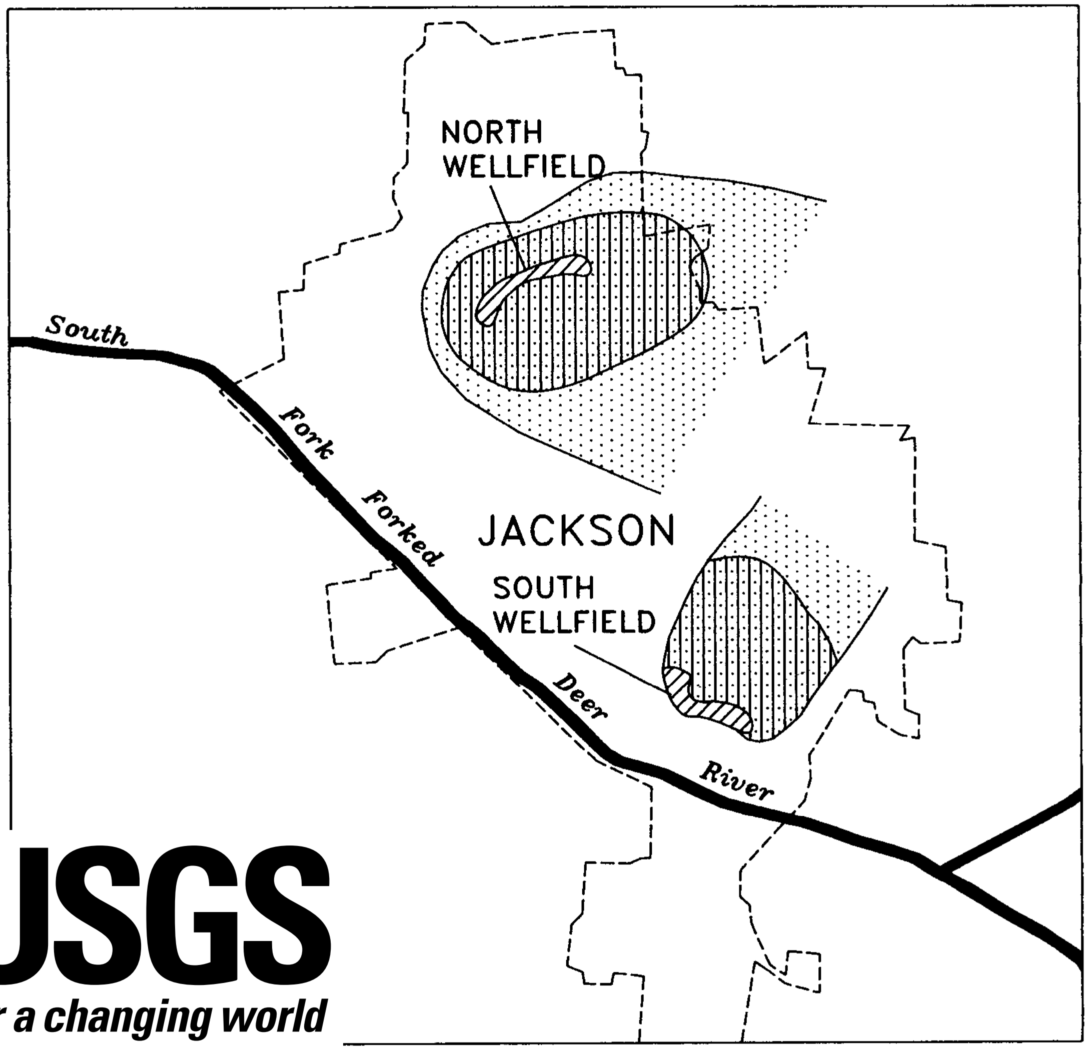
Water-Resources Investigations Report 89-4201

A PILOT STUDY FOR DELINEATION OF AREAS CONTRIBUTING WATER TO WELLFIELDS AT JACKSON, TENNESSEE



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Prepared by the
U.S. Geological Survey

in cooperation with the
TENNESSEE DEPARTMENT OF HEALTH AND ENVIRONMENT,
DIVISION OF GROUND WATER PROTECTION
and the
JACKSON UTILITY DIVISION

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By R.E. Broshears, J.F. Connell, and N.C. Short

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Nashville, Tennessee
1991

DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

Factors for converting inch-pound units to metric units are shown below.

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.4	millimeter (mm)
inch per year (in/yr)	2.54	centimeter per year (cm/y)
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	3.528×10^{-6}	meter per second (m/s)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
cubic foot per second (ft^3/s)	0.0283	cubic meter per second (m^3/s)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon per minute (gal/min)	3.785	liter per minute (L/min)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) by the following equation:

$$^{\circ}C = (^{\circ}F - 32)/1.8$$

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

Well-Numbering System: Wells are identified according to the numbering system used by the U.S. Geological Survey throughout Tennessee. The well number consists of three parts: (1) an abbreviation of the name of the county in which the well is located; (2) a letter designating the $7^1/2$- minute topographic quadrangle on which the well is plotted; and (3) a number generally indicating the numerical order in which the well was inventoried. The symbol Sh:O-169, for example, indicates that the well is located in Shelby County on the "O" quadrangle and is identified as well 169 in the numerical sequence. Quadrangles are lettered from left to right, beginning in the southwest corner of the county.

A PILOT STUDY FOR DELINEATION OF AREAS CONTRIBUTING WATER TO WELLFIELDS AT JACKSON, TENNESSEE

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ABSTRACT

The U.S. Geological Survey, in cooperation with the Tennessee Department of Health and Environment, Division of Groundwater Protection, and the Jackson Utility Division, conducted a pilot study to determine data needs and the applicability of four methods for the delineation of wellhead protection areas. Jackson Utility Division in Jackson, Madison County, Tennessee, pumps about 9 million gallons of ground water daily from two municipal wellfields that tap an unconfined sand aquifer. Under natural hydraulic gradients, ground water flows southward toward the South Wellfield at approximately 2 to 3 feet per day; natural flow toward the North Wellfield is from the east at 1 to 2 feet per day. Water quality generally is suitable for most uses. Concentrations of dissolved solids are low, and excessive iron is the only significant naturally occurring water-quality problem. However, trace concentrations of volatile organic compounds have been detected in water pumped from the South Wellfield; the highest concentration of a single compound has been 23 micrograms per liter of tetrachloroethylene. Potential sources of ground-water contamination in the Jackson area include a hazardous-waste site, municipal and industrial landfills, and underground-storage tanks. Some of the four methods for delineating wellhead protection areas did not adequately describe zones contributing flow to the wellfields. Calculations based on a uniform flow equation provided a preliminary delineation of zones of contribution for the wellfields and ground-water time-of-travel contours. Limitations of the applied methods motivated the design of a more rigorous hydrogeologic investigation.

INTRODUCTION

The Safe Drinking Water Act Amendments of 1986 authorize assistance to states for implementation of wellhead protection programs. The purpose of these programs is to protect areas around public-supply wells from contamination that could be detrimental to human health. The 1986 amendments define a wellhead protection area as the "surface and subsurface area surrounding a water well or wellfield, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or wellfield" (U.S. Environmental Protection Agency, 1987a). This definition, which is strictly hydrologic in nature, is used in this report; use of the term "wellhead protection area" in this report does not imply a regulatory or administrative unit. Because contaminant movement in hydrogeologic systems is a complex function of localized physical, chemical, and biological processes, delineation of sources of water to wells is a site-specific problem. Factors such as the radius of hydraulic influence of the well and the potential introduction and potential rate of travel of contaminants under local hydrologic and geochemical conditions must be assessed.

The State of Tennessee, through the Environmental Policy Group and the Department of Health and Environment, Division of Ground Water Protection, has been developing a comprehensive ground-water protection strategy. Local wellhead protection programs are an integral part of this strategy. In 1987, the U.S. Geological Survey (Geological Survey), in cooperation with the Tennessee Department of Health and Environment (TDHE), and the Jackson Utility Division (JUD), selected the city of Jackson, Tennessee, as the site for an investigation to demonstrate the hydrologic factors to be considered in determining sources of water to wells. Hydrologic information can then be used by appropriate federal, state, or local agencies to plan for ground-water protection. Historically, the quality of ground water in the Jackson area has been suitable for most uses. However, recent identification of volatile organic compounds in low concentrations in water pumped from several JUD wells has motivated the utility to seek a more comprehensive ground-water-protection strategy.

Purpose and Scope

The purpose of this investigation was to assess data needs and to demonstrate several methods for a preliminary delineation of areas contributing water to wellfields. The area selected for this pilot study was Jackson, Tennessee, and included two municipal wellfields operated by the Jackson Utility Division. The scope of the study was limited to a preliminary assessment of the local hydrogeologic framework and ground-water quality, mapping of potential sources of ground-water contamination, and an assessment of four methods used to delineate wellhead protection areas. This report presents results of the pilot study.

Objectives

The objectives of the study were to:

1. Develop a preliminary conceptualization of the hydrogeologic setting of the Jackson area;
2. Characterize water quality within the aquifer serving the JUD wellfields;
3. Map some of the obvious potential sources of ground-water contamination;
4. Delineate the boundaries of areas contributing water to wellfields using methods recommended by the U.S. Environmental Protection Agency (USEPA);
5. Design a plan to improve this preliminary assessment of ground-water flow and areas contributing recharge to the wellfields.

HYDROGEOLOGIC SETTING

Surface Features and Climate

The 120-mi^2 study area is in Madison County in the West Tennessee Plain unit of the Coastal Plain physiographic region (Miller, 1974), which is characterized by rolling sand uplands and broad river bottomlands. Total relief in the area is about 280 feet. The lowest point is 320 feet above sea level where the South Fork Forked Deer River leaves the western boundary of the area. The highest point is 600 feet above sea level near the eastern boundary of the area along the topographic divide between the Middle Fork Forked Deer and the South Fork Forked Deer Rivers (fig. 1). Mean annual precipitation at Jackson is about 53 inches (National Oceanic and Atmospheric Administration, 1986). Runoff in the northern third of the area is to the main stem and tributaries of the Middle Fork Forked Deer River, which has an average flow of 521 ft^3/s near Alamo, Tennessee, about 20 miles from Jackson (U.S. Geological Survey, 1974). Runoff in the southern two-thirds of the area is to the South Fork Forked Deer River, which has an average flow of 705 ft^3/s at Jackson.

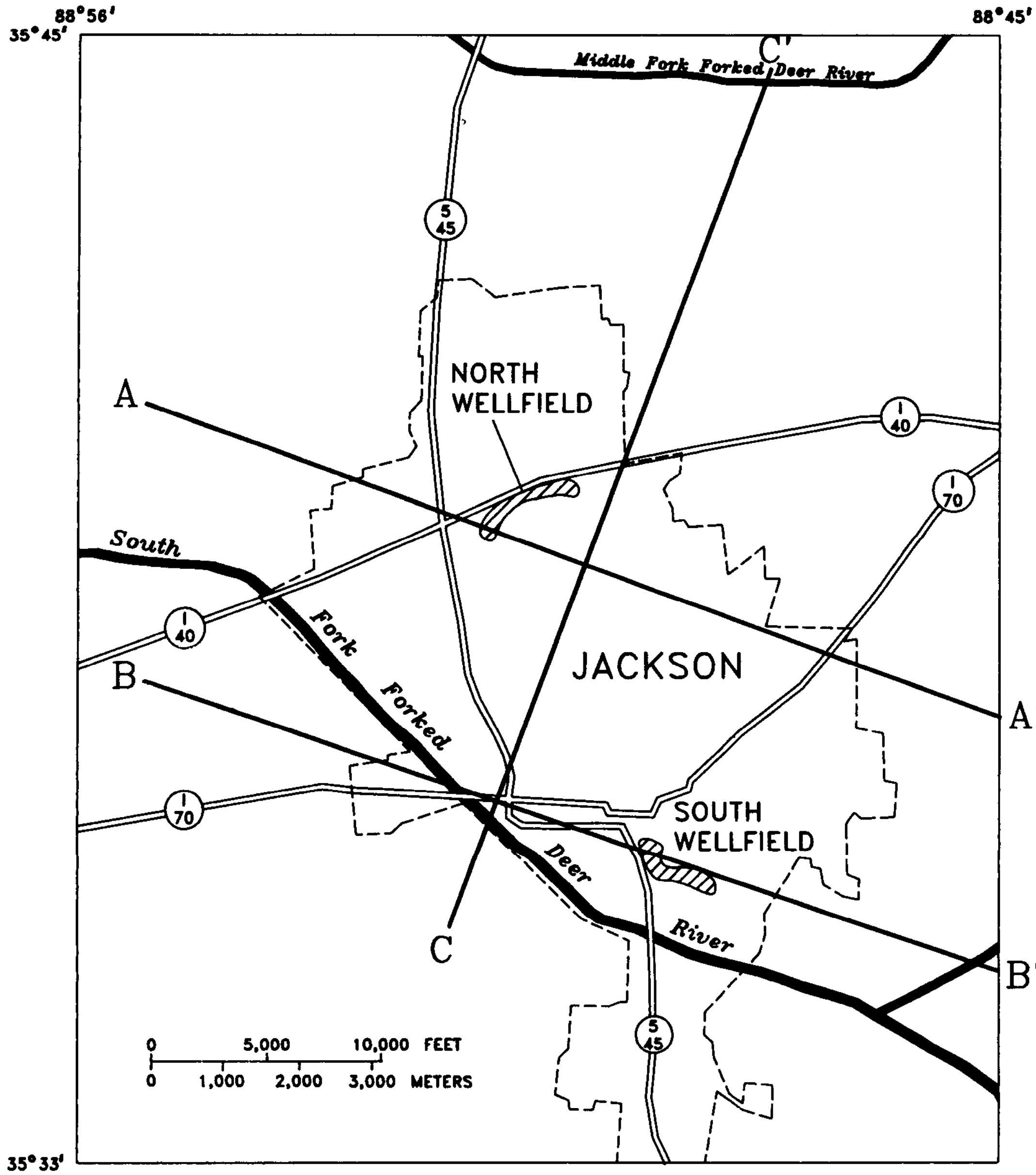
Geology

Description of the geology of the study area is based on a literature review and an analysis of approximately 700 well records from State and Geological Survey files. The study area is underlain by several hundred feet of unconsolidated sediments that dip gently to the northwest at 20 to 50 feet per mile (Nyman and Moore, 1963). The older sediments are Cretaceous in age (table 1) and underlie the area at depths of 300 feet near the southeast corner of the study area and as deep as 900 feet in the northwest corner. These sediments form a sequence of clays and sands with thin lenses of intervening clay. Overlying these

Table 1.—*Geologic units and equivalent hydrogeologic units underlying the Jackson area*

Series	Group	Formation	Thickness (in feet)	Lithology	Hydrogeologic units	Maximum yield (gal/min)
Post-Eocene		Alluvium and terrace deposits	0-100	Iron stained gravel, sand, and silt.	Upper aquifer	1,200
Eocene	Claiborne	Undifferentiated sediments	0-400	Fine to coarse, white to gray or yellow, lignitic sand and thin layers of sandy clay.		
	Wilcox	Undifferentiated sediments	0-200	Upper clay unit not known to be present in county. Lower unit is fine to coarse, light gray sand containing thin layers of clay.		
Paleocene	Midway	Porters Creek Clay	220	Dark gray to black clay containing a few layers of fine sand.	Midway confining unit	Less than 5
		Clayton Formation	40	Fine to medium, light green sand.		
Upper Cretaceous		Owl Creek Formation	40	Greenish gray to black clay.		
		Ripley Formation	360-410	Fine to coarse, gray, partly lignitic sand and a few intervening layers of clay	Lower aquifer	500

Modified from Nyman and Moore (1963)



EXPLANATION

SOUTH WELLFIELD — APPROXIMATE AREA OF WELLFIELD

C——C' LINE OF SECTION-- (Sections on figure 3)

----- JACKSON CITY LIMITS

5/45 MAJOR HIGHWAY AND NUMBER

Figure 1.--Location of the Jackson area and lines of hydrogeologic sections along traces A-A', B-B', and C-C'.

sediments is a 300-foot sequence of fine-grained materials including the Owl Creek Formation, Clayton Formation, and Porters Creek Clay.

The shallower sediments are Paleocene, Eocene, and younger in age. The base of this younger sequence crops out in the southeast corner of the area but is as deep as 600 feet in the northwest corner. These sediments are predominantly fine- to coarse-grained sands with subordinate clay interbeds. At least two clay beds, each about 20 feet thick, occur in the 400-feet thick section in the western half of the North Wellfield at Jackson. Elsewhere, the clay interbeds vary in thickness and are probably discontinuous laterally. Locally the lower of the two clays may be as thick as 100 feet. In ascending order, the younger sediments include the Fort Pillow Sand of the Wilcox Group, the Memphis Sand of the Claiborne Group (Parks and Carmichael, 1989; 1990), and the post-Eocene terrace deposits and alluvium (Nyman and Moore, 1963; Russell and Parks, 1975). Much of the area is capped by 5 to 10 feet of clay-rich silt.

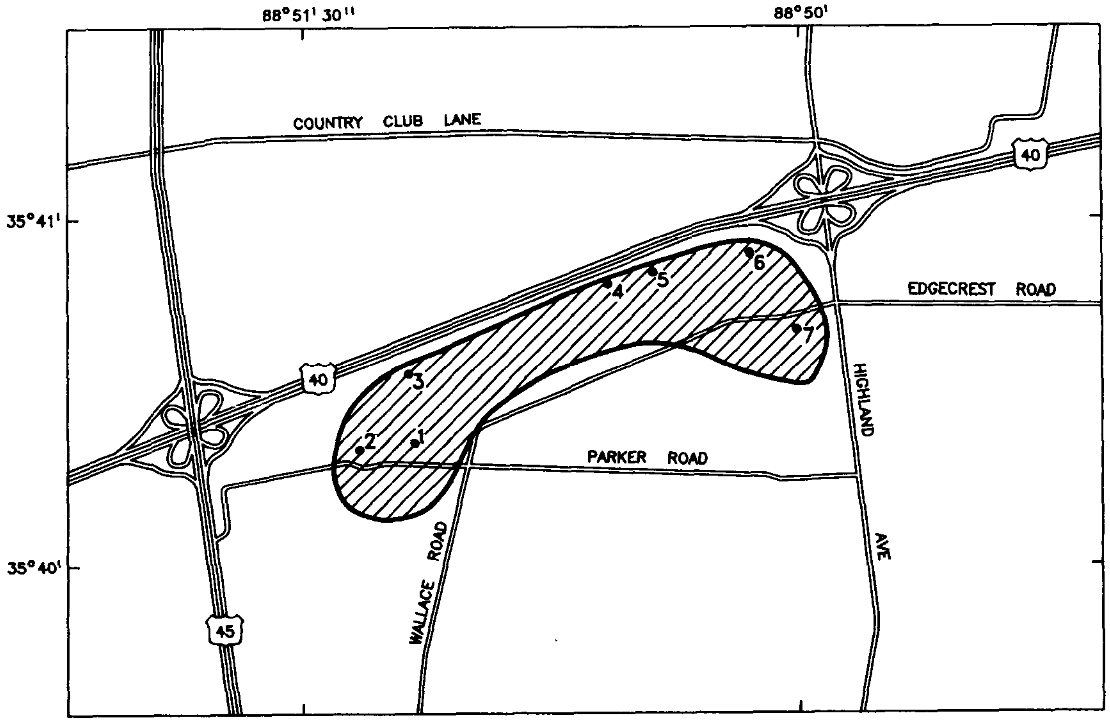
Conceptualization of the Ground-Water Flow System

Based on geologic and hydrologic evidence, the ground-water flow system can be separated into upper and lower aquifers. The sequence of fine-grained sediments capped by the Porters Creek Clay physically separates the two aquifers. Within the lower aquifer, sands in the Ripley Formation are the source of water flowing from deep wells in the Jackson area. Water in the lower aquifer is under artesian pressure, and heads are as much as 50 feet above land surface in the bottomlands of the South Fork Forked Deer River. Several wells tapping the lower aquifer are in the South Wellfield at Jackson (fig. 2), and they flow as much as 300 gal/min (Nyman and Moore, 1963). Because the lower aquifer does not crop out locally and is confined under 300 feet of fine-grained material throughout the study area, it is less vulnerable to contamination from the surface.

The upper aquifer is the most used water-bearing unit in the study area. Wherever it is saturated, the almost continuous sand section of the Memphis Sand overlying the Fort Pillow Sand is the source of water to shallow wells in the Jackson area. All wells operated by the JUD are screened in the upper aquifer. The sand is predominantly well-sorted and medium-grained at the North Wellfield (C.E. Nuzman, Layne-Central Company, written commun., 1977). The bottom of the aquifer is the Porters Creek Clay or any clay bed immediately overlying the Porters Creek Clay (table 1). The top of the aquifer is the water table, which is at or very close to land surface under bottomlands of the forks of the Forked Deer River and is as much as 170 feet below land surface in the area of the topographic divide near the North Wellfield. The upper aquifer pinches out toward its outcrop in the southeast corner of the area. It averages 120 feet in thickness near the South Wellfield (excluding clay interbeds), and 240 feet near the North Wellfield. It is greater than 500 feet thick near the northwest corner of the area (fig. 3).

The upper aquifer is essentially unconfined and receives direct recharge from rainfall everywhere except in the bottomlands, which are almost completely saturated. Discharge from the aquifer is to wells and to the forks of the Forked Deer River and the lower reaches of their tributaries. The water table is 60 to 80 feet above river levels between the two rivers. Ground water throughout the aquifer moves from areas of high water-table altitudes to areas of low water-table altitudes. An approximation of the pre-pumping water table based on water-level data and analytical techniques (Jacob, 1943), as explained later, is shown in figure 4. Because of the geographic position of the two rivers and the higher altitude of the Middle Fork Forked Deer River, the ground-water divide lies north-northeast of the topographic divide at the North Wellfield (fig. 4).

(A)



(B)

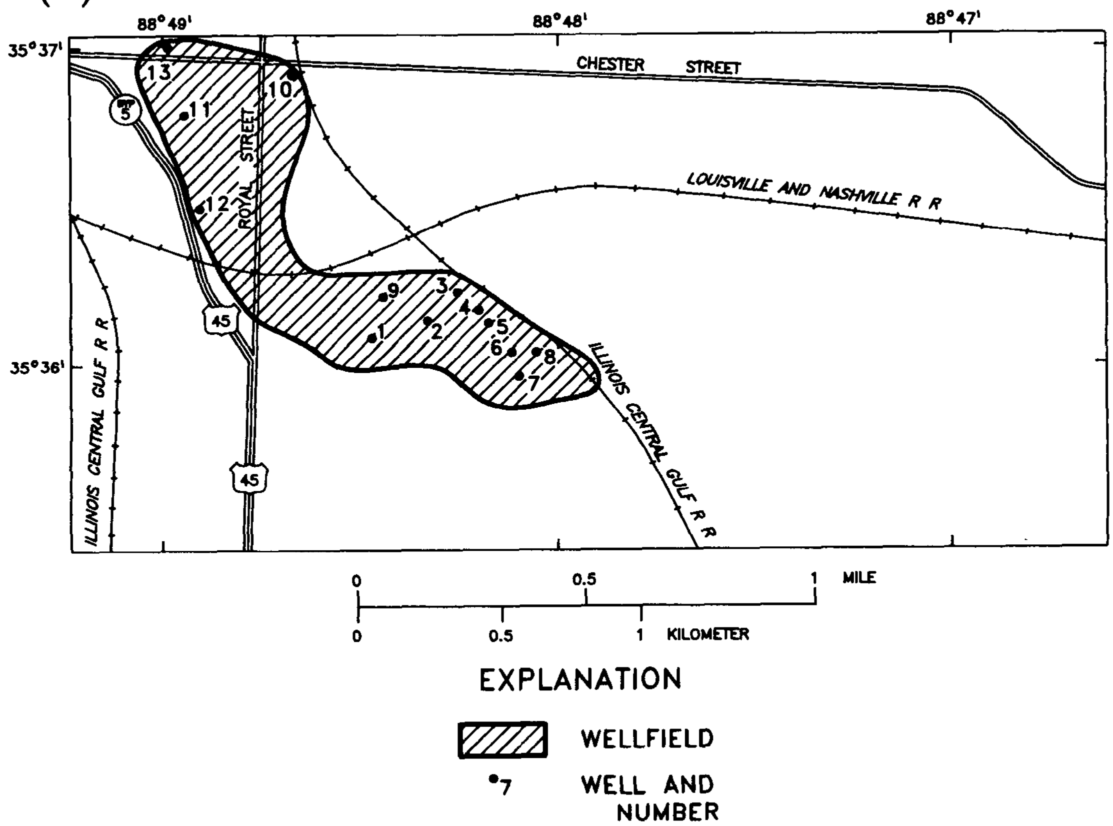


Figure 2.--Locations of wells in (A) North Wellfield and (B) South Wellfield.

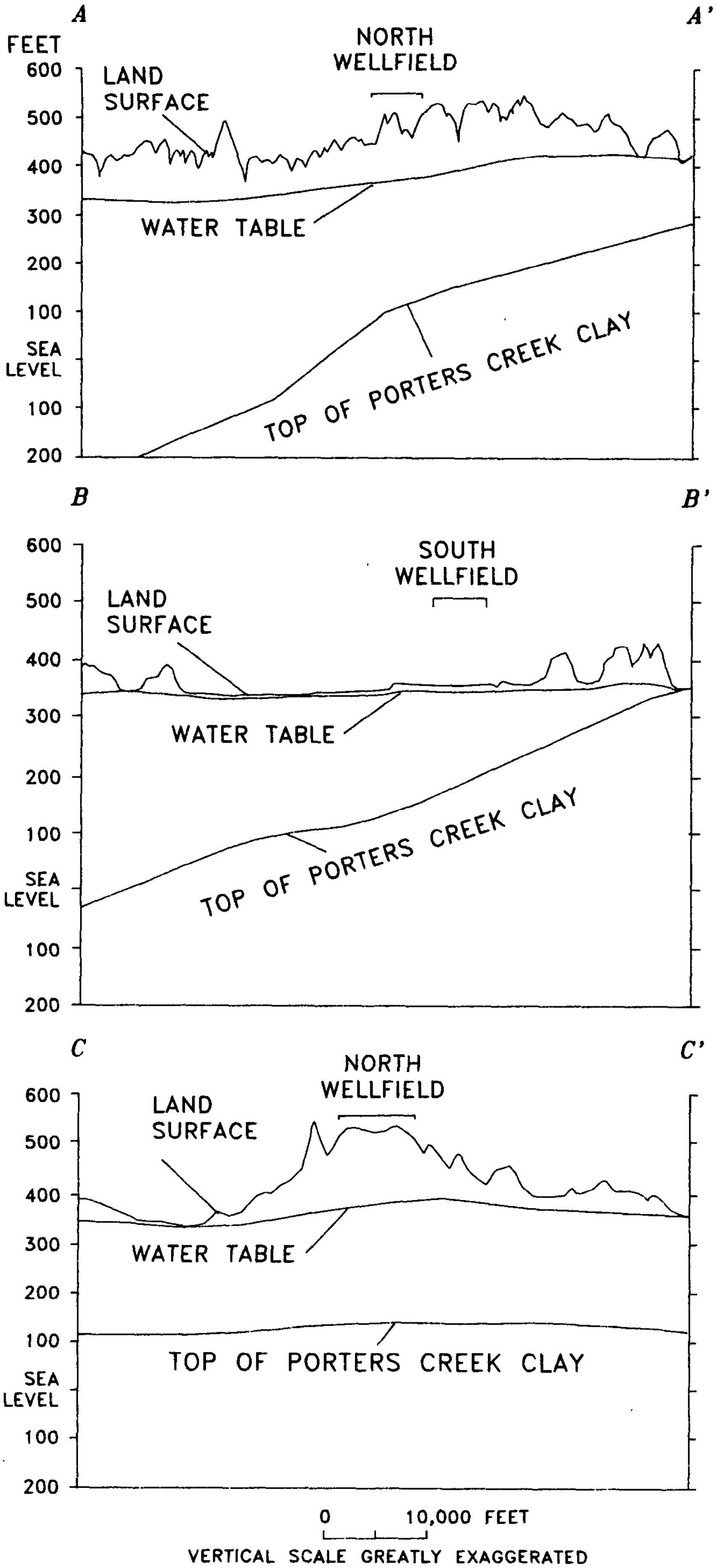
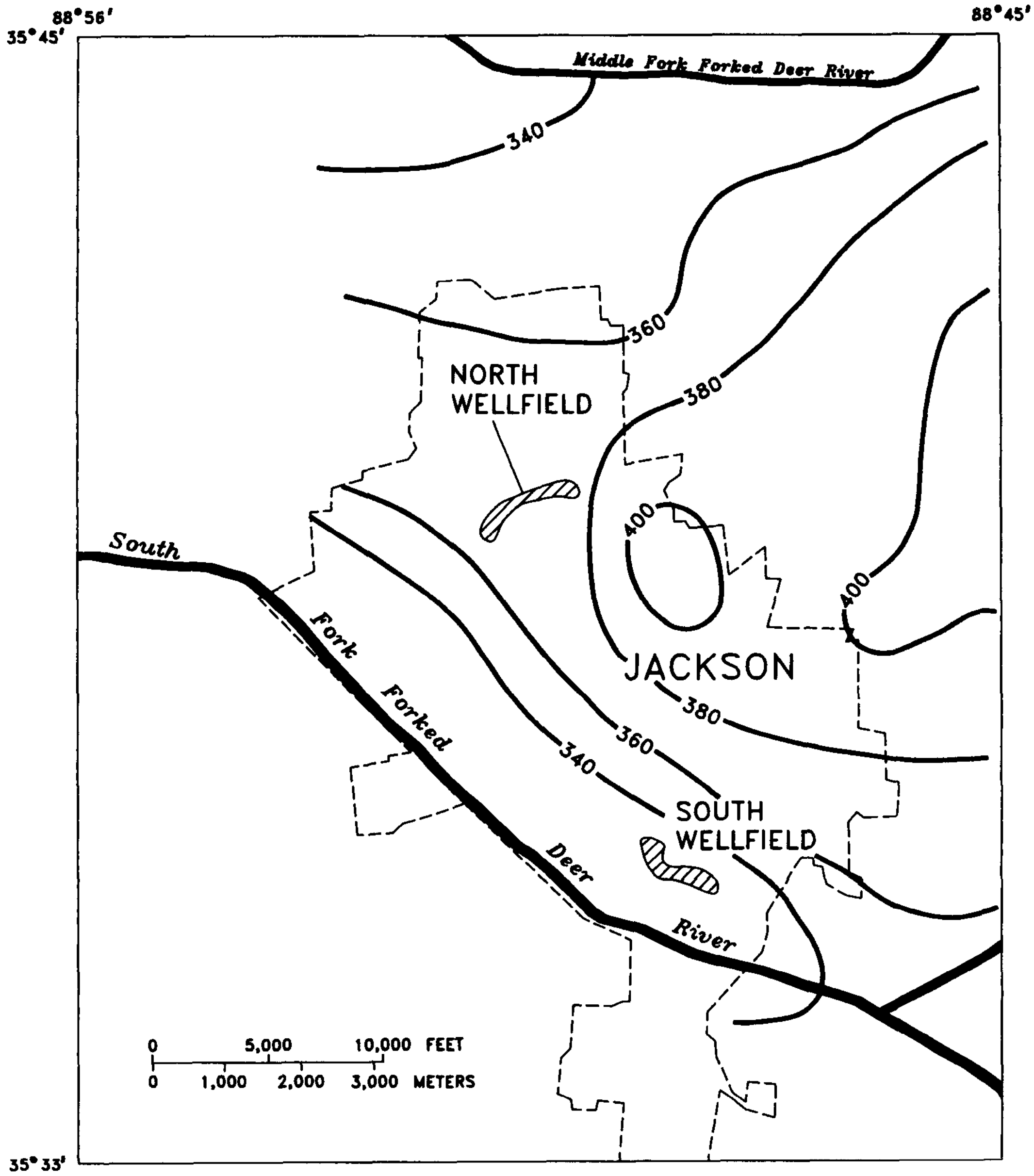


Figure 3.-- Hydrogeologic sections along lines A-A', B-B', and C-C'.



EXPLANATION

SOUTH WELLFIELD — APPROXIMATE AREA OF WELLFIELD

----- JACKSON CITY LIMITS

—340— WATER-LEVEL CONTOUR--Shows estimated altitude of water table. Contour interval 20 feet. Datum is sea level

Figure 4.--Estimated altitude of the water-table in the study area.

In response to the water-table gradient, ground-water flow is generally west along the water-table divide. North of the divide, flow is west and north toward the Middle Fork Forked Deer River; south of the divide, flow is west and south toward the South Fork Forked Deer River. In general, regional flow to the North Wellfield is from the east; regional flow to the South Wellfield is from the northeast (fig. 4).

Estimation of Hydrologic Variables

Quantification of ground-water flow in the study area requires the estimation of aquifer hydraulic properties and other hydrologic variables. These variables include ground-water recharge rates, hydraulic conductivity and transmissivity of water-bearing formations, porosity of aquifer materials, and the natural slope of the water-table surface. Because of the limited scope of this investigation, hydrologic variables were estimated from pre-existing data only. Single values, representing best available estimates for the spatial and temporal averages of each variable, were used. Uncertainties inherent in this approach are discussed in later sections.

Recharge

Precipitation that does not run off immediately to surface drains either returns to the atmosphere by evapotranspiration or infiltrates into the land surface and percolates to the water table. Estimates of recharge rates in Middle and East Tennessee vary from 4.1 to 16.8 in/yr (A.B. Hoos, U.S. Geological Survey, written commun., 1988). Zurawski (1978) reported a regional average of 11.5 in/yr for an area near Jackson. For the purposes of this investigation, the annual average ground-water recharge rate by percolation to the water table was assumed to be 12 in/yr.

Hydraulic Conductivity and Transmissivity

Estimates of hydraulic conductivity of the upper aquifer in the study area were derived from results of permeameter tests, aquifer tests, and digital ground-water flow models. These estimates were determined from data from other areas in West Tennessee having similar hydrogeologic settings and the results of local investigations. Based on permeameter tests in the laboratory, using medium-grained sands from the Memphis area, Nyman (1965) calculated an average hydraulic conductivity of 80 ft/d. From the results of 26 aquifer tests, Moore (1965) estimated an average hydraulic conductivity of 76 ft/d for the Memphis Sand. Hydraulic conductivity was estimated at 68 ft/d by Hosman and others (1968), who used the results of two aquifer tests in the lower Wilcox Group in Madison County. Hollyday (U.S. Geological Survey, written commun., 1988) analyzed data from an aquifer test by Nuzman (Layne-Central Company, written commun., 1977) to estimate a hydraulic conductivity of 95 ft/d for the area surrounding the North Wellfield in Jackson. Based on this collection of values, a uniform hydraulic conductivity of 80 ft/d was assumed for the study area.

Transmissivity is the product of hydraulic conductivity and thickness of saturated aquifer materials. Geologic logs were used to construct three hydrogeologic sections through the upper aquifer (fig. 3). The average saturated thickness near the North Wellfield was estimated at 240 feet, and the transmissivity was calculated to be 19,200 ft^2/d. The average saturated thickness near the South Wellfield was estimated at 120 feet, and the transmissivity was calculated to be 9,600 ft^2/d.

Porosity

Porosity is the ratio of openings (voids) to the total volume of aquifer material. The porosity of unconfined aquifers in West Tennessee has been estimated at 0.1 to 0.3 (Moore, 1965).

Nuzman (Layne-Central Company, written commun., 1977) used values of 0.15 to 0.20 for an electric analog model of ground-water flow in the area of the North Wellfield. Brahana (U.S. Geological Survey, written commun., 1987) used a porosity of 0.21 for the outcrop area of Wilcox sands near Jackson. Based on these estimates, and for the purposes of this investigation, a porosity of 0.20 was assumed for the study area.

Water-Table Configuration and Ground-Water Velocity

Because of the scarcity of reliable water-level measurements taken before development of JUD wellfields, the natural configuration of the water table in the Jackson area cannot be defined with confidence from existing data. A reasonable approximation of the water-table surface was drawn using a combination of selected water-level data and analytical techniques. Water-level data from 470 well logs were plotted, and after removal of outliers, areal averages were contoured. The data were then smoothed using a variation of Jacob's piezometric parabola (Jacob, 1943). This analytical technique invokes a volumetric balance between ground-water flow and recharge, with hydraulic gradients steepening linearly from ground-water divides to surface discharge areas. The estimated water-table surface is displayed in figure 4. Based on this estimated water table, the average hydraulic gradient in the area near the North Wellfield is estimated to be 0.0035 to the west; near the South Wellfield, it is estimated to be 0.0064 to the southwest. Given these gradients and previously assumed values for hydraulic conductivity and porosity, natural ground-water velocity toward the North Wellfield would be approximately 1 to 2 ft/d. Similarly, ground water would flow naturally toward the South Wellfield at approximately 2 to 3 ft/d.

Water-Use History

The first public-water utility in the Jackson area was formed in 1885. Called the Jackson Water Works, it established the South Wellfield between the Iselin Railyard and the Armory (fig. 2). In 1959, the Jackson Utility Division was created under the administration of the City of Jackson. The Jackson Utility Division was incorporated as an independent entity in 1976.

In the late nineteenth century, ground-water withdrawals from the South Wellfield averaged about 1 Mgal/d. The maximum production from this field occurred in 1980, just before the North Wellfield began operation. Current production from the South Wellfield is limited to about 1.5 Mgal/d, and withdrawals from the North Wellfield average 7.9 Mgal/d. The JUD serves about 19,000 residential, 1,765 commercial, and 246 industrial customers (Danny Lester, Jackson Utility Division, written commun., 1987).

Industrial pumping in the Jackson area averages 5.1 Mgal/d (Leanne Tippett, Tennessee Department of Health and Environment, Division of Groundwater Protection, written commun., 1987). As many as 100 industrial users are partially dependent on private wells for their water supply.

GROUND-WATER QUALITY

Water-quality data for 11 wells in the upper aquifer in the study area were retrieved from the National Water Data Storage and Retrieval System, a computer data base operated by the Geological Survey. Minimum, median, and maximum values for selected inorganic constituents and properties of samples from these 11 wells are shown in table 2. In addition, data from water-quality analyses for samples collected by JUD from its public-supply wells were examined. The range and median values for composite monthly

Table 2. — *Water-quality data for selected inorganic constituents and properties for the upper aquifer, Jackson area*

[Source is U.S. Geological Survey, Nashville, Tennessee, unpublished files, 1988; μg/L = micrograms per liter; mg/L = milligrams per liter; μS/cm = microsiemens per centimeter; < = less than]

Constituent or property	Minimum	Median	Maximum
Temperature, in degrees Celsius (°C)	14.5	16.0	18.0
Silica, dissolved (mg/L as SiO_2)	3.8	8.7	16
Iron, dissolved (μg/L as Fe)	<3	210	1,100
Magnesium, dissolved (mg/L as Mg)	.7	1.0	3.1
Calcium, dissolved (mg/L as Ca)	1.6	4.0	9.0
Sodium, dissolved (mg/L as Na)	1.0	3.2	11
Potassium, dissolved (mg/L as K)	.2	.6	3.8
Alkalinity, dissolved (mg/L as $CaCO_3$)	8	15	31
Sulfate, dissolved (mg/L as SO_4)	.2	.9	14
Chloride, dissolved (mg/L as Cl)	2.0	3.5	8.0
Fluoride, dissolved (mg/L as F)	<.1	<.1	.1
Nitrate, dissolved (mg/L as N)	.05	.07	.77
Solids, sum of dissolved constituents (mg/L)	29	36	68
Solids, residue at 180 °C (mg/L)	26	32	69
Hardness, (mg/L as $CaCO_3$)	8	14	18
Specific conductance (μS/cm at 25 °C)	32	46	94
pH (units)	5.4	5.9	6.9

samples from each wellfield from 1976 to 1986 are shown in table 3.

In general, the quality of ground water in the Jackson area is suitable for drinking and a variety of other uses with only minor treatment. The water is a soft, calcium sodium bicarbonate type and is low in dissolved solids. Of the inorganic constituents and properties for which the USEPA has established primary or secondary drinking-water standards, only iron, manganese, and turbidity values sometimes exceed recommended limits in the raw water. Treatment methods used by JUD include aeration, chemical oxidation, chlorination, and filtration. These processes have been effective in meeting all regulatory requirements for the finished water. The utility determines concentrations of priority pollutant trace constituents as required by law; maximum contaminant limits for the finished water have never been exceeded (Liba Ford, Jackson Utility Division, oral commun., 1987).

Concern for water quality in the South Wellfield increased in 1986-87 when samples from each well were analyzed for volatile organic compounds (VOC's). Tetrachloroethylene was detected in six wells with the maximum concentration of 21 μg/L occurring in well 5. Trichloroethylene was identified in three wells with the maximum concentration of 12 μg/L occurring in well 6. Traces of dichloroethylene were detected in three wells. In an unpublished report to JUD, Groundwater Management, Inc. (written commun., 1987) speculated that the source of these VOC's may be a leaky sewer receiving effluent from a past or present user of the compounds.

Table 3. – *Water-quality data for water pumped from the North and South Wellfields, Jackson Utility Division, 1976-1986*

[Source is Jackson Utility Division, written commun., 1987; μg/L = micrograms per liter, mg/L = milligrams per liter]

Constituent or property	Minimum	Median	Maximum
	South Wellfield		
Iron, dissolved (μg/L as Fe)	7	130	6,000
Manganese, dissolved (μg/L as Mn)	<1	165	2,100
Alkalinity (mg/L as $CaCO_3$)	7	30	74
Hardness (mg/L as $CaCO_3$)	26	58	100
pH (units)	4.8	5.8	6.4
	North Wellfield		
Iron, dissolved (μg/L as Fe)	1	140	2,800
Manganese, dissolved (μg/L as Mn)	4	20	70
Alkalinity (mg/L as $CaCO_3$)	11	15	20
Hardness, (mg/L as $CaCO_3$)	7	11	21
pH (units)	4.9	5.3	5.6

In response to the detection of VOC's in the water supply at the South Wellfield, JUD began treatment with powdered activated carbon. VOC concentrations were monitored at regular intervals using more sensitive analytical methods. Volatile organic compounds for which analyses were conducted are shown in table 4. The results of monthly analyses from September through December 1987 are presented in table 5

In September 1987, at least one VOC was detected in 10 of 11 wells sampled. Tetrachloroethylene, trichloroethylene, and chloroform were the most frequently detected VOC's, each compound being present in 7 of the 11 wells. Tetrachloroethylene was detected in the highest concentration (22 μg/L in well 4, and 19 μg/L in well 5). In the sample from well 7, the concentration of vinyl chloride was 2.4 μg/L; this concentration exceeds the drinking-water standard of 2.0 μg/L (U.S. Environmental Protection Agency, 1987b).

Table 4. – *Volatile organic compounds for which analyses were conducted on water samples from Jackson Utility Division wellfields*

Dichlorobromomethane	Carbon tetrachloride
1,2-Dichloroethane	Bromoform
Chlorodibromomethane	Chloroform
Toluene	Benzene
Chlorobenzene	Chloroethane
Ethylbenzene	Methyl bromide
Methyl chloride	Methylene chloride
Tetrachloroethylene	Trichlorofluoromethane
1,1-Dichloroethane	1,1-Dichloroethylene
1,1,1-Trichloroethane	1,1,2-Trichloroethane
1,1,2,2-Tetrachloroethane	1,2-Dichlorobenzene
1,2-Dichloropropane	1,2-trans-Dichloroethylene
1,3-Dichloropropane	1,3-Dichlorobenzene
1,4-Dichlorobenzene	2-Chloroethyl vinyl ether
Dichlorodifluoromethane	trans-1,3-Dichloropropene
cis-1,3-Dichloropropene	1,2-Dibromoethylene
Vinyl chloride	Trichloroethylene
Styrene	Xylenes

In addition to samples from individual wells, samples were collected after flow was composited at the South Treatment Plant. In these composite samples, the total concentration of VOC's declined as pumping time increased. The total VOC concentration was 7.3 μg/L after 10 minutes of pumping, but was only 0.4 μg/L after 2 hours of pumping. One possible explanation for this pattern is the presence of a diffuse local source of VOC contamination in one or more shallow stratigraphic horizons. As water levels declined locally during the pumping period, hydraulic connections with the source may have been severed. Additional sampling of water and geologic materials at well-defined depth intervals would be necessary to confirm or deny this hypothesis.

Sampling in October 1987, was limited to one sample from well 8 and to two samples of the composite flow. A total VOC concentration of 6.9 μg/L was measured in the untreated composite sample collected after 2 hours of pumping. No maximum contaminant levels for drinking water were exceeded.

Data from samples collected in November 1987 are similar to the September 1987 values (table 5). All 11 wells sampled in the South Wellfield contained detectable concentrations of VOC's. Again, tetrachloroethylene, trichloroethylene, and chloroform were the most frequently identified contaminants; the highest concentration of a single compound was 23 μg/L of tetrachloroethylene in well 4. The vinyl chloride concentration of 2.6 μg/L in well 7 exceeded the maximum contaminant level of 2.0 μg/L. The total VOC concentration in the untreated composite flow after 2 hours of pumping was 5.4 μg/L.

Also included in the November 1987 data were results of analyses on a composite sample from the North Wellfield. In this sample no VOC's were present in concentrations above the detection limit of 0.2 μg/L. In a sample collected after chlorination, however, the total concentration of trihalomethanes was 10.7 μg/L.

Sampling in December 1987 was limited to composite flow from the South Wellfield. After 2 hours of pumping, a total VOC concentration of 22 μg/L was detected in the untreated sample, with most of the contamination (17 μg/L) due to chloroform.

POTENTIAL SOURCES OF GROUND-WATER CONTAMINATION

Sites that represent potential sources of ground-water contamination in the study area were identified with the cooperation of State and local officials. These sites include hazardous-waste facilities, industrial and municipal landfills, underground storage tanks, and septic-tank systems.

Hazardous-Waste Sites

As of June 1986, the TDHE, Division of Superfund, had 263 entries on the State Superfund Eligibles List (Tennessee Department of Health and Environment, 1986). Only one of these entries is in the study area (fig. 5). Napthalene and pentachlorophenol have been detected in a monitoring well at this site (Tennessee Department of Health and Environment, 1986). This site is also the only location in the area that is licensed for the treatment, storage, or disposal of hazardous wastes under the Resource Conservation and Recovery Act (Tennessee Department of Health and Environment, Division of Solid Waste Management, written commun., 1986).

Table 5. — *Water-quality data for volatile organic compounds detected in samples*

[All analyses are in micrograms per liter (μg/L); detection limit is 0.2 μg/L for all
after 10 minutes of pumping; B = composite sample, raw water from South Wellfield after
minutes of pumping; D = composite sample, finished (treated) water from South Wellfield,
after 24 hours of pumping; F = composite sample, finished water from North Wellfield after

South Well-field number or sample identification (keyed to fig. 2)	Benzene	Carbon tetra-chloride	Chloro-dibromo methane	Chloro-form	Dichloro-bromo-methane	Bromo-form	1,2-Dichloro ethane
							September
2	0.2	ND	0.4	ND	ND	ND	ND
3	.2	ND	.3	ND	ND	ND	ND
4	ND	ND	ND	2.5	ND	ND	ND
5	.2	ND	ND	.5	ND	ND	ND
6	ND	ND	ND	.3	ND	ND	ND
7	1.4	ND	ND	ND	ND	ND	ND
9	ND	ND	ND	ND	ND	ND	ND
10	ND	ND	ND	.6	ND	ND	ND
11	ND	ND	ND	.8	ND	ND	ND
12	ND	ND	ND	.2	ND	ND	ND
13	ND	ND	ND	.3	ND	ND	ND
A	ND	ND	ND	.4	ND	ND	ND
B	.3	ND	ND	.3	ND	ND	ND
C	ND	ND	ND	ND	ND	ND	0.4
D	ND	ND	ND	.2	ND	ND	ND
							October
8	ND	ND	ND	ND	ND	ND	ND
C	.2	ND	ND	.9	ND	ND	ND
D	ND	ND	ND	.6	ND	ND	ND
							November
2	.3	ND	ND	.5	ND	ND	ND
3	ND	0.3	ND	ND	ND	ND	.7
4	ND	1.0	ND	2.1	ND	ND	.5
5	ND	ND	ND	.5	ND	ND	ND
6	ND	ND	ND	.2	ND	ND	ND
7	1.4	ND	ND	ND	ND	ND	ND
9	ND	ND	ND	ND	ND	ND	ND
10	ND	ND	ND	.5	ND	ND	ND
11	ND	ND	ND	.9	0.2	ND	.4
12	ND	ND	ND	ND	ND	ND	ND
13	ND	.2	ND	.3	ND	ND	ND
C	.2	ND	ND	.3	ND	ND	ND
D	ND	ND	ND	.2	ND	ND	ND
E	ND	ND	ND	ND	ND	ND	ND
F	ND	ND	2.9	4.0	2.9	0.9	ND
							December
C	.2	ND	ND	17	ND	ND	ND
D	ND	ND	ND	14	ND	ND	ND

substances; ND = not detected; A = composite sample, raw water from South Wellfield 60 minutes of pumping; C = composite sample, raw water from South Wellfield, after 120 after 120 minutes of pumping; E = composite sample, raw water from North Wellfield 24 hours of pumping]

1,2-trans Dichloro-ethylene	Dichloro-fluoro-ethane	Ethyl benzene	Methylene chloride	Tetra-chloro-ethylene	Toluene	Tri-chloro-ethylene	Vinyl Chloride	Xylenes
1987								
ND	ND	ND	ND	1.7	ND	ND	0.2	ND
ND	ND	ND	ND	4.6	ND	[0.5	.4	0.7
0.5	ND	ND	ND	22	ND	.4	ND	ND
.6	ND	ND	ND	19	ND	1.5	ND	ND
ND	ND	ND	ND	.2	ND	3.1	ND	ND
.4	ND	ND	ND	ND	ND	.4	2.4	ND
ND	ND	0.6	ND	ND	0.2	1.1	ND	2.9
ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	ND	ND	ND	2.8	ND	.3	ND	ND
ND	ND	ND	ND	7.1	ND	ND	ND	ND
ND	ND	ND	1.2	ND	ND	ND	ND	ND
ND	ND	ND	ND	5.3	ND	.8	ND	.8
.2	ND	ND	ND	4.0	ND	.5	.4	.6
ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	ND	ND	ND	ND	ND	ND	ND	ND
1987								
ND	1.0	ND	.8	.4	ND	.9	ND	ND
ND	ND	ND	ND	4.9	ND	.7	ND	.2
ND	ND	ND	ND	ND	ND	ND	ND	ND
1987								
ND	ND	ND	ND	2.0	ND	.2	.4	ND
ND	ND	ND	ND	ND	ND	ND	ND	ND
.6	ND	ND	ND	23	ND	.6	ND	ND
.5	ND	ND	ND	20	ND	1.6	.2	ND
ND	ND	ND	ND	.2	ND	3.3	ND	ND
.4	ND	ND	ND	ND	ND	.6	2.6	ND
ND	ND	ND	ND	.2	ND	ND	ND	ND
ND	ND	.2	ND	ND	ND	1.3	ND	1.1
ND	ND	ND	ND	3.6	ND	.5	ND	ND
ND	ND	ND	ND	7.3	ND	ND	ND	ND
ND	ND	ND	ND	1.6	ND	ND	ND	ND
ND	ND	ND	ND	4.3	ND	.6	ND	ND
ND	ND	ND	ND	.2	ND	ND	ND	ND
ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	ND	ND	ND	ND	ND	ND	ND	ND
1987								
ND	ND	ND	ND	4.5	ND	.5	ND	ND
ND	ND	ND	ND	.2	ND	ND	ND	ND

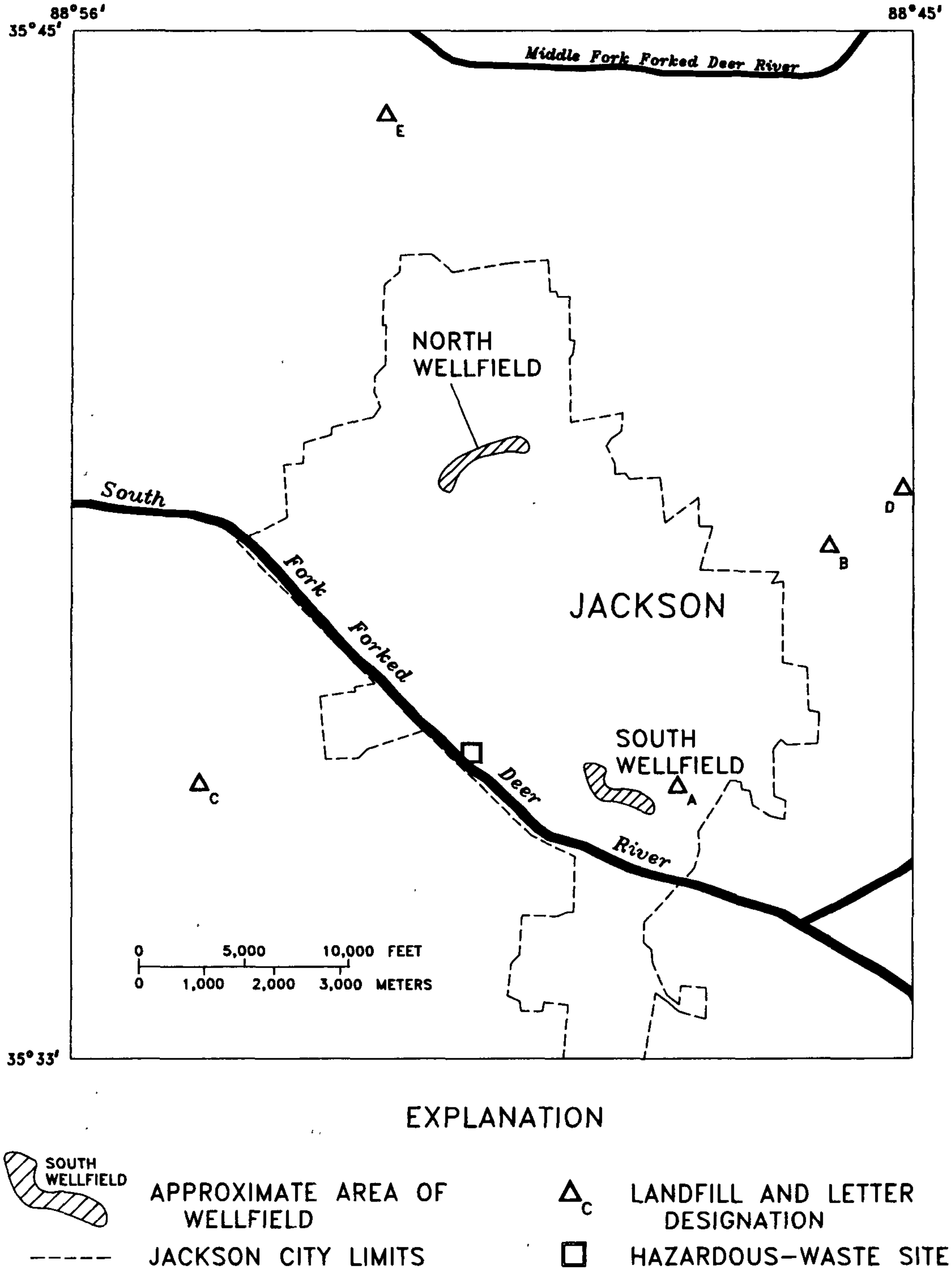


Figure 5.--Location of selected potential sources of ground-water contamination in the study area. (Information on location of landfill and hazardous waste sites from Tennessee Department of Health and Environment, 1986.)

Municipal and Industrial Landfills

Two municipal and three industrial landfills in the study area (table 6) have been licensed by the State (Tennessee Department of Health and Environment, Division of Solid Waste Management, written commun., 1986). From approximately 1950 to 1972, a municipal landfill was operated near the east edge of the South Wellfield (fig. 5, site A). Since 1972, municipal refuse has been deposited approximately 3 miles from the South Wellfield in a sanitary landfill along the eastern edge of a topographic divide (fig. 5, site B). An industrial landfill southwest of Jackson (fig. 5, site C) receives waste fiberglass, glass, and wastewater treatment sludge; the latter may contain chromium and wastewater solvents (Tennessee Department of Health and Environment, Division of Solid Waste Management, written commun., 1985). At another landfill (fig. 5, site D), wastes have included brick, tile, and wood scrap, as well as wastewater sludge. This sludge is rich in clay, aluminum hydroxide, and calcium sulfate. Concentrations of toxic metals extracted from the sludge have been below levels of concern (Tennessee Department of Health and Environment, Division of Solid Waste Management, written commun., 1986). In 1975, sludge from a sewage lagoon and up to 100 drums of varnish and solvents were buried near the Middle Fork Forked Deer River (fig. 5, site E). Trichloroethylene has been detected in ground water near the burial area (Tennessee Department of Health and Environment, Division of Solid Waste Management, written commun., 1986).

Underground Storage Tanks

An inventory of 56 underground storage tanks in the study area was compiled by the State (Leanne Tippett, Tennessee Department of Health and Environment, Division of Groundwater Protection, written commun., 1987). These tanks are used for storage of gasoline, fuel oil, and industrial solvents (fig. 6).

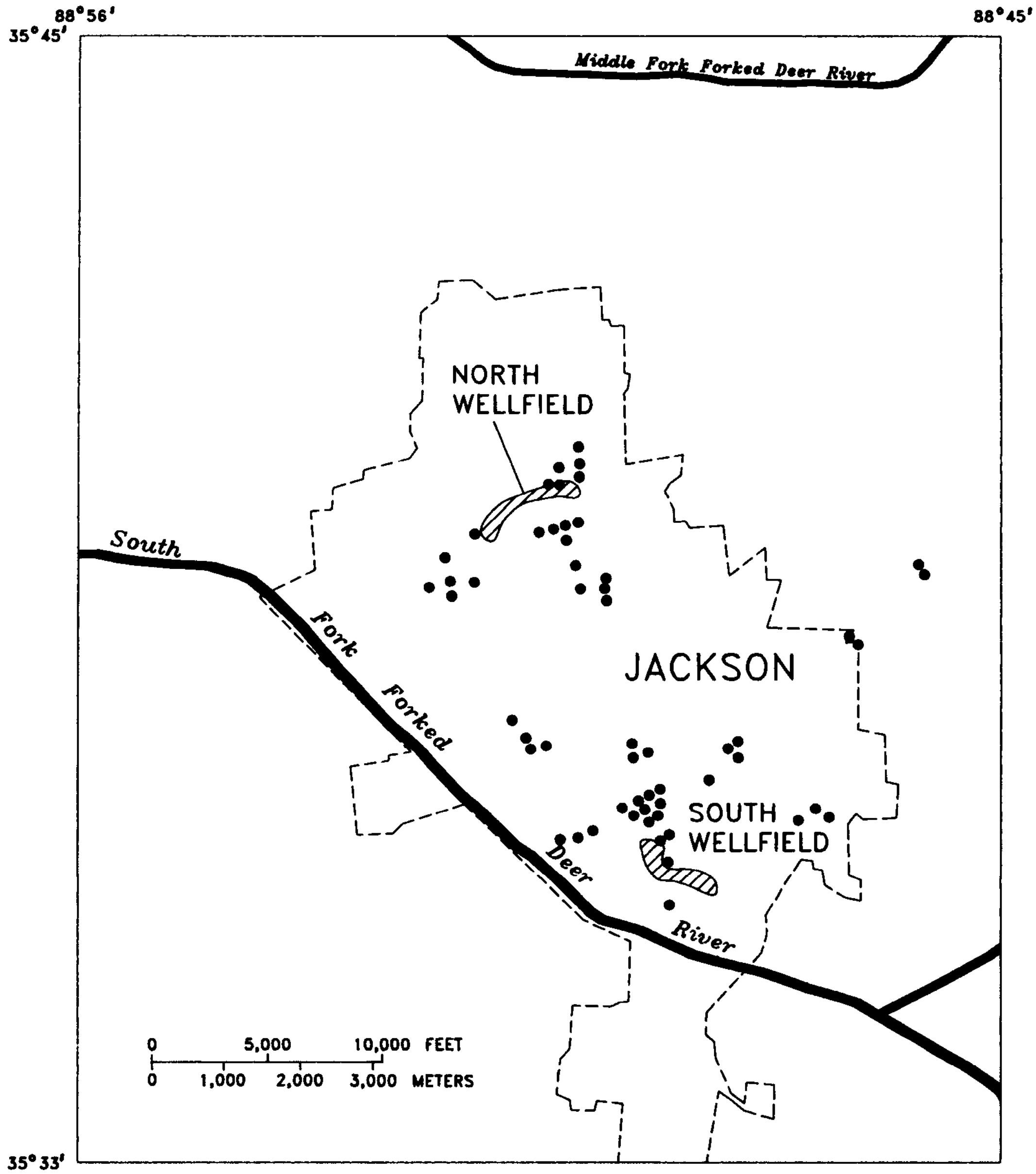
Septic-Tank Systems

No inventory of septic-tank systems in the study area was available (Brent Lewis, Madison County Health Department, oral commun., 1987). Septic-tank use is not extensive, however, because sewers have existed in the Jackson urban

Table 6.—*Municipal and industrial landfills in the Jackson area*

[Letters refer to symbols in figure 5]

Landfill	Type	Known wastes	Year(s) of operation
A	Municipal	Domestic and light industrial.	1950(?)-1972
B	Municipal	Domestic and light industrial.	1972-present
C	Industrial	Fiberglass; wastewater sludge possibly with chromium and solvents.	1979-present
D	Industrial	Scrap; alum sludge	1963-present
E	Industrial	Sewage lagoon sludge, varnish, solvents.	1975



EXPLANATION

APPROXIMATE AREA OF WELLFIELD

● UNDERGROUND–STORAGE TANK

----- JACKSON CITY LIMITS

Figure 6.--Location of underground-storage tanks in the study area. (Information on location of underground-storage tanks from Tennessee Department of Health and Environment, 1986.)

area since the nineteenth century. The area surrounding the North Wellfield was connected to the municipal wastewater treatment network before the wellfield was established.

DELINEATION OF AREAS CONTRIBUTING WATER TO WELLFIELDS

Areas around wellheads need to be protected from sources of contamination. The USEPA has published a set of guidelines to facilitate delineation of wellhead protection areas (U.S. Environmental Protection Agency, 1987a). The guidelines define operational goals for wellhead protection programs, conceptual criteria that address these goals, and techniques for applying the criteria to specific hydrogeologic situations.

Goals

The most comprehensive goal of a wellhead protection program is the complete prevention of sources of contamination within the entire area through which water may travel to a public-supply well. The entire recharge area is defined as the "zone of contribution" to the wellhead. Protecting the entire zone of contribution may not be feasible for technical or institutional reasons. A less stringent goal that could afford a reasonable degree of protection is the delineation of smaller buffer zones around wellheads. Buffer zones would be large enough to provide time and space for the natural attenuation of contaminant concentrations or time for remedial action by water managers.

Criteria

Delineation of wellhead protection areas to achieve a particular goal begins with a consideration of conceptual standards, or criteria, by which the goal can be reached. USEPA (1987a) has described five criteria that may be used:

1. Radial distance from the wellhead,
2. Thresholds of drawdown induced by pumping,
3. Average time of travel of ground water,
4. Flow boundaries, and
5. Assimilative capacity of the aquifer.

Methods applying these criteria differ widely in technical and nontechnical merit. Technical merit must be judged on the degree to which the method accounts for local processes controlling ground-water flow and contaminant transport within the flow system. Nontechnical factors include the time, expertise, institutional control measures, and other resources available to the program, as well as the relative costs of over-protection and under-protection of the aquifer.

Each of the five criteria and methods for their application are described below. A following section uses four of the criteria to delineate potential wellhead protection zones for the study area.

Distance

Perhaps the simplest criterion for the delineation of wellhead protection areas is radial distance from the center of pumping. In programs using this approach, distances have varied from 200 feet to 2 miles (USEPA, 1987a). Although drawing a circle around a wellhead is comparatively easy, determining an appropriate radius is not. Methods range from an arbitrary fixed radius to distances calculated on the basis of volumetric flow within specified time periods, flow balance between pumping and recharge, and drawdown thresholds. Although use of an arbitrary radius has no technical merit, calculations based on simplified hydrologic principles commonly suffer from unreasonable assumptions. For example, all methods based on a criterion of radial distance assume that flow is uniform from all directions. Flow resulting from natural gradients and the effects of spatial variability in hydraulic properties of the aquifer are not considered.

Drawdown

Drawdown induced by pumping steepens the hydraulic gradient surrounding a wellhead and thereby accelerates ground-water flow and contaminant migration toward the center of pumping. In some cases a wellhead protection area might be delineated by choosing a small threshold value for drawdown. Values chosen by various agencies have ranged from 0.05 to 1.0 foot (U.S. Environmental Protection Agency, 1987a).

There are three principal problems with using drawdown as a delineation criterion. First, in the absence of a well-calibrated ground-water flow model, drawdown usually is estimated by methods that do not account for spatially variable hydraulic properties. Second, the cone of depression caused by pumping does not correspond to the zone of contribution to the wellhead (Brown, 1963). For example, where there is a natural slope to the water table, areas naturally upgradient from a wellhead but outside its observable cone of depression eventually can contribute water to the wellhead. Conversely, areas naturally downgradient from the wellhead may experience drawdown due to pumping, but this drawdown may be insufficient to reverse the natural direction of flow away from the wellhead. Third, drawdown is not an independent predictor of ground-water travel time. For a given pumping rate, a highly transmissive aquifer may experience less drawdown yet faster ground-water velocities than a poorly transmissive formation.

Time of Travel

If wellhead protection areas are defined as buffer zones to permit adequate response times following episodes of contamination, ground-water travel time becomes a key consideration in their delineation. Use of time-of-travel criteria assumes that contaminants migrate no faster than the average ground-water velocity. The distributed nature of actual transport velocities is ignored. Due to dispersion, some contaminants may migrate faster than the average ground-water velocity; due to geochemical retardation and (or) degradation within the aquifer, other contaminants may migrate much slower, and their concentrations may become attentuated along the flow path. Thus time-of-travel criteria can lead to under-protection or over-protection of a ground-water resource.

Time-of-travel calculations are based on Darcy's law and can take into account both natural gradients and those induced by pumping. The technical merit of this approach is enhanced when the distribution of aquifer hydraulic properties and flow boundaries are considered. Methods of calculation vary from analytical techniques employing simplified flow equations to elaborate digital models simulating the flow system.

Flow Boundaries

The delineation of wellhead protection areas based on ground-water flow boundaries has obvious technical merit. By defining the entire aquifer surrounding a wellhead, the widest area that need be considered for protection can be mapped. Flow boundaries may exist as a consequence of natural hydrogeologic features, including ground-water flow divides, impermeable geologic materials, and surface-water reservoirs and drains. Pumping itself may create hydraulic boundaries, as the pumping-induced gradients are superimposed on the natural slope of the water table. Defining flow boundaries typically requires a more rigorous hydrogeologic investigation.

Assimilative Capacity

Wellhead protection areas might be managed to permit a limited discharge of contaminants into the ground-water system. Discharge limits would be determined on the basis of the capacity of the aquifer to assimilate contaminants to the degree that concentrations at the wellhead would not exceed thresholds of concern. Contaminant transport in ground water is a complex phenomenon that is controlled by the interplay of often poorly quantified physical, chemical, and biological processes. Understanding these processes has become a major goal of research efforts by academic, governmental, and private scientific teams around the world. Unfortunately, limitations on the state-of-the-science at this time render it infeasible to base wellhead protection programs on assimilative capacity for most contaminants. USEPA (1987a) did not identify any programs using this criterion.

Application to the Jackson Area

As described above, choice of criteria and methods for the delineation of wellhead protection areas must reflect a consideration of the hydrologic setting, available data and other resources, and nontechnical factors. This section documents calculations for the delineation of areas contributing water to the North Wellfield and South Wellfield of the JUD. The following methods of delineation were used:

1. Calculated fixed radius based on volumetric flow;

2. Calculated fixed radius based on a flow balance between pumping and recharge;

3. Calculated fixed radius based on simulated drawdown thresholds;

4. Flow boundaries and time of travel based on analytical techniques and ground-water divides.

For all four methods, pumping from each wellfield was represented as a single point withdrawal of ground water. Composite pumping rates are shown in table 7. The first three methods, which are based on radially symmetrical flow to the wellhead, do not account for radial asymmetry in the zone of contribution to each wellfield due to the natural slope of the water table. Although the fourth method incorporates more realistic hydrogeologic assumptions, values determined by this method are subject to errors in estimating the configuration of the unstressed water table, aquifer hydraulic properties, and the conceptualization of the wellfields as single point withdrawals.

All values used for aquifer properties and other hydrologic variables are shown in table 7.

Table 7.—*Hydrogeologic characteristics and water-use data for preliminary delineation of areas contributing water to wellfields in the Jackson area*

Variables and data	North Wellfield	South Wellfield
Hydraulic conductivity (ft/d)	80	80
Transmissivity (ft^2/d)	19,200	9,600
Aquifer thickness (ft)	240	120
Effective porosity	.2	.2
Recharge rate (ft/d)	.00274	.00274
Recharge rate (in/yr)	12	12
Hydraulic gradient	.0035	.0064
Pumping rate (ft^3/d)	1,056,000	200,500
Pumping rate (Mgal/d)	7.9	1.5

Justification for these estimated values and ranges was given in a previous section.

Volumetric Flow

A time-of-travel argument can be used in calculating a fixed radial distance for a wellhead protection area. This method assumes that flow is radially uniform, and that the entire saturated thickness of the aquifer contributes flow equally to the well. Under these conditions the volume of water withdrawn in a specified time can be equated with the volume of a cylinder with the well along its central axis (U.S. Environmental Protection Agency, 1987a, p. 4-9) (fig. 7):

$$Q\,t = \pi r^2 b\,n$$

where

Q = pumping rate, in cubic feet per day;
t = time of pumping, in days;
π = 3.1416;
r = radius of cylinder, in feet;
b = thickness of aquifer, in feet; and
n = porosity of aquifer.

This equation can be solved for the radius of the cylinder:

$$r = (Q\,t / \pi\, b\, n)^{1/2}$$

For the pumping rates, aquifer thicknesses, and porosity given in table 7, calculated fixed radii based on 5 years of pumping from each wellfield were:

North Wellfield	3,600 feet
South Wellfield	2,200 feet

Recharge Balance

A second method for calculating a fixed radius considers a flow balance between recharge and pumping. The rate at which water is pumped from a well is set equal to the product of the average recharge rate and a circular area through which that recharge might occur:

$$Q = \pi r^2 R$$

where

R = recharge, in feet per day;

and other symbols are as previously defined. This equation can be solved for the radius of the recharge area:

$$r = (Q / \pi R)^{1/2}$$

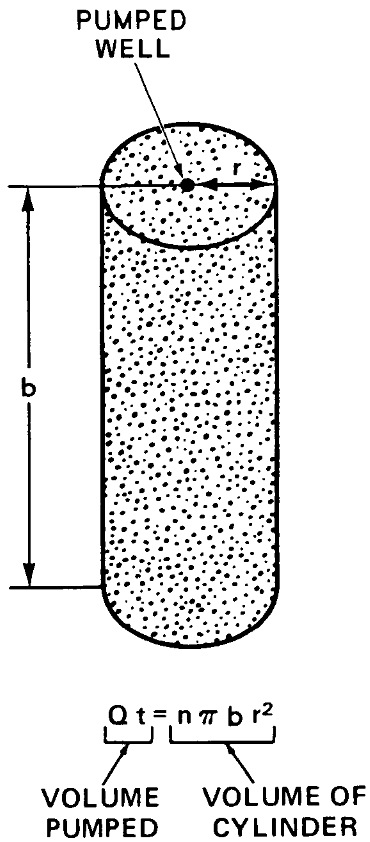
Given the data in table 7, the calculated fixed radii based on flow balances between recharge and pumping rates for the wellfields were:

North Wellfield	11,000 feet
South Wellfield	4,800 feet

Because recharge rates differ both seasonally and from year to year, the actual radius of the area required to balance recharge and pumping will vary with time. In most years the area will be greater during the drier summer and autumn months, and it will be smaller during the rest of the year. If this criterion is used, managers might profit from a consideration of radii that represent recurrence intervals of minimum recharge. For example, a wellhead protection effort might extend to boundaries representing an area required for recharge volume to equal pumping volume during a drought of a severity and duration expected to recur on average only once every 20 years.

Drawdown Threshold

A third method of delineation is based on thresholds of drawdown. Theis (1935) used an analogy with heat flow to develop a time-drawdown equation for the potentiometric



$$r = \sqrt{\frac{Q\,t}{\pi\, n\, b}}$$

WHERE
Q = Pumping Rate of Well
n = Aquifer Porosity
b = Aquifer Thickness
t = Travel Time to Well

(Any consistent system of units may be used.)

Figure 7.--Delineation of radical wellhead-protection areas using a volumetric balance between pumping and flow within an arbitrary time period. (Modified from U.S. Environmental Protection Agency, 1987a.)

surface surrounding a pumped well. The Theis equation is:

$$s = Q / (4 \pi T) (-0.577216 - \log(u) + u - u^2/2\,2! + u^3/3\,3! - u^4/4\,4! + ...)$$

where

s = drawdown in feet;
Q = pumping rate in cubic feet per day;
T = transmissivity, in feet squared per day;
u = $r^2 S / (4 T t)$;
r = radial distance from pumped well;
S = storage coefficient;
t = time since onset of pumping.

Use of the Theis equation assumes that transmissivity is constant, wells fully penetrate the aquifer, and water is withdrawn entirely from storage. These assumptions are never strictly met in unconfined aquifers. Nevertheless, the Theis equation closely approximates time-drawdown dynamics in unconfined situations where drawdown is small relative to saturated thickness. This condition often applies in a thick alluvial aquifer, particularly at distances well removed from the center of pumping and after pumping has continued for an extended period of time.

Contours for drawdowns of 0.05 and 1.0 foot were calculated for each wellfield using the Theis equation and the hydraulic properties in table 7. Times of pumping duration were 10, 30, 100, 300, and 1,000 days (table 8). Because the analysis assumes no recharge within the cone of depression, distances to the drawdown contours increase with time.

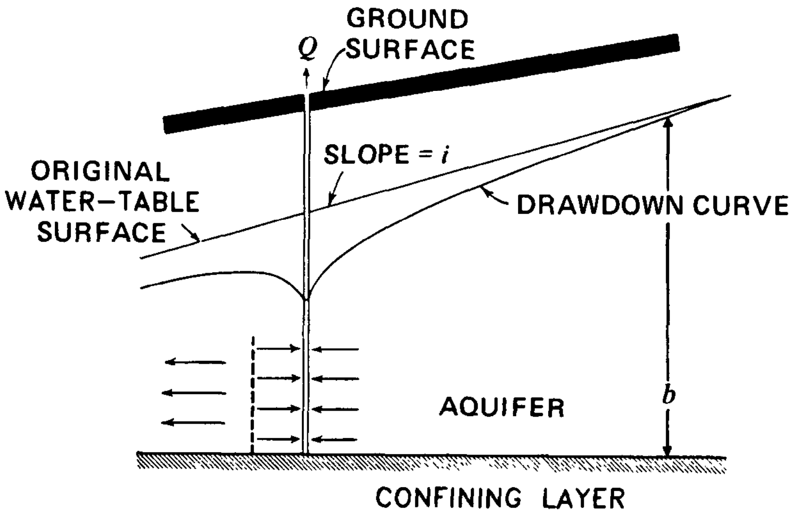
Flow and Time-of-Travel Boundaries

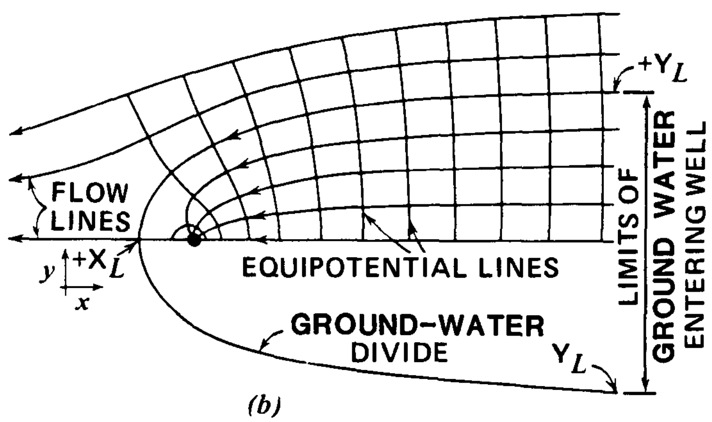
A fixed radius based on hydrologic calculations has technical merit in certain settings. However, the preceding methods are fully valid only when radial flow to the wellfield can be assumed. Due to the natural slope of the undisturbed water table, this situation does not exist in the Jackson area. Water flows naturally from potentiometric highs in the eastern central part of the study area to surface-water drains to the north and southwest. Pumping from the wellfields superimposes an additional gradient, which results in a flow field that is not radially symmetrical, as shown schematically in figure 8 for an assumed two-dimensional flow field. A more realistic three-dimensional flow field could be different.

Two noteworthy distances are labeled on the diagram in figure 8. The first is the distance to the downgradient null point. Because the gradient imposed by pumping diminishes with

Table 8.—*Calculated radial distances to drawdown contours after selected intervals of pumping from North and South Wellfields*

Duration of pumping, in days	Distance from South Wellfield to specified drawdown contour, in feet		Distance from North Wellfield to specified drawdown contour, in feet	
	1.0 foot	0.05 foot	1.0 foot	0.05 foot
10	950	2,100	1,900	3,400
30	1,600	3,700	3,400	6,000
100	3,000	6,700	6,100	11,000
300	5,200	12,000	11,000	19,000
1,000	9,500	21,000	19,000	35,000





$$-\frac{Y}{X} = \tan\left(\frac{2\pi Kbi}{Q} Y\right)$$

UNIFORM-FLOW EQUATION

$$X_L = -\frac{Q}{2\pi Kbi}$$

DISTANCE TO DOWN-GRADIENT NULL POINT

$$Y_L = \pm \frac{Q}{2Kbi}$$

BOUNDARY LIMIT as $X \rightarrow \infty$

EXPLANATION

● PUMPED WELL

Where:
Q = Well pumping rate
K = Hydraulic conductivity
b = Saturated thickness
i = Hydraulic gradient
π = 3.1416

Figure 8.—–Delineation of a bilaterally symmetrical wellhead–protection area using the uniform flow analytical model. (Modified from D.K. Todd, 1980.)

radial distance from the wellhead, at some point naturally downgradient from the wellhead, the pumping-induced gradient will be equal in magnitude and opposite in direction to the natural gradient. At this point the composite gradient is zero, and water is stagnant. The distance to this point can be calculated by setting the two gradients equal to each other. The gradient imposed by the well can be calculated by setting the pumping rate equal to ground-water flow through a cylinder of arbitrary radius:

$$Q = 2 \pi r b K I$$

where
I = hydraulic gradient imposed by pumping,

and other symbols are as previously defined. Use of this equation assumes that flow to the well is horizontal and radially uniform and that drawdown is negligible relative to aquifer thickness.

Equating the natural and pumping-induced gradients and solving for the distance to the downgradient null point, X:

$$I = Q / (2 \pi X b K) = i$$

$$X = Q / (2 \pi K b i)$$

where
i = gradient of the unstressed potentiometric surface.

For the pumping rates and other values of hydrogeologic variables listed in table 7, calculated distances to the downgradient null points for the wellhead areas were:

North Wellfield	2,500 feet
South Wellfield	520 feet

These distances are generally less than the radii calculated by previous methods. These calculations demonstrate that in this hydrogeologic setting, use of fixed-radius criteria will tend to over-predict contributions of flow from areas naturally downgradient from the wellfields.

The second noteworthy distance in figure 8 is the asymptotic width (W, or 2Y) of the flow field. At this width, flow attributable to the natural gradient equals the pumping rate:

$$Q = 2 Y b K i$$

where
Y = half of the asymptotic width.

The asymptotic width, W, of the zone of contribution can be calculated as:

$$W = 2Y = Q / K b i$$

Using the values in table 7, the asymptotic widths of the zones of contribution to the wellheads were calculated as:

North Wellfield	16,000 feet
South Wellfield	3,300 feet

These calculations demonstrate that in this hydrogeologic setting a much wider zone contributes recharge to the wellheads at locations naturally upgradient from the centers of pumping. Accordingly, use of fixed-radius criteria will tend to underestimate flow contributions from areas naturally upgradient from the wellfields.

This analytical approach has more technical merit than previous calculations of fixed radii because it accounts for both pumping-induced flow boundaries and the natural slope of the undisturbed water table. Natural flow boundaries may be used to delineate the upgradient extent of each wellhead protection area. In the most conservative approach, the protective effort would extend to the ground-water divide. Alternatively, time-of-travel criteria could be invoked. For flow toward a well under natural and pumping-induced gradients, average ground-water travel time can be calculated as (U.S. Environmental Protection Agency, 1987a, p. 4-12):

$$t = [n/(Ki)] [r + Z \ln(Z/(Z+r))]$$

where

$$Z = Q/(2\pi K b i)$$

The distance, r, to any specified time-of-travel contour can be calculated using an iterative algorithm. Along the axis of symmetry of the zone of contribution, distances to the 5-year time-of-travel contours for the two wellfields were calculated as:

North Wellfield	5,400 feet
South Wellfield	6,000 feet

It is noted that these distances are considerably longer than those calculated for the 5-year time-of-travel based on assumptions of radial flow to each wellhead. These calculations demonstrate that fixed-distance approaches can underestimate ground-water travel times from areas naturally upgradient from a wellhead.

Comparable distances to the 10-year time-of-travel contours were calculated as:

North Wellfield	8,900 feet
South Wellfield	11,000 feet

A conservative ground-water protection strategy would provide for spatially extreme centroids of pumpage from each wellfield. To this end, zones of contribution and time-of-travel contours were mapped based on several possible centroids of pumpage. For example, the zone of contribution and 5-year time-of-travel contour if 7.9 Mgal/d were withdrawn from wells 1, 2, and 3 in the North Wellfield (fig. 2) are shown in figure 9. Similar boundaries for a centroid of pumpage near wells 5, 6, and 7 in the North Wellfield are shown in figure 10. Also shown in figure 11 are zones of contribution and time-of-travel contours for the South Wellfield. These latter boundaries reflect pumpage of 1.5 Mgal/d from single wells located at the geographic extremes of the Wellfield. Composite zones of protection reflecting the areas of overlap for all scenarios of pumpage are shown in figure 11.

DESIGN FOR FUTURE STUDIES

The delineation of areas contributing ground water to wellfields is provisional because of uncertainties regarding conceptualization of the hydrogeologic system, representation of composite pumping, and estimates of hydrologic variables. An improved estimate of the zone of contribution to each wellfield and ground-water travel times within these zones could be developed from the results of a digital flow model of the study area. Such a model could account for the location and rate of withdrawal of individual wells, including any future changes in these values. The spatial variability in aquifer hydraulic properties and other hydrologic and geologic variables, including fluctuations in recharge rates, could also be taken into account.

Development of a reliable digital flow model requires a more rigorous understanding of the aquifer system. This effort would involve:

1. Collection of reliable water-level data from carefully-selected existing wells under constant hydrologic conditions to improve definition of the current potentiometric surface;
2. Investigation of base flow of streams draining the area to better define the water budget of the upper aquifer;
3. Survey of the area using surface geophysics to estimate stratigraphy and lithology;
4. Drilling at strategic locations to confirm stratigraphy, lithology, and water-table altitude by geologic logging, borehole geophysics, and water-level measurements;

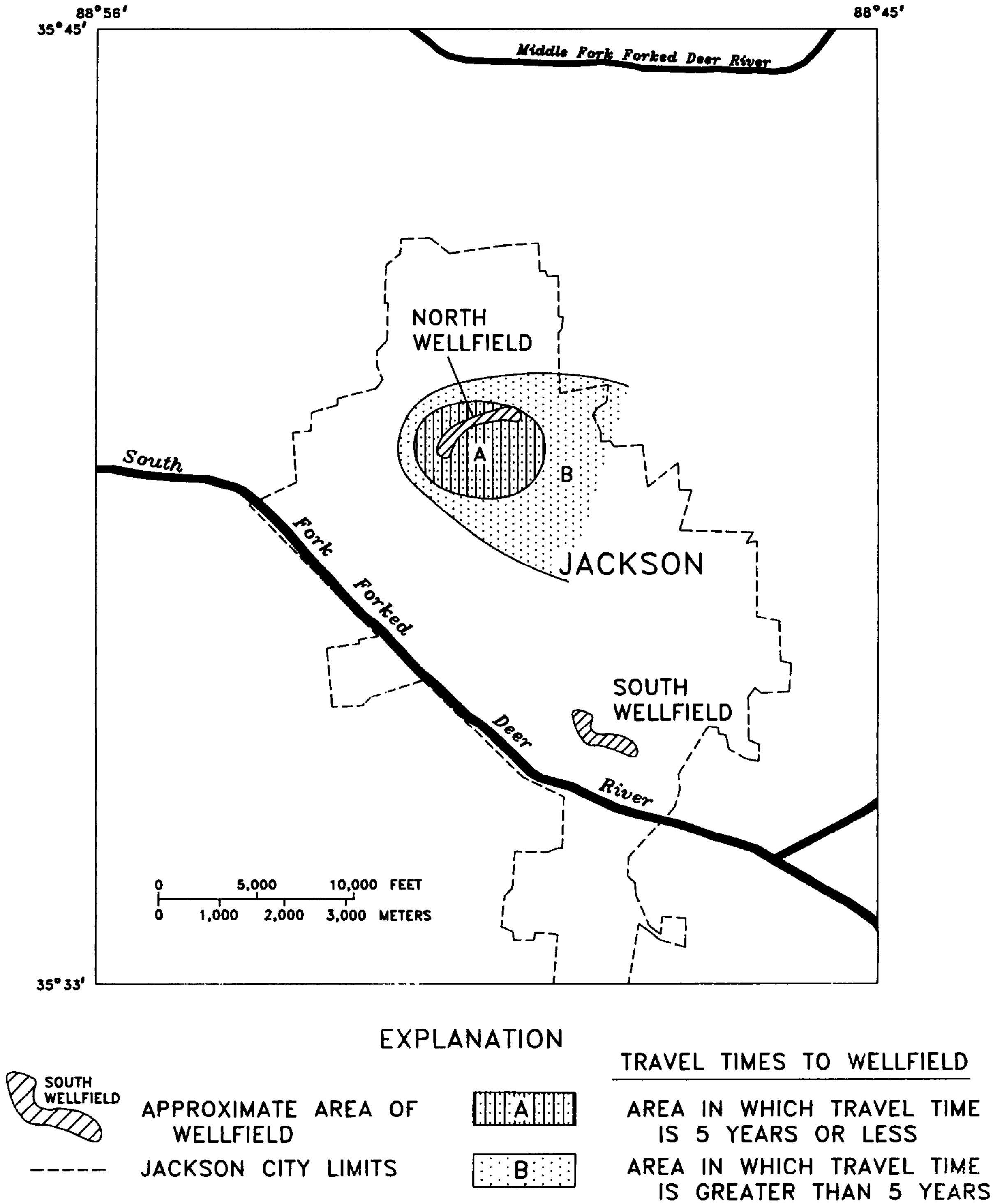


Figure 9.--Area contributing water to North Wellfield based on the uniform flow analytical model and all pumpage from wells 1, 2, and 3.

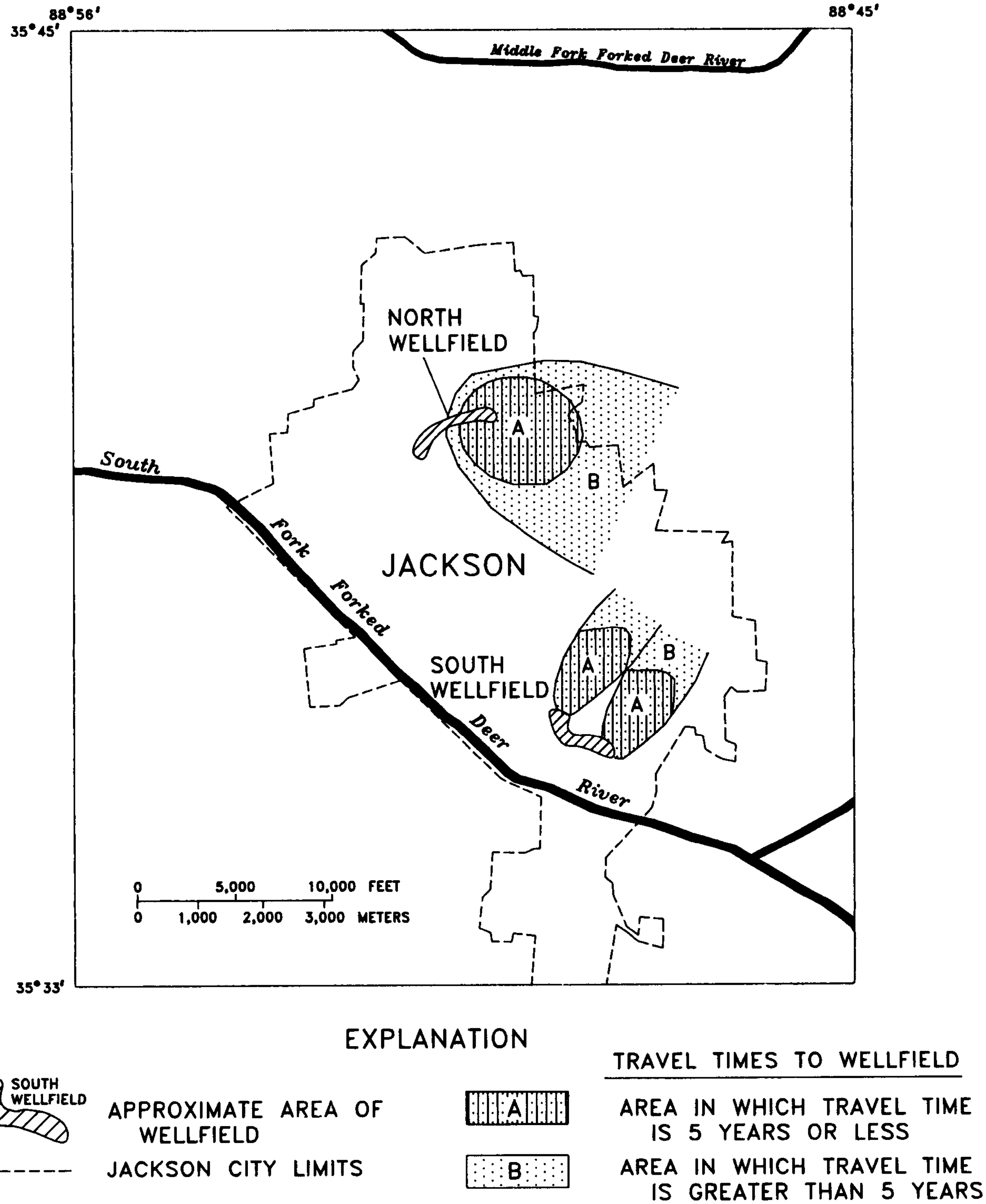


Figure 10.—Areas contributing water to North and South Wellfields based on the uniform flow analytical model and spatially extreme patterns of pumpage.

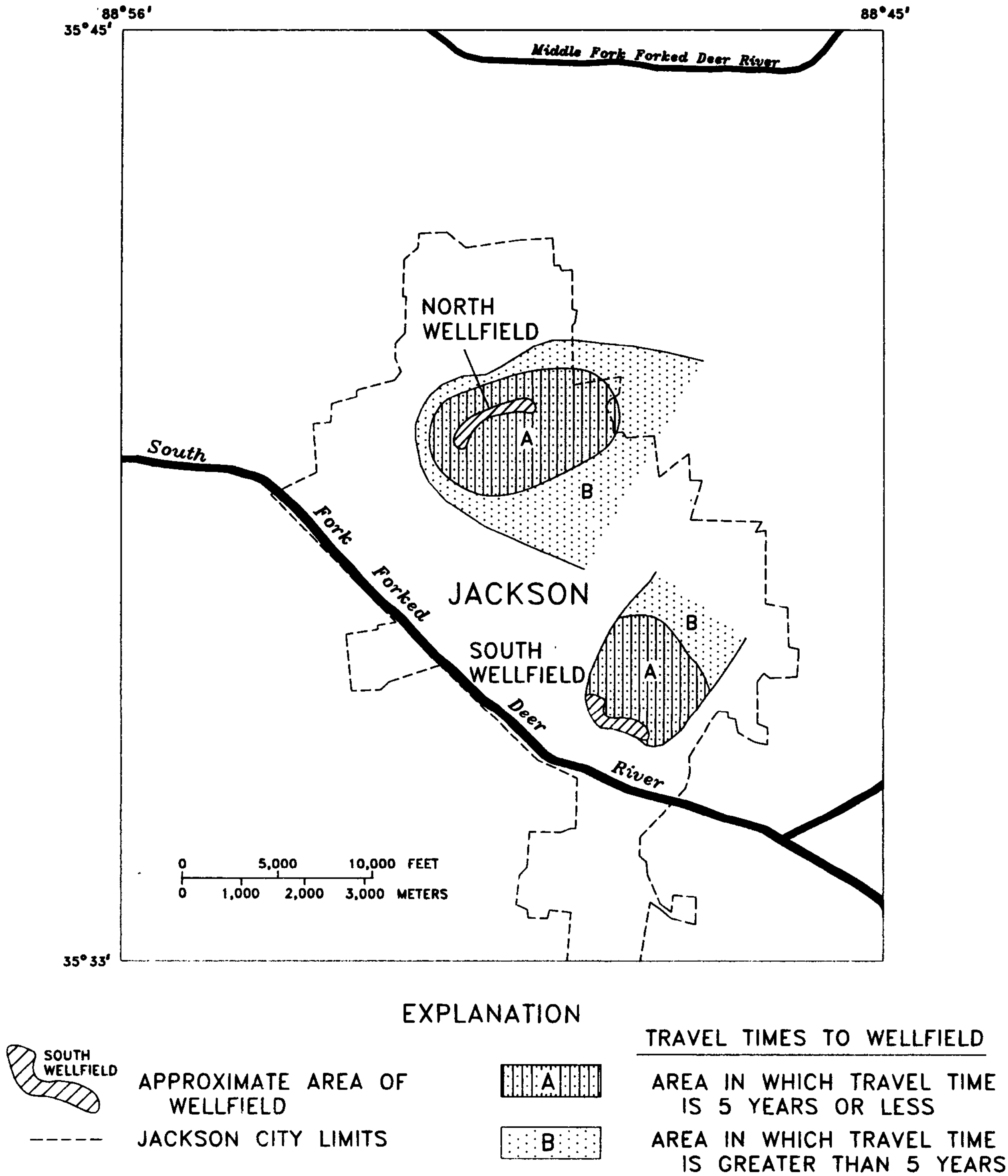


Figure 11.--Areas contributing water to North and South Wellfields based on the uniform flow analytical model and composite of all possible patterns of pumpage.

5. Installation of wells for the performance of aquifer tests to better quantify aquifer hydraulic properties and for long-term monitoring of water levels;

6. Collection of water-quality data to gain insight into chemical changes along flow paths and to detect early signs of contamination.

Additional water-quality data are needed, especially in areas near potential sources of contamination to the aquifer. Soil gases near underground-storage tanks in the potential recharge areas for each wellfield could also be analyzed to detect leakage of volatile organic compounds before extensive ground-water contamination occurs.

Management of a wellhead protection area requires integration of hydrogeologic principles and data with geographic and cultural information. Development of a geographic information system (GIS) for the study area would aid decision makers in planning for the protection of ground-water resources. This computerized data-management system would provide central storage and retrieval for all data relevant to the management of wellhead protection areas.

SUMMARY AND CONCLUSIONS

About 9 million gallons per day of ground water is pumped from two municipal wellfields tapping an unconfined sand aquifer in Jackson, Tennessee. The quality of this ground water is generally suitable for all uses, and present treatment methods have provided for compliance with drinking-water regulations. Potential sources of contamination exist, however, within areas calculated to provide recharge to the utility's wellfields. These potential sources of contamination include waste-disposal sites, underground-storage tanks, and potential spills of hazardous materials.

In 1987, the U.S. Geological Survey, in cooperation with the Tennessee Department of Health and Environment and the Jackson Utility Division, conducted a pilot study to assess and demonstrate the application of four methods for delineating wellhead protection areas around two wellfields in Jackson, Tennessee. Included were three methods for calculating a fixed radius based on (1) a volume of water pumped during a specified period, (2) a balance between pumping rate and recharge rate, and (3) a specified drawdown in water levels in the aquifer. The fourth method was an analytical approach that accounted for pumping-induced flow boundaries and time-of-travel for areas upgradient of the wellfields. Compared with the results of fixed-radius methods, the latter approach attributed greater contributions of recharge to areas naturally upgradient from the wellfields.

Although the fourth method incorporated more realistic hydrogeologic assumptions and was the only method that accounted for the natural slope of the water table, all four methods are subject to estimating errors because of uncertainties in assumptions about aquifer characteristics and conceptualization of the flow system. An improved estimate of the zone of contribution to each wellfield and ground-water travel times within these zones could be developed from the results of a digital flow model of the study area. Additional water-quality data are needed, especially in areas near potential sources of ground-water contamination. Development of a geographic information system (GIS) would aid decision makers in planning for the protection of ground-water resources.

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