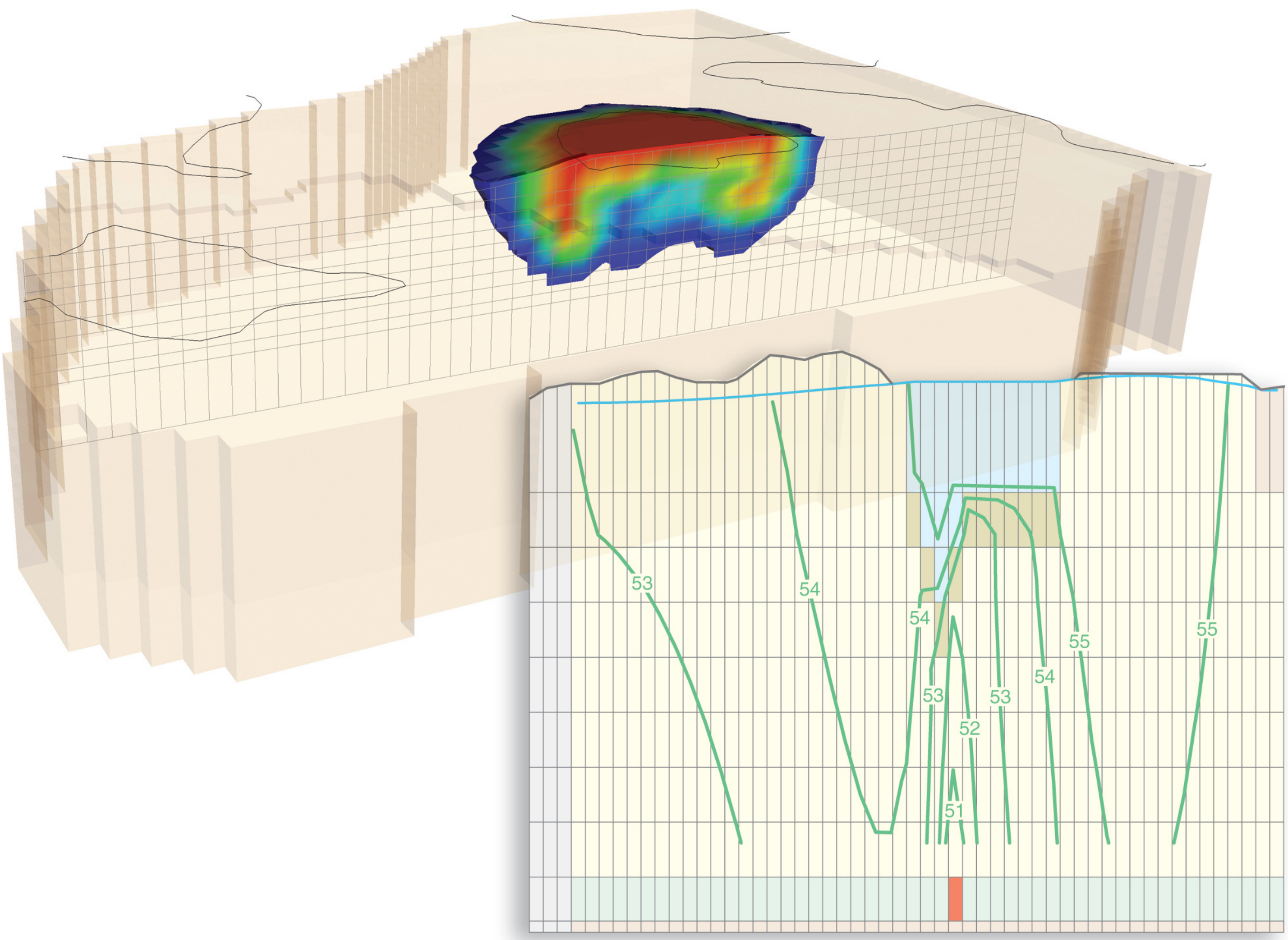
In cooperation with the Southwest Florida Water Management District

Simulated Effects of Ground-Water Augmentation on the Hydrology of Round and Halfmoon Lakes in Northwestern Hillsborough County, Florida



Water Resources Investigations Report 03-4322

U.S. Department of the Interior
U.S. Geological Survey

Simulated Effects of Ground-Water Augmentation on the Hydrology of Round and Halfmoon Lakes in Northwest Hillsborough County, Florida

By Richard M. Yager and P.A. Metz

Prepared in cooperation with the
SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT

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U.S. Department of the Interior
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Conversion Factors, Acronyms, Abbreviations and Datum

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
inch per month (in/mo)	25.4	millimeter per month (mm/mo)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
foot (ft)	0.3048	meter (m)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
acre	0.4047	hectare (ha)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

AET	Actual evapotranspiration
kaPa	kilopascal
MWL	meteoric waterline
NADP	National Atmospheric Deposition Program
R^2	Coefficient of determination
SWFWMD	Southwest Florida Water Management District
USGS	U.S. Geological Survey
g/cm^3	gram per cubic centimater
cm	centimeter
cm^3	cubic centimater
mo	month

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

$$°F = (1.8 \times °C) + 32$$

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

$$°C = (°F - 32) / 1.8$$

Vertical coordinate information is referenced to the National Vertical Datum of 1929 (NGVD of 1929); horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Simulated Effects of Ground-Water Augmentation on the Hydrology of Round and Halfmoon Lakes in Northwestern Hillsborough County, Florida

By Richard M. Yager *and* P.A. Metz

Abstract

Pumpage from the Upper Floridan aquifer in northwest Hillsborough County near Tampa, Florida, has induced downward leakage from the overlying surficial aquifer and lowered the water table in many areas. Leakage is highest where the confining layer separating the aquifers is breached, which is common beneath many of the lakes in the study area. Leakage of water to the Upper Floridan aquifer has lowered the water level in many lakes and drained many wetlands. Ground water from the Upper Floridan aquifer has been added (augmented) to some lakes in an effort to maintain lake levels, but the resulting lake-water chemistry and lake leakage patterns are substantially different from those of natural lakes. Changes in lake-water chemistry can cause changes in lake flora, fauna, and lake sediment composition, and large volumes of lake leakage are suspected to enhance the formation of sinkholes near the shoreline of augmented lakes.

The leakage rate of lake water through the surficial aquifer to the Upper Floridan aquifer was estimated in this study using ground-water-flow models developed for an augmented lake (Round Lake) and non-augmented lake (Halfmoon Lake). Flow models developed with MODFLOW were calibrated through nonlinear regression with UCODE to measured water levels and monthly net ground-water-flow rates from the lakes estimated from lake-water budgets. Monthly estimates of ground-water recharge were computed using an unsaturated flow model (LEACHM) that simulated daily changes in storage of water in the soil profile, thus estimating recharge as drainage to the water table.

Aquifer properties in the Round Lake model were estimated through transient-state simulations using two sets of monthly recharge rates computed during July 1996 to February 1999, which spanned both average conditions (July 1996 through October 1997), and an El Niño event (November 1997 through September 1998) when the recharge rate doubled. Aquifer properties in the Halfmoon Lake model were estimated through steady-state simulations of average conditions in July 1996. Simulated hydrographs computed by the Round and Halfmoon Lake models closely matched measured water-level fluctuations, except during El Niño, when the Halfmoon Lake model was unable to accurately reproduce water levels. Possibly, potential recharge during El Niño was diverted through ground-water-flow outlets that were not represented in the Halfmoon Lake model, or a large part of the rainfall was diverted into runoff before it could become recharge.

Solute transport simulations with MT3D indicate that leakage of lake water extended 250 to 400 feet into the surficial aquifer around Round Lake, and from 75 to 150 feet around Halfmoon Lake before flowing to the underlying Upper Floridan aquifer. These results are in agreement with concentrations of stable isotopes of oxygen-18 ($\delta^{18}O$) and deuterium (δD) in the surficial aquifer. Schedules of monthly augmentation rates to maintain constant stages in Round and Halfmoon Lakes were computed using an equation that accounted for changes in the Upper Floridan aquifer head and the deviation from the mean recharge rate. Resulting lake stages were nearly constant during the first half of the study, but increased above target lake stages during El Niño; modifying the computation of augmentation rates to account for the higher recharge rate during El Niño resulted in lake stages that were closer to the target lake stage.

Substantially more lake leakage flows to the Upper Floridan aquifer from Round Lake than from Halfmoon Lake, because the estimated vertical hydraulic conductivities of lake and confining layer sediments and breaches in the confining layer beneath Round Lake are much greater. Augmentation rates required to maintain the low guidance stages in Round Lake (53 feet) and Halfmoon Lake (42 feet) under average Upper Floridan aquifer heads are estimated as 33,850 cubic feet per day and 1,330 to 10,000 cubic feet per day, respectively. These rates equate to 26 inches per month of water applied to the entire surface of Round Lake and 0.34 to 2.5 inches per month of water applied to Halfmoon Lake.

Introduction

Pumping from the Upper Floridan aquifer has lowered water levels by more than 10 ft from predevelopment levels in parts of northwest Hillsborough County and surrounding areas (Southwest Florida Water Management District, 1996). These drawdowns have induced downward leakage from the overlying surficial aquifer and lowered the water table in many areas. The rate of leakage is lowest in areas where the permeability of the confining layer that separates the two aquifers is low; leakage is highest in areas where the confining layer is breached, thus increasing permeability. These breaches commonly occur beneath the many shallow lakes present in the area and are typically associated with collapse structures in the underlying limestone. Downward leakage of water beneath the lakes has lowered the water level in many lakes and drained many wetlands.

Ground water pumped from the Upper Floridan aquifer is currently (2002) added to 15 lakes in northwest Hillsborough County in an effort to maintain lake levels, and additional lakes are being considered for augmentation (Southwest Florida Water Management District, written commun., 2002). As water demands increase, many scientists, water managers, and citizens are concerned about the consequences of using ground water to restore lake levels. These concerns include (1) the chemistry of ground water is substantially different from that of natural lake water (Stewart and Hughes, 1974); (2) addition of ground water can cause changes in lake flora, fauna, and lake sediment composition; and (3) formation of sinkholes could be enhanced near augmented lakes (Metz and Sacks, 2002).

In 1995, the U.S. Geological Survey (USGS) began a 5-year study with the Southwest Florida Water Management District (SWFWMD) to study the effects of ground-water augmentation on lakes in northwestern Hillsborough County. In the first part of the study, Metz and Sacks (2002) provided a detailed description of the hydrogeology, water budgets, and water quality of three lake basins in northwest Hillsborough County: Round Lake and Dosson Lake, augmented and non-augmented lakes, respectively, that lie in areas affected by ground-water withdrawals; and Halfmoon Lake, a non-augmented lake that lies within a 2-mi radius of three major well fields. In the second part of the study, described herein, ground-water-flow and transport models were developed to estimate the losses to ground water at Round and Halfmoon Lakes during the 2-year period July 1996 through September 1998 and to assess the success of different augmentation strategies on maintaining lake levels. The location of the study lakes and the boundary of the ground-water-flow models are shown in figure 1.

Purpose and Scope

This report describes the exchange of water between Round and Halfmoon Lakes and the surrounding surficial aquifer, and presents estimates of leakage rates of lake water to the ground-water flow system. The report presents (1) computation of ground-water recharge using an unsaturated flow model; (2) results of flow simulations, including ground-water budgets and changes in water levels during the 3-year study; (3) results of transport simulations that depict the extent of leakage of lake water into the surficial aquifer; and (4) results of simulated augmentation strategies to maintain lake levels.

Previous Investigations

Regional ground-water-flow models that included Hillsborough County were developed by Hutchinson (1984), Bengtsson (1987) and Hancock and Basso (1993). Several investigators developed ground-water-flow models of small Florida lakes similar to those in Hillsborough County. Grubbs (1995) delineated contributing areas and the vertical flow paths between the surficial aquifer and the Upper Floridan aquifer in a ground-water-flow model of the Lake Five-O basin. Lee and Swancar (1997) simulated ground-water flow near Lake Lucerne and concluded that the geometry of a sinkhole complex beneath the lake was the primary control on lake leakage. Lee (2000) simulated transient water-table mounds and ground-water-flow reversals near Lake Barco in Putnam County. Swancar and Lee (2003) developed a ground-water-flow model of Lake Starr in Polk County to quantify ground-water inflow and lake leakage.

Other investigators have contributed to understanding the effects of ground-water augmentation on lake hydrology. Stewart and Hughes (1974) concluded that ground-water augmentation at Round Lake increased lake leakage and evaporation and altered the chemistry of lake water. Belanger and Kirkner (1994) determined that more than 90 percent of augmented surface water returned to the ground-water system at Mountain Lake in Polk County. Metz and Sacks (2002) concluded from their study of Round, Dosson, and Halfmoon Lakes that (1) lakes underlain by a thin or highly breached, intermediate confining unit (such as Round Lake) will require more augmentation to maintain lake levels than lakes in areas where the intermediate confining unit is thicker or more intact; (2) augmented lakes are maintained at levels higher than the surrounding water table, causing lateral leakage from the lake and limiting ground-water inflow to the lake; (3) the difference in head between augmented lakes and the underlying Upper Floridan aquifer is increased by augmentation and local pumping, resulting in a higher rate of vertical leakage of lake water; and (4) the increase in ground-water circulation in the leakage-dominated hydrogeologic setting at Round Lake has made the basin more susceptible to karst activity (limestone dissolution, subsidence and sinkhole development).

Acknowledgments

The authors express their appreciation to members of the Round and Halfmoon Lake Associations, as well as many private homeowners, for making the hydrologic investigation of these private lakes possible by permitting the drilling of wells,

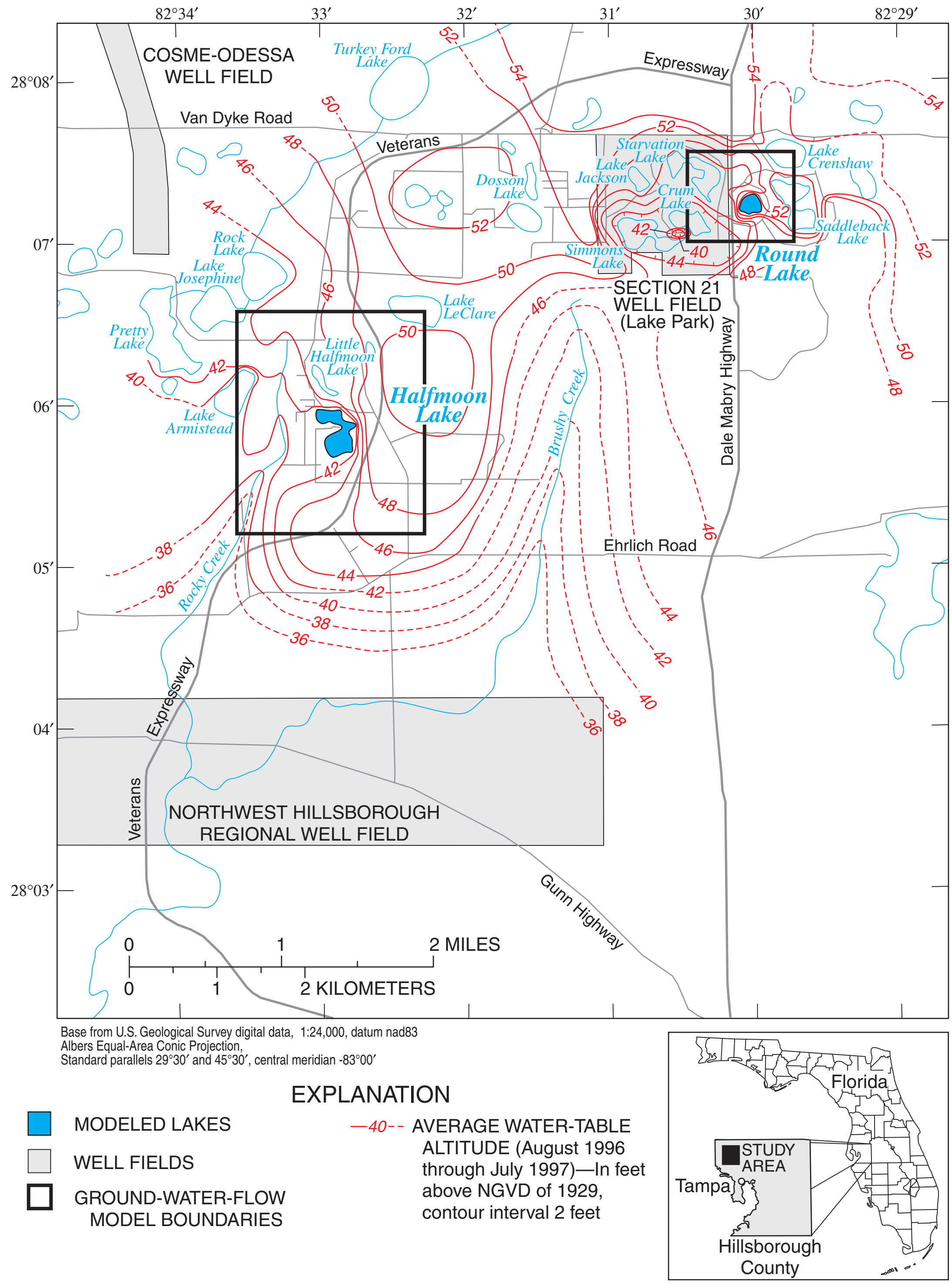


Figure 1. Location of study area showing Halfmoon Lake and Round Lake, Hillsborough County, Florida.

the installation of hydrologic instrumentation, and sampling of well water. Acknowledgments are extended to the Florida Department of Transportation for granting permission to drill monitor wells on public roadways and the city of St. Petersburg for permitting the installation of an evaporation site at the Section 21 well field (Lake Park). Other hydrologists from the U.S. Geological Survey also contributed to this study: Terrie M. Lee and J.W. Grubbs aided in the model designs and provided review comments, and Keith Halford designed and analyzed the aquifer tests conducted at Round, Dosson, and Halfmoon Lakes. The authors also would like to express their gratitude to Michael Hancock, Southwest Florida Water Management District, for his technical support.

Background

The study area is located in mantled karst terrain about 12 mi north of downtown Tampa, in northwest Hillsborough County, Fla. (fig. 1). This area lies within the Gulf Coastal Lowlands (White, 1970) in an area named Land-O-Lakes within the Tampa Plain (Brooks, 1981). The topographic setting is a relatively flat, sandy plain where elevations range from 40 to 60 ft above National Geodetic Vertical Datum of 1929 (NGVD of 1929). The lakes are in a layer or mantle of sand and clay that blankets the Upper Floridan aquifer, an extensive and highly productive limestone aquifer. Surface drainage on the sandy plain is poorly defined, but typically flows south and westward toward Tampa Bay. Brushy and Rocky Creeks drain the central and western parts of the study area, respectively.

Sinkholes are prevalent throughout the study area and include stable ancient depressions as well as actively forming depressions. Sinkholes result from dissolution of the deeper limestone by infiltrating ground water and the resulting collapse of the overlying sand and clay into the voids created by limestone dissolution. The limestone typically is not exposed at land surface, but remains buried beneath the surficial deposits, creating numerous depressions at land surface. Shallow depressions generally contain swamps or cypress domes, typical geomorphic features in the study area, whereas deep depressions, extending 15 to 20 ft below land surface, are filled with water to form sinkhole lakes. Many of these lakes have shapes that reflect the sinkholes that formed them, varying from circular to irregular. Lakes with an irregular and elongated shoreline commonly result when many small sinkholes coalesce (Sinclair and others, 1985).

Physical Setting

The climate of the study area is subtropical with warm, wet summers and relatively mild, dry springs. Long-term average rainfall is 49 in/yr and annual evaporation rates are high (48-59 in/yr) due to high solar radiation and water temperatures (Metz and Sacks, 2002). During the 1998 water year (October 1997 to September 1998), a tropical weather phenomenon, El Niño, produced record rainfall throughout the study area, resulting in about 40 in. of above-average annual rainfall (Metz and Sacks, 2002). Climatic conditions changed again during the 1999 water year with the onset of a weather pattern called La Niña, which was characterized by drier than normal conditions that resulted in below-average rainfall for the year (Metz and Sacks, 2002).

Round Lake is a privately owned, 11-acre lake located about 500 ft east of the Section 21 well field (fig. 1). This lake is augmented and received an average of 0.14 Mgal/d of water from the Upper Floridan aquifer during the 3-year study, enough to fill the lake 5.6 times (Metz and Sacks, 2002). The 30-acre topographic basin for Round Lake is bounded by Saddleback and Crenshaw Lakes to the east and Starvation and Crum Lakes to the west. Land use in this small drainage basin is residential with many homes located adjacent to the lake. There is no surface outlet from Round Lake, but a drainage ditch connects the northeastern side of the lake to Saddleback Lake, which occasionally allows overflow from that lake to enter Round Lake.

Round Lake has an average depth of about 9 ft at a lake level of 52.5 ft above NGVD of 1929 with several deep depressions (20-25 ft below the lake surface) along the northern and western shoreline (Metz and Sacks, 2002). Lake-bottom dredging at Round Lake was documented by Stewart and Hughes (1974) and later confirmed by verbal communication with local residents. A gelatinous brown-gray sediment from 1 to 3 ft thick covers much of the lake bottom, but is absent in some areas. Calcium carbonate has accumulated in the lake bottom sediments as a result of ground-water augmentation that has raised the alkalinity of the lake and enabled the proliferation of snails, such as *Planorbella* sp. (Brenner and Whitmore, 1999). Seismic-reflection data collected along 19 transects at Round Lake display a lack of continuity at the the surface of the limestone bedrock, suggesting breaches in the intermediate confining unit.

Halfmoon Lake is a privately owned, 33-acre lake that is located within an approximate 2-mi radius of three well fields: Section 21, Cosme-Odessa, and Northwest Hillsborough Regional (fig. 1). The topography of the 131-acre basin surrounding Halfmoon Lake is slightly elevated on the eastern side and slopes gently downward toward Rocky Creek on the western side. Land use within the Halfmoon Lake basin is mostly residential, but a 25-acre citrus grove is situated on the southeastern side of the lake. Several small cypress wetlands are present in the southern and northeastern sides of the basin. The northwestern side of the lake has an overflow weir structure that controls lake levels during periods of high rainfall.

The average depth of Halfmoon Lake is about 10 ft at a lake level of 41.4 ft above NGVD of 1929 (Metz and Sacks, 2002). A gelatinous brown-gray sediment from 1 to 4 ft thick covers much of the bottom of the lake, but is absent in some areas. Seismic-reflection data collected along 15 transects at Halfmoon Lake indicate possible subsidence features, based on the discontinuity of the limestone bedrock surface and the presence of dipping beds in overlying sediments.

Hydrogeologic Setting

The geologic units underlying the study area consist of sand, clay, and carbonate rocks that were deposited primarily in a marine environment. Deposition of each formation was followed by a period of erosion that resulted in the development of solution cavities and surface irregularities. The principal hydrogeologic units in the study area include the surficial aquifer, the intermediate confining unit, and the Upper Floridan aquifer. The surficial aquifer is unconfined and consists of sand and clayey sand that is separated from the Upper Floridan aquifer by the clay-rich intermediate confining unit. The Upper Floridan aquifer is a highly productive carbonate aquifer that is an abundant water-supply source for west-central Florida.

Surficial Aquifer

The surficial aquifer consists of an upper unit of fine sand, a middle unit of clayey sand, and a lower unit of sandy clay. Contacts between these units are indistinct, but the cohesive nature of the sand increases with depth because of the higher percentage of clay. Where more than one permeable zone is present or where the deposits are interbedded, this unit is commonly termed the surficial aquifer system. In this report, the deposits are considered to form a single homogeneous aquifer, which is referred to as the surficial aquifer. The average thickness of surficial deposits was about 30 ft near Round Lake and 40 ft near Halfmoon Lake (Metz and Sacks, 2002). Seismic reflection surveys indicate that the thickness of surficial deposits is greater beneath both lakes, suggesting subsidence of the limestone bedrock surface through voids and cavities beneath the lakes (Metz and Sacks, 2002).

The surficial aquifer is unconfined and contains a water table that is at a relatively shallow depth (about 0.5-10 ft below land surface) within the study area. Recharge to the water table is rapid, because the surface soils are generally permeable. Although wells in the surficial aquifer are not an important source of water supply because yields are relatively low (less than 5 gal/min), the surficial aquifer has a large storage capacity and serves as a substantial source of recharge to the underlying Upper Floridan aquifer. The hydraulic conductivity of the surficial aquifer ranges from 1 to 10 ft/d, based on aquifer tests conducted at Round, Dosson, and Halfmoon Lakes (P.A. Metz, U.S. Geological Survey, written commun., 1999).

Intermediate Confining Unit

The intermediate confining unit within the study area consists of the undifferentiated deposits of the Hawthorn Group (Southeastern Geological Society, 1986). The unit consists of dense, marine green-gray plastic clay that contains varying amounts of sand, chert, phosphate, organic material, and carbonate mud (Sinclair, 1974). Carr and Alverson (1959) and Sinclair (1974) describe the clay in the intermediate confining unit as a weathered residuum of the limestone in the underlying Tampa Member. The clay unit is variable in extent and thickness throughout the study area; Sinclair (1974) reported the presence of clay in 47 of 59 test holes that was as much as 20 ft thick and averaged about 4 ft thick. The vertical hydraulic conductivity of the intermediate confining unit was estimated as 5.0×10^{-4} ft/d from aquifer tests conducted at Halfmoon Lake (P.A. Metz, U.S. Geological Survey, written commun., 1999).

Localized breaches in the intermediate confining unit associated with subsidence features or sinkholes create permeable connections between the surficial aquifer and the underlying Upper Floridan aquifer. The breaches appear to be sand columns that form when material from the surficial aquifer moves downward through the collapsed clay and into limestone cavities. The sand columns generally are several feet or less in diameter, and channel recharge from the surficial aquifer to the Upper Floridan aquifer (Stewart and Parker, 1992). Three new sinkholes were reported near the perimeter of Round Lake during this 3-year study (Metz and Sacks, 2002).

Upper Floridan Aquifer

The Upper Floridan aquifer is the major water supply within the study area. This aquifer consists of limestone and dolomite and contains many solution-enlarged fractures that commonly yield large quantities of water to wells. Transmissivities determined from aquifer tests of the Upper Floridan aquifer vary throughout the study area and range from 15,000 to 70,000 ft^2/d (Wolansky and Corral, 1985; Southwest Florida Water Management District, 1994; and Langevin and others, 1998). The transmissivity of the Upper Floridan aquifer ranged from 15,000 to 20,000 ft^2/d in aquifer tests conducted at Halfmoon Lake (P.A. Metz, U.S. Geological Survey, written commun., 1999).

The Tampa Member is the uppermost geologic unit of the Upper Floridan aquifer in the study area and ranges from 20 to 240 ft thick (Stewart, 1968). The Tampa Member is described as tan to white, commonly sandy, fossiliferous, highly weathered in places, and commonly contains clay lenses and cavities. Sand and clay are common within the Tampa Member far below the typical depth range of clastic deposits, suggesting infilling of material from the surficial aquifer into cavities in the limestone. Many domestic and production wells tap the Tampa Member in the study area and well yields range from several to several hundred gallons per minute (Stewart, 1968).

Ground Water and Lake Interaction

Ground-water exchange with lakes is governed by horizontal and vertical head gradients in the surrounding surficial aquifer. Water levels and vertical head gradients in the surficial aquifer in northwest Hillsborough County are controlled by recharge and ground-water withdrawals from the underlying Upper Floridan aquifer. Withdrawals at each of the three well fields that lie within the study area average about 10 Mgal/d. Pumpage from the Upper Floridan aquifer has lowered water levels more than 10 ft since the 1960s and created a downward hydraulic gradient between the two aquifers. Water in the surficial aquifer generally flows downward toward pumping centers in the Upper Floridan aquifer through the intermediate confining unit. Surface drainage and sinkholes can influence flow directions locally, causing ground water to flow laterally toward these discharge areas.

The water table in the surficial aquifer (fig. 1) indicates that ground water discharges to Brushy and Rocky Creeks, the two largest perennial streams that traverse the study area. The hydraulic gradient in the Upper Floridan aquifer slopes west-southwest (fig. 2), and a cone of depression is apparent in the vicinity of the Section 21 well field. Boundaries chosen for the ground-water-flow models of Round and Halfmoon Lakes approximately coincide with ground-water divides in the surficial aquifer.

The water-table surface is uneven near Round Lake, reflecting the effects of lake augmentation and ground-water withdrawals from the Upper Floridan aquifer at the Section 21 well field. The concentric pattern of water-level contours around Round Lake (fig. 3A) is the result of ground-water augmentation, which raises the lake level above the adjacent water table, resulting in leakage around the entire lake perimeter that recharges the surrounding surficial aquifer. This pattern was temporarily altered during El Niño when ground-water levels were nearly equal or slightly higher than lake stage (fig. 4). Ground water in the surficial aquifer near Round Lake flows downward to the Upper Floridan aquifer and southwestward toward Crum Lake and the Section 21 well field (fig. 3B).

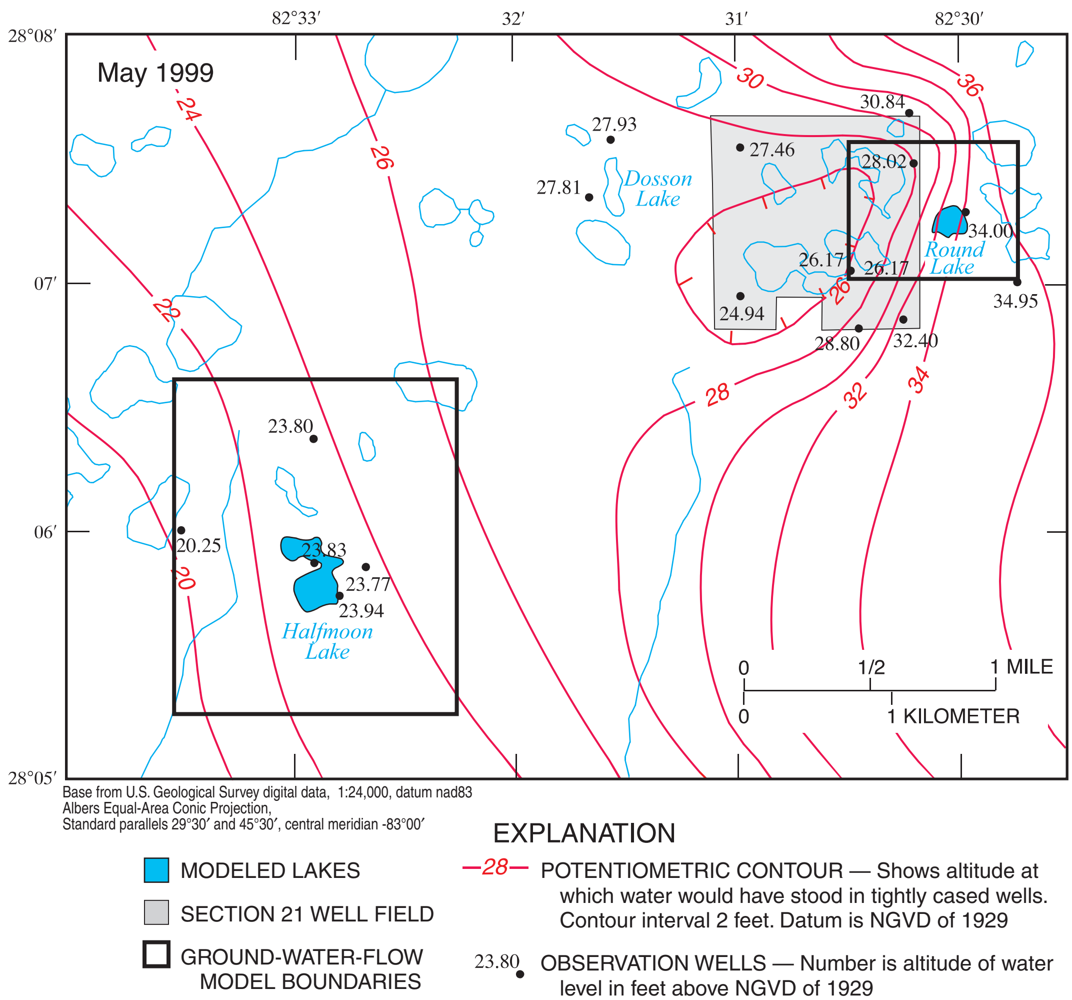


Figure 2. Potentiometric surface of the Upper Floridan aquifer and boundaries of ground-water-flow models, Hillsborough County, Florida.

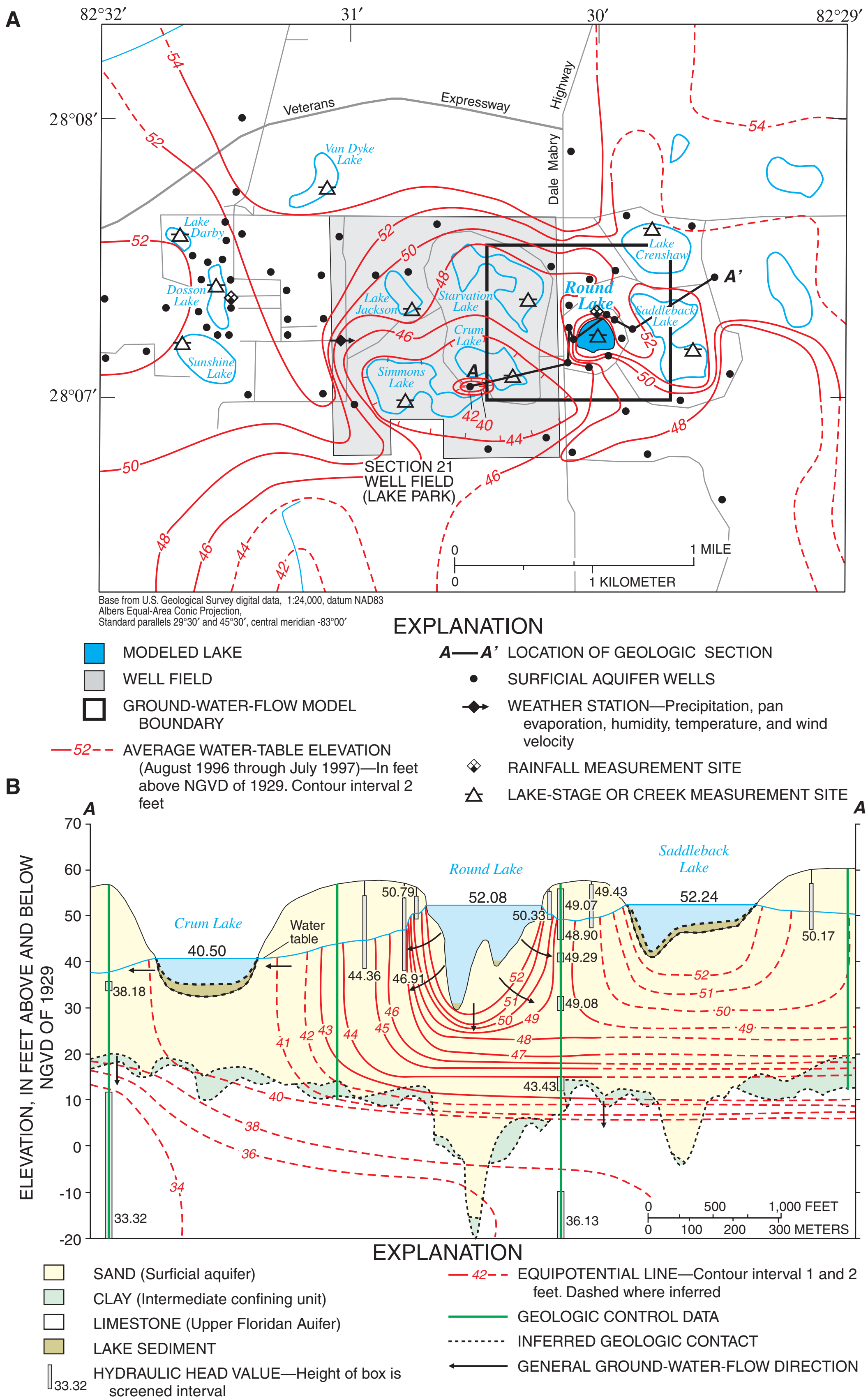


Figure 3. (A) Average water-table elevation, August 1996 to July 1997; and (B) generalized geologic section A-A′, showing distribution of hydraulic head and ground-water flowpaths near Round Lake basin during dry conditions, April 1997.

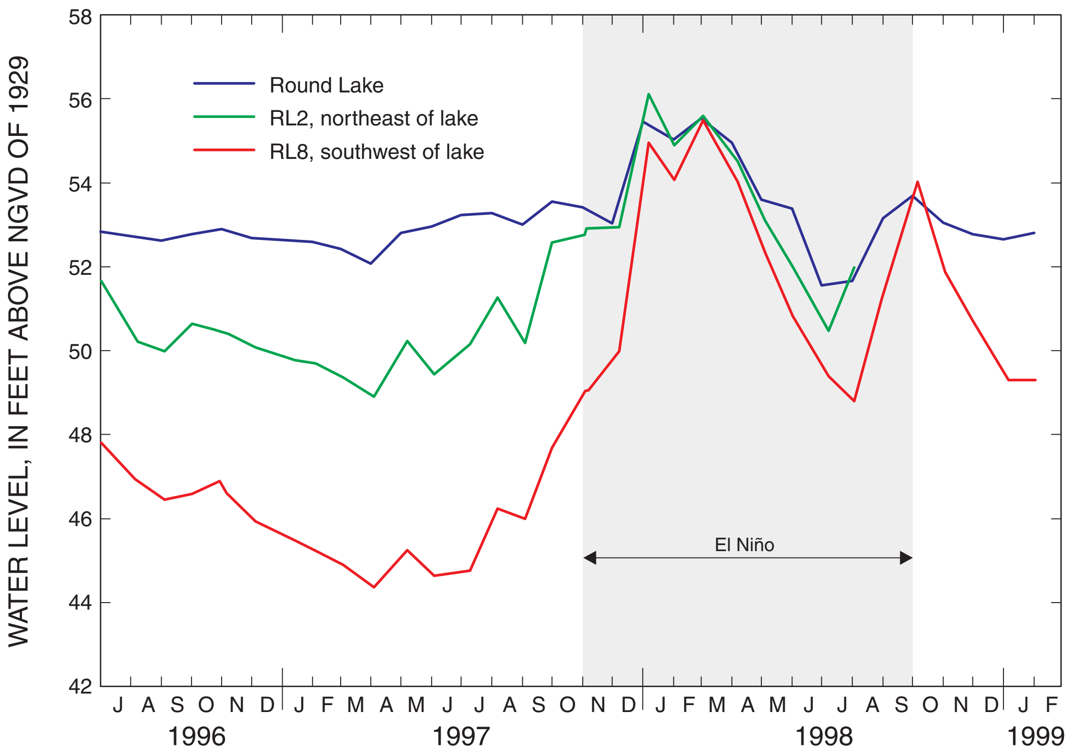


Figure 4. Stage in Round Lake and water levels in wells RL2 and RL8, northeast and southwest of lake, respectively, July 1996 to February 1999. (Well locations shown on fig. 14.)

The water-table surface near Halfmoon Lake, indicates a steady westward gradient from a local high east of the lake westward to Rocky Creek (fig. 5A). Ground water flows into Halfmoon Lake along its eastern and northern shores. During dry periods, the lake recharged the water table on the western and southwestern sides of the lake, where the water table was slightly lower than the lake and dipped southwestward toward Rocky Creek (fig. 6). During wet periods, the water-table on the western and southwestern shores was higher than the lake and ground-water inflow occurred around the entire lake perimeter. Ground water in the surficial aquifer flowed downward to the Upper Floridan aquifer and southwestward toward Rocky Creek (fig. 5B).

Lake-Water Budgets

Monthly water budgets were computed for each lake during the 3-year period (June 1996 to May 1999) using the following equation (Metz and Sacks, 2002):

$$\Delta S = P - E + A + S_i - S_o + G_i - G_o \quad , \qquad (1)$$

where

ΔS is the change in lake volume for a given time period;
P is precipitation;
E is evaporation;
A is total lake augmentation;
S_i is surface-water inflow;
S_o is surface-water outflow or direct pumping from the lake;
G_i is ground-water inflow; and
G_o is ground-water outflow (or lake leakage).

All of the terms in equation 1 can be measured or estimated directly with the exception of the ground-water-flow terms. The net ground-water flow G_{net} was computed by rearranging equation 1 as:

$$G_{net} = G_i - G_o = \Delta S - P + E - A - S_i + S_o \quad , \qquad (2)$$

where G_{net} is positive when ground-water inflow exceeds ground-water outflow, resulting in net ground-water inflow. Because G_{net} is computed as a residual to the rest of the budget, the net ground-water-flow term incorporates all of the errors or uncertainties in the other water-budget terms.

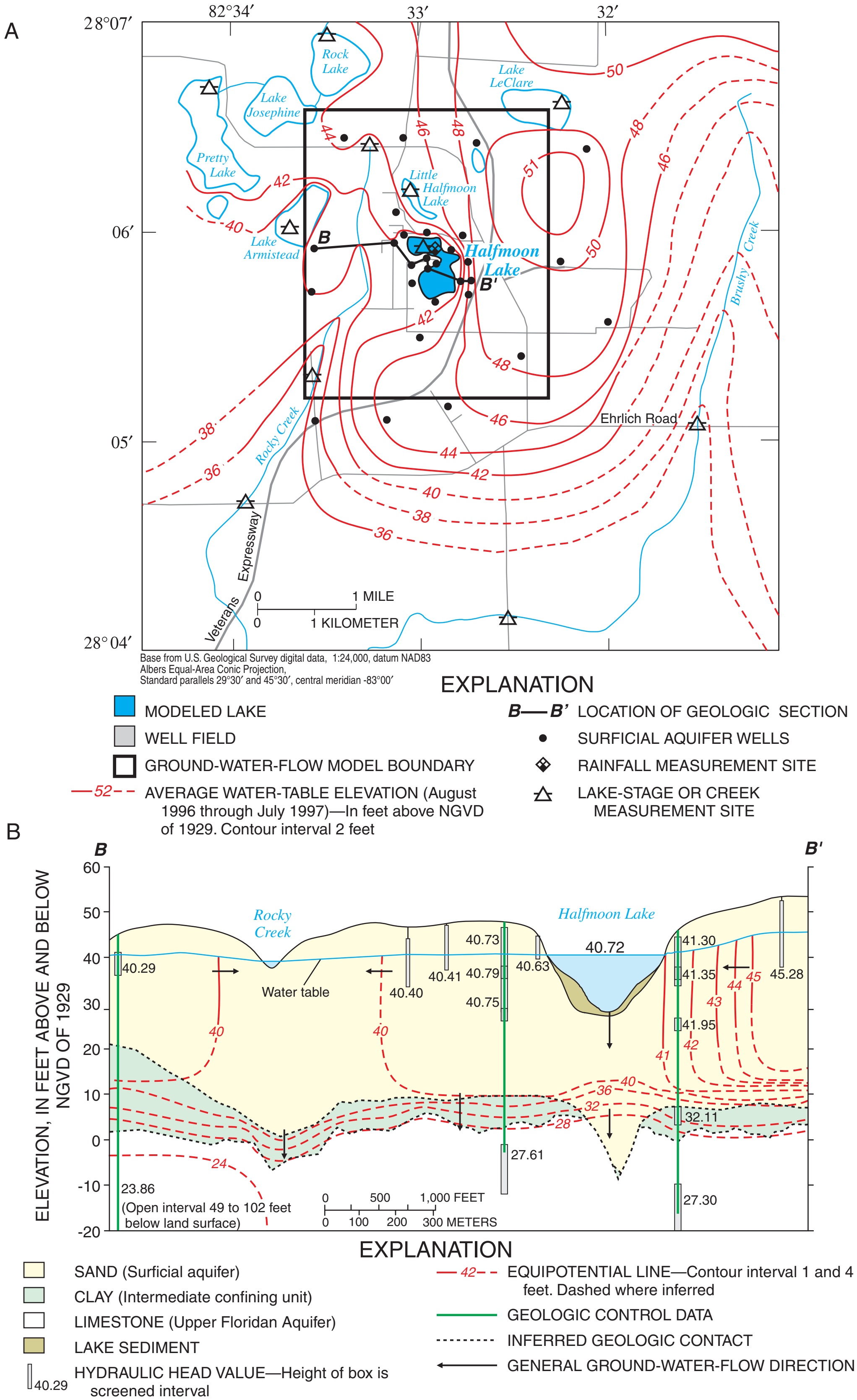


Figure 5. (A) Average water-table elevation, August 1996 to July 1997; and (B) generalized geologic section B-B′, showing distribution of hydraulic head and ground-water flowpaths near Halfmoon Lake basin during dry conditions, April 1997.

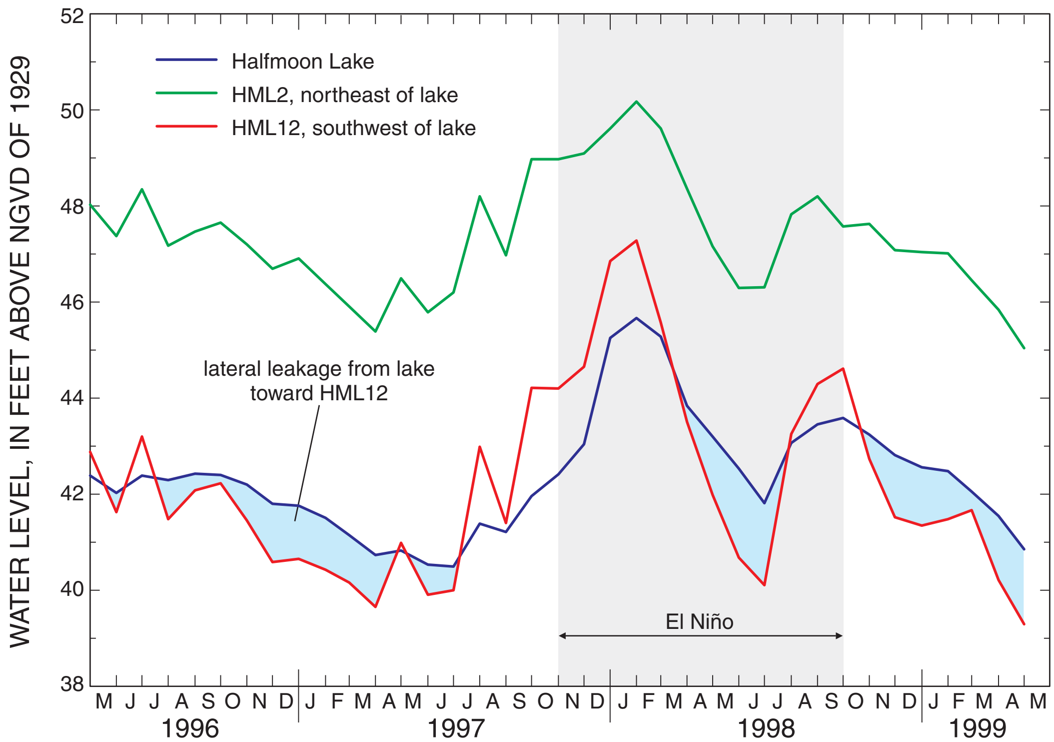


Figure 6. Stage in Halfmoon Lake and water levels in wells HML2 and HML12, northeast and southwest of lake, respectively, July 1996 to February 1999. (Well locations shown on fig. 19.)

Monthly net ground-water flows computed from lake-water budgets by Metz and Sacks (2002) were used to calibrate the ground-water-flow models of Round and Halfmoon Lakes discussed in this report. The budgets were prepared using daily precipitation measured at several gages within the study area and lake evaporation estimated from energy-budget data collected at Lake Starr, 60 mi to the east (Swancar and Lee, 2003). Lake-surface areas and volumes were calculated using data from continuous stage recorders and stage-volume relations developed for each lake.

Net ground-water flow from Round Lake was negative (leakage exceeded ground-water inflow) for all but 1 month during the study (December 1997; Metz and Sacks, 2002). Net ground-water losses during the 3-year period totaled 19.5×10^6 ft^3 (496 in.) of water based on a lake-surface area of 10.8 acres. The mean net leakage rate was 18.5 in/mo during average conditions (June 1996 to October 1997) and 10.4 in/mo during El Niño (November 1997 to September 1998). An estimated 4.7×10^5 ft^3 (12 in.) of water overflowed from Saddleback Lake to Round Lake through a drainage ditch during December 1997.

In contrast, net ground-water flow from Halfmoon Lake was negative in only 16 months of the 3-year period. During these months, Halfmoon Lake experienced flow-through conditions with ground water entering the lake along its northern and eastern shores and lake water leaking along the southern and western shores. Ground-water discharged to the lake around its entire perimeter during 10 months of the study: during summer (July-September) when evaporation from the lake surface was high; and during El Niño, when recharge to the surficial aquifer was high. During the remaining 10 months, the estimated net ground-water flow was less than the error in the calculation, indicating that outflows from the lake nearly balanced inflows. The mean net leakage rate from Halfmoon Lake was 2.5 in/mo during average conditions, and mean rates of net ground-water inflow to the lake were 3.3 in/mo during summer months and 5.9 in/mo during El Niño. An estimated 6.2×10^6 ft^3 (42.6 in.) of water was pumped from the lake to alleviate flooding during February and March 1998, and 2.3×10^6 ft^3 (17.4 in.) of lake water was discharged through a high-water weir during September and October 1998.

Ground-Water Recharge Simulation

Recharge to the surficial aquifer has been estimated on an annual basis in other studies in central Florida using ground-water chemistry and water-balance methods. Lee (1996) estimated recharge as 30 percent of rainfall at Lake Barco (110 mi northeast of the study area) by comparing chloride concentrations measured in ground water and atmospheric deposition. A similar value is obtained for northwest Hillsborough County by comparing the average chloride concentration in ground water near Round Lake with atmospheric deposition at the Verna well field and Chassahowitzka National Wildlife Refuge (50 mi southeast and 40 mi north of the study area, respectively), two sites that are part of the National Atmospheric Deposition Program (NADP). Chloride concentrations at RL11, a well apparently unaffected by chloride from septic discharge, averaged 2.8 mg/L in 1996 and 1997 (Metz and Sacks, 2002). Volume-weighted mean chloride concentration in atmospheric deposition at the two NADP sites multiplied by dry deposition was 0.91 mg/L during this period (http://nadp.sws.uiuc.edu/, accessed April 3, 2002). Comparing the chloride concentration in ground water to atmospheric deposition indicates that chloride in the surficial aquifer was enriched by a factor of 3.1. This indicates that about 67 percent of rainfall is lost to evapotranspiration, resulting in a recharge rate of 16 in/yr.

Recharge rates specified in other simulations of ground-water flow in Hillsborough County include 25 in/yr by Hutchinson (1984), 15 to 22 in/yr by Bengtsson (1987), and 10 to 30 in/yr by Hancock and Basso (1993). Transient simulations of ground-water flow constructed for this study required the use of monthly time periods, however, so monthly estimates of ground-water recharge were computed from daily simulations of the unsaturated zone that represented storage of water and drainage to the water table.

Unsaturated Flow Model

The unsaturated flow model LEACHM (Hutson and Wagenet, 1992) was used to compute daily recharge from the unsaturated zone to the surficial aquifer. The LEACHM model represents the unsaturated zone (soil profile) as a series of equally spaced layers, and computes the water content in the profile on a daily basis using specified rates of precipitation and potential evapotranspiration. Recharge is computed as the sum of daily drainage from the bottom of the soil profile. Overland runoff from precipitation is neglected in the simulations based on the lack of developed drainage in much of the study areas.

Water movement through the soil profile is computed by LEACHM using a capacity model described by Addiscott (1977) and Hutson and Wagenet (1992). An alternate computation method based on the Darcian Richards' equation was not used in this study because the data needed to specify additional soil properties were not available. The capacity model uses specified soil properties (texture, organic carbon content and bulk density) and an equation by Campbell (1974) to compute a water-retention curve that relates water content to matric potential for each soil layer. Matric potentials corresponding to moisture contents representing field capacity (W_f), wilting point (W_{wp}), and the division (W_d) between mobile (W_M) and immobile (W_I) water are specified and used to compute water fluxes through the soil profile. Precipitation is applied to the top soil layer, and water in excess of field capacity $(W_M - W_f)$ is transferred to the underlying layer. This procedure is repeated for each succeeding layer until either the water content is less than field capacity, or the lowest layer is reached, at which point drainage occurs.

On days without precipitation, the actual evapotranspiration is summed by computing surface evaporation and transpiration using a specified factor that represents the percentage of crop cover. Surface evaporation is extracted from the upper 2 in. of the soil profile, but limited to a rate less than a maximum based on the soil matric potential and hydraulic conductivity (Hutson and Wagenet, 1992). Transpiration removes water from throughout a specified root zone according to factors representing the root density in each layer, but water contents cannot be depleted below the plant wilting point W_{wp}. After evapotranspiration has been accounted for, the remaining mobile water in the soil profile $(W_M - W_I)$ is redistributed by moving water from each layer upward or downward to equilibrate hydraulic heads throughout the profile according to the following method:

(1) The hydraulic head h_i in layer i is:

$$h_i = \psi_i - z_i \quad , \tag{3}$$

where ψ is negative matric potential [L], and z is depth below land surface [L]. The model calculates the volume of water V_w required to move upward or downward so that the vertical hydraulic gradient between adjacent layers is zero, that is:

$$\psi_i - \psi_{i+1} = \Delta z \quad , \tag{4}$$

where Δz is the difference in depth [L].

(2) Half of the water $V_w/2$ is redistributed to each adjacent layer, thereby adjusting the hydraulic head profile toward equilibrium for a period of several days after rainfall.

Simulation Results

Three cases with different combinations of vegetation and soil texture were considered in estimating recharge with LEACHM. In each case, the unsaturated zone was represented by a 6.6-ft-long soil profile containing 20 4-in.-thick layers above a fixed water-table boundary. Evapotranspiration was represented from the unsaturated zone, but not from the water table. Simulations used monthly potential evaporation estimated from an energy balance computed for Lake Starr, 60 mi east of the study area (Swancar and Lee, 2003). Potential evapotranspiration was reduced by a factor of 8 percent to account for differences in temperature recorded at the Section 21 well field and Lake Starr (Metz and Sacks, 2002). Recharge in northwest Hillsborough County was estimated using daily precipitation recorded at the Section 21 well field and Round Lake. An alternative set of recharge estimates also was computed for the same three cases using the precipitation measured near Halfmoon Lake by averaging daily precipitation recorded at the Section 21 well field and the COSME well field, and adjusting this average using weekly precipitation recorded at Halfmoon Lake from December 1997 to March 1999.

Soils within the study area are spodisols of the Myakka series (sandy, siliceous, hyperthermic Aeric Haplaquods) common to poorly drained areas in the Coastal Plain of the southeastern United States (Bidlake and Boetcher, 1997). The soil texture within the profile was assumed uniform, with the exception of the top layer where an organic-carbon mass fraction of 3 percent was specified. A relatively coarse soil texture was specified in cases A and B with a silt mass fraction of 5 percent and a bulk density of 1.6 g/cm^3, whereas values specified in case C (8 percent and 1.4 g/cm^3, respectively) represented a fine-textured soil (table 1). Water-retention curves (fig. 7) were computed by LEACHM using matric potentials of -5 kPa for field capacity, -1,500 kPa for wilting point, and -200 kPa for the division between mobile and immobile water. Water contents at saturation were about 0.4 cm^3/cm^3 for the coarse-textured soil (cases A and B) and 0.47 cm^3/cm^3 for the fine-textured soil (case C).

Table 1. Soil properties specified in unsaturated flow model LEACHM

[Shading indicates change in specified property]

Soil property	Case A	Case B	Case C
Organic carbon content, in percent[1]	3	3	3
Silt content, in percent	5	5	8
Bulk density, grams per cubic centimeter	1.6	1.6	1.4
Water content at saturation, in percent	40	40	47
Matric potential, in kilopascals			
Field capacity	-5	-5	-5
Division between mobile and immobile water	-200	-200	-200
Wilting point	-1,500	-1,500	-1,500
Vegetation	shallow rooted	deep rooted	shallow rooted

[1]Top layer only.

Vegetation in the study areas includes grass, trees, and ornamental shrubbery common to residential areas in central Florida. An 8-in.-thick root zone was specified in cases A and C to represent shallow-rooted vegetation (such as grass), and a 48-in.-thick root zone was used in case B to represent deep-rooted vegetation (such as saw palmetto) (fig. 8). A permanent vegetative cover of 80 percent was specified in all three simulations.

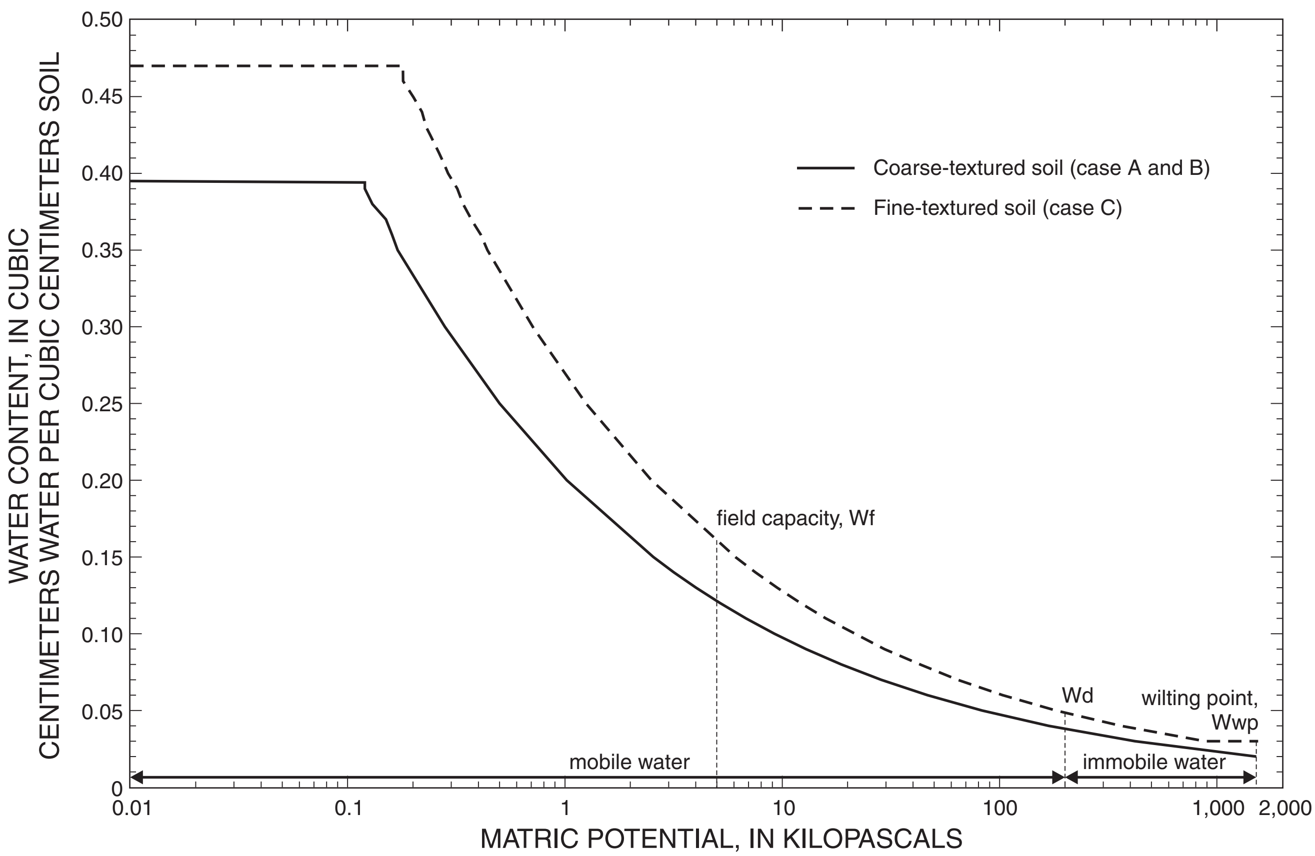


Figure 7. Water-retention curve, relating matric potential to water content for coarse-textured and fine-textured soils specified in cases A, B, and C.

Daily recharge was computed by LEACHM from March 1996 through March 1999 and accumulated monthly for use in the ground-water-flow models. Recharge computed for the first month was not considered in the analysis of simulation results, because the initial water content of the soil profile was unknown and specified as 0.2 at the beginning of unsaturated flow simulations. Rates of actual evapotranspiration (AET) and recharge, computed on an annual basis by LEACHM (table 2), were summarized for the following three periods by converting the monthly rates to equivalent annual rates: average conditions (April 1996 to October 1997), El Niño (November 1997 to September 1998), and La Niña (October 1998 to March 1999).

Computed AET rates for the coarse-textured soil under average conditions ranged from 35.7 in/yr for shallow-rooted vegetation (case A) to 42.9 in/yr for deep-rooted vegetation (case B). These rates compared favorably with the rate (40 in/yr) estimated by Bidlake and others (1996) for dry prairie vegetation at the T. Mabry Carlton, Jr., Memorial Reserve in Sarasota County using an energy-budget method. Computed AET rates during El Niño were less and ranged from 31.4 to 36.2 in/yr, because there were more rainy days and less evaporation during this time.

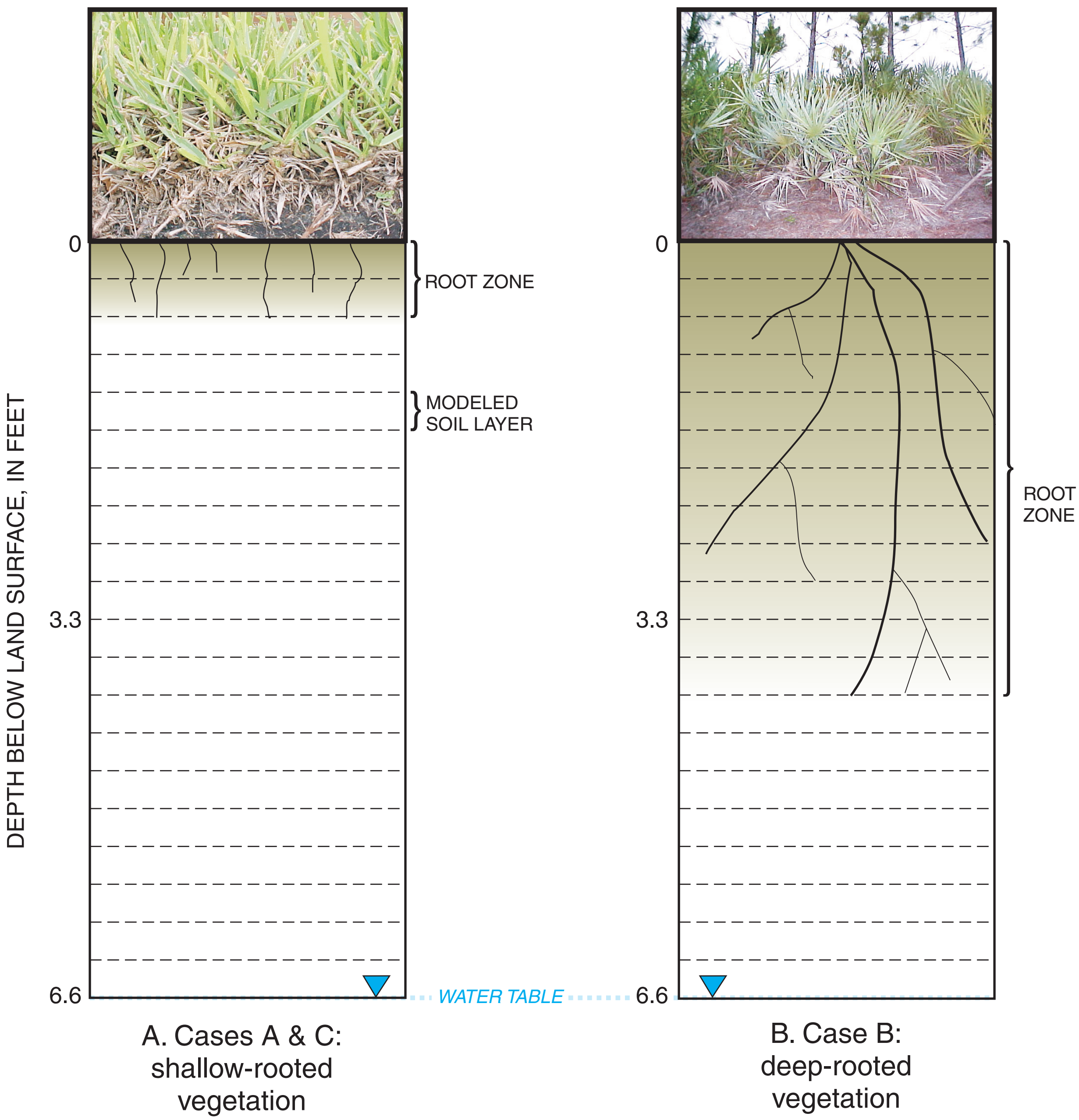


Figure 8. Soil profiles specified for shallow-rooted vegetation (cases A and C) and deep-rooted vegetation (case B) used in unsaturated flow model LEACHM.

Table 2. Evapotranspiration and recharge rates for northwest Hillsborough County, computed with unsaturated flow model LEACHM, for different types of vegetation and soils, and expressed on an annual basis for average conditions, El Niño, and La Niña

[Units are in inches per year]

Annual rate	Evapotranspiration	Recharge
Case A: shallow-rooted vegetation in coarse-textured soil		
Average	35.7	20.2
El Niño	31.4	52.3
La Niña	19.3	1.5
Case B: deep-rooted vegetation in coarse-textured soil		
Average	42.9	12.8
El Niño	36.2	47.4
La Niña	23.6	1.8
Case C: shallow-rooted vegetation in fine-textured soil		
Average	38.5	16.2
El Niño	33.7	49.9
La Niña	21.2	1.6

Computed recharge rates for average conditions ranged from 12.8 in/yr for deep-rooted vegetation (case B) to 20.2 in/yr for shallow-rooted vegetation (case A), or from 22 to 35 percent of precipitation. These results compare favorably with the recharge rate of 16 in/yr estimated from the comparison of chloride concentrations in ground water and atmospheric deposition, and with the previously reported range of rates (10-30 in/yr) used in other modeling studies of Hillsborough County. Computed recharge rates for the two vegetation types during El Niño were greater (47.4 in/yr for deep-rooted vegetation and 52.3 in/yr for shallow-rooted vegetation) and amounted to about 60 percent of the precipitation. Specifying a fine-textured soil (case C) reduced average recharge under shallow-rooted vegetation to 16.2 in/yr, because the field capacity of the soil was greater than in the case for the coarse-textured soil, and more of the precipitation that infiltrated the soil profile was retained and eventually lost to evapotranspiration. Recharge rates using precipitation recorded near Halfmoon Lake were similar to those computed using precipitation near Round Lake, and ranged from 14.8 to 22.1 in/yr for average conditions and 48.3 to 52.3 in/yr during El Niño.

The distribution of recharge computed for all three cases is highly variable and indicates that little recharge occurred from April 1996 to March 1997 when soil water content was generally less than field capacity as a result of limited precipitation (fig. 9). Recharge increased from April 1997 to September 1998 when the soil water content greatly exceeded field capacity, allowing most of the water to drain through the soil profile during the largest rainfall events. Almost no recharge occurred when the soil profile dried during La Niña (October 1998 to March 1999).

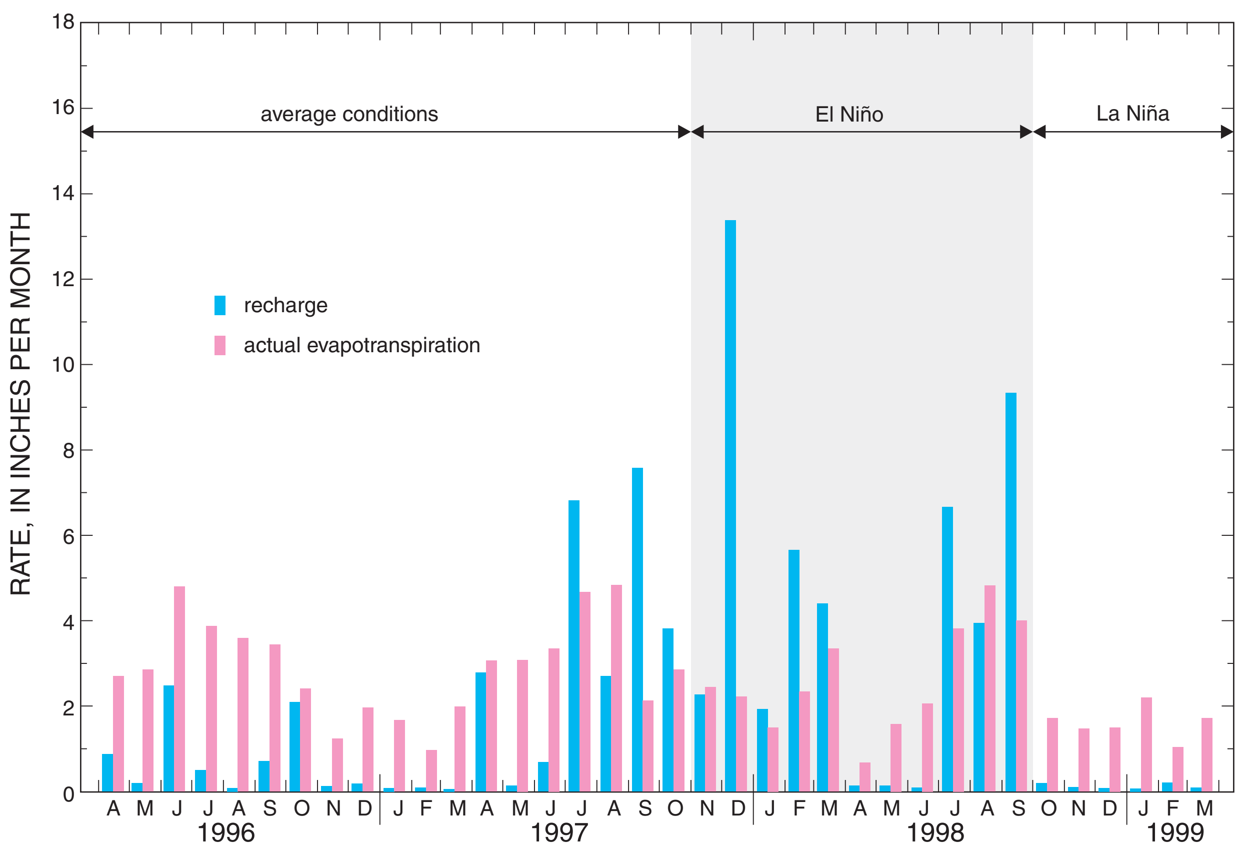


Figure 9. Monthly evapotranspiration and recharge, computed with unsaturated flow model LEACHM, for coarse-textured soil and shallow-rooted vegetation (case A) at Round Lake, April 1996 to March 1999.

Round Lake Basin Ground-Water Flow Simulation

Ground-water flow in the Round and Halfmoon Lakes study area was simulated using the three-dimensional, finite-difference model MODFLOW (McDonald and Harbaugh, 1988) to represent flow conditions during a 32-month period from July 1996 to February 1999. The flow models were calibrated to measured water levels and ground-water exchange rates based on lake-water budgets by using a nonlinear regression method in the program UCODE (Poeter and Hill, 1998). The effects of different augmentation scenarios discussed were assessed using both steady- and transient-state simulations.

Ground-water-flow models developed for the Round Lake basin included steady-state simulations of conditions in July 1996 and transient-state simulations during July 1996 to February 1999. Steady-state simulations provided initial conditions for the transient-state simulations and were used to depict flow paths and travel times of lake leakage to the Upper Floridan aquifer. Transient-state simulations were used to estimate aquifer properties with two sets of monthly recharge rates computed with the unsaturated flow model LEACHM.

Model Design

The modeled area covers 0.4 mi^2 and is bounded by the four lakes surrounding Round Lake (fig. 10). Ground-water flow is represented in 10 model layers with the surficial aquifer represented in model layers 1 through 8 (fig. 11). The saturated thickness of the top model layer (1) varies from 1 to 16 ft, because the layer is unconfined and the water table fluctuates during the 32-month simulation period. Parts of model layer 1 are dewatered (become dry) during conditions of low recharge in the simulation, so that model layer 2 becomes unconfined in some areas as well. As a result, the saturated thickness of model layer 2 fluctuates from 1 to 5 ft. The dry areas later resaturated during conditions of high recharge in the simulation through the rewetting capability provided in MODFLOW (Harbaugh and MacDonald, 1996). The remaining six layers representing the surficial aquifer are confined with a constant thickness of 5 ft. The intermediate confining unit and the Upper Floridan aquifer are represented by model layers 9 and 10, respectively, with specified thicknesses of 4 and 10 ft. The thickness specified for the Upper Floridan aquifer is arbitrary and has no affect on model simulations. Breaches in the confining layer beneath Round Lake (fig. 10), inferred from seismic reflection surveys, are represented by zones of higher vertical hydraulic conductivity in layer 9. Each of the 10 model layers is divided into a uniformly spaced grid of 75 ft with 49 rows and 54 columns that contains 1,971 active cells.

Specified flux boundaries are assigned in the uppermost model layer to represent recharge from the unsaturated zone to the surficial aquifer. Two sets of monthly recharge rates, computed by the unsaturated flow model LEACHM, were used in the MODFLOW simulations: high recharge rates in model RL-A (case A, coarse-textured soil with shallow-rooted vegetation); and low recharge rates in model RL-B (case B, coarse-textured soil with deep-rooted vegetation). Specified flux boundaries are also assigned in model layer 1 to represent (1) ground-water augmentation of Round Lake, based on monthly reported pumpage rates from the Upper Floridan aquifer; and (2) the net effects of rainfall and evaporation on Round Lake, based on the difference between measured precipitation at the Section 21 well field and the evaporation estimated from an energy budget computed for Lake Starr.

Specified-head boundaries that vary monthly are assigned to represent other inflows and outflows of water to and from the surficial aquifer. Ground-water flow to and from the four lakes that surround Round Lake (fig. 10) is represented in model layers 1, 2 and 3 based on monthly stage measurements made in the lakes. Finally, vertical leakage through the intermediate confining unit to the Upper Floridan aquifer is represented by assigning specified heads throughout model layer 10. Because of the large transmissivity of the Upper Floridan aquifer, leakage from the surficial aquifer was assumed to have little effect on the head in the Upper Floridan aquifer within the modeled area. The temporal distribution of head in model layer 10 was computed by interpolation among monthly water levels measured in 19 wells in the Upper Floridan aquifer. Lateral boundaries of the modeled area coincide with streamlines interpreted from the regional distribution of hydraulic head in the surficial aquifer (see fig. 3A) and are specified as no-flow in all layers, with the exception of underflow (lateral ground-water flow) toward the municipal well field southwest of Round Lake, which is represented by specified heads in model layers 4 to 8.

Calibration Procedure

Parameter values representing aquifer properties were adjusted through transient-state simulations to produce a model that approximated water levels measured from July 1996 to February 1999, and net ground-water flow to and from Round Lake estimated from monthly water budgets computed for the same period. A steady-state simulation representing conditions in July 1996 at the beginning of the simulation period provided initial conditions for the transient-state simulation. The transient-state simulation included 32 monthly periods to represent changes in recharge rates and augmentation well pumpage used to maintain the water level in Round Lake.

Model parameters were estimated through a nonlinear regression method (Cooley and Naff, 1990) that minimized differences between measured and computed heads and flows. Initial estimates were specified for seven parameters (table 3), including five that were estimated through nonlinear regression. The other two parameters (vertical hydraulic conductivity and specific storage of the surficial aquifer) were too insensitive to estimate through the regression. Model cells representing open water in Round Lake in model layers 1 to 3 were assigned a large horizontal and vertical hydraulic conductivity

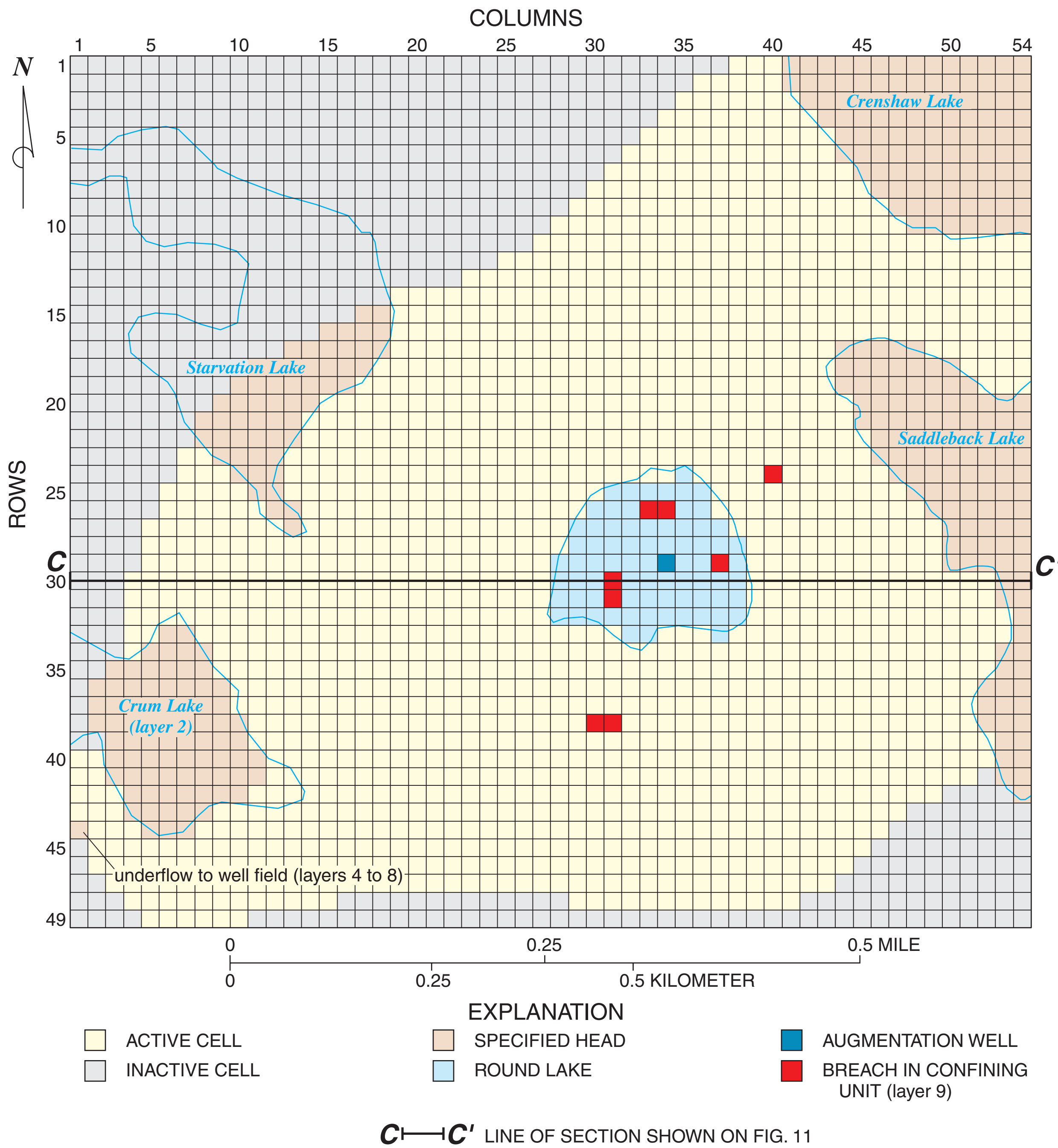


Figure 10. Boundary conditions and hydrologic features of the ground-water-flow model of the Round Lake basin.

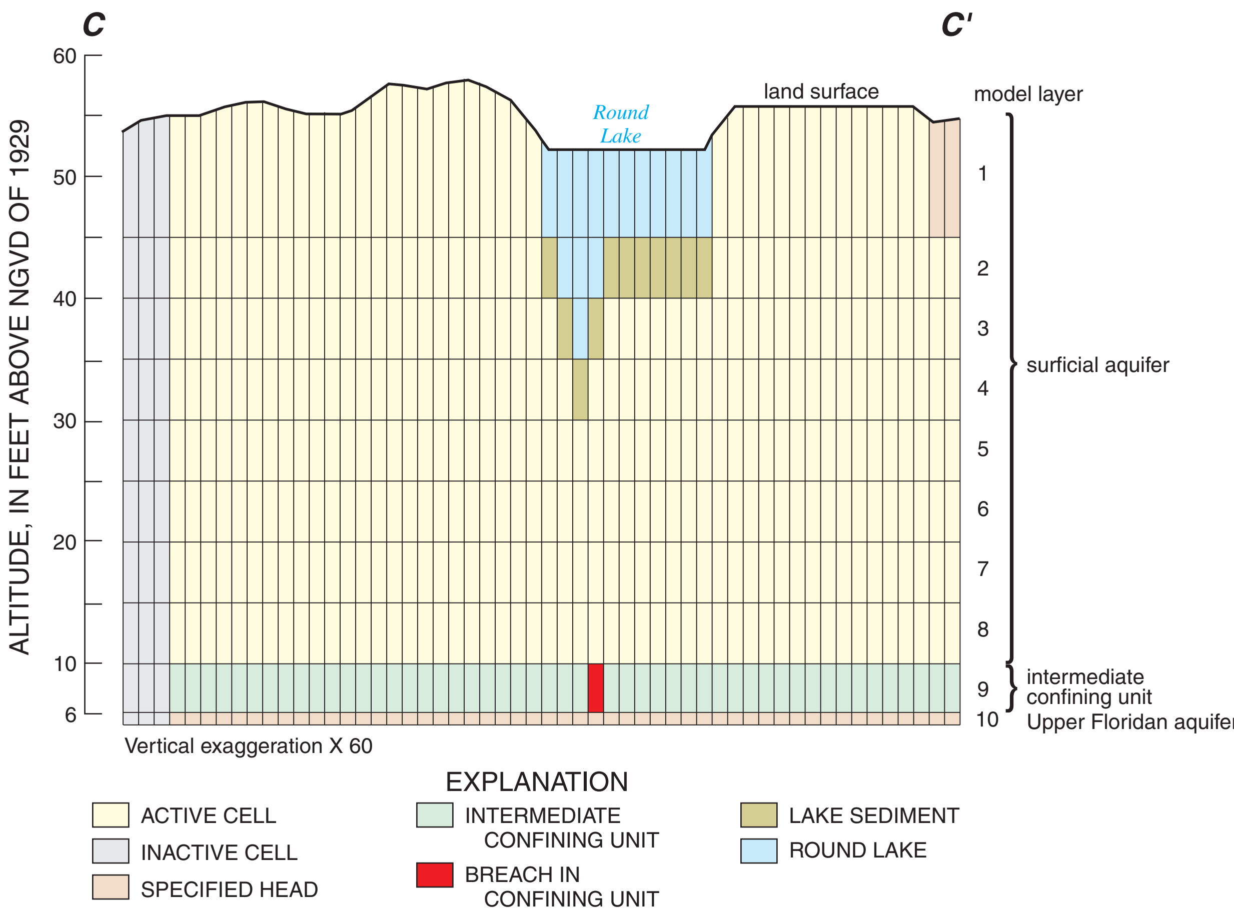


Figure 11. Model layers used to represent surficial and Upper Floridan aquifers in Round Lake basin.

Table 3. Optimum values of aquifer properties estimated for the Round Lake model area through nonlinear regression in transient-state simulations, and error in predicted heads and flows

[Shading indicates estimated parameters. ft/d, feet per day; ft^2, feet squared; ft, feet]

Parameter	Model RL-A: high recharge	Approximate individual 95-percent confidence interval	Coefficient of variation (percent)	Model RL-B: low recharge
Aquifer property				
Horizontal hydraulic conductivity of surficial aquifer, ft/d	12	11 - 13	[1]2.2	12
Vertical hydraulic conductivity, ft/d				
Surficial aquifer	2			2
Lake sediment[2]	[3]0.15			[3]0.15
Intermediate confining unit[2]	6×10^{-3}	5.6×10^{-4} - 6.4×10^{-4}	0.5	5.6×10^{-3}
Breaches in intermediate confining unit[2]	0.24	0.16 - 0.34	6.7	0.19
Storage—all units				
Specific yield	0.23	0.21 -0.24	3.5	0.21
Specific storage, ft^{-1}	1.2×10^{-6}			1.2×10^{-6}
Model error				
Sum of squared errors in heads and flows, ft^2	725			769
Standard error, ft				
Heads	1.05			1.10
Flows	1.90			1.74

[1]Reported for log-transformed parameter.
[2]Lake sediment, intermediate confining unit and breaches specified as isotropic.
[3]Effective value computed from Darcy's Law, no statistics reported.

(10,000 ft/d) to allow the water level to fluctuate during the transient simulation while maintaining a near-zero hydraulic gradient throughout the part of the model area representing the lake. Hydraulic conductivity of lake sediments, assumed to be isotropic, was estimated by the regression for model cells underlying the open-water cells (fig. 11). Simulated flow between the lake and the surficial aquifer occurred through cells representing aquifer material and through cells representing lake sediments. The effective hydraulic conductivity controlling the rate of flow was, therefore, a function of the hydraulic conductivities specified for both the aquifer material and lake sediments. This effective value was computed using Darcy's law and the results of steady-state simulations, as described in the next section.

Results of transient-state simulations were compared with 554 water levels measured in 18 surficial aquifer wells and in Round Lake during the simulated period, and 32 estimates of net ground-water flow rates from monthly water budgets. Heads computed by simulation were interpolated spatially and temporally to correspond to well locations and measurement times. Heads for wells with screens that spanned multiple model layers were computed near the midpoint of the well screen. Observations were weighted in the regression according to procedures in Hill (1992) to account for the different units associated with head measurements (42.6-57.5 ft) and flow measurements (3,200-32,200 ft^3/d), so weighted residuals are computed in constant units of feet. The weights were adjusted so that the residual in the head and flow measurements (difference between observed and computed values) were the same order of magnitude.

Simulation Results

Optimum Parameter Values

The parameter values estimated by nonlinear regression for the five aquifer properties are listed in table 3, together with their approximate individual confidence intervals and coefficients of variation. The confidence intervals were computed based on the method described in Hill (1992) under the assumption that the model is correct and linear in the vicinity of the optimum set of values, and the parameter values are normally distributed. The residuals are normally distributed based on the R^2_N statistic defined by Hill (1992), but the model is not effectively linear based on the modified Beale's measure (Cooley and Naff, 1990; Hill, 1994). The reported statistics are only approximate, therefore, because the model does not meet all the required assumptions, but they indicate qualitatively the relative reliability of the optimum parameter values.

The coefficients of variation for four of the parameter values estimated by nonlinear regression with model RL-A range from 0.5 to 7 percent, indicating that the model is sensitive to the estimated parameters and that the optimum values are accurately estimated. An inverse correlation was apparent between the parameters representing the vertical hydraulic conductivity of the intermediate confining unit and the breaches within it (r^2 = -0.91), but the regression was well conditioned and converged to optimum values for these parameters despite the correlation. Optimum parameter values obtained by regression with model RL-B fall within the approximate 95-percent confidence intervals associated with the values estimated with model RL-A.

The estimated hydraulic conductivity of the surficial aquifer is 12 ft/d, about double the value estimated from the pumping test at Round Lake (5 ft/d), and the estimated specific yield was 0.23. The vertical hydraulic conductivity of the surficial aquifer (2 ft/d) was based on the geometric mean hydraulic conductivity (6.5 ft/d) and vertical anisotropy (3.3) estimated from pumping test results, because the model sensitivity to the parameter was too small to include in the regression. The vertical hydraulic conductivities of the intermediate confining unit and the breaches within it were estimated as 6.0×10^{-3} and 0.24 ft/d, respectively. The vertical hydraulic conductivities (K_v) were computed from the corresponding leakance (L) using the following equation:

$$L = \frac{K_v}{b}, \qquad (5)$$

where the thickness (b) of the intermediate confining unit was assumed to be 4 ft from drilling logs near Round Lake. If the average thickness of the intermediate confining unit was more than 4 ft, then the estimated value of vertical hydraulic conductivity would be proportionately greater. Intermediate confining unit sediments and lake sediments are specified as isotropic in models RL-A and RL-B.

The effective hydraulic conductivity of the lake sediments was estimated from the results of steady-state simulations representing conditions in July 1996. The effective value (k) was computed from Darcy's law:

$$Q = kiA, \qquad (6)$$

where

Q is flow rate [L^3/T];
i is hydraulic gradient [dimensionless]; and
A is the lake-surface area [L^2/T].

The average hydraulic gradient was determined by inspection from hydraulic heads computed from the simulation, and the flow rate from the lake to the surficial aquifer was summed using the program ZONEBUDGET (Harbaugh, 1990). Estimated effective hydraulic conductivity of lake sediments with either the high or the low recharge condition were both about 0.15 ft/d.

Water Levels

Water levels in the surficial aquifer in June 1997 were near minimum for the 32-month simulation period. Heads computed by transient-state simulation with model RL-A (fig. 12A) indicated that in June 1997 ground water flowed in a southwest direction from Saddleback and Crenshaw Lakes toward the cone of depression created by the municipal well field west of the study area. Augmentation water maintained the stage of Round Lake about 2 ft above the adjacent water table, and simulated leakage from the lake occurred around the entire perimeter. Lake stage was about 5 ft above the sloping water-table surface from Saddleback Lake to Crum Lake (fig. 12B). The computed vertical distribution of head indicates predominantly downward flow beneath Round Lake toward the Upper Floridan aquifer. Heads in the surficial aquifer ranged from 52 ft near Round Lake to 40 ft near Crum Lake, whereas heads specified in the Upper Floridan aquifer ranged from 40 ft near Crenshaw Lake to 33 ft near Crum Lake. Heads computed by transient-state simulation with model RL-B display similar flow patterns of June 1997.

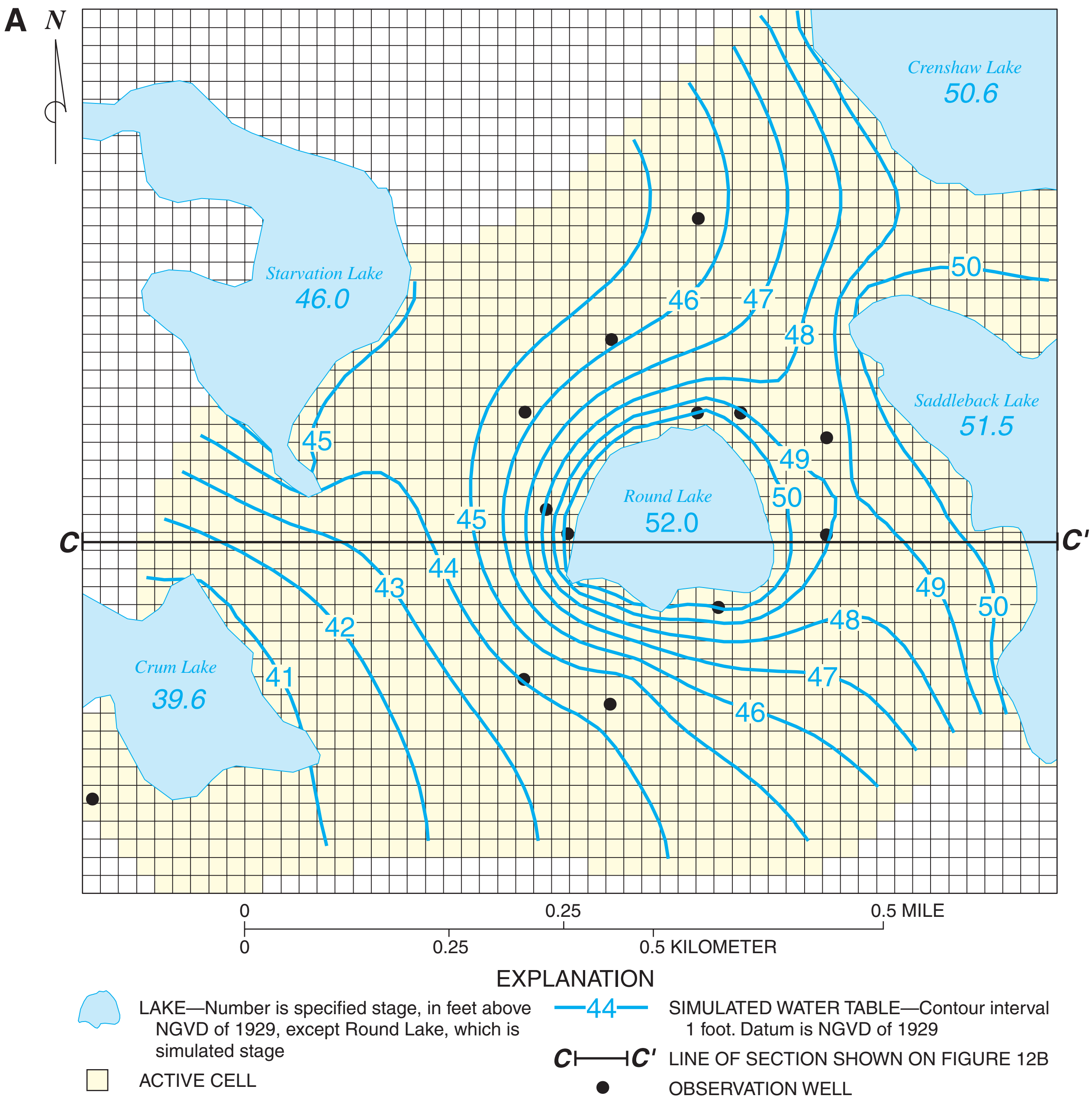


Figure 12A. Water table in June 1997 during average conditions, computed by transient-state simulation with model RL-A (high recharge), of the surficial aquifer near Round Lake: plan view.

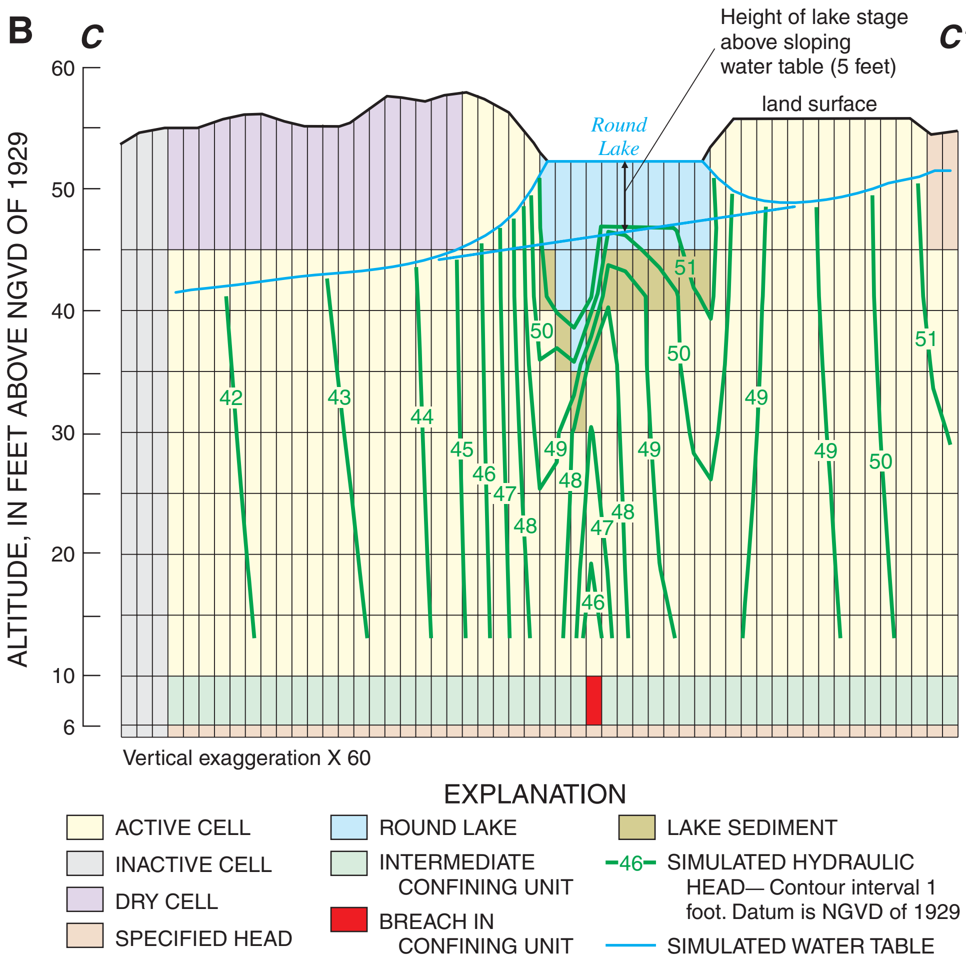
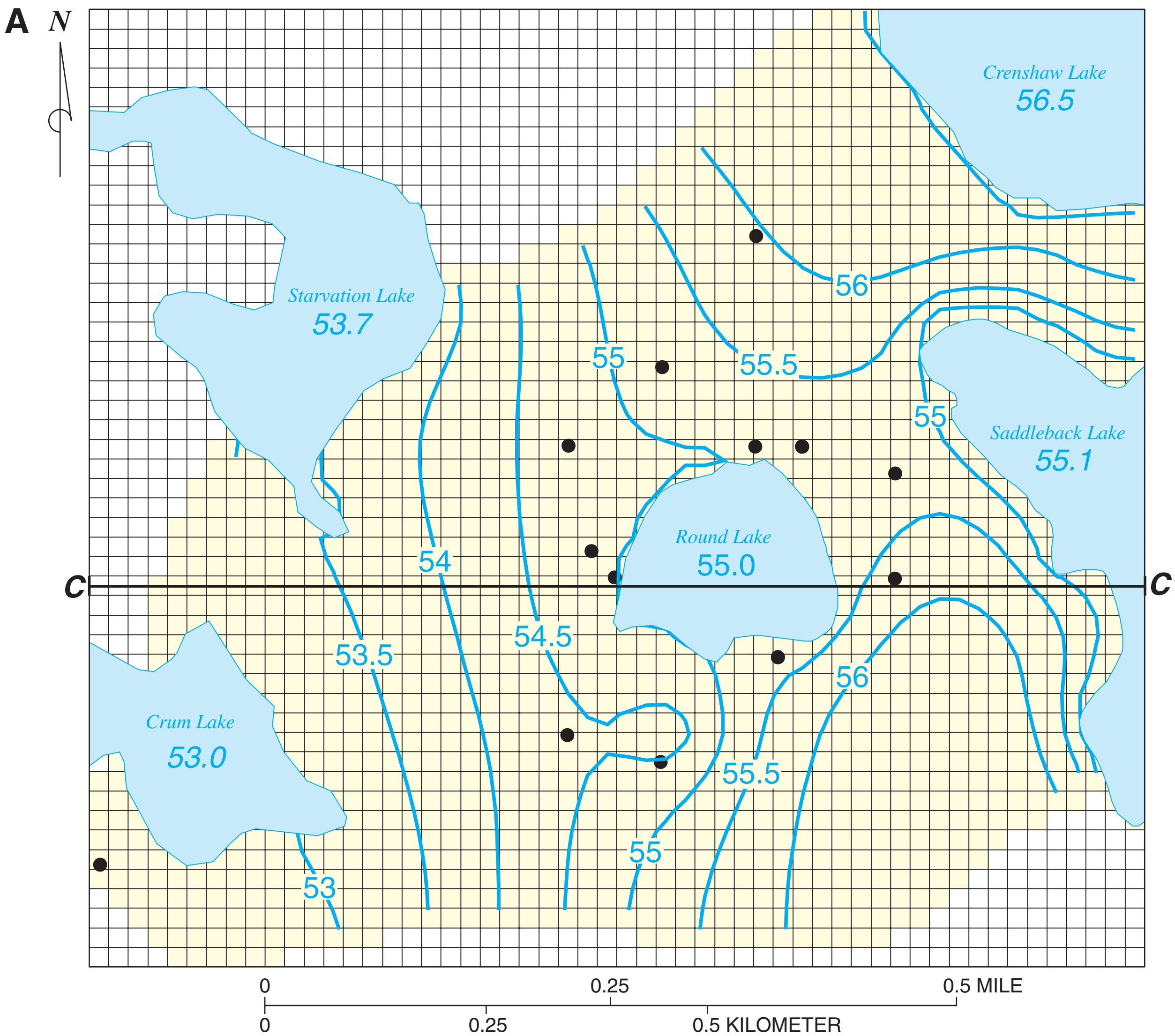


Figure 12B. Water table in June 1997 during average conditions, computed by transient-state simulation with model RL-A (high recharge), of the surficial aquifer near Round Lake: section view.

Water levels in the surficial aquifer in March 1998 were near maximum during El Niño conditions, and the computed head distribution (fig. 13A) indicates a much flatter, southwestly gradient ($1.5x10^{-3}$) than the computed gradient for June 1997 ($9.2x10^{-3}$). The stage in Round Lake (55 ft) was near the altitude of the adjacent water table, and the vertical gradient beneath the lake remained downward toward the Upper Floridan aquifer (fig. 13B). Heads in the aquifer system during March 1998 generally were higher than in June 1997, ranging from 55 ft near Round Lake to 53 ft near Crum Lake (fig. 13B), whereas heads specified in the Upper Floridan aquifer ranged from 44 to 37 ft.

Hydrographs of simulated water levels (fig. 14) indicate that model RL-A closely reproduces measured water-level fluctuations in response to changes in recharge and pumpage during the 32-month simulation period. Hydrographs in figure 14A-D depict water levels in Round Lake and three wells to the south and west screened in the upper half of the surficial aquifer, whereas hydrographs in figure 14E-H depict water levels in four wells screened at four different depths northeast of the lake. Simulated water levels are underpredicted by as much as 1 ft during average conditions (July 1996 to October 1997), and overpredicted by as much as 1.5 ft during La Niña conditions (September 1998 to February 1999) (for example, fig. 14A). This bias in model results is apparent in the distribution of model residuals (difference between measured and simulated heads), but the residual plots indicate that heads computed with model RL-A generally match the measured water levels quite well (fig. 15). The standard error in computed heads was 1.05 ft and the range of measured heads was 43 to 57 ft. The standard error in heads computed with model RL-B was slightly greater (1.1 ft), and computed head distributions were nearly equivalent to those computed with model RL-A.



EXPLANATION

LAKE—Number is specified stage, in feet above NGVD of 1929, except Round Lake, which is simulated stage

ACTIVE CELL

55 SIMULATED WATER TABLE—Contour interval 0.5 foot. Datum is NGVD of 1929

C—C′ LINE OF SECTION SHOWN ON FIGURE 13B

OBSERVATION WELL

Figure 13A. Water table in March 1998 during El Niño conditions, computed by transient-state simulation with model RL-A (high recharge), of the surficial aquifer near Round Lake: plan view.

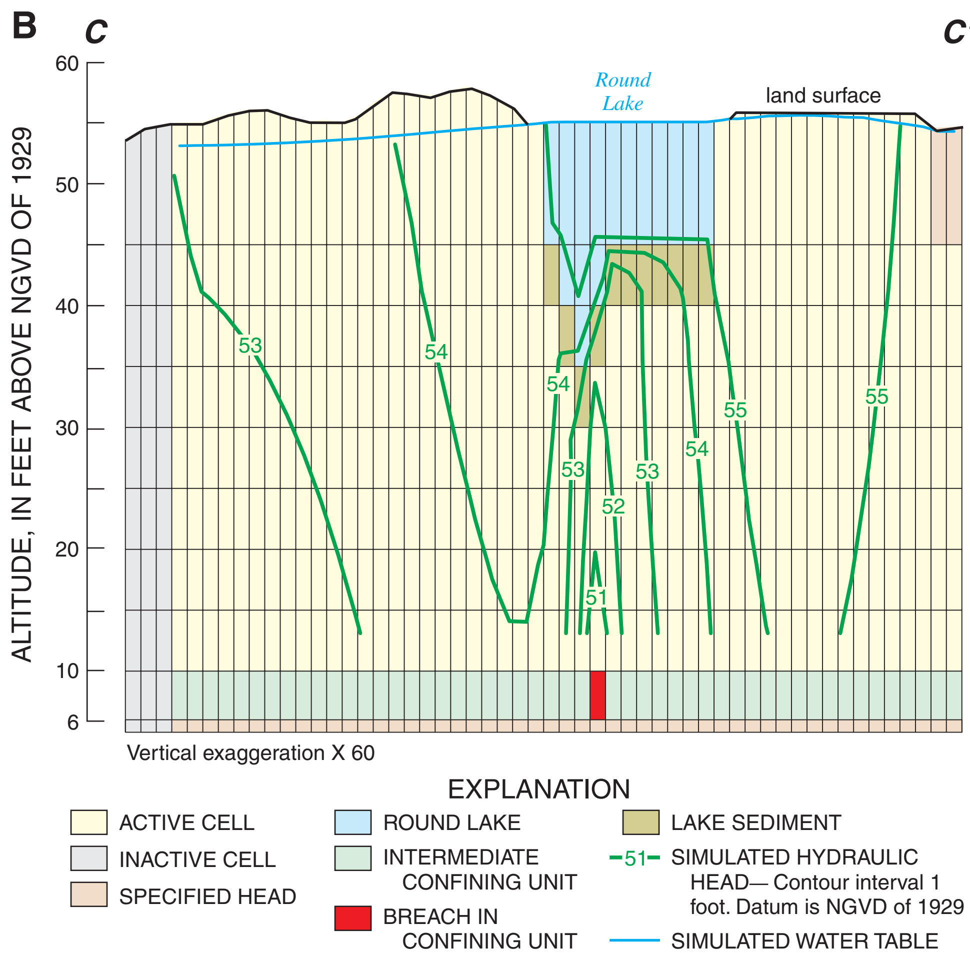


Figure 13B. Water table in March 1998 during El Niño conditions, computed by transient-state simulation with model RL-A (high recharge), of the surficial aquifer near Round Lake: section view.

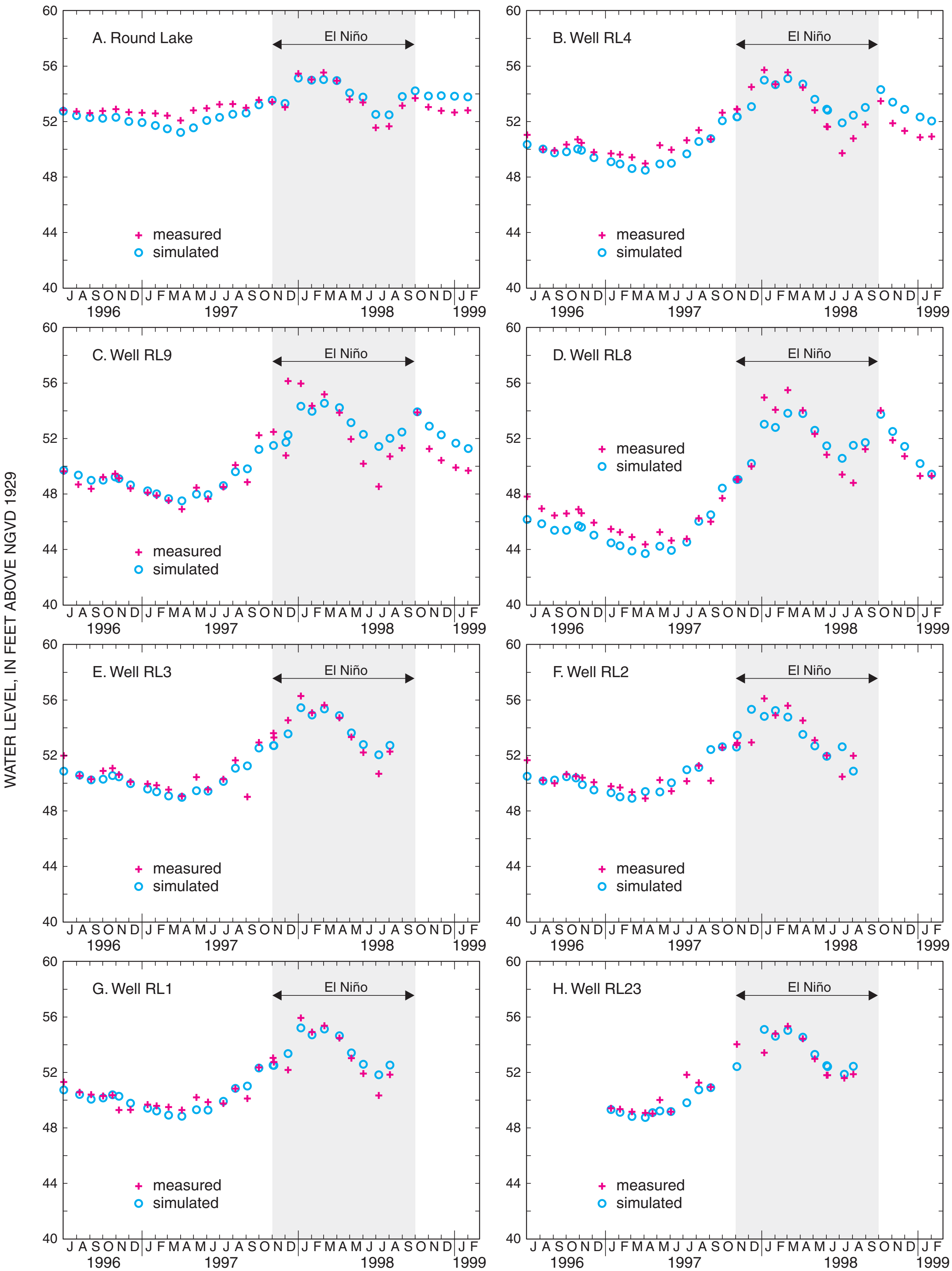


Figure 14. Water levels measured in the surficial aquifer near Round Lake and heads, computed by transient-state simulation with model RL-A (high recharge), July 1996 to February 1999: (A) Round Lake; (B) well RL4, (C) well RL9, (D) well RL8, (E) well RL3, (F) well RL2, (G) well RL1, (H) RL 23. (Location of wells and screened intervals on page 24.)

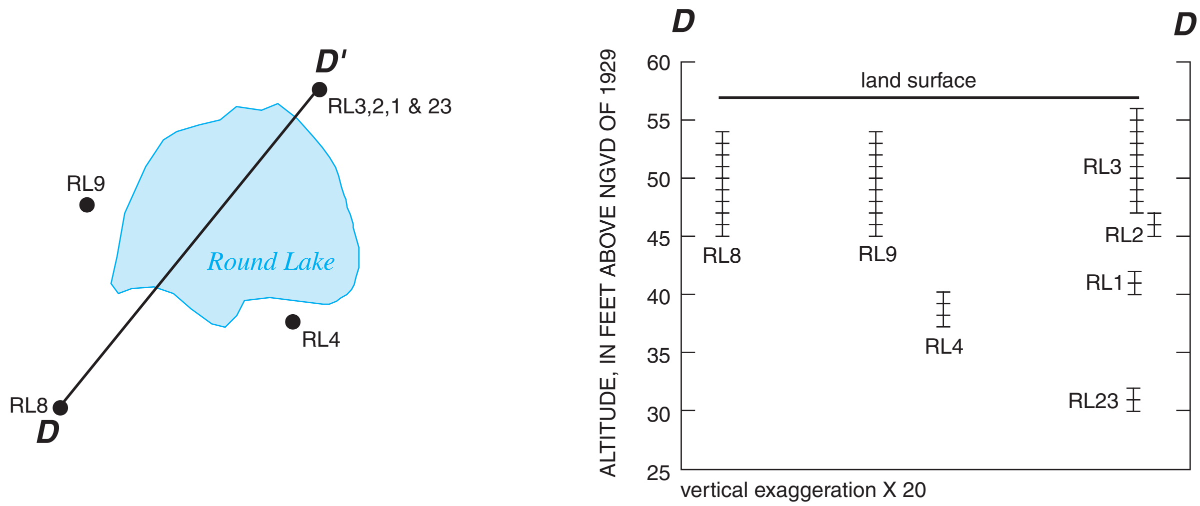


Figure 14. (Continued) Water levels measured in the surficial aquifer near Round Lake and heads, computed by transient-state simulation with model RL-A (high recharge), July 1996 to February 1999: location of wells and screened intervals.

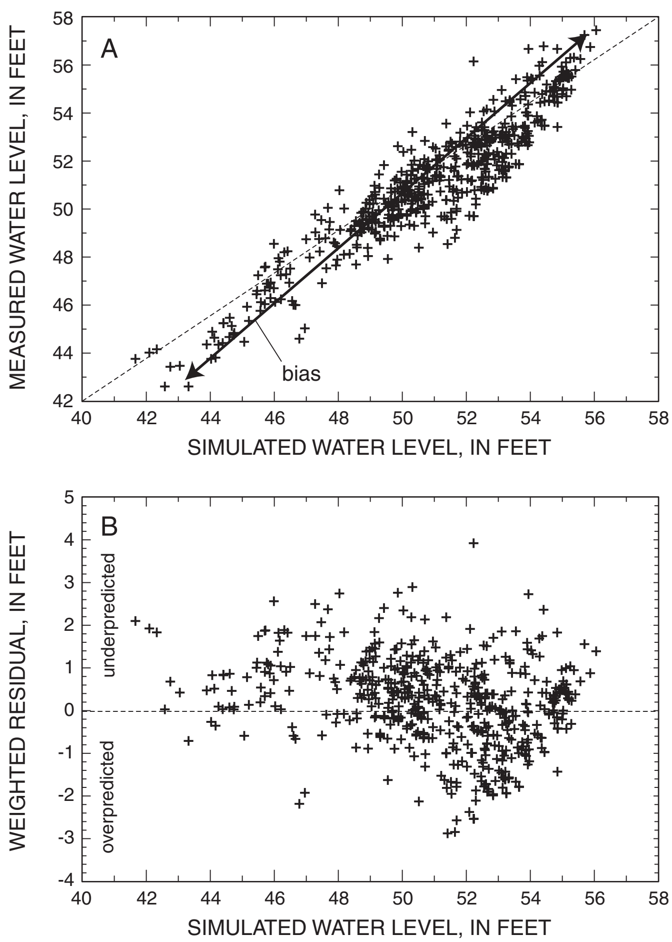


Figure 15. Measured heads, simulated heads, and residuals, computed from transient-state simulation with model RL-A (high recharge), of the surficial aquifer near Round Lake, July 1996 to February 1999: (A) measured and simulated values; (B) simulated values and residuals.

Water Budget

Simulated water budgets for the entire modeled area reflect the dramatic increase in recharge from average to El Niño conditions (table 4). During average conditions (July 1996 to October 1997), the mean recharge to the surficial aquifer was about 1.5 in/mo (3.6 cm/mo) and accounted for 36 percent of the computed inflows, whereas leakage from surrounding lakes (30 percent) and augmentation from the Upper Floridan aquifer (22 percent) accounted for most of the remainder. Recharge more than doubled to 3.3 in/mo (8.1 cm/mo) during El Niño conditions (November 1997 to September 1998), and accounted for 61 percent of computed inflows. Downward leakage to the Upper Floridan aquifer accounted for most of the outflow from the model area during both periods, with about 10 percent of leakage passing through breaches in the intermediate confining unit. The variability in recharge is evident in monthly budgets computed for the simulated period (fig. 16). Most of the recharge was temporarily stored in the surficial aquifer then released during succeeding months.

Net leakage (ground-water outflow) rates from Round Lake computed with model RL-A are similar to those estimated from monthly water budgets computed for Round Lake (fig. 17). Residuals generally are larger for months with lower leakage rates (fig. 18), which are not as accurately estimated from the monthly water budgets as are the larger rates. The standard error in flow rates was 1.9 ft for model RL-A and 1.74 ft for model RL-B.

Table 4. Simulated water budget for the Round Lake model area during average conditions and El Niño conditions, model RL-A

[Flow rates are in thousands of cubic feet per day; <, less than]

Inflow			Discharge		
Source	**Rate**	**Percentage of total**	**Location**	**Rate**	**Percentage of total**
Average (July 1996 to October 1997)					
Recharge	42.6	36	Net precipitation from Round Lake	0.2	< 1
Storage	14.1	12	Storage	25.7	22
Leakage from surrounding lakes	35.2	30	Underflow to municipal wells	< 0.1	< 1
Augmentation well	25	22	Downward leakage		
			Intermediate confining unit	83.8	72
			Breaches in confining unit	7.2	6
TOTAL	116.9	100	TOTAL	116.9	100
El Niño (November 1997 to September 1998)					
Recharge	95.5	61	Net precipitation from Round Lake	0.2	< 1
Storage	32.1	20	Storage	47.6	30
Leakage from surrounding lakes	22.9	15	Underflow to municipal wells	< 0.1	< 1
Augmentation well	7	4	Downward leakage		
			Intermediate confining unit	102.7	66
			Breaches in confining unit	7	4
TOTAL	157.5	100	TOTAL	157.5	100

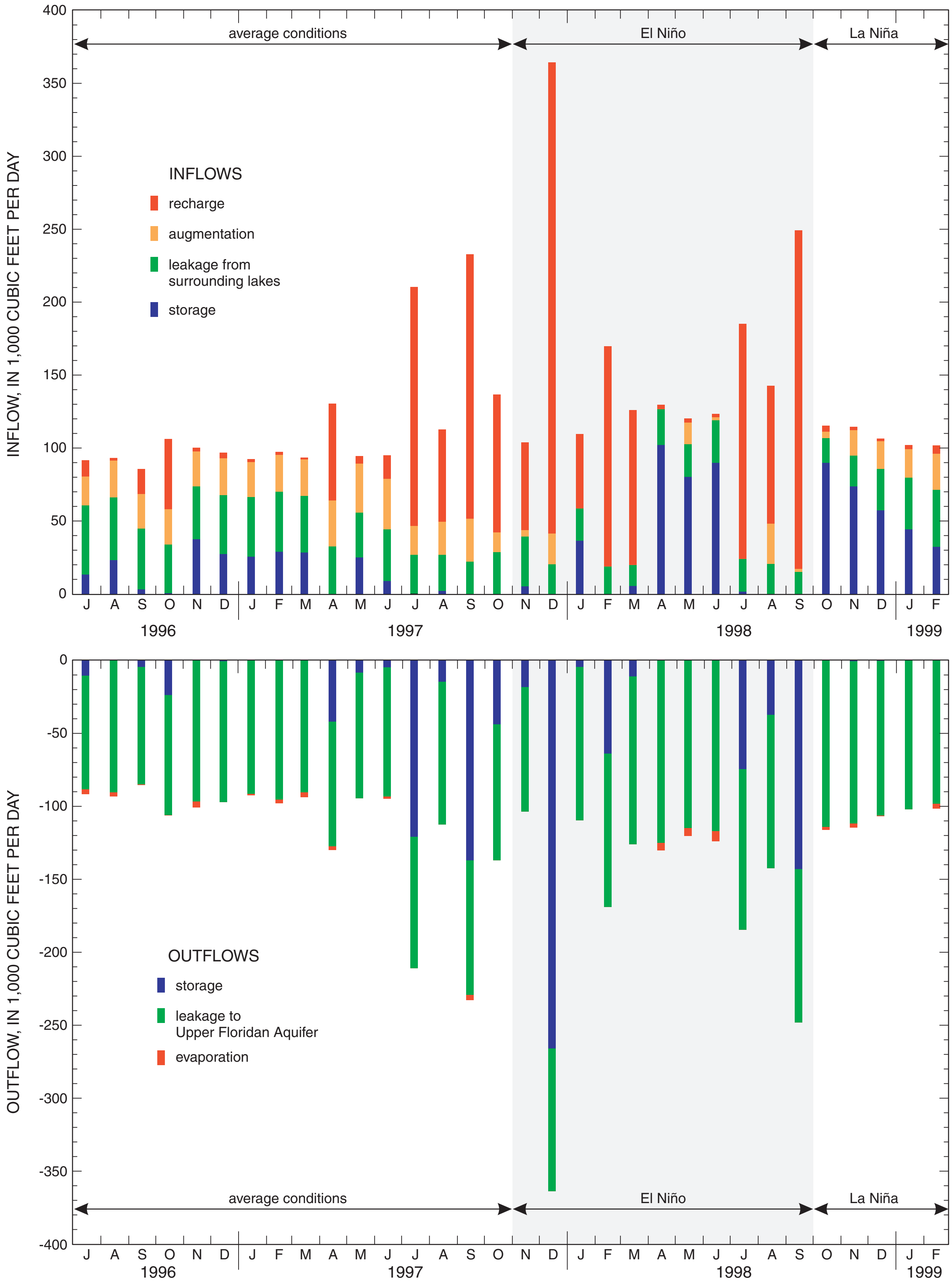


Figure 16. Simulated water budget for the surficial aquifer in the Round Lake model area, July 1996 to February 1999.

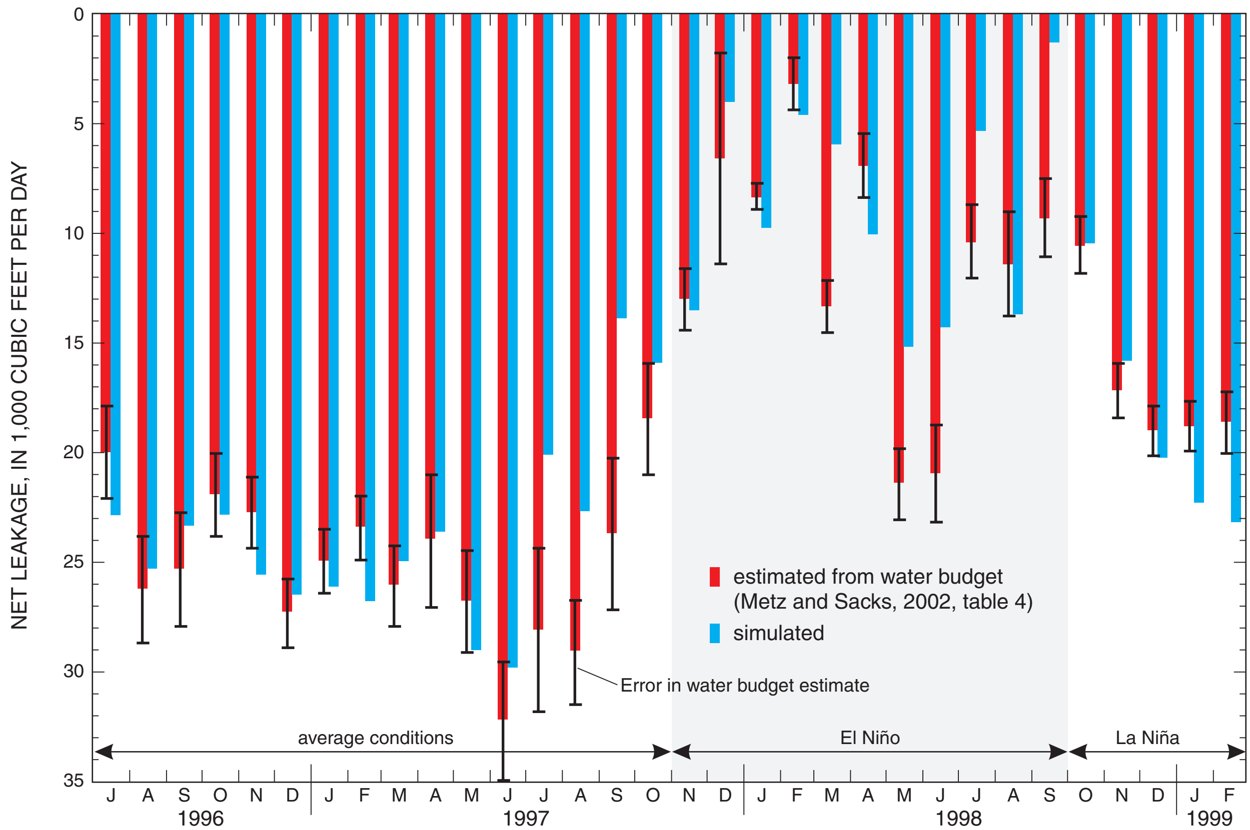


Figure 17. Simulated net leakage rates from Round Lake, computed from transient-state simulation with model RL-A (high recharge), and estimated rates from monthly water budgets, July 1996 to February 1999.

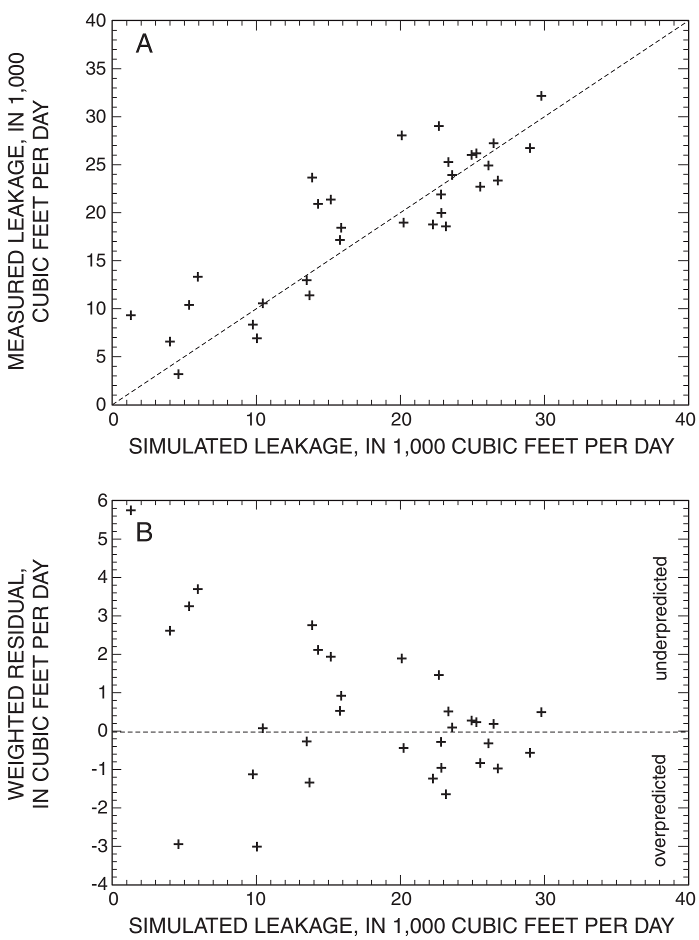


Figure 18. Simulated lake leakage rates and residuals, computed from transient-state simulation with model RL-A (high recharge), and estimated rates from monthly water budgets, July 1996 to February 1999: (A) measured and simulated values; (B) simulated values and residuals.

Halfmoon Lake Basin Ground-Water Flow Simulation

The ground-water-flow models developed for the Halfmoon Lake basin included steady-state simulations of conditions in July 1996 and transient-state simulations for part of the 3-year period (July 1996 to February 1999). Steady-state simulations provided initial conditions for the transient-state simulations and were used to estimate aquifer properties, because transient-state simulations were unable to accurately reproduce the observed changes in water levels. Steady-state simulations also were used to depict flow paths and travel times of lake leakage to the Upper Floridan aquifer. Transient-state simulations were used to estimate an alternate set of aquifer properties using measured data from the first 22 months of the study (July 1996 to April 1998) and the lower set of monthly recharge rates (case B, table 2) computed with the unsaturated flow model LEACHM.

Model Design

The modeled area covers 1.3 mi^2 bounded to the west by Rocky Creek and extending to the north and east to Lake LeClare (fig. 19). Ground-water flow is represented in eight model layers with the surficial aquifer represented by model layers 1 to 6 (fig. 20). The saturated thickness of the top model layer varies from 1 to 17 ft, because the layer is unconfined and the water table fluctuates during the 22-month simulation period. The remaining five layers representing the surficial aquifer are confined with a constant thickness of 5 ft. The intermediate confining unit and the Upper Floridan aquifer are represented by model layers 7 and 8, respectively, each with a specified thickness of 5 ft. The thickness specified for the Upper Floridan aquifer is arbitrary and has no effect on model simulations. Breaches in the confining layer beneath Halfmoon Lake, inferred from seismic reflection surveys, are represented by zones of higher vertical hydraulic conductivity in layer 8. Each of the eight model layers is divided into a uniformly spaced grid of 75 ft with 98 rows and 86 columns that contains 6,529 active cells.

Specified flux boundaries are assigned in model layer 1 to represent recharge from the unsaturated zone to the surficial aquifer. The set of lower monthly recharge rates computed by the unsaturated flow model LEACHM (case B, coarse-textured soil with deep-rooted vegetation) better represent conditions in July 1996, because a higher proportion of the modeled area is covered by deep-rooted vegetation than in the Round Lake area. Specified flux boundaries also are assigned in model layer 1 to represent evaporation from Halfmoon Lake, based on the difference between average measured precipitation at several locations (Halfmoon Lake, and the Section 21 and Cosme well fields), and evaporation estimated from an energy budget computed for Lake Starr.

Specified-head boundaries that vary monthly are assigned to represent other inflows and outflows of water to and from the surficial aquifer. Leakage from Lake LeClare is represented in model layers 1 to 3 based on the measured lake stage. Vertical leakage through the intermediate confining unit to the Upper Floridan aquifer is represented by assigning specified heads throughout model layer 8. The temporal distribution of head in model layer 8 was computed by interpolating monthly water levels measured in the Upper Floridan aquifer. Ground-water discharge to Rocky Creek is represented through a head-dependent flux (drain) boundary using monthly stream stages estimated from daily stages measured in Rocky Creek at a gaging station near Gunn Highway. The drain conductance was specified larger than the adjacent aquifer so the boundary functioned as a specified head that allowed outflow from the modeled area, but no inflow. Other lateral boundaries of the modeled area coincide with streamlines interpreted from the regional distribution of hydraulic head (see fig. 5) and are specified as no-flow in all layers.

Two zones were delineated in both the surficial aquifer and the intermediate confining layer in an attempt to better reproduce the observed water-table configuration in July 1996 and water-level fluctuations during the study (fig. 19). The fluctuation in measured water levels was about 4 to 5 ft in wells located more than 400 ft to the north and east of Halfmoon Lake (for example, wells HML-5 and HML-16), whereas the range was 6 to 7 ft in wells surrounding the lake and to the south and west (for example, HML-9 and HML-12). Separate hydraulic-conductivity values were estimated for each of these zones through nonlinear regression.

Calibration Procedure

Parameter values representing aquifer properties were adjusted through steady-state simulations to produce a model that approximated water levels measured in July 1996. Transient-state simulations were unable to accurately reproduce water levels measured during El Niño, so a shorter (22-month) simulation that approximated water levels and net ground-water flow from July 1996 to April 1998 was used to estimate an alternate set of aquifer properties.

Model parameters were estimated through the same nonlinear regression method used for the Round Lake model. Initial estimates were specified for nine parameters (table 5), six of which were estimated through nonlinear regression. The other three parameters (vertical hydraulic conductivity, specific storage, and specific yield of the surficial aquifer) were too insensitive to estimate through the regression. Model cells representing open water in Halfmoon and Little Halfmoon Lakes and an unnamed lake were assigned a large horizontal and vertical hydraulic conductivity (10,000 ft/d) in model layers 1 to 3, as in Round Lake simulations. The effective hydraulic-conductivity value of lake sediments was computed using Darcy's law and the results of steady-state simulations, as described previously.

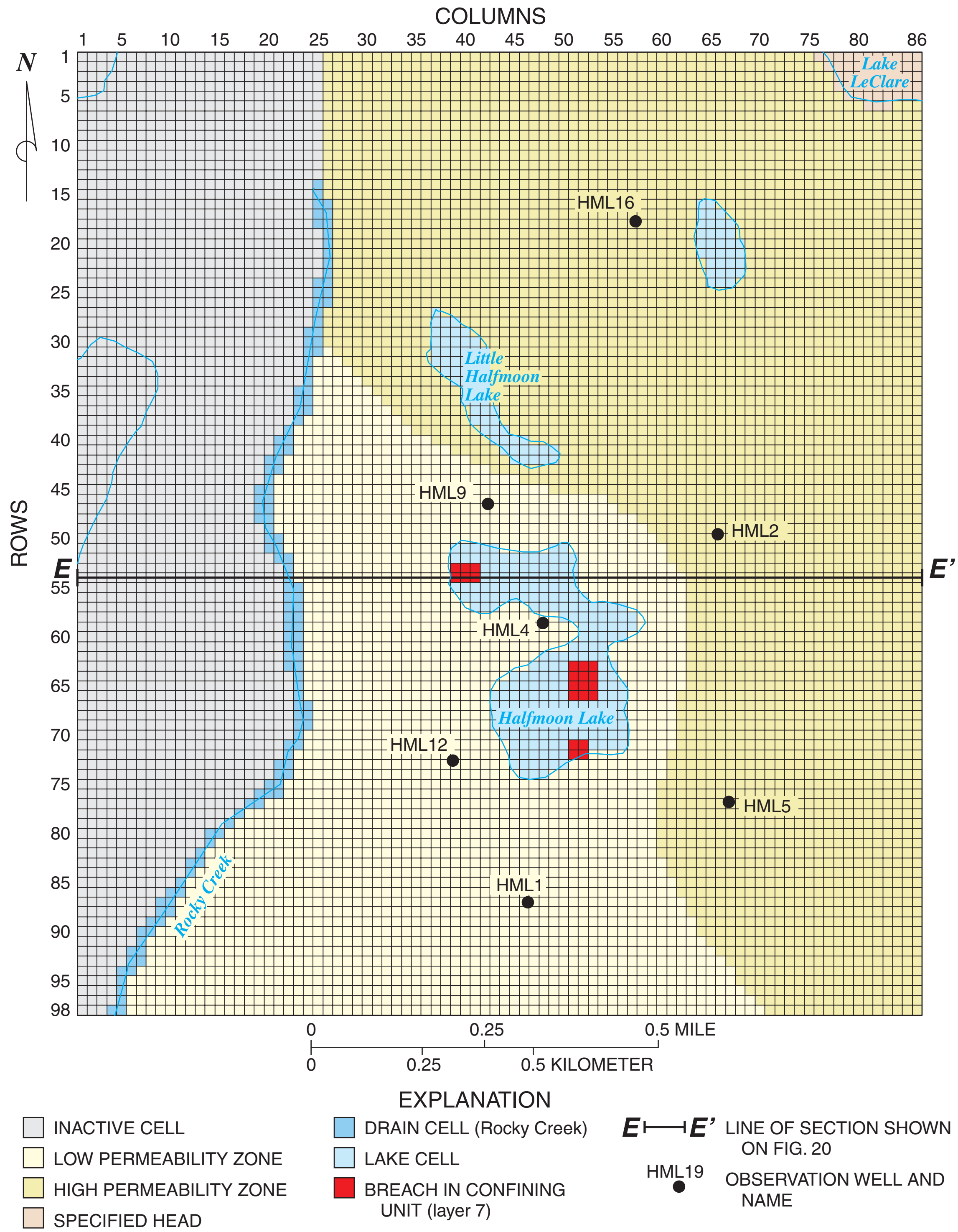


Figure 19. Boundary conditions and hydrologic features of the ground-water-flow model of the Halfmoon Lake basin.

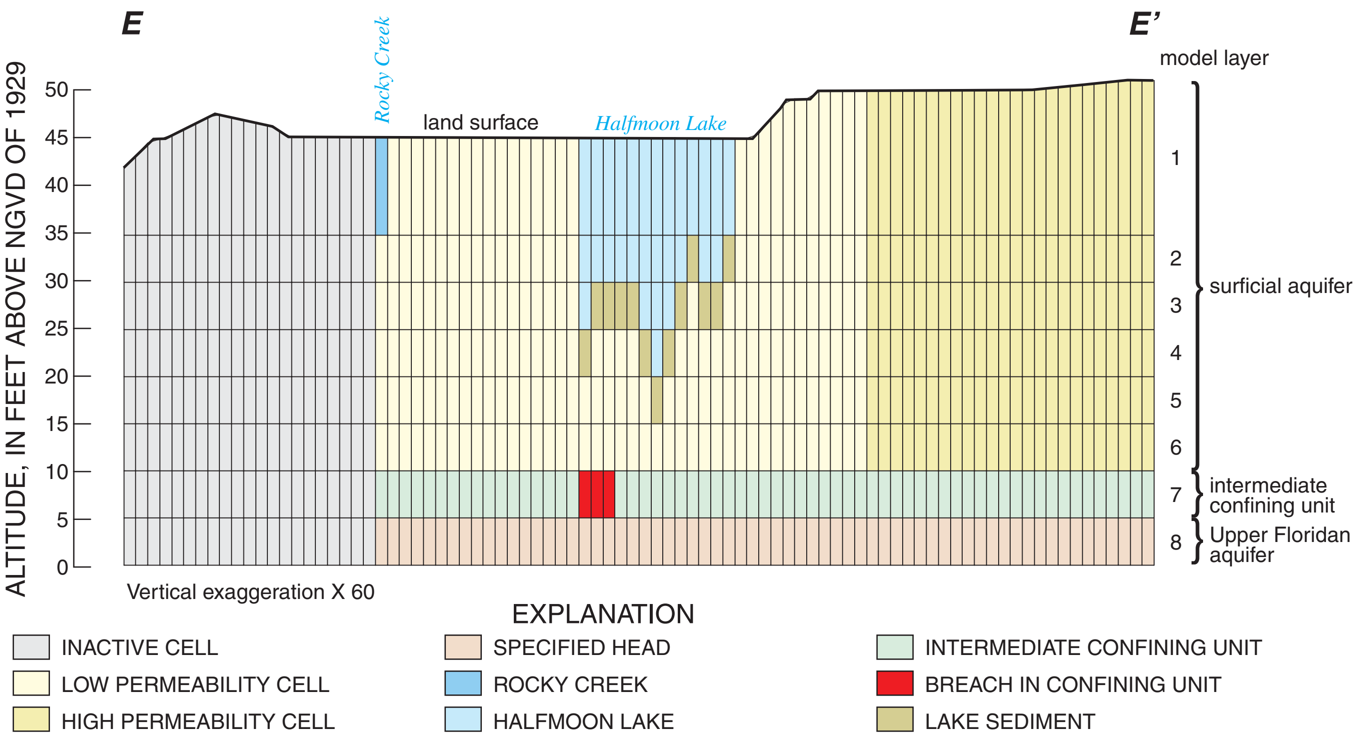


Figure 20. Model layers used to represent surficial and Upper Floridan aquifers in the Halfmoon Lake basin.

Table 5. Optimum values of aquifer properties estimated for the Halfmoon Lake model area through nonlinear regression in steady-state and transient-state simulations, and error in predicted heads and flows

[Shading indicates estimated parameters; ft/d, feet per day; ft, feet; ft^2, feet squared; NA, not applicable]

Parameter	Model HML-S: steady-state	Approximate individual 95-percent confidence interval	Coefficient of variation[1] (percent)	Model HML-T: transient	Coefficient of variation[1] (percent)
Aquifer property					
Horizontal hydraulic conductivity of surficial aquifer, ft/d					
Low permeability zone	3.9	2.3 - 6.9	20	6.1	6
High permeability zone	17.5	9.4 - 33	10	17.5	
Vertical hydraulic conductivity, ft/d					
Surficial aquifer	2			2	
Lake sediment[2]	[3]2.6×10^{-3}			[3]3.9×10^{-3}	
Intermediate confining unit[2]					
Beneath low permeability zone	7.5×10^{-4}	6.5×10^{-4} - 8.5×10^{-4}	0.8	1.3×10^{-3}	0.6
Beneath high permeability zone	5.5×10^{-4}	5×10^{-4} - 6×10^{-4}	0.5	1.2×10^{-3}	0.4
Breaches in intermediate confining unit[2]	2.2×10^{-2}	4.85×10^{-3} - 1.1×10^{-1}	14	4.6×10^{-3}	9
Storage—all units					
Specific yield	NA			0.27	
Specific storage, ft^{-1}	NA			1.2×10^{-6}	
Model error					
Sum of squared errors in heads and flows, ft^2	8.7			1,531	
Standard error, ft					
Heads	0.6			1.4	
Flows	0.2			4.3	

[1]Reported for log-transformed parameter.
[2]Lake sediment, intermediate confining layer and breaches specified as isotropic.
[3]Effective value computed from Darcy's law.

Results of steady-state simulations were compared with water levels measured in 25 wells and Halfmoon Lake, and baseflow to Rocky Creek at the model boundary estimated from the relation between baseflow and drainage area computed for the gaging station at Gunn Highway (fig. 1). Results of transient-state simulations were compared with 566 water levels measured at 26 surficial aquifer wells and in Halfmoon Lake during the 22-month period, and monthly net ground-water flow rates estimated from water budgets. Observations were weighted in the regression such that the residual in the head and flow measurements (difference between observed and computed values) were the same order of magnitude, as in Round Lake simulations.

Simulation Results

Optimum Parameter Values

Parameter values estimated by nonlinear regression for six of the seven aquifer properties in the steady-state simulation (model HML-S) are listed in table 5. The residuals are normally distributed based on the R^2_N statistic defined by Hill (1992), but the model is not effectively linear, based on the modified Beale's measure (Cooley and Naff, 1990; Hill, 1994). The reported statistics are only approximate, therefore, because the model does not meet all the required assumptions, but they indicate qualitatively the relative reliability of the optimum parameter values.

Coefficients of variation for five of the parameter values, estimated by nonlinear regression with model HML-S, range from 0.5 to 20 percent, indicating that the optimum values are not as accurately estimated as were parameters for the Round Lake model (0.5-7 percent, table 3). No correlation was apparent among the estimated parameters. The model is most sensitive to the parameter values estimated for the vertical hydraulic conductivities of the intermediate confining unit, and there is a small difference in the values estimated for the low and high conductivity zones. In contrast, there is a significant difference in the estimated values for the horizontal hydraulic conductivities for the zones, indicating that a difference in hydraulic conductivity is a possible cause of the differences in measured water-table fluctuations. The vertical hydraulic-conductivity value estimated for breaches in the intermediate confining unit is about 34 times the value estimated for the remainder of the unit.

Optimum parameter values obtained by regression with the transient-state simulation (model HML-T) for the surficial aquifer and lake sediments are similar to those estimated with the steady-state simulation (table 5). The largest differences in the values estimated by the two regressions are in the vertical hydraulic conductivities of the intermediate confining unit. Regression results for model HML-T suggest that the intermediate confining unit is more permeable than indicated by model HML-S, and that breaches in the confining unit are only four times more permeable than the remainder of the unit.

Estimated hydraulic conductivity of the surficial aquifer ranged from 4 to 6 ft/d for the zone surrounding Halfmoon Lake and extending south and west toward Rocky Creek, which is less than one-third the value that was estimated for the higher permeability zone north and east of the lake (18 ft/d). A value for the higher permeability zone could not be estimated with model HML-T, because the model was relatively insensitive to values greater than 18 ft/d. The sharp contrast in estimated hydraulic-conductivity values produced a relatively flat hydraulic gradient from Lake LeClare to Little Halfmoon Lake that steepened sharply near the shore of Halfmoon Lake, closely reproducing measured water levels in July 1996.

Vertical hydraulic conductivity of the surficial aquifer (2.4 ft/d) was specified from values used in the Round Lake model and computed from the estimated leakance using equation 5. Intermediate confining unit sediments and lake sediments are specified as isotropic in both models HML-S and HML-T.

The effective hydraulic conductivity of the lake sediments was estimated from the results of steady-state simulations of a hypothetical scenario based on conditions in July 1996. An augmentation rate of 6,000 ft^3/d was specified to the lake in the simulations to ensure that outflow from the lake occurred around the entire perimeter, thereby allowing an accurate calculation of the magnitude of flow. The effective value was computed from Darcy's law (eq. 6), as discussed previously for the Round Lake simulations. Estimated values for models HML-S and HML-T were 2.6×10^{-3} and 3.9×10^{-3} ft/d, respectively.

Water Levels

Water levels in the surficial aquifer in July 1996 were near average for the 3-year period. Heads computed by steady-state simulation with model HML-S (fig. 21A) indicate ground-water flowed southwest from Lake LeClare toward Halfmoon Lake and Rocky Creek. Breaches in the confining unit diverted ground-water flow beneath Halfmoon Lake, and the computed vertical distribution of head (fig. 21B) indicates predominantly downward flow beneath the lake toward the Upper Floridan aquifer. Simulated hydraulic heads indicate that water in the surficial aquifer flows toward Halfmoon Lake, reflecting both the effect of breaches in the confining layer beneath the lake and the net loss of water from the lake surface through evaporation during average conditions. Residual plots indicate that heads computed with model HML-S generally match the measured water levels reasonably well (figs. 21A and 22A), but there is some bias in model results, as heads are generally overpredicted by up to 1 ft. The standard error in computed heads was 0.6 ft and the range of measured heads was 42 to 50 ft.

Hydrographs of simulated water levels (fig. 23) indicate that model HML-T generally reproduces measured water-level fluctuations during average conditions (July 1996 to October 1997), but cannot accurately reproduce the rise in water levels during El Niño (starting November 1997), especially in areas more than 400 ft from the lake. Simulated water levels in

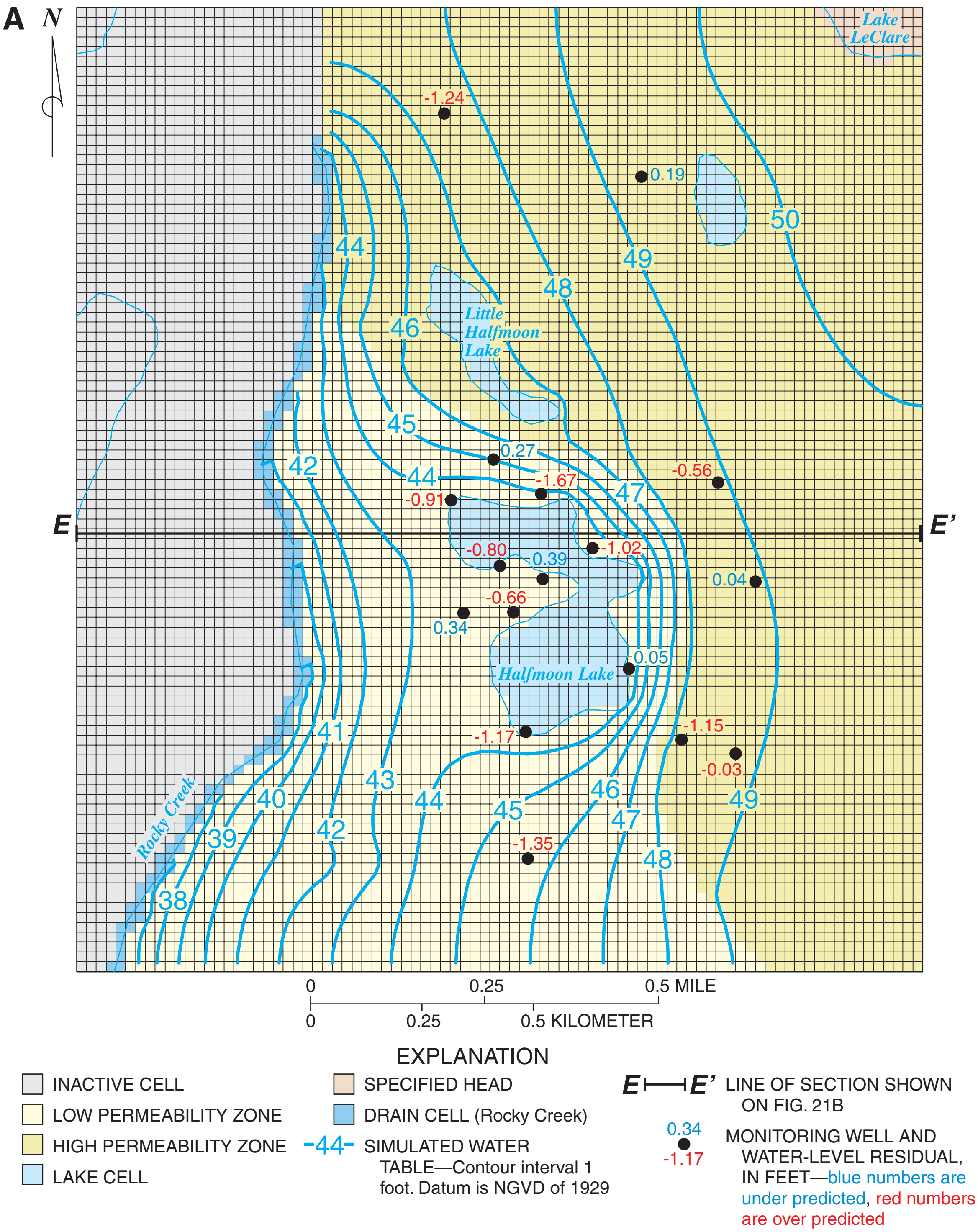


Figure 21A. Water table during average conditions (July 1996), computed by steady-state simulation with model HML-S, of the surficial aquifer near Halfmoon Lake: plan view with residual error.

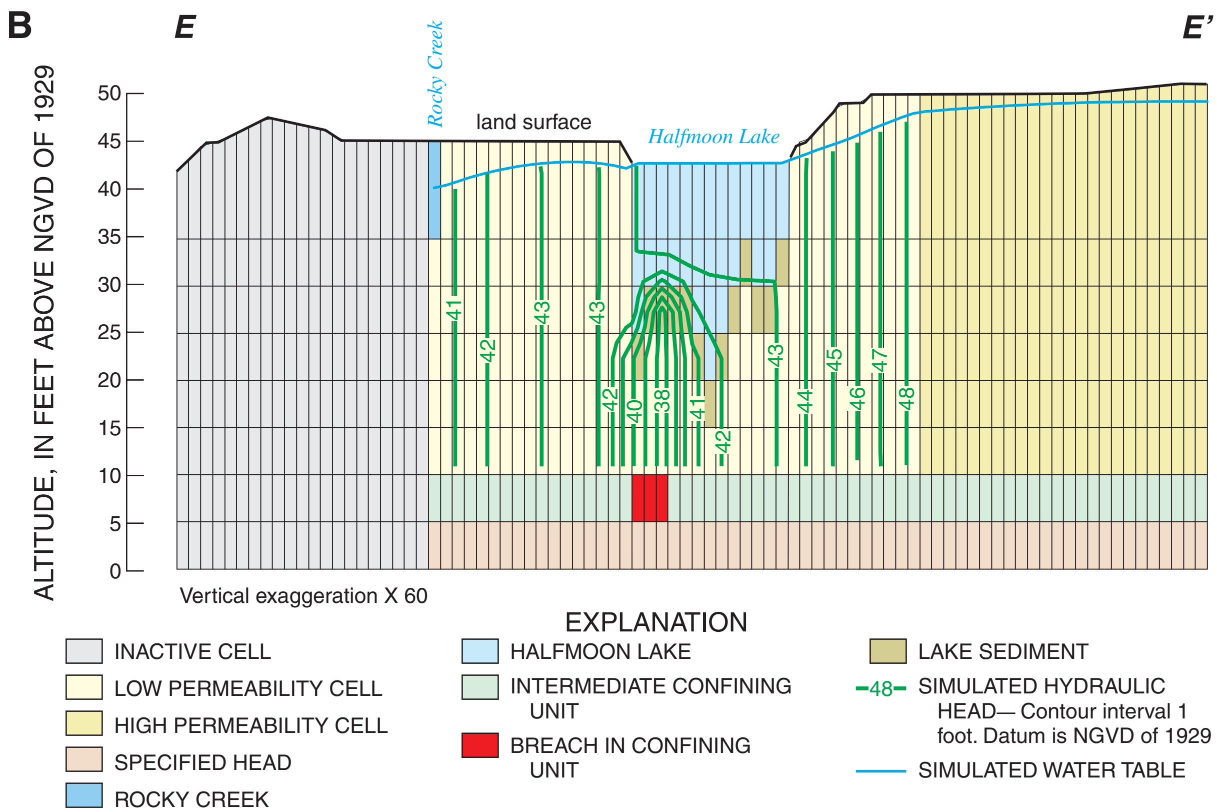


Figure 21B. Water table during average conditions (July 1996), computed by steady-state simulation with model HML-S, of the surficial aquifer near Halfmoon Lake: section view.

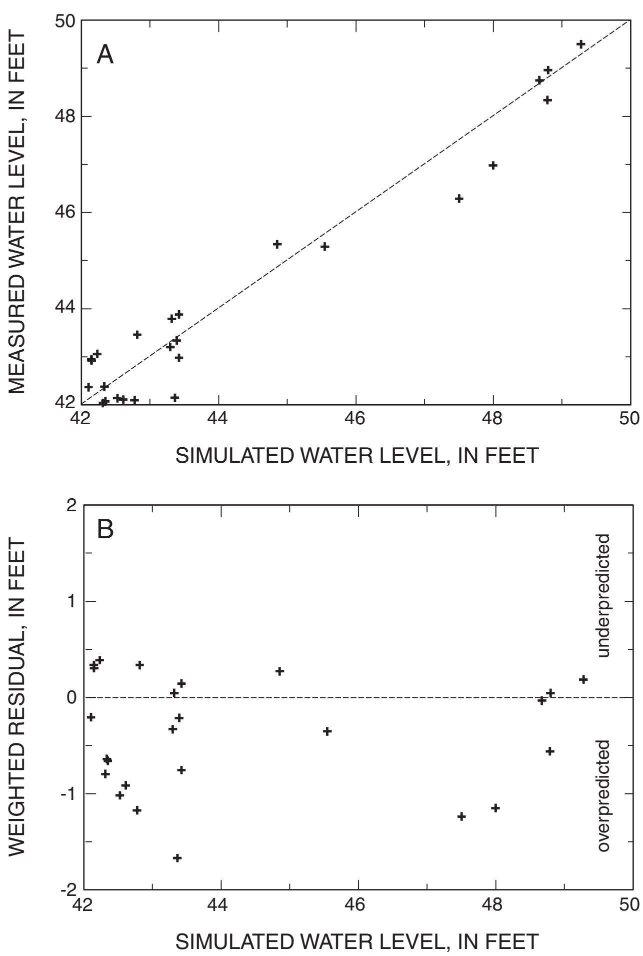


Figure 22. Measured heads, simulated heads, and residuals, computed by steady-state simulation with model HML-S, of the surficial aquifer near Halfmoon Lake, July 1996: (A) measured and simulated values; (B) simulated values and residuals.

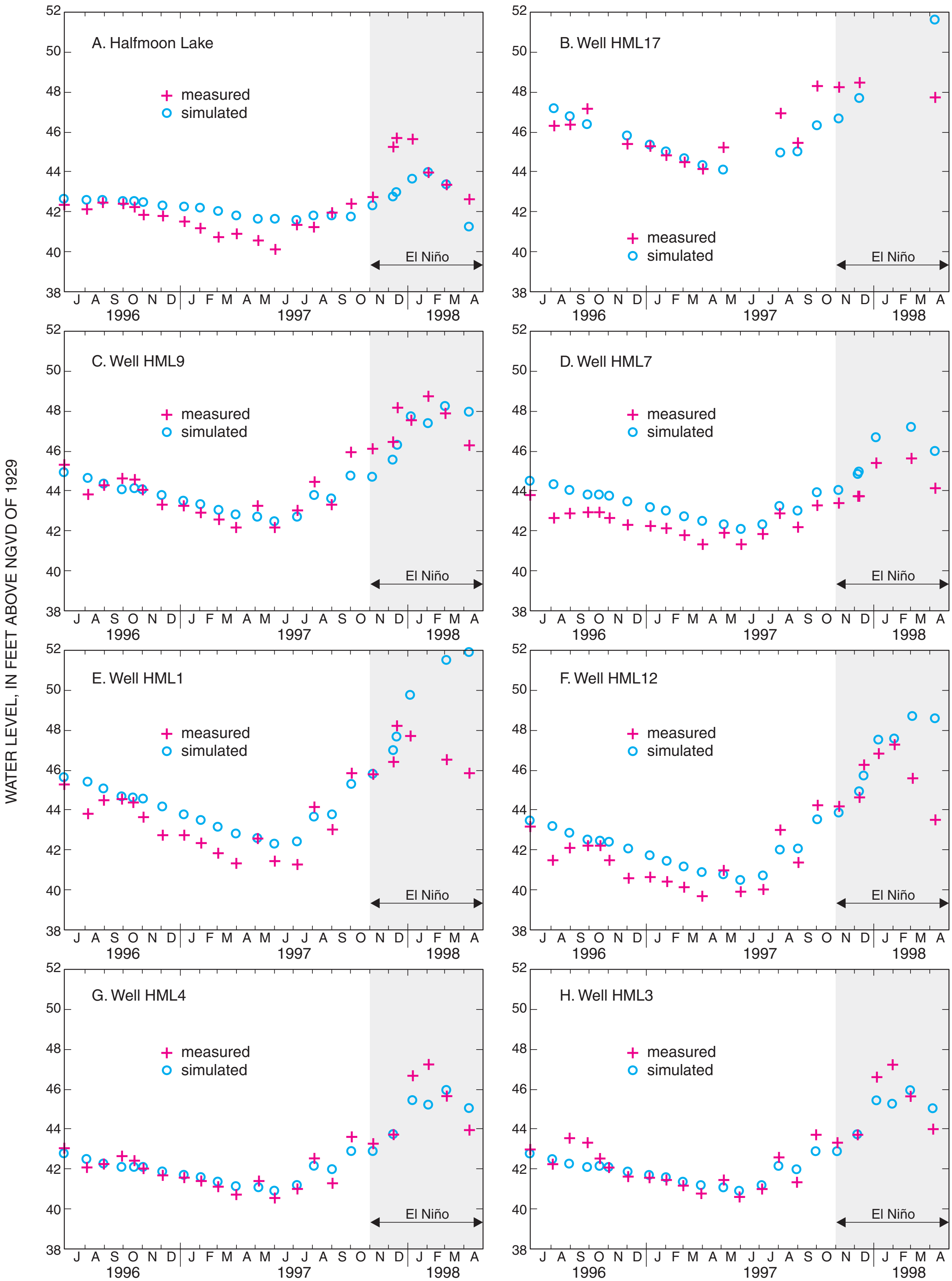


Figure 23. Water levels measured in the surficial aquifer near Halfmoon Lake and heads, computed by transient simulation with model HML-T, July 1996 to April 1998: (A) Halfmoon Lake; (B) well HML17; (C) well HML9; (D) well HML7; (E) well HML1; (F) well HML12; (G) well HML4; (H) well HML3. (Location of wells and screened intervals on page 35.)

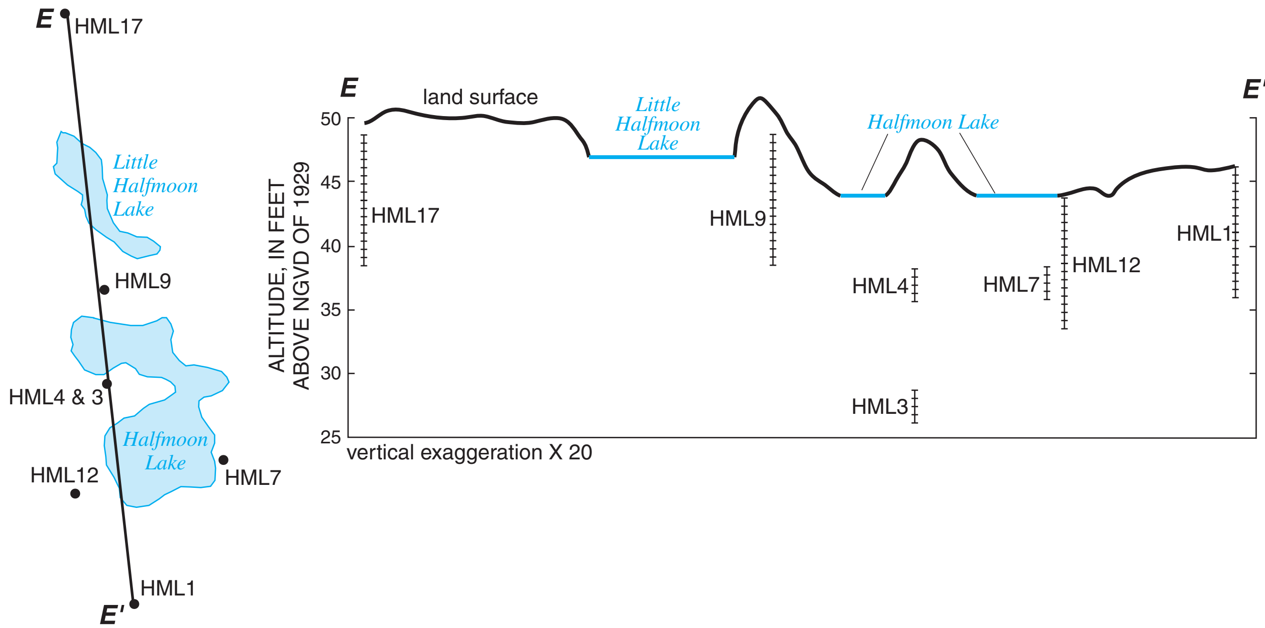


Figure 23. (Continued) Water levels measured in the surficial aquifer near Halfmoon Lake and heads, computed by transient simulation with model HML-T, July 1996 to April 1998: location of wells and screened intervals.

Halfmoon Lake display a dampened response to changes in recharge during the 22-month period--lake stage is overpredicted by about 1 ft during the summer of 1997 and underpredicted by about 2 ft in December 1997 shortly after the beginning of El Niño. Residual plots for model HML-T (fig. 24) indicate absolute errors as much as 4 ft in heads greater than 45 ft that were measured in areas upgradient from Halfmoon Lake. The standard error in computed heads was 1.4 ft and the range of measured heads was 39 to 53 ft.

Discrepancies between measured and simulated hydrographs could result from the monthly recharge rates specified in the simulation, possibly reflecting differences in rainfall received at Halfmoon Lake and at the daily precipitation gages (the Section 21 and Cosme well fields) used to compute recharge. Comparison of simulated and measured hydrographs for the 32-month period from July 1996 to February 1999 (fig. 25), however, indicates that discrepancies probably result from another source of model error. Simulated water levels for Halfmoon Lake (fig. 25A) match the measured levels reasonably well, with the exception of peak lake stages during El Niño and the decline in stage during La Niña. Moreover, simulated water levels for wells near the lake (for example, HML4, fig. 25B) agree closely with measured levels. Simulated water levels for well HML1 900 ft south of the lake (fig. 25C), however, are overpredicted by as much as 10 ft during El Niño, a pattern that also is apparent for several other wells north and east of the lake. Repeated attempts were made to improve the match in these areas during model calibration by testing different sets of parameter values, including additional breaches in the confining layer and changing the boundaries of hydraulic conductivity zones specified in the model. None of these attempts, however, were able to duplicate aquifer conditions during both average conditions and El Niño.

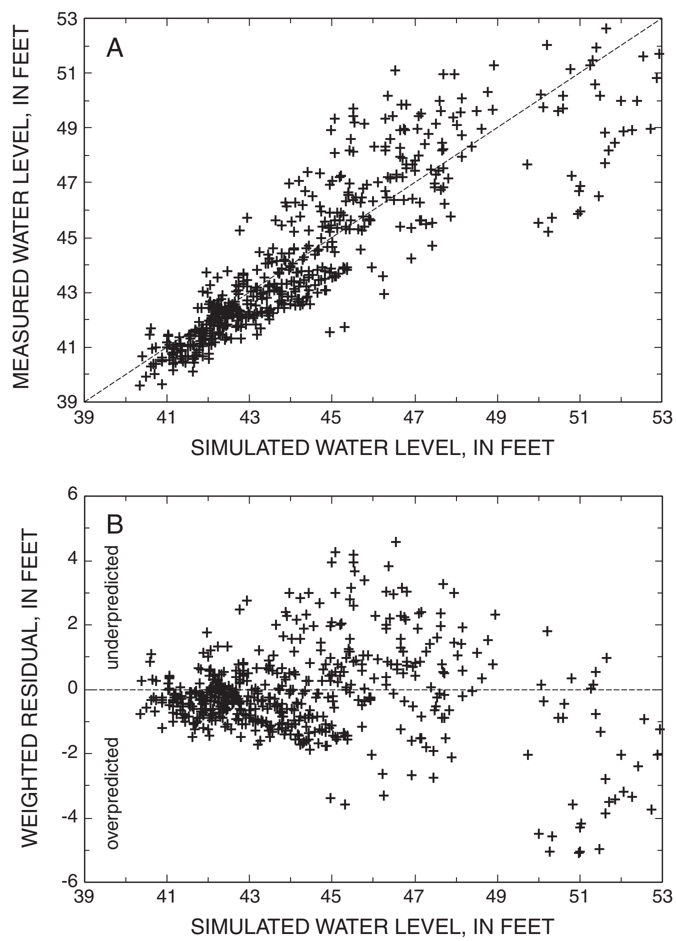


Figure 24. Measured heads, simulated heads, and residuals, computed from transient-state simulation with model HML-T, of the surficial aquifer near Halfmoon Lake, July 1996 to April 1998: (A) measured and simulated values; (B) simulated values and residuals.

Specified heads at the boundary representing the Upper Floridan aquifer largely control water levels in the surficial aquifer. Near the lake, breaches in the confining unit enhance the hydraulic connection between the aquifers, and simulated water levels for wells located in this area more closely match the measured levels. In areas distant from the lake, the simulated hydraulic connection between the aquifers through the intermediate confining layer is less permeable. The leakance value of the confining unit for these areas was adjusted in model simulations to produce water levels that matched those observed during the relatively dry conditions. The subsequent rise in water levels observed during El Niño was much less than simulated, suggesting that a large part of the rainfall was diverted through overland runoff to drainage channels before it could become recharge--this possibility was not considered in the estimation of recharge through unsaturated flow simulations with LEACHM.

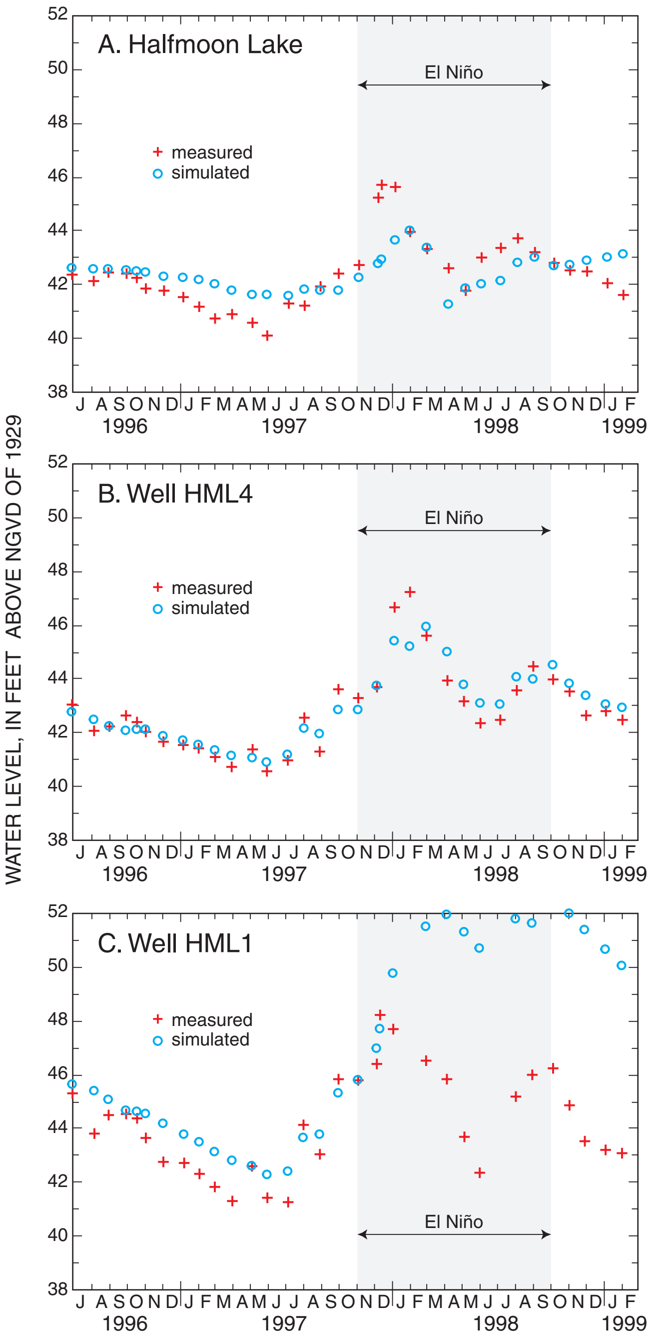


Figure 25. Water levels measured in the surficial aquifer near Halfmoon Lake and heads, computed by transient-state simulation with model HML-T, July 1996 to February 1999: (A) Halfmoon Lake; (B) well HML4; (C) well HML1. (Well locations shown on figure 19.)

Water Budget

The water budget for the entire modeled area computed by steady-state simulation (model HML-S) for average conditions in July 1996 (table 6) indicates that recharge was the principal source of inflow and that discharge to the Upper Floridan aquifer accounted for most of the outflow (88 percent). About 5 percent of the discharge flowed through breaches in the intermediate confining unit and about 11 percent flowed to Rocky Creek. The computed ground-water discharge to Rocky Creek (9,700 ft^3/d) agrees with the estimated baseflow (10,000 ft^3/d). The variability in recharge is evident in monthly basin budgets computed for the simulated period (fig. 26). Most of the recharge was temporarily stored in the surficial aquifer and then released during succeeding months, as in simulations for Round Lake.

Table 6. Simulated water budget for the Halfmoon Lake model area under average conditions, July 1996, model HML-S

[Flow rates are in thousands of cubic feet per day; <, less than]

Inflow			Discharge		
Source	Rate	Percentage of total	Location	Rate	Percentage of total
Recharge	85.4	99	Net precipitation from Halfmoon Lake	0.3	< 1
Leakage from Lake LeClare	09	1	Rocky Creek	9.7	11
			Downward leakage		
			Intermediate confining unit	72.2	83
			Breaches in confining unit	4.1	5
TOTAL	86.3	100	TOTAL	86.3	100

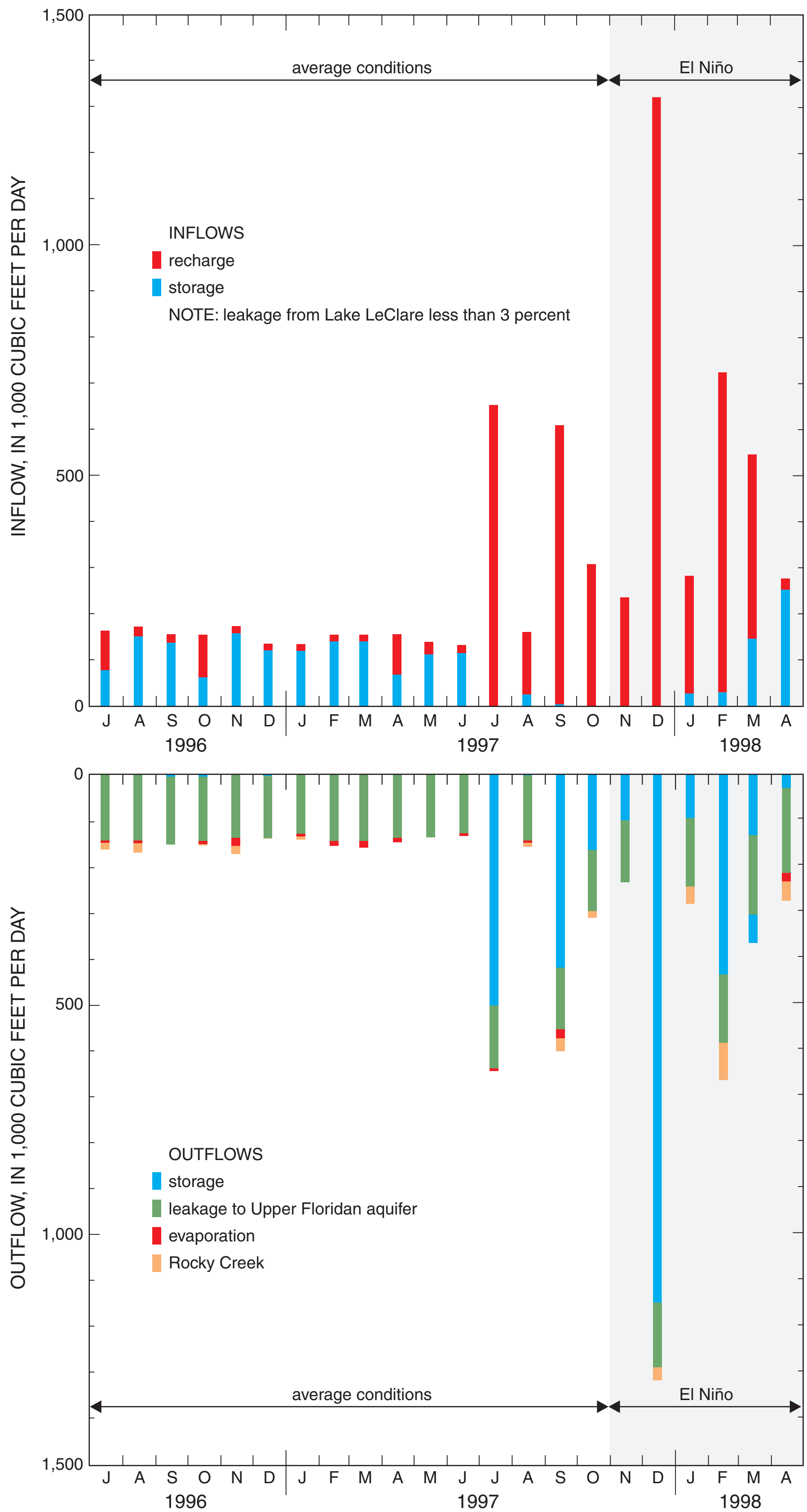


Figure 26. Simulated water budget for the Halfmoon Lake model area, July 1996 to April 1998.

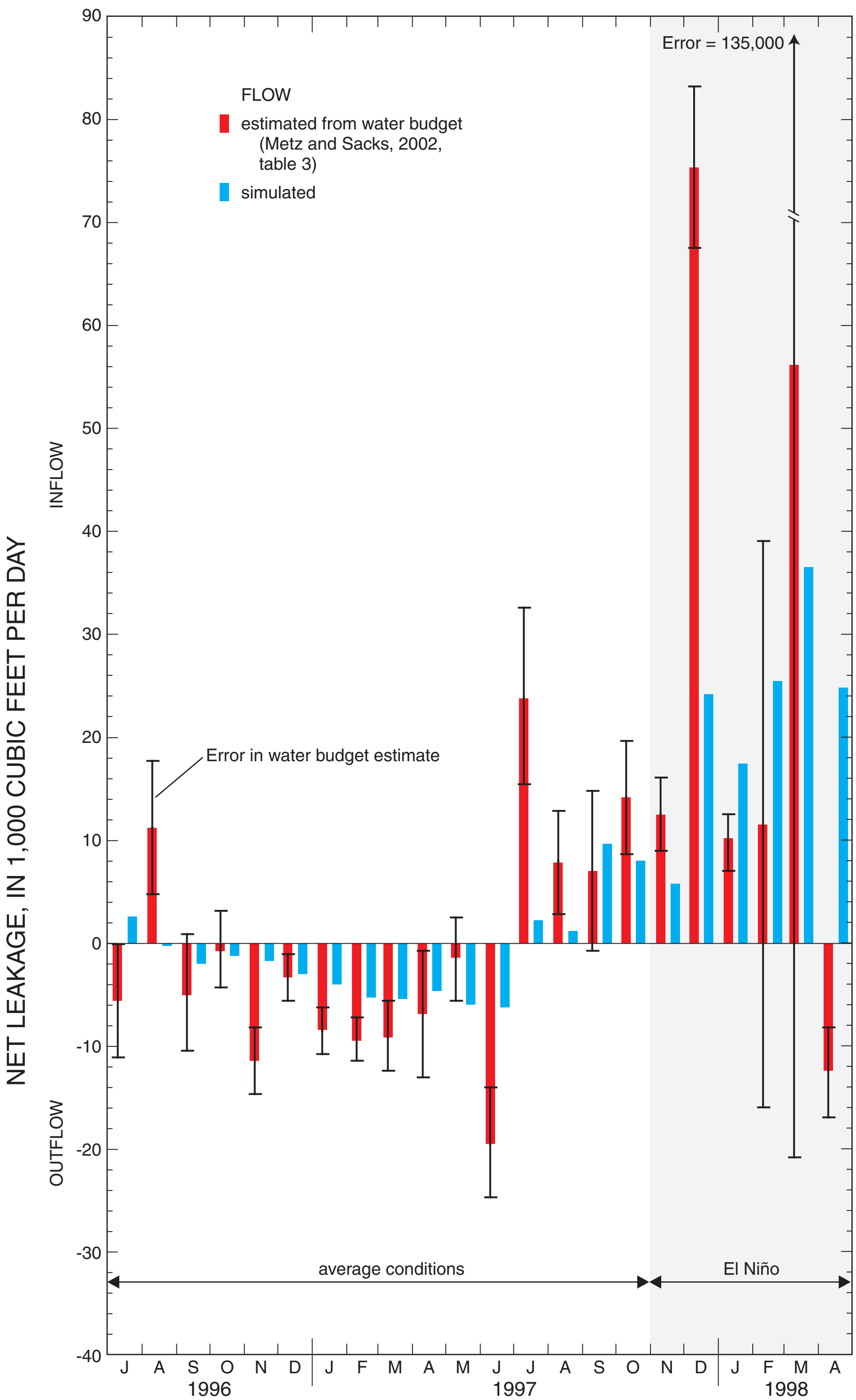


Figure 27. Simulated net leakage rates to and from Halfmoon Lake, computed from transient-state simulation with model HML-T, and estimated rates from monthly water budgets, July 1996 to April 1998.

Net ground-water flows to and from Halfmoon Lake computed by transient-state simulation with model HML-T (fig. 27) reproduce the general pattern of inflows and outflows to and from the lake as seen in the water budget. Simulated flows are underpredicted, however, particularly during El Niño when overland flow (not accounted for in the model) could have accounted for some of the inflow to the lake. Residuals display wide scatter, but no consistent pattern of bias is apparent (fig. 28), and the standard error in flow rates was 4.3 ft.

Simulated Effects of Lake Augmentation

The calibrated models developed for the Round Lake and Halfmoon Lake study areas were used in a series of subsequent simulations to delineate the extent of lake leakage into the surficial aquifer and to assess the effects of potential augmentation schedules on the maintenance of lake stages. Leakage of lake water was mapped in solute transport simulations of steady-state conditions under average recharge rates. Alternative augmentation schedules were computed from the relations between lake stages, augmentation rates, and Upper Floridan aquifer heads identified in steady-state simulations, and then applied in transient-state simulations of the study period.

Round Lake

The stage in Round Lake typically is maintained 5 ft above the sloping water-table surface by augmenting the lake with water pumped from the Upper Floridan aquifer. Downward leakage of lake water was simulated with the solute-transport model MT3D (Zheng and Wang, 1998) to delineate the extent of lake leakage in the surficial aquifer. Augmentation rates were adjusted monthly to account for seasonal variation in

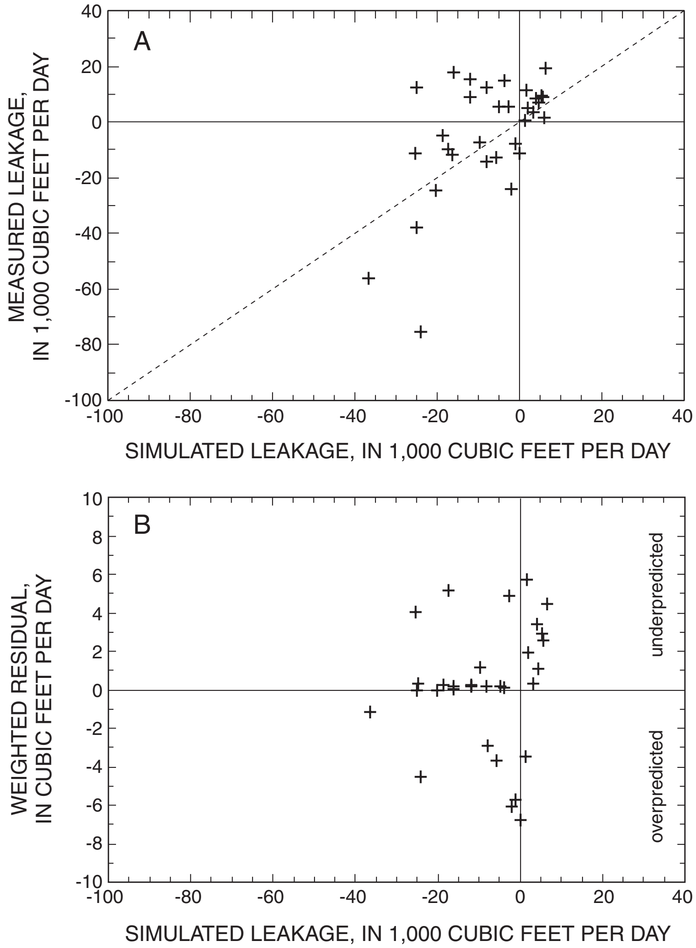


Figure 28. Simulated leakage rates and residuals, computed from transient-state simulation with model HML-T, and estimated rates from monthly water budgets, July 1996 to April 1998: (A) measured and simulated values, (B) simulated values and residuals.

recharge and changing water levels in the Upper Floridan aquifer to maintain a constant stage in Round Lake. A schedule of monthly augmentation rates, derived from the results of steady-state flow simulations, was applied in the transient-state simulation from July 1996 to February 1999 to assess the potential for using a prescribed augmentation schedule to maintain a constant lake stage.

Distribution of Lake Leakage

The solute-transport model was constructed to simulate advection and dispersion of leakage from Round Lake during 1 year under average conditions observed from July 1996 to October 1997. The model used the hydraulic-head distribution computed by a steady-state flow simulation with model RL-A (mean recharge rate of 20 in/yr). Water in Round Lake was represented by a constant concentration boundary, and water pumped from the Upper Floridan aquifer was represented by a constant flux boundary with a mean augmentation rate of 26,000 ft^3/d (135 gal/min). An arbitrary concentration of 100 mg/L was specified at both these boundaries so that simulated concentrations are equivalent to the percentage of lake water within a model cell. The numerical solution for the advective-dispersion equation was obtained using the method of characteristics (Zheng and Wang, 1998) to minimize the effects of numerical dispersion on model results.

Transport simulations considered dispersivity values of 0 and 50 ft. Leakage of lake water reached the intermediate confining unit about 150 days after the start of the simulation of advective transport in which zero dispersion was specified (fig. 29A). Most of the leakage exited from the perimeter of the lake and did not mix with water directly beneath the lake sediments until later in the simulation. The concentration distribution reached steady state after about 180 days when lake leakage extended about 250 ft from the lakeshore (fig. 29B).

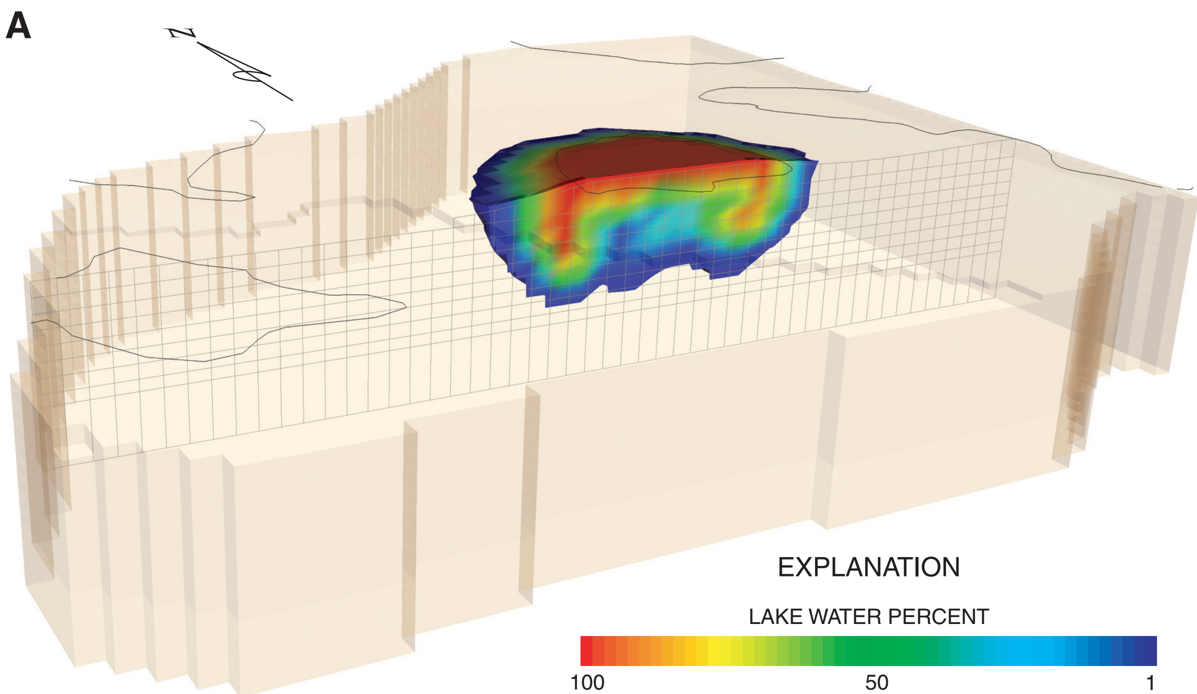


Figure 29A. Extent of lake leakage from Round Lake after 150 days (perspective view), as computed by steady-state simulation with solute-transport model with no dispersion.

Lake leakage did not reach several wells that surround the lake, a result that is in good agreement with data presented in Metz and Sacks (2002) on concentrations of stable isotopes measured in ground water from the surficial aquifer in the fall of 1997. Stable isotope concentrations of oxygen-18 ($\delta^{18}O$) and deuterium (δD) in ground water that is unaffected by lake leakage plot along the meteoric waterline (MWL), whereas $\delta^{18}O$ and δD concentrations in waters containing lake leakage plot along a mixing line extending between Round Lake water and the MWL (fig. 30). Stable-isotope concentrations of Round Lake water are enriched in $\delta^{18}O$ as a result of evaporation and plot below the MWL (Metz and Sacks, 2002). Three of the five wells where lake water was not detected (RL8, RL11, and RL12) are located beyond the extent of lake leakage, as delineated by the transport simulation (fig. 29B). The transport simulation indicates that one of the other wells, RL9 located about 100 ft west of the lake, contains more lake water (30 percent) than indicated by the stable-isotope concentrations (10 percent). Water sampled from the remaining well, RL3 located less than 100 ft from the lake, plots along the MWL and probably reflects recent recharge from precipitation.

Specifying longitudinal and transverse dispersivity values of 50 ft increased the extent of lake leakage and decreased the travel time to the intermediate confining unit. Lake water breached the intermediate confining unit within about 30 days, and a steady-state concentration distribution was reached after about 100 days when lake water extended about 400 ft from the lakeshore. Results of the transport simulation with dispersion also were consistent with the stable-isotope analyses, but lake water nearly reached wells RL8, RL11, and RL12, indicating that larger values of dispersivity would simulate lake leakage beyond areas where isotopic data indicated lake leakage.

Inspection of the distribution of lake leakage in steady-state simulations of average conditions using ZONEBUDGET indicated that 31 percent of the total leakage (26,000 ft^3/d) flowed horizontally through the shallow perimeter of the lake in model layer 1, whereas the remainder flowed vertically through the lake bottom represented by deeper model layers. A similar analysis of the transient simulation results with model RL-A indicates that a nearly equal percentage (29 percent) of the total leakage (29,700 ft^3/d) flowed through the lake perimeter in June 1997. Only 2 percent of the total leakage (6,000 ft^3/d) flowed through the lake perimeter in March 1998, however, when the lateral gradients within 500 ft of the lake ($1.1x10^{-3}$, fig. 13A) were much smaller than in June 1997 ($1.3x10^{-2}$, fig. 12A).

Potential Augmentation Schedules

Relations between Round Lake stage, heads in the Upper Floridan aquifer, and augmentation rates were defined for average conditions (July 1996 to October 1997) using a series of steady-state simulations with ground-water-flow model RL-A (mean recharge rate of 20 in/yr). The simulations considered the range in Upper Floridan aquifer heads measured during the

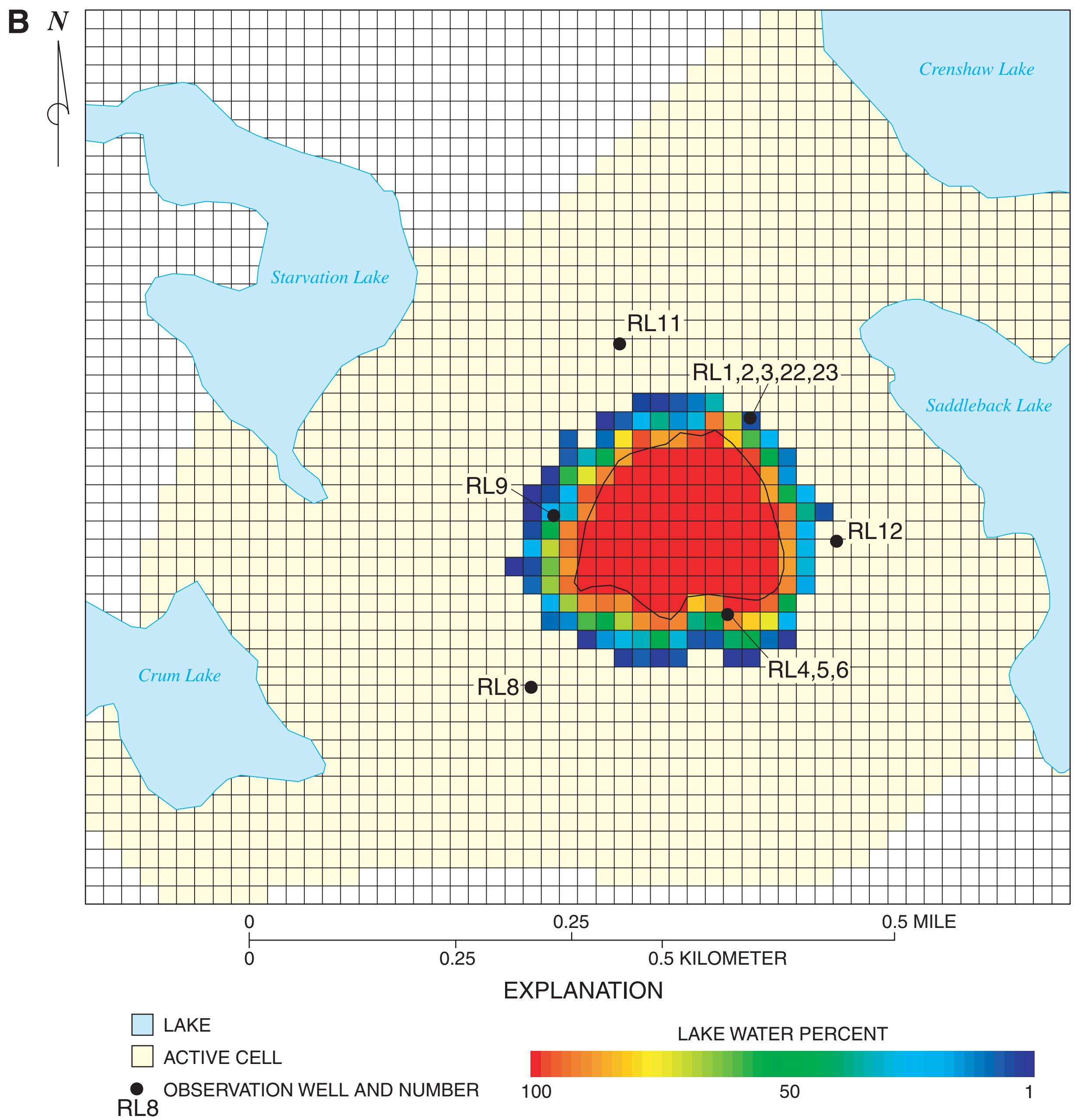


Figure 29B. Extent of lake leakage from Round Lake after 150 days (plan view), as computed by steady-state simulation with solute-transport model with no dispersion.

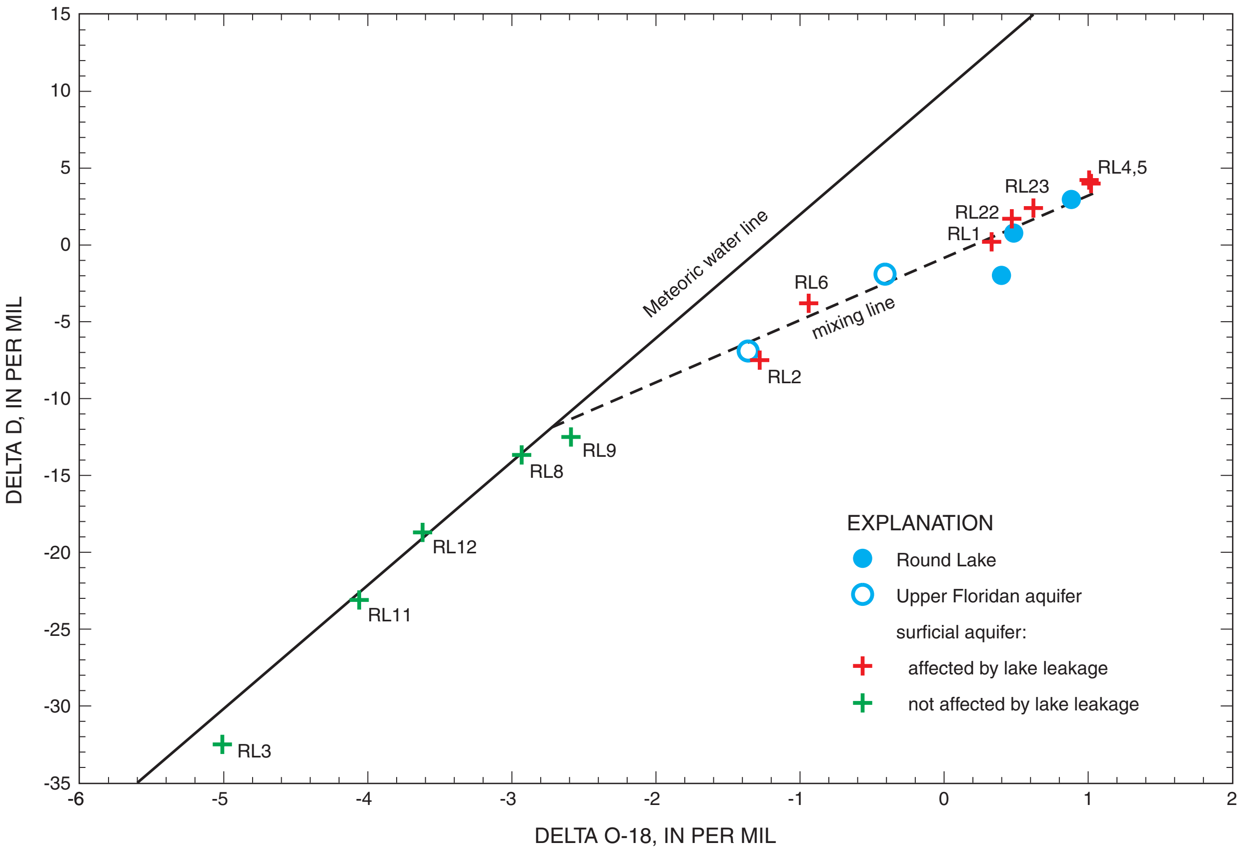


Figure 30. Relation between stable isotopes of oxygen-18 and deuterium in Round Lake and ground water sampled from wells screened in the surficial aquifer and the Upper Floridan aquifer.

study (34-44 ft) and augmentation rates that ranged from 0 to 50,000 ft^3/d (260 gal/min). The simulated Round Lake stage is proportional to both the Upper Floridan aquifer head and the augmentation rate, suggesting that under constant recharge conditions, the lake stage can be maintained by adjusting the augmentation rate to account for changing water levels in the Upper Floridan aquifer. For example, a lake stage of 52 ft can be attained with an Upper Floridan aquifer head of 38 ft by an augmentation rate of 30,000 ft^3/d (160 gal/min) under average recharge conditions (fig. 31). The augmentation rate (Q) required to maintain a specified lake stage can be computed from the following equation:

$$Q = b + m\Delta h , \qquad (7)$$

where

- b is the ordinate intercept on figure 31 that corresponds to the target lake stage, in cubic feet per day;
- m is -2,250 ft^3/d per foot, the average slope of the relations shown in fig. 31; and
- Δh is the height of the Upper Floridan head above the minimum level measured during the study (34 ft).

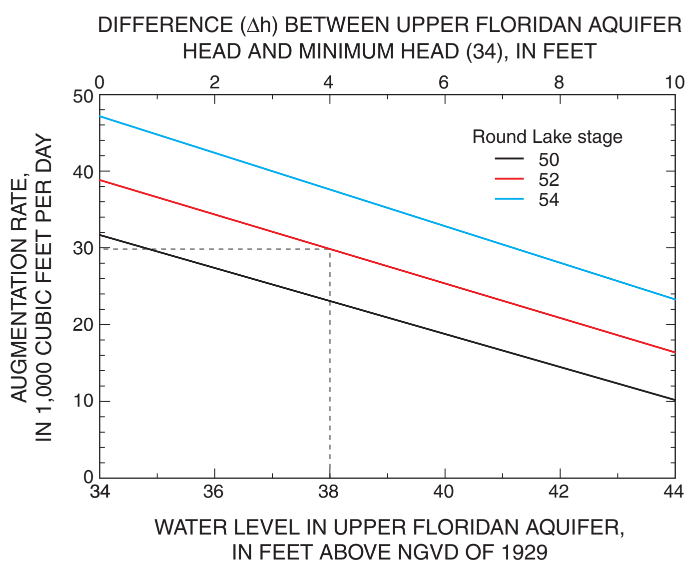


Figure 31. Relations between Round Lake stage, heads in the Upper Floridan aquifer, and augmentation rate, as computed by steady-state simulation with model RL-A (high recharge).

Monthly augmentation rates were computed using the following equation to maintain a constant lake stage of 52 ft during transient-state simulation during July 1996 to February 1999:

$$Q_i = b + m[\Delta h_i + (1 - R_{i-1} / R_a)] \quad , \qquad (8)$$

where

- Q_i is the augmentation rate in month *i,* in cubic feet per day;
- b is 38,850 ft^3/d;
- Δh_i is the height of the Upper Floridan head above 34 ft in the current month, in feet;
- R_{i-1} is the monthly recharge rate in the previous month, in feet per day; and
- R_a is the average monthly recharge rate, 0.00458 ft/d (20 in/yr).

The first term in square brackets in equation 8 adjusts the augmentation rate for the Upper Floridan aquifer head. The second term is an empirical expression that accounts for deviation in monthly recharge from the mean recharge rate used to derive the relations shown in fig. 31. The augmentation rates required to attain other desired lake stages can be computed by substituting in equation 8 the appropriate values for *b* derived from inspection of fig. 31. The *m*-values associated with different lake stages vary slightly, but are nearly constant throughout the range of Upper Floridan aquifer heads considered.

Transient-state simulations conducted with model RL-A using augmentation rates Q_i computed with equation 8, produced stages ranging between 52 and 53 ft in Round Lake during average conditions (July 1996 to October 1997), but yielded stages that were greater than 54 ft after the start of El Niño in November 1997, when the recharge rate more than doubled to 50 in/yr (fig. 32). An additional transient-state simulation was run in which Q_i values for November 1997 to February 1998 were computed using *m* and *b* values derived from steady-state simulations of El Niño conditions (mean recharge rate of 50 in/yr). In this simulation, Round Lake stage only exceeded 54 ft when recharge was highest in February and March 1998 (fig. 32). The simulated volume of water pumped from the Upper Floridan aquifer (564,000 ft^3) nearly equaled the actual pumped volume (554,000 ft^3). A third simulation, in which no augmentation was applied to Round Lake during the entire study, predicted that lake stage would have fallen below 45 ft during 1997, but would have recovered to nearly 50 ft during El Niño.

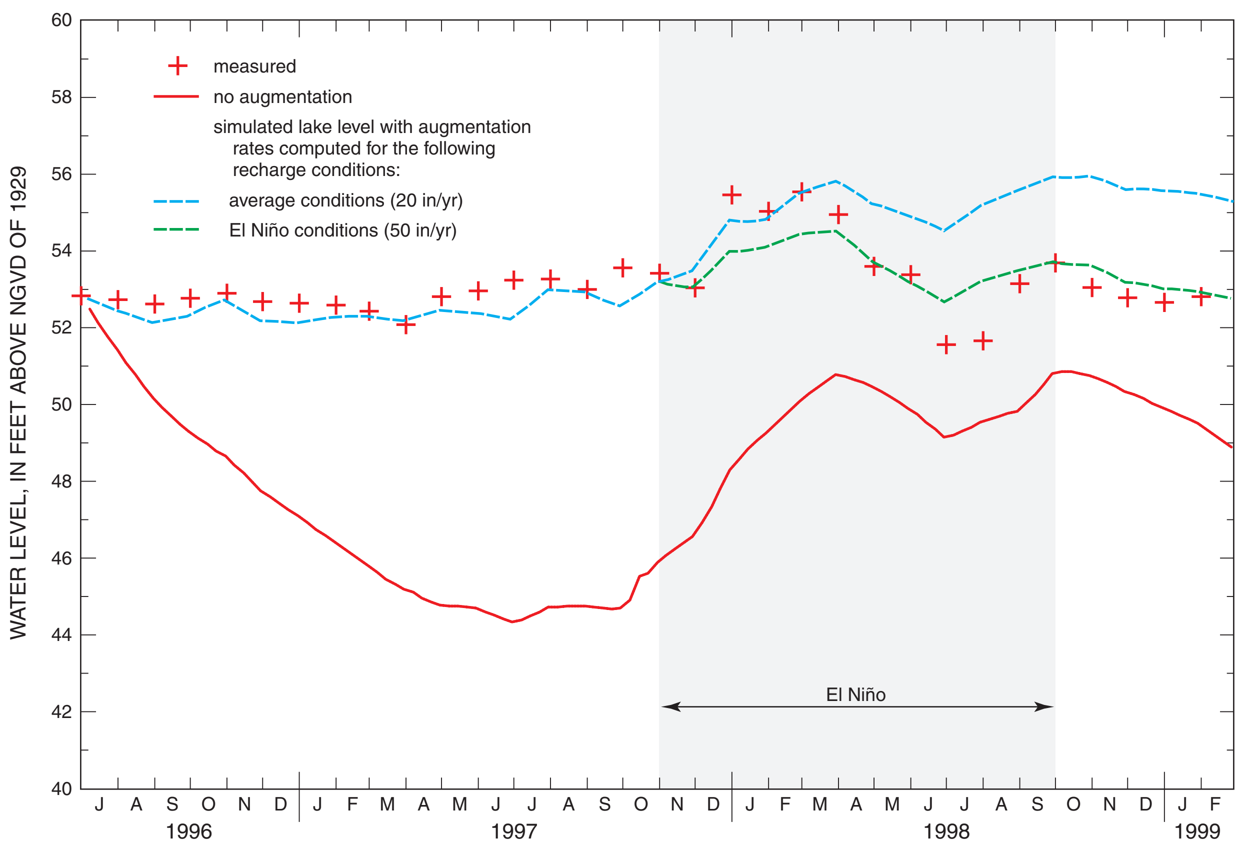


Figure 32. Water levels measured in Round Lake, July 1996 to February 1999, and water levels computed by transient-state simulation by model RL-A (high recharge) with prescribed augmentation schedule derived for recharge under average and El Niño conditions (20 and 50 inches per year, respectively).

These results indicate that a transient pumping schedule could be implemented to maintain the lake stage within about 1 ft of a predetermined elevation. The selection of the 52-ft stage in the simulation was arbitrary and slightly below the Round Lake guidance stage (53.26 ft) recommended by the SWFWMD (Michael Hancock, oral commun., 2002). The augmentation rate could be computed from the relations depicted in fig. 31 and monthly measurements of head in the Upper Floridan aquifer. Monthly augmentation rates computed using equation 8 would require estimates of monthly recharge. These recharge estimates could be computed from measurements of daily precipitation using the unsaturated flow model LEACHM, but might be difficult on a real-time basis. Simulation of El Niño conditions indicates that substantial changes in climatic conditions that cause increased precipitation would also have to be accounted for in the computation of augmentation rates.

An attempt was made to simulate a fluctuating stage in Round Lake to mimic natural conditions by varying the augmentation rates on a seasonal basis, but the transient simulation was unable to reproduce the desired pattern of smoothly raising and lowering the lake stage over the 2.5-ft range specified by the SWFWMD. The model-derived dependence of lake stage on Upper Floridan head is affected by recharge, as noted previously, and the method used to compute augmentation rates accounts for changes in recharge in an empirical manner. The method does reasonably well in computing rates to maintain a constant lake stage, but is not accurate enough to reproduce more complicated patterns, such as seasonal fluctuations.

Halfmoon Lake

Steady-state simulations of average conditions in July 1996 also were used to delineate the extent of lake leakage in the surficial aquifer around Halfmoon Lake, and to devise a schedule of monthly augmentation rates to maintain lake stage at a constant prescribed level. Leakage of lake water was simulated with the solute-transport model MT3D (Zheng and Wang, 1998) as in the Round Lake model. Monthly augmentation rates, adjusted to correct for seasonal variation in recharge and changing water levels in the Upper Floridan aquifer, were applied in transient-state simulations during July 1996 to February 1999.

Distribution of Lake Leakage

The solute-transport model simulated advection and dispersion of leakage from Halfmoon Lake for 2 years under average conditions using the hydraulic-head distribution computed for July 1996 by a steady-state flow simulation with model HML-S. Water in Halfmoon Lake was represented by an arbitrary constant concentration of 100 mg/L, as in the Round Lake model, so that simulated concentrations were equivalent to the percentage of lake water within a model cell.

Transport simulations considered dispersivity values ranging from 0 to 50 ft. Leakage of lake water breached the intermediate confining unit about 400 days after the start of the simulation in which zero dispersion was specified (fig. 33A,B). The concentration distribution reached steady state after about

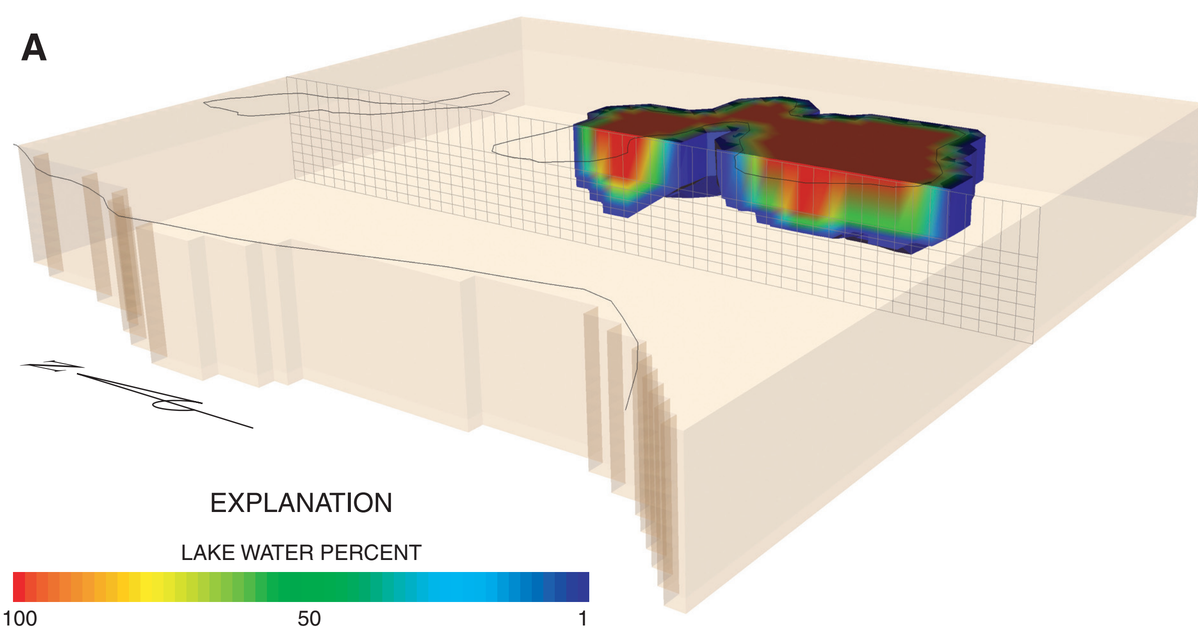


Figure 33A. Extent of lake leakage after 400 days from Halfmoon Lake (perspective view), as computed by steady-state simulation with solute-transport model with no dispersion.

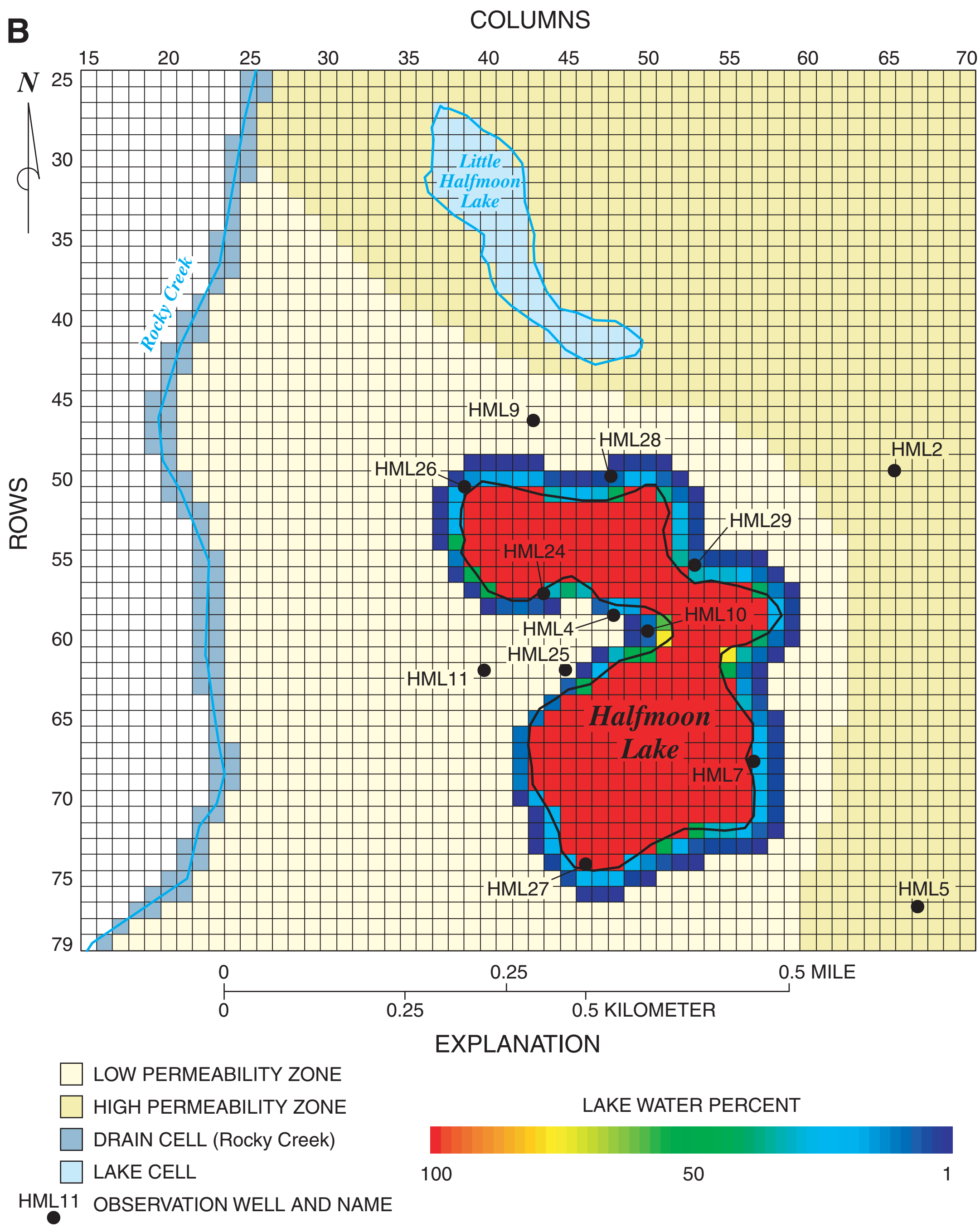


Figure 33B. Extent of lake leakage after 400 days from Halfmoon Lake (plan view), as computed by steady-state simulation with solute-transport model with no dispersion.

2 years when lake leakage extended about 75 ft from the lakeshore (fig. 33B). Specifying longitudinal and transverse dispersivity values of 50 ft increased the extent of lake leakage and decreased the travel time to the intermediate confining unit. Lake water breached the intermediate confining unit within about 40 days, and a steady-state concentration distribution was reached after about 300 days, when lake water extended less than 150 ft from the lakeshore.

Results of the transport simulations generally were consistent with the stable isotope analyses of $\delta^{18}O$ and δD in ground water near Halfmoon Lake. Metz and Sacks (2002) reported no evidence of lake leakage in stable-isotope concentrations in water sampled from wells along the lakeshore, suggesting that most of the lake leakage flows downward through the lake bottom. Solute transport simulations also indicate limited lateral movement of lake leakage, with less than 20 percent lake water computed for model cells adjacent to Halfmoon Lake. The predicted lateral movement of lake leakage is partially an artifact of the model design, because lake sediments are only represented beneath the lake in the flow model. The relatively coarse vertical discretization (5 ft) does not allow accurate representation of the sloping bottom near the perimeter of the lake.

Specifying additional model layers to better represent the lake bathymetry caused solver convergence problems, as a substantial part of the modeled area was dewatered during transient simulation. As a result, computed flow paths exit horizontally from the lake, rather than downward as expected under actual conditions.

Inspection of the distribution of ground-water exchange with Halfmoon Lake in the steady-state simulation using ZONEBUDGET indicated slightly more inflow to the lake (3,120 ft^3/d) than outflow (2,920 ft^3/d), because evaporation from the lake surface makes the lake a sink (discharge area) under average conditions. Nearly all the ground water discharging to the lake (96 percent) flowed though the shallow lake perimeter in model layer 1; the remainder flowed through deeper model layers representing the lake bottom. About 17 percent of the leakage from the lake flowed though the lake perimeter, while the remainder flowed through the lake bottom.

Potential Augmentation Schedule

Relations between Halfmoon Lake stage, heads in the Upper Floridan aquifer, and augmentation rates were defined for average conditions in July 1996 using steady-state simulations of ground-water flow with model HML-S and a recharge rate of 13 in/yr. The simulations considered the range in Upper Floridan aquifer heads measured during the study (24-34 ft) and augmentation rates that ranged from 0 to 15,000 ft^3/d (80 gal/min). The simulated Halfmoon Lake stage is proportional to both the Upper Floridan aquifer head and the augmentation rate, as in Round Lake, suggesting that under constant recharge conditions, fluctuations in lake stage can be minimized by adjusting the augmentation rate to correct for changing water levels in the Upper Floridan aquifer (fig. 34). An alternate set of steady-state simulations were conducted using aquifer properties estimated with the transient model HML-T. The augmentation rates required to maintain a specified lake stage under these conditions are greater than predicted with model HML-S (fig. 34), because the conductance of the intermediate confining unit is higher in these simulations.

Two sets of monthly augmentation rates were computed using equation 8 and the relations shown in figure 34 to maintain the Halfmoon Lake guidance stage of 43 ft (Michael Hancock, oral commun., 2002) during transient-state simulations from July 1996 to February 1999. Both sets of augmentation rates produced relatively constant lake stages during average conditions (July 1996 to October 1997), but lake stages diverged from the target level during El Niño when recharge rates increased dramatically (fig. 35), as in the Round Lake simulations. Predicted lake stages of both sets of augmentation rates were within 1 ft of the target stage, but slightly lower for the set computed with aquifer properties estimated by model HML-S (steady-state simulation), and slightly higher with properties estimated with model HML-T (transient-state simulation). Simulated volumes of water pumped from the Upper Floridan aquifer for 16-months (July 1996 to October 1997) were 37,000 ft^3 and 180,000 ft^3 for rates computed with model HML-S and HML-T, respectively. Additional water-level data documenting the response of lake stage and ground-water levels to lake augmentation are required to improve the estimates of the volume of water needed to maintain Halfmoon Lake stage for the observed range in Upper Floridan aquifer heads. Additional simulations of Halfmoon Lake during El Niño and La Niña were unwarranted due to the inability of the models to accurately reproduce water levels during these periods.

Comparison of Lake Leakage

Results of steady-state model simulations indicate substantially more lake leakage flows to the Upper Floridan aquifer from Round Lake than from Halfmoon Lake. The estimated vertical hydraulic conductivities (K_v) of lake and intermediate confining unit sediments and breaches in the confining unit are much larger for the Round Lake area than for the Halfmoon Lake area, resulting in larger leakage rates. The estimated K_v of lake sediments in Round Lake (0.2 ft/d) is about 70 times greater than the values estimated for Halfmoon Lake ($3x10^{-3}$ ft/d). Similarly, K_v values estimated for the confining unit and breaches in the unit are about 10 times greater at Round Lake ($6x10^{-3}$ and 0.2 ft/d, respectively) than Halfmoon Lake ($6x10^{-4}$ and 0.02 ft/d, respectively). The relative permeability of breaches in the confining unit is about 30 times greater than the K_v value of the rest of the confining unit in both models, although the ratio was estimated to be 10 times smaller by regression with transient-state simulations of Halfmoon Lake.

Steady-state simulations of average conditions in June 1997 indicate that about 30 percent of the 26,000 ft^3/d of the water pumped into Round Lake leaks through the shallow lake perimeter as a result of the steep lateral hydraulic gradients ($1.3x10^{-2}$) surrounding the lake. Under similar conditions at non-augmented Halfmoon Lake, only 17 percent of the total lake leakage of 2,920 ft^3/d flows through the lake perimeter, as lateral gradients surrounding the lake ($5.6x10^{-4}$) are much lower than those near Round Lake. Nearly all (96 percent) of the ground water entering Halfmoon Lake (3,120 ft^3/d), however, flows through the shallow lake perimeter.

As a result of the higher lateral and vertical leakage losses from Round Lake, much higher augmentation rates are required to maintain a given lake stage. For example, steady-state simulations for July 1996 indicate that an augmentation rate of 33,850 ft^3/d is required to maintain a stage of 53 ft in Round Lake (near the low guidance limit) at an Upper Floridan aquifer head of 38 ft. A comparable stage near the low guidance level of 41.4 ft in Halfmoon Lake requires a rate of 1,330 to 10,000 ft^3/d under an Upper Floridan aquifer head of 28 ft. These augmentation rates are equivalent to about 26 in/mo of water applied to the entire surface of Round Lake, as opposed to 0.34 to 2.5 in/mo applied to Halfmoon Lake.

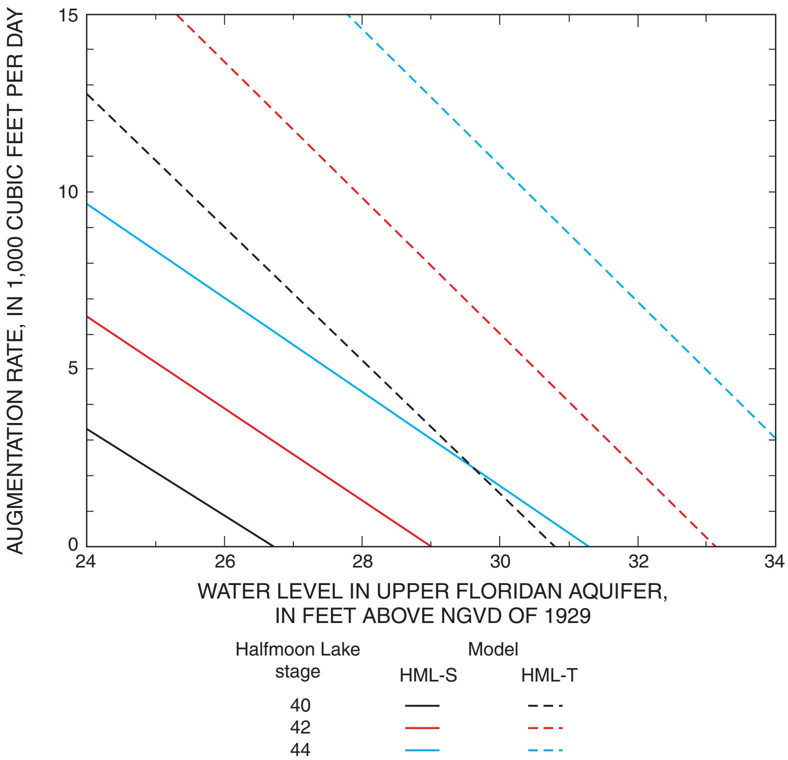


Figure 34. Relations between Halfmoon Lake stage, heads in the Upper Floridan aquifer, and augmentation rate, as computed by steady-state and transient-state simulation with models HML-S and HML-T, respectively.

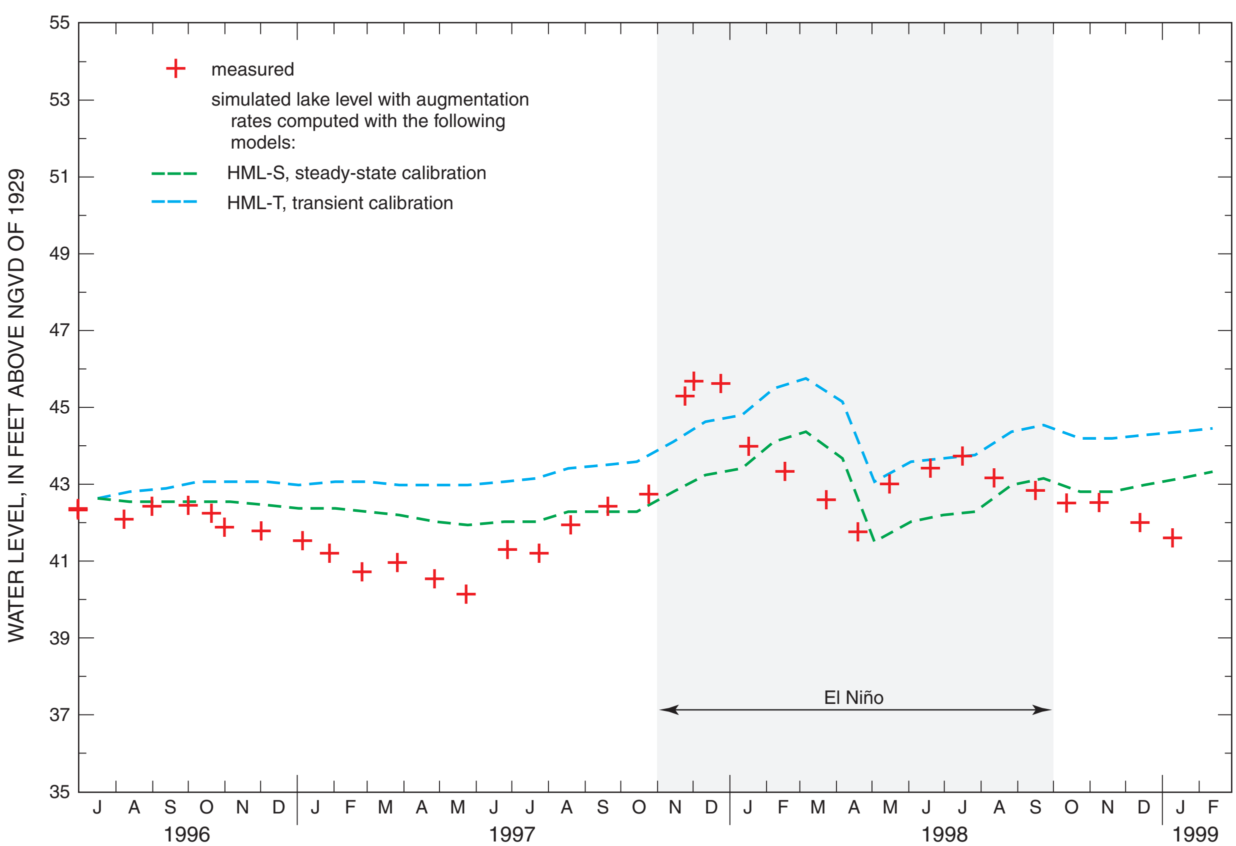


Figure 35. Water levels measured in Halfmoon Lake, July 1996 to February 1999, and water levels computed by transient-state simulations using augmentation rates computed with aquifer properties estimated by models HML-S and HML-T, with prescribed augmentation schedule derived for recharge under average conditions (13 inches per year).

Summary

Pumping from the Upper Floridan aquifer has lowered water levels and induced downward leakage from the overlying surficial aquifer, lowering the water table and lake levels in some parts of northwestern Hillsborough County. A detailed description of the hydrogeology and water quality of three lake basins in northwest Hillsborough County was provided in a previous study wherein lake-water budgets were used to estimate net ground-water flow to the lakes (Metz and Sacks, 2002). Based on the results of the previous study, numerical simulations were prepared to quantify hydraulic parameters that control the flow system, and to estimate the lake augmentation rates required to maintain lake levels during periods of below-average precipitation.

Ground-water-flow models were developed with MODFLOW for the Round Lake and Halfmoon Lake study areas to represent flow conditions during the 32 months from July 1996 to February 1999. Monthly estimates of ground-water recharge in the study areas were computed by an unsaturated flow model (LEACHM) that represented daily changes in storage of water in the soil profile and drainage to the water table. The ground-water-flow models were calibrated through nonlinear regression with UCODE to measured water levels, and monthly net ground-water-flow rates from the lakes were estimated from lake-water budgets. The calibrated models were used in a series of subsequent simulations to delineate the extent of lake leakage into the surficial aquifer and to assess the effects of potential augmentation schedules on maintaining lake stages.

Recharge through the soil profile was computed as daily drainage with the LEACHM model using specified rates of precipitation and potential evaporation. Three cases with different combinations of vegetation and soil texture were considered in unsaturated zone simulations: shallow-rooted (grass) and deep-rooted (saw palmetto) vegetation with a coarse-textured soil, and shallow-rooted vegetation with a fine-textured soil.

Computed actual evapotranspiration (AET) rates for the coarse-textured soil under average conditions (April 1996 to October 1997) were 36 and 43 in/yr for shallow-rooted and deep-rooted vegetation, respectively, and compared favorably with the rate of 40 in/yr, which was estimated previously for dry prairie vegetation in Sarasota County using an energy-budget method. Computed AET rates for El Niño (November 1997 to September 1998) were less (31-36 in /yr), because there were more rainy days during the period. Computed recharge rates for average conditions at Round Lake were 20 in/yr for shallow-rooted vegetation and 13 in/yr for deep-rooted vegetation, and compare favorably with the rate of 15 in/yr that was estimated from the comparison of chloride concentrations in ground water and atmospheric deposition. Computed recharge rates during El Niño were greater (52 and 47 in/yr, respectively), and amounted to about 60 percent of the precipitation.

The Round Lake model was calibrated through transient-state simulations to estimate aquifer properties with two sets of monthly recharge rates computed by LEACHM. The coefficients of variation for the estimated values ranged from 0.5 to 7 percent, indicating that the values were accurately estimated. Hydrographs of simulated water levels indicate that the Round Lake model closely reproduced measured water-level fluctuations in response to changes in recharge and pumpage during the 32-month simulation period; the standard error in heads was 1.1 ft. Computed water budgets for the entire model area reflected the dramatic increase in recharge from average conditions, when recharge totaled about 1.5 in/mo, to El Niño conditions, when recharge more than doubled to 3.3 in/mo. Most of the recharge was temporarily stored and then released during succeeding months. Leakage to the Upper Floridan aquifer accounted for most of the outflow from the model during average and El Niño periods (78 and 70 percent, respectively), with a relatively small proportion of this leakage passing through breaches in the intermediate confining unit (8 and 6 percent, respectively).

The Halfmoon Lake model was calibrated through steady-state simulations to produce a model that approximated water levels measured in July 1996. Transient-state simulations were unable to accurately reproduce water levels measured during El Niño, so a shorter (22-month) simulation period representing water levels and lake leakage rates from July 1996 to April 1998 was used to estimate an alternate set of parameter values. Coefficients of variation for five of the estimated parameter values ranged from 0.5 to 20 percent, indicating that the optimum values are not as accurately estimated as were parameters for the Round Lake model.

Hydraulic heads for the Halfmoon Lake model, which were computed with the steady-state simulations, match water levels measured in July 1996 quite well, and the standard error in heads was 0.6 ft. The computed steady-state water budget for the entire model area indicates that discharge to the Upper Floridan aquifer accounted for most of the ground-water outflow (88 percent, including about 5 percent to breaches in the intermediate confining unit), and nearly all of the remaining ground water discharged to Rocky Creek. Hydraulic heads computed with transient-state simulations generally reproduced measured water-level fluctuations during July 1996 to October 1997, but did not accurately reproduce the abrupt rise in water levels during El Niño. The discrepancy between measured and simulated hydrographs results from an unknown source of model error. Simulated water levels for Halfmoon Lake and wells near the lake match the measured levels reasonably well, but simulated water levels for wells more than 400 ft north and east of the lake are overpredicted by as much as 10 ft during El Niño. The poor match during El Niño suggests that a large part of the rainfall was diverted, possibly through overland runoff, before it could become recharge. Runoff was assumed to be negligible in the LEACHM estimates of recharge.

Solute transport simulations with MT3D were used to delineate the extent of lake leakage from Round and Halfmoon Lakes into the surficial aquifer under steady-state conditions with average recharge rates. Leakage of water from Round Lake breached the intermediate confining unit in about 130 days when zero dispersion was specified, and the concentration distribution reached steady-state after about 150 days when lake leakage extended about 250 ft from the lakeshore. Specifying longitudinal and transverse dispersivity values of 50 ft increased the extent of lake leakage (400 ft) and decreased the travel time to the intermediate confining unit (30 days). Results using zero dispersivity values of 50 ft were both in good agreement with concentrations of stable isotopes of oxygen-18 ($\delta^{18}O$) and deuterium (δD) that were measured in water from the surficial aquifer.

Leakage of water from Halfmoon Lake breached the intermediate confining unit in about 400 days with zero dispersion and a steady-state concentration distribution was reached after about 2 years when lake leakage extended about 75 ft from the lakeshore. Increasing the longitudinal and transverse dispersivity values to 50 ft increased the extent of lake leakage to 150 ft and decreased the travel time to the intermediate confining unit from 400 to 40 days. These results are generally consistent with the stable-isotope concentrations in ground water near Halfmoon Lake, which suggest that most of the lake leakage flows downward through the lake bottom.

Results of steady-state simulations indicate that lake stage is proportional to both the Upper Floridan aquifer head and the augmentation rate at Round Lake, indicating that fluctuations in lake stage can be minimized by adjusting the augmentation rate to account for changing water levels in the Upper Floridan aquifer under constant recharge conditions. Monthly augmentation rates were computed using an equation that accounted for changes in the Upper Floridan aquifer head and the deviation from the mean recharge rate on a monthly basis to maintain a constant lake stage.

In transient-state simulations of Round Lake, computed augmentation rates produced stages that were close to the target lake stage of 52 ft during average conditions (July 1996 to October 1997), but yielded stages that were greater than 54 ft after the start of El Niño in November 1997. When the equation was modified to account for the higher recharge rate during El Niño, the stage only exceeded 54 ft when recharge was highest in February and March 1998. Two sets of monthly augmentation rates were computed for Halfmoon Lake using parameter estimates obtained with both steady- and transient-state simulations. Both sets of augmentation rates produced a relatively constant lake stage near 43 ft during average conditions (July 1996 to October 1997), but the computed stage diverged from the target lake stage during El Niño, as in the Round Lake simulations.

Model simulations indicate that substantially more lake leakage flows to the Upper Floridan aquifer from Round Lake than from Halfmoon Lake, because the estimated vertical hydraulic conductivities (K_v) of Round Lake and the confining layer sediments and breaches in the confining layer are much larger. The estimated K_v of lake sediments in Round Lake is about 70 times greater than the value estimated for Halfmoon Lake, and the K_v values estimated for the confining layer and breaches in the layer are 10 times higher. Steady-state simulations indicate that about 30 percent of the leakage at Round Lake flows through the shallow lake perimeter, whereas only 17 percent of the leakage at Halfmoon Lake flows through the lake perimeter. This is because the lateral hydraulic gradients are steeper at Round Lake (1.3×10^{-2}) than at Halfmoon Lake (5.6×10^{-4}).

As a result of the higher lateral and vertical leakage losses from Round Lake, the augmentation rate required to maintain the low guidance level in Round Lake (53 ft) under average Upper Floridan aquifer heads (38 ft) is estimated as 33,850 ft^3/d, whereas only 1,330 to 10,000 ft^3/d is required to maintain a comparable level in Halfmoon Lake (42 ft) under similar conditions (Upper Floridan aquifer head of 28 ft). These augmentation rates are the equivalent of 26 in/mo of water applied to the entire surface of Round Lake, as opposed to 0.34 to 2.5 in/mo applied to Halfmoon Lake.

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