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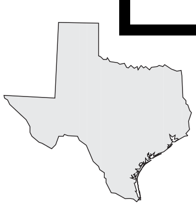
U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 96–4018



Prepared in cooperation with the
HARRIS-GALVESTON COASTAL SUBSIDENCE DISTRICT

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1996

U.S. DEPARTMENT OF THE INTERIOR

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U.S. GEOLOGICAL SURVEY

Gordon P. Eaton, Director

For additional information write to:

District Chief
U.S. Geological Survey
8011 Cameron Rd.
Austin, TX 78754–3898

Copies of this report can be purchased from:

U.S. Geological Survey
Branch of Information Services
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(Plate is in pocket)

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Abbreviations:

ft, foot
ft^2/d, square foot per day
ft/s, foot per second
in/yr, inch per year
mi^2, square mile
Mgal/d, million gallons per day
pCi/L, picocurie per liter
TU, tritium unit

Estimated Depth to the Water Table and Estimated Rate of Recharge in Outcrops of the Chicot and Evangeline Aquifers near Houston, Texas

By J.E. Noble, P.W. Bush, M.C. Kasmarek, *and* D.L. Barbie

Abstract

In 1989, the U.S. Geological Survey, in cooperation with the Harris-Galveston Coastal Subsidence District, began a field study to determine the depth to the water table and to estimate the rate of recharge in outcrops of the Chicot and Evangeline aquifers near Houston, Texas. The study area comprises about 2,000 square miles of outcrops of the Chicot and Evangeline aquifers in northwest Harris County, Montgomery County, and southern Walker County. Because of the scarcity of measurable water-table wells, depth to the water table below land surface was estimated using a surface geophysical technique, seismic refraction. The water table in the study area generally ranges from about 10 to 30 feet below land surface and typically is deeper in areas of relatively high land-surface altitude than in areas of relatively low land-surface altitude. The water table has demonstrated no long-term trends since ground-water development began, with the probable exception of the water table in the Katy area: There the water table is more than 75 feet deep, probably due to ground-water pumpage from deeper zones. An estimated rate of recharge in the aquifer outcrops was computed using the interface method in which environmental tritium is a ground-water tracer. The estimated average total recharge rate in the study area is 6 inches per year. This rate is an upper bound on the average recharge rate during the 37 years 1953–90 because it is based on the deepest penetration (about 80 feet) of postnuclear-testing tritium concentrations. The rate, which represents one of several components of a complex regional hydrologic budget, is considered reasonable but is not definitive because of uncertainty regarding the assumptions and parameters used in its computation.

INTRODUCTION

Knowledge of the rate of recharge to the Chicot and Evangeline aquifers in the Houston, Texas, area is important to local, State, and Federal agencies. The aquifers provide much of the water supply for all uses in the Houston region. Knowledge of the rate of recharge is a key part of understanding the sources of water that sustain pumpage.

Ground-water resources and development of the Chicot and Evangeline aquifers in Harris and Montgomery Counties have been studied since about 1930. At least five ground-water-flow models have been constructed to analyze the flow system in the Houston region (Wood and Gabrysch, 1965; Jorgensen, 1975; Meyer and Carr, 1979; Carr and others, 1985; and Ryder and Ardis, 1991). Results of the model studies indicate that large regional cones of depression have developed in the potentiometric surfaces of the hydrogeologic units pumped, and that recharge to the Chicot and Evangeline aquifers to sustain the pumpage is occurring. Numerous other studies also document water-level declines in the units pumped, for example, Gabrysch and Coplin (1990); Kasmarek and others (1995). However, study of any measurable effects of pumping stresses on water-table altitudes in the outcrop areas of the Chicot and Evangeline aquifers has been outside the scope of the previous studies.

In 1989, the U.S. Geological Survey (USGS), in cooperation with the Harris-Galveston Coastal Subsidence District, began a field study to determine the depth to the water table (uppermost boundary of the saturated zone) and to estimate the rate of recharge in outcrops of the Chicot and Evangeline aquifers, as independent support or confirmation of results obtained from model studies. The study area comprises about 2,000 mi^2 of outcrops of the Chicot and Evangeline aquifers in northwest Harris County, Montgomery County, and southern Walker County (fig. 1).

Purpose and Scope

The purpose of this report is to present estimated depths to the water table in the study area and an estimated rate of recharge in the outcrops of the Chicot and Evangeline aquifers. Depth to the water table below land surface was estimated using a surface geophysical technique called seismic refraction. Seismic surveys were done at 280 sites in the study area to provide point data from which a map showing estimated depth to the water table was constructed. Change in the depth to the water table from historical depths is discussed. An estimated rate of recharge in the aquifer outcrops was computed using environmental tritium as a ground-water tracer. Tritium concentrations in samples from 41 wells distributed throughout the study area and reflecting a wide range of depths provide the basis for the recharge-rate computation. The estimated recharge rate is discussed in light of the assumptions necessary to compute it, in comparison to rates obtained using other methods, and in the context of a regional hydrologic budget.

Geology and Hydrogeology

The stratigraphy of the study area (fig. 2) results from a series of discontinuous, regressive depositional episodes separated by the deposition of alternating, transgressive marine shales. These episodes created depositional systems that control the direction and rate of present-day recharge to the sedimentary units. Each system is identified by a characteristic lithology, geometry, and orientation. The principal depositional system in the study area consists of fluvial braided to meanderbelt facies interspersed with interfluvial-interdeltaic floodbasin facies. Solis (1981) reports that the braided stream deposits grade downdip into wider, meanderbelt point-bar sands that interconnect and develop thick sand accumulations in association with faulting. Regionally, these sands are vertical pathways for recharge to deeper stratigraphic units. The floodbasin facies consist of overbank clays, shales, and silts deposited between the meanderbelts. Both the fluvial facies and the floodbasin facies have been reworked by periodic transgressive events, obscuring the distinction between them.

The Chicot aquifer and underlying Evangeline aquifer consist of Cenozoic deposits of gravel, sand, silt, and clay. The Chicot aquifer is composed of Holocene alluvium; the Holocene/Late Pleistocene Deweyville Formation; and the Pleistocene Beaumont Clay, Lissie Formation, fluviatile terrace deposits, and Willis Sand. The Evangeline aquifer is composed of the Pliocene Goliad Sand and the upper part of the Miocene Fleming Formation. The Evangeline aquifer overlies the Burkeville confining unit and the Jasper aquifer, both part of the Fleming Formation. Regionally, these sediments crop out in subparallel belts that strike southwest-to-northeast across the study area and thicken downdip to the southeast. Although the principal unit of the Evangeline aquifer, the Goliad Sand, does not crop out in the study area, outcrops of the other sedimentary units of the Chicot and Evangeline aquifers comprise the recharge areas, as delineated by Gabrysch (1977) (fig. 1). The saturated zone in the outcrop areas is characterized by unconfined conditions; whereas confined conditions, controlled by the surficial Beaumont Clay, prevail in downdip areas adjacent to the study area.

Hydraulic properties of the Chicot aquifer do not differ appreciably from those of the Evangeline aquifer. Meyer and Carr (1979) used aquifer-test data to estimate that transmissivity in the Chicot aquifer ranges from about 3,000 to 25,000 ft^2/d; and in the Evangeline aquifer, from about 3,000 to 15,000 ft^2/d. Although the Evangeline aquifer generally has lower horizontal hydraulic conductivity than the Chicot aquifer, the Evangeline aquifer usually is more transmissive because of its greater average thickness (Meyer and Carr, 1979, p. 12).

Acknowledgments

The USGS acknowledges assistance in the study by personnel from Harris, Montgomery, and Walker Counties; the Texas Department of Transportation; North Harris Community College of Tomball; Friendswood Development Corporation; and the U.S. Forest Service.

ESTIMATED DEPTH TO THE WATER TABLE

Typically, maps showing depth below land surface or altitude above sea level of an aquifer's water table or potentiometric surface are constructed from water-level measurements in wells open to the aquifer.

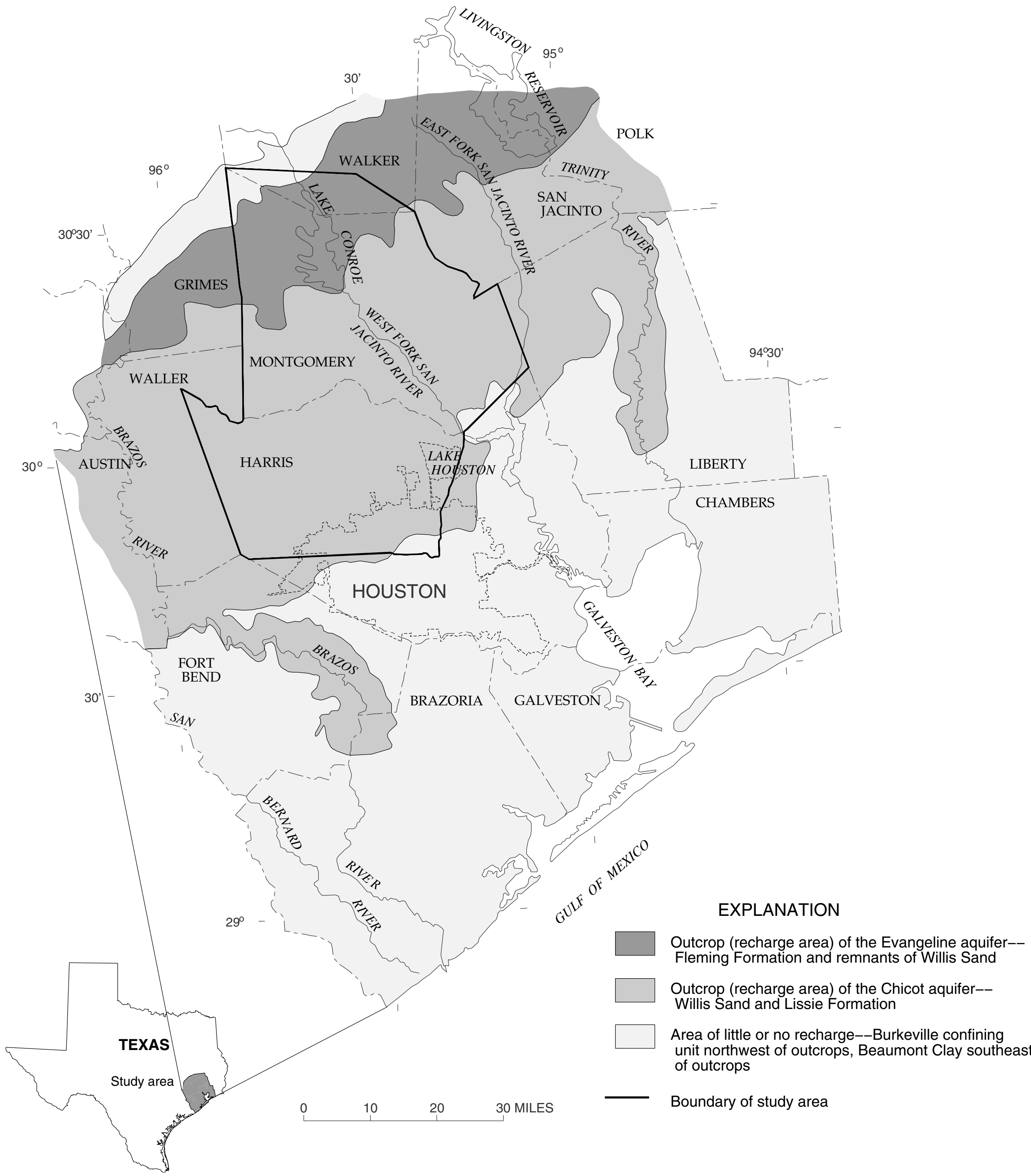

Figure 1. Location of study area and outcrops of the Chicot and Evangeline aquifers near Houston, Texas.

Geologic units				Hydrogeologic units
System	Series	Stratigraphic unit		Aquifer and confining units
Quaternary	Holocene	Alluvium		Chicot aquifer
		Deweyville Formation		
	Pleistocene	Fluviatile terrace deposits, undivided ?	Beaumont Clay	
			Lissie Formation	
		Willis Sand		
Tertiary	Pliocene	Goliad Sand		Evangeline aquifer
	Miocene	Fleming Formation		
				Burkeville confining unit
				Jasper aquifer

Figure 2. Correlation chart showing geologic and hydrogeologic units in the study area near Houston, Texas. (Modified from the University of Texas, Bureau of Economic Geology, 1968, 1982; Baker, 1979.)

Water-level data have been collected by the USGS from numerous observation and water-supply wells in the Chicot and Evangeline aquifers for several decades. However, very few of the wells for which data are available are shallow wells accessible for water-level measurement that tap only the uppermost part of the regionally continuous saturated zone. Because of this lack of necessary water-level data in the study area, an indirect method of computing the depth below land surface of the water table at selected sites, the seismic-refraction method, was used to obtain sufficient data from which to construct a map showing depth to the water table.

Seismic-Refraction Method and Field Application

The use of the seismic-refraction method to estimate depth to the water table is a recognized surface geophysical technique (Zohdy and others, 1974, p. 80). The method takes advantage of the fact that compressional sound-wave velocities in unconsolidated or semiconsolidated clastic rocks increase abruptly at the water table. For example, sound-wave velocities in unsaturated, unconsolidated sands and gravels range from 400 to 600 ft/s; at the water table, the velocity range increases by a factor of 10 to 4,000 to 6,000 ft/s (Haeni, 1988, p. 22).

The method, the details and assumptions of which are described by Haeni (1988), involves measuring the time required for compressional sound waves to travel down through the Earth's layers (unsaturated zone and near-surface saturated zone in this application) and return to an array of detectors (geophones) located on the land surface. As shown in figure 3a, the geophones closest to the sound source record arrival times of sound waves that have traveled directly through the unsaturated zone; whereas the geophones beyond a specific distance from the sound source (the crossover distance) record arrival times of refracted waves that have traveled through the unsaturated zone, along the water table, and back up to the surface. This phenomenon follows the laws of physics that govern the propagation of sound (Haeni, 1988, p. 3). The wave arrival times can be graphed as a function of the source-to-geophone distances, which yields a time-distance curve (fig. 3b). The slope of the time-distance curve changes at the crossover distance. The slope of the first segment of the curve is the inverse of the velocity in the unsaturated zone (velocity equals distance divided by time), and the slope of the second segment of the curve is the inverse of the velocity in the saturated zone. The crossover distance is a function of the velocities in both zones and the thickness of the unsaturated zone (depth below land surface to the water table). The depth to the water table can be computed from the equation

$$z = \frac{x}{2}\sqrt{\frac{v_2 - v_1}{v_2 + v_1}}, \qquad (1)$$

where

z = depth below land surface to the water table,

x = crossover distance,

v_1 = velocity of sound in the unsaturated zone, and

v_2 = velocity of sound in the saturated zone (Dobrin, 1976, *in* Haeni, 1988, p. 4).

Seismic-refraction surveys were done at 280 sites in the study area. Data were collected using a 12-channel seismograph, a straight-line array of 12 geophones, and, as a sound source, an 8-gage black-powder shotgun shell detonated remotely in a water-filled auger hole. The distance from the sound source to the first geophone was 5 ft, and the spacing between the geophones ranged from 1 to 50 ft. Reliable data (arrival times of compressional sound waves at the geophones) were obtained to depths of about 75 ft.

Water-Table Depth from Seismic Refraction

A depth to the water table at each of the 280 sites was computed using a USGS computer program for seismic interpretation, SIPT (Scott, 1977). SIPT computes the sound-wave velocities and the crossover distance from the recorded seismograph data and solves equation 1 to obtain depth to the water table.

To confirm that depths to the water table computed from the seismic-refraction data accurately estimate actual depths to the water table, water-table depths computed from seismic-refraction data at 14 sites were compared to actual water-table depths measured in shallow wells at the sites (table 1). The 14 seismic-verification sites were selected to coincide with known water-well sites.

At 9 of the 14 seismic-verification sites, the difference between the seismic-computed and measured water-table depths averaged less than 2 ft (table 1). At the remaining sites, however, seismic-computed depths are appreciably shallower than measured water levels. The seismic-refraction method yields depth to the top

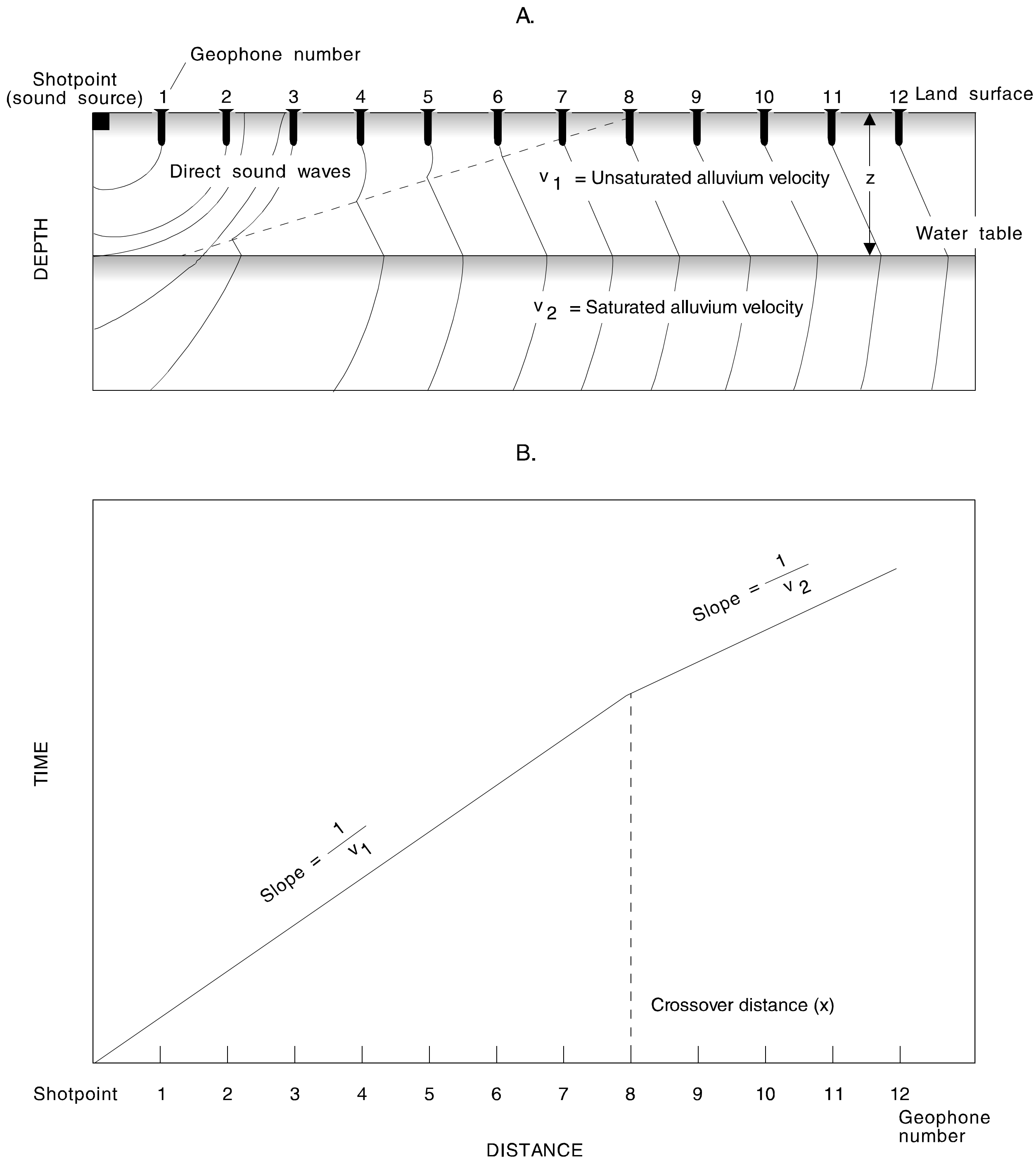

Figure 3. Diagrams showing (A) sound-wave propagation in unsaturated and saturated zones and detection at land surface, and (B) the corresponding time-distance curve. (Modified from Haeni, 1988, fig. 2.)

Table 1. Measured and seismic-computed water-table depths at seismic-verification sites near Houston, Texas

Seismic-verification site no. (pl. 1)	State well no. or local name	Screened interval or depth below land surface (feet)	Measured water level below land surface (feet)	Seismic-computed water level below land surface (feet)
1	LJ–65–12–303	49–55	11.5	10
2	Bath Road.sv	Reported shallow	[1]30	30
3	LJ–65–02–313	138–148	70.9	69
4	TS–60–45–414	70–80	53.6	17
5	YU–60–28–802	171–181	75.7	70
6	TS–60–38–805	19	11.4	8
7	Peach Creek.sv	28–40	11.5	12
8	TS–60–37–309	51–61	20.8	21
9	LJ–65–13–839	51–53	20.9	8
10	LJ–65–02–311	27–30	24.9	6
11	Fairfield.sv	40	18.2	18
12	Boudreaux Road.sv	56	37.8	19
13	TS–60–37–602	36	20.2	22
14	Caney Creek.sv	40	30.6	12

[1]Reported water level.

of the uppermost saturated zone. Where appreciable differences occur, a possible explanation is that seismic refraction has detected the top of a zone of perched water (ground water above and separated from the regionally continuous body of ground water by an unsaturated zone) rather than the regionally continuous water table. Another possible explanation is that the well is open to zones substantially deeper than the water table, the hydraulic heads (water levels) of which are lower than the water table.

Topographic maps were used extensively in construction of contours depicting depth to the water table (pl. 1), as the water table was assumed to be a subdued replica of the land surface. The results of comparisons of water levels from seismic-verification sites influenced the construction of contours: Care was taken to ensure that the depths determined from seismic refraction represent depths to the regionally continuous water table rather than depths to perched zones of saturation. Where depths appeared anomalously small, a judgment was made whether to retain or delete depths in question. Because the data-culling process is subjective, undoubtedly some depths that represent potential perched zones of saturation remained in the data base as the contours were constructed. Nevertheless, in most places the configuration of the map is believed to reflect the depth to the water table.

Sites where data indicate water-table depth greater than about 75 ft were not contoured. The seismic-refraction method as applied in the study area is not reliable for detecting water tables deeper than about 75 ft.

The map of plate 1 (based on a subset of the original 280 seismic-survey sites; sites with seismic-refraction depths believed to represent perched zones of water were omitted) shows that the water table in the study area generally ranges from about 10 to 30 ft below land surface. Although not shown on the map, the depth to water typically is deeper in areas of relatively high land-surface altitude than in areas of relatively low land-surface altitude. This general relation between topographic relief and water-table altitude is associated with local flow systems, as originally described by Tóth (1963). Generally, recharge occurs in topographically high areas, and some fraction of the recharge (that which does not flow vertically downward to deeper aquifer zones) discharges in adjacent topographically low areas, such as those occupied by streams.

An exception to the regional generalization about the relation between topographic relief and water-table altitude is in the southwestern part of the study area near Katy, where the water table is deeper than 75 ft below land surface. A probable explanation for the relatively deep water table near Katy is that pumpage from deeper zones in the aquifers in the Houston region (about 320 Mgal/d in 1994 [Harris-Galveston Coastal Subsidence District, written commun.,1995]) has induced recharge in the area, which in turn has lowered the water table from its original altitude. The latest comprehensive regional ground-water-flow model that includes the Houston region is the source of this explanation. A map of simulated induced recharge or reduced discharge in outcrop areas of the aquifers caused by pumpage (Ryder and Ardis, 1991, fig. 39) shows part of the area of greatest increase in recharge in the Houston region (3 to 4 in/yr) coincident with the southwestern part of the study area where the water table is deeper than 75 ft.

With the probable exception of the water table in the Katy area, the water table has demonstrated no long-term trends since ground-water development began. Long-term water-level data from shallow wells in the study area are scarce, but three available hydrographs (fig. 4) support this assumption: No appreciable water-level trend is apparent. Another indication that the water table has not changed appreciably in most of the study area is its relative proximity to land surface. Mapped water-table depths generally in the 10- to 30-ft range do not allow for appreciable decline to have occurred.

ESTIMATED RATE OF RECHARGE

Tritium, a radioactive isotope of hydrogen with an atomic mass of 3, makes an excellent tracer for studying ground-water processes that occur on a scale of less than 100 years (Plummer and others, 1993, p. 257). Tritium is particularly suited for recharge studies because it enters the hydrologic cycle as part of the water molecules in precipitation, has a half-life[1] of 12.43 years, and its concentrations in precipitation were increased substantially by atmospheric nuclear testing during 1953–62.

Tritium is produced naturally by the interaction of cosmic radiation with nitrogen and oxygen in the upper atmosphere (Pearson and others, 1975, p. 4). Before atmospheric nuclear testing, the amount of tritium in the environment was very small. Concentrations in precipitation before 1953 are not well known. Thatcher (1962, *in* Plummer and others, 1993, p. 260) estimates a probable range in concentration of 2 to 8 TU (1 TU equals 1 tritium atom in 10^{18} hydrogen atoms, or 3.24 pCi/L). Payne (1972, *in* Knott and Olimpio, 1986, p. 10) estimates a range of 2 to 25 TU. Beginning in 1953 as a result of the start of atmospheric nuclear testing, the concentrations of tritium in precipitation began to rise, peaking at about 2,000 TU at Waco, Tex., the nearest USGS sampling station, in May 1962.

Because of radioactive decay, ground water derived exclusively from precipitation before 1953 would have maximum tritium concentrations of 0.2 to 0.8 TU by the early 1990s (Plummer and others, 1993, p. 260). If ground water has larger tritium concentrations, some fraction of the water must have come from precipitation after 1953. Thus tritium can be a marker for recharge that occurred after 1953; and further, the greatest depth below the water table at which postnuclear-testing tritium concentrations are found can be used to compute a rate for recharge that has occurred since 1953.

Method of Computing Recharge Rate Using Environmental Tritium

Andres and Egger (1985) call the method of computing recharge rate using environmental tritium in this study the interface method, in which "interface" refers to the deepest point below the water table to which tritium at postnuclear-testing concentrations has traveled. The basis for the method is that the vertical distance downward from the water table that tritium at postnuclear-testing concentrations has traveled is equal to the rate of travel multiplied by the time of travel (time difference between tritium sampling year and 1953). Put succinctly,

$$\text{distance(depth)} = \text{rate} \times \text{time} . \qquad (2)$$

The method requires the assumption that ground-water flow is mainly vertical and downward (Plummer and others, 1993, p. 260). The outcrop lithology created by specific depositional systems, as previously

[1]The time required for one-half of the atoms of a radioactive element to disintegrate.

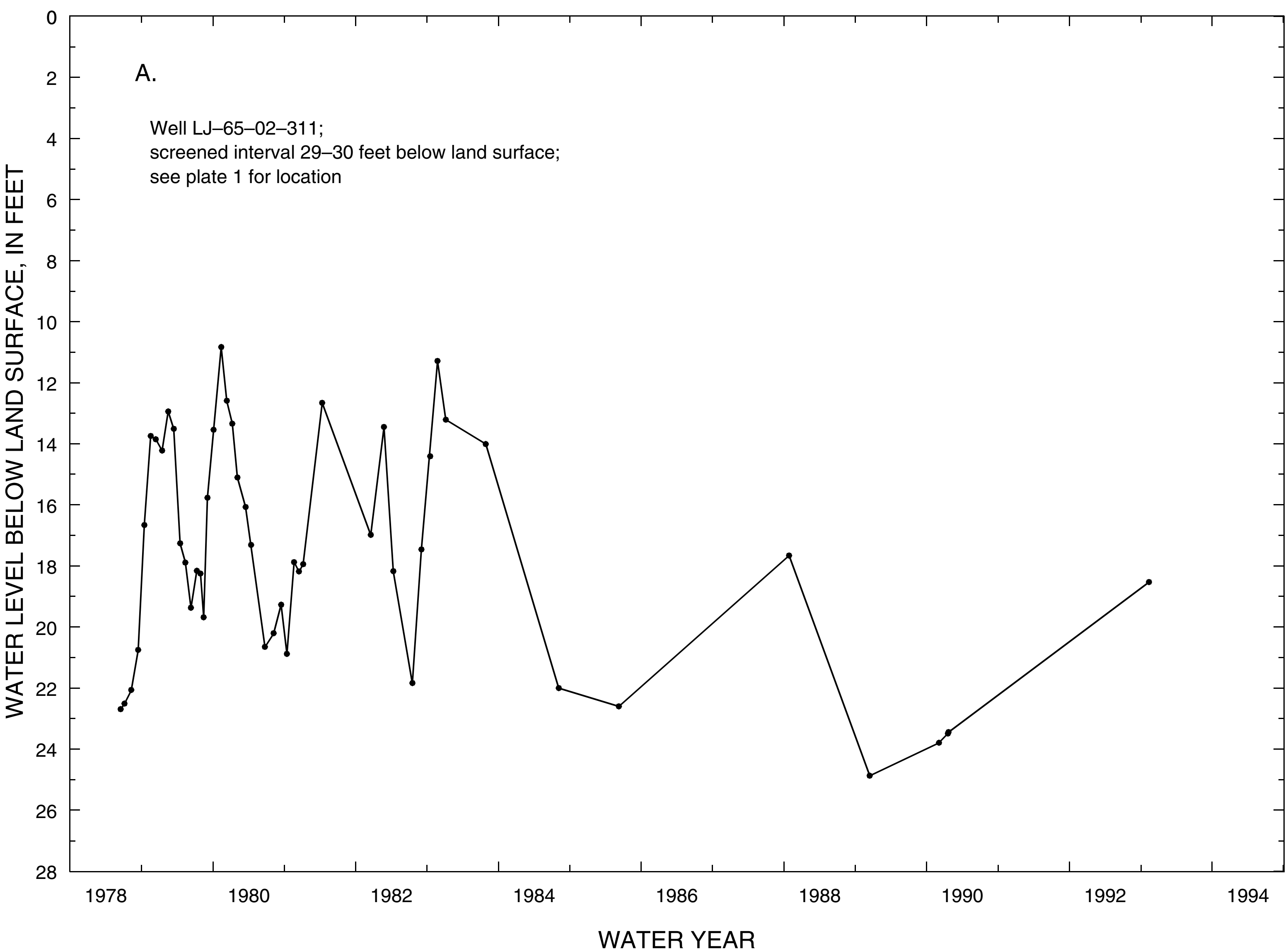

Figure 4. Hydrographs of water-table wells (A) LJ–65–02–311, (B) LJ–65–12–725, and (C) TS–60–45–803 completed in the Chicot aquifer near Houston, Texas.

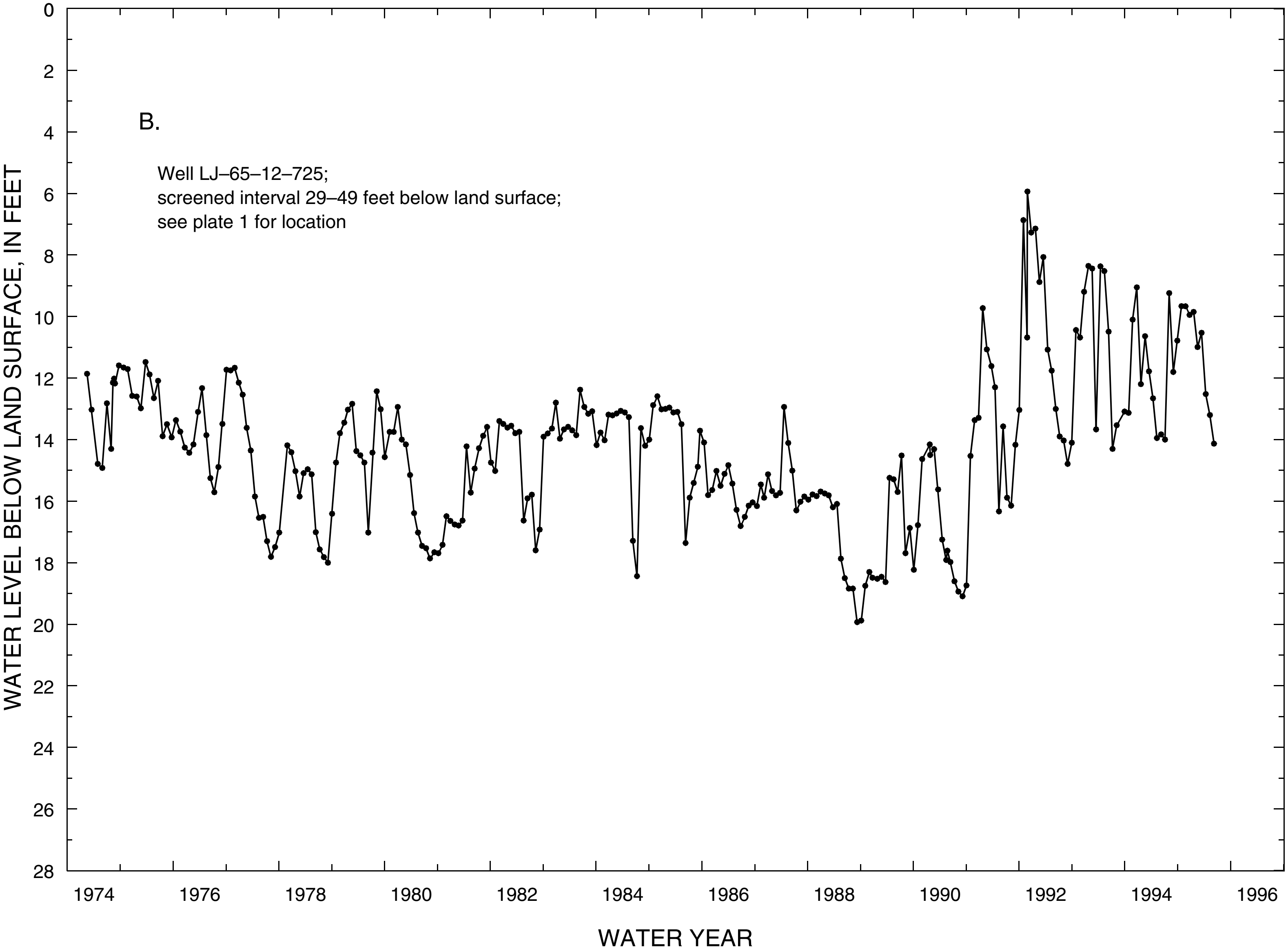

Figure 4. Continued.

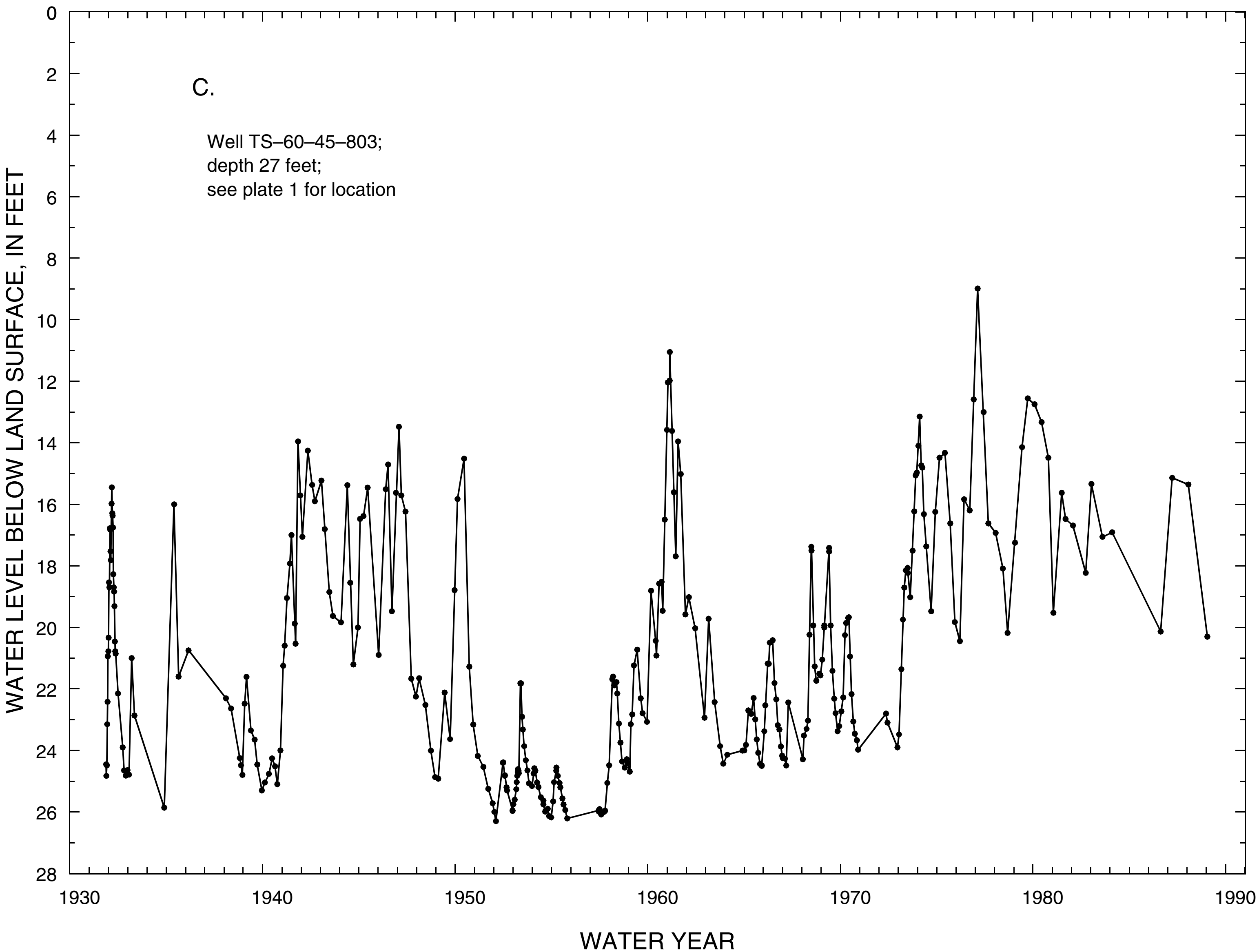

Figure 4. Continued.

described, is conducive to vertical flow, particularly in the near-surface parts of the saturated zone. Mainly downward vertical flow is a reasonable assumption when the study area is considered from a broad perspective as part of the principal recharge area of a vast regional aquifer system: On a regional scale, ground water in the principal recharge area moves downward as a "slug" from the water table to deeper parts of the aquifer system; although on a local scale, it is acknowledged that some fraction of the recharge discharges in topographically low areas, commonly to streams.

An implicit assumption of the method is that the water table demonstrates no long-term trends during the period from 1953 to the time of sampling. With the probable exception of the water table in the southwestern part of the study area as previously discussed, this assumption is believed to be valid.

The method also is based on the assumptions that tritium moves within the aquifer at a rate equal to the average interstitial velocity of ground-water flow. The volume of water per unit area that entered the saturated zone during the period between the tritium sampling year and 1953 divided by the length of the period (average specific discharge during the period) is equal to the average recharge rate during the period. Given those assumptions and the fact that, in ground-water flow,

$$\frac{\text{specific discharge}}{\text{effective porosity}} = \text{average interstitial velocity} \quad (3)$$

(Lohman and others, 1972, p. 13), an equation for recharge rate is developed from equations 2 and 3 as follows:

$$\text{depth} = \text{average interstitial velocity} \times \text{time}, \quad (4)$$

$$\text{depth} = \frac{\text{specific discharge} \times \text{time}}{\text{effective porosity}}, \quad (5)$$

$$\text{depth} = \frac{\text{recharge rate} \times \text{time}}{\text{effective porosity}}, \quad (6)$$

and finally,

$$\text{recharge rate} = \frac{\text{depth} \times \text{effective porosity}}{\text{time}}. \quad (7)$$

Because the recharge rate computed from equation 7 (commonly expressed in inches per year) is based on the deepest penetration below the water table of postnuclear-testing tritium concentrations, it represents an upper bound on the average recharge rate during the time between the tritium sampling year and 1953.

Field Application of the Method and Computation of Recharge Rate

A total of 41 shallow wells, 19 completed in the Chicot aquifer and 22 in the Evangeline aquifer (fig. 5), were selected for tritium sampling on the basis of location and screened interval. The selection objective was to obtain samples from locations distributed throughout the study area and from as many depths as possible. The wells were sampled in two phases between July 1989 and May 1990. At least three casing volumes of water were pumped from each well before sampling to ensure that samples were representative of water from the screened intervals. Samples from the first phase were analyzed by a USGS laboratory in Reston, Va., where the reporting limit for tritium at the time of analysis was 0.6 TU. Samples from the second phase were analyzed by a University of Miami (Fla.) laboratory, where the reporting limit for tritium at the time of analysis was 0.2 TU.

The results of tritium analyses (table 2) indicate that tritium concentrations range from less than reporting limits to 13 TU. To determine the subsurface location of the tritium interface, depth below the water table was graphed as a function of tritium concentration (fig. 6). The graph shows that the deepest penetration below the water table of postnuclear-testing tritium concentrations is about 80 ft. Accordingly, a depth of 80 ft is used in the recharge-rate computation.

Determining effective porosity, the amount of interconnected pore space available for fluid transmission (Lohman and others, 1972, p. 10), is problematic. In coarse homogeneous sediments, effective porosity can equal total porosity. However, in heterogeneous sediments of gravel, sand, silt, and clay (as in outcrops of the Chicot and Evangeline aquifers), effective porosity is less than total porosity because not all of the total porosity is available for fluid transmission. These sediments typically contain void spaces isolated from the interconnected void spaces that transmit fluid; and fluid passageways blocked by adhesive films around materials of small particle size (Daly, 1982, p. 24). Methods for determining effective porosity from laboratory core analysis are available (American Petroleum Institute, 1960, *in* Wolff, 1982, p. 4; Daniels and others, 1989, *in* Daniels and others, 1991, p. 27); core sampling and analysis, however, were beyond the scope of work

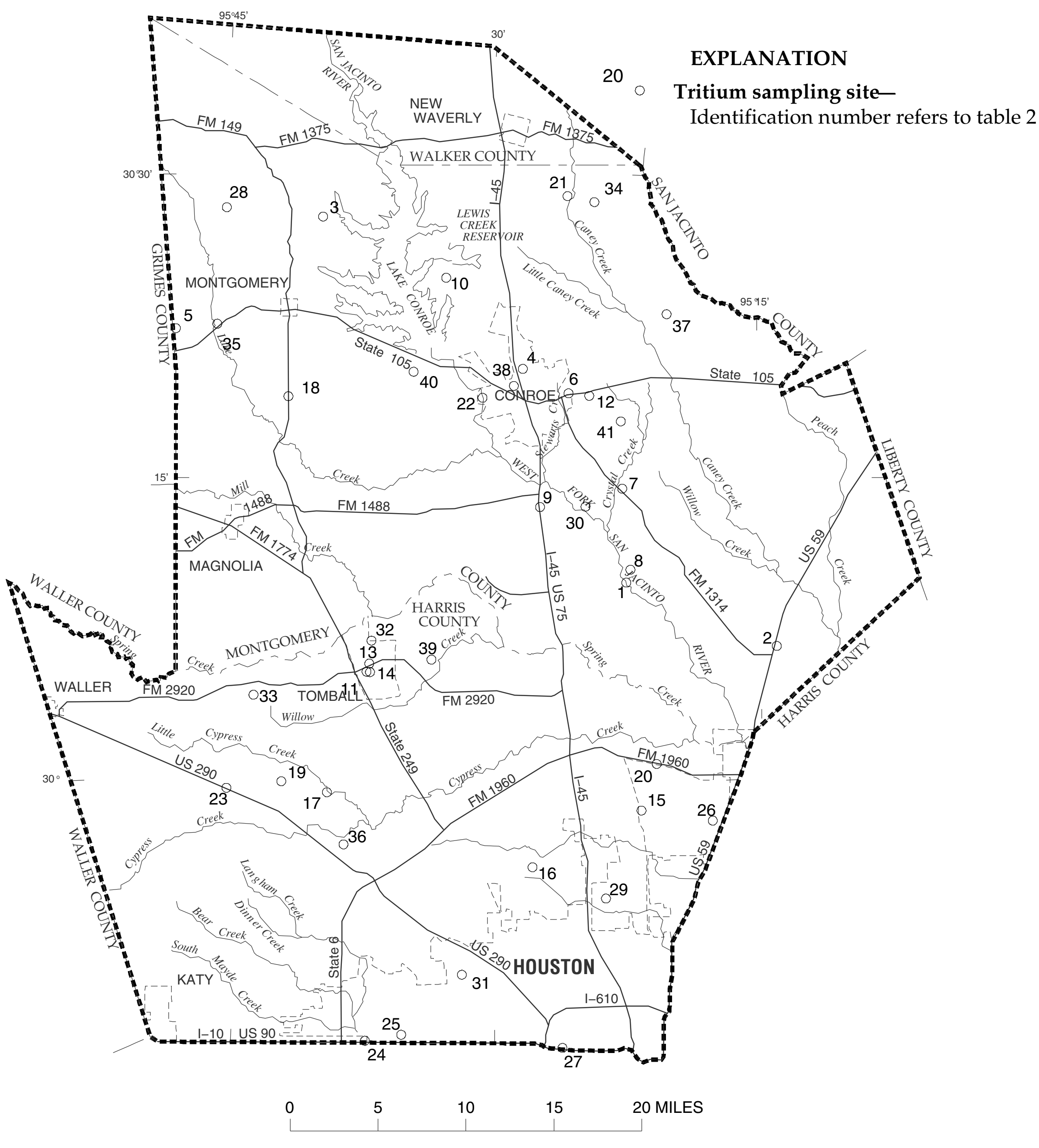

Figure 5. Location of tritium sampling sites near Houston, Texas.

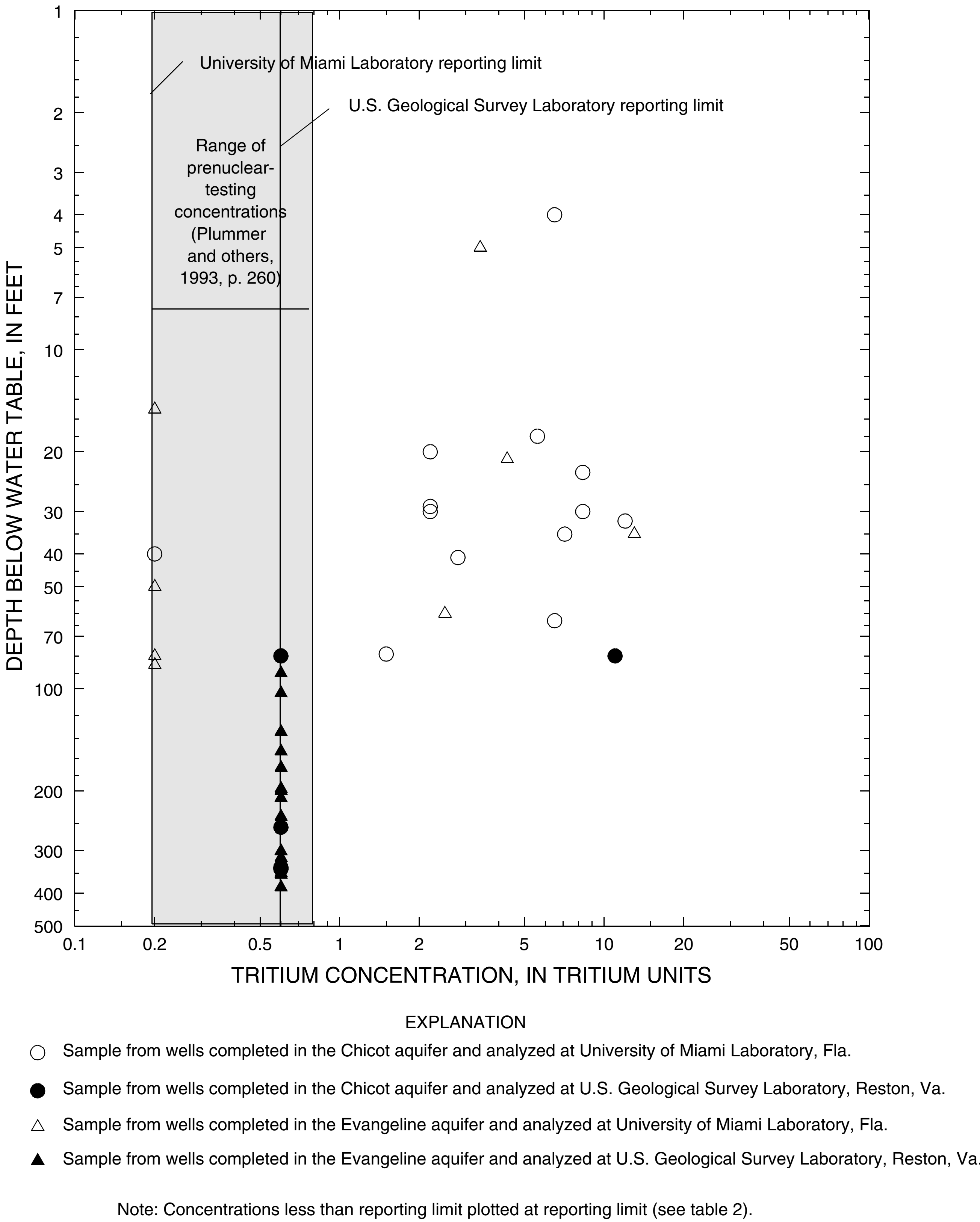

Figure 6. Sample depth below the water table as a function of tritium concentration in samples from selected wells in the Chicot and Evangeline aquifers near Houston, Texas, 1989–90.

Table 2. Environmental tritium concentrations in samples from selected wells in the Chicot and Evangeline aquifers near Houston, Texas

[Samples from wells 1–20 analyzed at U.S. Geological Survey Laboratory, Reston, Va. (reporting limit 0.6 tritium unit); samples from wells 21–41 analyzed at University of Miami Laboratory, Fla. (reporting limit 0.2 tritium unit); <, less than]

Tritium sampling site no. (fig. 5)	State well no.	Screened interval below land surface (feet)	Depth to center of screen (feet)	Measured or estimated depth to water table (feet)	Center-of-screen depth below water table (feet)	Tritium (sample) concentration (tritium units)
			Chicot aquifer			
22	TS–60–44–610	23–33	28	10	18	5.6
23	LJ–65–02–311	27–30	29	25	4	6.5
24	LJ–65–12–734	27–33	30	10	20	2.2
25	LJ–65–12–725	29–49	39	10	29	2.2
26	LJ–65–06–111	30–35	33	10	23	8.3
29	LJ–65–05–930	37–42	40	10	30	8.3
30	TS–60–53–316	40–50	45	10	35	7.1
31	LJ–65–12–303	49–55	52	12	40	<.2
32	LJ–60–60–111	50–60	55	25	30	2.2
27	LJ–65–13–839	51–55	53	21	32	12
33	LJ–60–59–403	51–61	56	15	41	2.8
36	LJ–65–03–620	68–78	73	10	63	6.5
1	TS–60–54–702	80–90	85	5	80	11
39	LJ–60–60–206	81–96	89	10	79	1.5
2	TS–60–63–110	85–95	90	10	80	<.6
13	LJ–60–60–101	248–293	271	15	256	<.6
15	LJ–65–06–107	300–395	348	10	338	<.6
16	LJ–65–05–408	335–365	350	10	340	<.6
17	LJ–65–03–304	336–356	346	10	336	<.6
			Evangeline aquifer			
21	TS–60–37–203	20–30	25	20	5	3.4
28	TS–60–34–301	32–47	40	25	15	<.2
34	TS–60–37–309	51–61	56	21	35	13
35	TS–60–34–904	61–69	65	15	50	<.2
37	TS–60–38–704	70–80	75	15	60	2.5
38	TS–60–45–414	70–80	75	54	21	4.3
40	TS–60–44–214	85–95	90	10	80	<.2
41	TS–60–46–406	90–100	95	10	85	<.2

Table 2. Environmental tritium concentrations in samples from selected wells in the Chicot and Evangeline aquifers near Houston, Texas—Continued

Tritium sampling site no. (fig. 5)	State well no.	Screened interval below land surface (feet)	Depth to center of screen (feet)	Measured or estimated depth to water table (feet)	Center-of-screen depth below water table (feet)	Tritium (sample) concentration (tritium units)
			Evangeline aquifer—Continued			
3	TS–60–35–204	110–130	120	30	90	<0.6
4	TS–60–45–114	118–128	123	20	103	<.6
5	TS–60–42–202	146–161	154	20	134	<.6
6	TS–60–45–513	158–168	163	10	153	<.6
7	TS–60–53–315	165–196	181	10	171	<.6
8	TS–60–54–405	205–215	210	10	200	<.6
9	TS–60–53–210	212–222	217	20	197	<.6
10	TS–60–36–802	215–235	225	15	210	<.6
11	LJ–60–60–110	237–395	316	15	301	<.6
12	TS–60–45–613	245–250	248	10	238	<.6
14	LJ–60–60–103	260–400	330	15	315	<.6
18	TS–60–43–511	342–384	363	10	353	<.6
19	LJ–65–03–209	360–407	384	35	349	<.6
20	LJ–60–62–715	390–400	395	10	385	<.6

in this study. Accordingly, an appropriate effective porosity to use in the computation of recharge rate in the Chicot and Evangeline outcrop area was determined from hydrogeologic literature and judgment based on knowledge of the lithologic characteristics of the outcrops.

Knott and Olimpio (1986), in a somewhat similar application of equation 7 to compute recharge rates at two sites in a "relatively homogeneous" sand and gravel aquifer using environmental tritium, assumed that effective porosity is the same as total porosity. Total porosities of 36 and 34 percent were determined from laboratory analyses and used in their recharge-rate computations.

Based on numerous laboratory analyses, Morris and Johnson (1967, tables 5, 6) report mean total porosities for gravel, sand, silt, and clay of 31, 34, 46, and 48 percent, respectively. Other compilers of large numbers of total porosities of unconsolidated sedimentary deposits (Manger, 1963, table 4; Wolff, 1982, table 4.2.1) report values of generally similar magnitudes. Thus a reasonable assumption is that total porosity in the outcrops of the Chicot and Evangeline aquifers probably is in the 30- to 50-percent range. Although materials of small particle size typically have larger total porosities than materials of large particle size, materials of small particle size have proportionately less interconnected pore space and, consequently, smaller effective porosities than materials of large particle size (Daly, 1982, p. 25). The degree to which effective porosity differs from total porosity in the Chicot and Evangeline aquifers is controlled primarily by the fraction of aquifer sediments consisting of fine-grained sand, silt, and clay particles. In turn, the spatial distribution of these sediments controls the direction and rate of recharge to the aquifers. These lithologic characteristics, and the particle size and distribution of sediments in the Chicot and Evangeline aquifers, are direct results of the depositional episodes noted previously.

The authors infer from the information available and from consultation with other scientists familiar with the hydrogeology of the study area (E.T. Baker, U.S. Geological Survey, oral commun., 1995; D.J. Nyman, U.S. Geological Survey (retired), oral commun., 1995; J.M. Sharp, Jr., Department of Geology, University of Texas, oral commun., 1995; L.E. Garner, Bureau of Economic Geology, University of Texas, oral commun., 1995) that effective porosity in the outcrop area of the Chicot and Evangeline aquifers likely ranges from about 20 to 25 percent. Accordingly, an effective porosity in the middle of that range (23 percent) is used in the recharge-rate computation.

Using 37 years as the tritium "travel time" (sampling year 1990 minus 1953) and the above estimates for interface depth (80 ft) and effective porosity (0.23), average recharge rate is computed from equation 7:

$$\text{recharge rate} = \frac{80\ \text{ft} \times 0.23}{37\ \text{yr}} \times 12\frac{\text{in}}{\text{ft}} = 6\frac{\text{in}}{\text{yr}}.$$

Evaluation of Recharge Rate

As readily seen from equation 7, the accuracy of the computed recharge rate as an upper bound on the average recharge rate between 1953 and 1990 depends directly on the accuracy of the interface depth and the effective porosity. Although the graph of depth below the water table as a function of tritium concentration (fig. 6) shows a well-defined break between prenuclear- and postnuclear-testing tritium concentrations, a potential source of error in the interface depth is the fact that only 5 of the 41 wells sampled for tritium (table 2) had measured water levels; the remainder (of necessity) were estimated from seismic refraction. The tenuous nature of the effective porosity estimate is evident from the discussion in the previous section.

From a regional perspective, recharge moves downward as a "slug" into the deep regional flow system. However, as previously discussed, some fraction of the recharge discharges locally—a fraction that is not accounted for in equation 7. Thus the computed average recharge rate represents total recharge to the saturated zone, not net recharge to the deep regional flow system. An implication of local discharge is that the assumption of vertical flow, while reasonable from a regional perspective, is violated to some extent on a local scale: If the downward flow of water (and thus tritium) from the water table is not predominantly vertical, the actual average recharge rate could be different from the 6 in/yr computed assuming vertical flow.

The computed average recharge rate compares favorably with ranges of recharge rate obtained from two recent studies using methods other than environmental tritium. The latest comprehensive regional ground-water-flow model that includes the Houston region indicates simulated recharge rate in the range of 0 to 4 in/yr in the study area of this report (Ryder and Ardis, 1991, fig. 38). This range of recharge rate is compatible with the computed average rate of 6 in/yr, considering the fact that regional ground-water-flow models, by virtue of their relatively large grid-block spacing, cannot simulate local flow systems (Sun and Johnston, 1994, p. 7). Only part of the total recharge, depending on the grid spacing, topographic relief, and stream density, is simulated.

A water-budget analysis involving rainfall and runoff data from four basins in the recharge areas of the Chicot and Evangeline aquifers and two basins in adjacent parts of the aquifers confined beneath the Beaumont Clay yielded an estimated 4 to 10 in/yr recharge (R.K. Gabrysch and Fred Liscum, U.S. Geological Survey [retired], and U.S. Geological Survey, written commun., 1995). Recharge computed from a basin water budget represents the fraction of total recharge that is not discharged within the basin—a rate that probably is less than total recharge but more than net recharge to deep aquifer zones.

The natural regional ground-water-flow system in the Houston region has been profoundly altered by decades of substantial withdrawals of water. Large regional cones of depression have developed in the potentiometric surfaces of the hydrogeologic units pumped. Simulated regional horizontal flow vectors superimposed on cones of depression in permeable zones of the Chicot and Evangeline aquifers (Ryder and Ardis, 1991, figs. 44–46) indicate that water to sustain pumpage in the Houston region flows toward the center of pumpage from tens of miles away in all directions. Thus, the sources of water to sustain pumpage—induced recharge, capture from natural discharge, and storage in permeable zones and confining units—are spread over a very large geographic area. An estimated recharge rate for the study area (regardless of its veracity) represents one of several components of a complex regional hydrologic budget.

Tempered by the above information, an average total recharge rate of 6 in/yr in the study area is considered a reasonable estimate. However, it is not definitive because of uncertainty regarding the assumptions and parameters used in its computation.

CONCLUSIONS

Several conclusions regarding the depth to the water table and the rate of recharge in outcrops of the Chicot and Evangeline aquifers follow from the analyses of seismic-refraction and environmental tritium data.

1. The water table in the study area generally ranges from about 10 to 30 ft below land surface and typically is deeper in areas of relatively high land-surface altitude than in areas of relatively low land-surface altitude.

2. In the southwestern part of the study area near Katy, the water table is more than 75 ft below land surface. A probable explanation for the relatively deep water table near Katy, indicated by recent regional ground-water-flow modeling, is that ground-water pumpage from deeper zones in the aquifers in the Houston region (about 320 Mgal/d in 1994) has induced recharge in the area, which in turn has lowered the water table from its original altitude.

3. With the exception of the water table in the Katy area, the water table has demonstrated no long-term trends since ground-water development began. Mapped water-table depths generally in the 10- to 30-ft range do not allow for appreciable decline to have occurred.

4. The estimated average total recharge rate in the study area is 6 in/yr. This rate is an upper bound on the average recharge rate during the 37 years 1953–90 because it is based on the deepest penetration (about 80 ft) of postnuclear-testing tritium concentrations. The rate is total recharge to the saturated zone, rather than net recharge to the deep regional flow system, because some fraction of the total recharge discharges locally, mainly to streams.

5. The estimated average total recharge rate, which represents one of several components of a complex regional hydrologic budget, is considered reasonable because it compares favorably with recharge rates in the study area obtained from recent ground-water-flow modeling and water-budget analyses. However, the rate is not definitive because of uncertainty regarding the assumptions and parameters used in its computation.

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