	23	345	0.07
	Qof		Moderately consolidated	64-72	8	66	0.12				
				72-88	16	111	0.14				
Vasquez	Qol	Gravelly sand with some silt.	Unconsolidated	35-59	19	24	0.79				
		Sand with some gravel and silt.						43-51	8	14	0.57
		Silty sand with some gravel and clay.		59-71	12	21	0.57	51-71	20	20	1.00
		Silty sand with clay.		71-89							
Little Beaver	Qoa	Sandy silt with some gravel and clay	Unconsolidated	42-48	6	56	0.11	31.5-40	8.5	96	0.09
	Qof	Silty sand with some gravel and clay.	Moderately consolidated	48-67	19	203	0.09	40-67	27	345	0.08
			Well consolidated					67-77	10	141	0.07

Table 16. Calculated increase (or decrease) in concentration of chemical constituents in water during household use. (Calculated by subtracting concentrations in tapwater [given in table 11] from concentrations in septic-tank wastewater [table 12])

[Wastewater concentrations used for Vasquez are seepage pit results for samples collected 6-8-88. Data from near Fresno are based on monitoring during 1977-80 at a rural residence occupied by two persons (Nightingale and McCormick, 1985). --, no data; μS/cm, microsiemen per centimeter at 25 degrees Celsius; mg/L, milligram per liter; μg/L, microgram per liter; <, less than value shown]

Constituent	Site						
	Cheyenne-I	Vasquez	Choctaw	Kiowa	Cheyenne-II	Cajon	Fresno
Specific conductance (μS/cm)	910	494	523	243	1,174	528	354±10
Nitrogen (mg/L)	[1]52	33	46	21	49	62	15±1.5
Orthophosphate-phosphorus (mg/L)	7.2	18	1.2	4.9	--	--	6.0±0.5
Organic carbon (mg/L)	--	17	42	10	40	63	--
Calcium (mg/L)	2	13	13	8	23	--	11±3
Magnesium (mg/L)	3	1.8	2.8	0	6	--	2±1
Sodium (mg/L)	125	54	40	17	158	--	29±1
Potassium (mg/L)	10	10	13	4.9	9.9	--	9±1
Chloride (mg/L)	80	31	31	9	62	--	19±1
Sulfate (mg/L)	0	20	36	-10	130	--	5±2
Alkalinity as calcium carbonate (mg/L)	373	162	198	97	408	--	160±10
Fluoride (mg/L)	0	.2	.2	.1	.2	--	--
Silica (mg/L)	4	10	6	3	16	--	6±2
Boron (μg/L)	1,300	30	200	-20	640	--	--
Iron (μg/L)	65	60	390	270	180	--	--
Manganese (μg/L)	13	38	39	20	31	--	--
Strontium (μg/L)	-20	90	80	30	360	--	--
Zinc (μg/L)	8	<2	50	20	17	--	--
Lithium (μg/L)	14	-4	-2	-3	6	--	--

[1]Ammonia and organic nitrogen only.

Table 17. Median concentrations of selected constituents in tapwater, septic-tank, seepage-pit, and suction-lysimeter samples

[From data in table 11 (tapwater), table 12 (septic tank and seepage pit), and table 10 (suction lysimeters). ft, foot; mg/L, milligram per liter; µS/cm, microsiemen per centimeter at 25 degrees Celsius; <, less than reporting limit]

Source of sample	Depth of lysimeter (ft)	Specific conductance (µS/cm)	Nitrogen, NO₂ + NO₃ (mg/L as N)	Nitrogen, ammonia (mg/L as N)	Nitrogen, ammonia + organic (mg/L as N)	Nitrogen, organic (mg/L as N)	Nitrogen, (mg/L as N)	Chloride (mg/L)	Organic carbon (mg/L as C)
Toltec site (new)									
Tapwater	—	181	0.570	<0.010	<0.20	<0.20	0.57	4.6	—
Septic tank	—	—	—	—	—	—	—	—	—
Seepage pit	—	—	—	—	—	—	—	—	—
Suction lysimeter	33	692	.280	5.85	12	6.2	12	23	—
	40	702	8.00	.030	.90	.87	8.9	20	—
	50	770	17.0	.020	1.3	1.3	18	23	—
	73	710	13.5	.035	1.0	.96	15	41	—
Cheyenne-I site (established)									
Tapwater	—	780	1.30	<0.010	<0.20	<0.20	1.3	100	—
Septic tank	—	1,690	—	—	53	—	53	180	—
Seepage pit	—	—	—	—	—	—	—	—	—
Suction lysimeter	37	2,000	41.0	.030	1.0	.97	42	220	3.6
	42	2,300	30.0	.050	1.6	1.6	32	260	5.4
	63	1,250	31.5	.025	.90	.88	32	145	2.5
	73	2,140	33.0	.100	1.3	1.2	34	240	4.1
	92.5	2,250	4.80	.060	1.7	1.6	6.5	—	—
	106	1,290	6.70	.030	1.2	1.2	7.9	280	4.0
	[1]113	2,300	1.10	.070	.60	.53	1.7	510	6.9
Vasquez site (new)									
Tapwater	—	202	1.10	<0.010	<0.20	<0.20	1.1	7.7	—
Septic tank	—	—	—	—	—	—	—	—	—
Seepage pit	—	822	3.9	28.5	24	<.10	28	30	24.5
Suction lysimeter	35	1,150	5.00	.030	.90	.87	5.9	71	—
	43	1,030	<.100	1.54	.80	.80	.80	34	—
	51	900	6.40	.015	.60	.58	7.0	36	—
	71	840	4.30	.030	.70	.67	5.0	30	—
Choctaw site (established)									
Tapwater	—	212	0.440	0.010	<0.20	<0.20	0.44	8.2	—
Septic tank	—	735	.260	6.10	46	40	46	39	42
Seepage pit	—	—	—	—	—	—	—	—	—
Suction lysimeter	33	1,550	6.40	.050	.80	.75	7.2	88	—
	48	1,560	11.5	.050	1.3	1.2	13	110	—
	80	1,010	20.5	.040	1.4	1.4	22	70	—
	[2]131	1,130	.630	.020	.40	.38	1.0	190	—

Table 17. Median concentrations of selected constituents in tapwater, septic-tank, seepage-pit, and suction-lysimeter samples --Continued

Source of sample	Depth of lysimeter (ft)	Specific conductance (µS/cm)	Nitrogen, $NO_2 + NO_3$ (mg/L as N)	Nitrogen, ammonia (mg/L as N)	Nitrogen, ammonia + organic (mg/L as N)	Nitrogen, organic (mg/L as N)	Nitrogen, (mg/L as N)	Chloride (mg/L)	Organic carbon (mg/L as C)
Little Beaver site (new)									
Tapwater	—	345	0.740	<0.010	<0.20	<0.20	0.74	14	--
Septic tank	--	--	--	--	--	--	--	--	--
Seepage pit	--	--	--	--	--	--	--	--	--
Suction lysimeter	31.5	2,500	20.0	.070	1.1	1.0	21	89	--
	40	1,100	4.60	.030	.45	.42	5.0	80	--
	67	980	20.0	.030	.70	.67	21	81	--
	77	2,600	20.0	.220	3.6	3.4	24	--	--
Kiowa site (established)									
Tapwater	--	402	0.790	<0.010	<0.20	<0.20	0.79	28	--
Septic tank	--	645	.20	18.0	22	4.0	22	37	10
Seepage pit	--	--	--	--	--	--	--	--	--
Suction lysimeter	32	1,290	9.60	.030	.75	.72	10	78	--
	67.5	830	15.5	.025	.50	.48	16	48	--
	107.5	1,220	15.5	.085	1.8	1.7	17	66	8.3
	149	825	1.30	.040	1.3	1.3	2.6	83	--
Cheyenne-II site (established)									
Tapwater	--	736	1.20	<0.010	<0.20	<0.20	1.2	98	--
Septic tank	--	1,910	0	31.0	50	19	50	160	40
Seepage pit	--	1,890	<.100	8.90	60	51	60	160	37
Suction lysimeter	10	--	--	--	--	--	--	--	--
	67	1,570	43.0	.055	1.4	1.3	44	190	--
	98	--	--	--	--	--	--	--	--
Cajon site (established)									
Tapwater	--	222	0.890	0.030	<0.20	<0.20	0.89	6.8	.6
Septic tank	--	750	--	44.0	63	19	[3]40	--	63
Seepage pit	--	747	--	41.0	40	<.10	[3]63	--	43
Suction lysimeter	35	1,040	31.0	.055	1.7	1.6	33	68	--
	70	720	29.0	.230	1.6	1.4	31	35	3.9
	97.5	530	32.0	.300	1.8	1.5	34	33	6.6
	130	710	34.	.330	1.4	1.1	35	35	15
	160	1,200	35.0	.440	1.7	1.3	37	--	7.6
	199	580	15.0	.105	.70	.60	16	50	--
	243	2,280	1.10	.190	1.2	1.0	2.3	71	6.1
	[2]257	660	3.05	.875	1.4	2.2	4.4	130	15

[1]Includes only analyses when water table was above suction lysimeter (11-27-89 to 1-11-90).

[2]Suction lysimeter was below water table.

[3]$NO_2 + NO_3$ not analyzed. Nitrogen assumed to be equal to ammonia + organic nitrogen.

Table 18. Nitrogen isotope data from selected suction lysimeters and monitoring wells, 1989-90

[Data taken from tables 10 and 14; ft, foot; mg/L, milligram per liter]

Site name	Depth (ft)	Date (mo-yr)	Nitrate (mg/L as N)	$\delta^{15}N$ (per-mil)
Suction lysimeters				
Cheyenne-I	37	7-89	32	8.7
Cheyenne-I	42	7-89	38	7.9
Cheyenne-I	63	7-89	31	8.7
Cheyenne-I	73	7-89	35	8.3
Cheyenne-I	92.5	7-89	32	7.8
Cajon	243	6-90	.8	7.1
Wells				
Apple Ranchos	199	8-89	4.1	8.1
Rincon	233	8-89	1.0	5.3

Table 19. Specific conductance, concentrations of selected chemical constituents, and nitrogen-isotope ratios in samples from lysimeters at Cajon residential site, 1991–93

[Nitrogen and organic carbon concentrations from November 5, 1991; oxygen concentrations from April 22, 1992; and isotope data from November 13, 1991. ft, foot; µS/cm, microsiemen per centimeter at 20 degrees Celsius; --, no data]

Depth (ft)	Specific conductance (µS/cm)						Constituent concentration (mg/L)					$\delta^{15}N$, in nitrate (per-mil)
	9-23 1991	11-05 1991	11-13 1991	2-13 1992	4-22 1992	3-29 1993	Nitrate as N	Ammonium, as N	Kjeldahl nitrogen	Carbon, organic	Oxygen, dissolved	
35	585	462	472	478	473	448	28	0.03	0.5	2.9	3.7	10.5
70	755	491	485	486	525	435	27	.15	.7	3.4	4.5	9.5
97.5	547	517	493	491	488	468	34	.08	.4	3.0	4.4	8.2
130	617	590	547	540	525	470	38	.15	.8	4.2	--	7.8
160	588	547	564	567	555	493	36	.14	.7	3.5	6.1	7.8
199	468	391	395	401	418	535	18	.24	.4	2.1	5.0	14.8
243	487	274	248	285	--	264	.52	.04	.5	4.4	7.1	--
257	358	1,017	1,329	1,013	1,003	1,088	.13	.05	.8	14	--	--

Table 20. Organic priority pollutants detected in wastewater samples from septic tanks and seepage pits

[Concentrations in micrograms per liter; ND, not detected; --, not analyzed]

Organic priority pollutant	Septic tanks				Seepage pits	
	Cheyenne-I[1]	Choctaw	Kiowa[2]	Cheyenne-II	Vasquez	Cheyenne-II
Purgeable priority pollutants						
Chloroform	—	4.1	0.6	ND	ND	ND
Toluene	—	9.3	ND	350	0.3	230
Benzene	—	ND	ND	.2	ND	ND
Chlorobenzene	—	ND	ND	.3	ND	ND
Diethylphthalate	—	ND	—	ND	5.0	ND
Ethylbenzene	—	ND	ND	2.2	ND	.3
Methylene chloride	—	ND	ND	ND	ND	11
Tetrachloroethylene	—	ND	ND	260	ND	170
Extractable priority pollutants						
1,2-Dichlorobenzene	—	ND	ND	120	ND	66
1,4-Dichlorobenzene	—	ND	56	21	ND	ND
Di-n-octylphthalate	—	13	—	ND	ND	12
2,4-Dimethylphenol	ND	ND	ND	23	ND	29
Phenol (C6H-50H)	ND	24	47	17	37	12
Bis-2-ethylhexylphthalate	—	49	—	ND	32	ND
Vinyl chloride	—	ND	ND	7.5	ND	ND
Trichloroethylene	—	ND	ND	ND	ND	5.2
Xylene	—	ND	ND	.7	ND	ND

[1]Analyzed for acid-extractable priority pollutants only.
[2]Analyzed for purgeable and acid-extractable priority pollutants only.

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Table 21. Extractable organic compounds, other than priority pollutants, tentatively identified in wastewater samples

[Estimated concentrations in microgram per liter. CAS No., a universal identification number for chemical compounds contained in the Chemical Abstracts Service register]

CAS No.	Compound	Concentration

Septic tank at Choctaw

CAS No.	Compound	Concentration
107-92-6	Butanoic acid	220
109-52-4	Pentanoic acid	410
142-61-1	Hexanoic acid	410
106-44-5	4-Methylphenol	700
498-81-7	$\alpha,\alpha,4$-Trimethyleyclo-hexanemethanol	50
74663-85-7	Nonylcyclopropane	130
143-07-7	Dodecanoic acid	780
112-72-8	1-Tetradecanol	490
1002-84-2	Pentadecanoic acid	160
57-11-4	Octadeconoic acid	1,200

Septic tank at Cheyenne-II

CAS No.	Compound	Concentration
108-88-3	Methylbenzene	40
106-44-5	4-Methylphenol	270
143-07-7	Dodecanoic acid	50
58-08-2	Caffeine	100
57-10-3	Hexadecanoic acid	420
36653-82-4	1-Hexadecanol	50
57-11-4	Octadecanoic acid	440

Seepage pit at Cheyenne-II

CAS No.	Compound	Concentration
108-88-3	Methylbenzene	40
143-07-7	Dodecanoic acid	50
4536-30-5	2-(Dodecyloxy)ethanol	110
58-08-2	Caffeine	120
2091-29-4	9-Hexadecenoic acid	110
57-10-3	Hexadecanoic acid	460
57-11-4	Octadecanoic acid	360

Table 22. Parameters and values used in the model

[ft^3/d, cubic foot per day; ft/d, foot per day; ft, foot; mg/L, milligram per liter]

	Model parameter	Parameter value
Q_{in}	**Quantity of ground-water inflow**	2,314,224 ft^3
	Hydraulic conductivity (K)	20 ft/d
	Hydraulic gradient (dh/dl)	0.0012 ft/ft
	Vertical mixing depth (b)	50 ft
	Aquifer width (w)	5,280 ft
N_{in}	**Nitrate-N concentration of ground-water inflow**	2 mg/L
Q_{st}	**Quantity of septic-tank wastewater**	10,939,968 ft^3
	Average septic-tank discharge	23.4 (ft^3/d)/house
	Housing density	1 house/acre
	Number of acres in model area	1,280 acres
N_{st}	**Nitrate-N concentration of septic-tank wastewater**	50 mg/L
Q_{gw}	**Quantity of underlying ground water**	836,352,000 ft^3
	Aquifer length (l)	10,560 ft
	Aquifer width (d)	5,280 ft
	Vertical-mixing depth (b)	50 ft
	Aquifer porosity	30 percent
$N_{gw}^{n=0}$	**Nitrate-N concentration of underlying ground water**	2 mg/L