Recharge to the Surficial Aquifer System in Lee and Hendry Counties, Florida

U.S. Geological Survey
Water-Resources Investigations Report 95-4003

Prepared in cooperation with the
South Florida Water Management District

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By Richard K. Krulikas and G.L. Giese

U.S. GEOLOGICAL SURVEY

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Tallahassee, Florida
1995

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Abstract

Protection of ground-water recharge areas against contamination is of great interest in Florida, a State whose population depends heavily on ground water and that is experiencing rapid growth. The Florida Legislature is considering implementation of a tax incentive program to owners of high-rate recharge lands that remain undeveloped. High-rate recharge was arbitrarily set at 10 or more inches per year. The U.S. Geological Survey, in cooperation with the South Florida Water Management District, conducted a study to investigate the efficacy of several methods for estimating recharge to the surficial aquifer system in southwestern Florida and to map recharge at a scale of 1:100,000.

Four maps were constructed at a scale of 1:100,000 for Lee and Hendry Counties, depicting the configuration of the water table of the surficial aquifer system, direction of ground-water flow, general soil characteristics, and recharge rates. Point recharge rates calculated for 25 sites in Lee County from comparisons of chloride concentrations in precipitation and in water from the surficial aquifer system ranged from 0.6 to 9.0 inches per year. Local recharge rates estimated by increases in flow along theoretical flow tubes in the surficial aquifer system were 8.0 inches per year in a part of Lee County and 8.2 inches per year in a part of Hendry County. Information on oxygen isotopes in precipitation and water from the surficial aquifer system was used to verify that the source of chlorides in the aquifer system was from precipitation rather than upward leakage of saline water. Soil maps and general topographic and hydrologic considerations were used with calculated point and local recharge rates to regionalize rates throughout Lee and Hendry Counties. The areas of greatest recharge were found in soils of flatwoods and sloughs, which were assigned estimated recharge rates of 0 to 10 inches per year. Soils of swamps and sloughs were assigned values of 0 to 3.0 inches per year; soils of tidal areas and barrier islands, soils of the Everglades, and soils of sloughs and freshwater marshes were assigned values of 0 to 2.0 inches per year; lastly, soils of manmade areas were assigned values of 0.5 to 1.5 inches per year. Small isolated areas of high-rate recharge (greater than 10 inches per year) might exist in Lee and Hendry Counties, but the maximum rate calculated in this study was 9.0 inches per year. Despite low natural recharge rates, lowering of the water table through pumping or canalization could create a potential for induced recharge in excess of 10 inches per year in parts of Lee and Hendry Counties.

INTRODUCTION

The population of Lee and Hendry Counties (fig. 1) has increased greatly over the last few decades, with accompanying needs for increased water supply for domestic, industrial, and agricultural uses. The population of Lee County reached an estimated 307,000 by 1988, more than doubling during the previous 14 years (Lee County Planning Department, written commun., 1990). This does not include the influx of tourists and seasonal residents, who increase the population substantially during the winter months, when rainfall recharge is at its lowest. The estimated population of Hendry County was about 18,600 in 1980 and

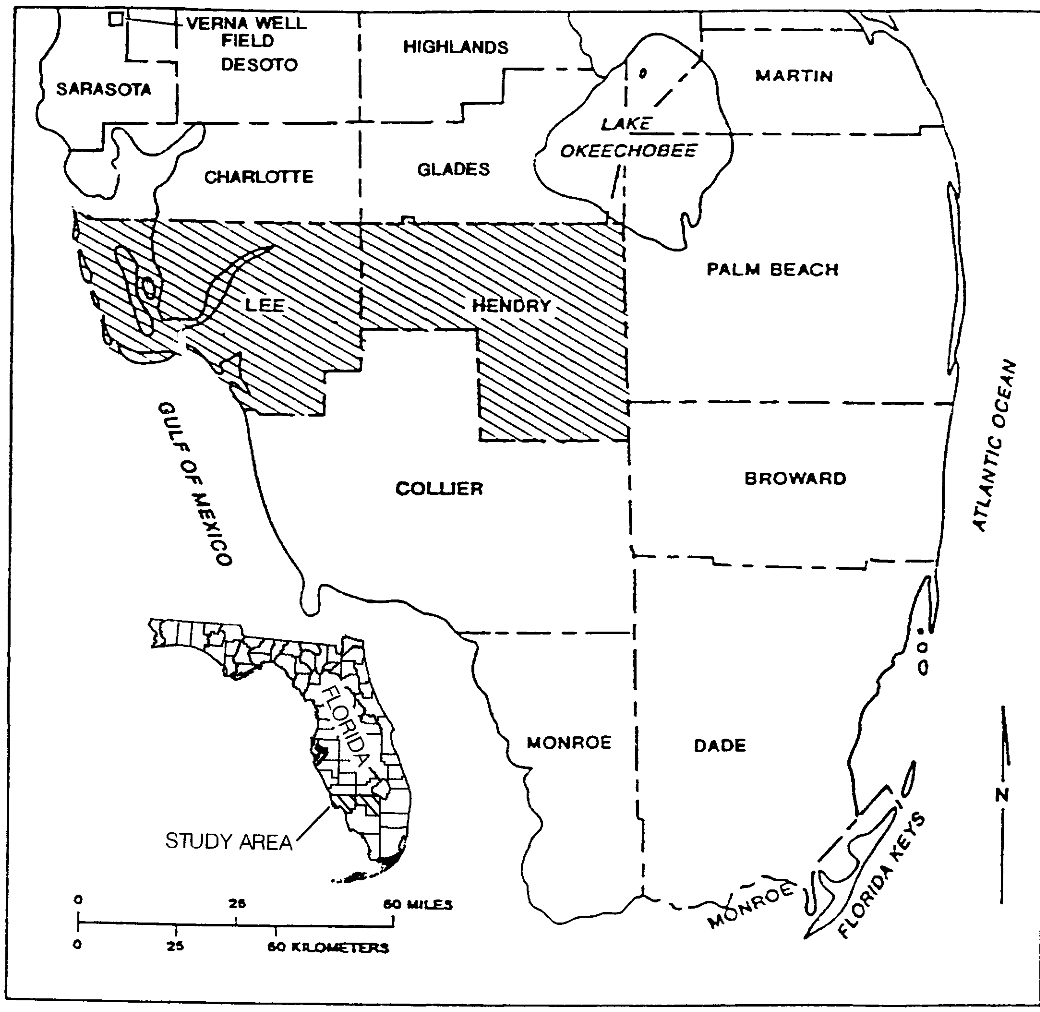

Figure 1. Location of Lee and Hendry Counties in southwestern Florida.

increased to about 25,770 in 1990, attributable mainly to the increase in agricultural activities, particularly row crops and citrus. This growth in population and increase in agricultural activities in both counties have led to increased pressures on fresh surface-water and ground-water supplies for public, domestic, industrial, and agricultural needs. The low topographic relief and lack of surface drainage in much of the area preclude large reservoir storage, and parts or all of the deeper aquifers and coastal rivers contain saline water. Thus, the surficial aquifer system is the only viable freshwater source in many parts of the study area.

The total 1990 freshwater use in Lee and Hendry Counties was 161 and 493 Mgal/d (million gallons per day), respectively (Marella, 1992). Of these totals, ground-water sources accounted for 76 and 35 percent of the totals, or 123 and 174 Mgal/d, respectively. Of the ground water used, water from the surficial aquifer system accounted for 66 and 51 percent, or 82 and 89 Mgal/d, respectively.

The climate of Lee and Hendry Counties is humid subtropical. Rainfall averages 54 in/yr (inches per year) in Lee County and 50 in/yr in Hendry County. However, rainfall is unevenly distributed throughout the year, with the summer period receiving about 60 percent of the annual amounts. Thus, the fall, winter, and spring periods are relatively dry, and in areas where the surficial aquifer system is heavily pumped, ground-water levels may decline substantially, then recover to levels at or near land surface during the summer wet season, when infiltration from rainfall recharges the surficial aquifer system. Water levels in well L-1985 (fig. 2) confirm this annual cycle both before and after drawdown effects of pumpage from Lee County public-supply wells. Examination of long-term hydrographs indicates that, thus far, recharge during the wet season throughout Lee and Hendry Counties has been enough in most years to prevent significant long-term decline of water levels in the surficial aquifer. Whether or not seasonal recoveries will occur in the future depends on the magnitude of recharge relative to withdrawals.

In 1988, Florida voters approved the "Bluebelt Amendment" which authorizes special tax treatment to owners of land in designated high-recharge areas that is left in an undeveloped state. High recharge, for purposes of this study, is arbitrarily defined as 10 in/yr or more. The U.S. Geological Survey, in cooperation with the South Florida Water Management District, began a study in that same year to examine recharge in southern Florida. Lee and Hendry Counties were selected for pilot studies because of the rapidly increasing water needs of the area.

Purpose and Scope

This report describes ground-water recharge to the surficial aquifer system in southern Florida in general and in Lee and Hendry Counties in particular and evaluates the feasibility of mapping recharge at a scale of 1:100,000 in both counties. Point values of recharge rates were calculated by comparisons of chloride concentration in precipitation with chloride concentration in the surficial aquifer system at 25 locations. Comparisons of oxygen isotopes in precipitation and water from the surficial aquifer system were used to verify that the source of chlorides in the surficial aquifer system was from precipitation rather than upward leakage of saline waters. Point values determined by the chloride ratio method were corroborated by calculation of local recharge rates along theoretical flow tubes at two

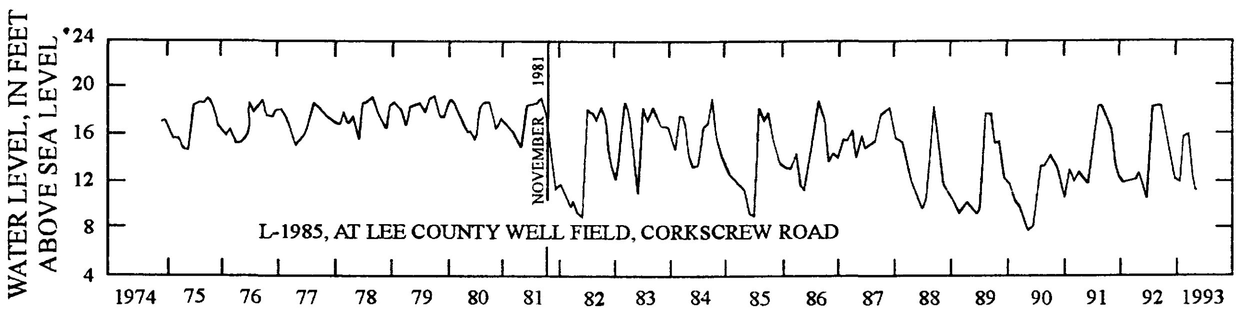

Figure 2. Ground-water levels in surficial aquifer well L-1985, Lee County, 1974-93. (Lee County Well Field at Corkscrew Road came online in November 1981.)

locations. Finally, maps of soil types along with general topographic considerations were used with point and local recharge rate calculations to regionalize recharge rates in Lee and Hendry Counties.

Description of Study Area

The study area encompasses 1,975 mi^2 (square miles) in southwestern Florida and includes Lee and Hendry Counties (fig. 1). In Lee County, elevations range from sea level along the Caloosahatchee River estuary and the Gulf of Mexico to 35 ft (feet) above sea level along State Highway 82 near the Lee-Hendry County line (pl. 1). In Hendry County, elevations range from sea level along the Caloosahatchee River estuary to 55 ft above sea level along the Collier-Hendry County line (pl. 2).

Surface Drainage

The Caloosahatchee River, a major source of drinking water for Fort Myers and parts of Lee County (La Rose and McPherson, 1980), is the principal drainage for northern Lee and Hendry Counties. The river is used for recreation, agricultural, and municipal needs. Small south-trending tributaries discharge into the Caloosahatchee River on the north side in Lee County, and primary tributaries (Orange River, Dog Canal, and Bedman Creek) discharge on the south side (pl. 1). The Orange River receives drainage from canals inland, designed to reduce flooding in the vicinity of Lehigh Acres. This river flows into the Caloosahatchee River, 7 mi (miles) downstream from Franklin Locks, and is influenced by tidal fluctuations. Dog Canal connects with the eastern boundary of the Lehigh Acres canal system. The canal flows into the Caloosahatchee River near Alva, more than 6 mi upstream from Franklin Locks, where a water level of 2.5 to 3.5 ft above sea level is maintained.

Most of the area in Lee County south of State Highway 82 drains to the southwest toward the Gulf Coast. Surface-water drainage is predominantly into the Tenmile Canal, Imperial River, Estero River, Hendry Creek, and the Cape Coral canal system (pl. 1). The Cape Coral canal system is located at Cape Coral in western Lee County and includes 420 mi of canals (David Kyrk, City of Cape Coral Utilities Department, oral commun., 1993). Many of the canals in eastern and southern Cape Coral are affected by Gulf tides. Water levels in the mostly freshwater nontidal reaches are generally higher than those in the salty tidal reaches throughout the canal system (weirs separate the tidal reaches from the nontidal reaches).

The primary tributaries that discharge into the Caloosahatchee River in Hendry County are the Townsend Canal, Roberts Canal, and Jacks Branch (pl. 2). Flow into the river is regulated by the Ortona and Moore Haven Locks north of the Glades-Hendry County line and by Franklin Locks (pl. 1), where a water level of 2.5 to 3.5 ft above sea level is maintained. Surface-water drainage in the eastern and southeastern parts of Hendry County is predominantly into the L-1, L-2, L-3, North Feeder Canal, and West Feeder Canal (pl. 2) and ultimately into the Big Cypress Swamp (Klein and others, 1964).

Because of the low topographic relief of the area and the good hydrologic interconnection between ground water and surface water, the rivers and canals exert widespread control on the adjacent water table. Where river and canal water levels are low relative to adjacent land surface, more storage is available in adjacent parts of the surficial aquifer system for infiltration of precipitation and subsequent recharge to the surficial aquifer system.

Hydrogeology

The surficial aquifer system consists of deposits ranging in age from late Miocene to Holocene. Deposits primarily include unconsolidated, fine- to medium-grained, quartz sand interbedded with sandy limestone, shell fragments, and gray or green sandy clay. In Lee County, the thickness of the surficial aquifer system ranges from land surface to about 95 ft, with greater thicknesses to the east and south. In Hendry County, the thickness of the surficial aquifer system ranges from land surface to about 120 ft, with greater thicknesses to the northeast.

The surficial aquifer system in Lee and Hendry Counties is composed of two distinct water-yielding units, known as the surficial aquifer and the lower Tamiami aquifer (figs. 3 and 4). Separating the surficial aquifer and the lower Tamiami aquifer is a semiconfining unit that retards (but does not prevent) the flow of ground water between the units. The surficial aquifer is present throughout both counties. The lower Tamiami aquifer is present in eastern Hendry County (fig. 4) but is absent in northern Lee and western Hendry Counties.

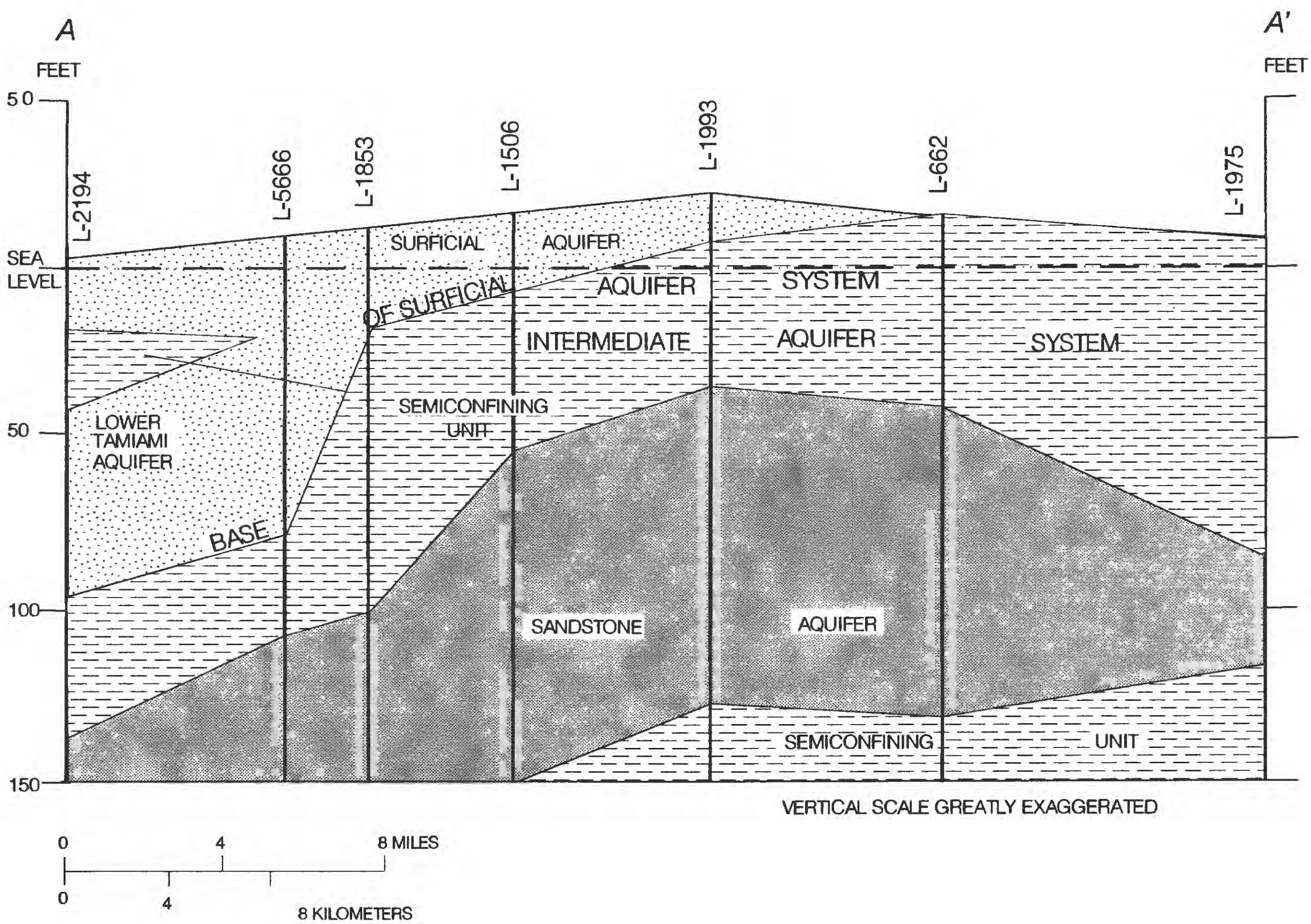

Figure 3. Hydrogeologic section A-A′ in Lee County (location of section shown on plate 1).

Detailed descriptions of the hydrogeology are presented by Boggess and others (1981) and Smith and Adams (1988).

Previous and Related Studies

A map report by Visher and Hughes (1975) showed the difference between rainfall and potential evaporation in Florida. Stewart (1980) mapped recharge areas and rates to the Floridan aquifer system statewide at a scale of 1:200,000. Henderson (1984) reported on a soil survey of Lee County. Aucott (1988) utilized information gained from numerical modeling of the Floridan aquifer system to revise Stewart's 1980 recharge map. Belz and others (1990) reported on a soil survey of Hendry County. Vecchioli and others (1990) reported on pilot studies of recharge in Okaloosa, Pasco, and Volusia Counties. Finally, Swain (1995, in press) reported on use of field infiltrometer tests in the stochastic modeling of recharge effects.

Acknowledgments

The authors thank the local weather observers, supplied by the local television affiliates (WINK and WBBH), for their assistance in the collection of water samples of precipitation from several storm events during May, June, and July 1989. Appreciation is also extended to Dr. Peter Swart and his graduate students from the University of Miami Stable Isotope Laboratory for their diligent and timely analysis of the water samples and their input in interpreting the results.

RECHARGE TO THE SURFICIAL AQUIFER SYSTEM

Vecchioli and others (1990) discussed ground-water recharge concepts as applied to the Florida hydrologic setting. The definition of ground-water recharge adopted in that study is used here. That is, ground-water recharge is the replenishment of ground

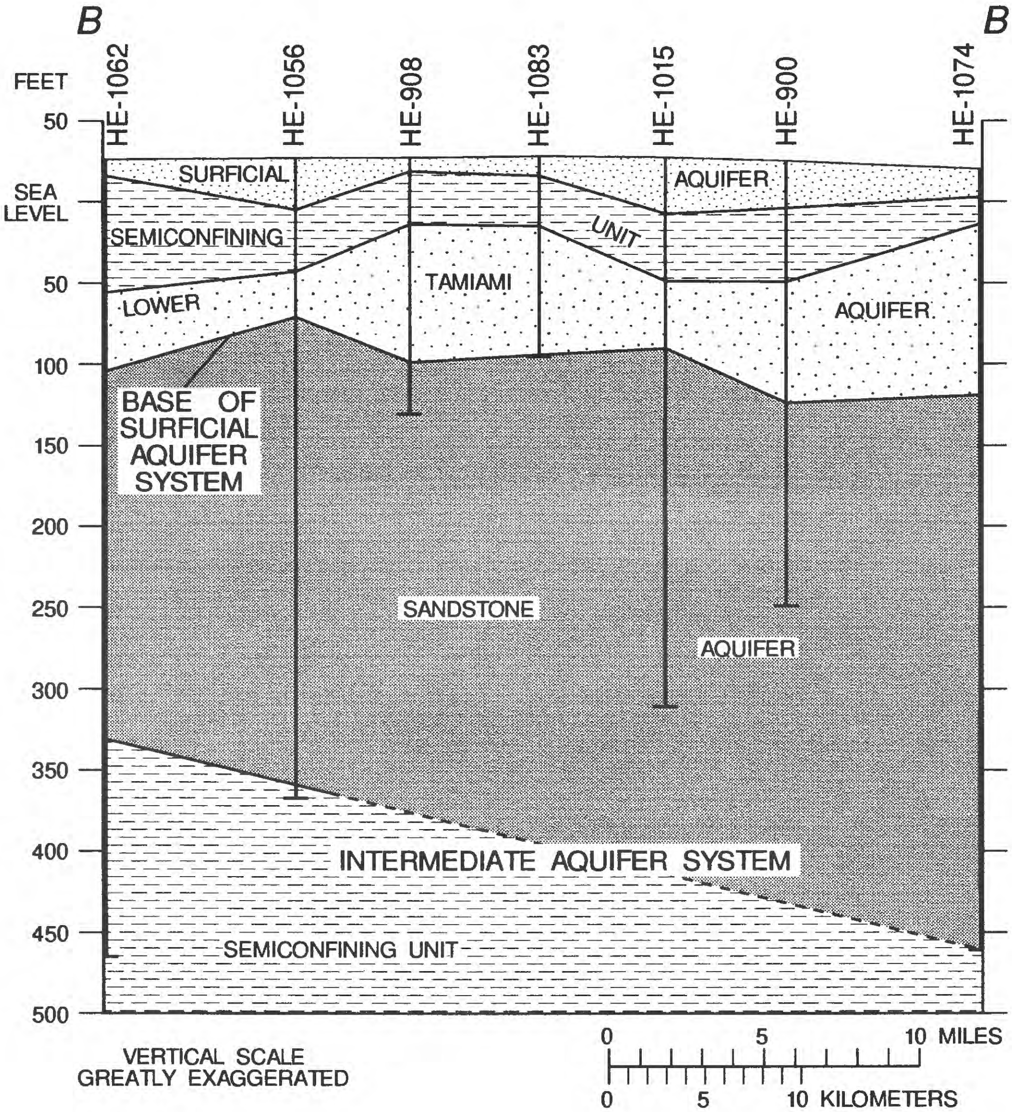

Figure 4. Hydrogeologic section B-B′ in Hendry County (location of section shown on plate 2).

water by downward infiltration of water from rainfall, streams, lakes, sinkholes, canals, and other sources (American Society of Civil Engineers, 1987, p. 222). It represents accretions to the zone of saturation, whose upper surface is the water table. Recharge is both the process and amount of accretion to ground-water storage and flow. This definition extends also to water moving downward from one aquifer to another through intervening confining beds. Discharge is the depletion of ground-water storage by upward flow to rivers, canals, springs, lakes, swamps, other wetlands, overlying aquifers, and wells. Where the water table is at or near land surface, evaporation and transpiration by plants may account for significant ground-water discharge. For purposes of this report, water leaking upward to the surficial aquifer system from lower aquifers is not considered recharge. Although it does represent an accretion of water to the surficial aquifer system, upward leakage is considered as a separate item for water-budget accounting purposes.

Recharge is part of the natural hydrologic cycle as illustrated in figure 5. Precipitation has several possible alternate fates. It may return to the atmosphere quickly through evaporation and transpiration by plants; it can run overland to streams, lakes, swamps, and other lowlands; or it may infiltrate to the water

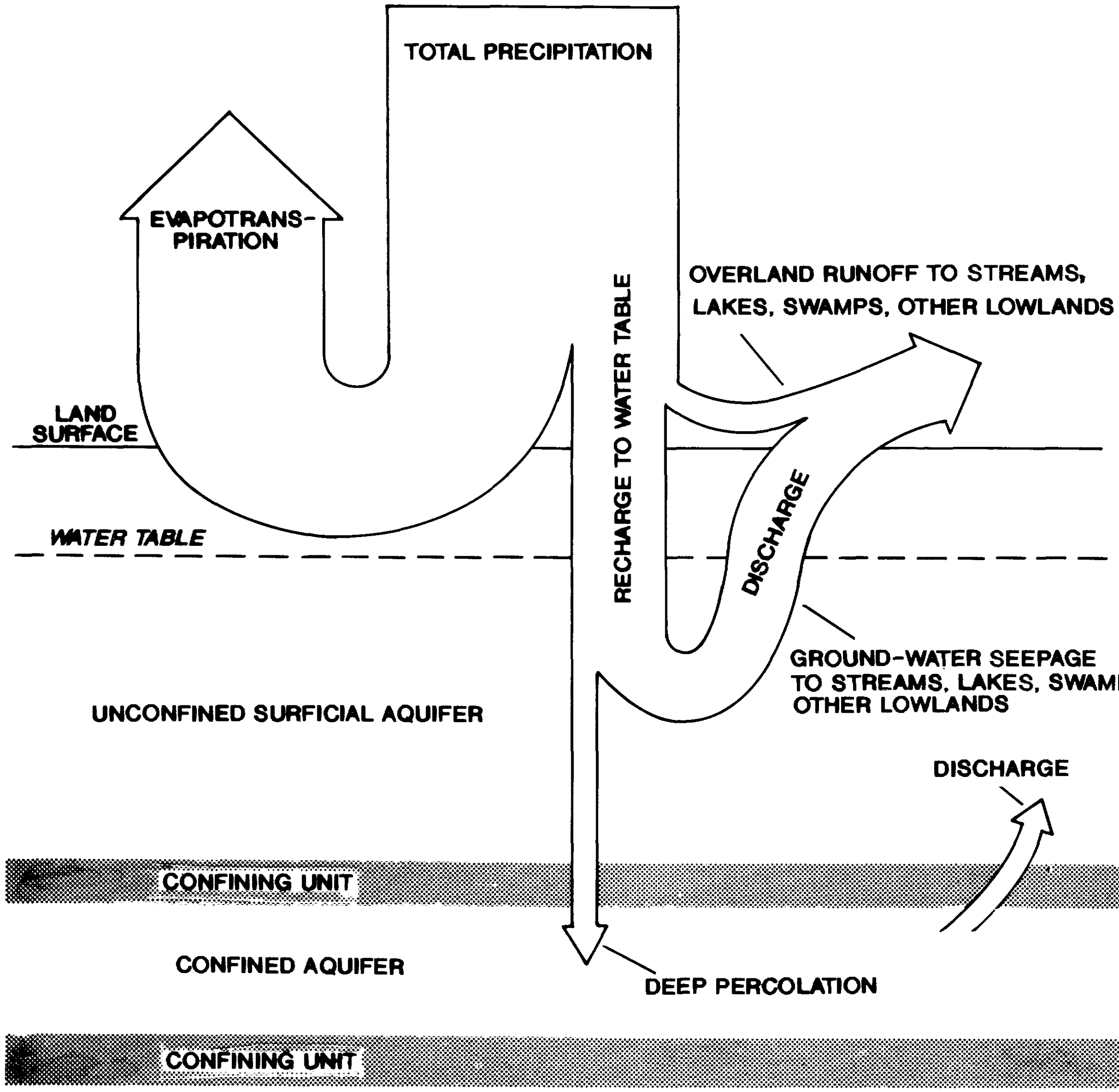

Figure 5. Relative magnitudes of water-budget components in Lee and Hendry Counties.

table as recharge. Eventually, recharge returns to the atmosphere. For steady-state conditions, discharge balances recharge.

In Lee and Hendry Counties, only a small percentage of the annual rainfall infiltrates to the water table in an average year. Most of the precipitation that falls is returned to the atmosphere by evaporation and transpiration by plants before reaching the water table. Very little overland runoff occurs. Of more than 53 in. (inches) of annual rainfall in Pasco County, 100 mi to the north of Lee County, the maximum annual recharge rate for natural conditions found by Vecchioli and others (1990) was less than 12 in/yr. Maximum rates for Lee and Hendry Counties for natural conditions should be less than Pasco County because of the generally lower topographic relief results in the water table being closer to the land surface, increasing water available for evapotranspiration. Additionally, incident solar radiation is greater in Lee and Henry Counties than in Pasco County, increasing the potential for evapotranspiration on that account.

Visher and Hughes (1975) published a map of the difference between rainfall and potential evaporation for Florida. The difference was zero in all of Lee County and the western half of Hendry County. When the water table is at land surface, such as would be the case under natural conditions for at least part of an average year in most of Lee and Hendry Counties, actual evaporation approaches potential evaporation and is the major process of removal of excess rainfall, leaving little opportunity for recharge.

Factors Affecting Recharge

Vecchioli and others (1990) discuss, in general terms, the factors that determine how much of precipitation becomes recharge, including: (1) texture and gradation of surface and near-surface deposits and their vertical permeability; (2) water requirements of the vegetation; (3) frequency, intensity, and volume of rainfall; (4) topography; and (5) temperature (American Society of Civil Engineers, 1987, p. 56).

To this might be added a sixth factor; and that is, nearness of the water table to the land surface. Places where the water table is very near the land surface are often wetlands of one type or another. Wetland areas predominate in Lee and Hendry Counties and are more often indicative of discharge areas than recharge areas in southern Florida. There is little opportunity for precipitation to recharge the surficial aquifer system in such wetland areas. Precipitation either runs off or is lost to evapotranspiration. Thus, areas where the water table is near the land surface are areas of little recharge in Lee and Hendry Counties and are, in fact, discharge areas in most cases. Aucott (1988) shows that all of Lee and Hendry Counties are discharge areas for the Floridan aquifer system.

Where heavy pumpage exists, however, and water tables are artificially lowered, there may be a large potential for induced recharge in many parts of Lee and Hendry Counties, perhaps in excess of the 10 in/yr considered to be high recharge. Thus, although this report deals primarily with natural recharge, it is recognized that the amount of recharge that could be induced to replenish water lost through pumping would also be of great interest to water users and managers and should be taken into account in calculations of available water supply.

Estimation of Point and Local Recharge Rates

Many methods have been used to estimate rates of ground-water recharge or to gain insight into recharge processes. Some involve direct measurement of infiltration; others involve comparisons of water-quality constituents or isotope ratios between precipitation and ground water or direct comparisons of rainfall with ground-water levels in soils of known porosity. Some methods use hydraulic analysis of ground-water flow through modeling or analytical techniques. Analysis of streamflow records to determine baseflow of streams is a widely used approach in the Southeastern United States. Determination of recharge as a residual in water budgets is another approach often used. Each approach has its own merits for particular situations, and it is largely a matter of judgment which method (or combination of methods) is employed.

Lack of streamflow records for natural conditions and inability to determine drainage areas with available topographic maps precluded estimation of recharge rates utilizing streamflow records in Lee and Hendry Counties. Instead, a combination of methods utilizing water chemistry and ground-water hydraulics was used to estimate rates.

At 25 locations in Lee County, point recharge was calculated by comparison of chloride concentration in precipitation and water from the surficial aquifer system. Comparisons of oxygen isotopes in precipitation and water from the surficial aquifer system at 39 locations were used to verify that the source of water in the surficial aquifer system was from precipitation rather than from upward leakage of saline water. Point recharge values derived from analysis of chloride were then corroborated by calculation of local recharge along theoretical ground-water flow tubes. Finally, as described later, maps of soil types along with general topographic considerations were used with point or local recharge rates estimated from the above techniques to regionalize recharge rates in Lee and Hendry Counties.

Chloride Concentration Ratios

The ratios of chloride concentration in rainfall to chloride concentration in ground water have been used by previous investigators to estimate recharge to the ground-water system. Vacher and Ayers (1980) estimated recharge to the ground-water system in Bermuda using rainfall and the ratio of chloride concentration in rainfall to chloride concentration in ground water by the following expression:

$$R = \left(\frac{Cl_p}{Cl_{gw}}\right)P \qquad (1)$$

where R is the recharge rate, in inches per year; Cl_p is chloride concentration of precipitation, in milligrams per liter; Cl_{gw} is chloride concentration of ground water, in milligrams per liter; and P is precipitation (rainfall), in inches per year.

The concept behind this technique is that precipitation in coastal areas contains some chloride (Cl^-) due to aerosols and that, where transport of Cl^- from underlying aquifers can be ruled out, precipitation is the only source of Cl^- in the surficial aquifer system. Furthermore, it is assumed that the Cl^- ion behaves conservatively and is not depleted by any chemical reaction in the surficial aquifer system. This last assumption is supported by Feth (1981). Evapotranspiration involves fluxes back to the atmosphere with essentially no Cl^-, thereby concentrating the remaining soil-water excess or recharge. For example, if nine-tenths of incoming rainfall is returned to the atmosphere through evapotranspiration, then the concentration of the infiltrating water that reaches the water table would be 10 times that of the original precipitation ($Cl_{gw}=10Cl_p$). Substituting $10Cl_p$ for Cl_{gw} in equation 1, for 60 in. of rainfall:

$$R = \left(\frac{Cl_p}{10Cl_p}\right) 60 = 6 \ inches \qquad (2)$$

This approach to estimating ground-water recharge was evaluated for Lee County. Water samples from 39 observation wells completed in the surficial aquifer system and from 6 precipitation collection sites (pl. 1) were collected by the U.S. Geological Survey in April, May, and June 1989, and were analyzed for chloride concentrations. Water was pumped from each well in sufficient quantity to ensure that at least three well-casing volumes of water were removed before sampling. Analyses for chloride concentrations were made by the U.S. Geological Survey using analytical techniques described by Fishman and Friedman (1985). At the precipitation collection sites, local weather observers aided the U.S. Geological Survey in the collection of water samples from several storms events of 1 in. or greater in May and June 1989.

Chloride concentrations from the 6 precipitation collection sites and the 39 ground-water wells ranged from 4 to 6 mg/L (milligrams per liter) (table 1) and 4 to 1,050 mg/L, respectively. However, the chloride values for rainfall are higher by about one-half an order of magnitude or more than those values from the Verna Well Field site (site number 104100) of the National Atmospheric Deposition Program (NADP)/National Trends Network (NTN). Rainfall samples from this site, near Sarasota (fig. 1), averaged 0.69 mg/L of chloride during 1988. Samples were composited weekly and, unlike rainfall sample collectors used in the present study, sample collectors in the NADP program were covered between precipitation events, minimizing evapoconcentrations. In addition, the NADP site included storm events for the entire calendar year previous to the collection of ground-water samples from wells that tap the surficial aquifer. Consequently, the precipitation chloride concentration data derived from the NADP/NTN data are more likely to be representative of long-term conditions than are the data collected at the six precipitation collection sites in the present study. For these reasons, 1988 chloride values from the Verna NADP site were taken to be typical of precipitation in the Lee County area, and the higher values obtained from the six precipitation sites used in the current study were disregarded.

Precipitation, after it strikes the land surface, dissolves additional chloride ions from dryfall deposition previous to the rainfall event. Baker (1991) estimated mean dry bucket:wet bucket ratios for Florida to be 0.42 for chloride. Assuming all the dryfall is dissolved by precipitation, average total chloride concentration of water at the land surface for 1988 would be (0.69) (1.42) = 0.9798, or about 1.0 mg/L, and this adjusted value was used as the chloride concentration of rainfall in all chloride ratio analyses in this study. Fourteen of the 39 ground-water sample sites were eliminated from consideration because samples contained high-chloride concentrations thought to be from saltwater intrusion or from deeper artesian waters, or the samples were from sites near the shoreline (Gulf or river) or a swamp and judged to be in a discharge area rather than a recharge area. Oxygen isotope ratios, as described later, were used as a corroborating guide to the removal of some of the data sets. The analyses of the remaining 25 ground-water samples (ranging from 6 to 90 mg/L in chloride concentration in table 2) were used in conjunction with equation 1 to estimate recharge to the surficial aquifer system. Using a value of 54 in/yr for annual rainfall, calculated recharge rates ranged from 0.6 to 9.0 in/yr (table 2).

Oxygen Isotope Ratios

Stable isotope techniques have been used previously by Swart and others (1989) and Meyers (1990) to

Table 1. Rainfall, chloride, delta oxygen 18, and delta deuterium values from precipitation collection sites in Lee County

[Site locations are shown on plate 1. Delta oxygen 18 is the difference between the ratio of oxygen 18 to oxygen 16 in the sample and the same ratio in Standard Mean Ocean Water. Refer to equation 3 in text. Delta deuterium is the difference between the ratio of ^2H commonly written D from the name deuterium to ^1H in the sample to the same ratio in Standard Mean Ocean Water. Delta oxygen 18 and delta deuterium units in parts per thousand (called per mil by analogy with percent)]

Site No.	Site name	Latitude	Longitude	Date of collection	Rainfall (inches)	Chloride (milligrams per liter)	Delta oxygen 18 (per mil)	Delta deuterium (per mil)
1	Pine Island	263745	0820730	05-21-89	1.5	6	-6.808	-42.2
				05-27-89	1.0	6	-8.572	-58.4
2	Fort Myers	263716	0815310	06-02-89	2.5	4	-4.310	-3.9
3	Lehigh	263840	0813550	05-27-89	1.0	5	-7.835	-53.5
				06-06-89	3.0-4.0	4	-2.649	-11.9
4	Sanibel	262550	0820618	05-27-89	1.5	4	-4.285	-20.8
5	San Carlos	262803	0814924	06-06-89	1.0-2.0	4	-5.319	-34.5
				06-07-89	2.0-3.0	6	-1.926	-3.5
6	Bonita Springs	262044	0814518	05-27-89	2.5	4	-4.980	-29.4

study evaporating water from other areas in southern Florida. These techniques were used in this study primarily to verify that the source of chlorides in waters from the surficial aquifer system was from precipitation rather than from upward leakage of saline waters from the deeper aquifer system and to distinguish recharge from discharge areas. As discussed in the previous section, isotope ratios indicated that only 25 of the 39 observation wells yielded water affected solely by recharge. The geochemical techniques used in determining the stable isotope ratios involve the measurement of the isotope species $H_2{}^{16}O$ (water molecule with oxygen 16), $H_2{}^{18}O$ (water molecule with oxygen 18), and $HD\,{}^{16}O$ (water molecule with deuterium) in a water sample. The hydrogen isotopic ratio, *D/H*, is determined from $HD\,{}^{16}O$ and $H_2{}^{16}O$, and the oxygen isotopic ratio, $^{18}O/^{16}O$, is determined from $H_2{}^{18}O$ and $H_2{}^{16}O$. Variability in $^{18}O/^{16}O$ of natural waters is only a few parts per hundred; therefore, it is convenient to determine the difference between the $^{18}O/^{16}O$ ratio of a sample and that of a standard, in parts per thousand, defined as delta ^{18}O ($\delta^{18}O$) (Gonfiantini, 1981). Thus:

$$\delta^{18}O = \frac{(^{18}O/^{16}O)\ sam - (^{18}O/^{16}O)\ std}{(^{18}O/^{16}O)\ std} \times 1{,}000 \qquad (3)$$

where *sam* is sample and *std* is standard.

For ^{18}O, the normal reference standard is Standard Mean Ocean Water (SMOW) as defined by Craig and Gordon (1965). In practice, each laboratory has its own standard (or set of standards) that has been calibrated against the SMOW scale. During a measurement, the isotopic ratio of the sample is compared to that of the laboratory standard (by means of a mass spectrometer), and the result is recalculated to the SMOW scale.

Delta ^{18}O ($\delta^{18}O$) and delta deuterium (δD) are, by the definition of the SMOW scale, zero for ocean water. Spatial variations in isotopic composition of ocean water are relatively small, except where there is a large influx of freshwater, which creates an increase of ^{16}O concentrations relative to normal seawater values (Drever, 1988).

Delta ^{18}O in natural waters ranges from -50 to +10 parts per thousand. Ranges in the hydrogen isotopic ratio, *D/H*, are about eight times these limits

Table 2. Chloride concentrations, calculated recharge rates, delta oxygen 18, and delta deuterium for ground-water samples from wells completed in the surficial aquifer system in Lee County

[Well locations are shown on plate 1. Latitudes, longitudes, and well depths are given in table 3. Calculated recharge rate is $(Cl_p/Cl_{gw})P$ where Cl_p is chloride concentration of precipitation, in milligrams per liter (average 1 milligram per liter for Cl_p); Cl_{gw} is chloride concentration of ground water, in milligrams per liter; and P is precipitation (rainfall), in inches per year (average 54 inches per year for P). Delta oxygen 18 is the difference between the ratio of oxygen 18 to oxygen 16 in the sample and the same ratio in Standard Mean Ocean Water. Delta deuterium is the difference between the ratio of ^{2}H commonly written D from the name deuterium to ^{1}H in the sample and the same ratio in Standard Mean Ocean Water. Delta oxygen 18 and delta deuterium units in parts per thousand (called per mil by analogy with percent). Refer to equation 3 in text. Dashes indicate data that were not used due to various environmental influences]

Well No.	Date of collection	Chloride (milligrams per liter)	Calculated recharge rate (inches/year)	Delta oxygen 18 (per mil)	Delta deuterium (per mil)
L-246	04-23-89	--	--	0.38	2.37
L-721	04-23-89	14	3.9	-2.28	-11.39
L-726	04-24-89	6	9.0	-2.59	-15.30
L-728	04-24-89	32	1.7	-1.34	-1.69
L-730	04-25-89	6	9.0	-3.28	-12.06
L-739	04-24-89	30	1.8	-.39	-3.76
L-954	04-24-89	--	--	-3.03	-2.82
L-1136	04-26-89	80	0.7	-2.10	-8.37
L-1137	04-23-89	10	5.4	-3.07	-15.90
L-1138	04-24-89	50	1.1	-.59	-3.73
L-1403	04-24-89	--	--	-2.55	-8.88
L-1457	04-25-89	--	--	-1.99	-10.55
L-1964	04-25-89	22	2.4	.89	-8.22
L-1976	04-24-89	--	--	-2.31	-12.79
L-1978	04-24-89	14	3.8	-3.10	-13.46
L-1985	04-24-89	22	2.4	-1.59	-.81
L-1992	04-25-89	--	--	-2.51	-4.53
L-1995	04-23-89	26	2.1	-.74	-9.32
L-1997	04-24-89	60	.9	-.38	-1.02
L-1999	04-24-89	36	1.5	-1.44	-8.62
L-2191	04-23-89	14	3.9	-2.90	-12.61
L-2195	04-24-89	30	1.8	-1.20	-2.70
L-2202	04-24-89	48	1.1	-2.89	-8.39
L-2204	04-23-89	24	2.2	-.84	-2.58
L-2217	04-24-89	90	.6	-.11	-4.02
L-2308	04-24-89	14	3.9	-2.06	-10.36
L-2549	04-23-89	--	--	-1.30	-11.74
L-3203	04-26-89	46	1.1	-.11	-9.22
L-3205	04-26-89	--	--	-2.34	-15.32
L-3206	04-26-89	--	--	-1.02	-4.29
L-3207	04-26-89	--	--	-1.41	-7.08
L-3208	04-23-89	--	--	-1.89	-8.78
L-3209	04-24-89	34	1.6	-1.75	-8.65
L-3210	04-23-89	52	1.0	-2.79	-10.57
L-3211	04-26-89	--	--	-.05	-11.42
L-3212	04-26-89	50	1.1	-2.29	-10.77
L-3213	04-26-89	--	--	-1.97	-13.22
L-3214	04-23-89	64	.8	-.57	-16.30
L-3215	04-23-89	--	--	-1.40	-19.21

(Drever, 1988, p. 371). The principal cause of such variations is the evaporation and condensation cycle. During evaporation, the heavier isotopes of hydrogen and oxygen are fractionated (preferentially left behind), and the lighter isotopes are concentrated in the evaporated water vapor. When water vapor condenses to form rain, additional fractionation takes place in the reverse direction with the liquid being isotopically heavier than the vapor. In general, because of fractionation, rain becomes progressively isotopically lighter in δD and $\delta^{18}O$ from the Equator toward the Poles, from the coast inland, and from lower to higher elevation (Drever, 1988).

Ground water from 39 observation wells and 6 precipitation collection sites was sampled for oxygen and hydrogen stable isotopic composition in Lee County (pl. 1). Two to three well volumes of water were pumped from each well using a gas-engine centrifugal pump to sample water that was in contact with the rock units. Collected water samples were stored in plastic bottles and analyzed for stable oxygen and hydrogen isotopic composition at the University of Miami Stable Isotope Laboratory.

The oxygen isotopic composition of the water was determined by carbon dioxide equilibration with 0.06102 in^3 (cubic inch) of sample. Equilibration was obtained by shaking the sample for 24 hours at 77 degrees Fahrenheit (method from Epstein and Mayeda, 1953). Experiments using this technique showed that equilibrium was attained in samples of normal salinity in less than 5 hours. Hydrogen was prepared from 1 to 5 µL (microliters) of sample by reduction over zinc or uranium (Friedman and O'Neil, 1977). The isotopic ratios of both gases were determined using a Finnigan-MAT 251 at the University of Miami Stable Isotope Laboratory. Reproducibility of oxygen isotopic analyses, determined by replicate analyses of standards within a single batch of equilibrations, is within about 0.2 part per thousand, and hydrogen is within 1.0 part per thousand (Swart and others, 1989).

With the exception of one analysis, all samples of precipitation fall close to the relation defined for global precipitation known as the meteoric water line (fig. 6). The range of $\delta^{18}O$ for precipitation was between -9 and -2 per mil SMOW, and the range of δD was between -58 and -3.5 per mil SMOW (table 1). These values for rainfall are in good agreement with those determined for southeastern Florida by Swart and others (1989).

Analyses of ground-water samples indicate two distinct groups based on *O* and *H* isotopic composition (fig. 6 and tables 1 and 2). All water samples collected to the east of the urban areas of Fort Myers and Cape Coral trend away from the meteoric water line (flatter slope) in a manner characteristic of evaporating waters (Craig and Gordon, 1965). This is consistent with recharge to the surficial aquifer system after some evaporation has occurred with enrichment with respect to deuterium and oxygen 18. Based on this trend, these waters are considered to be derived from a precipitation source and are similar to trends shown by Swart and others (1989) and Meyers (1990) for evaporating waters from other areas of southern Florida. A similar shift toward the slightly isotopically heavier $\delta^{18}O$ value can be caused by exchange with calcium carbonate in the limestone aquifers (Drever, 1988, p. 371). However, the slope of the trend is more similar to that determined by Swart and others (1989) and Meyers (1990) for evaporating waters.

In contrast to eastern Lee County, ground water in western Lee County near the Cape Coral area was isotopically heavier, with some wells plotting below the meteoric water line (fig. 6). Water in this area tends to have a higher chloride concentration (table 1) but does not have an isotopic composition similar to marine water. The most likely source for the higher chloride concentration is the underlying artesian intermediate aquifer system (fig. 3), which has an isotopic composition similar to that seen in the surficial aquifer in western Lee County (Meyers, 1990). This indicates a discharge rather than recharge area.

At present (1995), there is no method for relating $\delta^{18}O$ and δD values directly to recharge amounts, as is the case for chloride ratios. This technique is useful, however, for tracing ground-water movement and for identifying mixing of waters from different sources. As such, this technique can be useful for distinguishing discharge areas from recharge areas and, therefore, for identifying areas where the chloride ratio technique or other methods may yield valid quantitative results.

Flow-Tube Analysis

The configuration of the local water table and the hydraulic conductivity of the surficial aquifer system need to be known to produce an accurate flow-tube analysis. The water-table contours on plates 1 and 2 at the back of this report represent water-level averages (tables 3 and 4) for October 1982-91 in Lee County and

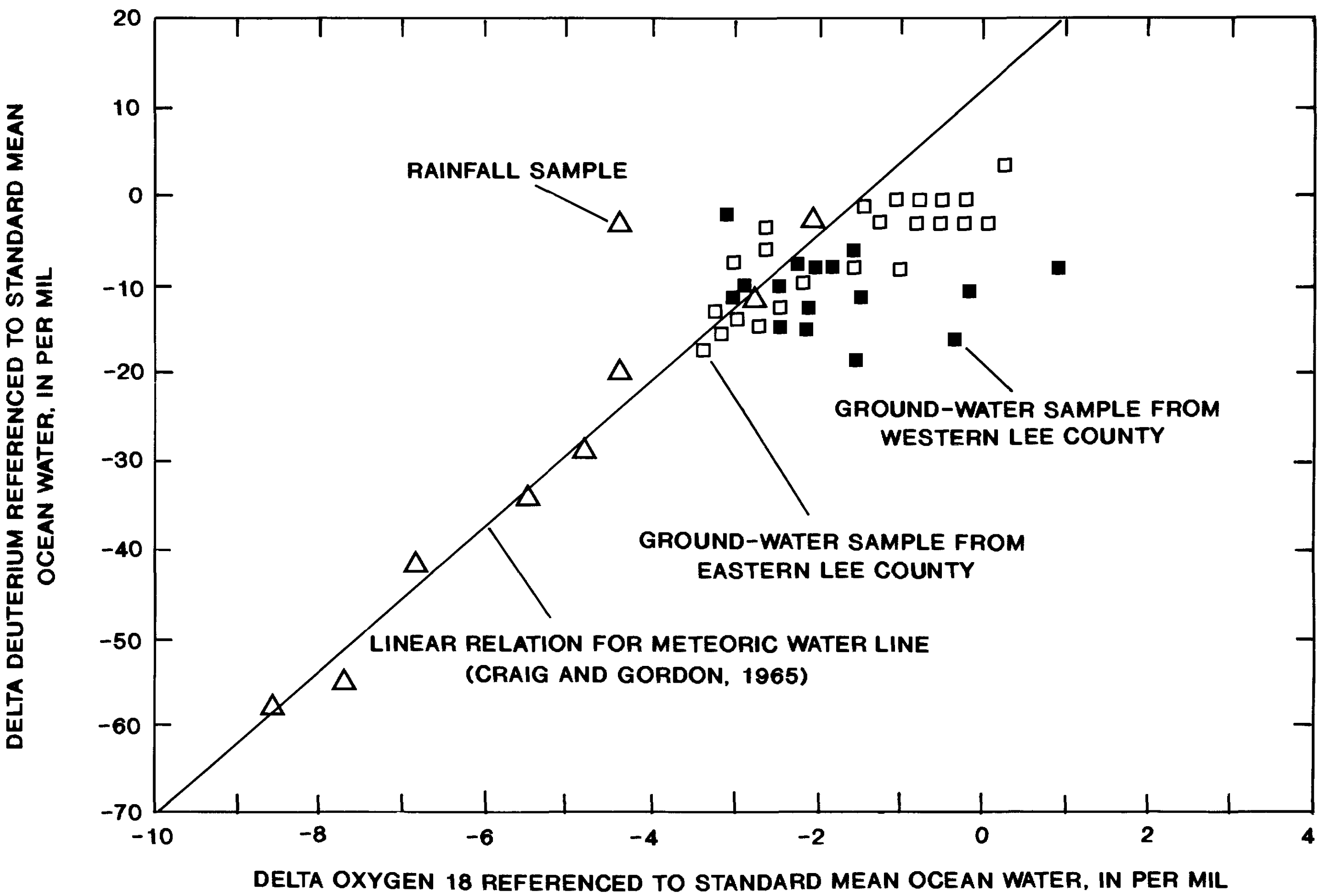

Figure 6. Relation between delta deuterium and delta oxygen 18 in rainfall and ground-water samples collected in Lee County

Table 3. Water levels from wells completed in the surficial aquifer system in Lee County, October 1982-91

[Well locations shown on plate 1]

Local well number	Latitude	Longitude	Well depth (feet)	Water levels, in feet above sea level										10-year average
				1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	
L-246	263802	0814935	28	17.76	8.21	17.13	18.32	16.94	18.53	16.99	16.86	18.27	17.16	17.62
L-721	264153	0820223	18	3.16	3.31	3.70	3.03	2.88	3.28	2.30	3.38	2.31	3.06	3.04
L-726	264425	0814540	19	12.61	12.88	12.97	12.77	12.99	13.53	12.40	13.14	13.94	13.60	13.08
L-728	263712	0814612	19	19.69	20.28	18.57	19.94	19.40	20.67	18.19	19.44	20.14	19.16	19.55
L-730	263127	0813516	19	27.77	27.64	27.13	27.47	27.08	27.18	26.64	27.45	26.76	26.71	27.18
L-739	262657	0814435	20	17.37	17.28	15.80	16.77	16.03	17.80	16.37	17.48	16.14	16.08	16.71
L-954	263903	0815504	14	3.38	.66	.15	3.91	2.63	3.45	.90	1.58	2.79	4.94	2.44
L-1136	263528	0815922	20	4.82	4.82	4.41	4.87	4.45	5.31	4.16	4.56	4.73	5.08	4.72
L-1137	263950	0813554	20	19.24	19.66	17.40	18.75	19.34	19.74	17.64	19.12	18.21	17.82	18.69
L-1138	262703	0813402	20	21.59	22.18	22.21	22.12	21.84	22.18	22.04	22.03	22.64	22.28	22.11
L-1403	262549	0820353	12	2.47	2.44	.79	2.30	2.21	2.17	.09	2.15	2.35	2.19	1.92
L-1457	262622	0820220	11	1.86	2.44	1.88	2.12	2.16	2.47	1.94	2.20	3.30	2.55	2.29
L-1964	263344	0813617	27	26.54	26.52	25.60	26.80	25.98	28.19	25.34	25.89	26.75	25.63	26.32
L-1976	264359	0814247	15	11.07	11.44	10.98	11.02	11.14	12.15	10.62	12.03	11.99	11.60	11.40
L-1978	264320	0813657	17	15.25	15.54	13.10	14.62	14.25	15.36	14.04	15.14	12.58	14.83	14.47
L-1985	262713	0814147	50	16.91	16.93	15.60	17.61	13.93	18.12	12.52	15.63	13.73	16.43	15.74
L-1992	263353	0813358	29	23.88	24.16	23.32	23.95	23.59	24.38	23.33	23.53	23.97	23.45	23.76
L-1995	263251	0814528	27	23.26	23.54	22.97	23.94	22.48	23.78	22.88	23.55	24.44	23.60	23.44
L-1997	261954	0814101	20	14.73	15.00	11.83	11.91	12.18	13.21	12.91	13.02	13.01	15.07	13.29
L-1999	263041	0804331	26	24.21	24.37	22.64	23.70	23.22	24.20	21.34	23.84	24.82	24.17	23.65
L-2191	264144	0815203	26	10.10	9.74	9.95	9.71	9.30	10.34	8.72	9.34	9.26	10.05	9.65
L-2195	261957	0814322	15	12.15	12.59	10.66	10.89	9.78	13.14	10.16	10.71	10.79	12.60	11.35
L-2202	265329	0813404	17	14.92	15.01	12.28	14.05	14.33	15.31	13.65	14.42	13.16	14.46	14.16
L-2204	263329	0813943	26	28.35	27.10	25.82	26.50	27.38	28.15	25.20	27.37	27.21	26.37	26.95
L-2217	264608	0814541	18	24.78	25.33	23.80	23.94	24.64	26.66	23.81	25.36	25.40	25.61	24.93
L-2308	262552	0814857	14	12.92	13.29	12.18	13.38	12.49	13.46	12.41	11.33	14.02	13.86	12.93
L-2549	263955	0820831	80	6.40	6.49	6.42	7.34	6.18	6.52	5.65	6.56	5.59	6.59	6.37
L-3203	263813	0815528	18	4.34	4.40	4.14	4.54	4.30	4.75	4.04	4.25	4.31	4.61	4.37
L-3205	263257	0815857	18	.81	1.21	.96	2.00	.58	.95	.97	.64	1.03	1.31	1.05
L-3206	263253	0820142	18	2.18	2.32	2.44	3.06	2.10	2.50	1.95	1.83	2.25	2.19	2.28
L-3207	263440	0820220	18	2.21	2.25	2.27	2.92	1.96	2.29	1.72	1.81	2.00	2.01	2.14
L-3208	263743	0820412	18	1.36	1.40	1.81	1.96	1.21	.94	1.27	.90	1.09	1.46	1.34
L-3209	264537	0815522	18	19.81	19.81	19.24	19.32	19.08	19.44	18.83	18.97	19.30	19.48	19.33
L-3210	264002	0820128	19	4.40	4.50	4.78	5.27	4.50	4.81	3.79	4.65	3.99	5.32	4.60
L-3211	263819	0815858	19	6.70	6.71	6.44	6.70	6.48	6.95	6.33	6.56	6.71	7.37	6.70
L-3212	263621	0815637	18	2.22	2.27	1.85	2.66	1.65	2.35	1.60	.33	2.26	2.39	1.96
L-3213	263357	0815756	18	1.85	2.28	1.89	2.64	2.15	3.75	2.57	2.60	3.41	3.96	2.71
L-3214	263955	0820831	18	6.43	6.46	6.58	7.32	6.22	6.56	5.69	6.60	5.63	6.64	6.41
L-3215	263117	0820510	18	2.92	3.38	2.64	4.36	3.01	3.10	1.92	3.11	2.94	3.46	3.08

Table 4. Water levels from wells completed in the surficial aquifer system in Hendry County, October 1987-91

[Well locations shown on plate 2]

Local well number	Latitude	Longitude	Well depth (feet)	Water levels, in feet above sea level					5-year average
				1987	1988	1989	1990	1991	
HE-3	261859	080585401	10	18.38	17.09	17.46	15.59	18.44	17.39
HE-5	263700	081070001	13	24.98	23.32	23.45	24.48	23.90	24.03
HE-339	263700	080550001	13	12.01	13.53	12.17	13.51	12.96	12.84
HE-554	263310	081250902	15	30.34	28.24	29.83	30.33	30.23	29.79
HE-558	264235	081310602	14	14.92	14.46	15.07	15.14	15.41	15.00
HE-569	263930	081301503	17	22.85	23.10	22.79	23.77	23.28	23.16
HE-851	263845	081260703	13	28.24	26.34	27.92	27.60	27.03	27.43
HE-852	263548	081200601	14	28.53	26.73	27.15	27.59	27.69	27.54
HE-854	263515	081012001	14	20.41	19.02	19.20	19.98	20.01	19.72
HE-856	263035	081073502	11	27.16	25.38	25.34	25.96	27.31	26.23
HE-857	264535	081130701	17	17.29	15.61	16.66	17.11	16.51	16.64
HE-858	264235	081074401	17	20.00	19.85	20.09	20.01	19.90	19.97
HE-860	262735	081044601	14	25.21	23.00	23.29	23.08	23.89	23.69
HE-862	261735	080534002	11	11.27	10.14	11.77	11.39	12.65	11.44
HE-1027	263514	081170701	7	28.43	26.73	28.42	28.33	27.97	27.98
HE-1036	263213	081040801	10	24.52	23.29	23.04	23.31	24.30	23.69
HE-1043	262214	081113002	10	21.47	20.18	20.27	20.37	22.97	21.05
HE-1062	261746	081061803	10	17.46	16.64	16.53	14.13	17.89	16.53
HE-1069	264046	081022802	13	16.74	15.86	17.85	16.22	16.11	16.56
HE-1077	263839	081203901	10	25.05	25.24	24.50	24.98	26.27	25.21

October 1987-91 in Hendry County. Water levels measured from numerous observation wells (7-80 ft deep) completed in the surficial aquifer system were highest in eastern Lee and western Hendry Counties and lowest along coastal Lee County and the Caloosahatchee River in both counties. Water levels can be influenced by various factors including rainfall, ground-water withdrawals, ground-water discharge, topography, evapotranspiration, downward leakage, and tidal fluctuations in the Gulf of Mexico and canals.

Flowlines and equipotential lines were drawn on plates 1 and 2 according to established rules for graphical flow-net construction, assuming homogeneous and isotropic media (Ledengren, 1967). The flowlines show ground-water flow from recharge to discharge areas—from the higher elevations of eastern Lee County toward the Gulf of Mexico and the Caloosahatchee River (pl. 1) and from the higher elevations of western Hendry County near LaBelle toward the Caloosahatchee River (pl. 2). Infiltration in the interstream higher elevations is generally more effective in recharging the surficial aquifer system than infiltration near points of discharge from the surficial aquifer system. Consequently, topographic setting is important. Soil that has high vertical hydraulic conductivity might not be an effective recharge area if it is adjacent to a stream, but soil that has relatively low hydraulic conductivity might be an effective recharge area if it is in a relatively high flat interstream area.

The flowlines indicate direction of flow at every point in a flow domain. A flow tube can be delineated along flowlines (fig. 7). Incremental recharge to the flow tube can be calculated from the application of Darcy's law to recharge estimation. Darcy's law is $Q = -K\, dh/dl\, A$ where K is the horizontal hydraulic conductivity of the aquifer, dh is the downgradient head minus the upgradient head, dl is the length of the flow path along which dh occurs, and A is the cross-sectional area through which the flow occurs.

Flow from h_2 to h_1 (fig. 7) is:

$$Q_1 = -K\frac{(h_1 - h_2)}{L_1}A_1$$

$$\frac{Q_1}{A_1} = -K\frac{(h_1 - h_2)}{L_1} \qquad (4)$$

$$\frac{Q_1}{A_1} = K\frac{(h_2 - h_1)}{L_1}$$

Switching h_1 and h_2 removes the minus sign.

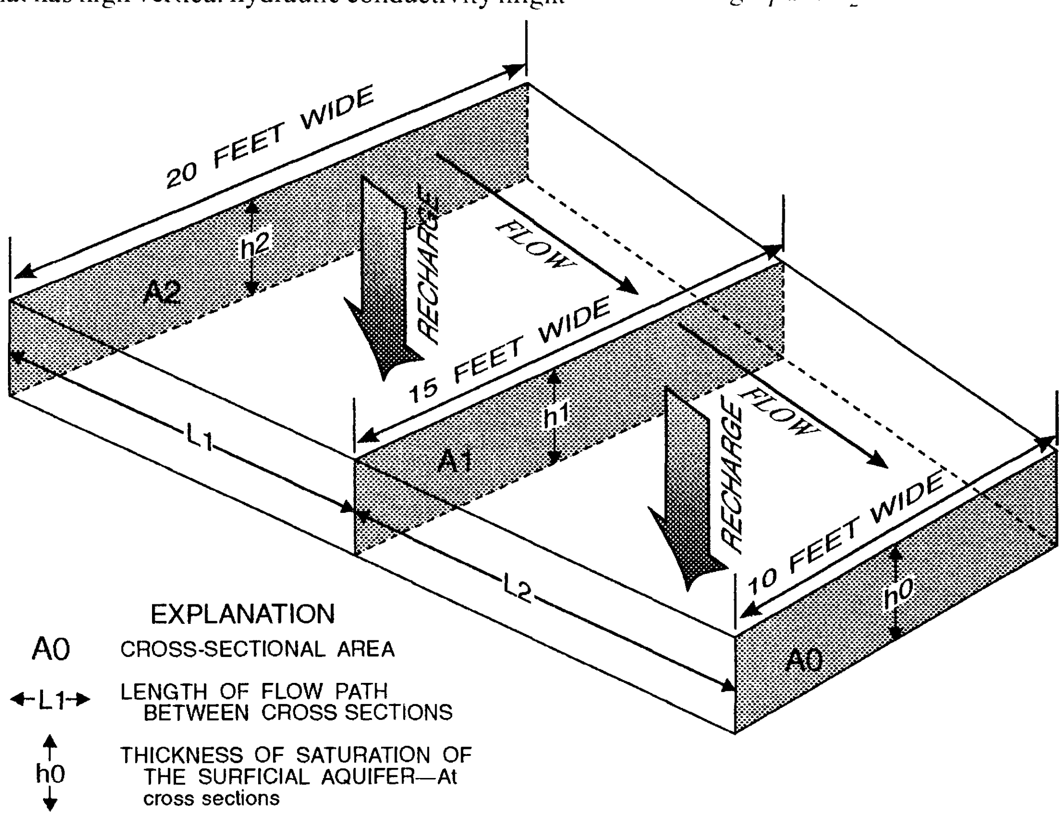

Figure 7. Diagram of flow-tube analysis.

Flow from h_1 to h_0 is:

$$Q_2 = -K\frac{(h_0 - h_1)}{L_2}A_2$$
$$\frac{Q_2}{A_2} = -K\frac{(h_0 - h_1)}{L_2} \qquad (5)$$
$$\frac{Q_2}{A_2} = K\frac{(h_1 - h_0)}{L_2}$$

Switching h_1 and h_0 removes the minus sign.

Therefore, recharge in an area is the downgradient flow minus the upgradient flow:

$$R = \frac{Q_2}{A_2} - \frac{Q_1}{A_1}$$
$$R = K\frac{(h_1 - h_0)}{L_2} - K\frac{(h_2 - h_1)}{L_1}$$
$$R = K\left[\frac{h_1 - h_0}{L_2} - \frac{h_2 - h_1}{L_1}\right] \qquad (6)$$
$$R = \Delta q = \frac{Q_2}{A_2} - \frac{Q_1}{A_1} = K\left[\frac{(h_1 - h_0)}{L_2} - \frac{(h_2 - h_1)}{L_1}\right]$$

where R is recharge to the flow tube, in cubic feet per day per square foot; Δq is specific discharge, in feet per day; Q is discharge, in cubic feet per day; A is cross-sectional area (aquifer thickness times distance between flowlines); K is hydraulic conductivity, in feet per day; h is head, in feet; and L is length of flow path, in feet.

If K is replaced by the transmissivity, T, then Q values are multiplied by the aquifer thickness, b, and the value obtained must be divided by b to yield R. Whether using T or K, detailed information is needed regarding the aquifer thickness and hydraulic conductivity or transmissivity. Missimer and Associates (1978) estimate an average K of 60 ft/d (feet per day) and a range from 40 to 90 ft/d for the surficial aquifer system near Sanibel. Using the average K value and using a flow-tube example from plates 1 and 2, the following results are obtained:

$$R_{Lee\ County} = K\left[\frac{(h_1 - h_0)}{L_2} - \frac{(h_2 - h_1)}{L_1}\right]$$
$$= 60\ ft/d\left[\frac{10 - 5\ ft}{5,174\ ft} - \frac{15 - 10\ ft}{5,016\ ft}\right] \qquad (7)$$
$$= 0.00183\ ft/d \bullet 365\ days/yr \bullet 12\ in/ft$$
$$= 8.0\ in/yr$$

$$R_{Hendry\ County} = K\left[\frac{(h_1 - h_0)}{L_2} - \frac{(h_2 - h_1)}{L_1}\right]$$
$$= 60\ ft/d\left[\frac{(20 - 15\ ft)}{8,976\ ft} - \frac{(25 - 20\ ft)}{9,504\ ft}\right] \qquad (8)$$
$$= 0.00186\ ft/d \bullet 365\ days/yr \bullet 12\ in/ft$$
$$= 8.2\ in/yr$$

This result provides an estimate of change of flow between the middle of L_1 and the middle of L_2 that is equal to the amount of recharge in the part of the flow tube between the middle of L_1 and the middle of L_2 for Lee and Hendry Counties, respectively.

These recharge rates can be viewed as representing an average of the rates within the area of the flow tube. There can be places within the flow tube area where local recharge is greater or less than the average rate given. The values obtained, 8.0 and 8.2 in/yr, are within the ranges obtained by the chloride ratio method and, thus, serve to corroborate the chloride ratio results.

Regionalized Recharge Rates

Soils characteristics of Lee and Hendry Counties were used along with general topographic and hydrologic considerations to group soil types with regard to potential recharge rates. Ranges of recharge rates were then assigned to each soil grouping based on local values estimated by the chloride ratio method or flow-tube analysis. Soil types and associated recharge rates are shown on plates 3 and 4.

There are four main soil types for Lee County (soils of flatwoods and sloughs, soils of swamps and sloughs, soils of tidal areas and barrier islands, and soils of manmade areas) and three main soil types for Hendry County (soils of flatwoods and sloughs, soils of the Everglades, and soils of sloughs and freshwater marshes). The delineation of soil types on plates 3 and 4 were based on U.S. Department of Agriculture soil survey maps (Henderson, 1984; Belz and others, 1990), depicting general soil characteristics of Lee and Hendry Counties.

Soils of flatwoods and sloughs constitute about 70 percent of the land area in both Lee and Hendry Counties and are predominant in central and northern Lee County (pl. 3) and in central and western Hendry County (pl. 4). Deposits consist of nearly level, poorly drained, sandy soils with a sandy, organic-stained subsoil underlain by a loamy subsoil. The native vegetation is slash pine, and wetter areas commonly have cypress, sawpalmetto, and pine that are mainly used for urban development or wildlife habitat. Recharge is present throughout this soil type with low runoff and low duration of standing water indicating water infiltration. Calculated recharge rates by the method of chloride ratios for 17 sites in Lee County for this soil type ranged from 0.6 to 9.0 in/yr. Because of its lateral proximity to Lee County, Hendry County soils of flatwoods and sloughs are expected to have recharge rates similar to those found in Lee County, though no ground-water samples were collected in Hendry County for this study. The flow-tube analysis from the previous section was made in this soil type, and the resulting recharge rates (8.0 in/yr for Lee County and 8.2 in/yr for Hendry County) do confirm moderate recharge rates in this soil type for both counties. The range of natural average annual recharge assigned to this soil type is 0 to 10 in/yr for both Lee and Hendry Counties. The lower wetter areas would tend to have recharge in the lower end of the range, and the drier slash pine areas would tend to have recharge near the upper end of the range.

Soils of swamps and sloughs constitute about 9 percent of the land area in Lee County and are predominant in the southeastern part of the county and along the northern reaches of the Caloosahatchee River (pl. 3). Deposits consist of nearly level, poorly drained, deep to moderately deep, sandy soils with some loamy, sandy subsoil throughout. The native vegetation in the areas (cypress, pine, and sawpalmetto) is used mainly for wildlife habitat and rangeland. There is little to no recharge in this soil type as the areas have standing water, high evapotranspiration rates, and low infiltration rates during the wet season. Calculated recharge rates by the chloride ratio method for four sites in Lee County for this soil type ranged from 1.5 to 2.4 in/yr. A range of between 0 and 3 in/yr has been assigned to this soil type for average annual recharge in Lee County. This named soil type is not present in Hendry County.

Soils of tidal areas and barrier islands constitute about 11 percent of the land area in Lee County and are predominant along Cape Coral, Estero, Sanibel Island, Fort Myers, and Pine Island (pl. 3). Deposits consist of nearly level, very poorly drained, mucky soils that are relatively organic and sandy throughout with a varying mixture of shell fragments on the tidal areas and barrier islands along the Gulf Coast. Native vegetation in the areas is natural—mainly mangroves and various grasses. This soil type is considered to be in a discharge area as the land-surface altitude is only slightly above sea level. Consequently, ground water is discharged from the surficial aquifer system into the streams, rivers, and the Gulf of Mexico. Although four wells sampled in this study were in this soil type, all were disregarded because of relatively high-chloride concentrations thought to be the result of the presence of saltwater rather than evapoconcentration of precipitation. Nevertheless, small rates of recharge are possible in the higher areas in this soil type and a range of between 0 and 2 in/yr has been assigned to this soil type for average recharge.

Soils of manmade areas constitute about 10 percent of the land area in Lee County and are predominant in the vicinity of Cape Coral (pl. 3). Deposits consist of nearly level, relatively poorly drained soils with a mixture of sands, shell fragments, and limestone fragments throughout. The soils were formed by earth-moving operations in areas designated for urban development. In addition, a complex network of canals has been excavated throughout Cape Coral where water levels are controlled by a series of weirs. This soil type is considered to be in a discharge to little recharge area because most of the rainfall runs off to canals. Recharge from canals to the manmade soils occurs in some areas when the canal water level is higher than the water table below the adjacent land. Normally, however, the canals drain water from the surficial aquifer system, thereby lowering water levels and creating some storage potential for recharge to the system which would not have been available under natural conditions. Calculated recharge rates by the chloride ratio method for four sites in Lee County for this soil type ranged from 0.7 to 1.1 in/yr. A range of between 0.5 and 1.5 in/yr has been assigned to this soil type for average recharge.

Soils of the Everglades constitute about 11 percent of the land area in Hendry County and are predominant in the area along the Hendry-Palm Beach County line (pl. 4). Deposits consist mainly of nearly level, poorly to very poorly drained soils underlain by limestone; some soils are sandy throughout, organic, and have a thin muck surface layer. Drainage and water control have been established in most of the area, so the soils can be used primarily for improved pasture or sugarcane. Under natural conditions, these soils are not suitable for cultivating crops because of wetness. There is little to no recharge in this soil type under natural conditions, as the area has standing water, high evapotranspiration rates, and low infiltration rates. A range of between 0 and 2 in/yr has been assigned to these areas for natural average annual recharge. Where drained, a potential for induced recharge may exist, which together with amounts that would naturally occur, could exceed 2 in/yr. However, no data were collected in this soil type to confirm recharge rates for either natural or drained conditions.

Soils of sloughs and freshwater marshes constitute about 19 percent of the land area in Hendry County and are predominant in the central and southern parts of the county (pl. 4). Deposits consist of nearly level, poorly to very poorly drained, sandy, loamy, and organic soils with a loamy subsoil. The native vegetation in the areas (grasses, cypress pine, and sawpalmetto) is used for improved or native pasture. The soils are severely limited for most agricultural uses by the high-water table; however, if water control is adequate, the soils are suitable for various vegetable, citrus, and improved pasture crops. Under natural conditions, there is little to no recharge in this soil type as the areas have standing water, high evapotranspiration rates, and low infiltration rates. A range of between 0 and 2 in/yr has been assigned to these areas for natural recharge.

Soils of flatwoods and sloughs are the only main soil type considered to transmit significant recharge to the surficial aquifer system in Lee and Hendry Counties, as confirmed by the chloride-ratio and flow-tube analyses made for flatwoods and sloughs. However, recharge amounts in this soil type vary, depending on local topography and the hydraulic characteristics of the local soils.

More refined estimates of natural recharge could be made if more detailed topographic maps become available at, for example, a 2-ft contour interval and if finer soil groupings had been used. It is possible that isolated small areas of high natural recharge rates (greater than 10 in.) do exist in Lee and Hendry Counties, but the maximum rate calculated in this study was 9.0 in/yr. A high water table is a limiting factor for natural recharge in many parts of the study area.

Natural recharge rates for most of Lee and Hendry Counties are low. From the standpoint of water use and water management, however, rates of recharge, which could be induced by lowering the water table through pumping, could be much higher and should be taken into account in calculating pumping rates which could be sustained in an area. Such lowering of the water table has already occurred in much of the study area, thereby increasing the potential for recharge. Potential recharge could be defined as the amount of recharge that would actually occur if the water table remained below the reach of evaporation and transpiration. Information from soil surveys conducted by the U.S. Department of Agriculture throughout Florida on infiltration capacity of soil types could be used along with knowledge of rainfall, evaporation, and evapotranspiration to produce maps of potential recharge to the surficial aquifer system. However, such an effort is beyond the scope of this study.

CONCLUSIONS

Two methods used to calculate recharge to the surficial aquifer in Lee and Hendry Counties were both viable techniques for estimating recharge in areas of low topographic relief typical of southwestern Florida. The chloride concentration ratio method, in which the ratio of chloride concentrations in precipitation to chloride concentration in the surficial aquifer is multiplied by rainfall to produce a point recharge value, was considered valid for 25 of 39 sites tested in Lee County. Estimated average annual recharge among the 25 sites varied from 0.6 to 9.0 in/yr, using this method. The flow-tube method, in which increases in flow are calculated along a theoretical flow tube in the surficial aquifer to produce local recharge values, yielded recharge rates of 8.0 and 8.2 in/yr, respectively, for parts of Lee and Hendry Counties.

Both the chloride concentration ratio method and the flow-tube analysis are suitable alternative methods for estimating recharge rates. The chloride concentration ratio method is simpler to apply because it does not require knowledge of hydraulic conductivity of the surficial aquifer system or detailed information on water levels. Oxygen isotope information is useful in identifying origins and paths of water in the surficial aquifer system and in identifying whether or not recharge from rainfall was present in the ground water.

The maximum recharge rate calculated for this study was 9.0 in/yr, calculated by the chloride ratio method in a soil of the flatwoods and sloughs type in Lee County. This soil type was the only one considered to have significant natural recharge, with a mapped areal range of between 0 and 10 in/yr, on average. Soils of swamps and sloughs were assigned a range of between 0 and 3.0 in/yr and soils of tidal areas and barrier islands, soils of the Everglades, and soils of sloughs and freshwater marshes all had assigned ranges of between 0 and 2.0 in/yr. Lastly, soils of manmade areas were assigned values of between 0.5 and

1.5 in/yr. These mapped values were assigned based on calculated point and local recharge values and general considerations related to topography and hydraulic characteristics of soil types. Generally, topographically low and wet areas tended to have little or no recharge.

Although no high-rate recharge areas were found in this study, it is possible that small isolated areas exist within which natural recharge rates are greater than 10 in/yr. Despite low natural recharge rates, however, lowering of the water table through pumping or canalization could create a potential for induced recharge in excess of 10 in/yr in many parts of Lee and Hendry Counties. Additionally, these higher induced rates could be taken into account when calculating pumping rates which could be sustained without excessive drawdown to the surficial aquifer system.

In conclusion, it is feasible to map annual recharge rates at a scale of 1:100,000 in Lee and Hendry Counties. However, only broad ranges of recharge rates can be determined at present, given the low topographic relief and lack of means for directly measuring ground-water discharge to streams which, for steady-state conditions, equals ground-water recharge.

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