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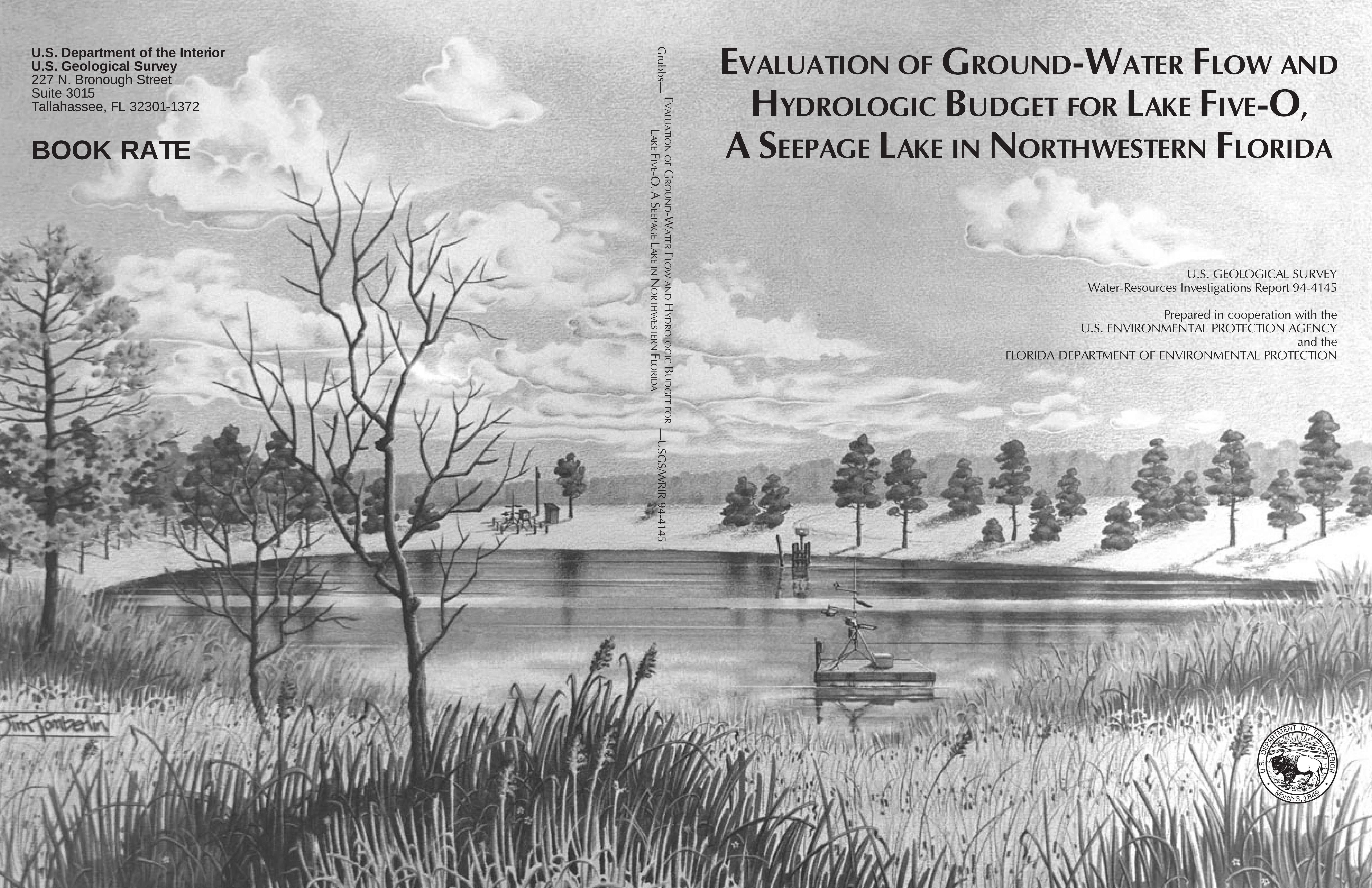
BOOK RATE

Grubbs— EVALUATION OF GROUND-WATER FLOW AND HYDROLOGIC BUDGET FOR LAKE FIVE-O, A SEEPAGE LAKE IN NORTHWESTERN FLORIDA —USGS/WRIR 94-4145

EVALUATION OF GROUND-WATER FLOW AND HYDROLOGIC BUDGET FOR LAKE FIVE-O, A SEEPAGE LAKE IN NORTHWESTERN FLORIDA

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 94-4145

Prepared in cooperation with the
U.S. ENVIRONMENTAL PROTECTION AGENCY
and the
FLORIDA DEPARTMENT OF ENVIRONMENTAL PROTECTION



U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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By J.W. Grubbs

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U.S. DEPARTMENT OF THE INTERIOR
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CONTENTS

FIGURES

TABLES

Conversion Factors, Vertical Datum, Acronyms, and Additional Abbreviations

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
hectare	2.471	acre
cubic meter (m^3)	35.31	cubic foot
centimeter per year (cm/yr)	0.3937	inch per year
meter per day (m/d)	3.281	foot per day
meter per year (m/yr)	3.281	foot per year
square meter per day (m^2/d)	10.76	square foot per day
cubic meter per day (m^3/d)	35.31	cubic foot per day
newton per cubic meter (N/m^3)	0.006366	pound per cubic foot
pascal (Pa)	0.02089	pound per square foot

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:

$$°F = 1.8(°C) + 32$$

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

Acronyms

ANC acid neutralizing capacity
NOAA National Oceanographic and Atmospheric Administration

Additional abbreviations

$\mu eq/L$ microequivalents per liter

Evaluation of Ground-Water Flow and Hydrologic Budget for Lake Five-O, A Seepage Lake in Northwestern Florida

By J.W. Grubbs

Abstract

Temporal and spatial distributions of ground-water inflow to, and leakage from Lake Five-O, a softwater, seepage lake in northwestern Florida, were evaluated using hydrologic data and simulation models of the shallow ground-water system adjacent to the lake. The simulation models indicate that ground-water inflow to the lake and leakage from the lake to the ground-water system are the dominant components in the total inflow (precipitation plus ground-water inflow) and total outflow (evaporation plus leakage) budgets of Lake Five-O. Simulated ground-water inflow and leakage were approximately 4 and 5 times larger than precipitation inputs and evaporative losses, respectively, during calendar years 1989-90. Exchanges of water between Lake Five-O and the ground-water system were consistently larger than atmospheric-lake exchanges. A consistent pattern of shallow ground-water inflow and deep leakage was also evident throughout the study period. The mean time of travel for ground-water that discharges at Lake Five-O (time from recharge at the water table to discharge at the lake) was estimated to be within a range of 3 to 6 years. Flow-path evaluations indicated that the intermediate confining unit probably has a negligible influence on the geochemistry of ground-water inflow to Lake Five-O. The hydrologic budgets and flow-path evaluations provide critical information for developing geochemical budgets for Lake Five-O, and for improving the understanding of the relative importance of various processes that regulate the acid-neutralizing capacity of softwater seepage lakes in Florida.

INTRODUCTION

The acidification of lakes through the atmospheric deposition of mineral acids has been found to adversely affect a number of aquatic organisms and habitats, particularly in the northeastern United States and Canada. Florida has a larger number and higher percentage of acidic lakes than any other major region in the United States (Pollman and Canfield, 1991). Although acidic depositional impacts are less evident in Florida lakes (Brenner and others, 1990, p. 376), the low cation-exchange capacities of soils in soft-water lake regions suggests that these lakes could be vulnerable to further, perhaps harmful, levels of acidification. At present, a quantitative understanding of the relative importance of the various processes that regulate the acid-neutralizing capacity (ANC) in Florida lakes is lacking. Improving the understanding of ANC regulation is hampered by the uncertainty associated with the hydrology of seepage lakes, which are the largest class of lakes in Florida (Pollman and Canfield, 1991). Seepage lakes, by definition, have no surface inlets or outlets, and their hydrology is often poorly understood because the exchange of water between these lakes and their adjacent ground-water systems is difficult to quantify. Developing a quantitative understanding of seepage lake ANC regulation requires a better understanding of the magnitude and timing of contributions of water from, and losses to, adjacent ground-water systems, as well as knowledge of the history (residence time and contact with various lithologies) and chemistry of ground water that discharges to seepage lakes.

In 1988, two parallel, 4-year studies were begun to describe the hydrologic and chemical dynamics of two soft-water, seepage lakes: Lake Five-O in Bay County in northwestern Florida (fig. 1), and Lake Barco in north-central Florida (Pollman and others, 1991). The objective of these studies was to quantify the relative importance of-ground water contributions of ANC and in-lake transformation processes in the regulation of ANC in acidic, seepage lakes (Pollman and others, 1991). To satisfy this objective, hydrologic and geochemical budgets were developed for both lakes through direct and indirect measurement of hydrologic, meteorologic, and water-quality variables, and through the use of hydrologic and geochemical models.

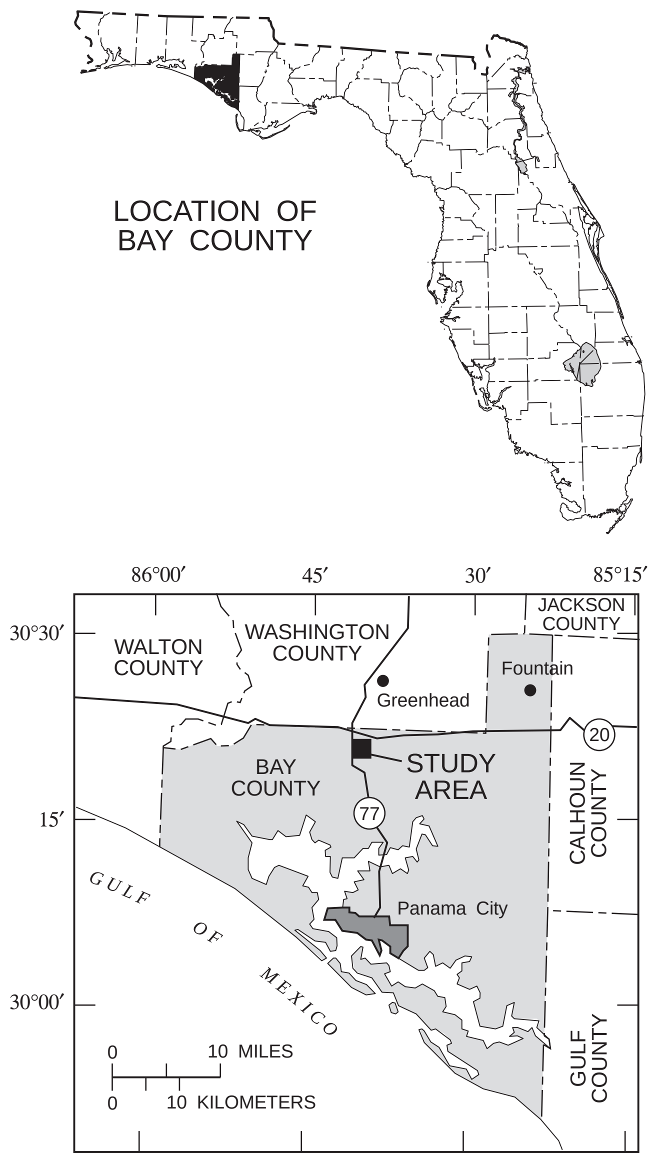

Figure 1. Location of Lake Five-O study area.

The studies at Lake Five-O and Lake Barco were conducted by KBN Engineering and Applied Sciences, Tetra Tech, and the U.S. Geological Survey. The studies were supported with funding or assistance from the U.S. Environmental Protection Agency, the U.S. Geological Survey, the Florida Electric Power Coordinating Group, the Electric Power Research Institute, Southern Company Services, and the Florida Department of Environmental Protection. The role of the U.S. Geological Survey in the study of Lake Five-O was to develop a hydrologic budget for the lake and collect samples of lake water, ground water, and precipitation for chemical analysis (Andrews and others, 1990). The hydrologic budget for Lake Five-O was developed using direct measurements of precipitation, energy-budget estimates of lake evaporation (Sacks and others, 1994), and calibrated models of the ground-water flow system adjacent to the lake.

Purpose and Scope

This report describes (1) the hydrology of the ground-water flow system near Lake Five-O, (2) the development and calibration of simulation models of the ground-water flow system near Lake Five-O, and (3) the hydrologic budget of Lake Five-O, as determined from model simulation results and data collected during 1988-91. The report is based on hydrologic and lithologic data that were collected from July 1988 to February 1991 at Lake Five-O and the immediate vicinity. These data are presented in the context of a conceptual model of the ground-water flow system, which formed the basis for subsequent mathematical models of the flow system. The report presents the results of simulations using several steady-state models and a transient model and presents a monthly hydrologic budget for Lake Five-O for calendar years 1989 and 1990. Simulated ground-water flow paths and residence times are also presented in the report.

Previous Studies

Several articles and reports which describe various aspects of the studies at Lake Barco and Lake Five-O have been published. Andrews and others (1990) described the study area of Lake Five-O and presented a preliminary evaluation of the hydrogeologic setting and water quality of the lake.

Pollman and others (1991) presented preliminary water budgets and evaluations of processes controlling alkalinity regulation in lakes Barco and Five-O. Sacks and others (1992) described the hydrogeologic setting and presented a preliminary data analysis for the hydrologic budget at Lake Barco. Sacks and others (1994) presented final lake evaporation estimates for lakes Barco and Five-O, and evaluated the various factors that influence evaporation and alternative techniques for estimating lake evaporation at both lakes.

Description of Study Area

Lake Five-O is in the Crystal Lake Karst area of the Dougherty Karst physiographic district (Brooks, 1981). This area is characterized by coastal terrace deposits that have been modified by extensive karst development (Brooks, 1981). The Lake Five-O watershed is part of a relict marine terrace of Pleistocene age, lying between 21 and 52 m above sea level (Schmidt and Clark, 1980). Soils in the region are deep, excessively drained, and consist of very permeable, Lakeland series sands (Duffee and others, 1984). Vegetation in the area includes various species of pine and scrub oak trees, which are common to excessively drained sand ridges and terraces in Florida. Residential development in the area is sparse, and pine tree cultivation is the dominant land use (Andrews and others, 1990). The trees in the watershed were harvested to the periphery of the lake basin (approximately 50 m from the shoreline) in the spring of 1988, before the study began, and the watershed was planted with sand pine in the fall of 1988 (Pollman and others, 1991).

The physiography of the Lake Five-O study area is typical of the Crystal Lake Karst region. Lake Five-O and surrounding lakes lie in steep-sided depressions (slopes of 8-12 percent) and are surrounded by a mostly flat plateau area with land surface altitudes ranging from 25 to 30 m above sea level (fig. 2). Lake Five-O is relatively deep, with the altitude of the relatively flat bottom ranging from 2.5 m above sea level to -0.15 m below sea level (Andrews and others, 1990). The maximum lake depth ranged from 13.5 to 15.4 m during the study period, with a mean daily value of 14.5 m. The surface area of Lake Five-O ranged from 10.4 to 11.3 hectares, with a mean daily value of 10.9 hectares. Lake volume ranged from 9.09×10^5 m^3 to 1.11×10^6 m^3, with a mean daily value of 1.02×10^6 m^3.

The climate of Bay County is humid subtropical, with an annual average temperature of 21 °C, and monthly average temperatures ranging from 12 °C in January to 28 °C in July (Schmidt and Clark, 1980). Mean-annual precipitation is approximately 160 cm, with the wettest months of summer and early fall (June through September) typically accounting for nearly half of the annual precipitation. Distinct dry periods typically occur in the spring months of April and May, and fall months of October and November. Mean annual lake evaporation is approximately 120 cm, and is typically lowest in winter and greatest in summer. The large difference between mean annual precipitation and evaporation (approximately 40 cm), accounts in large part for the high annual runoff (50-100 cm) in this region (Rumenik, 1988). The precipitation total for the first full year of the study period, 1989, was approximately 25 percent above normal, whereas in 1990, the total was approximately 25 percent below normal.

Acknowledgments

The author gratefully acknowledges the Rosewood Timber Company and George H. Eubank, Forest Manager, for granting access to Lake Five-O. The author is also grateful for technical support provided by representatives of the U.S. Environmental Protection Agency, the Florida Electric Power Coordinating Group, the Electric Power Research Institute, Southern Company Services, and the Florida Department of Environmental Protection. Finally, the author would like to acknowledge the work performed by Hal Davis, U.S. Geological Survey, in refining the initial interpretation of the seismic reflection survey.

GROUND-WATER FLOW SYSTEM NEAR LAKE FIVE-O

The following sections describe the water-level monitoring network, hydrogeology and ground-water flow system near Lake Five-O. The physical extent, lithologic characteristics, and estimated values of hydraulic properties are presented for each of the hydrogeologic units that influence the hydrology of Lake Five-O. Descriptions of the total hydraulic head (head) distribution, conceptual boundary conditions, and preliminary estimates of ground-water flow to and from Lake Five-O are also presented to emphasize essential features of the ground-water flow system.

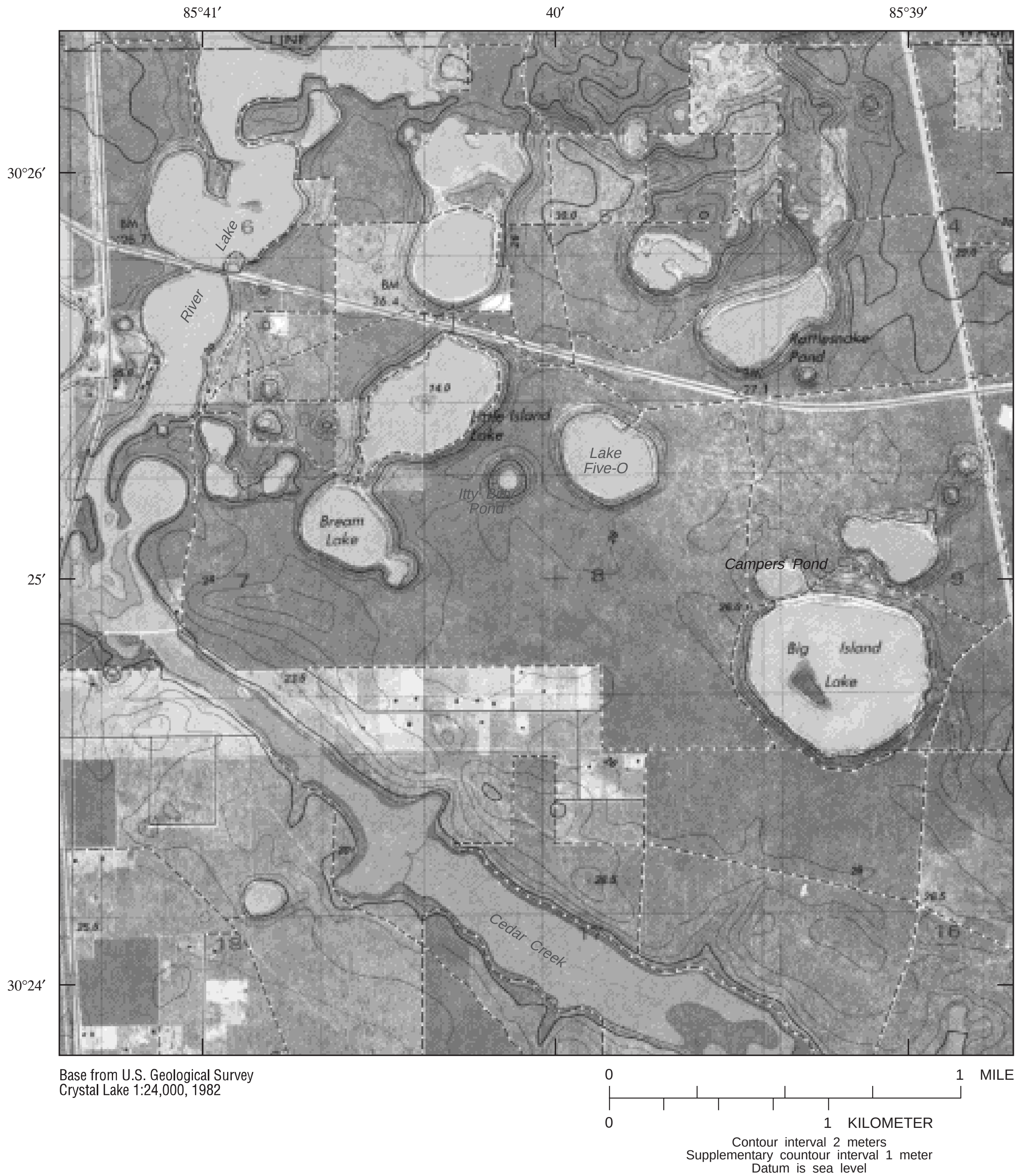

Figure 2. Topography of the Lake Five-O study area.

Collectively, this information defines a conceptual model of the ground-water system near Lake Five-O. This conceptual model forms the basis for subsequent numerical (simulation) models of the ground-water flow system.

A water-level monitoring network was established at the study site to collect water-level and water-quality data from the ground-water system adjacent to Lake Five-O. The network consisted of 55 wells finished at various depths and locations in the surficial aquifer, intermediate confining unit, and Upper Floridan aquifer, and 6 water-level stations at Lake Five-O and 5 surrounding lakes (fig 3). A description of each well is given in table 1. Wells near the lake margin have the prefix “pz” or “lp”, and the remaining wells have the prefix “w”. Groups of wells that are clustered together but screened at different altitudes are referred to as well or piezometer nests, and are identified by a decimal number that follows one of the above prefixes. The number before the decimal indicates the well nest number and the number following the decimal indicates the well within a particular well nest. For example, well w1.5 is the fifth well located in well nest 1. Water-level (head) data from the wells and lakes were used to describe temporal variations in the head distribution near Lake Five-O, evaluate patterns of ground-water inflow and leakage, and infer hydraulic characteristics

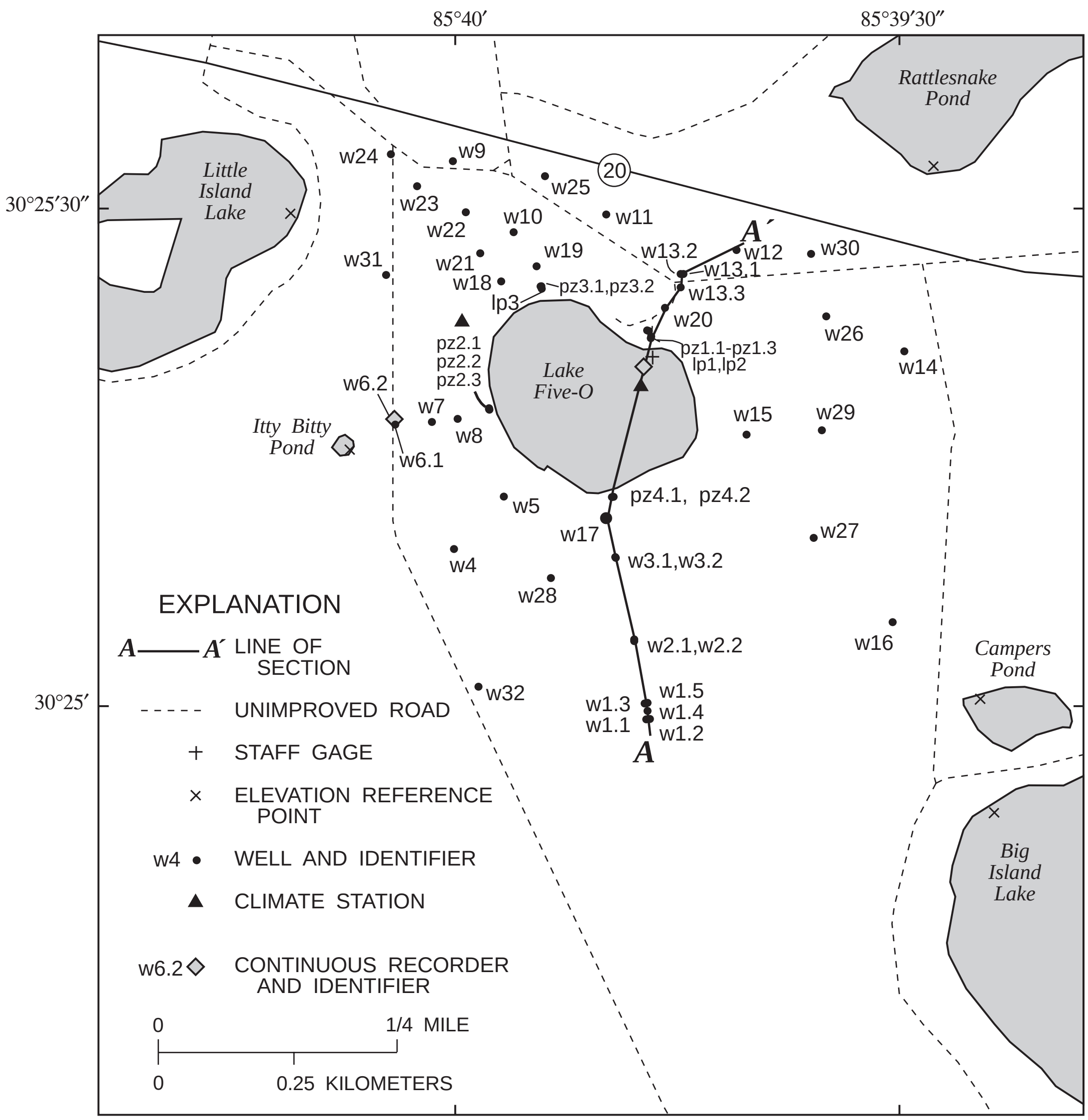

Figure 3. Location of data-collection sites in the Lake Five-O study area.

Table 1. Description of monitoring wells in the Lake Five-O study area

[SA, surficial aquifer; ICU, intermediate confining unit; UFA, Upper Floridan aquifer]

Well identifier	Latitude-longitude	Altitude of top of well casing, in meters above sea level	Well depth, in meters	Well screen length, in meters	Hydro-geologic unit
w1.1	30°24′58″ 85°39′47″	27.68	11.35	1.52	SA
w1.2	30°24′58″ 85°39′46″	27.50	17.60	1.52	SA
w1.3	30°24′59″ 85°39′47″	27.40	25.96	1.52	ICU
w1.4	30°24′58″ 85°39′47″	27.44	31.54	1.52	ICU
w1.5	30°24′59″ 85°39′47″	27.22	42.28	1.52	UFA
w2.1	30°25′02″ 85°39′48″	26.87	9.30	1.52	SA
w2.2	30°25′02″ 85°39′48″	26.98	18.04	1.52	SA
w3.1	30°25′07″ 85°39′49″	26.80	10.72	1.52	SA
w3.2	30°25′07″ 85°39′49″	26.84	18.40	1.52	SA
w4	30°25′08″ 85°40′00″	25.28	10.58	1.52	SA
w5	30°25′11″ 85°39′56″	26.58	12.28	1.52	SA
w6.1	30°25′15″ 85°40′04″	22.83	9.22	1.52	SA
w6.2	30°25′15″ 85°40′04″	23.07	11.36	1.52	SA
w7	30°25′15″ 85°40′01″	26.88	12.36	1.52	SA
w8	30°25′16″ 85°40′00″	26.78	12.41	1.52	SA
w9	30°25′31″ 85°40′00″	26.91	12.19	1.52	SA
w10	30°25′27″ 85°39′56″	29.06	12.15	1.52	SA
w11	30°25′28″ 85°39′50″	26.87	12.00	1.52	SA
w12	30°25′26″ 85°39′41″	27.01	12.22	1.52	SA
w13.1	30°25′24″ 85°39′44″	27.01	12.41	1.52	SA
w13.2	30°25′24″ 85°39′44″	27.08	18.53	1.52	SA
w13.3	30°25′23″ 85°39′44″	26.61	40.81	1.52	UFA
w14	30°25′20″ 85°39′29″	27.62	10.82	1.52	SA
w15	30°25′15″ 85°39′40″	27.62	12.17	1.52	SA
w16	30°25′03″ 85°39′30″	27.54	11.14	1.52	SA
w17	30°25′10″ 85°39′50″	25.73	28.14	1.52	ICU
w18	30°25′24″ 85°39′57″	22.81	11.14	0.91	SA
w19	30°25′25″ 85°39′54″	23.00	10.75	0.91	SA
w20	30°25′22″ 85°39′45″	22.95	10.52	1.52	SA
w21	30°25′26″ 85°39′58″	27.76	15.50	0.91	SA
w22	30°25′28″ 85°39′59″	27.38	15.51	0.91	SA
w23	30°25′30″ 85°40′02″	27.24	16.58	0.91	SA
w24	30°25′31″ 85°40′04″	22.54	12.08	0.91	SA
w25	30°25′30 85°39′54	27.33	15.54	0.91	SA
w26	30°25′22 85°39′34	27.13	15.75	0.91	SA
w27	30°25′08 85°39′35	27.08	15.68	0.91	SA
w28	30°25′06 85°39′53	25.68	13.12	0.91	SA
w29	30°25′15 85°39′35	28.68	14.70	0.91	SA
w30	30°25′25 85°39′36	27.57	16.29	0.91	SA
w31	30°25′24 85°40′05	26.71	15.71	0.91	SA
w32	30°25′00 85°40′00	25.28	10.57	0.91	SA
pz1-1	30°25′21 85°39′47	16.00	8.34	0.91	SA
pz1-2	30°25′21 85°39′47	15.97	5.94	0.91	SA
pz1-2A	30°25′21 85°39′47	16.23	6.34	1.52	SA
pz1-3	30°25′21 85°39′47	16.17	10.56	1.52	SA
lp1	30°25′21″ 85°39′46″	14.94	3.36	0.91	SA
lp2	30°25′20″ 85°39′46″	14.79	1.67	0.91	SA

Table 1. Description of monitoring wells in the Lake Five-O study area—Continued

[SA, surficial aquifer; ICU, intermediate confining unit; UFA, Upper Floridan aquifer]

Well identifier	Latitude-longitude	Altitude of top of well casing, in meters above sea level	Well depth, in meters	Well screen length, in meters	Hydro-geologic unit
lp3	30°25′23″ 85°39′54″	14.76	1.40	0.91	SA
pz2-1	30°25′16″ 85°39′57″	17.87	6.86	1.52	SA
pz2-2	30°25′16″ 85°39′57″	17.94	9.77	1.52	SA
pz2-3	30°25′16″ 85°39′57″	17.94	12.84	1.52	SA
pz3-1	30°25′24″ 85°39′54″	15.44	11.16	1.52	SA
pz3-2	30°25′24″ 85°39′54″	15.45	3.75	1.52	SA
pz4-1	30°25′12″ 85°39′49″	17.57	5.54	1.52	SA
pz4-2	30°25′12″ 85°39′49″	17.64	12.12	1.52	SA

of the hydrogeologic units of interest. Cuttings, sediment cores, and geophysical surveys from the above wells were also used to describe the hydrogeology of the study area.

Local Hydrogeology

The hydrogeologic setting of the study area has been previously discussed by Andrews and others (1990). They identified three hydrogeologic units that influence the hydrology of Lake Five-O: the surficial aquifer, the intermediate confining unit, and the Upper Floridan aquifer. A revised version of their preliminary hydrogeologic section, A-A′, is shown in figure 4.

The surficial aquifer consists of an unconsolidated layer of very permeable sands of Pliocene to Holocene age which extend from land surface (26-30 m above sea level) to an altitude of 3 to 9 m above sea level in the plateau of the study area (Andrews and others, 1990). The grain-size distribution of the surficial sediments within 2 m of land surface is characterized by fine to coarse sands with a silt-clay fraction of less than 5 to 10 percent (Duffee and others, 1984). Horizontal hydraulic-conductivity estimates from slug tests of 23 wells screened within the surficial aquifer ranged from 8 to 75 m/d, with median, and lower and upper quartile values of 19, 12 and 23 m/d, respectively (Andrews and others, 1990). This range of values is consistent with the range of 13 to 17 m/d given by the Soil Conservation Service (Duffee and others, 1984) for Lakeland sands, and a range of 5 to 54 m/d using Hazen's approach (Fetter, 1988, p. 81). Given the well sorted, sandy character of the surficial aquifer sediments, the ratio of horizontal to vertical hydraulic conductivity (anisotropy) of the surficial sediments was assumed to be low, probably within a range of 1 to 20. These characteristics also suggest that the porosity of the sands in the surficial aquifer is probably within a range of 0.25 to 0.50 (Fetter, 1988), and specific yield within a range of 0.10 to 0.30 (Johnson, 1967; Walton, 1970). Based on the sediment compressibility estimates of Freeze and Cherry (1979, p. 55) and Domenico and Schwartz (1990, p. 111) and the estimate given by Lohman (1979, p. 8), specific storage of the surficial sediments is probably within a range of 10^{-6} to 10^{-3} m^{-1}.

The surficial aquifer is underlain by the Jackson Bluff Formation (intermediate confining unit) of Pliocene age, which consists of calcareous, sandy clay to clayey sand with large quantities of shell material, and seams of fossiliferous sandy limestone (Andrews and others, 1990). A thin, dense shelly clay layer, approximately 1.5-m thick, occurs at the base of the intermediate confining unit in the study area (Andrews and others, 1990). In the plateau of the study area, the top and bottom of the intermediate confining unit occur at altitudes of 3 to 9 m above and 4 to 14 m below sea level, respectively. Lithologic data and a reflection surface from a seismic reflection survey indicate that nearer the lake, the top of the intermediate confining unit dips toward several depressions in the top of the unit (figs. 4 and 5). These depressions are most likely the result of the collapse of the intermediate confining unit and surficial aquifer into one or more voids created by dissolution of the underlying limestone aquifer. Highly permeable sands from the

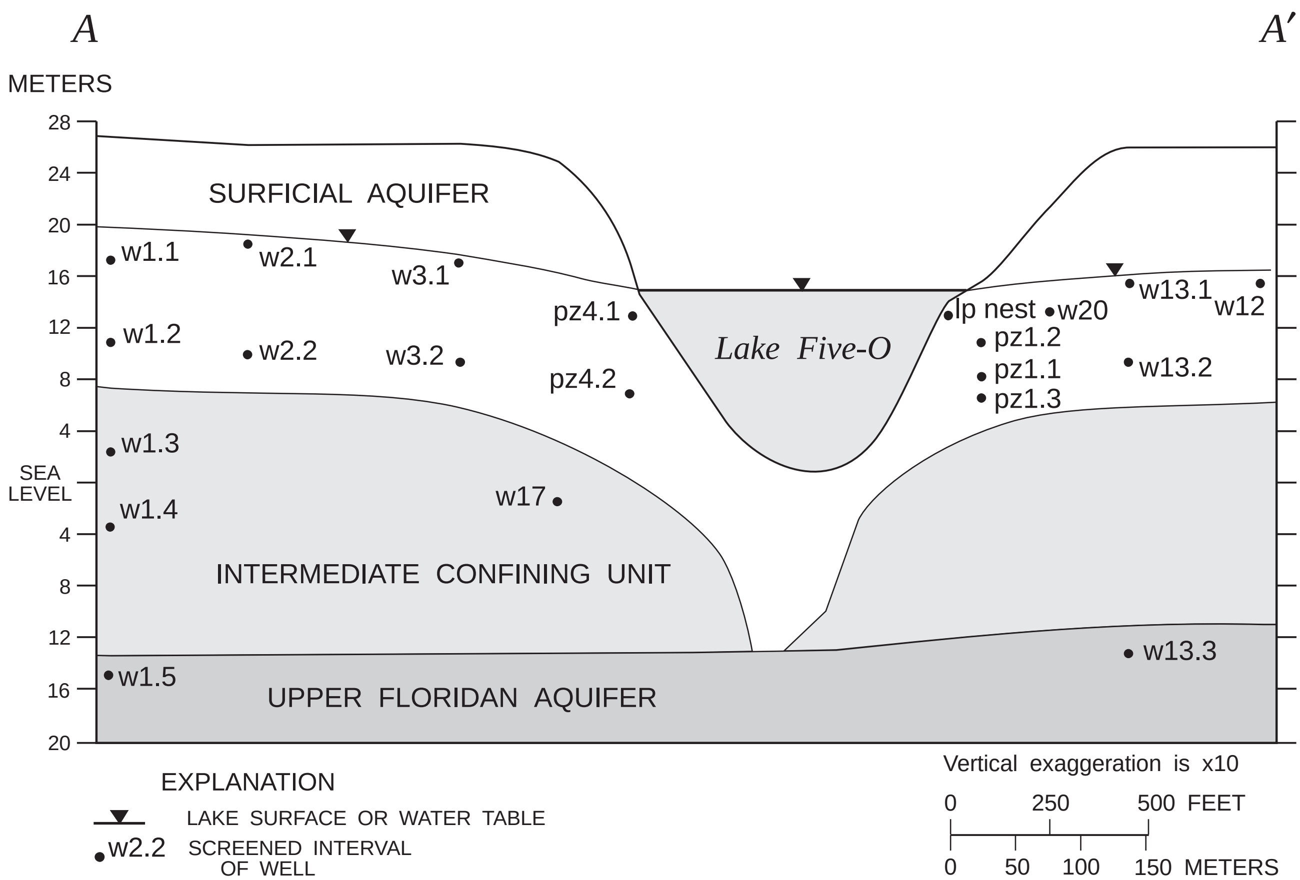

Figure 4. Hydrogeologic section A-A′ through Lake Five-O showing midpoints of screened intervals of observation wells used to construct the section. (Location of section is shown in figure 3. Hydrogeologic section A-A′ revised from Andrews and others, 1990.)

surficial aquifer have probably filled these breaches, thus creating a high conductance pathway between the surficial aquifer and the Upper Floridan aquifer.

Estimates of the hydraulic properties of the intermediate confining unit were based on the lithologic characteristics of the unit, previously published data, and limited slug test data. Lithologic data indicate that conductive properties may vary considerably within the intermediate confining unit. The 1.5-m-thick clay layer at the base of the intermediate confining unit seems to be much less conductive and more continuous than the limestone and sandy-clay/clayey-sand facies in the overlying intermediate confining-unit sediments (Andrews and others, 1990). Maslia and Hayes (1988, pl. 3) presented a highly generalized map of leakance (vertical hydraulic conductivity divided by thickness) which indicates that the regional leakance of the sediments overlying the Upper Floridan aquifer is within the range of 5×10^{-5} to 5×10^{-4} d^{-1} in northern Bay and southern Washington Counties. Leakance values for the intermediate confining unit are probably smaller than these regional estimates, because the regional values are averaged over large areas, within which confining unit is often breached. Given these regional leakance estimates and the lithologic information collected at the study site, the vertical hydraulic conductivity of the basal clay layer was assumed to be within the range of 10^{-11} to 10^{-5} m/d. Determining representative hydraulic conductivity values for intermediate confining-unit sediments that overlie the basal clay is difficult because of the poorly sorted nature and variable composition of unconsolidated sediments within the unit, and the lack of information on the extent and degree of secondary porosity of the limestone beds within the unit. A slug test conducted at well w1.3 (fig. 3) yielded an estimated range in horizontal hydraulic conductivity of 0.03 to 0.15 m/d. However,

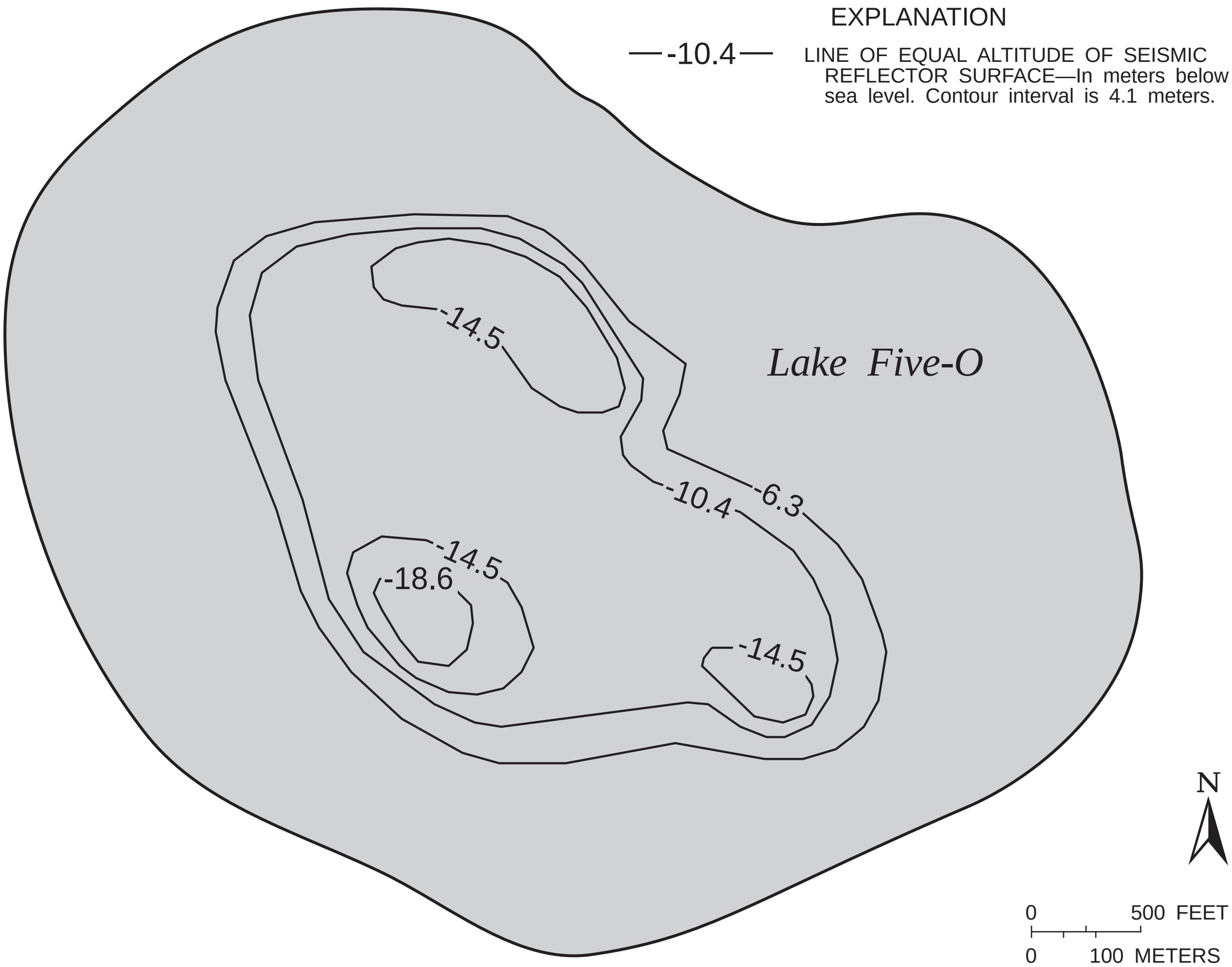

Figure 5. Altitude of seismic reflector surface beneath Lake Five-O. (Hal Davis, U.S. Geological Survey, written commun., 1991.)

the results of this test are extremely limited because of the heterogeneity of the unit. Horizontal hydraulic conductivity values for the intermediate confining unit sediments in the study area (excluding the basal clay layer) were assumed to vary over a much larger range (10^{-3} to 1 m/d) than that indicated by the single slug test. The anisotropy of these intermediate confining-unit sediments was assumed to be within 10 to 1,000. The porosity of the intermediate confining unit was assumed to be in the range of 0.10 to 0.50, and specific storage was assumed to be in the range of 10^{-6} to 10^{-3} m^{-1}(Freeze and Cherry (1979, p. 55); Lohman (1979, p. 8); Domenico and Schwartz (1990, p. 111).

The Floridan aquifer system consists of a thick sequence of mostly Paleocene to early Miocene age carbonate rocks (Miller, 1986) that underlie Florida, and parts of Alabama, Georgia, and South Carolina. The permeability of the Floridan aquifer system is largely attributed to secondary porosity resulting from the dissolution of the carbonate rock (Maslia and Hayes, 1988, p. 20). Miller (1986) subdivided the Floridan aquifer system into the Upper and Lower Floridan aquifers, which are separated in most areas by a middle confining unit. The Upper Floridan aquifer influences the hydrology of many of the lakes and streams near the study area. In the study area, the top of the Upper Floridan aquifer is at depths of 4 to 14 m below sea level, and the aquifer has a thickness of approximately 180 m. The study area lies at the southern extent of a belt of high transmissivity in the Floridan aquifer system, which has resulted from a highly interactive surface-water and ground-water flow (Maslia and Hayes, 1988, p. 21). Estimates of transmissivity of the Floridan aquifer system in the study area range from 9 x 10^3 to 6 x 10^4 m^2/d (Maslia and Hayes, 1988, pl. 6).

Ground-Water Movement

Hydrologic data collected during the study provided the basis for a preliminary description of ground-water flow near Lake Five-O. Hydraulic head and lithologic information were used to conceptualize ground-water flow within and between the hydrogeologic units. The head data were also used to define the location and characteristics of boundaries of the flow system. Precipitation, evaporation, and lake-volume data were used to compute preliminary estimates of ground-water inflow to and leakage from Lake Five-O. In this report, the term ground-water inflow refers to the flow of water into Lake Five-O from the contiguous ground-water system, and the term leakage refers to the flow of water from Lake Five-O to the contiguous ground-water system.

Head Distribution and Ground-Water Flow near Lake Five-O

Head fluctuations during the study period were generally consistent with the typical seasonal patterns of precipitation in northwestern Florida (wet conditions during the summer and dryer conditions during the fall and spring). Heads rose during the wet summer seasons of 1989 and 1990, and fell during dry periods during the spring months of 1989 and 1990, and the fall of 1990 (fig. 6). These seasonal head changes also occurred in a consistent manner throughout the Lake Five-O flow system (fig. 6), which resulted in approximately constant spatial distributions of head over the range of meteorologic conditions that occurred during the study (figs. 7-10). This indicates that patterns of ground-water flow were also reasonably consistent during the study period.

Head data from the monitoring network indicated a consistent pattern of ground-water flow toward Lake Five-O. With the exception of a small area adjacent to the northwest lake margin, water-table altitudes were consistently higher than the stage of Lake Five-O, and water-table altitudes increased with distance from the lake (figs. 7-10). Higher water-table altitudes were observed in the southern part of the study area and decreased to the northwest. This head distribution resulted in a steeper horizontal head gradients south of the lake and smaller gradients northwest of the lake. This suggests that ground-water inflow rates are largest south of the lake and descrease to the northwest. This pattern of ground-water flow was observed throughout the study period, over a wide range of hydrologic conditions, which indicates ground-water inflow to Lake Five-O occurred around most of the lake perimeter throughout the study period.

The head data also indicated a strong potential for downward leakage from Lake Five-O to the Upper Floridan aquifer (fig. 9-11). Differences between the stage of Lake Five-O and the head in the Upper Floridan aquifer (as estimated from heads at wells 1.5 and 13.3) ranged from 1.3 to 2.2 m (fig. 11). Abrupt declines in this head difference were observed during the summer (June-August) of 1989, but abrupt increases were observed during the summer of 1990 (fig. 11). This indicates that leakage from Lake Five-O decreased during the summer of 1989 and increased to a maximum in the summer of 1990.

Changes in this head difference (and therefore leakage from Lake Five-O) are probably due to regional variations in recharge to the Upper Floridan aquifer during the two periods. This hypothesis is supported by observed water levels from a long-term Upper Floridan aquifer monitoring well in nearby Greenhead, Fla. (approximately 9 km north of Lake Five-O), and by regional precipitation data. The water-level changes in the Greenhead well were similar to those observed in the Upper Floridan wells at Lake Five-O. Water levels in the Upper Floridan aquifer at Lake Five-O rose more rapidly than those in wells in the surficial aquifer at the site in the summer of 1989, but showed little increase in the summer of 1990. This suggests that regional recharge to the Upper Floridan aquifer was probably greater than recharge in the immediate vicinity of Lake Five-O during the summer of 1989, and less than recharge in the vicinity of Lake Five-O in the summer of 1990. Precipitation totals at two climatic stations located north of Lake Five-O, in an area where the Upper Floridan aquifer crops out, were comparable to those measured at Lake Five-O during the summer of 1989, but much lower than those measured at Lake Five-O during the summer of 1990. Although the hydraulic head differences between the lake and the Upper Floridan aquifer changed seasonally during the study, the stage of Lake Five-O was consistently greater than the head in the Upper Floridan aquifer, which indicates that the lake leaked throughout the study period.

The head data also indicate that significant hydraulic conductivity differences exist within the intermediate confining unit and between the surficial aquifer and intermediate confining unit. As previously

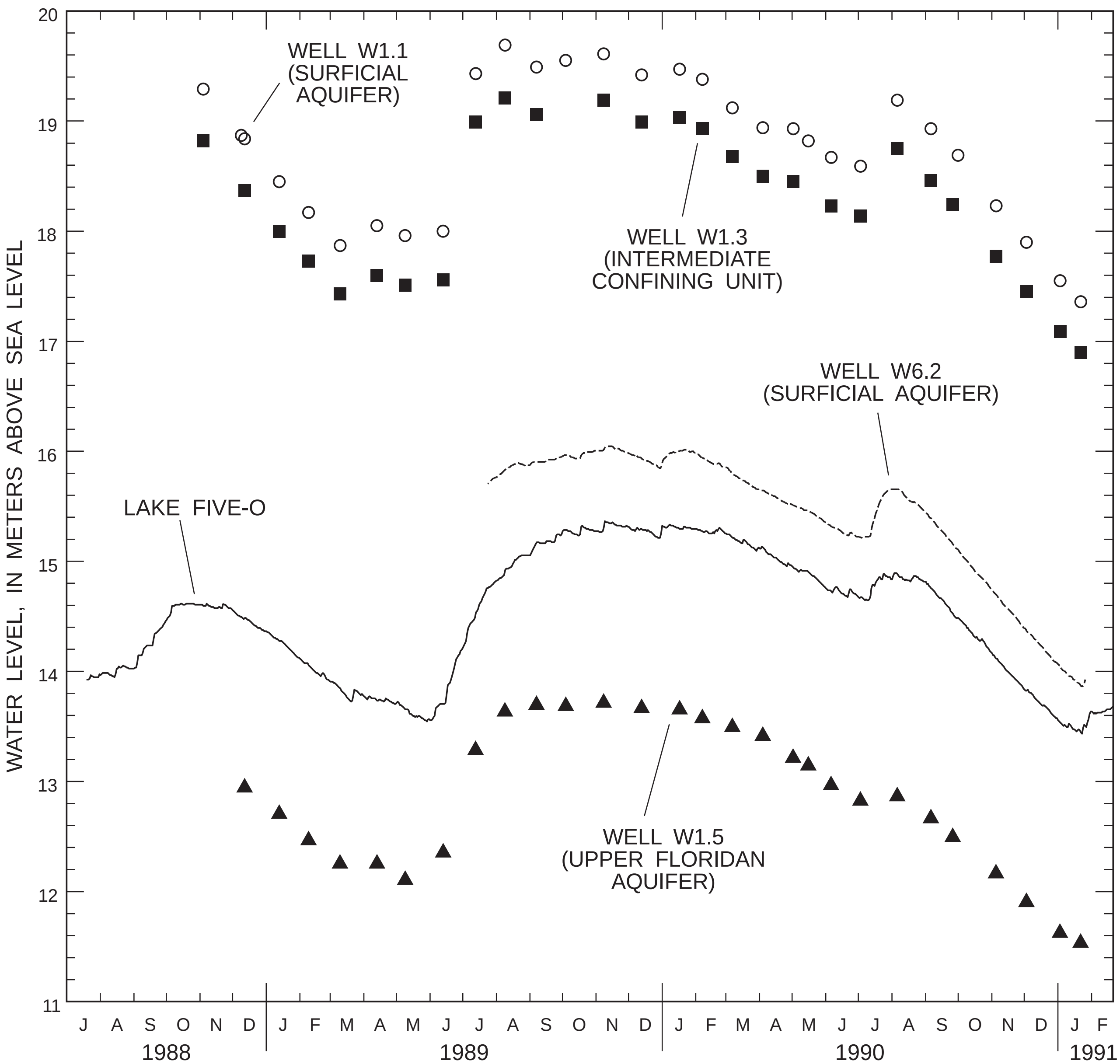

Figure 6. Water levels of Lake Five-O and selected ground-water monitoring wells, July 1988 to February 1991.

discussed, Andrews and others (1990) indicated that the confining properties of the intermediate confining unit are probably not evenly distributed within the unit, with the dense, shelly clay layer at the base of the unit being the most effective confining layer within the unit. Their conclusion was based on the large head loss (5.2-5.8 m) that occurred across the basal clay layer (fig. 9 and 10). The head loss across this layer was much greater than that between wells 1.3 and 1.4 (less than 0.05 m) (fig. 9 and 10), which are screened within the unit. An abrupt decrease in hydraulic conductivity at the surficial aquifer/intermediate confining unit contact is indicated by relatively large vertical head losses of 0.43 to 0.61 m across this contact at well nest 1 (fig. 9-11). The lower hydraulic conductivity of the intermediate confining unit sediments (relative to that of the surficial aquifer sediments) limits the downward movement of water from the surficial aquifer to the intermediate confining unit.

The head data also corroborated the seismic reflection interpretation, which indicated that three breaches in the intermediate confining unit exist

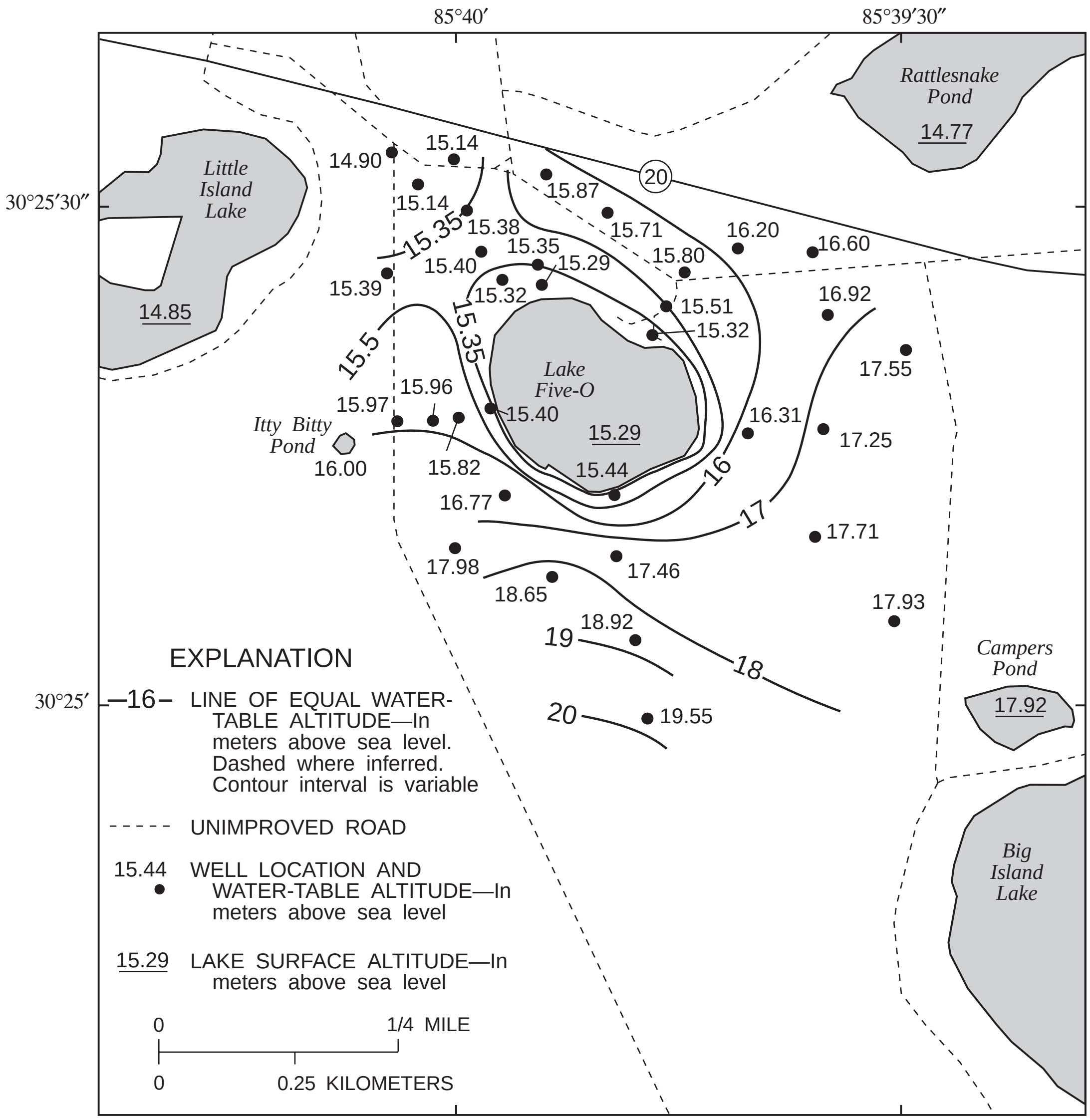

Figure 7. Water-table configuration near Lake Five-O, October 4, 1989.

beneath Lake Five-O. Vertical head differences between the surficial aquifer and Upper Floridan aquifer were much smaller near Lake Five-O (1.3-2.2 m) than those beyond the lake basin at well nests 13 and 1 (5.2-5.8 m) (fig. 9-11). The most plausible explanation for this difference is that Lake Five-O and the surficial aquifer leak large volumes of water through one or more highly conductive breaches in the intermediate confining unit under Lake Five-O. Downward leakage through these confining unit breaches probably represents the dominant sink for the shallow ground-water system and is largely responsible for the pattern of horizontal ground-water flow toward the lake (figs. 7 and 8).

Boundary Conditions

Three boundaries were used to characterize the ground-water flow system near Lake Five-O: (1) a lateral, no-flow boundary, (2) an upper free-surface boundary defined by the water table and the water surface of Lake Five-O, and (3) a lower specified-head boundary at the base of the intermediate confining unit. This section describes essential features of each of these boundaries.

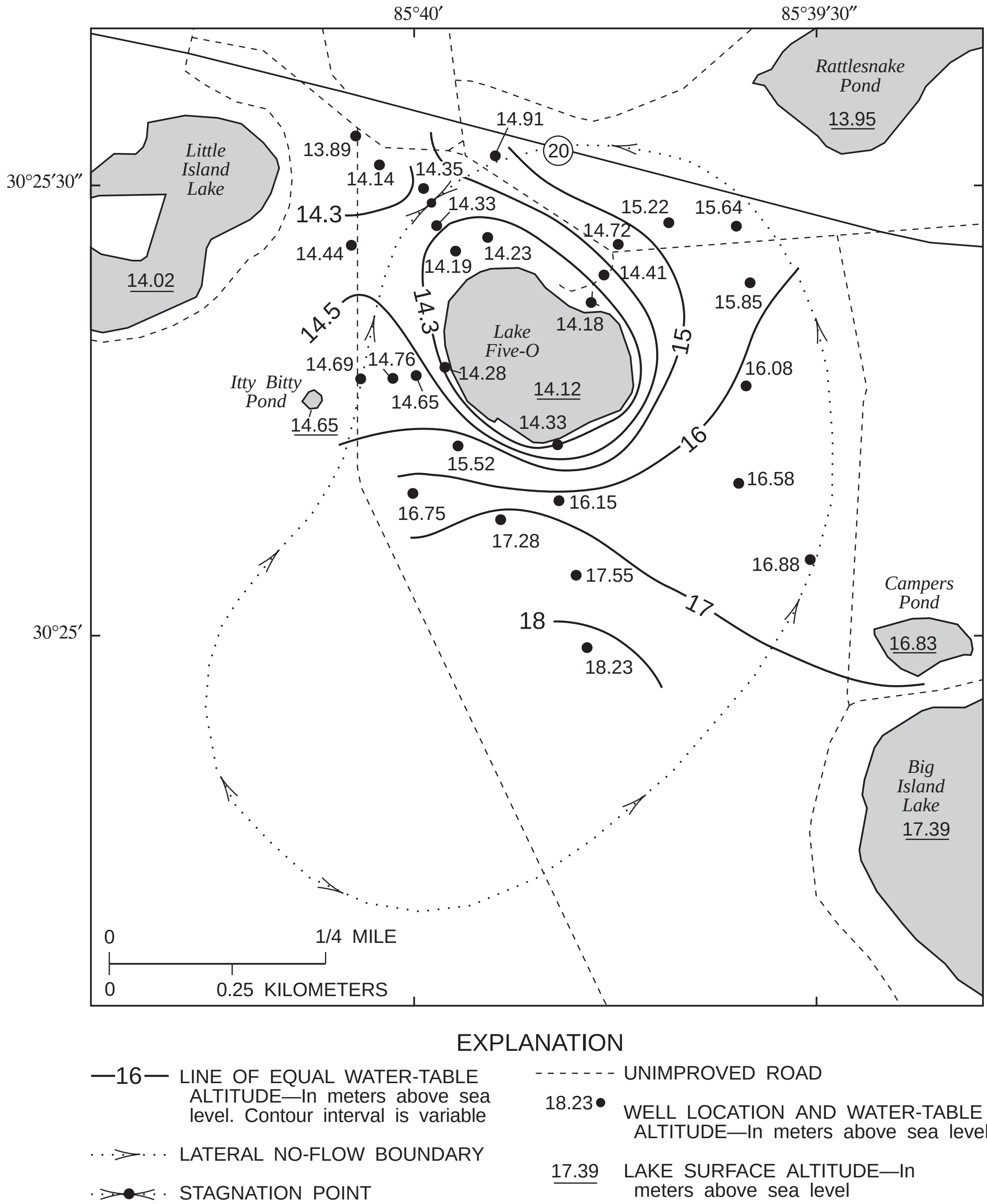

Figure 8. Water-table configuration near Lake Five-O, November 5, 1990.

Lateral Boundary

A lateral, no-flow boundary was used to define the perimeter of the shallow ground-water system. This boundary restricts the exchange of water between the surficial flow system near Lake Five-O and surrounding lakes and streams. The existence and location of this boundary was inferred from water-table and topographic maps. The no-flow boundary is defined by ground-water flowlines that are coincident with water-table divides. These flowlines originate south of the lake, encircle the lake, and terminate at a stagnation point on the water-table surface, northwest of Lake Five-O (fig. 8). Although head data is insufficient to define the southern extent of this boundary,

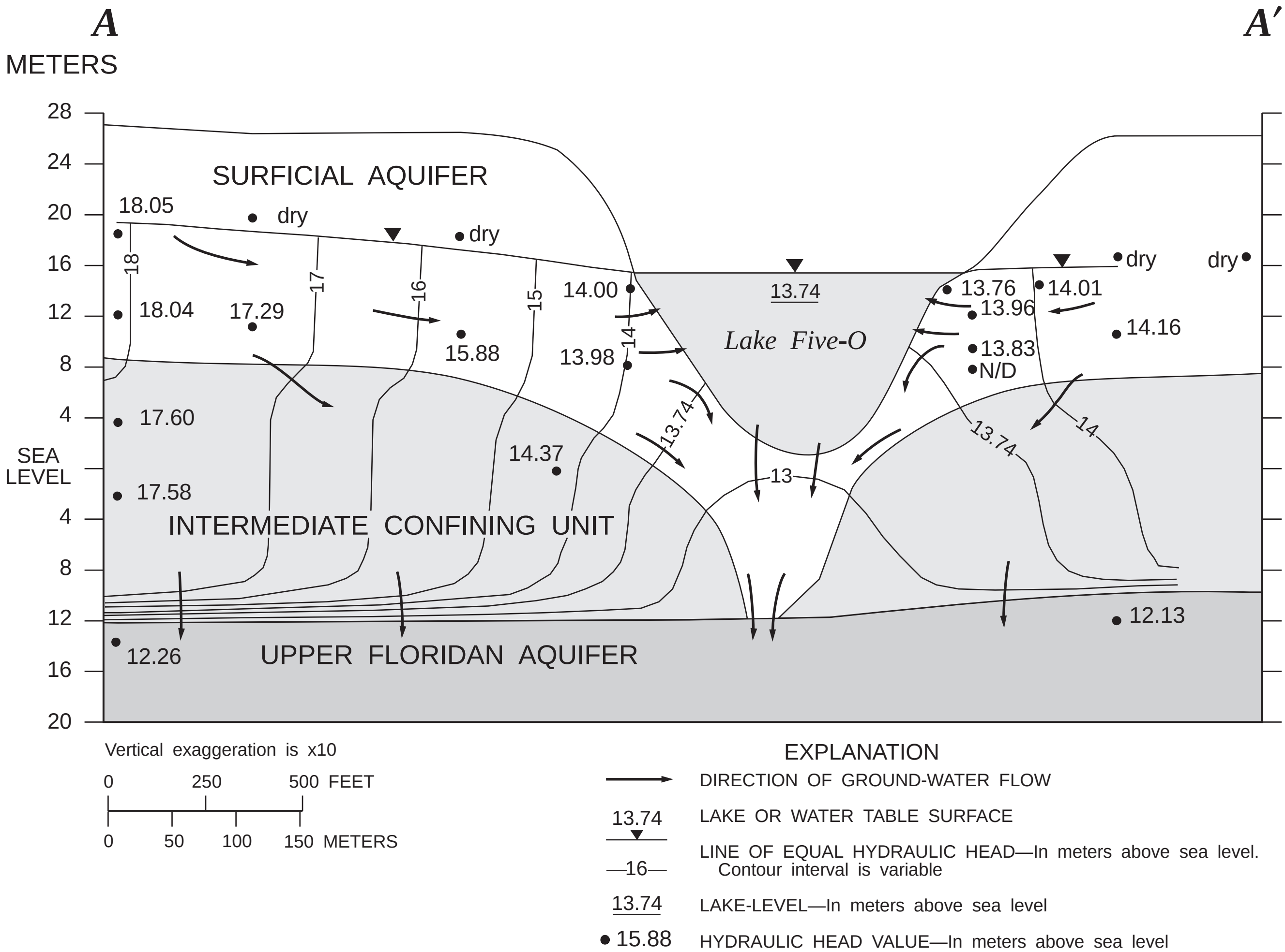

Figure 9. Hydrogeologic section A-A′ through Lake Five-O, showing vertical head distribution near the lake for April 13, 1989. (Location of section is shown in fig. 3).

data from 7.5 minute topographic maps indicate that water levels in Bream Lake and Cedar Creek (fig. 2) are generally lower than minimum water levels observed in wells south of Lake Five-O. This indicates the existence of a no-flow boundary between southern limits of the well network and Bream Lake and Cedar Creek. Occasionally during the study, inflow gradients were observed from Campers Pond toward Lake Five-O; however, these gradients were generally much smaller than those observed in active areas of the surficial flow system, and were similar in magnitude to head gradients in the relatively stagnant area northwest of Lake Five-O. A lateral no-flow boundary between Campers Pond and Lake Five-O was considered a reasonable representation of the limits of the shallow flow system at Lake Five-O, because of the intermittent and weak nature of the inflow gradients in this part of the study area.

Upper Boundary

The upper boundary of the ground-water and lake flow system was defined by the water table and lake surfaces. The location of these boundaries is partially determined by the flux of water across these boundaries (recharge rates for the water table and net-precipitation rates for the lake surface). Values of recharge over the water-table boundary were estimated from (1) an analysis of the daily water-level hydrograph at well 6.2, (2) measurements of chloride concentrations of water in the surficial aquifer and atmospheric deposition rates of chloride, and (3) previous estimates of recharge for similar areas in northwestern Florida.

The method of computing recharge from well-hydrograph data is based on a water budget for a volume of the surficial aquifer at the water table with a unit surface area, negligible moisture content above

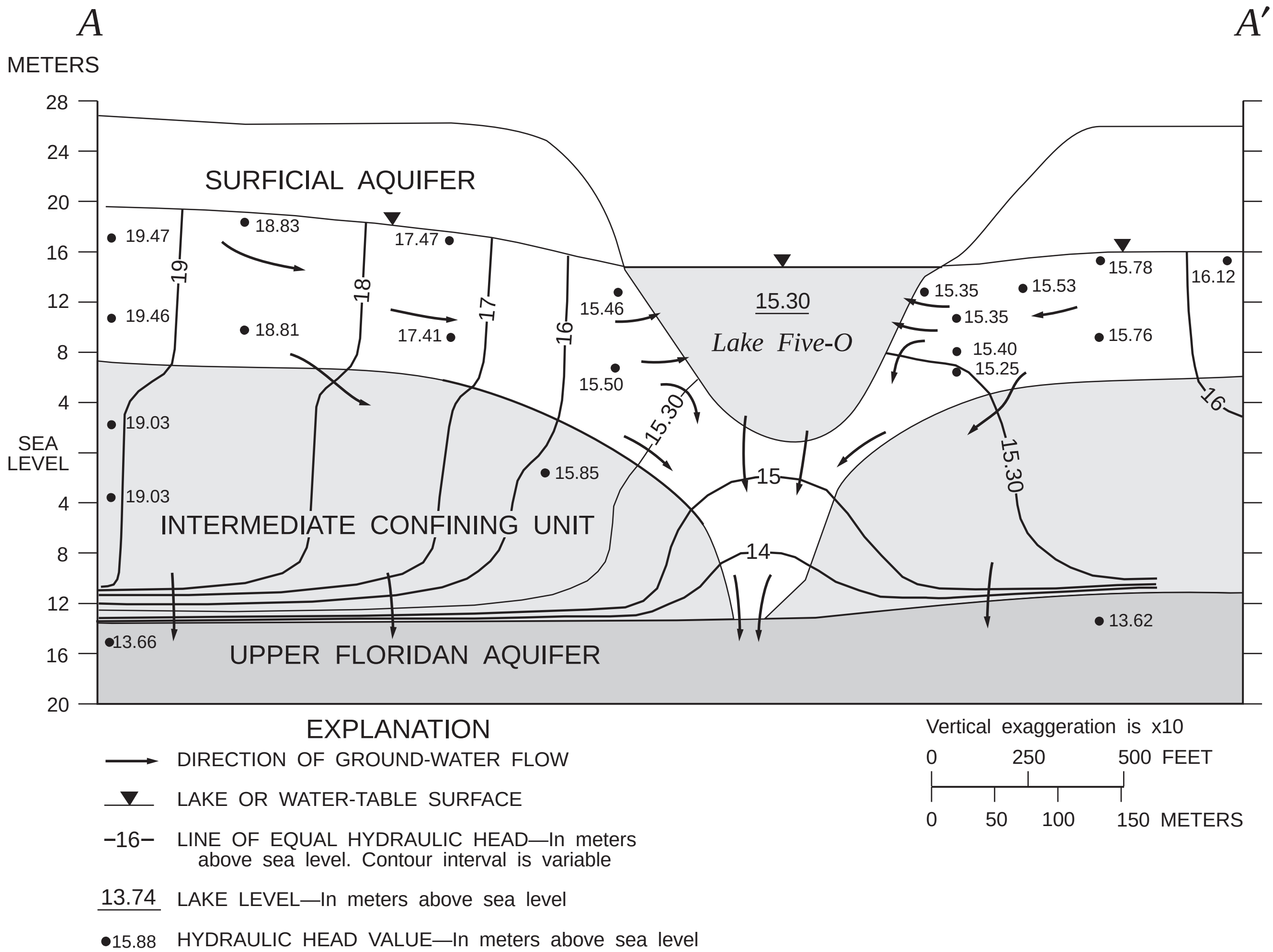

Figure 10. Hydrogeologic section A-A′ through Lake Five-O, showing vertical head distribution near the lake for January 17, 1990. (Location of section is shown in fig. 3.)

the water table, and lacking any internal sources or sinks. Under these conditions, the following conservation equation holds:

$$\dot{V}(t) = S_y\dot{h}(t) = \dot{R}(t) - \dot{Q}_o(t) \qquad (1)$$

where $\dot{V}(t)$ is the rate of volume change of the aquifer per unit area at time t; S_y is the specific yield of the surficial aquifer (dimensionless); $\dot{h}(t)$ is the rate of change of the altitude of the water table at time t; $\dot{R}$ is the recharge rate at time t, in units of volume per unit area per unit time or, equivalently, length per unit time; and $\dot{Q}_o(t)$ is the volume per unit area per unit time. Equation 1 can be rearranged and integrated over a given time interval, Δt, to obtain an estimate of recharge that occurred during that interval:

$$R_{\Delta t} = \int_{\Delta t}\dot{R}(t)dt = S_y\int_{\Delta t}\dot{h}(t)dt + \int_{\Delta t}\dot{Q}_o(t)dt \qquad (2)$$

During dry conditions, recharge can be assumed to be negligible relative to storage changes, and outflow can be estimated using the following equation if a water-table hydrograph and an estimate of specific yield are available:

$$\int_{\Delta t}\dot{Q}_o(t)dt = -S_y\int_{\Delta t}\dot{h}(t)dt = S_y\bar{h}_{recess}\Delta t \qquad (3)$$

where $\bar{h}_{recess}$ is the absolute value of the average change in the water-table altitude during a given hydrograph recession under suitably dry conditions. For a system in which the hydraulic head gradients are approximately constant over time, the outflow rate can be assumed to be constant, and can be estimated using the following equation:

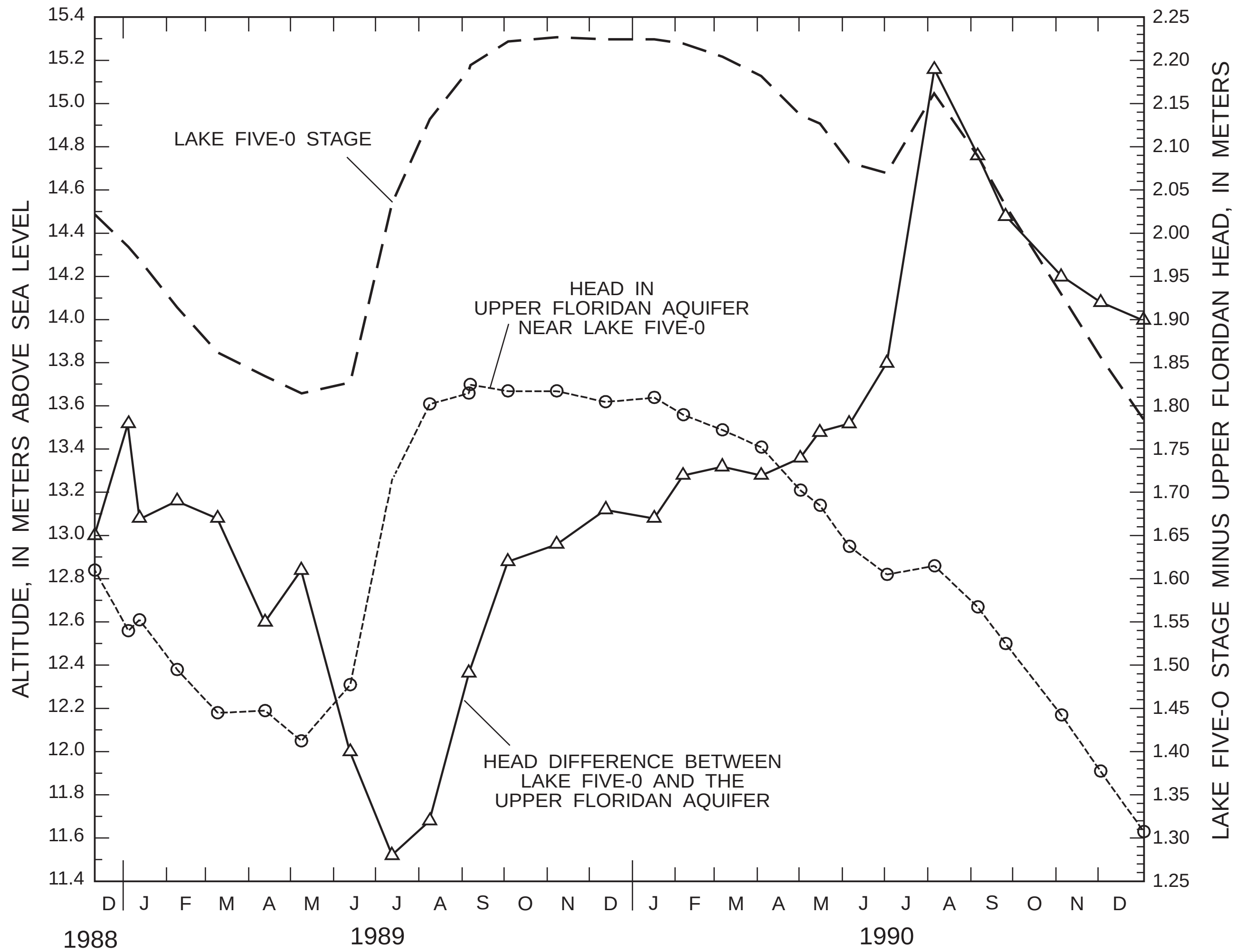

Figure 11. Comparison of Lake Five-O stage and head in the Upper Floridan Aquifer, December 1988 to January 1991.

$$\int_{\Delta t} \dot{Q}_o(t)dt = \int_{\Delta t} c_{\dot{Q}_o} dt = c_{\dot{Q}_o}\Delta t = S_y \bar{h}_{recess}\Delta t \qquad (4)$$

where $c_{\dot{Q}_o}$ represents the constant outflow rate. Equation 4 implies that $c_{\dot{Q}_o} = S_y \bar{h}_{recess}$. Thus, a recharge volume for any period can be obtained by combining equations 2 and 4:

$$R_{\Delta t} = S_y\left[\int_{\Delta t} \dot{h}(t)dt + \bar{h}_{recess}\Delta t\right] \qquad (5)$$

where $R_{\Delta t}$ is recharge over time interval Δt.

The terms $\dot{h}(t)$ and $\bar{h}_{recess}$ in equation 5 were obtained from head data from well 6.2, with the latter term computed from data from August 1990 to January 1991. Specific yield was varied from 0.10 to 0.30 to obtain upper and lower limits, respectively, for discharge. The analysis of the water-level hydrograph at well 6.2 indicated that average annual recharge at Lake Five-O for 1989-90 was between 36 and 144 cm (20-90 percent of precipitation). The analysis also indicated that monthly recharge rates were generally in the range of 18 to 166 cm/yr, but were as low as zero during dry periods, and as high as 612 cm/yr during summer rainy periods.

Average annual recharge was also estimated with a method that used precipitation rates and chloride concentrations (Vacher and Ayers, 1980) as follows:

$$\bar{R} = \bar{P}\frac{[Cl^-_{atmos}]}{[Cl^-_{SA}]} \qquad (6)$$

where R is the average annual recharge, P is the average annual precipitation, $[Cl^-_{atmos}]$ is the “effective” chloride concentration due to atmospheric loading (wet plus dry deposition), and $[Cl^-_{SA}]$ is the average chloride concentration of water in the surficial aquifer. The “effective” chloride concentration due to atmospheric loading, $[Cl^-_{atmos}]$, was computed as the product of the volume weighted mean concentration of chloride in precipitation (19 $\mu eq/L$) and the average ratio of total atmospheric chloride deposition (wet plus dry deposition) and wet deposition of chloride in Florida, 1.4 (Baker, 1991). The upper and lower quartile of chloride concentrations in water from the surficial aquifer wells (excluding those measured in samples from the wells at the margins of Lake Five-O) were 51 and 68 $\mu eq/L$, respectively. Given an average annual precipitation rate of 160 cm, the above chloride concentrations indicate that average annual recharge to the surficial aquifer in the study area is within a range from 61 to 81 cm.

The recharge rates calculated in the above well hydrograph and chloride analyses were in reasonable agreement with rates reported by Vecchioli and others (1990), who used a base flow separation technique to estimate recharge for a three-county area immediately west of Bay County. They reported average annual recharge estimates ranging from 76 to 102 cm for areas with basin characteristics similar to those at Lake Five-O. Rates at Lake Five-O may be smaller than those reported by Vecchioli and others, because annual precipitation minus potential evaporation (net precipitation) is 10 to 15 cm higher in the area they studied.

Net-precipitation rates for the lake surface part of the upper boundary were estimated as the difference between measured precipitation and estimated lake evaporation. Long-term average net precipitation was estimated using historic monthly precipitation data and estimates of historic lake evaporation at Lake Five-O. Monthly precipitation totals were obtained from a National Oceanic and Atmospheric Administration (NOAA) weather station in Fountain, Fla. (approximately 24 km east-northeast of Lake Five-O) for the period April 1955 to February 1989, and from measurements at Lake Five-O for the period March 1989 to December 1990. Long-term average lake evaporation was based on estimates of monthly lake evaporation that were obtained using two methods. For the period of October 1962 through May 1989, monthly lake evaporation was estimated at Lake Five-O using a relation between energy-budget evaporation at Lake Five-O and pan evaporation from the nearest NOAA pan evaporation site in Milton, Fla. (Sacks and others, 1994) which is located about 125 km west of Lake Five-O. For the period of June 1989 to December 1990, estimates of monthly lake evaporation were made by Sacks and others (1994). These estimates of monthly precipitation and evaporation were used to compute monthly mean values of precipitation and evaporation at Lake Five-O, which were then summed to obtain estimates of average annual precipitation and evaporation of 157 cm and 118 cm, respectively. Average annual net precipitation at Lake Five-O was then computed as the difference between these two values, or 39 cm. This estimate of net precipitation compares favorably with the range of 30 to 38 cm reported by Visher and Hughes (1975), which was based on lake evaporation for the period 1946-55 and precipitation for the period 1931-60. During the study at Lake Five-O, net precipitation rates generally ranged from -4 to 76 cm/yr, and were as low as -153 cm/yr during the dry fall of 1990, and as high as 510 cm/yr during the extremely wet summer of 1989. Annual net precipitation values during the study period were more extreme than any of the values from the period of estimated record. The 85 cm of net precipitation measured during 1989 was larger than any annual estimate available at Lake Five-O, whereas the -10 cm measured in 1990 was the smallest value among the available data.

Lower Boundary

The lower boundary of the conceptual system was defined as the contact between the base of the intermediate confining unit and the Upper Floridan aquifer, and was characterized by the head distribution along this contact. This head distribution was assumed to have a value that, although variable with time, is the same everywhere on the lower boundary (uniform spatial distribution) for a given moment in time. The assumption of a uniform spatial distribution is supported by the small to negligible difference between concurrently measured heads at the two wells screened within the Upper Floridan aquifer (wells w1.5 and w13.3), and the assumed large transmissivity of the Upper Floridan aquifer at Lake Five-O.

Net Ground-Water Flow to Lake Five-0

Net ground-water flow (ground-water inflow minus leakage) to Lake Five-O was estimated using a water balance approach that used measurements of precipitation, lake evaporation, and lake volume changes. This net ground-water flow analysis made it possible to make a qualitative assessment of the significance of lake-ground-water exchanges during the study period. The analysis also made it possible to make quantitative estimates of minimum ground-water inflow and leakage rates during the study period and for long-term average conditions.

Methods

The method used to compute net ground-water flow was virtually the same as that used by Pollman and others (1991) and can be described as follows:

The hydrologic budget for Lake Five-O is given as:

$$\Delta V_i = \Delta\hat{V}_i - \varepsilon_{\Delta\hat{V},i}$$
$$= \left(\hat{P}_i - \varepsilon_{\hat{P},i}\right) - \left(\hat{E}_i - \varepsilon_{\hat{E}_i}\right) \quad (7)$$
$$+ \left(\hat{Q}_{I,i} - \varepsilon_{\hat{Q}_{I,i}}\right) - \left(\hat{Q}_{O,i} - \varepsilon_{\hat{Q}_{O,i}}\right)$$

where: ΔV_i is the lake volume change during time interval i, P_i is precipitation, E_i is lake evaporation, $Q_{I,i}$ is ground-water inflow to Lake Five-O, $Q_{O,i}$ is leakage from Lake Five-O to the contiguous ground-water system, and $\varepsilon_{\hat{\theta},i} = \hat{\theta}_i - \theta_i$ is the error associated with the estimate, $\hat{\theta}_i$, of the hydrologic variable θ_i (for example, $\hat{P}_i$ is the estimate of the actual amount of precipition, P_i, that occurred during time interval i, and $\varepsilon_{\hat{P},i} = \hat{P}_i - P$ is the error associated with the precipitation estimate, $\hat{P}_i$). The above hydrologic budget equation assumes that surface runoff to Lake Five-O is negligible. An analysis of lake volume changes that occurred immediately after rainstorms corroborated this assumption.

Equation 7 can be rearranged to solve for net ground-water flow:

$$Q_{net,i} = Q_{I,i} - Q_{O,i} = \left(\hat{Q}_{I,i} - \varepsilon_{\hat{Q}_{I,i}}\right) - \left(\hat{Q}_{O,i} - \varepsilon_{\hat{Q}_{O,i}}\right) \quad (8)$$

$$Q_{net,i} = \left(\Delta\hat{V}_i - \varepsilon_{\Delta\hat{V},i}\right) - \left(\hat{P}_i - \varepsilon_{\hat{P},i}\right) + \left(\hat{E}_i - \varepsilon_{\hat{E},i}\right) \quad (9)$$

Thus an estimate of $Q_{net,i}$ can be computed as:

$$\hat{Q}_{net,i} = \Delta\hat{V}_i - \hat{P}_i + \hat{E}_i \quad (10)$$

Note that $Q_{net,i} = \hat{Q}_{net,i} - \varepsilon_{\hat{Q}_{net,i}}$ and

$$\varepsilon_{\hat{Q}_{net,i}} = \varepsilon_{\Delta\hat{V}_i} - \varepsilon_{\hat{P}_i} + \varepsilon_{\hat{E}_i}$$

With the exception of the error terms, all of the terms on the right side of equation 9 were measured directly or indirectly. Volume per unit area estimates of evaporation were obtained from the energy budget estimates and regression relation with the Milton, Fla., NOAA station pan data (Sacks and others, 1994), and volume per unit area estimates of precipitation were given by precipitation measurements at Lake Five-O and the Fountain, Fla. NOAA station. Volumetric estimates of precipitation and evaporation ($\hat{P}_i$ and $\hat{E}_i$, respectively) were computed from the volume per unit area estimates by multiplying total precipitation or evaporation (in volume per unit surface area units) by lake area. Lake volume changes and lake area were estimated using lake-stage measurements and the relation between lake volume and stage that was developed from a bathymetric survey of Lake Five-O (Andrews and others, 1990).

Although the error, $\varepsilon_{\hat{Q}_{net,i}}$, associated with a given net ground-water flow estimate, $\hat{Q}_{net,i}$ is unknown, the uncertainty of $\hat{Q}_{net,i}$ can be characterized by computing a confidence interval as follows:

$$\hat{Q}_{net,i} \pm z_{\alpha/2}\sigma_{\varepsilon_{\hat{Q}_{net,i}}} \quad (11)$$

where $z_{\alpha/2}$ is the standard normal deviate for an $\alpha/2$ level of significance and $\sigma_{\varepsilon_{\hat{Q}_{net,i}}}$ is the standard deviation of $\varepsilon_{\hat{Q}_{net,i}}$.

This approach assumes that the error, $\varepsilon_{\hat{Q}_{net,i}}$, associated with $\hat{Q}_{net,i}$ follows a normal distribution with mean equal to zero ($\hat{Q}_{net,i}$ is assumed to be unbiased) and a variance equal to $\sigma^2_{\varepsilon_{\hat{Q}_{net,i}}}$.

The standard deviation of the error associated with the net ground-water flow estimate, $\sigma_{\varepsilon_{\hat{Q}_{net,i}}}$, was computed as follows (Pollman and others, 1991):

$$\sigma_{\varepsilon_{\hat{Q}_{net,i}}} = \sqrt{\left[(\hat{P}_i)(CV_{\hat{P}_i})\right]^2 + \left[(\hat{E}_i)(CV_{\hat{E}_i})\right]^2 + \left[(\Delta\hat{V}_i)(CV_{\Delta\hat{V}_i})\right]^2} \quad (12)$$

where $CV_{\hat{\theta}_i} = \sigma_{\varepsilon_{\hat{\theta}_i}} / \hat{\theta}_i$ is the coefficient of variation for hydrologic variable θ.

Estimates of lake volume change were assumed to have a coefficient of variation of 5 percent (Winter, 1981). Monthly precipitation estimates were assumed to have a coefficient of variation of 15 percent (Winter, 1981) for periods where data was available at Lake Five-O, and 30 percent during January and February 1989, when precipitation at Lake Five-O was estimated with data from a nearby NOAA weather station in Fountain, Fla. This latter value was obtained by summing the “at site” coefficient of variation (15 percent) and the average of the absolute value of the difference between precipitation at Lake Five-O and the Fountain station for the 3 months (March, April, and May 1989) when concurrent data were available for the two sites. Coefficient of variation values for the lake evaporation estimates were obtained from Sacks and others (1994). The mean, lower quartile, and upper quartile of their monthly coefficient of variation values were 15, 11, and 17 percent, respectively. For the months of January through May 1989, when lake evaporation was estimated using a regression relation between energy-budget estimates and pan estimates (Sacks and others, 1994), the evaporation coefficient of variation was assumed to be equal to the sum of the standard error of regression and the energy budget coefficient of variation for the same month in 1990.

Results

The results of the monthly net ground-water flow computations and associated errors are listed in table 2 and are shown in figure 12. The temporal distribution of net ground-water flow is consistent

Table 2. Monthly net ground-water flow to Lake Five-O, 1989-90

[All units are in cubic meters, unless otherwise noted; $\sigma_{\varepsilon,\hat{Q}_{net}}$ is the standard deviation of the error component of the net ground-water flow estimate. Negative values of net ground-water flow indicate that leakage exceeded ground-water inflow.]

Month	Average lake volume	Change in lake volume	Precipitation	Evaporation	Net ground-water flow	$\sigma_{\varepsilon,\hat{Q}_{net}}$	$\sigma_{\varepsilon,\hat{Q}_{net}}$ in percent of net ground-water flow
				1989			
Jan.	989,700	-26,100	3,800	3,200	-26,700	2,300	9
Feb.	964,000	-21,900	6,900	4,100	-24,700	2,600	10
Mar.	943,300	-13,900	17,700	7,900	-23,700	3,300	14
Apr.	935,200	-8,700	10,600	11,000	-8,300	2,800	34
May	922,500	-14,700	8,900	13,800	-9,900	2,900	29
June	945,600	69,100	56,800	12,000	24,400	9,300	38
July	1,024,800	66,700	26,300	13,300	53,700	5,400	10
Aug.	1,068,400	26,200	20,900	12,300	17,600	3,700	21
Sept.	1,091,800	22,300	21,500	16,800	17,700	3,700	21
Oct.	1,103,400	3,100	15,100	13,000	1,000	2,700	270
Nov.	1,108,200	4,100	13,800	9,400	-300	2,300	770
Dec.	1,102,700	1,000	13,500	7,900	-4,600	2,300	50
				1990			
Jan.	1,107,000	-3,100	3,800	3,300	-3,500	1,500	43
Feb.	1,103,000	-4,800	5,700	4,800	-5,800	1,300	22
Mar.	1,092,000	-15,500	9,600	8,600	-16,500	2,000	12
Apr.	1,076,100	-17,800	12,000	11,100	-18,700	2,400	13
May	1,058,600	-22,000	9,400	15,100	-16,300	2,400	15
June	1,041,300	-9,100	23,700	14,300	-18,500	4,200	23
July	1,046,400	17,900	31,300	15,000	1,600	5,300	330
Aug.	1,055,600	-2,400	16,000	15,600	-2,800	3,600	130
Sept.	1,033,300	-35,600	3,900	17,900	-21,600	2,900	13
Oct.	998,600	-35,100	5,500	15,400	-25,200	2,800	11
Nov.	963,200	-35,600	800	11,300	-25,100	2,600	10
Dec.	932,000	-28,900	7,000	7,400	-28,600	2,600	9

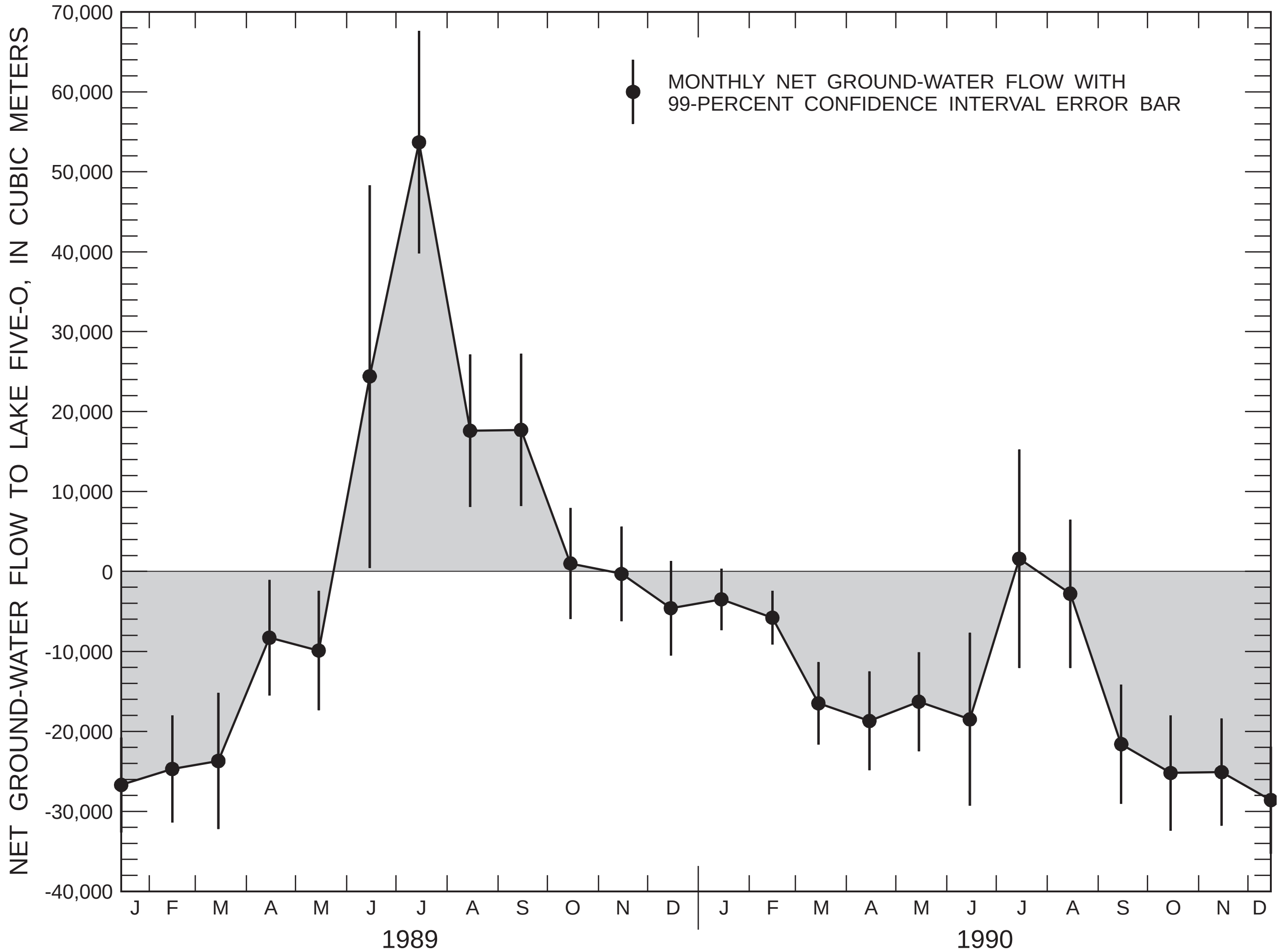

Figure 12. Computed montly net ground-water flow to Lake Five-O during 1989-90.

with seasonal patterns of precipitation in northwestern Florida. The computed monthly net ground-water flow peaked during the summer wet season in 1989 and 1990 (fig. 12). The large, positive peak for the summer of 1989 resulted from the historically high precipitation during this period. The effect of precipitation on ground-water inflow and leakage is evident when the shaded areas above and below the line defined by $\hat{Q}_{net} = 0$ are evaluated (fig. 12). The total area above this "zero line" represents the sum of all months with positive values of net ground-water flow, and the total area below the "zero line" represents the sum of all months with negative values of net ground-water flow. During the wet year of 1989, the areas above and below the line are approximately equal, which indicates that ground-water inflow was approximately equal to leakage during 1989. However, the shaded area above the "zero line" was much smaller than the area below the line during the dryer year of 1990. This indicates that leakage from Lake Five-O greatly exceeded ground-water inflow during 1990.

The significance of ground-water inflow and leakage to the water budget of Lake Five-O is illustrated by a plot of cumulative net precipitation inputs (precipitation minus evaporation) and cumulative changes in lake volume over time in fig. 13). If Lake Five-O were completely isolated from the ground-water system, and one assumes that surface runoff is negligible and that errors in estimating atmospheric fluxes and lake volume changes are reasonably small and unbiased, then graphs of cumulative net precipitation inputs and cumulative changes in lake volume should be approximately coincident. However, during the winter and spring seasons in 1989 and 1990 and the fall season of 1990, the volume of Lake Five-O decreased much faster than predicted by atmospheric

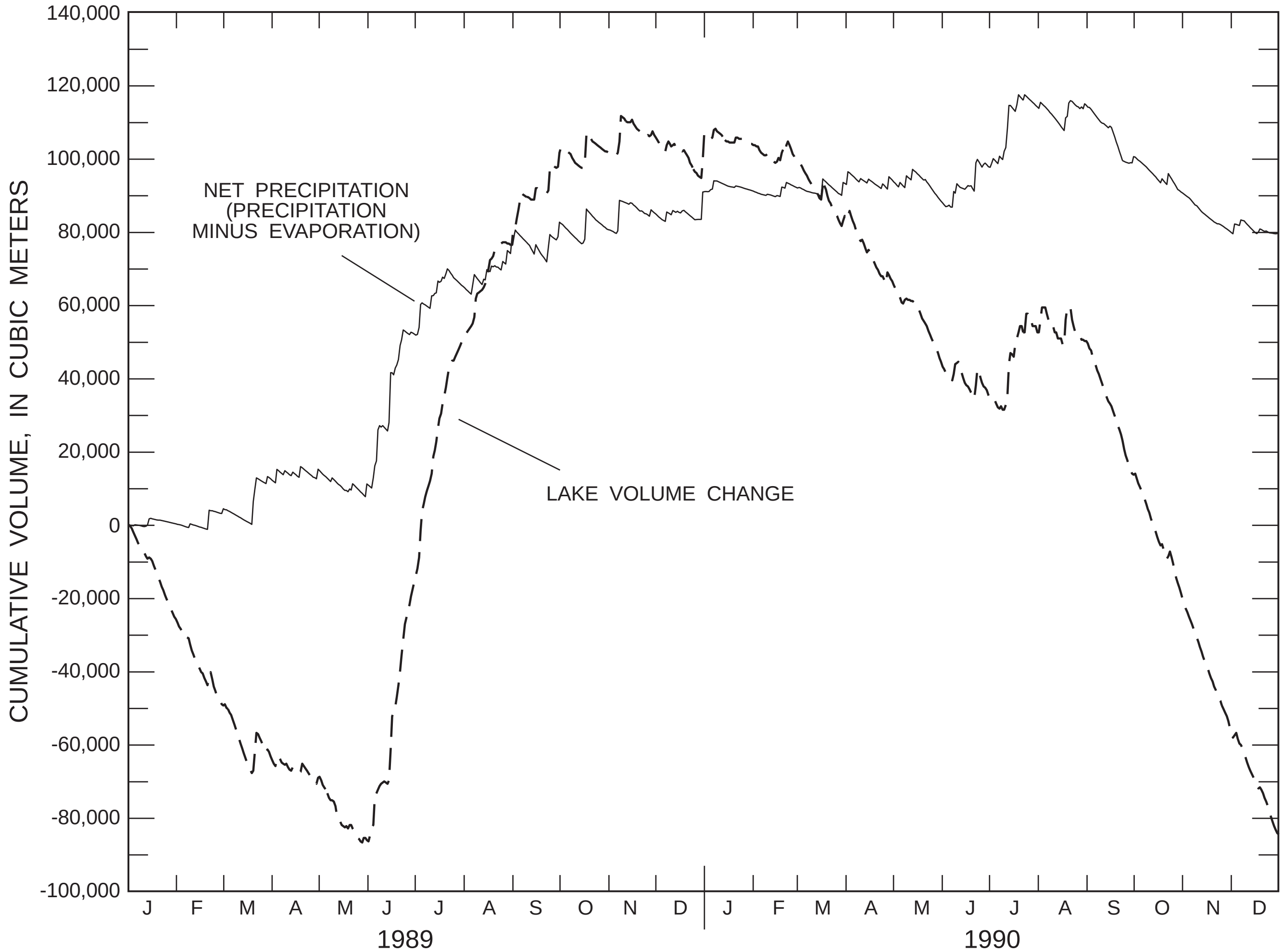

Figure 13. Cumulative daily net-precipitation inputs and cumulative daily lake-volume changes for Lake Five-O, 1989-90.

fluxes alone. In addition, the lake volume increased much faster than predicted by net atmospheric inputs during the summer of 1989, and, to a lesser extent, during the summer of 1990. These observations indicate that ground-water inflow and leakage are significant components of the water budget of Lake Five-O.

The net ground-water flow estimates also provide some insight into the magnitude of the components of net ground-water flow, ground-water inflow and leakage. This is accomplished by noting that negative values of net ground-water flow represent minimum estimates of leakage, and positive values of net ground-water flow represent minimum estimates of ground-water inflow (Pollman and others, 1991). Thus, the monthly net ground-water flow values indicate that monthly inflow and leakage rates of at least 5.4×10^4 and 2.9×10^4 m^3, respectively, occurred during the study period (table 2). Because the head difference between Lake Five-O and the Upper Floridan aquifer was greater than or near 1.7 m for most months in the study period, the large negative net ground-water flow values of -26,700 to - 23,700 m^3observed in January-March 1989 (when the Lake Five-O-Upper Floridan aquifer head difference was approximately 1.7 m) should represent minimum leakage estimates for most months. This indicates that leakage from Lake Five-O was at least 760 to 880 m^3/d during 1989-1990, which represents at least 68 to 71 percent of the total outflow (lake evaporation plus leakage) from the lake during 1989-90.

Estimates of minimum annual ground-water inflow and leakage during the study period can be made by summing months with positive net ground-water flow values and assigning these to ground-water inflow, and by summing months with negative net ground-water flow values and assigning these to ground-water outflow (Pollman and others, 1991).

This procedure results in estimates of minimum annual ground-water inflow of 35 percent and 1 percent of the total inflow (precipitation plus ground-water inflow) budget for 1989 and 1990, respectively. Minimum annual leakage was estimated to be 45 percent and 56 percent of total outflow for 1989 and 1990, respectively. This approach should yield estimates of ground-water inflow and outflow that are well below expected values, because it assumes that ground-water inflow and leakage do not occur simultaneously. Head differences between the near-lake wells and Lake Five-O, and between Lake Five-O and the Upper Floridan aquifer indicate that significant ground-water inflow and leakage occurred concurrently, throughout the study period.

An estimate of minimum long-term average ground-water inflow to Lake Five-O can be derived from estimates of leakage from the above analysis, and average annual precipitation minus lake evaporation (net precipitation). The equation for this calculation is as follows:

$$\ddot{Q}_{in} = \ddot{Q}_{out} - (\ddot{P} - \ddot{E})\ddot{A}_{avg} + \Delta\ddot{V}, \qquad (13)$$

where $\ddot{Q}_{in}$ is average annual ground-water inflow; $\ddot{Q}_{out}$ is average annual leakage; $\ddot{P} - \ddot{E}$ is average annual net-precipitation; $\ddot{A}_{avg}$ is average annual lake surface area; and $\Delta\ddot{V}$ is average annual lake volume change, which is assumed to be zero.

Assuming that (1) average annual net precipitation is equal to 39 cm (see discussion of boundary conditions), (2) the average annual lake surface area equals 10.9 hectares (average area during the study period), and (3) the average annual leakage is at least 880 m^3/d (estimated minimum leakage rate for most of 1989-90), then the minimum average annual ground-water inflow is estimated to be at least 760 m^3/d, or 62 percent of the estimated average annual total inflow to Lake Five-O.

SIMULATION OF GROUND-WATER FLOW

A computer program by McDonald and Harbaugh (1988) was used to simulate ground-water flow within the surficial aquifer and intermediate confining unit near Lake Five-O. The program uses a finite difference scheme to integrate the equation for three-dimensional, saturated ground-water flow under equilibrium (steady-state) or nonequilibrium (transient) conditions. The resulting system of equations was solved using either the "strongly implicitly procedure" (McDonald and Harbaugh, 1988, p. 12-1), or the "preconditioned conjugate-gradient" method (Hill, 1990). A subprogram that allows for time-variant specified-head boundaries (Leak and Prudic, 1991) was also used in conjunction with the main modeling program. The following sections describe the development and calibration of the steady-state and transient ground-water flow models, and the results of flow-path simulations using the calibrated flowfields.

Model Development

Three-dimensional models were developed to represent the Lake Five-O ground-water system under steady-state and transient conditions. The horizontal grid and boundary conditions used in the steady-state and transient models are shown in figure 14. The horizontal grid is composed of 81 rows and 57 columns. All rows in the grid have a constant width of 20 m. Columns 7 through 67 also have a constant width of 20 m, and columns 4 through 1 progressively increase in size westward from 30 to 100 m (expansion factor of 1.5). In vertical section, the numerical models represent the sediments from the land surface to the uppermost part of the Upper Floridan aquifer and are discretized into seven horizontal layers of varying thickness (fig. 15). Layer 1 was simulated as a water-table layer, whereas layers 2-6 were represented as confined layers. Layer 7 was treated as a specified-head boundary representing the Upper Floridan aquifer.

The model grid described above makes it possible to approximate the geometry of the major lithologic contacts and aquifer boundaries. The extent of the surficial aquifer and intermediate confining unit is approximated by assigning a single value or limited number of values of hydraulic properties to a section of the model domain (parameter zone) representing these lithologic units (fig. 15). Several parameter zones were also used to represent hydraulic property variations within the surficial aquifer and intermediate confining unit, or within model layers (fig. 15). A basal clay zone is used to represent the dense, low-permeability clay layer at the base of the intermediate confining unit. A plateau zone was introduced during the calibration process to represent increased anisotropy in the upper 5 to 10 m of the intermediate confining unit in the plateau area. Another parameter zone (the transition zone) was introduced to more

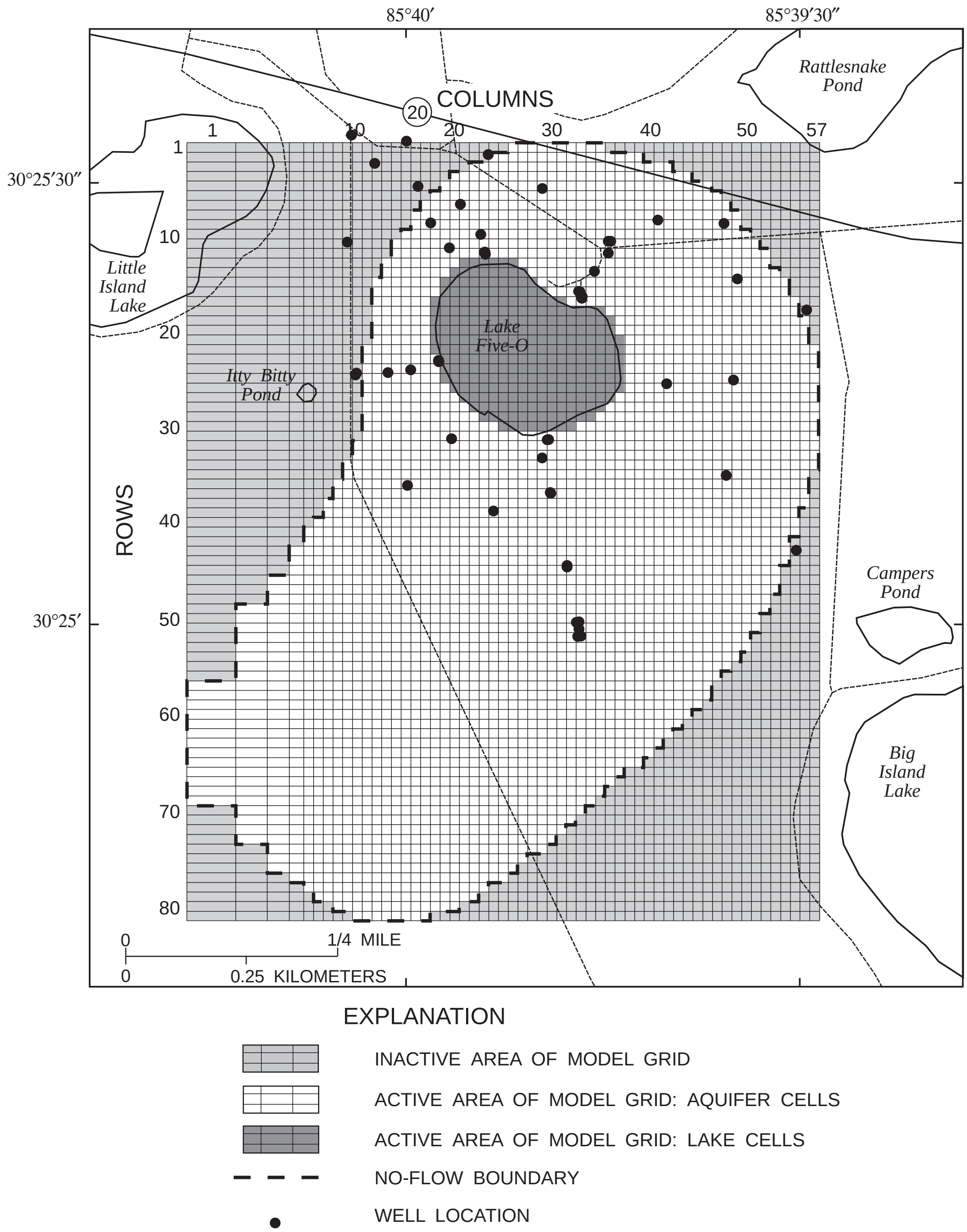

Figure 14. Areal discretization and boundary conditions for simulation models of the ground-water flow system near Lake Five-O.

accurately represent the geometry of the contact between the surficial aquifer and intermediate confining unit where this contact dips toward the breaches in the intermediate confining unit. A lakebed sediment zone is used to represent lower permeability sediments (relative to the surficial aquifer) in surficial aquifer cells contiguous with and beneath the lake in model layers 3 and 4. The top of the Upper Floridan aquifer, which defines the lower boundary of the simulation models, is set at a constant altitude of 13.7 m below sea level.

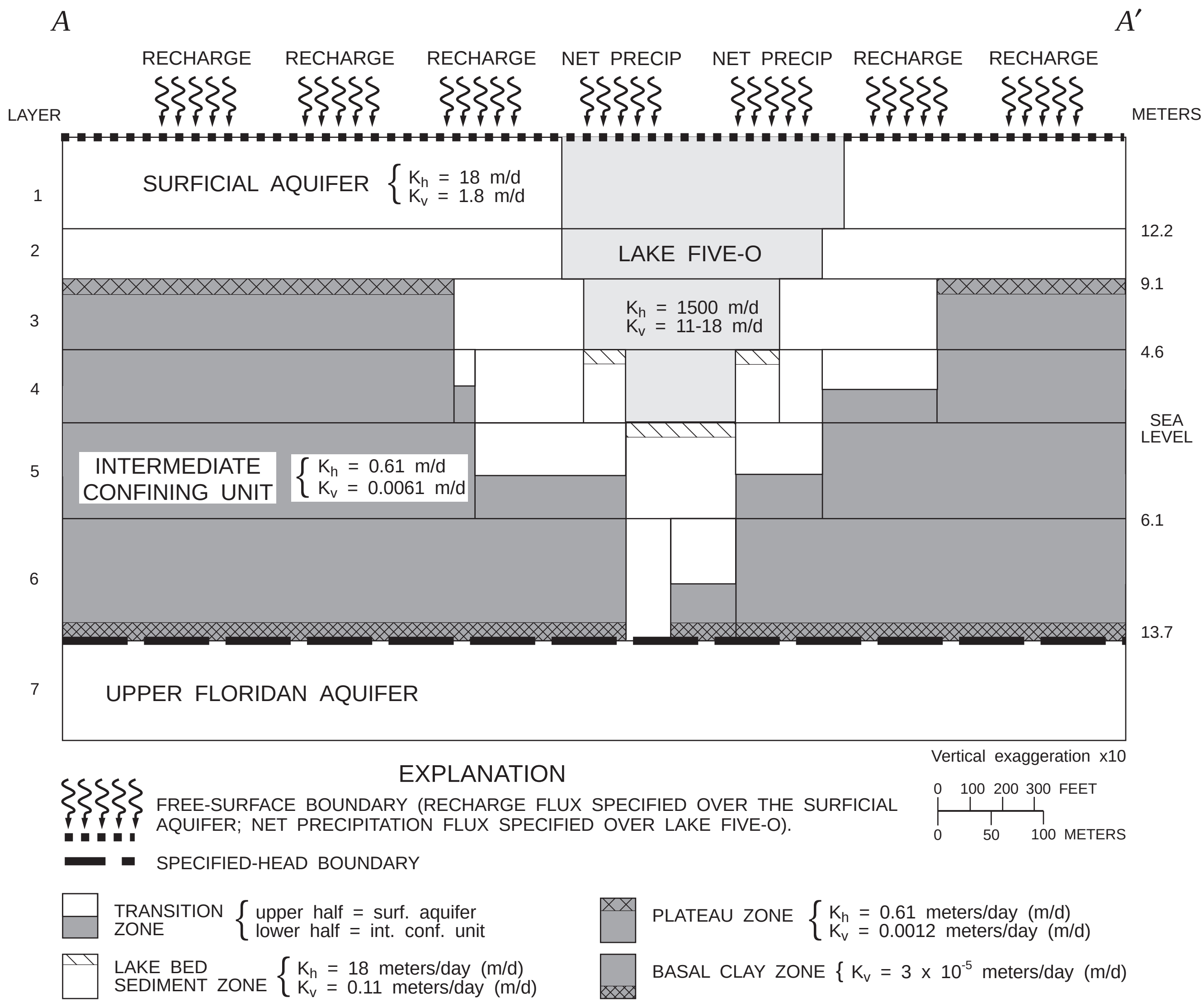

Figure 15. Vertical discretization, boundary conditions, and calibrated values of hydraulic conductivity for simulation models of the ground-water flow system near Lake Five-O.

Lake Five-O is represented in the model by a zone of highly conductive material in layers 1-4 (fig. 15). For transient simulations, the storage properties of this lake zone are identical to those of water. The physical extent of this lake zone was determined with data from the bathymetric survey and by reproducing the relation between lake stage and lake volume that was developed from this survey.

Within-layer variations in horizontal hydraulic conductivity are accounted for by using "equivalent" hydraulic conductivity values (Freeze and Cherry, 1979, p. 33), which were computed using a weighted mean algorithm (Freeze and Cherry, 1979, p. 34). For example, the transmissivity of cells in the transition zone was computed as follows:

$$T = LK_{h,\,eq}$$

$$= L\left\{\frac{\left[(K_{h,\,SA})\frac{L}{2}\right]}{L} + \frac{\left[(K_{h,\,ICU})\frac{L}{2}\right]}{L}\right\} \qquad (14)$$

$$= L\left(\frac{K_{h,\,SA}}{2} + \frac{K_{h,\,ICU}}{2}\right)$$

where T is transmissivity, L is the layer thickness, $K_{h,\,eq}$ is the equivalent horizontal hydraulic conductivity, and $K_{h,\,SA}$ and $K_{h,\,ICU}$ are the horizontal hydraulic conductivities for the surficial aquifer and intermediate confining unit, respectively. Vertical flow between model layers is simulated using the leakance parameter (vertical hydraulic conductivity divided by flow path distance). Leakance values were calculated (from equivalent vertical hydraulic conductivity values) using a harmonic mean algorithm (Freeze and Cherry, 1979, p. 34; McDonald and Harbaugh, 1988, p. 5-12, equation 49) when vertical hydraulic conductivity varied within a model layer or across contiguous model layers.

The boundary conditions for the simulation models (figs. 14 and 15) are identical to those described in the previous discussion of ground-water flow near Lake Five-O. Lateral no-flow boundaries encircle the ground-water basin and are coincident with water-table divides previously described. Free-surface boundaries are used for the upper surface of the models (water-table boundary for the aquifer and a lake-surface boundary for Lake Five-O). The use of a free-surface boundary at the lake made it possible to predict lake stage and volume fluctuations in response to changing hydrologic conditions, and also greatly simplified calibration of the transient model. Recharge and net precipitation functions are used to represent the flux of water across the upper surface of the models. Net precipitation was computed from precipitation and evaporation data, as previously discussed. Recharge was determined by model calibration using values within limits indicated by base flow, precipitation, well hydrograph, and chloride data. Upper Floridan aquifer head values (representing the specified head boundary at the base of the model) were obtained by averaging measured heads at wells w1.5 and w13.3. Values of recharge, net precipitation, and Upper Floridan aquifer head are constant in space and time for the steady-state models, and constant in space, variable with time for the transient model. Although heads were not computed by the model for layer 7 because of the specified-head boundary condition, this layer is active because it can vary with time and can act as a source or sink of water for the overlying active layers.

Calibration of Steady-State Models

Four steady-state models were calibrated to hydrologic conditions observed on four different dates: December 12, 1988; May 9, 1989; October 4, 1989; and August 6, 1990. These models were developed to satisfy one or more of the following objectives: (1) refine the “premodeling” or prior estimates of hydraulic properties and their spatial distribution, (2) provide initial conditions for transient simulations, and (3) provide flowfields necessary for evaluation of flow paths and residence times of ground water that discharges to Lake Five-O (ground-water inflow). The model calibrated to December 12, 1988, conditions was developed with objectives (1) and (2) in mind. The August 6, 1990, steady-state model was developed to provide initial conditions for a preliminary transient simulation of the latter part of the study period (August 6, 1990 through January 22, 1991). The rationale for this transient simulation is discussed in a later section that describes the calibration of the full transient model (conditions from December 12, 1988 through January 22, 1991). Finally, steady-state models of May 9, 1989, and October 4, 1989, were developed to evaluate ground-water flow paths and residence times for low water-level and high water-level conditions, respectively.

The steady-state models were calibrated by comparing simulated and observed heads, and by comparing the simulated leakage from Lake Five-O with the minimum estimate of leakage from the preceding section describing net ground-water inflow to Lake Five-O. The head calibration criteria was set at ±0.3 m, which represents approximately 5 percent of the total head loss within the shallow ground-water flow system near Lake Five-0. Simulated leakage from Lake Five-O was also required to be greater than 880 m^3/d for an acceptable calibration.

Although the real ground-water system is never at equilibrium, this condition can be approached during sustained hydrograph peaks or plateaus, where inputs to the system are approximately equal to outputs, and at the end of extended hydrograph recessions, when storage changes over time are small. One of these conditions was present during each of the above calibration dates (fig. 6). Steady-state conditions were most closely approximated for December 12, 1988, and two factors indicate that head distribution on this date may also be representative of long-term average conditions. First, local precipitation data and head data from the long-term Upper Floridan aquifer well at Greenhead, Fla. suggest that antecedent conditions (as estimated by 1987 and 1988 data) at Lake Five-O were comparable to long-term average conditions. Second, heads in the Lake Five-O ground-water system on December 12, 1988, were probably similar to their long-term averages.

This conclusion is based, in part, on the similarity of heads in the surficial aquifer on December 12, 1988, to average heads during the study period. The average heads during the study period are assumed to be representative of long-term average conditions because study-period precipitation and evaporation rates were similar to their respective long-term averages. Additionally, the head in the Greenhead well on December 12, 1988, was approximately equal to the long-term average value, which indicates that the head in the Upper Floridan aquifer at Lake Five-O on December 12, 1988, may have been representative of long-term average conditions. The December 12, 1988, model was the first of the steady-state models to be calibrated.

During the first attempts at calibrating the December 12, 1988, steady-state model, the location of the southwestern limit of the lateral no-flow boundary was based on the extrapolated water-table contours given by Andrews and others (1990), and was approximately concident with the unimproved road in this area. Values of hydraulic conductivity, leakance, and recharge were varied within preestablished ranges, but all configurations consistently underestimated heads observed south of Lake Five-O. This problem of underestimating heads was solved by extending the southwestern limits of the no-flow boundary into the plateau area southeast of Bream Lake (figs. 2 and 8). The new location of this boundary was approximately coincident with a topographically defined basin boundary in this area, and was supported by head data from subsequent placement of a shallow well (w32) west of well nest 1.

After adjusting the location of the southwestern no-flow boundaries, calibration efforts resumed with a simple model configuration with uniform distributions of horizontal hydraulic conductivity (K_h = 18 and 0.06 m/d in the surficial and intermediate confining unit, respectively) and anisotropy (K_h: K_v = 10:1) within each unit, and a single value of vertical hydraulic conductivity for the basal clay unit ($K_v = 7 \times 10^{-6}$ m/d). The root mean square error of the head differences (head RMSE) was within the calibration criteria at this point, but the simulated heads were low for the lake (-0.40 m) and high in the intermediate confining unit wells, w1.3 and w1.4 (approximately 0.50 m). Net precipitation was increased over the lake to raise the simulated lake stage, but lake stage showed little sensitivity to net precipitation. The lake stage was more sensitive to anisotropy in the deeper lake sediments, and a suitable head match for the lake and surficial wells was obtained by increasing the anisotropy of the lake sediments from 10:1 to approximately 140:1 in layers 3 and 4.

The final adjustments to the steady-state model centered on improving the simulation of the head loss that occurred across the contact between the surficial aquifer and intermediate confining unit at well nest 1 (defined by the head difference between wells w1.2 and w1.3). Some improvement was achieved by increasing the horizontal hydraulic conductivity in the intermediate confining unit from 0.06 m/d to 0.6 m/d. Recharge was then increased to 0.65 m/yr to increase heads in the surficial aquifer and lake, which had dropped moderately (because of the increase in the horizontal hydraulic conductivity in the intermediate confining unit). The final model configuration was obtained by increasing the anisotropy of the plateau parameter zone by a factor of 5 (which reduced the leakance between the surficial aquifer and intermediate confining unit in the plateau area by a factor of 5). This reduction was also supported by trial runs of the transient model, which showed an improved head response for wells w1.3 and w1.4. The calibrated values of hydraulic conductivity are shown in figure 15.

The head RMSE for the final configuration of the December 12, 1988, model was 0.16 m, and simulated heads for this configuration were within -0.13 to 0.27 m of observed heads for all wells except w3.1 and w3.2, which were underestimated by 0.38 and 0.31 m, respectively. For this final model configuration, simulated leakage from Lake Five-O to the contiguous ground-water system was 1,900 m^3/d, which was greater than the estimated lower limit of 800 m^3/d. Simulated ground-water inflow to Lake Five-O was 1,800 m^3/d.

Calibrations of the other steady-state models (for simulating conditions on May 9, 1989, October 10, 1989, and August 6, 1990) were achieved by adjusting the recharge and net precipitation rates only. Simulated leakage was greater than the 800 m^3/d minimum in all of these models. For the low-water model (May 9, 1989), recharge and net precipitation were set at 0.60 and -0.25 m/yr, respectively. The head RMSE for this match was 0.18 m, and simulated heads were within -0.21 to +0.11 m of observed heads for all wells except 28, 3.1 and 3.2, which were underestimated by 0.66, 0.37 and 0.37 m, respectively. For the high-water model (October 10, 1989), recharge and net precipitation were set at 0.66 and 0.25 m/yr, respectively. The head RMSE for this match was

0.23, and simulated heads were within -0.18 to +0.30 m of observed heads for all wells except 28, 3.1, and 3.2, which were underestimated by 0.84, 0.39, and 0.34 m, respectively. For the simulation of the summer 1990 hydrograph peak (August 6, 1990, model), values of recharge and net precipitation were identical to those used in the simulation of conditions on October 10, 1989. The head RMSE for this match was 0.22 m, and simulated heads were within -0.52 to +0.27 m of observed heads for all wells. The poorer correspondence of simulated and observed heads for this simulation is attributed to the brevity of the summer 1990 peak, which provided less time for the system to approach steady-state conditions. The simulated water table for conditions observed on October 4, 1989, is represented by the contour map shown in figure 16. Similar water table configurations were evident in the steady-state simulations of conditions on December 12, 1988, May 9, 1989, and August 6, 1990.

The sensitivity of the steady-state models to changes in model inputs was examined by varying model input variables, such as recharge and hydraulic conductivity, and comparing the model output to

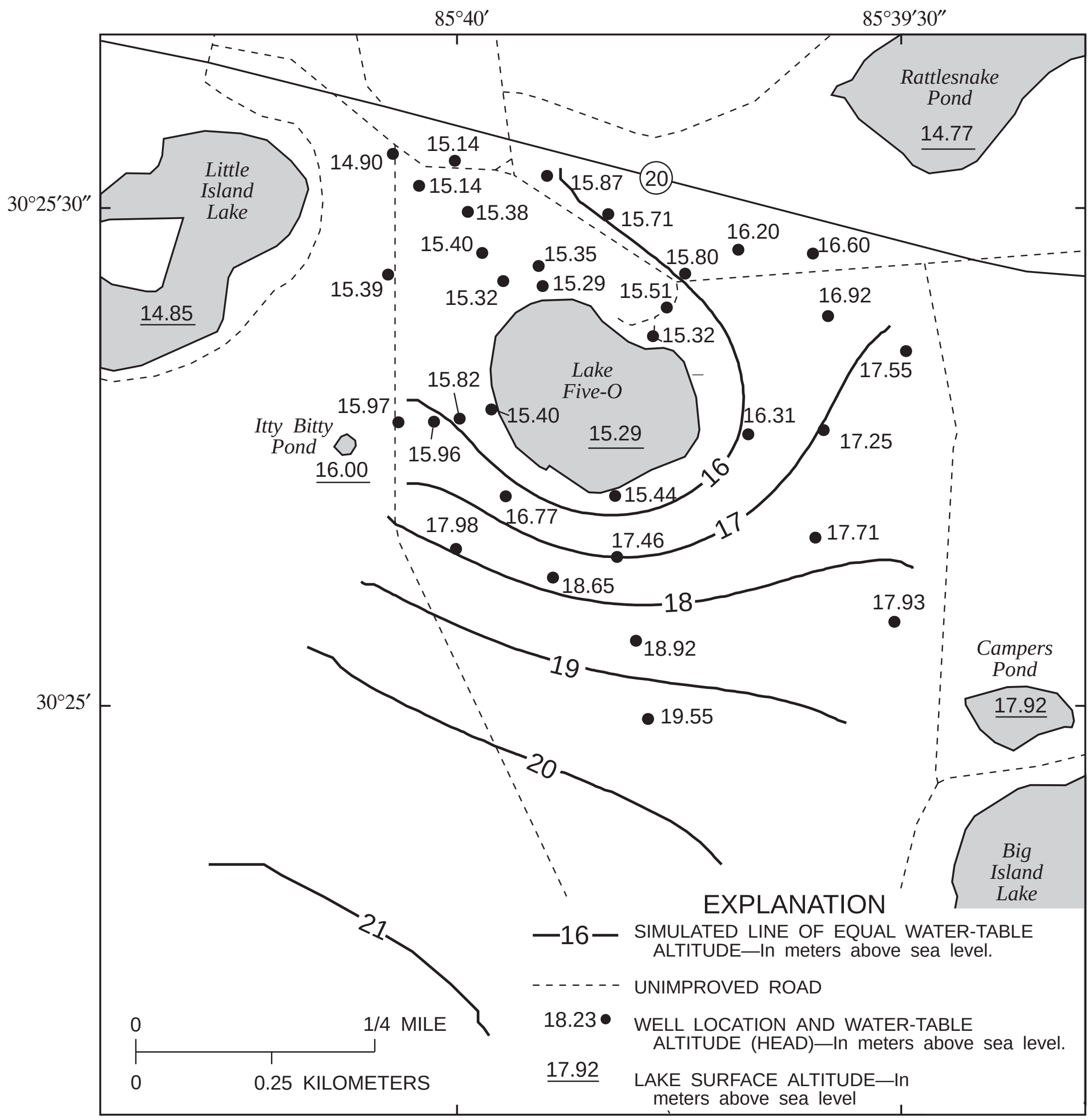

Figure 16. Simulated and observed water levels in the surficial aquifer near Lake Five-O, October 4, 1989.

that of the calibrated model for conditions on December 12, 1988. The input variables were varied within their probable ranges (established prior to modeling); therefore, statements regarding the sensitivity of the models to a given variable are only valid for the probable range established for that variable. Three model outputs were examined in the sensitivity analysis: simulated heads, ground-water inflow to Lake Five-O, and leakage from Lake Five-O. The head RMSE statistic was the primary means of evaluating the sensitivity of simulated heads (head response) to changes in model inputs, and differences between simulated heads and heads observed on December 12, 1988, were used to compute this statistic.

The head response of the steady-state models was most sensitive to changes in recharge, horizontal hydraulic conductivity and anisotropy of the surficial aquifer, and horizontal hydraulic conductivity of the intermediate confining unit ($K_{h,\,ICU}$). The sensitivity of the models to these variables is evident in the steep slopes of the head sensitivity curves (relations between head RMSE and change from calibrated value) for these variables (figs. 17 and 18). Despite the relatively gentle slope of the $K_{h,\,ICU}$ head sensitivity curve for values within 0.05 to 1 times the calibrated value of $K_{h,\,ICU}$ (fig. 17), heads in wells screened within the intermediate confining unit were quite sensitive to changes in $K_{h,\,ICU}$ over this range. For example, when the $K_{h,\,ICU}$ was set to 0.05 times the calibrated value, the difference between the simulated and observed head at well w1.4 increased from -0.08 to -0.86 m, whereas the head RMSE only increased from 0.16 to 0.29 m. The smaller head RMSE change (relative to the change in the heads of the intermediate confining unit wells) is explained by the fact that (1) the head RMSE statistic is more heavily weighted toward heads in the surficial aquifer, because more wells were constructed in the surficial aquifer than in the intermediate confining unit, and (2) heads in the surficial aquifer were much less sensitive to changes in $K_{h,\,ICU}$ than were heads in the intermediate confining unit.

The head response of the steady-state models was only partially sensitive to changes in the anisotropy of the intermediate confining unit, and insensitive to changes in net-precipitation and the leakance of

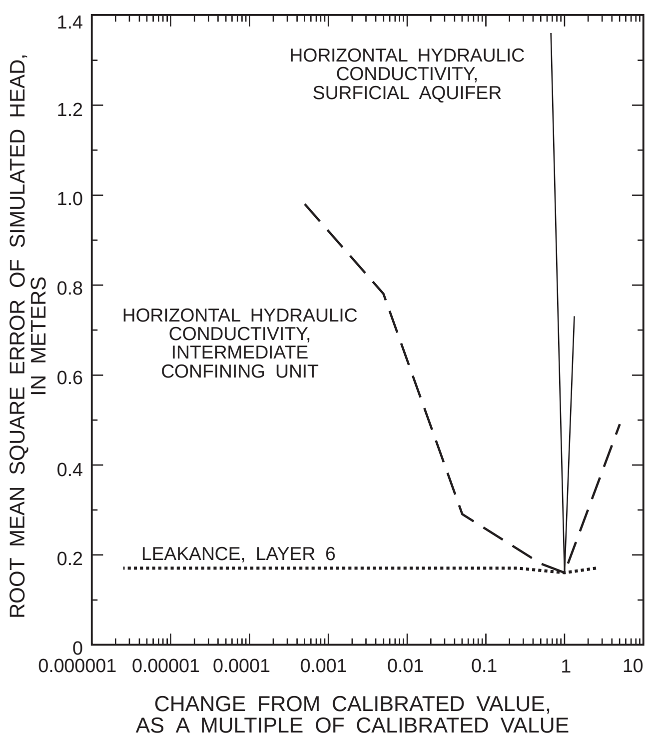

Figure 17. Sensitivity of steady-state models of ground-water flow system near Lake Five-O to changes in horizontal hydraulic conductivity and leakance of layer 6.

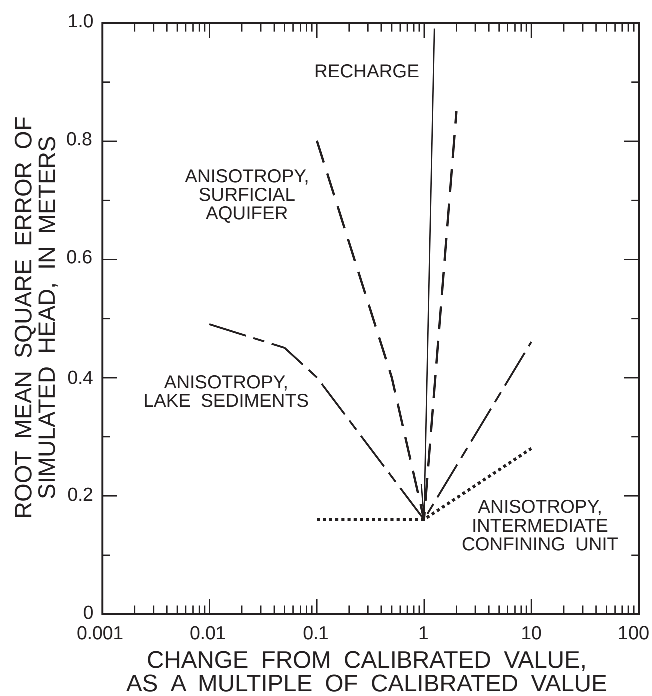

Figure 18. Sensitivity of steady-state models of ground-water flow system near Lake Five-O to changes in recharge and anisotropy.

the base of the intermediate confining unit (figs. 17 and 18). Heads in the intermediate confining unit changed appreciably when the anisotropy of the intermediate confining unit was increased to 10 times the calibrated value (although heads in the surficial aquifer, and hence head RMSE, increased only moderately). However, the heads did not change appreciably when the anisotropy of the intermediate confining unit was decreased by a factor of 10 (fig. 18).

Rates of ground-water inflow to and leakage from Lake Five-O were generally insensitive to changes in model input variables, with ground-water inflow and leakage rates generally within 3 percent of the calibrated values. Ground-water inflow and leakage rates were most sensitive to changes in recharge and lakebed anisotropy. The largest changes in ground-water inflow and leakage rates were a 35 percent increase in ground-water inflow and leakage (resulting from a 25 percent increase in recharge) and an 8 percent decrease in ground-water inflow and leakage (resulting from an order of magnitude increase in lakebed anisotropy).

A final steady-state modeling exercise was conducted to evaluate changes in ground-water inflow and leakage rates that might occur during several years of above average or below average precipitation. Estimates of the 90th percentiles of average annual precipitation rates, net precipitation rates, and Upper Floridan aquifer head were used to represent values that might occur during a typical wet period, and estimates of the 10th percentiles of these stresses were used to represent values that might occur during a typical dry period. Recharge rates for the wet or dry period simulations were obtained by multiplying the wet or dry period precipitation rates by the ratio of the recharge rate used in the steady-state simulation of conditions during December 12, 1988, and the long-term average precipitation rate. The results of this analysis indicate that ground-water inflow and leakage rates might increase by approximately 30 percent from the values obtained from the December 12, 1988, model during extended wet periods, and decrease by approximately 30 percent during extended dry periods.

Calibration of Transient Model

Calibration of the transient model consisted of determining values of storage properties and developing a function that defined temporal changes in recharge rates from December 12, 1988, to January 22, 1991. The hydraulic conductivity distributions in the transient model were identical to those in the calibrated steady-state models. Temporal discretization was accomplished by dividing the simulation period into 43 stress periods, and assigning recharge rates, net precipitation rates, and beginning and ending Upper Floridan aquifer head values to each of these periods (table 3). During summer wet periods, stress period intervals ranged from 1 day to 2 weeks, and were defined by periods of little or no precipitation and periods of more intense precipitation. During the remainder of the study period, when rainfall was more moderate, stress period intervals were approximately 1 month in length. The quality of the transient calibration was determined by comparing the shape of simulated and observed well hydrographs, and by comparing simulated and computed monthly net ground-water flow volumes.

Calibration of the transient model began with a storage property calibration in which values of specific yield in layer 1 and specific storage in layers 2-6 were systematically adjusted in an effort to simulate the slope of well hydrographs during period the of August 6, 1990, to January 22, 1991. Recharge was assumed to be negligible during most of this period, because rainfall was well below normal and the water-level hydrograph for well w6.2 showed a steep and generally uninterrupted recession (fig. 6). This assumption made it possible to calibrate specific yield and specific storage independently of recharge. The storage properties of lake cells did not require calibration: the specific yield for lake cells in layer 1 was fixed at a value of 1, and the specific storage of lake cells in layers 2-4 was fixed at a value of 4.5×10^{-6} m^{-1}, which is equal to the product of the compressibility of water and the specific weight of water at 22 °C (4.5×10^{-10} Pa^{-1} and 9.8×10^{3} N/m^{3}, respectively). Eight stress periods were used in the storage property calibration, and the duration and boundary stresses for all but the first of these stress periods coincide with those given for stress periods 36 through 43 in table 3. The first stress period in the storage property calibration was 3 days shorter than stress period 36, because the simulation period for the storage property calibration began 3 days after the beginning of stress period 36. Recharge was also set to zero in the first stress period of the storage property calibration because rainfall amounts were negligible and the hydrograph of well w6.2 showed a steady

Table 3. Temporal discretization and upper and lower boundary stresses used in the transient model of ground-water flow near Lake Five-O

[m/d, meters per day; UFA, Upper Floridan aquifer]

Stress period	Begin date	End date	Duration, in days	Recharge rate, in m/d	Net-precipitation rate, in m/d	Beginning UFA head, in meters	Ending UFA head, in meters
1	12-12-88	1-12-89	32	0.00000	-0.00117	12.84	12.61
2	1-13-89	2-08-89	27	.00000	- .00013	12.61	12.38
3	2-09-89	3-09-89	29	.00000	.00147	12.38	12.18
4	3-10-89	4-12-89	34	.00249	.00314	12.18	12.20
5	4-13-89	5-08-89	26	.00133	- .00064	12.20	12.05
6	5-09-89	5-31-89	23	.00218	- .00164	12.05	12.10
7	6-01-89	6-09-89	9	.00295	.02068	12.10	12.24
8	6-10-89	6-14-89	5	.00311	- .00287	12.24	12.36
9	6-15-89	6-25-89	11	.01509	.02352	12.36	12.71
10	6-26-89	7-02-89	7	.00774	- .00149	12.71	12.95
11	7-03-89	7-06-89	4	.00606	.02043	12.95	13.09
12	7-07-89	7-11-89	5	.00494	- .00280	13.09	13.23
13	7-12-89	7-23-89	12	.00328	.00791	13.23	13.47
14	7-24-89	8-06-89	14	.00288	- .00421	13.47	13.59
15	8-07-89	8-08-89	2	.00166	.02398	13.59	13.61
16	8-09-89	9-05-89	28	.00073	.00358	13.61	13.68
17	9-06-89	10-03-89	28	.00222	.00040	13.68	13.67
18	10-04-89	11-08-89	36	.00220	.00163	13.67	13.67
19	11-09-89	12-12-89	34	.00161	- .00073	13.67	13.62
20	12-13-89	1-16-90	35	.00222	.00169	13.62	13.64
21	1-17-90	2-06-90	21	.00121	- .00094	13.64	13.56
22	2-07-90	3-06-90	28	.00068	.00033	13.56	13.49
23	3-07-90	4-03-90	28	.00041	.00154	13.49	13.41
24	4-04-90	5-01-90	28	.00027	- .00079	13.41	13.21
25	5-02-90	6-05-90	35	.00056	- .00165	13.21	12.95
26	6-06-90	6-10-90	5	.00134	.01065	12.95	12.91
27	6-11-90	6-21-90	11	.00104	- .00168	12.91	12.85
28	6-22-90	6-24-90	3	.00210	.02421	12.85	12.84
29	6-25-90	6-30-90	6	.00108	- .00202	12.84	12.83
30	7-01-90	7-03-90	3	.00135	.00667	12.83	12.82
31	7-04-90	7-06-90	3	.00144	- .00404	12.82	12.82
32	7-07-90	7-14-90	8	.00911	.01807	12.82	12.84
33	7-15-90	7-23-90	9	.00506	.00295	12.84	12.85
34	7-24-90	8-01-90	9	.00263	- .00375	12.85	12.86
35	8-02-90	8-02-90	1	.00000	.01522	12.86	12.86
36	8-03-90	8-16-90	14	.00099	- .00467	12.86	12.82
37	8-17-90	8-22-90	6	.00130	.01120	12.82	12.78
38	8-23-90	9-05-90	14	.00000	- .00212	12.78	12.67
39	9-06-90	9-25-90	20	.00000	- .00607	12.67	12.50
40	9-26-90	11-04-90	40	.00000	- .00226	12.50	12.17
41	11-05-90	12-02-90	28	.00000	- .00329	12.17	11.91
42	12-03-90	1-02-91	31	.00000	.00015	11.91	11.64
43	1-03-91	1-22-91	19	.00000	.00260	11.64	11.55

decline during this period. The calibrated head distribution from the steady-state simulation of August 6, 1990, was used as the initial conditions (initial head distribution) for the August 6, 1990, to January 22, 1991 simulation period.

A suitable match to the August 6, 1990, to January 22, 1991, hydrograph recession was obtained by using a constant value of specific yield of 0.14 for aquifer cells in layer 1, and a constant specific storage value of 3 x 10^{-6} m^{-1} for aquifer cells in layers 2-6. Storativity values for individual model layers (in layers 2-6) were then calculated by multiplying layer thickness by the calibrated specific storage value of 3 x 10^{-6} m^{-1}. Specific yield was determined by initially setting specific storage to 3 x 10^{-6} m^{-1} and evaluating the correspondence between simulated and measured head declines for specific yield values of 0.10 to 0.30. The calibrated value of specific yield was then used in subsequent model runs in which specific storage was varied within the predefined limits. None of the head matches from these runs, however, showed significant improvement over those obtained with specific storage equal to 3 x 10^{-6} m^{-1}. The calibration process for specific yield and specific storage is illustrated in figure 19, which depicts the RMSE of predicted hydrograph slope (slope RMSE) for various values of specific yield and specific storage (at an abscissa coordinate equal to one, specific yield and specific storage are equal to their respective calibrated values). Figure 19 indicates that the calibrated values of specific yield and specific storage yielded the minimum slope RMSE values, and that the model was much more sensitive to changes in specific yield than to changes in specific storage.

The final calibration process consisted of systematically adjusting the recharge function to reproduce well hydrographs and monthly estimates of net ground-water flow during 1989 and 1990. Initial recharge estimates for each stress period were computed using equation 5 and the calibrated value of specific yield (from the first phase of the transient calibration). This preliminary recharge function was checked for mass balance errors and adjusted during the transient calibration to achieve acceptable hydrograph and net ground-water flow matches. The calibrated recharge function fell within upper and lower preliminary estimates (based upon calibrated specific yield and minimum and maximum water-table recession rates) for all months, with the exception of June 1989 and July 1990, when recharge rates were highest.

Simulated and measured heads are shown for Lake Five-O and selected wells in figure 20. Simulated well hydrographs reproduced the shape of measured hydrographs for almost all of the wells. Simulated heads were generally within 0.30 m of observed heads during the study period. Head differences at some wells were as large as 0.43 to 0.52 m near the summer 1989 and 1990 hydrograph peaks. The largest differences between observed and simulated heads consistently occurred at wells w3.1, w3.2, and w28, where heads were generally underestimated by 0.36, 0.36, and 0.64 m. Simulated heads at Lake Five-O and the near-lake piezometer nests were generally within 0.15 m of measured heads, with maximum differences less than 0.30 m.

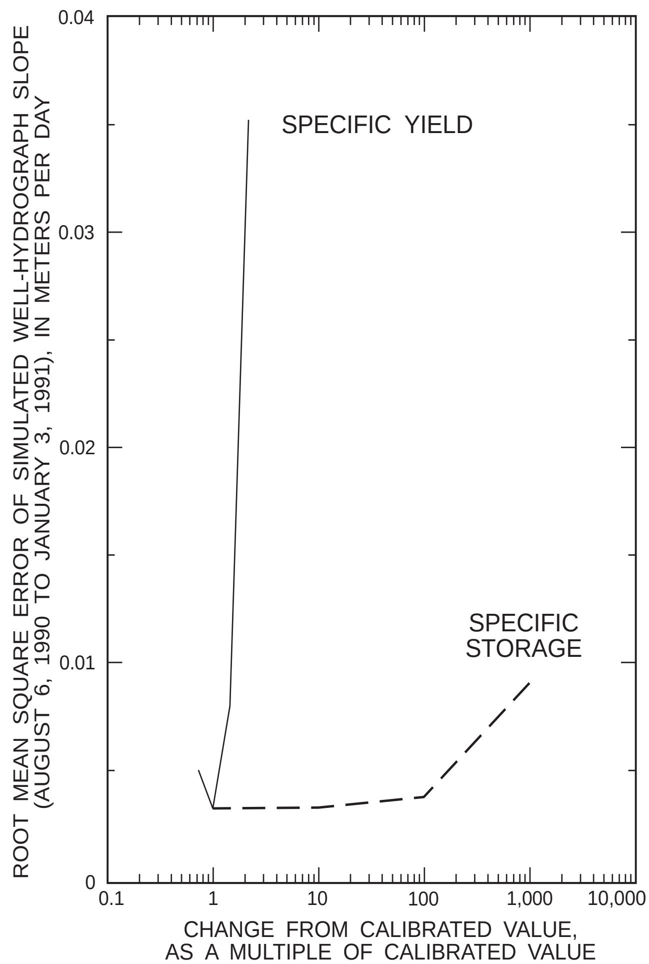

Figure 19. Sensitivity of transient model of the ground-water flow system near Lake Five-O to changes in aquifer storage properties.

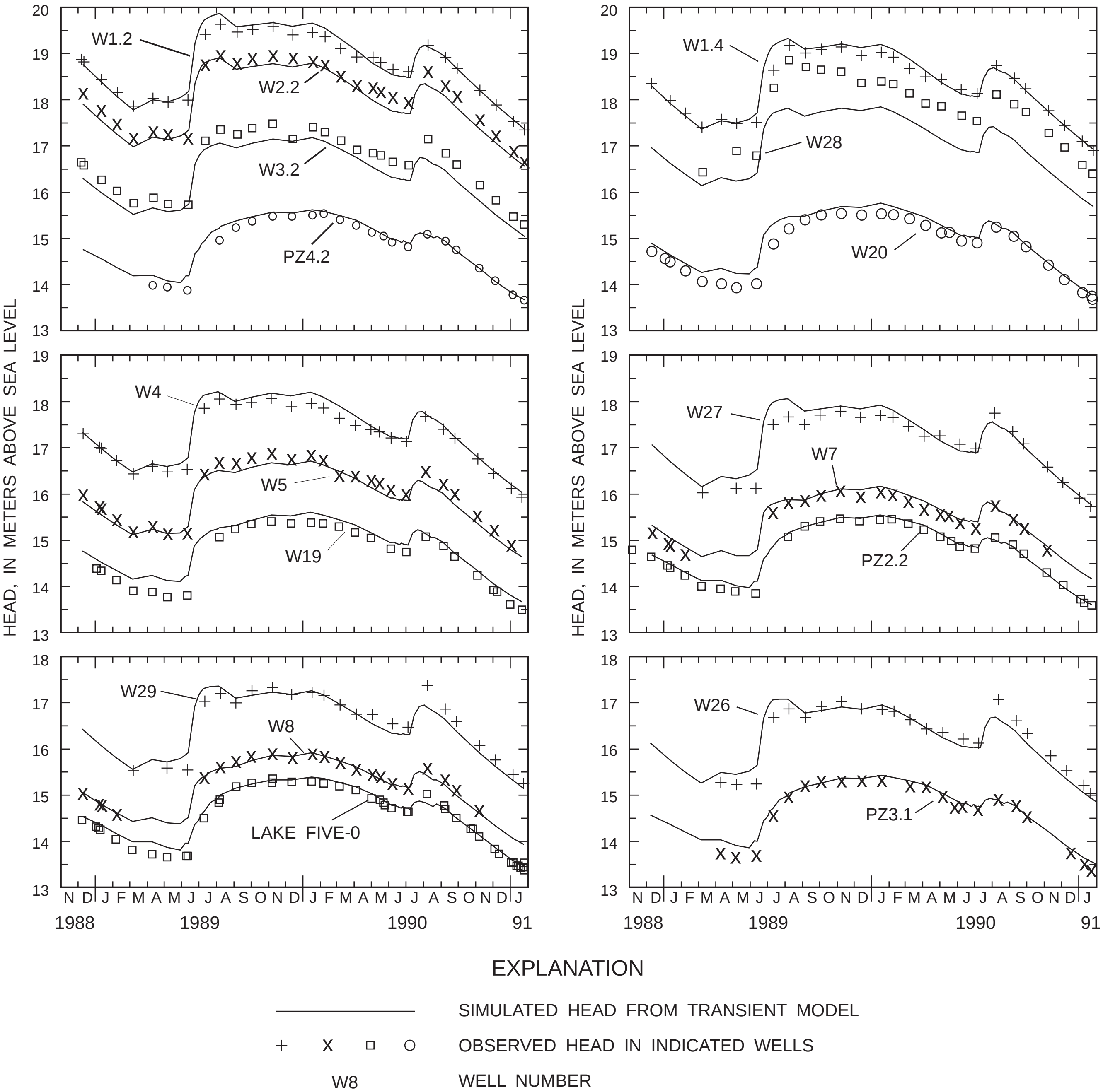

Figure 20. Simulated and observed heads for Lake Five-O and adjacent ground-water system, December 12, 1988, through January 22, 1991.

Simulated and computed net ground-water flow to Lake Five-O is shown in figure 21. Simulated net ground-water flow values were within the 99 percent confidence intervals of the computed values for 18 of the 24 months. The largest absolute differences between simulated and computed net ground-water flow occurred in January, June, July and September of 1989. None of these differences were unreasonably large when compared to the magnitude of simulated ground-water inflow and leakage. Differences between simulated and computed monthly net ground-water flow were within -10 and +14 percent of total inflow or total outflow for 20 of the 24 months during 1989 and 1990, and were within ±26 percent of the total inflow or outflow for all months in 1989 and 1990.

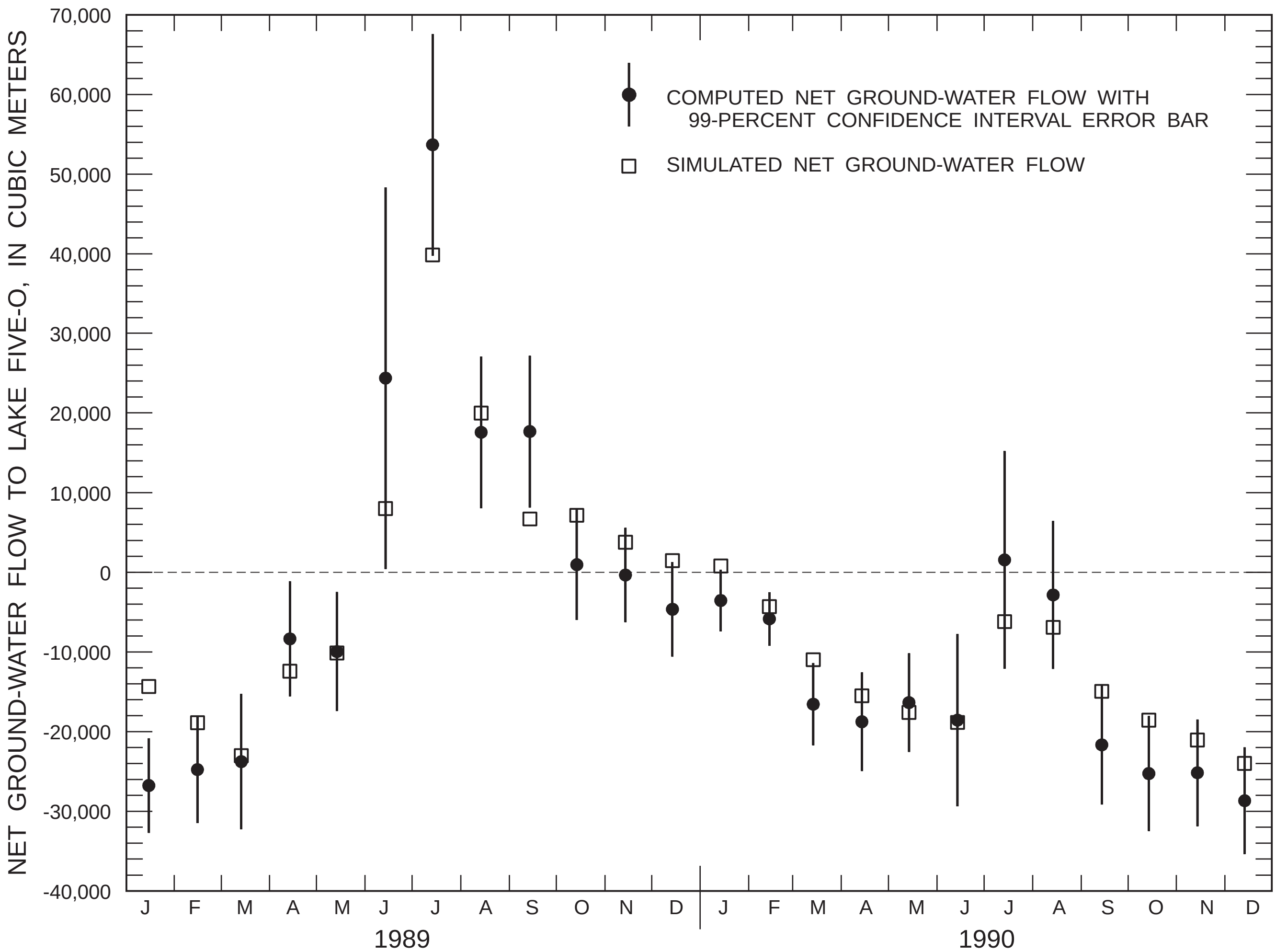

Figure 21. Simulated and computed monthly net ground-water flow to Lake Five-O, 1989-90.

Thus, even the largest differences between simulated and computed net ground-water flow represented less that 30 percent of total inflow to, or total outflow from Lake Five-O. The temporal distribution of these differences are further described in a later section describing the hydrologic budget for Lake Five-O.

Flow-Path Simulations

A particle tracking program (Pollock, 1989) was used to evaluate ground-water pathlines (flow paths) and residence times for hypothetical parcels of ground water (particles) that discharge to Lake Five-O. Flow-path simulations were conducted using the head distributions from the December 12, 1988, May 9, 1989, and October 4, 1989, steady-state simulations (medium, low, and high water-level conditions respectively). Porosity values were assumed to be constant within a given lithologic unit (surficial aquifer or intermediate confining unit). A range of residence times was calculated by conducting a series of flow-path simulations in which porosity values were varied within the probable ranges established for the surficial aquifer (0.25-0.50) and intermediate confining unit (0.10-0.50).

Results of a flow path simulation where particles were placed along the entire surface of the lakebed and allowed to flow in reverse toward their points of recharge to the water table are shown in figure 22. These results indicate that most of the surrounding ground-water basin contributes to Lake Five-O. Recharge between the contributing area and ground-water basin boundaries bypasses Lake Five-O and discharges to the Upper Floridan aquifer. The residence times for inflow particles (traveltime from

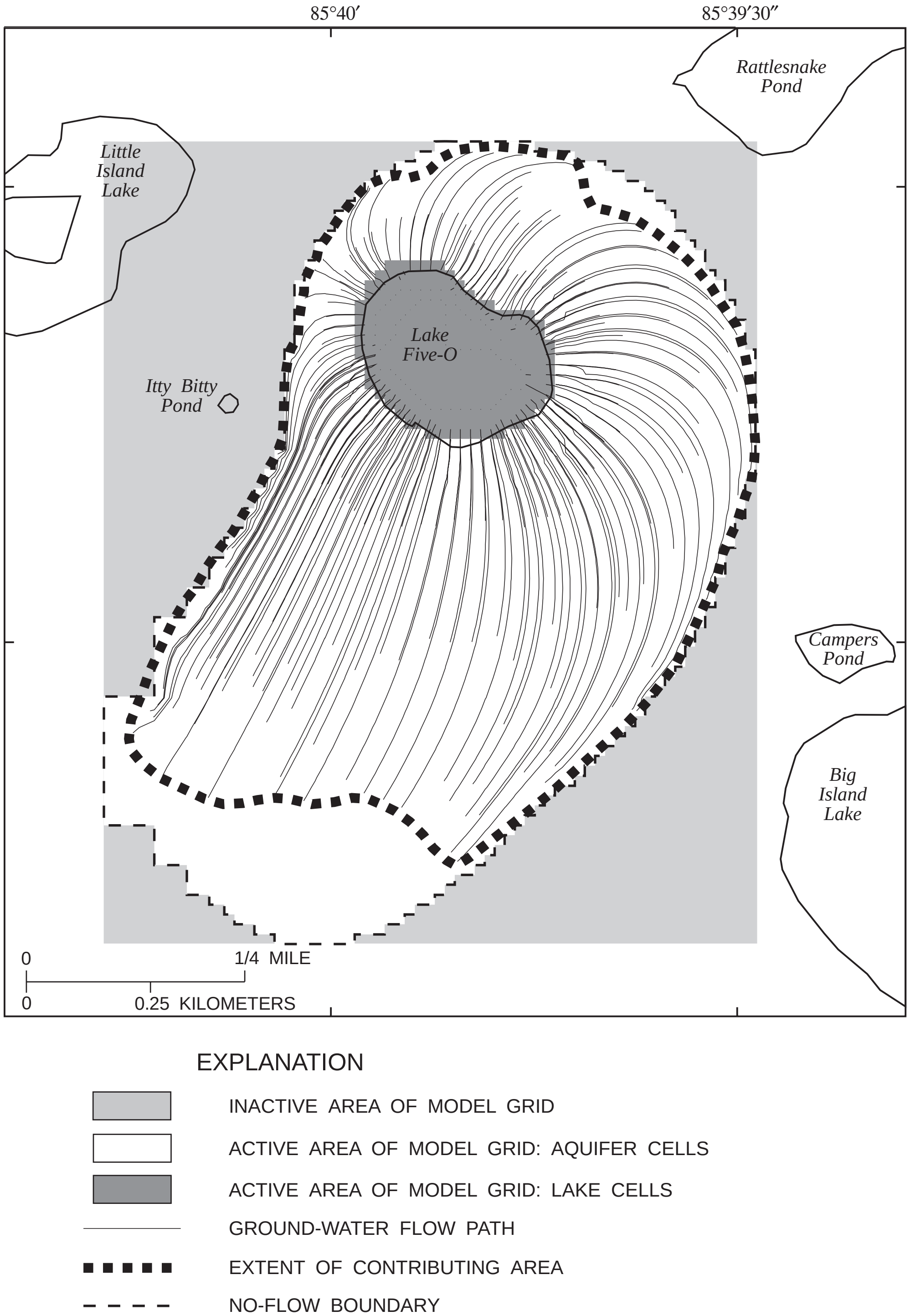

Figure 22. Contributing area to Lake Five-O, as defined by ground-water flow paths of particles that discharge to the lake.

recharge at the water table to discharge at the lake) generally ranged from 0.6 to 9 years, and showed little variation between high and low water conditions. Mean residence time was estimated to be within a range of 3 to 6 years.

The vertical character of ground-water flow within and between the surficial aquifer and intermediate confining unit is shown in figure 23. The flowlines are deflected downward at two points (stagnation points) an infinitesimal distance outside

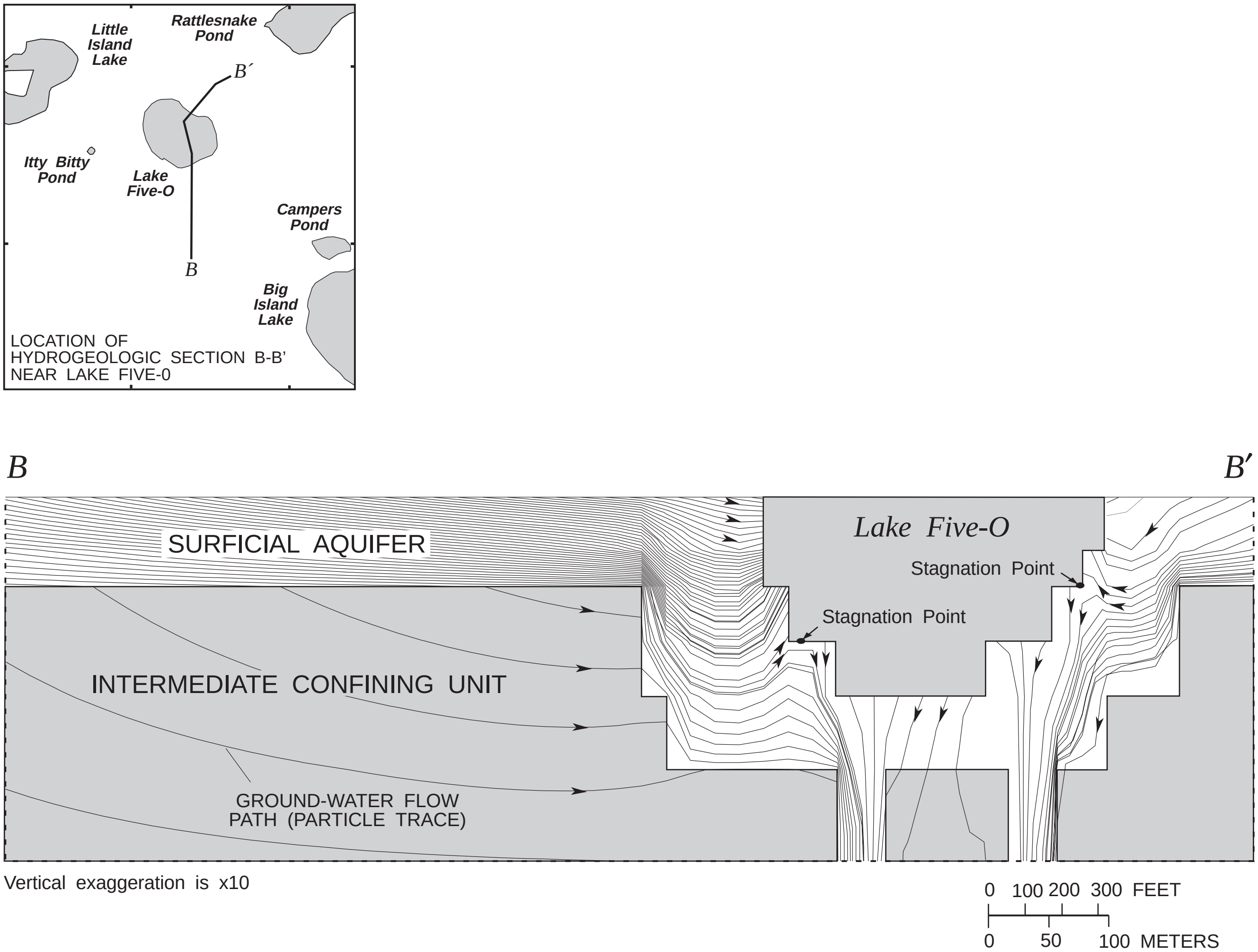

Figure 23. Particle traces projected onto hydrogeologic-section B-B′ near Lake Five-O.

the lakebed where the head in the ground-water flow system is the same as the altitude of the lake surface (figs. 9, 10, and 23) Ground-water inflow to Lake Five-O occurs above these points, and leakage from the lake to the contiguous ground-water system occurs below these points. The location of these stagnation points did not change appreciably from low to high water conditions. The simulated flow paths in figure 23 also indicate that almost all of the ground-water flow near Lake Five-O occurs within the surficial aquifer, and that ground water that discharges to Lake Five-O does not move through the intermediate confining unit.

HYDROLOGIC BUDGET FOR LAKE FIVE-O

The expression for the hydrologic budget of Lake Five-O was previously given in equation 7. In this expression, five variables were considered significant in the hydrologic budget of Lake Five-O: lake volume change, ground-water inflow to the lake, leakage from the lake to the contiguous ground-water system, and precipitation and evaporation over the surface of the lake. As previously mentioned, lake volume changes, precipitation, and evaporation were all measured or estimated before development of the ground-water models. The estimates of these variables made it possible to estimate net ground-water flow prior to modeling, but not the individual components that comprise net ground-water flow: ground-water inflow and leakage. With the calibration of the ground-water flow models, it was possible to calculate ground-water inflow to, and leakage from Lake Five-O, using the simulated ground-water flowfields from the these models. At this stage of the analysis, a complete hydrologic budget for Lake Five-O was available which explicitly accounted for each of the relevant hydrologic variables. The following section describes the hydrologic budget for Lake Five-O during the 1989-90 study period. Particular emphasis is given to the description of temporal and spatial variations in ground-water inflow and leakage because these variables represent such a large part of the hydrologic budget of Lake Five-O. The relation between the estimates of the hydrologic variables during the study period and the long-term average values of these variables is also discussed, as are changes in the hydrologic budget that might occur in response to changing boundary conditions.

The results of the ground-water flow simulations indicate that the ground-water system is the dominant source of water for Lake Five-O. During the 1989-90 study period, simulated ground-water inflow was estimated to be approximately 1.2 x 10^6 m^3 (average inflow of 1.7 x 10^3 m^3/d), which is approximately 4 times larger than estimated precipitation inputs (3.4 x 10^5 m^3) for this period. The simulation results also indicate that the ground-water system is the dominant sink for water leaving Lake Five-O. Leakage from Lake Five-O was estimated to be approximately 1.4 x 10^6 m^3 (1.9 x 10^3 m^3/d), which is approximately 5 times larger than estimated evaporation losses (2.6 x 10^5 m^3) for this period. The lake volume decreased by 8.4 x 10^4 m^3 or 8 percent from January 1, 1989, to December 31, 1990, and varied from a minimum of 9.1x 10^5 m^3 to a maximum of 1.1x 10^6 m^3.

The temporal distribution of water inputs (precipitation and ground-water inflow) to Lake Five-O indicates that both precipitation and ground-water exhibited a strong seasonal dependence, and that Lake Five-O received large volumes of ground water throughout the study period under a variety of climatic conditions (fig. 24). Monthly precipitation inputs ranged from approximately 800 to 5.7 x 10^4 m^3 during 1989 and 1990, with the largest values occurring during the summer wet periods and the smallest values occurring during the typically dryer winter, spring, and fall seasons. Monthly ground-water inflows to Lake Five-O ranged from approximately 3.5 x 10^4 to 8.4 x 10^4 m^3 (fig. 24). The highest simulated ground-water inflow volumes also occurred during summer wet periods in 1989 and 1990; the lowest values occurred during the relatively dry winter-spring seasons of 1989 and 1990, and the fall of 1990 (fig. 24).

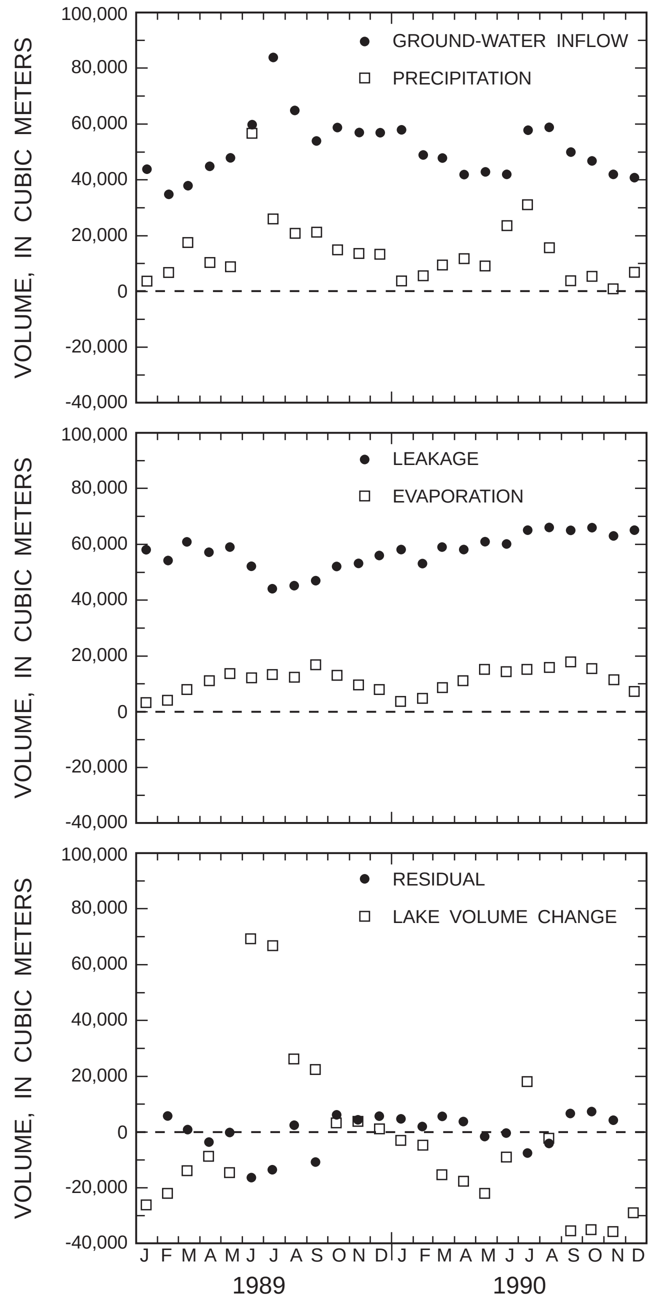

Figure 24. Monthly hydrologic-budget components for Lake Five-O, 1989-90.

Simulated ground-water inflows were consistently larger than concurrent precipitation inputs to the lake. During the wetter than normal year of 1989 (precipitation was approximately 25 percent above normal), ground-water inflow was approximately 3 times greater than precipitation. Although simulated ground-water inflow decreased moderately in 1990 (precipitation was approximately 25 percent below normal), the ratio of simulated ground-water inflow to precipitation (Q_i:P) increased to 4.5:1. Similar patterns were evident in the distribution of the monthly ground-water inflow and precipitation values (fig. 24). The ratio, Q_i:P, was lowest during the summer wet periods, but ground-water inflow still remained larger than precipitation inputs during these periods. The largest Q_i:P values occurred during dry winter months in 1989 and 1990 and during the dryer than normal fall of 1990.

The above relations between ground-water inflow and precipitation indicate several characteristics of the temporal distribution of water inputs to Lake Five-O. First, the seasonal distribution of ground-water inflow is consistent with the typical seasonal distribution of precipitation, with the highest inflow rates occurring during the wet summer season and the smallest inflow rates occurring during the dryer winter, spring, and fall seasons. Second, ground-water inflow is consistently greater than precipitation over monthly and longer time scales. Finally, ground-water inflow to Lake Five-O can increase relative to precipitation during dry periods.

Seasonal patterns were evident in the temporal distribution of evaporation losses, but were not evident in leakage losses from Lake Five-O (fig. 24). Monthly evaporation losses from Lake Five-O ranged from 3.2 x 10^3 to 1.8 x 10^4 m^3, and showed a strong seasonal dependence with the smallest rates occurring in the winter months, and the largest rates occurring during the summer months (fig. 24). This seasonal dependence in the volumetric estimates of evaporation from Lake Five-O follows directly from that observed in the volume per unit area evaporation estimates of Sacks and others (1994). Examination of the seasonal distribution of historic estimates of evaporation from Lake Five-O (using the Milton NOAA station regression relations) indicates that the seasonal distribution of evaporation during the study is representative of the typical seasonal distribution. Simulated monthly leakage from Lake Five-O to the contiguous ground-water system ranged from 4.4 x 10^4 to 6.6 x 10^4 m^3 (fig. 24). The monthly leakage values were directly related to the head difference between the lake and Upper Floridan aquifer (fig. 11), and exhibited no obvious seasonality. Minimum leakage rates occurred during the summer of 1989, when the head difference between the lake and Upper Floridan aquifer was at a minimum (1.3 m). Leakage rates returned to their pre-summer 1989 levels during the fall of 1989 through the spring of 1990, and increased to their maximum levels in the summer and fall of 1990, when the head difference between Lake Five-O and the Upper Floridan aquifer was a maximum (1.9-2.2 m).

Simulated leakage volumes were consistently greater than concurrent evaporative losses throughout the study period. The ratio of leakage to evaporation (Q_o:E) was 5.1:1 in 1989, and increased to 5.3:1 in the dryer year of 1990. Simulated leakage from Lake Five-O exceeded evaporative losses for all months during the study, with maximum values of Q_o:E occurring during the winter seasons, when lake evaporation was at a minimum (fig. 24). These observations indicate that leakage is consistently greater than lake evaporation over monthly and longer timescales. This conclusion is analogous to that observed for ground-water inflow and precipitation, and indicates that exchanges of water between the ground-water system and Lake Five-O are consistently greater than atmospheric-lake exchanges.

The temporal distribution of lake volume changes (fig. 24) reflects the temporal distribution of total inflow (precipitation plus ground-water inflow) to Lake Five-O. Monthly lake volume change ranged from -3.6 x 10^4 to 6.9 x 10^4 m^3. Lake volume changes were greatest during the dry periods in the winter and early spring of 1989, spring 1990, and fall 1990, and during the wet periods of the summer and early fall of 1989 and summer 1990. Lake volume changes were smallest from October 1989 through February 1990. Although lake volume changes are, by definition, a function of inputs and outputs, almost all of the variability in temporal distribution of lake volume change can be explained by variations in input. This dependence exists because the temporal distributions of precipitation and ground-water inflow are much more variable than those of evaporation and leakage.

The temporal distribution of the residuals from the monthly hydrologic budget (difference between simulated and computed net ground-water flow) is given in figure 24. The magnitude of the residuals in the monthly budget ranged from -1.6 x 10^4 to 1.2 x 10^4 m^3. A moderate inverse relation existed between the residuals and lake volume changes, in that larger, positive-value residuals usually occurred when lake volume decreased significantly, and smaller, negative-value residuals usually occurred when lake volume increased significantly. Given the above dependence of lake volume changes on total inflow, this indicates that ground-water inflow is probably underestimated in months with large increases lake volume, and over-estimated in months with large decreases in lake volume.

The spatial distribution of simulated ground-water inflow and leakage indicated little variation between high and low water conditions. High rates of simulated ground-water inflow occurred around all but the northwestern margin of Lake Five-O, with the highest rates occurring along the southern margin. Although ground-water inflow rates were greatest at shallow depths, the simulations indicate that ground-water inflow occurs at appreciable depths in some regions of the lake. Approximately 90 percent of the total ground-water flow to Lake Five-O was accounted for in the upper 6 m of the lake (layers 1 and 2). Simulated leakage was limited to deeper areas of Lake Five-O, with approximately 90 percent of total leakage occurring through the bottom third of Lake Five-O (depths greater than 10 m). The highest rates were located in the vicinity of the confining bed breaches.

Comparison of the depth distribution of ground-water inflow during high- and low-water periods also indicated that changes in ground-water inflow were primarily a result of increases in the saturated thickness of the surficial aquifer rather than major changes in head gradients across most of the lakebed. Ground-water inflow rates at depths greater than 1 to 3 m (layers 2-4) showed no significant changes between high- and low-water conditions, which indicates that head gradients were unchanged in deeper lakebed areas that receive ground-water inflow. In particular, between May 9, 1989, and October 4, 1990, when simulated ground-water inflow increased approximately 25 percent, shallow head gradients near Lake Five-O decreased slightly. This resulted in less ground-water inflow to the lake per unit area of lakebed; however, the increase in the inundated area of the shallow lakebed more than offset the effects of reduced inflow gradients.

Although the study period included unusually wet periods and unusually dry periods, the average ground-water inflow and leakage rates during the study are probably similar to long-term, average inflow and leakage rates. This conclusion is supported by the similarity between study period average precipitation and net precipitation rates (158 and 37 cm/yr, respectively) and long-term average rates (157 and 39 cm/yr, respectively). Additionally, local precipitation data and head data from the Upper Floridan aquifer well at Greenhead suggest that antecedent conditions (as estimated by 1987 and 1988 data) at Lake Five-O were comparable to long-term average conditions. The average ground-water inflow and leakage values from the transient model (1.7×10^3 and 1.9×10^3 m^3/d, respectively) were also similar to the values obtained from the steady-state model of conditions on December 12, 1988, (1.8×10^3 and 1.9×10^3 m^3/d, respectively), which were considered representative of long term, average conditions. Thus, long-term, average ground-water inflow to, and leakage from Lake Five-O are expected to be approximately 1.7×10^3 to 1.8×10^3 m^3/d and 1.9×10^3 m^3/d, respectively (approximately 4 and 5 times precipitation and evaporation, respectively).

Long-term average ground-water inflow and leakage rates seem to be relatively insensitive to drawdown in the Upper Floridan aquifer, which could result from increased pumpage of the aquifer. Potential effects of drawdown were evaluated in a series of steady-state simulations in which the head assigned to the lower boundary was systematically lowered. Average annual recharge and net precipitation rates were used in all of these simulations, and the location of the lateral (ground-water divide) boundaries were assumed to be unaffected by the imposed drawdowns. The results of the simulations indicated that drawdowns of up to 5 m below the long-term average head in the Upper Floridan aquifer would produce only modest declines in ground-water inflow and leakage rates. At the maximum drawdown of 5 m, ground-water inflow and leakage decreased by only 7 percent, despite the fact that lake stage and volume decreased by approximately 4 m and 50 percent, respectively. This small decline in ground-water inflow and leakage rates may be explained by two factors. First, the total input to the flow system (recharge to the surficial aquifer plus net precipitation over Lake Five-O) was virtually constant for all of the drawdown scenarios. Second, potentially larger reductions in ground-water inflow and leakage rates (because of lowered water levels and corresponding reductions in the area of the lakebed through wich ground-water inflow and leakage occur) were offset by an increase in the head gradients between the lake and the ground-water system. This increase in the head gradients would most likely result from a reduction in the saturated thickness (and therefore transmissivity) of the surficial aquifer in response to declining water levels.

The significance of the ground-water inflow and leakage components of the hydrologic budget of Lake Five-O emphasizes the importance of considering the interactions between lakes and contiguous ground-water systems when developing hydrologic budgets for Florida lakes. When these interactions are poorly understood, the exchange of water between the lake and the ground-water system may be underestimated, because hydrologic budget analyses are often based on the assumption that ground-water inflow (or leakage) is negligible when net leakage (or net ground-water inflow) is indicated. This conclusion is supported by the analyses of head data, computed net ground-water inflow, and the ground-water flow simulations at Lake Five-O, all of which indicated that the lake consistently receives large volumes ground-water inflow and leaks large volumes of water to the ground-water system. This conclusion is also consistent with recent work by several investigators. Based on their preliminary net ground-water flow and geochemical analyses of lakes Barco and Five-O, Pollman and others (1991) indicated that previous studies had underestimated ground-water inflow to some seepage lakes in northwestern Florida. Stauffer and Canfield (1992) used a mass-balance analysis (Stauffer, 1985) of silica to infer that ground-water inflow rates for seepage lakes in northwestern Florida were one to two orders of magnitude greater than the rate of 0.01 m^3/m^2-yr estimated by Baker and others (1988). Similar results were obtained for several lakes in ridge provinces in peninsular Florida. Stauffer and Canfield (1992) also noted that previous work by Deevey (1988) probably underestimated ground-water inflow and leakage rates, because the hydrologic budget used in that study was based on the assumption that ground-water inflow and leakage do not occur simultaneously. This negative bias is a particular problem in lakes, such as Lake Five-O, that continuously receive ground water and leak to the ground-water system simultaneously.
The analysis of the ground-water flow system and hydrologic budget of Lake Five-O underscores the importance of physical and chemical ground-water data when developing hydrologic budgets for seepage lakes.

SUMMARY

As part of a larger study of geochemical processes in acidic seepage lakes in Florida, a study of the hydrology and hydrologic budget of Lake Five-O in northwestern Florida was conducted during 1988-91. As with most seepage lakes in karst settings, developing a quantitative understanding of the hydrology of Lake Five-O was complicated by the difficulty of quantifying exchanges of water between the lake and its contiguous ground-water system. A primary objective of the work at Lake Five-O was to improve the understanding of the ground-water flow system near Lake Five-O, and to develop a hydrologic budget for the lake. Quantitative studies of the hydrology of seepage lakes, such as Lake Five-O, can provide information that is critical to understanding the geochemistry of these lakes.

The hydrogeology near Lake Five-O is characterized by three distinct lithologic units: a very permeable, sandy surficial aquifer; a less permeable, calcareous, sandy-clay to clayey-sand intermediate confining unit; and, at the base of the system, a sequence of highly transmissive carbonate rocks that comprise the Upper Floridan aquifer in the study area. Seismic surveys indicated that the intermediate confining unit has been breached under the lake, providing a high conductance pathway for the downward movement of water from the surficial aquifer and lake to the Upper Floridan aquifer.

Head data collected during the study indicated a consistent pattern of flow toward Lake Five-O and a strong potential for ground-water inflow to and leakage from the lake over a wide range of hydrologic conditions throughout the study period. The head data also indicated that ground-water inflow occurs at appreciable depths around much of the perimeter of Lake Five-O, and that the largest rates of ground-water inflow occur along the southern margin of the lake, where head gradients are larger. Heads in the surficial aquifer, lake, and intermediate confining unit were consistently higher than those in the underlying Upper Floridan aquifer, indicating a consistent potential for downward flow from the shallow system to the Upper Floridan aquifer. Head differences between the surficial and Upper Floridan aquifers were much smaller near Lake Five-O relative to the surrounding plateau area, which is consistent with the interpretation of effective breaching of the intermediate confining unit under the lake.

Precipitation, evaporation, and lake volume data also indicated that the ground-water flow to Lake Five-O and leakage from the lake to the ground-water system are significant components in the hydrologic budget of the lake. The volume of Lake Five-O increased much faster than predicted by net-precipitation inputs alone, during the summer of 1989 and, to a lesser extent, during the summer of 1990. Conversely, during relatively dry periods in the spring of 1989, and the spring and fall of 1990, lake volumes decreased much faster than predicted by net atmospheric losses. The precipitation, evaporation, and lake volume data were also used to compute estimates of net ground-water inflow (ground-water inflow minus leakage) and minimum estimates of study period and long-term average ground-water inflow and leakage rates. The latter analysis indicated that long-term average ground-water inflow and leakage represent at least 62 percent and 70 percent of the total inflow and outflow budgets of Lake Five-O, respectively.

Simulation models of the ground-water flow system near Lake Five-O indicate that ground-water inflow and leakage are the dominant components in the inflow and outflow budgets of the lake, and that ground-water inflow and leakage are considerably larger than the minimum estimates given by the net ground-water flow analysis. During 1989-90, ground-water inflow and leakage were estimated to be 1.2×10^6 and 1.4×10^6 m^3, respectively. Ground-water inflow and leakage are approximately 4 and 5 times larger than precipitation and evaporation, respectively. The temporal distribution of simulated ground-water inflow and leakage also indicated that exchanges of water between the ground-water system and lake were consistently larger than atmospheric-lake exchanges throughout 1989-90. The relative importance of exchanges of water between the ground-water system and lake generally increase when atmospheric-lake exchanges are at seasonal minimums. Climatic data and model results indicated that average rates of ground-water inflow and leakage for the study period were probably representative long-term, average rates.

The spatial distributions of simulated ground-water inflow and leakage exhibited little variation between dry and wet periods. The highest rates of inflow were predicted for the southern margin of Lake Five-O. Analysis of the depth distribution of ground-water inflow indicated that temporal changes in ground-water inflow were primarily the result of changes in the saturated thickness of the surficial aquifer, rather than major changes in head gradients or reversals of flow along the lakebed. Simulated leakage was limited to deeper areas of the lakebed, with the highest leakage rates located in the vicinity of the confining bed breaches.

Residence times and flow paths of ground-water inflow were evaluated using a particle tracking program and head distributions from steady-state model simulations. Mean residence time of ground-water discharging to Lake Five-O was estimated between 3 and 6 years. Flow-path evaluations indicated that ground water discharging at the lake has had negligible contact with the sediments in the intermediate confining unit.

The dominance of ground water in the hydrologic budget of Lake Five-O is contrary to previous studies that suggested that ground-water contributions are generally small relative to precipitation inputs in seepage lakes. The simulation results at Lake Five-O are consistent with recent work that indicates that these studies might have significantly underestimated ground-water inflow to many seepage lakes. This recent work, coupled with the results obtained at Lake Five-O, emphasizes the importance of ground water in the hydrology of Florida seepage lakes.

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