Estimating Ground-Water Exchange with Lakes Using Water-Budget and Chemical Mass-Balance Approaches for Ten Lakes in Ridge Areas of Polk and Highlands Counties, Florida

By Laura A. Sacks, Amy Swancar, and Terrie M. Lee

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Conversion Factors, Vertical Datum, Acronyms, and Additional Abbreviations

Multiply	By	To obtain
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
acre	4,047	square meter
acre	0.4047	hectare
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
inch per month (in/mo)	2.54	centimeter per month
inch per year (in/yr)	2.54	centimeter per year

Temperature in degrees Celsius (ºC) can be converted to degrees Fahrenheit (ºF) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (ºF) can be converted to degrees Celsius (ºC) as follows:

$$°C = (°F - 32) / 1.8$$

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

Acronyms and Additional Abbreviations used in Report:

Cl	chloride
G_{net}	net ground-water flow
mg/L	milligrams per liter
mL	milliliter
N	nitrogen
Na	sodium
NWS	National Weather Service
P	phosphorus
r^2	coefficient of determination
S_o	surface-water outflow
SWFWMD	Southwest Florida Water Management District
USGS	U.S. Geological Survey
δ	delta
$\delta^{18}O$	delta oxygen-18
δ_a	isotopic composition of atmospheric moisture
δD	delta deuterium
δ_E	isotopic composition of evaporating water
µS/cm	microsiemens per centimeter

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Abstract

Water budget and chemical mass-balance approaches were used to estimate ground-water exchange with 10 lakes in ridge areas of Polk and Highlands Counties, Florida. At each lake, heads were monitored in the surficial aquifer system and deeper Upper Floridan aquifer, lake stage and rainfall were measured continuously, and lakes and wells were sampled three times between October 1995 and December 1996.

The water-budget approach computes net ground-water flow (ground-water inflow minus outflow) as the residual of the monthly water-budget equation. Net ground-water flow varied seasonally at each of the 10 lakes, and was notably different between lakes, illustrating short-term differences in ground-water fluxes. Monthly patterns in net ground-water flow were related to monthly patterns of other hydrologic variables such as rainfall, ground-water flow patterns, and head differences between the lake and the Upper Floridan aquifer.

The chemical mass-balance approach combines the water budget and solute or isotope mass-balance equations, and assumes steady-state conditions. Naturally occurring tracers that were analyzed for include calcium, magnesium, sodium, potassium, chloride, and bromide, the isotopes deuterium and oxygen-18. Chloride and sodium were the most successful solute tracers; however, their concentrations in ground water typically varied spatially, and in places were similar to that in lake water, limiting their sensitivity as tracers. In contrast, the isotopes were more robust tracers because the isotopic composition of ground water was relatively uniform and was distinctly different from the lake water. Ground-water inflow computed using the chemical mass-balance method varied significantly between lakes, and ranged from less than 10 to more than 150 inches per year. Both water-budget and chemical mass-balance approaches had limitations, but the multiple lines of evidence gained using both approaches improved the understanding of the role of ground water in the water budget of the lakes.

INTRODUCTION

Characterizing the exchange of ground water with lakes is an important prerequisite to managing water levels and water quality in Florida lakes. Numerous lake basins are within the sand hills and ridges of Florida’s Central Lakes District (Brooks, 1981). Rainfall quickly percolates through the permeable sands to the water table, favoring ground-water flow over surface-water drainage. As a result, about 70 percent of Florida’s 7,800 lakes are seepage lakes, having no natural surface flow into or out of them (Palmer, 1984). In the absence of direct pumping and engineered stormwater drainage, the stage of seepage lakes is affected by the local climate (rainfall and evaporation) and by the exchange of ground water with the lake. Lake stage can also be influenced by pumping from the underlying

Upper Floridan aquifer by inducing vertical ground-water outflow (Barcelo and others, 1990; Yobbi, 1996). Differences in how individual lakes respond to similar climatic conditions and pumping stresses is partly attributable to differences in their local hydrogeologic setting, which controls the interaction between the lake and adjacent ground-water system (Winter, 1976; Winter and Pfannkuch, 1984; Lee and Swancar, 1997).

Ground water also can have a strong influence on the chemical composition of lake water, even when it is a relatively minor part of a lake's water budget (Schwartz and Gallup, 1978; Baker and others, 1988; Kenoyer and Anderson, 1989). Solutes that originate in the shallow ground water can occur naturally from geologic or atmospheric sources (Stauffer, 1985; Baker and others, 1986; Pollman and others, 1991) or can be derived from anthropogenic sources such as septic tank leachate or fertilizers (Fellows and Brezonik, 1981; Stauffer, 1991; Tihansky and Sacks, 1997). As a lake basin becomes developed, ground water can become enriched in major ions and nutrients because of anthropogenic sources. If this enriched ground water flows into the lake, it can eventually affect the water quality of the lake. In order to understand a lake's nutrient or chemical budget, ground-water inputs and losses also must be quantified.

Previous basin-scale studies of seepage lakes in Florida indicate that the ground-water component to lake-water budgets can vary widely (Grubbs, 1995; Lee, 1996; Lee and Swancar, 1997). For example, ground-water inflow to two seepage lakes ranged from less than 20 percent to more than 75 percent of water inputs (Lee and Grubbs, in press). These studies provided detailed descriptions of ground-water flow patterns around lakes and quantified ground-water exchanges using detailed water budgets and ground-water flow models. As a result, the understanding of the various factors affecting ground-water exchange has greatly improved. The site-specific nature and limited time frame of these basin-scale studies, however, make it difficult to extrapolate results to the larger population of lakes in Florida. Contemporaneous studies of ground-water exchange are needed for a larger number of lakes. With this information we can begin to make comparisons between lakes and to characterize how lakes respond to hydrologic conditions within a region.

More simplified approaches are clearly needed to understand the relative importance of ground water in the water budget of lakes in Florida. Recent approaches have improved our understanding of the magnitude of ground-water exchange with lakes by combining chemical evidence of ground-water inflow to the lake with hydrologic data (Stauffer, 1985; Krabbenhoft and others, 1990; Pollman and others, 1991). In 1995, the U.S. Geological Survey (USGS) began a cooperative study with the Southwest Florida Water Management District (SWFWMD) to better understand ground-water/lake interactions in ridge areas of Florida. This study examines lakes at three different scales: (1) multiple-basin (or regional) scale using relatively simple techniques, (2) topographic basin scale for use as a long term study site (Lake Starr), and (3) intrabasin scale to study the specific process of recharge on ground-water inflow and outflow. This report summarizes results from the multiple-basin scale study, which uses both water and chemical budgets to determine ground-water contributions and losses from lakes.

Purpose and Scope

This report presents estimates of the amount of ground water in the water budgets of 10 lakes in Polk and Highlands Counties based on water-budget and chemical mass-balance approaches. Water budgets were computed monthly for the 15-month study period, October 1995 through December 1996, with net ground-water flow (ground-water inflow minus outflow) computed as the residual to the water budget equation. Heads in the shallow surficial aquifer system were mapped monthly in the vicinity of each lake to define ground-water head gradients around the lakes and to delineate regions of ground-water inflow and outflow. The head in the deeper Upper Floridan aquifer also was measured monthly near each lake to define the vertical head gradient between the lake and the Upper Floridan aquifer.

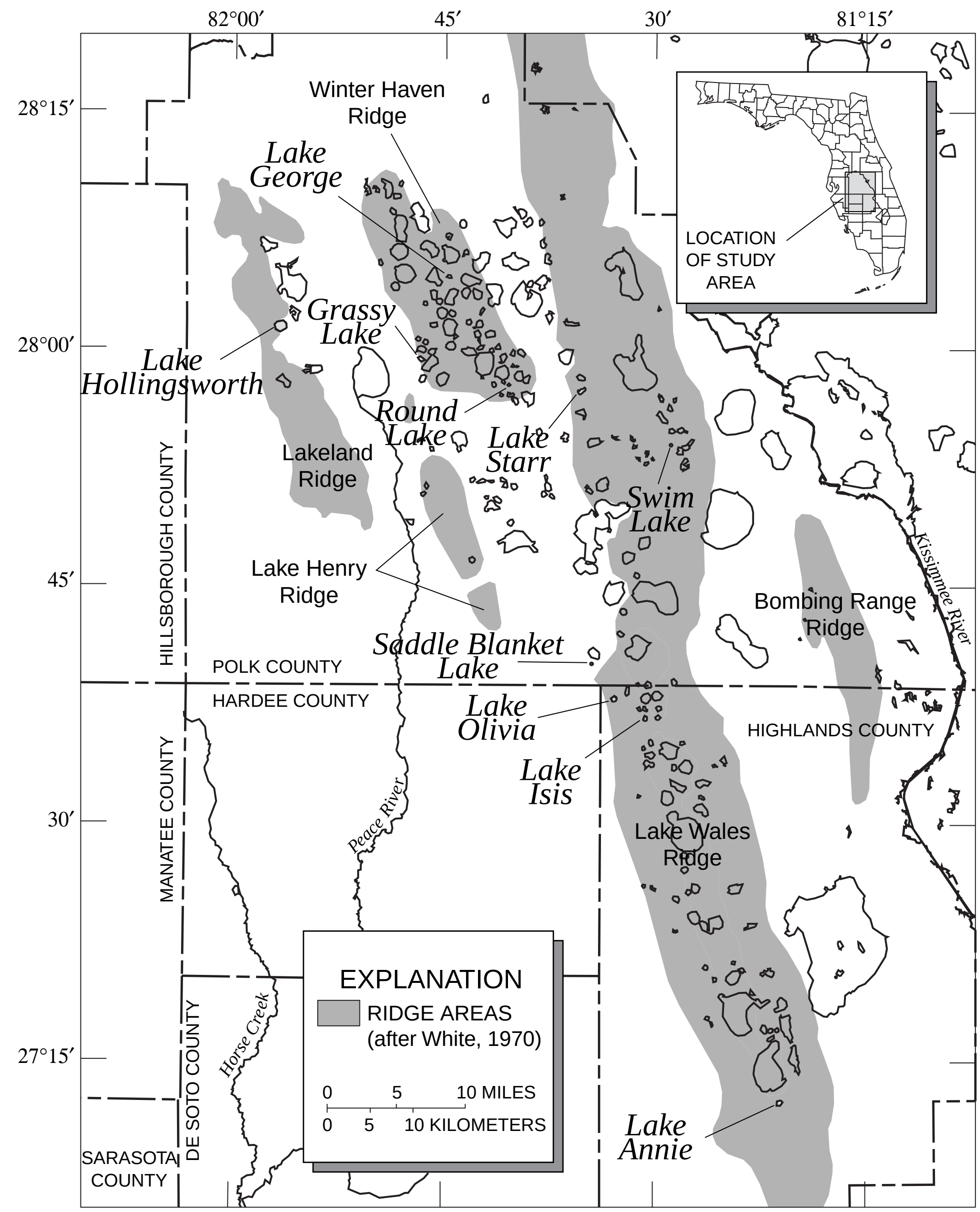
Lakes and selected wells were sampled three times during the study for major ions, selected trace elements, and nutrients; the isotopes deuterium and oxygen-18 were sampled twice in lakes and selected wells. The chemical mass-balance method was used to independently compute annual ground-water inflow and outflow using a steady-state approach. Inorganic solutes and the stable isotopes of water were considered as conservative tracers. Computed ground-water inflow results from the various tracers are presented, and limitations to this approach are discussed.

Acknowledgments

The authors thank Archbold Biological Station, The Florida Chapter of The Nature Conservancy, city of Lakeland, city of Avon Park, Highlands County, and numerous private land owners for access to their property and for permitting the USGS to install, monitor, and sample ground-water wells. Without their cooperation, this project would not have been possible. We also thank our local observers (Peggy Davis, Robert Desness, Nancy Deyrup, John Hodgkinson, David Little, Bal Sukhraj, and James Thornhill) for collection of data at the lakes. Finally, we thank USGS employees Richard Earp and Timothy O'Hare for dedicated and thorough data collection for this project.

PHYSICAL SETTING

The 10 study lakes are in ridge and upland areas of Polk and Highlands Counties (fig. 1), in an area characterized by numerous lakes. Polk County ranks fourth in the State in the number of lakes per county (Gant, 1993). The physical setting of the lake, including its hydrogeologic setting, is important in controlling how ground water interacts with a lake.



Base from Southwest Florida Water Management District digital data, 1:250,000, 1992
Universal Transverse Mercator projection, Zone 17

Figure 1. Locations of the study lakes in central Florida.

General descriptions of Florida lakes are available elsewhere (for example, Brenner and others, 1990; Schiffer, 1998).

Much of the study area is within the Central Lakes District (Brooks, 1981) and includes the Lake Wales Ridge, Lakeland Ridge, and Winter Haven Ridge as defined by White (1970). In this mantled karst terrain, unconsolidated sands and clays overlie an irregular limestone surface. As the underlying limestone dissolves, overlying sands and clays subside. The resulting sinkholes and surface depressions often hold water, forming lakes. Some lakes have no surface drainage (seepage lakes), whereas others are connected to surface flow (drainage lakes), depending on the local hydrogeologic setting, manmade features, head gradients, and topography. Lakes can undergo multiple episodes of subsidence and infilling, and this can influence hydrogeologic units beneath the lake (Tihansky and others, 1996).

Hydrostratigraphic units influencing ground-water/lake interactions are the surficial aquifer system, intermediate confining unit, and Upper Floridan aquifer. Within the study area, the surficial aquifer system ranges from about 50 to 300 ft thick and is composed of unconsolidated sand and clay (Barr, 1992; Tihansky and others, 1996). These surficial deposits thicken from north to south and on ridges. The surficial aquifer system is separated from the underlying carbonate Upper Floridan aquifer by the intermediate confining unit/intermediate aquifer system. This unit is heterogeneous, with clay-rich beds of low transmissivity hydraulically separating the surficial aquifer system from the Upper Floridan aquifer. However, sinkholes and subsidence features often modify and breach the confining unit, particularly beneath lakes (Lee and others, 1991; Sacks and other, 1992a; Evans and others, 1994; Tihansky and others, 1996). The top of the Upper Floridan aquifer is about 100 ft below land surface in the northern part of the study area and 600 ft below land surface in the southern part of Highlands County (Tibbals, 1990; Tihansky and others, 1996).

Ground-water flow around lakes is influenced by the lake's local hydrogeologic setting. A cross section through a typical lake is shown in figure 2. Lakes receive ground-water inflow from the surrounding surficial aquifer system. The area of influence can vary widely, depending upon the specific lake basin, and does not necessarily correspond to the topographic drainage area. In addition, ground water flowing towards a lake from the upper part of its topographic basin might not intercept the lake; instead, this water could move downward and bypass the lake (Lee, 1996). Ground water typically enters a lake in shallow areas near the shore (McBride and Pfannkuch, 1975; Fellows and Brezonik, 1980). Some lakes receive ground-water inflow around their entire perimeter. Other lakes, called flow-through lakes, have distinct areas of ground-water inflow and outflow around their perimeters.

Lakes "leak" or lose water as ground-water outflow. Ground-water outflow can have both lateral and vertical components, which are controlled by separate factors. Lateral ground-water outflow is driven by local and regional head gradients within the surficial aquifer system. The vertical component of

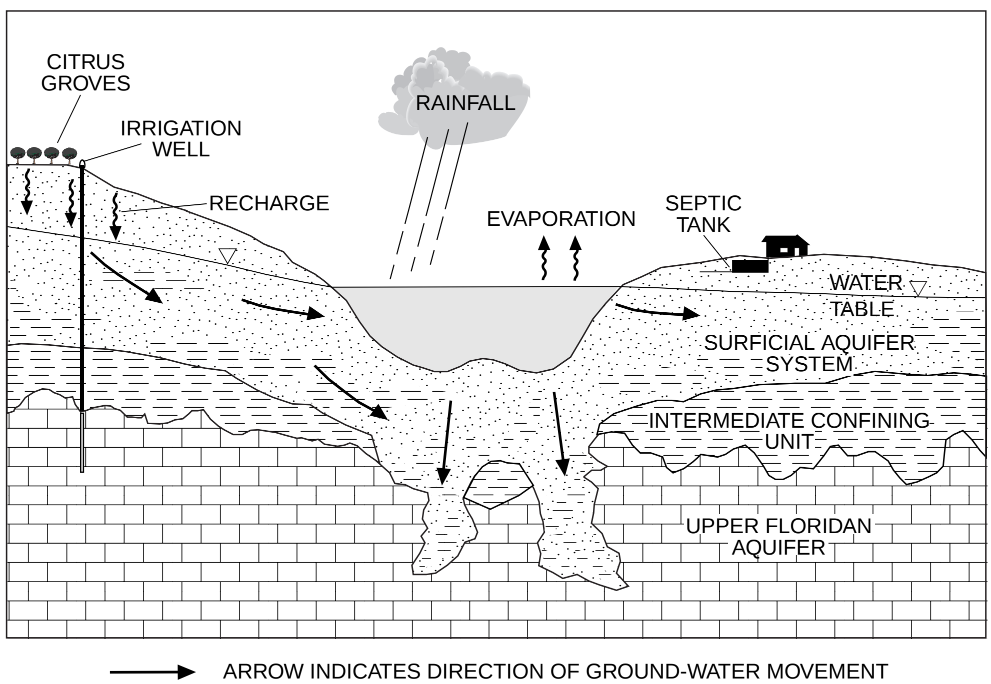


Figure 2. Generalized cross section of ground-water flow and hydrogeology through a Florida ridge lake (modified from Tihansky and Sacks, 1997).

flow is driven by downward head gradients between the lake and the Upper Floridan aquifer, and ground-water outflow ultimately moves downward to recharge the deeper aquifer. Breaches in confinement beneath a lake can cause preferential pathways for vertical ground-water outflow. This vertical ground-water outflow, however, can be inhibited where lake sediments are thick (Cornett and others, 1989; Guyonnet, 1991; Lee and Swancar, 1997).

The climate in the study area is humid subtropical. Average annual rainfall is about 50 in/yr, with about 60 percent occurring during the summer months. Rainfall from winter frontal activity generally is not as intense as summer rainstorms. Annual average lake evaporation is estimated to be between 48 and 50 in/yr (Farnsworth and others, 1982). However, lake evaporation can be higher during periods of drought (Sacks and others, 1994; Lee and Swancar, 1997). Pan evaporation rates are highest between April and August. Evaporation from shallow lakes tend to follow this same trend, but evaporation from deep lakes can be seasonally lagged (Sacks and others, 1994).

Description of Study Lakes

A number of factors were taken into consideration during the selection of the 10 study lakes. Lakes with a wide range of physical features were selected to get as many representative lake types as possible. These features included surface area, depth, topographic steepness of the basin, and stage response during periods of drought or excess rainfall. In this report, lake basin is defined topographically and is equivalent to a surface-water drainage basin in other settings. Other factors considered in lake selection were geographic distribution in the ridge areas of Polk and Highlands Counties, length of stage record at the site, previous studies at the lake, and relatively uniform land use in the basin (in order to better define ground-water inflow chemistry). Another selection factor was the cooperation of property owners in allowing access to the lake for installing and monitoring wells in the basin.

Seven of the study lakes are seepage lakes; the other three lakes have some channelized surface-water inflow or outflow. Physical characteristics of each lake are included in table 1. The lakes range in surface area from 5 to 356 acres, and maximum depths range from 6 to 65 ft. Lakes Annie and Isis are the deepest, and Lake Hollingsworth and Saddle Blanket Lake are the shallowest. Most study lakes are impacted to some degree by human development, and only two lakes, Lake Annie and Saddle Blanket Lake, are in pristine, undeveloped settings. One of the study lakes is unnamed on USGS topographic maps, but in this report it is referred to by its local name, Swim Lake. The Saddle Blanket Lake referred to in this report is the larger of the two lakes named together as Saddle Blanket Lakes; the smaller lake is referred to as the "adjacent pond" in this report.

Three of the seepage lakes lose water as a result of direct pumping and one gains water from stormwater inflow. Lake Isis receives stormwater inflow through a 4-ft-diameter pipe draining a nearby highway, and residents with homes adjacent to Lake Isis often pump water directly from the lake for lawn watering. During dry periods, water is pumped directly out of Round Lake to irrigate citrus. Water was pumped out of Grassy Lake for 2 months of the study (November and December 1995), following a wet summer and fall, to alleviate flooding of houses built in low-lying areas.

The three lakes that have channelized surface-water inflow or outflow vary widely in the degree that the flow is engineered. Lake Annie has a natural outflow stream on the north shore of the lake and has intermittent inflow through two shallow dredged channels on the south side (Battoe, 1987). Surface-water outflow from Lake George flows through a 10-in.-diameter pipe and into a channel that also drains the wetland area on the southeast side of the lake. Lake Hollingsworth is in an urban setting. Water enters the lake through a network of 67 storm drains and two pipe connections from upgradient lakes. Surface water flows out of the lake through a controlled outflow structure to a stream on its southeast shore.

Bathymetric data were either collected or compiled from existing maps. From these data, stage-volume and stage-area relations were computed. Although stage-volume and stage-area relations were not linear over the entire range of lake depths, they were linear in the shallow water depths representing the range in lake stage during the study (table 2). These relations allowed change in lake volume to be directly related to change in lake stage. Similarly, volumetric water fluxes could be related to linear fluxes by dividing them by the average lake surface area during the time period. Bathymetric maps of each study lake are shown in figures 3 through 7.

Table 1. Location and physical features of the study lakes

[undev., undeveloped; res., residential; S_o, surface-water outflow; S_i, surface-water inflow; int., intermittent; pump, water pumped directly from lake; St, stormwater inflow; irr., irrigation; --, not applicable; ft, feet; ft msl; feet above sea level]

Lake	Station identification number[1]	County	Section	Township	Range	Principle land use in basin	Surface outflows or inflows
Annie	02270700	Highlands	6	38S	30E	undev.	S_o, S_i (int.)
George	02293463	Polk	5	28S	26E	citrus	S_o (pipe)
Grassy	02294440	Polk	2	29S	25E	citrus, res.	pump (flooding)
Hollingsworth	02294342	Polk	30	28S	24E	res.	S_o (weir), S_i (pipe), St
Isis	02269184	Highlands	15	33S	28E	citrus, res.	St, pump (lawn irr.)
Olivia	02269172	Highlands	6	33S	28E	res.	--
Round	02294048	Polk	13	29S	26E	citrus	pump (citrus irr.)
Saddle Blanket	02269168	Polk	25	32S	27E	undev.	--
Starr	02293763	Polk	14	29S	27E	citrus, res.	--
Swim	02266923	Polk	1	30S	28E	citrus	--

Lake	Mean depth[2] (ft)	Maximum depth (ft)	Surface area (acres)	Lake perimeter (ft)	Reference stage[3] (ft msl)	Basin steepness[4] (dimensionless)	Topographic basin area (acres)
Annie	30	65	92	7,659	110	0.0347	183
George	8	15	59	6,431	130	0.0325	189
Grassy	11	23	76	7,364	130	0.0191	318
Hollingsworth	4	6	356	14,927	131	0.0288	1,072
Isis	28	64	50	5,534	110	0.0337	590
Olivia	16	47	86	7,224	115	0.0127	564
Round	15	28	31	4,167	131	0.0445	119
Saddle Blanket	6	11	6	1,936	118	0.0273	77
Starr	17	33	134	10,753	105	0.0577	739
Swim	15	30	5	1,706	97	0.0493	57

[1]Equivalent to the downstream order number.
[2]Lake volume divided by surface area at average stage during study.
[3]Stage for which lake depth, suface area, and permimeter were computed.
[4]Average slope between the lake and the topographic basin divide for the four compass directions.

Table 2. Linear regression equations of stage-volume and stage-area relations for shallow water depths for the study lakes

[ft msl, feet above sea level; V, lake volume; A, lake surface area; all regressions significant to alpha level of 0.05]

Lakes	Stage range equation computed for (ft msl)	Linear regression equation to compute volume from lake stage[1]	Linear regression equation to compute surface area from lake stage[2]
Annie	[3]97 - 110	$V = 3.167 \times 10^6 * \text{stage} - 2.296 \times 10^8$	$A = 1.119 \times 10^5 * \text{stage} - 8.334 \times 10^6$
George	129 - 130	$V = 2.540 \times 10^6 * \text{stage} - 3.085 \times 10^8$	$A = 1.410 \times 10^5 * \text{stage} - 1.574 \times 10^7$
Grassy	128 - 132	$V = 3.301 \times 10^6 * \text{stage} - 3.918 \times 10^8$	$A = 1.460 \times 10^5 * \text{stage} - 1.568 \times 10^7$
Hollingsworth	128 - 132	$V = 1.341 \times 10^7 * \text{stage} - 1.695 \times 10^9$	$A = 1.373 \times 10^6 * \text{stage} - 1.650 \times 10^8$
Isis	107 - 113	$V = 2.148 \times 10^6 * \text{stage} - 1.764 \times 10^8$	$A = 5.746 \times 10^4 * \text{stage} - 4.152 \times 10^6$
Olivia	113 - 117	$V = 3.710 \times 10^6 * \text{stage} - 3.654 \times 10^8$	$A = 1.091 \times 10^5 * \text{stage} - 8.843 \times 10^6$
Round	130 - 132	$V = 1.335 \times 10^6 * \text{stage} - 1.550 \times 10^8$	$A = 3.700 \times 10^4 * \text{stage} - 3.508 \times 10^6$
Saddle Blanket	115 - 120	$V = 2.739 \times 10^5 * \text{stage} - 3.051 \times 10^7$	$A = 2.029 \times 10^4 * \text{stage} - 2.108 \times 10^6$
Starr	104 - 106	$V = 5.855 \times 10^6 * \text{stage} - 5.184 \times 10^8$	$A = 1.920 \times 10^5 * \text{stage} - 1.432 \times 10^7$
Swim	95 - 99	$V = 2.280 \times 10^5 * \text{stage} - 1.888 \times 10^7$	$A = 1.362 \times 10^4 * \text{stage} - 1.089 \times 10^6$

[1]Stage in feet; volume in cubic feet.
[2]Stage in feet; area in square feet.
[3]Greater than stage range during study, but relation generated from existing bathymetric map (Eckblad, 1974; Battoe, 1987).

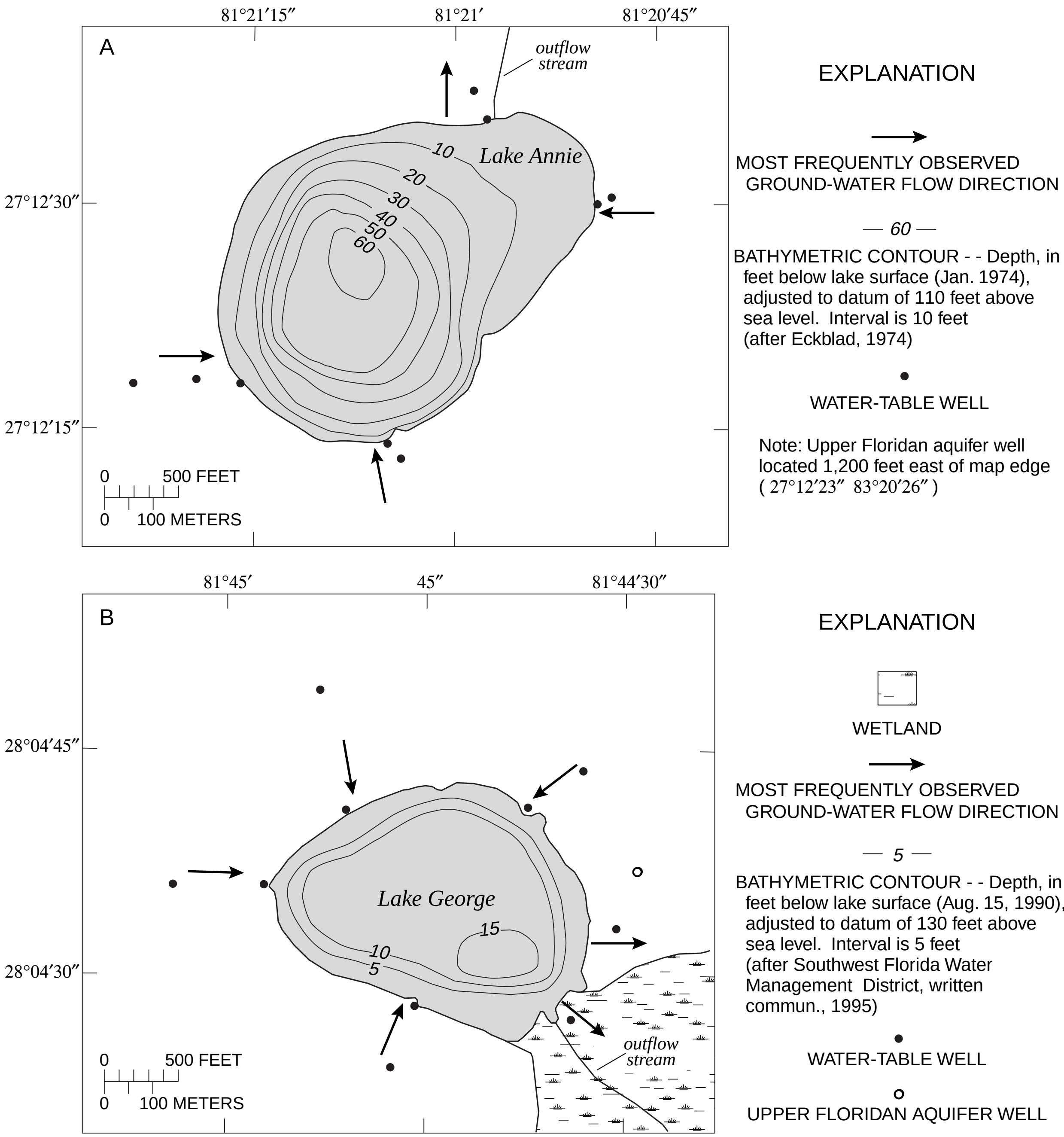


Figure 3. Locations of monitoring wells, general ground-water flow patterns, and bathymetric map of (A) Lake Annie, Highlands County, and (B) Lake George, Polk County , Florida.

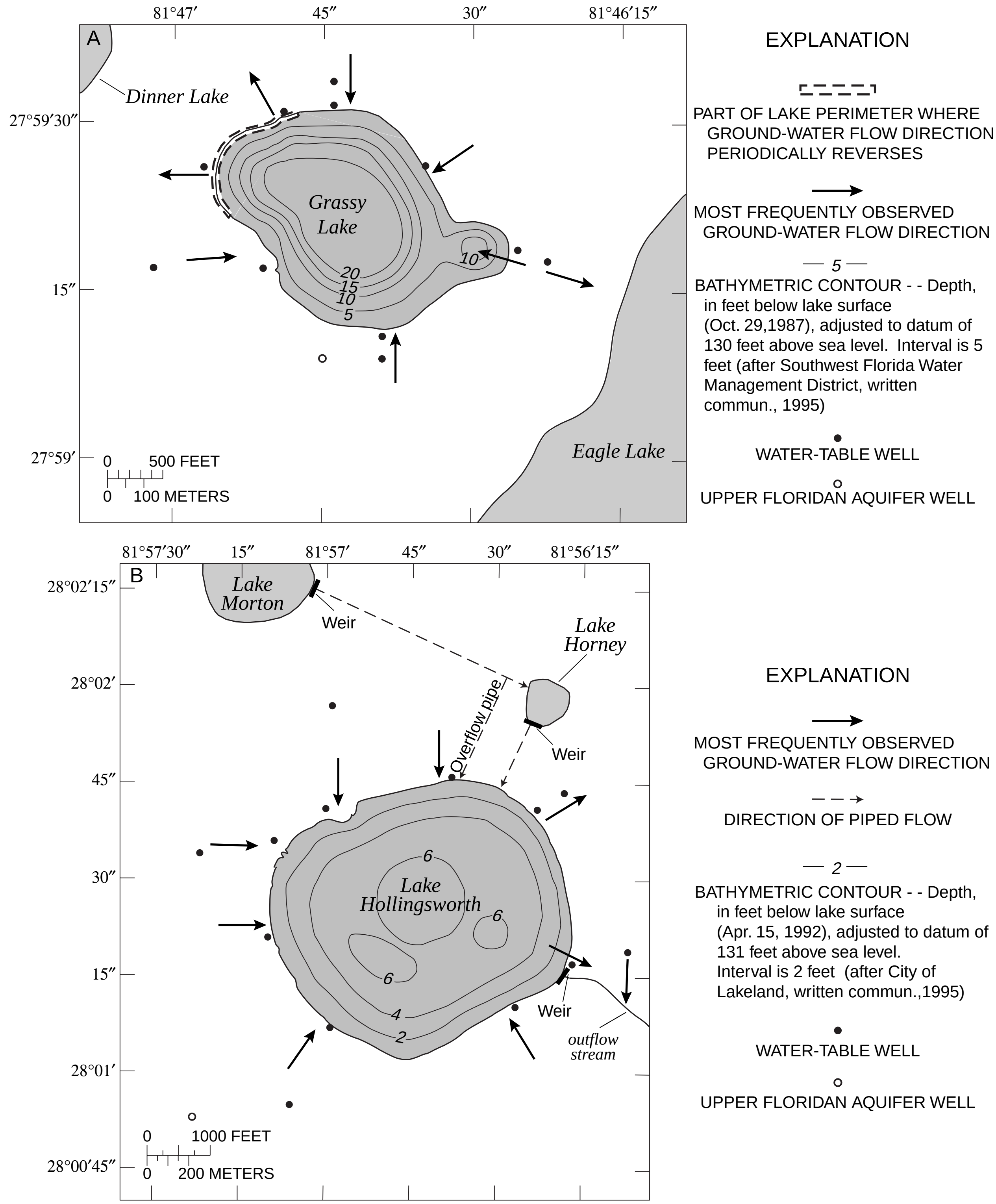


Figure 4. Locations of monitoring wells, general ground-water flow patterns, and bathymetric map of (A) Grassy Lake and (B) Lake Hollingsworth, Polk County, Florida.

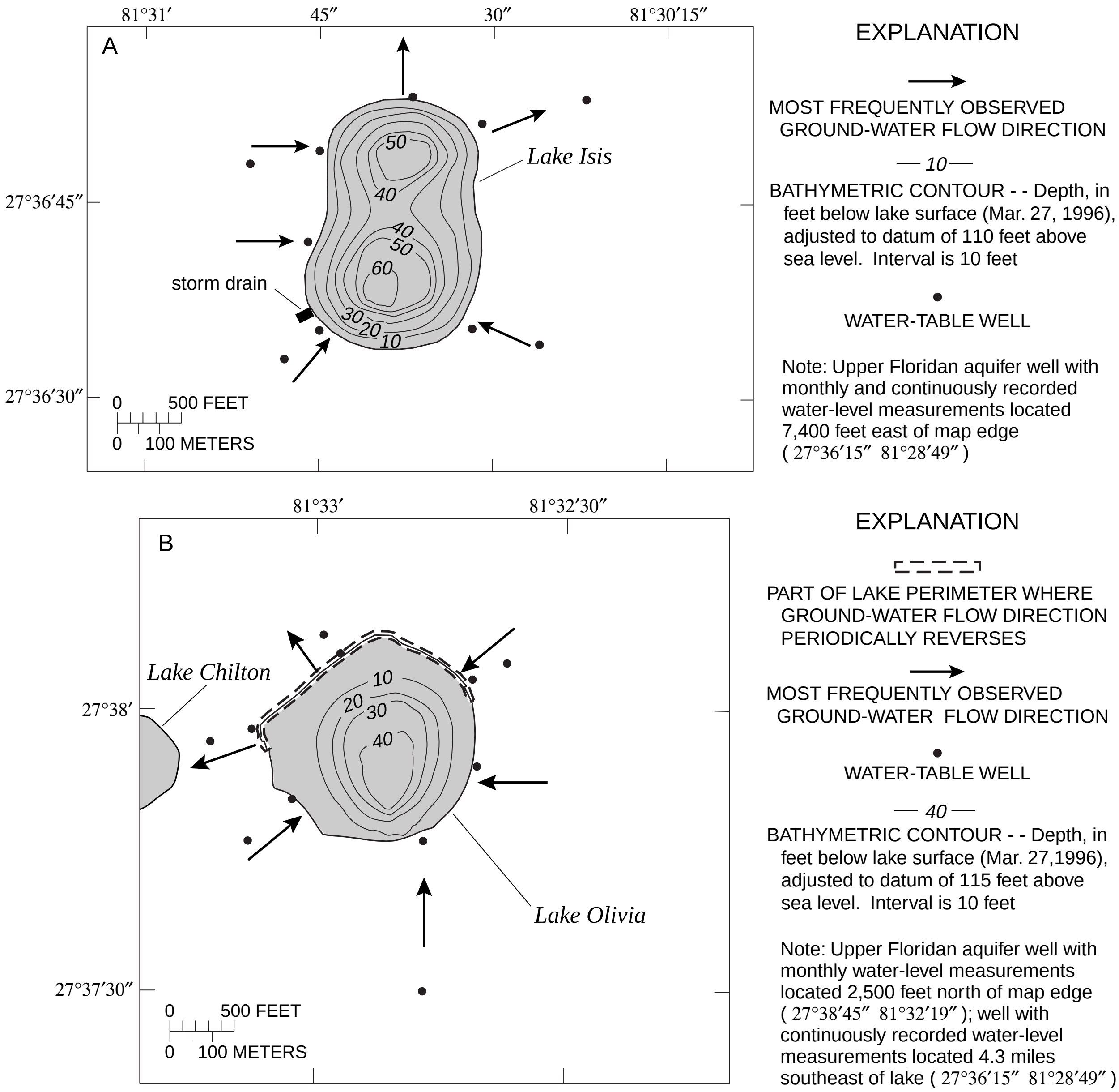


Figure 5. Locations of monitoring wells, general ground-water flow patterns, and bathymetric map of (A) Lake Isis and (B) Lake Olivia, Highlands County, Florida.

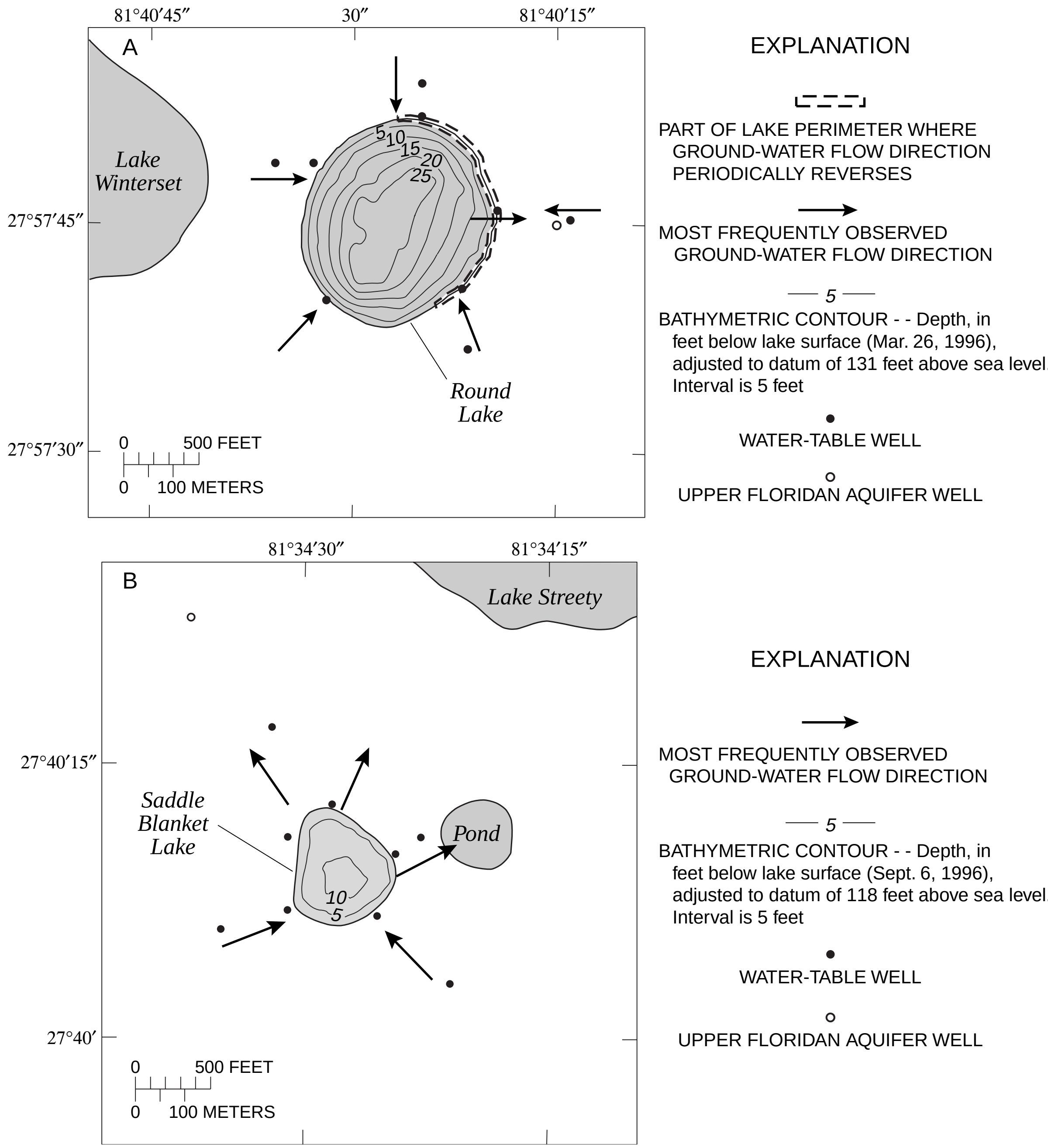


Figure 6. Locations of monitoring wells, general ground-water flow patterns, and bathymetric map of (A) Round Lake and (B) Saddle Blanket Lake, Polk County, Florida.

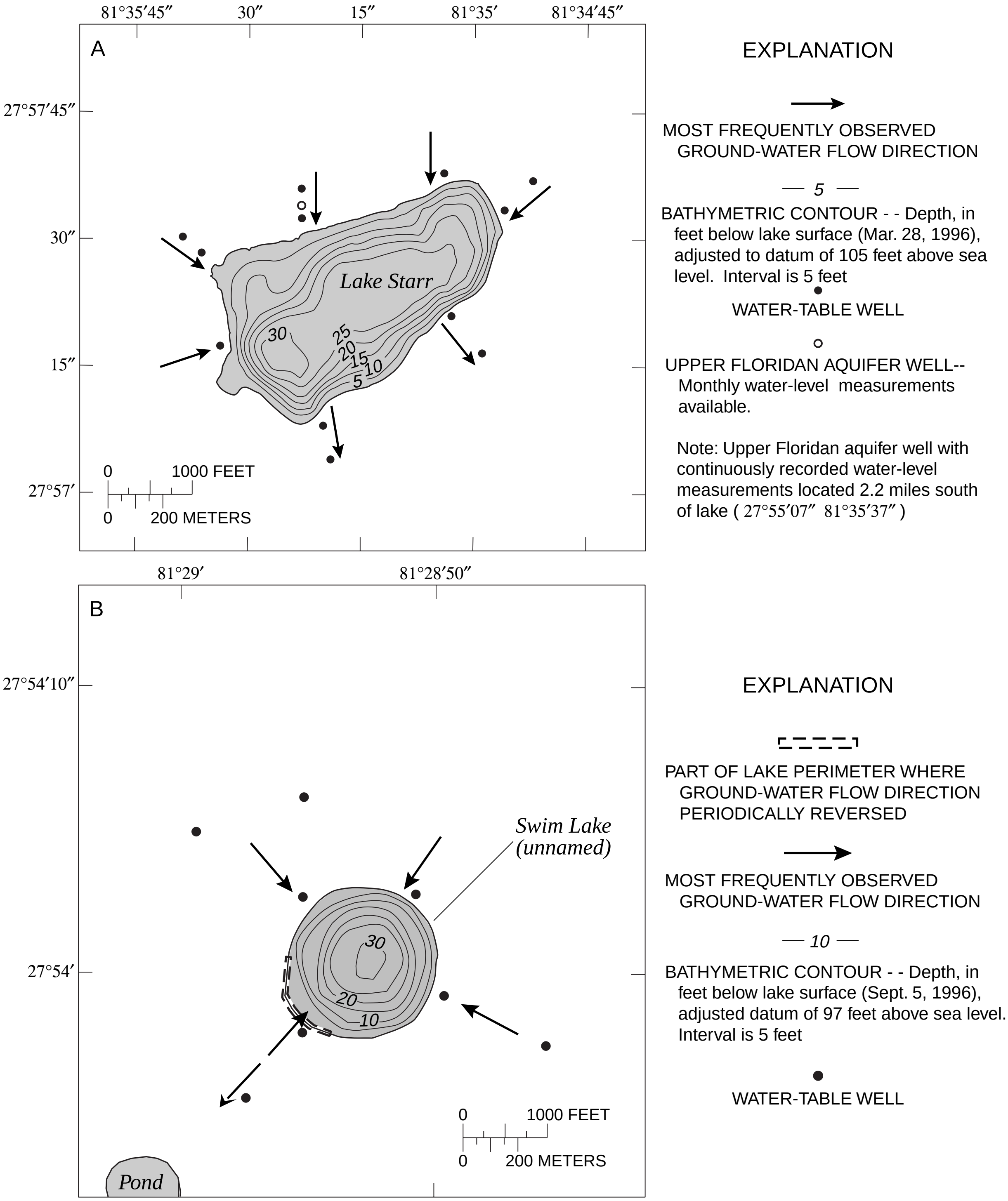


Figure 7. Locations of monitoring wells, general ground-water flow patterns, and bathymetric map of (A) Lake Starr and (B) Swim Lake, Polk County, Florida.

Ground-Water Flow Patterns Around Lakes

A water-level monitoring network was established in each lake's topographic basin to collect head data from the ground-water system. In general, this network consisted of 10 surficial aquifer system wells, with 6 wells near the lake shore and 4 wells in the upper part of the basin. Depending on lake size and other characteristics, the number of wells in some basins varied slightly from this pattern. The monitoring wells consisted of 2-in.-diameter polyvinyl chloride finished 5 to 10 ft below the water table with a 5-ft screened interval. At Lake Annie, wells with 4-ft screened intervals were used because a suitable network had already been established in a previous study (Battoe, 1987). Water-level data from the wells and lakes were used to describe temporal variations in the head distribution and evaluation patterns of ground-water inflow and outflow.

Water levels in wells were measured monthly between October 1995 and December 1996. From this information, water-table maps were constructed, and areas of ground-water inflow and outflow were delineated. Well and lake hydrographs were constructed to evaluate the response of ground water and lakes to recharge and precipitation. Daily lake stage and monthly ground-water levels for all sites are published in annual USGS data reports for southwest Florida (Coffin and Fletcher, 1998a, b).

Monthly water-level measurements also were made in an Upper Floridan aquifer well near each lake to monitor vertical head gradients between the lake and the deeper aquifer. Heads in the Upper Floridan aquifer can vary considerably within a given day or month due to changing pumping stresses in the area. Thus, monthly instantaneous measurements are highly dependent upon pumping conditions at the time of observation. If available, continuously recorded water levels in Upper Floridan aquifer wells are useful in defining monthly average vertical head gradients. Two wells with continuous recorders were available within 5 mi of the three study lakes: ROMP 43xx near Lakes Isis and Olivia and ROMP 58 near Lake Starr.

General ground-water flow patterns in the vicinity of each lake are shown in figures 3 through 7. The direction of flow most frequently observed (more than half the time) is shown in these figures; areas where near-shore flow reversals were observed are also shown. Most study lakes had distinct areas of ground-water inflow and outflow, and can be classified as flow-through lakes. Ground-water flow directions do not necessarily correspond to topography. Lakes with surface-water outflow (Lakes Annie, George, and Hollingsworth) had lateral ground-water outflow on the side of the lake with surface outflow (figs. 3a, 3b, and 4b). Some lakes were flow through for most of the study, but had ground-water inflow around their entire perimeter following periods of high recharge (for example, Grassy Lake and Lake Olivia; figs. 4a and 5b). Other lakes had very stable ground-water flow regimes around the lakes, although water-table gradients changed seasonally in response to recharge (for example, Lakes Isis and Starr; figs. 5a and 7a).

The percentage of lake perimeter that exhibits ground-water inflow or outflow varies between lakes, and can vary seasonally at a given lake. For most lakes, between 67 and 80 percent of the perimeter can be characterized as ground-water inflow (table 3). Swim Lake had ground-water inflow around its entire perimeter for most of the study (94 percent). Saddle Blanket Lake had the smallest amount of its perimeter as ground-water inflow (less than 50 percent). Outflow water-table gradients sometimes slope toward the topographic basin divides and can be driven by lower levels in nearby lakes. For example, ground-water outflow is toward a nearby lake on the north side of Lake Isis, the west side of Lake Olivia, and the north and east sides of Saddle Blanket Lake (figs. 5a, 5b, and 6b, respectively). The degree of confinement to the Upper Floridan aquifer near a lake can also affect areas of lateral outflow. Ground-water outflow occurs on the south side of Lake Starr (fig. 7a), where sinkhole features probably indicate less confinement of the Upper Floridan aquifer. Ground-water flow characteristics of the study lakes are listed in table 3.

Table 3. Ground-water flow characteristics of the study lakes, October 1995 through December 1996

[gw, ground water; UFA, Upper Floridan aquifer; ft, feet]

Lake	Percent of lake perimeter that is: gw inflow[1]	Percent of lake perimeter that is: gw outflow[1]	Percent of time 100 percent gw inflow	Average head difference between lake and UFA (ft)
Annie	78	22	0	62
George	73	27	0	8
Grassy	87	13	44	26
Hollingsworth	80	20	0	51
Isis	72	28	0	22
Olivia	71	29	13	35
Round	80	20	0	22
Saddle Blanket	45	55	0	40
Starr	67	33	0	2
Swim	94	6	69	10

[1]Extrapolated linearly between wells. Averaged over study period for lakes with transient water-table configurations.

Downward head gradients exist between all lakes and the Upper Floridan aquifer. Ridge areas of Polk and Highlands Counties are important recharge areas to the Upper Floridan aquifer (Aucott, 1988; Tibbals, 1990; Yobbi, 1996). Head differences generally increase to the south in the study area, and average head differences during the study range from 2 ft at Lake Starr to 62 ft at Lake Annie (table 3). Head gradients are influenced by a number of factors, including degree of confinement, pumping stresses in the area, and regional flow patterns within the Upper Floridan aquifer.

WATER-BUDGET APPROACH

The water-budget method was used to compute annual (1996) and monthly (October 1995 through December 1996) net ground-water flow (ground-water inflow minus outflow) for the 10 lakes. Net ground-water flow estimates can give insight into seasonally important processes and allow comparisons between lakes. However, absolute ground-water inflow and outflow cannot be distinguished because only the net flow is computed.

Methods

A lake's water budget is computed by measuring or estimating all of the lake's water gains and losses, and measuring the corresponding change in lake volume over the same time period:

$$\Delta V = P - E + S_i - S_o + G_i - G_o \qquad (1)$$

where ΔV is change in lake volume, P is direct precipitation, E is lake evaporation, S_i is surface-water inflow and storm-water inflow, S_o is surface-water outflow and direct pumping, G_i is ground-water inflow, and G_o is ground-water outflow. Water budget terms can be expressed in volumetric units (precipitation and evaporation multiplied by the average lake surface area during that time), or in linear units over the given time period (by dividing change in lake volume and volumetric fluxes by lake surface area). For this report, linear units of inches are used, which allows for a better comparison between lakes of different surface areas. This also allows for ground-water fluxes to be more readily compared to lake-level fluctuations and rainfall, which are measured in linear units. However, ground-water fluxes are inherently more important in the water budget of a smaller lake because of the higher ratio of lake perimeter to surface area, compared to a larger lake (Millar, 1971; Fellows and Brezonik, 1980).

Equation 1 can be rearranged to solve for net ground-water flow (G_{net}, ground-water inflow minus ground-water outflow):

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

When G_{net} is positive, ground-water inflow exceeds outflow, and this value can be considered the minimum amount of ground-water inflow in the lake's water budget. Similarly, when G_{net} is negative, net ground-water outflow occurs from the lake, and this value can be considered to be the minimum amount of ground-water outflow in the lake's water budget.

G_{net} is a residual term, and, thus, uncertainties (or errors) associated with each term of the water budget must be assessed in order to estimate the uncertainty associated with the computed net ground-water flow. The uncertainty or error in net ground-water flow can be computed as:

$$e_{Gnet} = \sqrt{(e_{\Delta V} \cdot \Delta V)^2 + (e_P \cdot P)^2 + (e_E \cdot E)^2 + \left(e_{S_i} \cdot S_i\right)^2 + \left(e_{S_o} \cdot S_o\right)^2} \qquad (3)$$

where e_{Gnet} is the uncertainty or error in net ground-water flow, in inches, and e is the error or uncertainty in each of the water budget terms, in percent (Lee and Swancar, 1997). Uncertainties in budget terms can be from measurement error, extrapolation of regional data to a specific site, and uncertainties in computed or assumed parameters used to calculate the term (Winter, 1981). Uncertainty values used in the error analysis include those estimated from the literature (Winter, 1981), standard error of regressions (for computed values), and an assessment of uncertainties in calculated values. The uncertainty for G_{net} calculated from equation 3 should be considered a maximum error because it assumes that all of the errors are in the same direction and do not cancel each other out.

Estimating Components of the Water Budget

Each component of the water budget in equation (2) was measured directly or indirectly, and a percent uncertainty was assumed. The 10 lakes were instrumented with a stage recorder and tipping bucket rain gage, which recorded stage to 0.01 ft and rainfall to 0.01 in. electronically every 15 minutes. Continuous data were collected between October 1, 1995, and January 1, 1997. A local observer also read the lake stage on a staff gage and measured weekly rainfall in a storage rain gage. Stage measurements were converted to lake volume using stage-volume relations (table 2). For linear units, the change in volume for a given time period was normalized to the average lake surface area for that time period, using stage-area relations. A 5 percent uncertainty was assumed for change in volume in the water budget (Lee and Swancar, 1997).

Tipping bucket rain gages can underestimate rainfall, particularly during high intensity storms (Sacks and others, 1992a; Bidlake and Boetcher, 1996). For each lake, rainfall totals from the storage and tipping bucket rain gages were compared for the same time interval. If the tipping bucket gage consistently read lower, a best-fit regression line through zero was used to correct daily rainfall for that particular gage. In cases when the rain gage malfunctioned and observer data were not available, estimates of rainfall were made based on regression relations between rainfall and change in lake stage. A 5 percent uncertainty in rainfall was assumed, based on comparisons of monthly rainfall from two rain gages on different sides of Lake Starr.

For two of the three lakes with surface-water outflows, the volume of outflow was related to lake stage. At Lake Annie, monthly discharge measurements were made at the outflow stream using a point-velocity meter and standard USGS procedures (Rantz and others, 1982). At Lake George, volumetric measurements from the discharge pipe were made at various lake stages, and the stage at zero flow was determined. For these lakes, linear regressions between stage and discharge were generated. For Lake Annie, the relation was surface-water outflow (S_o) = 5.0705 * stage - 556.6 (coefficient of determination, r^2, = 0.94; standard error = 0.255 ft^3/s; stage range 109.90 to 110.54 ft; all regressions in the report are significant to an alpha level of 0.05 unless otherwise noted). For Lake George, the relation was S_o = 0.7855 * stage - 102.02 (r^2 = 0.89; standard error = 0.0793 ft^3/s; stage range = 129.85 (no flow; surveyed elevation of bottom of pipe) to 130.60 ft). Surface-water outflow was computed from the electronically recorded 15-minute stage data, and summed by day. Uncertainty in the estimate was assumed to be the standard error from the regression plus an assumed measurement error (9 percent for Lake Annie and 7 percent for Lake George).

For the other lake with surface-water outflow, Lake Hollingsworth, estimating outflow was more complicated. The outflow structure was replaced during the study (February 1996). The original structure was a rectangular sharp-crested weir, which had water flowing over the top. Discharge over this weir was computed using theoretical calculations that relate discharge to the geometric configuration of the structure, the height of the water over the structure, and a weir coefficient (computed as a function of the height of the water over the weir) (Horton, 1907; Prasuhn, 1987, p. 249). Estimates of outflow discharge before January 1996 were not reliable because of insufficient data. Because of this, water budgets for Lake Hollingsworth were only computed for 1996. The new outflow structure at Lake Hollingsworth was a bottom-opening sluice gate. The gate was adjusted occasionally during the study, and date, time, and size of the gate opening were recorded for each change. Discharge measurements were made at the outflow stream using a point-velocity meter and standard USGS procedures (Rantz and others, 1982) at least one time for each of the four gate settings. The discharge measurements were used to calibrate discharge coefficients using an equation relating discharge through the gate to the geometric configuration of the opening and the height of the water at the structure (Prasuhn, 1987, p. 252). Discharge coefficients used were 0.230, 0.633, 0.256, 0.412, and 0.363 for 0.5-in., 1.0-in., 2.0-in. (before August 3, 1996), 2.0-in. (after August 29, 1996), and 5.6-in. gate settings, respectively. Surface-water outflow was computed from the electronically recorded 15-minute stage data, and summed by day. Assumed uncertainties in computed discharge were based on estimated uncertainties in weir or discharge coefficients.

Lake Hollingsworth also receives surface-water inflow from upgradient Lake Horney (fig. 4b). This water flowed over a rectangular, sharp-crested weir and into a pipe network to Lake Hollingsworth. The stage of Lake Horney was measured weekly beginning in February 1996, and stage between measurements was interpolated linearly. Stage in January 1996 was estimated based on a linear regression with the stage of upgradient Lake Morton, which was measured weekly. Daily discharge from Lake Horney to Lake Hollingsworth was estimated using a theoretical weir coefficient that varied as a function of the height of the water over the weir. The uncertainty in inflow estimates to Lake Hollingsworth from Lake Horney was assumed to be 40 percent, based on uncertainty in the weir coefficient and the estimated error associated with weekly stage measurements; for January 1996, the standard error of regression for estimating stage was also considered in the uncertainty in the inflow term. Most of the time, piped flow from Lake Morton drains directly into Lake Horney. Following high rainfall, however, when the stage of Lake Morton increases rapidly because of stormwater inflow, some of the outflow from Lake Morton is diverted to Lake Hollingsworth (B.C. Sukhraj, City of Lakeland, oral commun., 1997). For daily rainfall events greater than 2 in., it was assumed that the equivalent stormwater over the Lake Morton basin is diverted directly into Lake Hollingsworth. The uncertainty in inflow estimates to Lake Hollingsworth from Lake Morton was assumed to be 50 percent.

Only one other lake, Lake Annie, receives direct surface-water inflow. This inflow occurs intermittently in two shallow, dredged channels that drain stormwater and the adjacent ground water when water-table altitudes are high. Estimates of surface-water inflow to Lake Annie were based on limited discharge measurements of flow in the western-most channel, field observations, and an analysis of change in lake stage. During the study period, significant flow occurred only during the fall of 1995. A 50 percent uncertainty was assumed for these estimates.

Stormwater is a significant inflow component to two of the study lakes, Lake Hollingsworth and Lake Isis. Lake Hollingsworth has 67 storm drains flowing into the lake (G. Medley, City of Lakeland, oral commun., 1997). A previous study separated the lake basin into subbasins and estimated stormwater runoff by categorizing land use and associated impervious and pervious areas in each subbasin (Dames and Moore, 1992). For that study, a runoff coefficient of 0.70 was used for directly connected impervious areas and a runoff coefficient of 0.05 was used for pervious areas. During the current study, runoff from the two upgradient lake basins (Lake Morton and Lake Horney) was not used in computing direct stormwater inflow to Lake Hollingsworth because inflow from these lakes was computed separately. The total area contributing to stormwater inflow was divided by lake surface area, and stormwater inflow was equivalent to about 70 percent of the rain falling directly on the lake. For Lake Isis, stormwater runoff enters the lake from a 4-ft-diameter pipe draining about 1 mi. of a 4-lane highway. The paved area that this pipe drains was estimated using aerial photographs, schematics of the storm drain plan from the Florida Department of Transportation, and field reconnaissance. Estimates of stormwater inflow from this paved area, with an associated runoff coefficient of 0.75, compared closely to an analysis of lake stage increase for days when total rainfall was greater than 0.5 in. Storm-water inflow was estimated to be equivalent to 20 percent of rain falling directly on the lake. A 30 percent uncertainty was assumed for stormwater inflow for both lakes.

Water was pumped directly out of several of the study lakes. To alleviate flooding of homes in low-lying areas adjacent to Grassy Lake, water was pumped to nearby Eagle Lake for 2 months of the study (November and December 1995). Round Lake was pumped during dry periods to irrigate a nearby citrus grove. Pumping rates were measured by the SWFWMD using an ultrasonic flow meter (M.L. Phillippi, Southwest Florida Water Management District, written commun., 1996). Both pumps had hourly meters, so meter readings were related to the volume of water pumped. A 5 percent uncertainty in these estimates was assumed. At Lake Isis, lake-front residents pumped water out of the lake for lawn irrigation. Estimates of this pumping volume were made based on the number of inlet pipes in the lake, average lot size, and typical lawn watering habits. A 100 percent uncertainty was assumed for this estimate.

Evaporation was not measured directly. Monthly lake evaporation was estimated from pan evaporation data from the National Weather Service (NWS) site at Lake Alfred in Polk County, multiplied by a pan coefficient. Pan coefficients vary monthly and were estimated by comparing monthly pan evaporation rates at Lake Alfred to the more accurate energy-budget evaporation rates from nearby Lake Lucerne for the 1986 water year (Lee and Swancar, 1997). Evaporation rates at lakes with below average rainfall can be higher than rates at lakes with normal or above normal rainfall. Reduced cloud cover and increased solar radiation lead to warmer lake temperatures and, thus, higher evaporation rates. Rainfall varied significantly over the study area; lakes further north had above average rainfall, whereas those further south had below average rainfall. Much of this rainfall deficit was during the summer months, when evaporation is high. A weak but statistically significant relation exists between late spring and summer monthly pan evaporation at Lake Alfred and rainfall departure from normal ($r^2 = 0.20$; standard error = 0.73 in., which is less than 10 percent of monthly pan evaporation during summer months). For those lakes with significantly less summer rainfall compared to Lake Alfred, the regression relation was used to compute monthly pan evaporation for specific months. This was done for June through August 1996 for Lake Isis, Lake Olivia, and Saddle Blanket Lake, and for August 1996 for Round Lake and Lake Annie.

Evaporation from deep lakes (mean depth greater than about 16 ft) is seasonally lagged compared to shallow lakes (Sacks and others, 1994). At deep Florida lakes, evaporation is lower in the spring because incoming energy is stored as heat in the deeper parts of the lake, rather than being available for evaporation. Conversely, evaporation at a deep lake is higher in the fall because this extra stored heat is being released and is available for evaporation. For the deepest lakes (Lakes Annie and Isis), which had mean depths greater than 20 ft, pan evaporation coefficients were adjusted lower for the winter and spring months and higher for the fall months to better reflect this lag in evaporation. Monthly temperature profiles at Lake Annie and Lake Isis reflect the heat exchange characteristics of deep, warm monomictic lakes (that is, they stratify from spring to late fall and mix in the winter). In contrast, temperature profiles at shallow Lake George (mean depth 8 ft) respond more rapidly to changes in air temperature, and the lake essentially behaves like an evaporation pan. Because seasonal lake evaporation rates are more difficult to estimate than annual rates, a 20 percent uncertainty was assumed for monthly evaporation and a 10 percent uncertainty was assumed for annual evaporation (Winter, 1981; Pollman and others, 1991).

Net Ground-Water Flow Results

Net ground-water flow varied seasonally at each of the 10 lakes, and was notably different between lakes. Monthly net ground-water flow, estimated uncertainty, and other components of the water budget are included in the appendix. Seasonal variability of net ground-water flow is a relative indicator of how important ground water is in the lake's water budget. Lakes with more seasonal variability in monthly net ground-water flow are more responsive to seasonal changes in recharge or aquifer pumping stresses. In contrast, less variability in monthly net ground-water flow can indicate that ground water is not as important in the lake-water budget or that the lake is not as influenced by short-term hydrologic stresses. Lake Annie had the greatest variability (more than 20 in.) in the amount of monthly net ground-water flow, and Lake George had the least variability (less than 5 in.). Of the seepage lakes, Swim Lake and Lake Isis had the greatest variability in monthly net ground-water flow (16.5 and 12.8 in., respectively), whereas Lake Starr, Round Lake, and Lake Olivia had the least variability (between 5 and 6 in.).

Annual (1996) net ground-water flow ranged from 180 in/yr at Lake Annie to -44 in/yr at Lake Isis (table 4). Except for Lake Annie, annual net ground-water flow is correlated to annual rainfall (fig. 8). Rainfall at the study lakes ranged from less than 40 in/yr to more than 55 in/yr during 1996. Seepage lakes with below average rainfall (less than the 30-year average at the nearest NWS site) had negative net ground-water flow (Lake Isis, Lake Olivia, Saddle Blanket Lake, and Round Lake), whereas those with above average rainfall had positive net ground-water flow (Grassy Lake, Lake Starr, and Swim Lake). All of the surface-water drainage lakes (Lakes Annie, George, and Hollingsworth) had positive net ground-water flow. Lake Annie had high positive net ground-water flow but below average rainfall for 1996; ground-water inflow has to be high at this lake to sustain the continuous surface-water outflow. Annual net ground-water flow would presumably be even higher at Lake Annie during a year with above average rainfall. Because net ground-water flow is so strongly influenced by rainfall deficit or surplus, annual comparisons of net ground-water flow between lakes are only meaningful if annual rainfall is similar. For example, Lakes Isis and Olivia had similar 1996 rainfall (about 40 in.), but net ground-water flow was more negative at Lake Isis than Lake Olivia (-44 and -14 in/yr, respectively). Greater ground-water outflow and reduced ground-water inflow at Lake Isis, compared to Lake Olivia, probably account for these differences.

Table 4. Water-budget terms, computed net ground-water flow, uncertainty in net ground-water flow, and estimated ground-water outflow and inflow for the study lakes for calendar year 1996

[Units in inches per year, rounded to nearest inch; P, precipitation; E, evaporation; S_i, surface-water inflow; S_o, surface-water outflow; ΔV, change in lake volume; G_{net}, net ground-water flow (ground-water inflow minus outflow); e_{Gnet}, uncertainty or error in net ground-water flow; est, estimated; G_o, ground-water outflow; G_i, ground-water inflow; --, not applicable; n/a, not available because monthly net ground-water flow always greater than 0]

Lake	P	E	S_i	S_o	ΔV	G_{net}	e_{Gnet}	est G_o[1]	est G_i[2]
Annie	43	53	1	173	-2	180	29	n/a	n/a
George	52	52	--	37	2	39	13	n/a	n/a
Grassy	55	52	--	--	19	16	6	17	33
Hollingsworth	57	52	[3]55	72	-2	11	20	42	53
Isis	41	55	[4]8	[5]3	-52	-44	7	84	40
Olivia	39	55	--	--	-29	-14	6	43	29
Round	46	53	--	[5]2	-17	-7	6	38	31
Saddle Blanket	38	55	--	--	-40	-23	6	49	26
Starr	55	52	--	--	8	5	6	25	30
Swim	52	52	--	--	6	7	6	85	92

[1]Most negative monthly net ground-water flow multiplied by 12, which assumes that minimal ground-water inflow occurs during that month and that ground-water outflow is uniform during the year.
[2]Computed from water budget, using estimated G_o from previous column.
[3]Includes surface-water inflow (15 inches) and stormwater inflow (40 inches).
[4]Stormwater inflow.
[5]Direct pumping from lake.

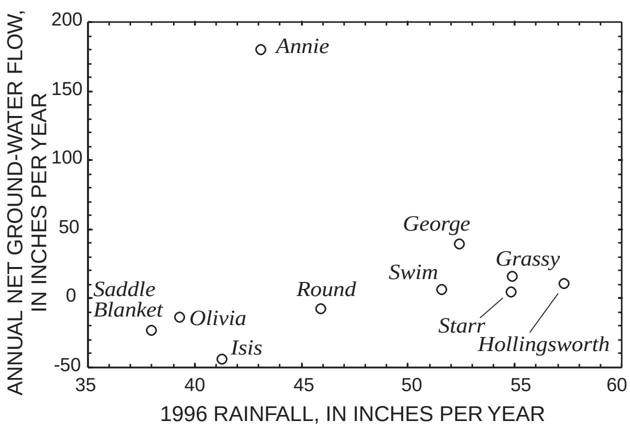


Figure 8. Relation between annual net ground-water flow and rainfall for calendar year 1996 at the study lakes.

Although the net ground-water flow method does not allow ground-water inflow and outflow to be readily distinguished, an approximation of ground-water outflow can be derived from the month with the most negative net ground-water flow (appendix). Months with the most negative ground-water outflow typically have low rainfall. Thus, it is assumed that ground-water inflow is minimal and that net ground-water flow is predominantly ground-water outflow during this month. Further, it is assumed that ground-water outflow remains relatively constant throughout the year, allowing the monthly outflow estimate to be extrapolated for the year, but ground-water inflow is more seasonally variable. This assumption is based on Lee and Grubbs (in press) and Lee (1996), who found that monthly ground-water outflow varied by less than 40 percent, whereas monthly ground-water inflow varied by more than 100 percent. Ground-water pumping, however, can seasonally affect the downward head gradient and amount of ground-water outflow, which this approach ignores. The estimate of ground-water outflow computed in this manner can then be used with the other water-budget terms to estimate ground-water inflow.

The study lakes had large differences in the annual estimate of ground-water inflow and outflow (table 4). Swim Lake and Lake Isis had the highest ground-water outflow (greater than 80 in/yr), and Grassy Lake and Lake Starr had the lowest ground-water outflow (less than 30 in/yr). Other than Lake Annie, which had at least 180 in/yr of ground-water inflow (based on net ground-water flow), Swim Lake had the highest ground-water inflow, followed by Lakes Hollingsworth and Isis (table 4). Grassy Lake, Lake Olivia, Round Lake, Saddle Blanket Lake, and Lake Starr had similarly low ground-water inflow estimates (between 26 and 33 in/yr).

Monthly patterns in net ground-water flow can be related to monthly patterns of other hydrologic variables. Thus, cause and effect can sometimes be inferred. Net ground-water flow results are presented for each study lake in the following sections, and important controlling factors on net ground-water flow are discussed. These sections are separated into seepage lakes and surface-water drainage lakes. The seepage-lake section is divided into two sections based on rainfall during the study. This facilitates comparisons between lakes under similar climatic conditions.

Seepage Lakes

For most seepage lakes, there was a seasonal pattern of positive net ground-water flow in summer months (June through September, normally the wet season) and negative net ground-water flow (net ground-water outflow) during drier months. Seepage lakes in the southern part of the study area, however, had below average rainfall and not all of them displayed this seasonal pattern.

Lakes with Below Average Rainfall

Seepage lakes with below average rainfall in 1996 were Lake Isis, Lake Olivia, Saddle Blanket Lake, and Round Lake. Monthly net ground-water flow and stage hydrographs for these lakes are shown in figure 9. The rainfall deficit was most extreme in northern Highlands County and southern Polk County, in the vicinity of Lake Isis, Lake Olivia, and Saddle

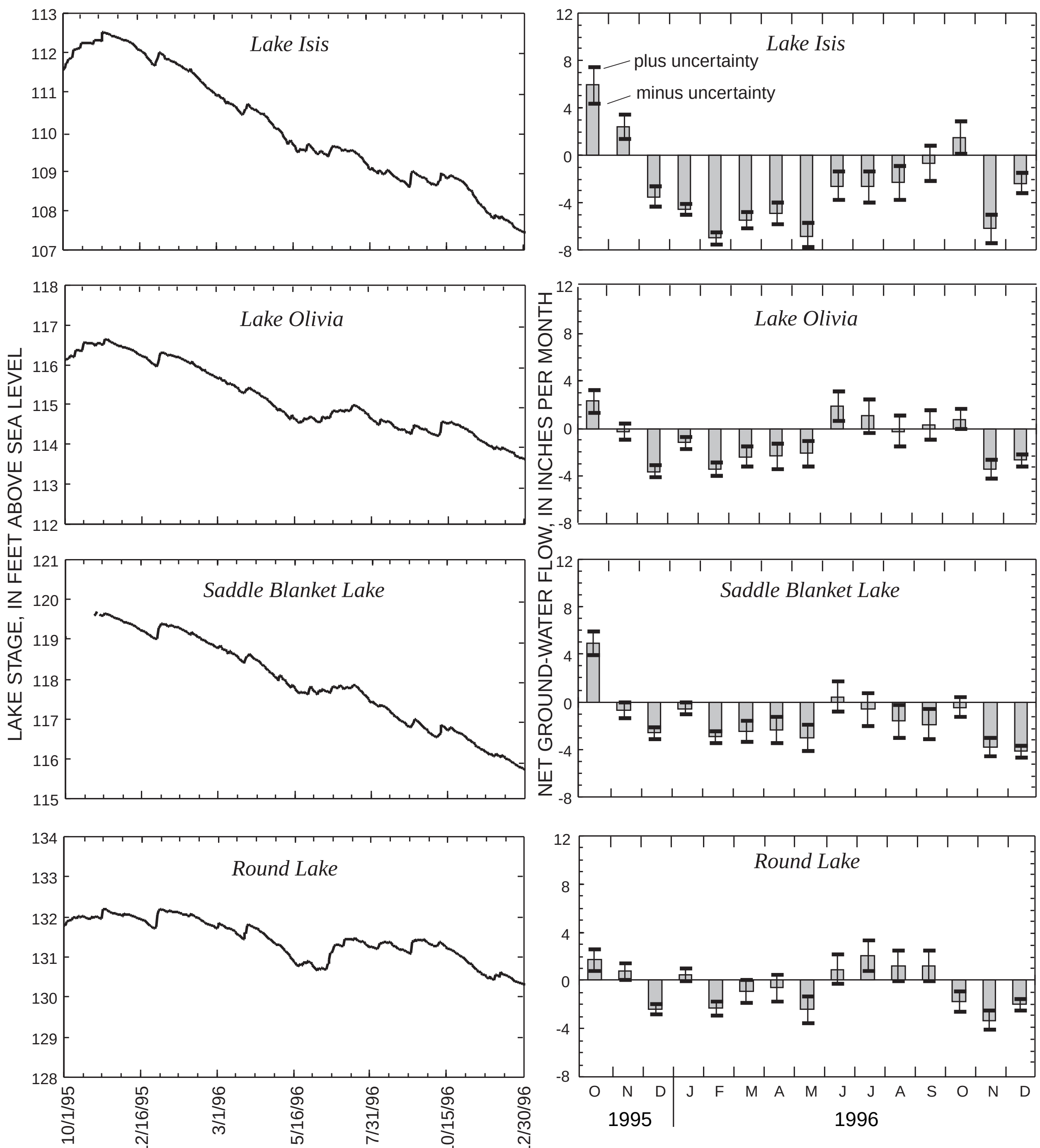


Figure 9. Stage hydrographs and monthly net ground-water flow for seepage lakes with below average rainfall during 1996: Lake Isis, Lake Olivia, Saddle Blanket Lake, and Round Lake.

Blanket Lake. These lakes also started out at a high stage because of a wet summer in 1995. Total rainfall was more than 11 in. above normal in 1995 at the nearest NWS site. Much of the 1996 rainfall deficit at these lakes occurred during the summer, which is typically the wet season. Lake Isis and Saddle Blanket Lake had negative net ground-water flow (net ground-water outflow) for all months except one during 1996, and as a result their stage dropped significantly. In contrast, Lake Olivia received more ground water than it lost for 4 months between June and October 1996, and, as a result, its stage did not drop as dramatically.

Despite having similar amounts of rainfall, Lake Isis had more positive net ground-water flow during wet periods and more negative net ground-water flow during dry periods than nearby Lake Olivia and Saddle Blanket Lake (fig. 9). Lake Isis is a deep lake (mean depth of 28 ft) with a steep-sloped lake bottom. It also has a steeper and larger topographic basin than Lake Olivia and Saddle Blanket Lake. The south and west side of Lake Isis receives ground-water inflow, and the north and northeast side has ground-water outflow (fig. 5a). Lateral outflow is probably driven by a 10-ft head difference between Lake Isis and a lake 0.3 mi to the north. In addition to the lateral outflow, Lake Isis appears to be well connected to the underlying Upper Floridan aquifer. For example, net ground-water flow was more negative (net ground-water outflow) during months with higher head gradients between the lake and the Upper Floridan aquifer (difference computed between monthly average lake stage and monthly average head for a well with a continuous recorder). Ground-water inflow paths at Lake Isis are probably relatively long and deep, as evidenced by the best relation between monthly net ground-water flow being with 4 months cumulative rainfall (rainfall for the month when net ground-water flow was computed plus the three preceding months; to maximize the period of record, rainfall before the study was estimated from the nearest NWS site) (table 5). The higher net ground-water flow during the early, wet part of the study indicates that Lake Isis is capable of receiving significant amounts of ground-water inflow. However, the higher amount of ground-water outflow creates a "threshold" that recharge must exceed before the lake level can rise.

Table 5. Summary of strength of linear relations between monthly net ground-water flow and cumulative rainfall and between monthly net ground-water flow and head difference between the lake and the Upper Floridan aquifer for the study lakes

[No., number; diff; difference; inst. mst, instantaneous measurements (one reading per month); cont. mst, continuously recorded measurements; r^2, coefficient of determination; all regressions significant to alpha level of 0.05 unless otherwise noted; --, well with continuously recorded head data not available within 5 miles of lake]

Lake	No. months cumulative rainfall[1]	Cumulative rainfall r^2	Head diff. inst. mst r^2	Head diff. cont. mst r^2
Annie	4	0.78	0.46	--
George	[2]5	[2].78	.29	--
Grassy	[3]2	[3].87	.50	--
Hollingsworth	4	.47	[4].03	--
Isis	4	.77	.57	0.76
Olivia	2	.81	[4].19	.63
Round	2	.68	[4].20	--
Saddle Blanket	2	.69	[4].37	--
Starr	4	.71	[4].28	.81
Swim	1	.62	[4].13	--

[1]Includes month when net ground-water flow computed; rainfall for months before the data collection period from nearest National Weather Service site; relations listed are strongest of those tested (1 to 6 months).
[2]Using rainfall collected at site only (September 1995 through December 1996).
[3]For months not affected by pumping (October 1995, and May through December 1996).
[4]Regression not statistically significant at alpha level of 0.05.

In contrast, ground water appears to be less significant in Lake Olivia's water budget than in Lake Isis' budget. This is illustrated by comparing the stage hydrographs and monthly net ground-water flow at Lakes Isis and Olivia during the study (fig. 9 and appendix). The stage of Lake Olivia rose less than Lake Isis's stage during the early, wet part of the study (October to November 1995). During this period, net ground-water flow at Lake Olivia was only 23 percent of that at Lake Isis. Similarly, Lake Olivia's stage dropped less than Lake Isis's stage during the dry period of 1996 (January to May 1996), during which time Lake Isis lost 2.5 times more water to net ground-water outflow (negative net ground-water flow) than Lake Olivia did. Lake Olivia is shallower (mean depth 16 ft), has a flatter topographic basin, and has shallower depths to the water table in its basin than Lake Isis. The water-table configuration around Lake Olivia varied depending upon rainfall conditions. Most of the time, the lake was a flow-through lake, with outflow toward a nearby lake (Lake Chilton, which is about 3 ft lower) and sometimes toward the north (fig. 5b). However, following periods of high recharge, water-table mounding caused flow reversals, and the entire perimeter contributed ground-water inflow to the lake. During these times, net ground-water flow was greatest. Ground-water inflow paths at Lake Olivia are relatively short, shown by a good linear relation between monthly net ground-water flow and 2 months cumulative rainfall (table 5). Lake Olivia also might not be as influenced by short-term stresses in the deeper aquifer as Lake Isis. The linear relation between monthly net ground-water flow and the head difference between the lake and the Upper Floridan aquifer was not as strong at Lake Olivia ($r^2 = 0.63$,) compared to at Lake Isis ($r^2 = 0.76$; using the same Upper Floridan aquifer well with continuously recorded head data; table 5).

Saddle Blanket Lake had the lowest rainfall of the study lakes (about 38 in. for 1996). Monthly net ground-water flow was typically between the amounts calculated for Lakes Isis and Olivia (fig. 9). Saddle Blanket Lake is shallow (mean depth 6 ft) and much smaller (6 acres) than Lakes Isis and Olivia (50 and 86 acres, respectively). Saddle Blanket Lake received significant amounts of ground-water inflow during the early, wet part of the study, but during the dry period, ground-water outflow dominated the ground-water component of its budget. Ground-water inflow paths are relatively short, as seen by the best relation between net ground-water flow being with 2 months cumulative rainfall (table 5). Much of this ground-water outflow was probably lateral. The water table was lower than the lake around much of its perimeter, and inflow occurred only along the southern perimeter of the lake (fig. 6b). Lateral ground-water outflow is driven by head gradients toward the adjacent pond (about 1.5 ft lower than Saddle Blanket Lake), Lake Streety (0.3 mi north and 14 ft lower than Saddle Blanket Lake), and a nearby wetland to the northwest. During most of the study, change in stage at Saddle Blanket Lake paralleled that at Lake Olivia. However, during the latter part of 1996, when direct rainfall and evaporation were very similar at both lakes, Saddle Blanket Lake's stage dropped more rapidly than Lake Olivia's, indicating that it lost more water through ground-water outflow than Lake Olivia. During this period, the stage at the adjacent pond dropped to an extremely low level because of prolonged direct pumping for citrus irrigation. This lower pond stage probably induced more lateral outflow from Saddle Blanket Lake during this period, as indicated by a steeper slope in the water table near the northeast side of the lake.

Net ground-water flow at Round Lake was less variable than at Lake Isis and Saddle Blanket Lake (fig. 9). Round Lake showed a distinct seasonal response of net ground-water inflow during the wet season (June through September) and net outflow during the dry season. This lake is farther to the north and had slightly more rainfall than the other lakes with below average rainfall. Net ground-water flow is best related to 2 months cumulative rainfall (table 5), indicating that ground-water inflow paths to Round Lake are relatively short. The water table is depressed adjacent to the east side of the lake, indicating that ground-water outflow is occurring into the surficial aquifer system. This pattern occurs even though head gradients in the upper part of the basin are toward the lake (fig. 6a). This outflow might indicate an area of preferential downward flow, intercepting flow from the upper basin that would otherwise have entered the lake. The water-table gradient in the near-shore area sometimes reversed from outflow to inflow conditions. These reversals in gradient probably are in response to water-table mounding near the lake following recharge events. Surficial sediments contained more clay at this lake basin than at other sites, which also could influence heads in the shallow surficial aquifer system. Round Lake is occasionally pumped for citrus irrigation. Pumping was very low during the study (less than 1.0 in/mo) and did not appear to affect net ground-water flow.

Lakes with Above Average Rainfall

Swim Lake, Lake Starr, and Grassy Lake had rainfall in 1996 exceeding the 30-year mean at the nearest NWS site, and, as a result, annual net ground-water flow was positive (fig. 8). Monthly net ground-water flow at these lakes generally was more positive than at the rainfall deficit lakes, particularly during the wet season. However, significant differences in monthly net ground-water flow occurred between lakes (fig. 10).

Swim Lake had the widest range of monthly net ground-water flow of any of the seepage lakes. This lake is small (about 5 acres) and relatively deep for its size (mean depth 15 ft). Higher net ground-water flow at Swim Lake is partially related to the larger ratio of lake perimeter to surface area at this lake, compared to larger lakes. During wet months, the lake received significant amounts of net ground-water inflow (fig. 10). Conversely, during dry months, ground-water outflow exceeded inflow. Ground-water inflow paths are short because net ground-water flow is best related to rainfall in the same month, rather than a cumulative response (table 5). During June 1996, when almost 12 in. of rain fell, lake stage increased by almost 16 in. This is direct evidence for large amounts of ground-water inflow following this high rainfall event (fig. 11). The water

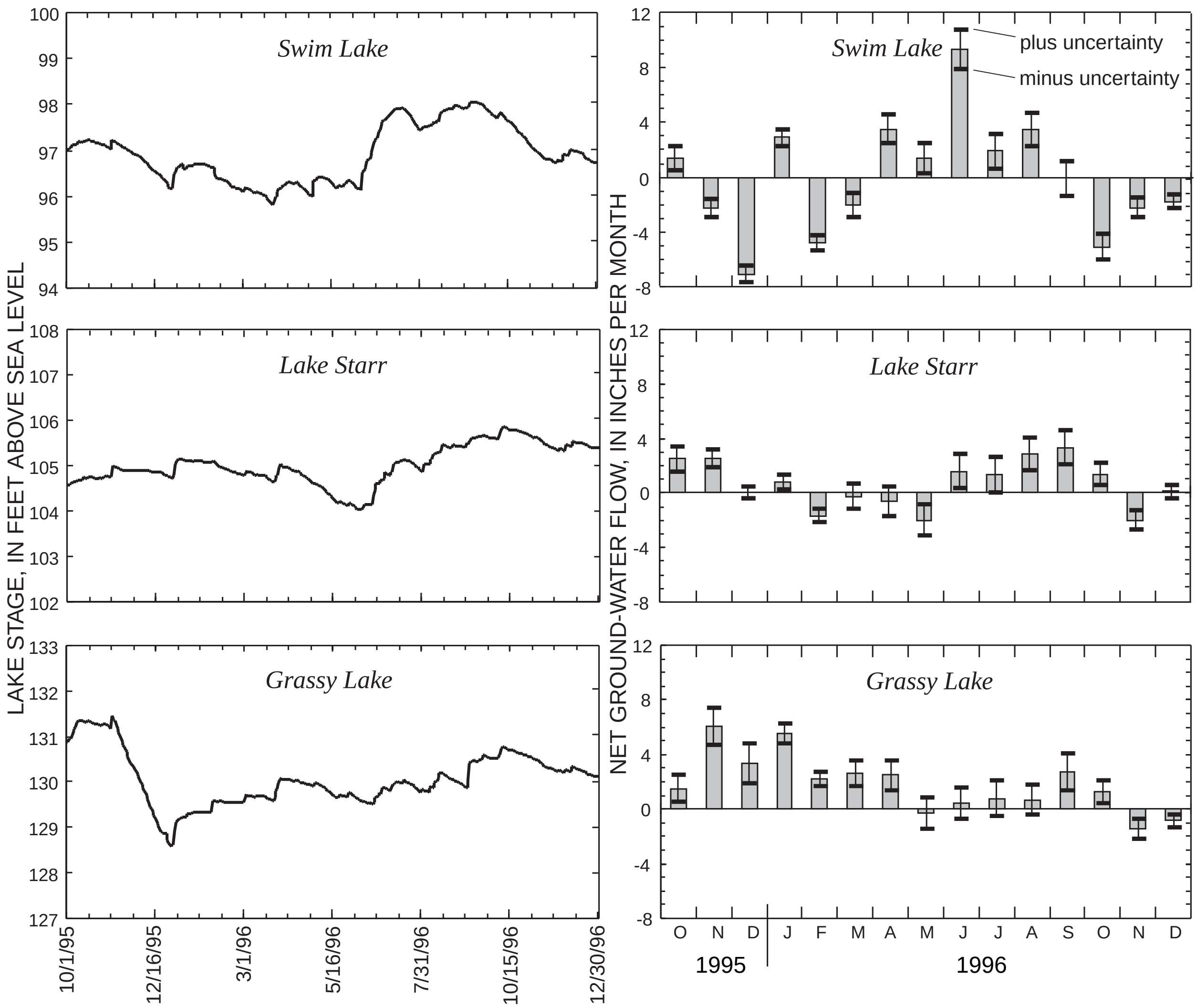


Figure 10. Stage hydrographs and monthly net ground-water flow for seepage lakes with above average rainfall during 1996: Swim Lake, Lake Starr, and Grassy Lake.

table was higher than the lake around its entire perimeter for most of the study (fig. 7b). However, lateral ground-water outflow did occur at the southwest side of the lake during dry periods. Other than during these dry periods, ground-water outflow is dominated by vertical, rather than lateral, ground-water outflow; thus, outflow probably is controlled by head differences between the lake and the Upper Floridan aquifer. Swim Lake is within an extensive citrus growing area, where heads in the Upper Floridan aquifer are expected to be influenced by short-term pumping stresses. No statistically significant relation was found between net ground-water flow and the head difference between the lake and the Upper Floridan aquifer; however, instantaneous monthly head measurements in the Upper Floridan aquifer might not have been representative of average monthly head values, particularly because of the intensity of ground-water pumping in the area.

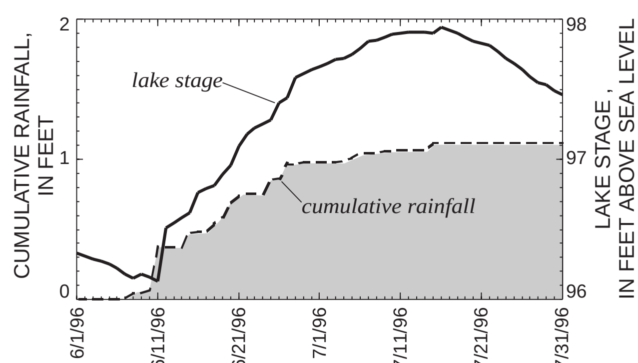


Figure 11. Cumulative daily rainfall and daily stage of Swim Lake, June through July 1996.

Monthly net ground-water flow did not vary as much at Lake Starr as it did at Swim Lake (fig. 10). The seasonal pattern of net ground-water flow is very pronounced, with the highest net ground-water flow at the end of the wet season, compared to the more flashy nature of Swim Lake. Lake Starr is a flow-through lake, with ground-water inflow occurring on its north and west sides, and ground-water outflow occurring on its south/southeast side (fig. 7a). Sinkholes are present on the outflow side of the lake, which indicates that the south side of the lake might have less confinement and a better connection to the Upper Floridan aquifer. Lake Starr is the largest seepage lake (134 acres) and has the steepest basin (table 1). Ground-water inflow paths are probably long, as evidenced by monthly net ground-water flow being best related to 4 months of cumulative rainfall (table 5), resulting in the seasonal pattern of net ground-water flow. Net ground-water flow is also related to the difference between monthly average lake stage and head in the Upper Floridan aquifer at a well with a continuous recorder ($r^2 = 0.81$; table 5).

Grassy Lake had positive net ground-water flow for most of the study (fig. 10). Lake stage was high in the early part of the study following above average rainfall during the summer and fall of 1995. As a consequence, several homes built in low-lying areas were flooded, and the lake was lowered by pumping into an adjacent lake at a rate of about 20 in/mo during November and December 1995. This pumping induced additional ground-water inflow (as indicated by high positive net ground-water flow) during the pumped period, as well as during the following 4 months (January through April). During much of the study, the lake had a minor outflow head gradient on its west/northwest perimeter (fig. 4a). However, inflow occurred around the entire perimeter during the period influenced by pumping and following a month of high recharge (September 1996) when net ground-water flow was significantly higher than during previous or following months. Grassy Lake has the shallowest topographic basin of the study lakes, and transient water-table mounds can develop following periods of high recharge. This mounding can contribute significant amounts of ground-water inflow to the lake. Ground-water inflow paths to Grassy Lake are relatively short, as evidenced by a good linear relation between monthly net ground-water flow and 2 months cumulative rainfall (table 5). The lake also probably does not have a large ground-water outflow component, indicated by less negative net ground-water flow compared to other seepage lakes during dry periods.

Surface-Water Drainage Lakes

Lakes with surface-water drainage tend to have more positive net ground-water flow than the seepage lakes (fig. 12). They also tend to have less stage change than seepage lakes because surface-water outflow moderates the stage fluctuations. The three study lakes with surface-water drainage are Lakes Annie, George, and Hollingsworth.

Lake Annie by far had the largest amount of positive net ground-water flow of all the study lakes (fig. 12). This is consistent with very high estimates of ground-water inflow (345 in/yr) from an earlier study of the lake (Battoe, 1987). Large amounts of ground water must flow into the lake to sustain the continuously flowing outflow stream. Lake Annie is a deep lake (mean depth of 30 ft), and, thus, may intercept deeper ground-water flow paths. Because the lake is in a flow-through setting with respect to the surficial aquifer system, ground-water inflow must be very high in the area of inflow. Lateral ground-water outflow occurs on the north side of the lake, which coincides with the area of surface-water outflow (fig. 3a). Net ground-water inflow occurred during all months, although there was a distinct seasonal pattern of higher net inflow during the wet season and lower net inflow during the dry season. Ground-water inflow paths are relatively long, indicated by a good linear relation between monthly net ground-water flow and 4 months cumulative rainfall (table 5).

Lake George also always had positive net ground-water flow throughout the study, although it was about 20 percent of the net ground-water flow at Lake Annie (normalized to lake surface area; fig. 12). Surface-water outflow at Lake George is constrained to a pipe in an artificially bermed area, which then flows into a small stream through a wetland (fig. 3b). Lake George is a flow-through lake, and ground-water outflow occurs in the area of surface-water outflow. The lake is shallow (mean depth of 8 ft), but the basin is relatively steep. Ground-water inflow paths are probably long because monthly net ground-water flow is best related to 5 months of cumulative rainfall (table 5). Thus, net ground-water flow at Lake George lags behind the period of most intense rainfall and is seasonal in nature, with the highest net ground-water flow occurring at the end of the wet season, and the lowest

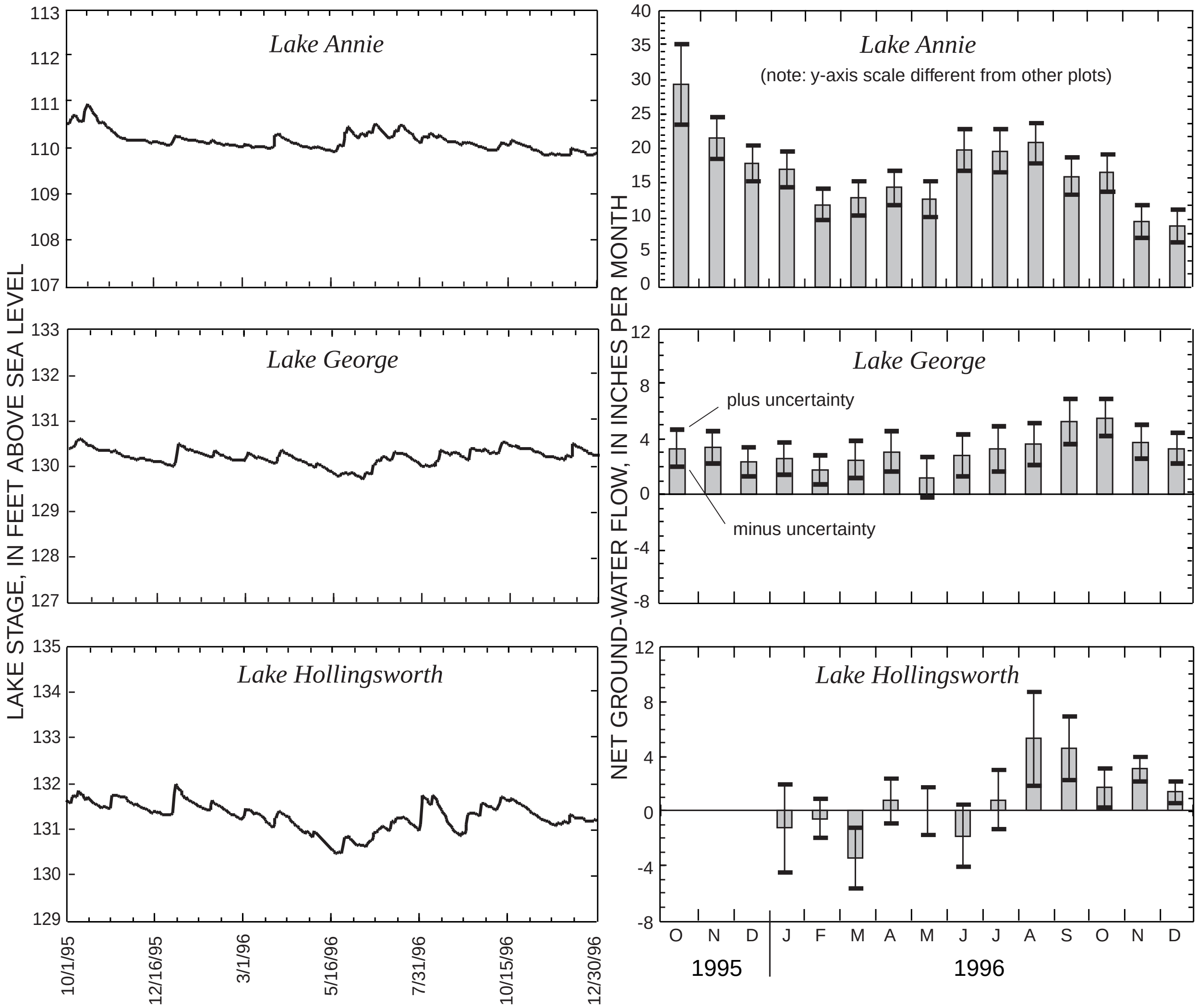


Figure 12. Stage hydrographs and monthly net ground-water flow for surface-water drainage lakes: Lakes Annie, George, and Hollingsworth.

net ground-water flow occurring at the end of the dry season.

Lake Hollingsworth is the largest and most engineered of the study lakes. An engineered lake is more hydraulically complex because it no longer responds only to natural hydrologic influences. In addition, uncertainties in net ground-water flow are high because surface-water flows are relatively difficult to quantify (fig. 12 and appendix). Surface-water outflow at Lake Hollingsworth is controlled by an adjustable gate structure, and so stage fluctuations and surface-water outflow rates are not natural. When the outflow gate was opened to its widest setting (during August 1996), surface-water discharge was about four times higher than for the previous month. The resultant stage decline apparently induced additional ground-water inflow, and net ground-water flow was almost six times higher than during the previous month. Ground-water inflow paths to Lake Hollingsworth are probably relatively long, as the best relation was between monthly net ground-water flow and 4 months cumulative rainfall (table 5). Clay-rich sediments in the upper part of the basin maintain both the water table and upgradient lakes at higher elevations than Lake Hollingsworth. For example, the water table at the well 1,800 ft north-northwest of the lake was 39 ft higher than the lake, and the stage of upgradient Lake Morton (0.6 mi north of Lake Hollingsworth) was 47 ft higher than Lake Hollingsworth (fig. 4b). Thus, downward recharge through the surficial aquifer system apparently is limited in this area, and most flow in the shallow surficial aquifer system is probably lateral toward Lake Hollingsworth. Under these conditions, the potential contributing ground-water area to Lake Hollingsworth is large. An earlier study of Lake Hollingsworth estimated that ground-water inflow to the lake was very high (about 240 in/yr; Romie, 1994).

Factors Affecting Ground-Water Exchange with Lakes

Numerous factors can affect ground-water exchange with lakes. These factors include recharge, artificial lowering of lake stage, pumping stresses from the deeper Upper Floridan aquifer, and physical features such as lake depth, basin steepness, and degree of confinement between the lake and the Upper Floridan aquifer. These factors can be classified into those that influence lateral ground-water flow and those that influence vertical ground-water flow.

Lateral Ground-Water Flow

Head gradients between the lake and the adjacent surficial aquifer system influence both lateral ground-water inflow and outflow. Where the water table is higher than the lake, ground-water inflow can occur. If the gradient increases, either due to natural recharge or artificial pumping of a lake, ground-water inflow can increase. Both near-shore and upper-basin recharge processes can influence ground-water inflow. The relative importance of these processes, however, varies between lakes.

The near-shore process of water-table mounding occurs when the water table rises rapidly in response to high recharge. This is more likely to occur in near-shore areas where the unsaturated zone is thin and recharge is efficient. Transient mounds that form on the outflow perimeter of a lake can temporarily reverse the direction of ground-water flow. As a result, ground-water outflow areas become ground-water inflow areas. This, in turn, can increase ground-water inflow and reduce lateral ground-water outflow. Of the study lakes, those in the flattest topographic settings, Grassy Lake and Lake Olivia (table 1), are most likely to experience near-shore flow reversals. Ground-water inflow to these lakes tends to be dominated by relatively short, rapid inflow paths. For example, at Grassy Lake almost 10 in. of rain fell during September 1996, and ground-water inflow occurred around the entire lake perimeter. As a result, net ground-water flow was much higher during that month compared to previous or following months (fig. 13). Similarly, months with the highest net ground-water flow at Lake Olivia corresponded to those with the highest rainfall, when ground-water inflow occurred over 80 to 100 percent of the lake perimeter (fig. 13). Other studies of Florida lakes have observed transient mounding only within 75 ft of the lake margin (Lee and Swancar, 1997; Lee, 1996). This process might be underrepresented in our study because near-shore wells typically were not installed this close to the lake, and because below average rainfall limited ground-water recharge at some of the study lakes. Monthly measurements of water levels in wells also limited the number of observations for which transient events could be observed.

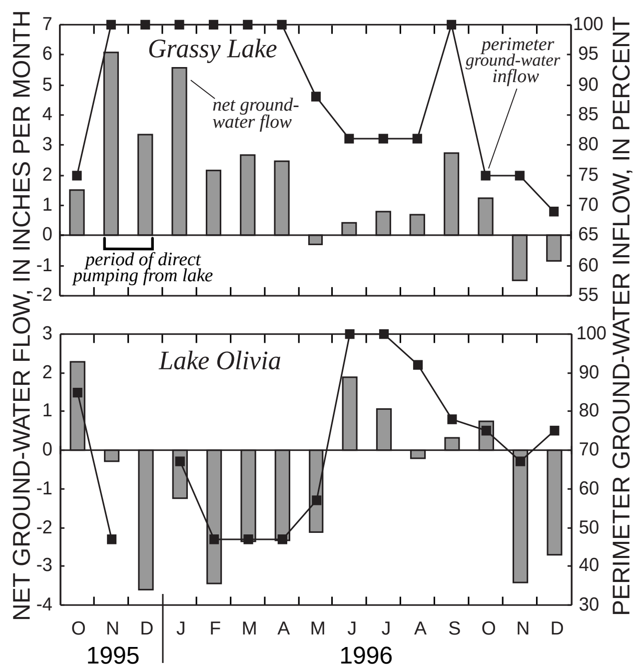


Figure 13. Monthly net ground-water flow for Grassy Lake and Lake Olivia, plotted with percent of lake perimeter that receives ground-water inflow, for the period October 1995 through December 1996.

Other lakes have a longer response time before recharge influences ground-water inflow (for example, Lakes Annie, Isis, and Starr; table 5). These lakes, which are typically in steeper topographic basins, have longer and possibly deeper inflow paths. Upper parts of the basin are probably important contributing areas of ground-water inflow to the lakes. In a steeper basin, depth to the water table is greater, and it takes longer for recharge to affect the water table. Thus, for these lakes, increases in net ground-water flow typically occur over a succession of 3 to 4 months, instead of within the month of greatest rainfall. For example, at Lake Starr the greatest net ground-water flow occurred in September 1996, at the end of the wet season, even though rainfall was lower that month than the previous 3 months (fig. 10).

Artificial lowering the level of a lake can quickly change the lateral head gradients between the lake and the adjacent surficial aquifer system. When a lake is lowered faster than the surrounding surficial aquifer system, the increased head gradient induces additional ground-water inflow. A lake can be artificially lowered by direct pumping or by increasing outflow from a control structure on an engineered lake. Grassy Lake was lowered by direct pumping from the lake (November and December 1995) in response to flooding of near-shore homes. Because the lake was lowered faster than the water table, the water-table gradient toward the lake increased during this period, which, in turn, induced significant amounts of ground-water inflow. This is illustrated by ground-water inflow occurring around the entire lake perimeter and net ground-water flow increasing, not only during the 2 months of pumping, but also during the following 4 months (fig. 13). More than half the equivalent volume of water directly pumped from the lake recharged the lake as ground-water inflow during and following the pumping period. Thus, direct pumping to alleviate near-shore flooding around a lake is not particularly efficient because induced ground-water inflow replaces some of the volume of water pumped from the lake.

At Lake Hollingsworth, the outflow gate was opened wider during one of the study months (August 1996), which lowered the lake level rapidly in a manner similar to direct pumping (fig. 12). Because of the increased lateral head gradient toward the lake, net ground-water flow to the lake increased during this period of high surface-water outflow. A volume equivalent to one-third of the water that left the lake as additional surface-water outflow entered the lake as increased ground-water inflow during this month. As a result of the additional ground-water inflow, lake stage decline was reduced.

In areas where the water table is lower than the lake, lateral ground-water outflow occurs. All of the study lakes had an area of the lake perimeter where the water table was lower than the lake sometime during the study. Some lakes had very stable outflow head gradients, whereas others had reversals in flow due to transient water-table mounding. The lateral outflow head gradient from a lake can increase in response to low recharge, downgradient hydraulic stresses in the system, or short-term increases in lake stage due to surface-water inflow or augmentation.

Water-table gradients away from a lake can be controlled by a lower stage in a downgradient lake or by areas where confinement of the underlying aquifer is reduced. Several of the flow-through study lakes had lateral ground-water outflow that appeared to be controlled by water-table gradients between the study lake and a downgradient lake (for example, Lake Isis, Lake Olivia, and Saddle Blanket Lake). Hydraulic stresses on a downgradient lake can change these gradients and affect lateral ground-water outflow. For example, at Saddle Blanket Lake water from the adjacent pond was pumped for citrus grove irrigation. The extreme lowering of the pond's stage between September and December 1996 caused a steeper slope in the water table away from Saddle Blanket Lake toward the pond. This, in turn, probably increased lateral ground-water outflow from Saddle Blanket Lake, indicated by the large negative net ground-water flow during November and December 1996 (fig. 9).

Lateral ground-water outflow also can be controlled by reduced confinement between the surficial aquifer system and Upper Floridan aquifer in areas peripheral to a lake (Sacks and others, 1992a; Evans and others, 1994; Lee, 1996). Reduced confinement can provide a more efficient route for downward flow to the Upper Floridan aquifer. Increased downward flow reduces the water-table elevation, thereby causing lateral ground-water outflow in these areas. This might be the case at Round Lake and Lake Starr. On the east side of Round Lake, flow is towards the lake in the upper basin, yet this flow does not intercept the lake because the near-lake well is in an area of ground-water outflow (fig. 6a). It is likely that this is an area of reduced confinement, allowing a route for preferential downward flow. Hydrostratigraphic data were not collected for this study, and, thus, the degree of confinement at Round Lake can only be inferred. However, at Lake Starr, which is the focus of a more detailed water-budget study, considerable data exist on confinement characteristics in the basin. Ground-water inflow occurs on the side of the basin with good confinement between the surficial aquifer system and the Upper Floridan aquifer, whereas lateral ground-water outflow occurs on the south side of the lake, which is a less confined area with several sinkholes.

Finally, lateral ground-water outflow can be induced if a lake is at an artificially high level. This was not the case for any of our study lakes, but it has been noted in other studies in Florida (Stewart and Hughes, 1974; Belanger and Kirkner, 1994). Augmenting the level of a lake can cause it to "mound" above the surrounding water table, decreasing or eliminating ground-water inflow and increasing lateral ground-water outflow (K.A. Stelman, U.S. Geological Survey, written commun., 1997).

The depth and size of a lake are other physical characteristics that can affect the lateral exchange of water between a lake and the ground water. A deeper lake has the potential to receive more ground-water inflow than a shallow lake because the deeper lake intercepts a larger part of the surficial aquifer system (Lee and Grubbs, in press). Lakes Annie and Isis are the deepest of the study lakes (table 1). Lake Annie had the highest net ground-water inflow of all the study lakes (table 4), and Lake Isis had high net ground-water inflow during the early wet part of the study (fig. 9 and appendix). For circular lakes, a smaller lake has a larger ratio of lake perimeter to surface area than a larger lake. Thus, a small lake has the potential to have more lateral ground-water inflow relative to its surface area than a large lake (Millar, 1971; Fellows and Brezonik, 1980). However, the influence of lake size varies between lakes and is dependent on lake depth and hydrogeologic setting. This variability is exemplified by the differences in net ground-water flow for the two smallest study lakes, Swim Lake and Saddle Blanket Lake (which both have surface areas less than 10 acres). Swim Lake had a large amount of ground-water exchange, whereas Saddle Blanket Lake had minimal ground-water inflow, and ground-water exchange was dominated by ground-water outflow (figs. 9 and 10; appendix).

Vertical Ground-Water Flow

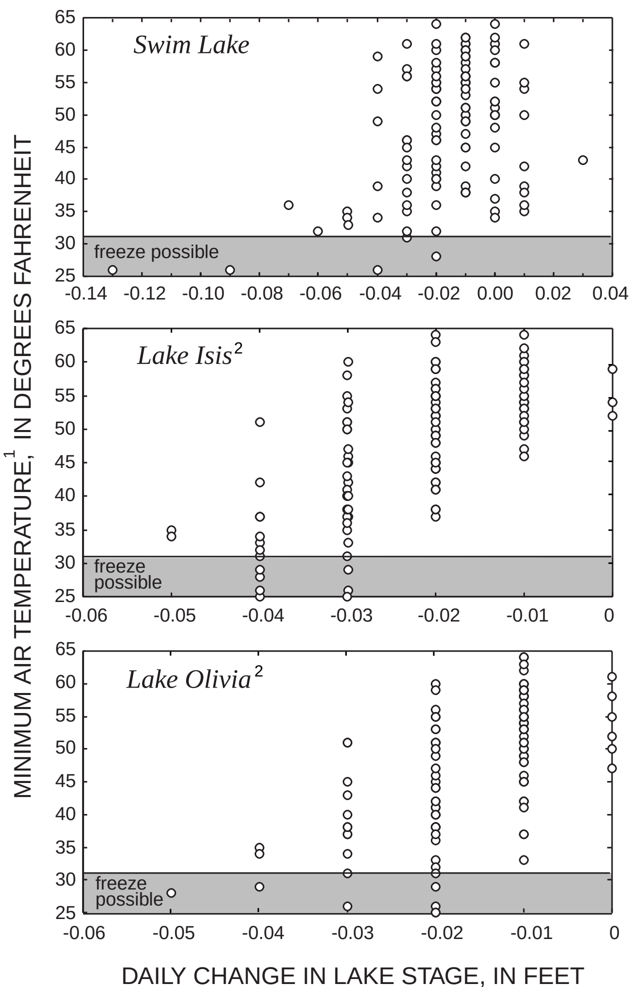
A downward head gradient exists between all of the study lakes and the Upper Floridan aquifer, indicating a potential for downward ground-water outflow to the deeper aquifer. Thus, the deeper aquifer never contributes ground-water inflow to the study lakes, but it does influence vertical ground-water outflow. In contrast to lateral ground-water outflow described in the preceding section, this vertical outflow is controlled by the head difference between the lake and the deeper aquifer and by the physical characteristics of the sublake geology. For example, a deeper lake can lose more water through vertical ground-water outflow because it occupies a deeper subsidence feature, and, thus, is closer to the influence of the Upper Floridan aquifer. Thickness of lake sediments and disruption in sublake confining units also influence vertical ground-water outflow.

Pumping from the Upper Floridan aquifer can influence the short-term downward head difference between a lake and the aquifer. For this reason, a single monthly aquifer head measurement can greatly misrepresent overall monthly conditions. Hydraulic conditions are more accurately represented by computing the difference between monthly average lake stage and monthly average head in the deeper aquifer (when a well is available with continuously recorded head data). For example, at Lake Starr there was a much better relation between monthly net ground-water flow and the head difference computed from continuously recorded water levels in an Upper Floridan aquifer well outside of the basin ($r^2 = 0.81$), compared to the difference computed from a monthly water-level measurement in a well near the lake ($r^2 = 0.28$, which is not a statistically significant regression to alpha level of 0.05) (table 5). A continuously monitored Upper Floridan aquifer well was in the general proximity (less than 5 mi) of Lakes Isis, Olivia, and Starr. These lakes had much better linear relations between monthly net ground-water flow and the vertical head difference (average $r^2 = 0.73$) compared to the seven lakes with only instantaneous head measurements (average $r^2 = 0.28$ and many of these regressions were not statistically significant to alpha level of 0.05) (table 5). Thus, results can be inconclusive for lakes without a nearby Upper Floridan aquifer well with a continuous recorder.

During months with larger downward head differences, net ground-water flow can be more negative. Interpreting these data, however, is complicated because pumping from the deeper aquifer and rainfall are inversely related. For example, during the dry season, increased pumping for citrus-grove irrigation occurs at the same time that recharge and ground-water inflow are low. During the wet season, there is less pumping for irrigation and ground-water inflow is higher. Net ground-water flow results reflect the combined effects that climate and pumping have on lateral and vertical exchange of ground water; thus, results cannot readily distinguish between these correlated inflow and outflow terms.

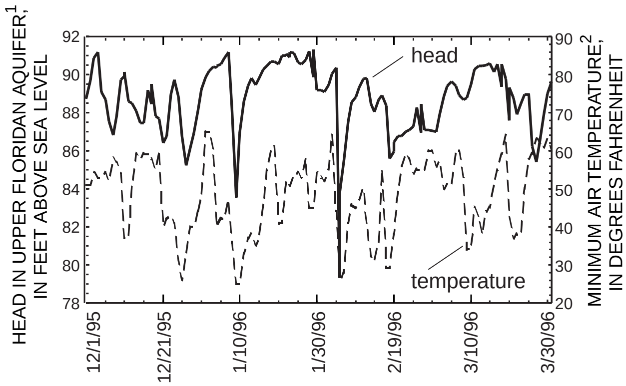
More direct evidence of the effects of pumping from the Upper Floridan aquifer on ground-water outflow from a lake is seen during cold periods, when citrus growers pump large amounts of water from the aquifer to protect their crops from frost damage. At Swim Lake, which is a small lake surrounded by citrus agriculture, lake stage declined significantly during these cold periods (fig. 14). It is likely that these above-normal declines in lake stage were caused by ground-water outflow induced by increased withdrawals from the Upper Floridan aquifer. However, head gradients between the lake and the Upper Floridan aquifer during these cold periods could not be quantified because a deep well with a continuous recorder was not available near Swim Lake.

Similar observations of lake stage declines during cold periods were made at other study lakes, although they were less pronounced than at Swim Lake (fig. 14). For example, stage declines at Lakes Isis and Olivia were typically greater during periods when a freeze was possible than at other times. Lake Isis has citrus agriculture only in its upper basin, and Lake Olivia does not have any citrus agriculture in its basin. Thus, regional-scale effects of pumping on heads in the Upper Floridan aquifer are probably being observed. This is supported by daily head data from an Upper Floridan aquifer well near Lake Isis, where head declines of as much as 11 ft were observed during cold periods (fig. 15).



1 Air temperature from nearest National Weather Service site.
2 Air temperature from following day.

Figure 14. Relation between minimum air temperature and daily change in lake stage, for days without rain between December 1995 and March 1996, and December 1996, for Swim Lake, Lake Isis, and Lake Olivia.



1Head data from ROMP43xx (Southwest Florida Water Management District, written commun.,1997).

2Temperature data from National Weather Service site Avon Park 2W.

Figure 15. Head in the Upper Floridan aquifer plotted with minimum air temperature, for the period December 1995 to March 1996, for a site near Lake Isis, Highlands County, Florida.

CHEMICAL MASS-BALANCE APPROACH

The chemical mass-balance approach was used to estimate ground-water inflow and outflow for the 10 study lakes. This is in contrast to the water-budget approach discussed in the previous section, which only allowed the net ground-water flow to be computed. In addition, when using steady-state assumptions, the chemical mass-balance approach computes long-term estimates of ground-water inflow and outflow. In contrast, the water-budget approach computes short-term flow estimates over the time frame considered (for example, monthly or during the study year) but cannot be used to infer the longer term or steady-state nature of net ground-water flow.

Methods

The approach used to compute ground-water inflow relies on the use of a naturally occurring tracer. This tracer can be a conservative inorganic solute, such as magnesium, chloride, or calcium (for example, Stauffer, 1985; Pollman and others, 1991; Krabbenhoft and Webster, 1995). Alternatively, the conservative tracer can be the isotope of the water molecule itself (for example, Dinçer, 1968; Turner and others, 1984; Krabbenhoft and others, 1990). Krabbenhoft and others (1994) discuss the use of both isotope and solute tracers in computing ground-water fluxes to lakes.

Theory

The chemical mass-balance approach uses a naturally occurring tracer, and combines the water budget equation (1) with the solute or isotope mass-balance equation below:

$$\Delta(VC_L) = PC_P - EC_E + S_iC_{S_i} - S_oC_L + G_iC_{G_i} - G_oC_L \quad (4)$$

where Δ is change over a specified time period of the mass of the tracer in the lake (V, lake volume, times C_L, the concentration of the tracer in the lake) and C is the concentration of the tracer in precipitation (P), evaporation (E), surface-water inflow (S_i), and ground-water inflow (G_i); the tracer concentration of surface-water outflow (S_o) and ground-water outflow (G_o) are assumed to equal that of the lake. The tracer is assumed to be conservative; that is, it is not significantly involved in any geochemical or biological reactions that significantly alter its concentration. Steady-state assumptions also require that the chemical composition of the lake is representative of longer-term hydrologic conditions than just the conditions during the study (Pollman and others, 1991; Pollman and Lee, 1993). The water budget equation (1) can be rearranged to solve for G_o and substituted into equation (4). This equation can then be rearranged to solve for G_i, resulting in the following equation, which eliminates G_o (and associated errors in its estimate) from this approach:

$$G_i = \frac{PC_P - EC_E + S_iC_{S_i} - (P - E + S_i)C_L}{(C_L - C_{G_i})} \quad (5)$$

Ground-water outflow can then be calculated by solving the steady-state water budget equation (1).

Precipitation (P) used in equation 5 was the 10-year (1987-96) average rainfall from the NWS site closest to each lake (table 6), and evaporation (E) was the 10-year average pan evaporation from the Lake Alfred NWS site, adjusted using a pan coefficient of 0.70 (53.1 in.). Surface-water inflow (S_i) (for Lakes Annie and Hollingsworth) was assumed to equal annual values measured during the water-budget study period (table 4). Storm-water inflow for Lakes Hollingsworth and Isis was estimated as a percentage of the 10-year average rainfall using methods described in the water-budget section. Surface-water outflow cancels out when equations (1) and (4) are combined and, thus, does not need to be defined in equation (5).

Table 6. Selected hydrologic and chemical parameters used for the chemical mass-balance approach (equation 5)

[in/yr, inches per year; δ_E, isotopic composition of evaporating water; δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; VWM, volume-weighted mean; Cl, chloride; Na, sodium; δ_a, isotopic composition of atmospheric moisture]

Lake	P[1] (in/yr)	δ_E for δD[2] (per mil)	δ_E for δD[3] (per mil)	δ_E for $\delta^{18}O$[3] (per mil)
Annie	51.4	-52.0	-47.4	-10.31
George	53.1	-35.6	-29.2	-6.07
Grassy	51.5	-32.6	-26.0	-5.37
Hollingsworth	54.8	-23.8	-17.3	-4.61
Isis	48.9	-52.6	-49.3	-10.25
Olivia	48.9	-34.4	-29.4	-6.77
Round	51.5	-22.3	-16.1	-3.44
Saddle Blanket	48.9	-14.6	-14.6	0.16
Starr	49.4	-30.8	-24.3	-4.64
Swim	49.4	-59.9	-53.7	-10.98

Parameters the same for each lake:

VWM rainfall concentration: for Cl = 0.82 mg/L[4], for Na = 0.45 mg/L[4], for δD = -20.6 per mil, for $\delta^{18}O$ = -3.89 per mil

δ_a back-calculated using Lake Starr water budget using Cl as a tracer: for δD = -105.3 per mil, for $\delta^{18}O$ = -17.95 per mil

[1]Average for 1987-96 from nearest National Weather Service rainfall site.
[2]Using δ_a assuming isotopic equilibrium with rainfall.
[3]Using δ_a back-calculated from Lake Starr water budget using Cl as a tracer.
[4]From Pollman and Canfield (1991) and Baker (1991).

Equation 5 was solved using different solutes (chloride, sodium, calcium, magnesium, potassium, and bromide, for selected lakes only) and the stable isotopes of the water molecule (deuterium and oxygen-18). Concentrations of tracers were measured in ground-water and lake-water samples collected during the study. Solute tracer concentrations in rainfall were estimated from 5-year volume-weighted mean concentrations at a site in Highlands County (Pollman and Canfield, 1991) and were adjusted for dry deposition based on Baker (1991) (table 6). The ratios of deuterium and oxygen-18 in rainfall and stormwater inflow were estimated as the volume-weighted mean concentration of these isotopes in rainwater collected at Saddle Blanket Lake. Solute concentrations in stormwater inflow (Lake Isis and Hollingsworth only) were estimated from several point samplings during storm events. For a solute tracer, the concentration of the solute in evaporating water (C_E) is essentially zero, and the term EC_E can be omitted from equation 5. However, the isotopic composition of evaporating water is not zero, and this term needs to be included when deuterium and oxygen-18 are used as tracers.

Estimating Deuterium and Oxygen-18 in Evaporating Water

The greatest challenge to using deuterium (δD) and oxygen-18 ($\delta^{18}O$) as conservative tracers is defining the isotopic composition of evaporating water (Krabbenhoft and others, 1990). Isotope ratios are defined in delta (δ) notation normalized to Vienna Standard Mean Ocean Water, and are expressed in units of per mil. Following nomenclature from Krabbenhoft and others (1990) and originally derived by Craig and Gordon (1965), the isotopic composition of evaporating water (δ_E) can be defined as:

$$\delta_E = \frac{\alpha'\delta_L - h\delta_a - \varepsilon}{(1 - h + 0.001\Delta\varepsilon)} \qquad (6)$$

where δ is the δD or $\delta^{18}O$ composition of evaporating water (E), lake water (L), and atmospheric moisture (a); α' is the equilibrium isotope fractionation factor at the temperature of the air-water interface (which is equivalent to $1/\alpha$ defined by Majoube, 1971, and is a function of the average water-surface temperature of the lake); h is relative humidity normalized to average lake water-surface temperature, expressed as a fraction; ε is the total fractionation factor, expressed in per mil, and is equal to $1000\ (1 - \alpha') + \Delta\varepsilon$; and $\Delta\varepsilon$ is the kinetic fractionation factor, expressed in per mil (estimated as 12.5 (1 - h) for δD and 14.2 (1 - h) for $\delta^{18}O$; Gonfiantini, 1986). Variables α', h, ε, and $\Delta\varepsilon$ are all functions of climatic variables of air temperature, lake water-surface temperature, and humidity. Assuming these are the same at all of the lakes (which is probably a reasonable assumption because of their geographic proximity; Krabbenhoft and others, 1994), δ_E can be solved as a function of δ_L (which was measured) and δ_a (which was not measured).

Besides direct measurement of δ_a (Krabbenhoft and others, 1990), which was beyond the scope of this study, δ_a can be estimated by either assuming it is in isotopic equilibrium with rainwater, which was collected at one of the study lakes, or by back-calculating δ_a from a lake with a “known” water budget. Both approaches were attempted for this study. When back-calculating δ_a, the ground-water inflow to Lake Starr computed using chloride as a tracer was used. Values are included in table 6. Ideally, ground-water inflow also would be independently corroborated using a more accurate method like three-dimensional, ground-water flow modeling.

When δ_a was assumed to be in equilibrium with rainwater, the isotopic composition of evaporating water (δ_E) was estimated monthly using equation (6). From these monthly values, an annual volume-weighted mean δ_E was computed for each lake. An example for Swim Lake is shown in table 7. The volume-weighted mean δ_E was very similar to that computed using annual average climatic variables. For $\delta^{18}O$, there was an average of 3 percent difference between δ_E computed from monthly values and from annual mean values; for δD, the average difference was 14 percent, which is probably related to the poorer analytical precision for δD (2 per mil) compared to $\delta^{18}O$ (0.2 per mil). Thus, it may be sufficient to compute δ_E for Florida lakes from annual average data, rather than from monthly values, because the seasonal climatic variability is relatively low compared to more temperate regions.

Table 7. Monthly mean values used to compute the isotopic composition of evaporating water at Swim Lake using deuterium and assuming atmospheric moisture in isotopic equilibrium with rainwater

[h, relative humidity; temp., temperature; deg. C, degrees Celcius; α', equilibrium fractionation factor; $\Delta\varepsilon$, kinetic fractionation factor; ε, total fractionation factor; $\varepsilon_{\delta p-\delta a}$, equilibrium fractionation factor between δ_P and δ_a; δ isotopic composition of rainwater (P), atmospheric moisture (a), lake water (L), and evaporating water (E); E, evaporation]

Month-year	h[1,2]	Air temp.[1] (deg C.)	α'	$\Delta\varepsilon$	ε	δ_P[3]	$\varepsilon_{\delta p-\delta a}$[4]	δ_a[5]	δ_L[6]	δ_E[7]	E[8]
Jan-96	0.673	14.7	0.91599	4.09	88.1	-18.8	91.7	-110.5	-6.45	-59.4	2.3
Feb-96	0.696	15.1	0.91648	3.80	87.3	-11.8	91.1	-102.9	-6.43	-70.1	2.4
Mar-96	0.625	16.3	0.91773	4.68	87.0	-38.8	89.6	-128.4	-6.42	-33.0	4.0
Apr-96	0.635	20.4	0.92184	4.56	82.7	-14.1	84.8	-98.9	-6.40	-69.9	5.3
May-96	0.627	24.9	0.92628	4.66	78.4	-13.1	79.6	-92.6	-6.42	-69.5	5.4
Jun-96	0.634	25.8	0.92705	4.58	77.5	-23.2	78.7	-101.9	-6.43	-51.0	5.4
Jul-96	0.657	27.5	0.92863	4.29	75.7	-18.5	76.9	-95.4	-6.45	-54.7	6.2
Aug-96	0.632	26.5	0.92777	4.59	76.8	-1.7	77.9	-79.6	-6.47	-87.4	5.3
Sep-96	0.646	26.2	0.92748	4.42	76.9	-21.1	78.2	-99.3	-6.48	-52.5	6.2
Oct-96	0.672	23.2	0.92459	4.10	79.5	-29.5	81.6	-111.1	-6.50	-32.7	4.1
Nov-96	0.632	19.4	0.92086	4.60	83.7	-17.6	85.9	-103.5	-6.48	-65.1	3.5
Dec-96	0.694	16.8	0.91820	3.83	85.6	-5.7	89.1	-94.8	-6.47	-83.2	2.3
Average	0.652	21.4	0.92287	4.35	81.5	-20.7	83.6	-104.3	-6.45	-55.2	[9]-59.9

[1]From Lake Starr (July through December); for January through June, data from Tampa International Airport, adjusted with linear regression equation computed for overlapping data.

[2]Normalized to lake water-surface temperature: vapor pressure of air divided by saturation vapor pressure at lake water-surface temperature.

[3]Averaged between months when sample overlapped months; for January, estimated from average for December, February, and March samples.

[4]Computed as 1000 (α - 1), where $\alpha = 1/\alpha'$.

[5]Assumed to be in isotopic equilibrium with rainwater ($\delta_a = \delta_P - \varepsilon_{\delta p-\delta a}$).

[6]Extrapolated linearly between April and October samplings.

[7]Computed using equation 6.

[8]From the 1996 water budget.

[9] Volume-weighted δ_E, in per mil, computed by summing monthly δ_E times E, and then dividing by total E for year.

Sample Collection

Ground water and lake water were sampled three times during the study. The three samplings were designed to define seasonal and annual variability in water quality. The sampling times were at the end of the 1995 wet season (October to early December), at the end of the 1996 dry season (April to May), and at the end of the 1996 wet season (October to November). During the first sampling, all monitoring wells finished in the shallow part of the surficial aquifer system were sampled. During the following samplings, only near-lake wells were sampled. It was assumed that these near-lake wells intercept the ground water entering the lake. For the last sampling, wells sampled at most lakes were near-lake wells with ground-water inflow head gradients (that is, with the most frequently observed flow direction toward the lake, figs. 3 through 12); for Grassy Lake, Lake Olivia, Round Lake and Lake Starr, wells with ground-water outflow gradients were also sampled. Results were primarily used to quantify the range of concentrations in ground-water inflow.

Samples were collected from wells after the volume of water in the casing was purged at least three times, and after field measurements of temperature, pH, and specific conductance stabilized. Dissolved oxygen and acid neutralizing capacity (alkalinity) were measured in the field. Dissolved oxygen was measured with a field meter in a flow-through chamber to eliminate exposure to the atmosphere. Acid neutralizing capacity was determined by titration with sulfuric acid, using the Gran titration method (Stumm and Morgan, 1981). Samples were collected with a peristaltic pump, except when depth to water exceeded the pump capacity; in those cases, a bailer was used to purge and sample the wells.

Before the lakes were sampled, lateral and vertical stratification were evaluated by measuring profiles of temperature, specific conductance, and dissolved oxygen in about five locations in the lake. Most lakes did not show lateral or vertical stratification in specific conductance, indicating that the lakes were chemically well mixed for major solutes. The two deepest lakes (Lake Annie and Isis) occasionally had subtle vertical stratification of specific conductance in the deepest 10 ft, but this represented a very small part of the total lake volume. Thus, one representative sample was collected at all lakes. Samples were collected from a depth of 3 to 4 ft using a peristaltic pump.

Ground-water and lake-water samples were collected for major ions, selected trace constituents, and dissolved nutrients. Samples were filtered through a 0.45 micrometer in-line filter for anion, cation and nutrient analysis. Cation and trace metal samples were collected in acid-washed bottles and acidified with 1 mL of 70 percent nitric acid. Nutrient samples were chilled immediately. Samples were analyzed by the USGS laboratory in Ocala, Florida. Analyte-free deionized water was run through sampling equipment for field blanks. Most solutes were below the laboratory detection limit in the blanks; solutes that were detected were always at or near the detection limit and were far below concentrations in the ground water or lakes. About 10 percent of the samples were collected in duplicate to better define analytical precision.

During the spring and fall 1996, deuterium and oxygen-18 samples were collected from each lake and from at least two ground-water inflow wells in each lake basin. For three lake basins (Grassy Lake, Round Lake, and Lake Starr), all near-lake wells were sampled for δD and $\delta^{18}O$. Unfiltered samples were collected in glass bottles with polyseal caps for isotope analysis. Isotope samples were analyzed by the USGS Isotope Fractionation Laboratory in Reston, Virginia.

Tracer concentrations in surface-water inflow to Lake Hollingsworth and in stormwater inflow to Lakes Hollingsworth and Isis needed to be estimated. During the spring and fall 1996 samplings, water was collected at the outflow structure of Lake Horney, which drains directly into Lake Hollingsworth through a pipe network. Point stormwater inflow samples were collected for Lakes Hollingsworth and Isis. For Lake Hollingsworth, three storm drains were sampled during 2 different storm events. For Lake Isis, three storm events were sampled. Whole samples were collected, immediately chilled, and sent to the laboratory for filtration, preservation, and analysis.

Rainwater was collected for δD and $\delta^{18}O$ analysis from Saddle Blanket Lake. A modified storage rain gage was used as a sample collector, with the funnel emptying directly into a sample bottle. A plastic ball was placed inside the funnel so that water from the bottle was sealed from the atmosphere except during rain events. This method has proven successful in preventing evaporation and subsequent isotopic enrichment of rainwater samples (Scholl and others, 1995). A mesh screen was used over the funnel to keep out large debris and to contain the plastic ball during high intensity rain events. The sampler was mounted about 5 ft above the ground. Samples were collected approximately once a month for about a year. Selected rainfall samples were also analyzed for bromide to evaluate its use as a tracer.

General Water Quality Characteristics

Before using the chemical mass-balance approach, general characteristics of ground-water and lake-water quality were examined. These data are useful in defining spatial variability in ground-water inflow concentration, and in illustrating the influence of ground water on lake-water quality. Complete analytical data are available in the USGS annual data report for southwest Florida (Coffin and Fletcher, 1998a, b).

Ground Water

Land use significantly influences the ground-water quality in the shallow surficial aquifer system. The presence of sandy soils combined with high recharge rates can readily transport fertilizers and other solutes applied at land surface. This can result in enrichment of many ions over background concentrations. The study area is characterized by heavy citrus agriculture and increasing amounts of residential development. Undeveloped lake basins are very rare. Land use is a significant factor when applying the chemical mass-balance method because major-ion concentrations in ground water can be quite variable in a developed basin. Ranges of selected constituents in ground water are included in table 8, and the composition of median ground-water inflow for each lake basin is illustrated by stiff diagrams (fig. 16).

Two of the study lakes were in undeveloped basins (Lake Annie and Saddle Blanket Lake). In these basins, ground water from the shallow part of the surficial aquifer system was relatively dilute (specific conductance typically less than 100 µS/cm) and slightly acidic (pH values typically less than 5). Generally, sodium and chloride were the dominant ions in ground water, and calcium, magnesium, and sulfate were depleted relative to evaporative concentration of atmospheric deposition (wet plus dry deposition). Nitrate concentrations were negligible (Tihansky and Sacks, 1997).

Table 8. Range and median water-quality and isotopic data for water from the surficial aquifer system in near-lake, inflow wells for each lake basin

[All units in milligrams per liter unless noted; no., number of; sp. cond., specific conductance, µS/cm, microsiemens per centimeter at 25 degrees Celsius; min, minimum value; max, maximum value; med, medium value; ANC, acid neutralizing capacity; δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; <, less than; N, nitrogen; $CaCO_3$, calcium carbonate]

Lake	No. wells[1]	Sp. cond., field (µS/cm)			Field pH (standard units)			Calcium, dissolved			Magnesium, dissolved			Sodium, dissolved			Potassium, dissolved		
		min	max	med	min	max	med	min	max	med	min	max	med	min	max	med	min	max	med
Annie	2	51	72	62	3.93	4.29	4.11	0.09	0.20	0.15	0.2	1.0	0.6	1.7	3.9	3.5	<0.01	0.01	<0.01
George	4	195	386	270	4.03	6.90	4.63	14	20	18	5.0	13	8.5	2.8	6.9	5.5	10	20	15
Grassy	5	101	551	186	3.91	6.57	5.49	5.0	30	16	1.4	33	3.6	1.1	18	4.3	1.4	23	6.6
Hollingsworth	6	117	312	179	4.40	6.52	5.07	2.8	56	4.8	1.0	5.0	3.6	1.8	28	7.0	0.2	2.5	0.8
Isis	4	75	282	139	4.39	6.17	5.27	3.3	16	8.3	2.0	9.0	3.4	2.3	12	4.8	0.2	7.9	0.8
Olivia	4	34	264	98	4.85	6.37	5.43	2.5	20	8.7	0.2	2.6	1.6	0.1	27	4.7	<0.1	4.2	1.7
Round	4	275	597	370	4.12	4.55	4.26	12	44	25	6.0	29	16	3.5	11	5.7	8.8	25	15
Saddle Blanket	2	59	126	93	3.65	4.53	4.19	0.05	2.6	1.0	0.2	0.8	0.5	1.8	8.7	6.1	0.2	0.6	0.4
Starr	5	33	385	153	4.19	6.87	4.91	2.4	26	9.7	0.6	13	1.8	0.9	18	2.8	0.4	13	1.8
Swim	4	261	478	308	4.23	4.81	4.48	19	32	22	5.0	16	8.4	2.4	9.6	4.8	13	19	15

Lake	Chloride, dissolved			Sulfate, dissolved			ANC, total, as $CaCO_3$			Nitrate, dissolved as N			δD[2] (per mil)			$\delta^{18}O$[2] (per mil)		
	min	max	med	min	max	med	min	max	med	min	max	med	min	max	med	min	max	med
Annie	3.4	7.1	6.6	1.2	7.2	3.3	-6.9	-3.3	-4.2	<0.02	<0.02	<0.02	-24.5	-19.5	-22.5	-4.58	-3.98	-4.23
George	14	29	19	12	58	39	-6.0	14	1.0	7.6	24	12	-17.9	-10.4	-12.0	-3.34	-2.43	-2.73
Grassy	2.4	55	14	6.8	35	23	-7.3	62	12	<0.02	37	3.5	-23.2	-11.3	-18.4	-4.07	-2.29	-3.48
Hollingsworth	2.6	62	16	0.7	28	5.7	-1.6	141	3.2	<0.02	4.7	1.6	-16.7	-13.8	-16.0	-3.33	-3.08	-3.20
Isis	6.1	25	12	7.1	40	20	-2.0	47	3.1	0.14	11	1.6	-23.9	-16.5	-20.8	-4.38	-3.53	-4.17
Olivia	1.1	48	7.3	<0.2	22	9.5	5.1	35	11	<0.02	1.4	<0.02	-23.1	-18.9	-22.7	-4.43	-3.70	-4.21
Round	22	44	32	0.3	100	38	-4.9	1.4	-3.1	11	36	23	-21.2	-4.6	-14.1	-3.92	-1.20	-2.63
Saddle Blanket	3.7	21	9.3	<0.2	15	4.5	-13	-0.3	-3.9	<0.02	<0.02	<0.02	-26.7	-16.8	-20.0	-4.79	-3.50	-3.94
Starr	1.5	78	5.8	2.4	55	18	-5.1	60	0.5	0.45	12	1.2	-24.6	-17.5	-22.6	-4.51	-3.75	-4.26
Swim	5.8	18	9.0	33	81	43	-4.3	-0.54	-2.8	16	28	21	-21.0	-12.7	-18.2	-3.61	-2.68	-3.46

[1]Number of wells used to define ground-water inflow; near-lake wells with inflow head gradients more than half the time (figs. 3-12); each well sampled three times (fall 1995, spring 1996, fall 1996).

[2]Isotopes only sampled twice; two near-lake inflow wells sampled at each lake basin except Grassy Lake, Round Lake, and Lake Starr, where all near-lake inflow wells were sampled.

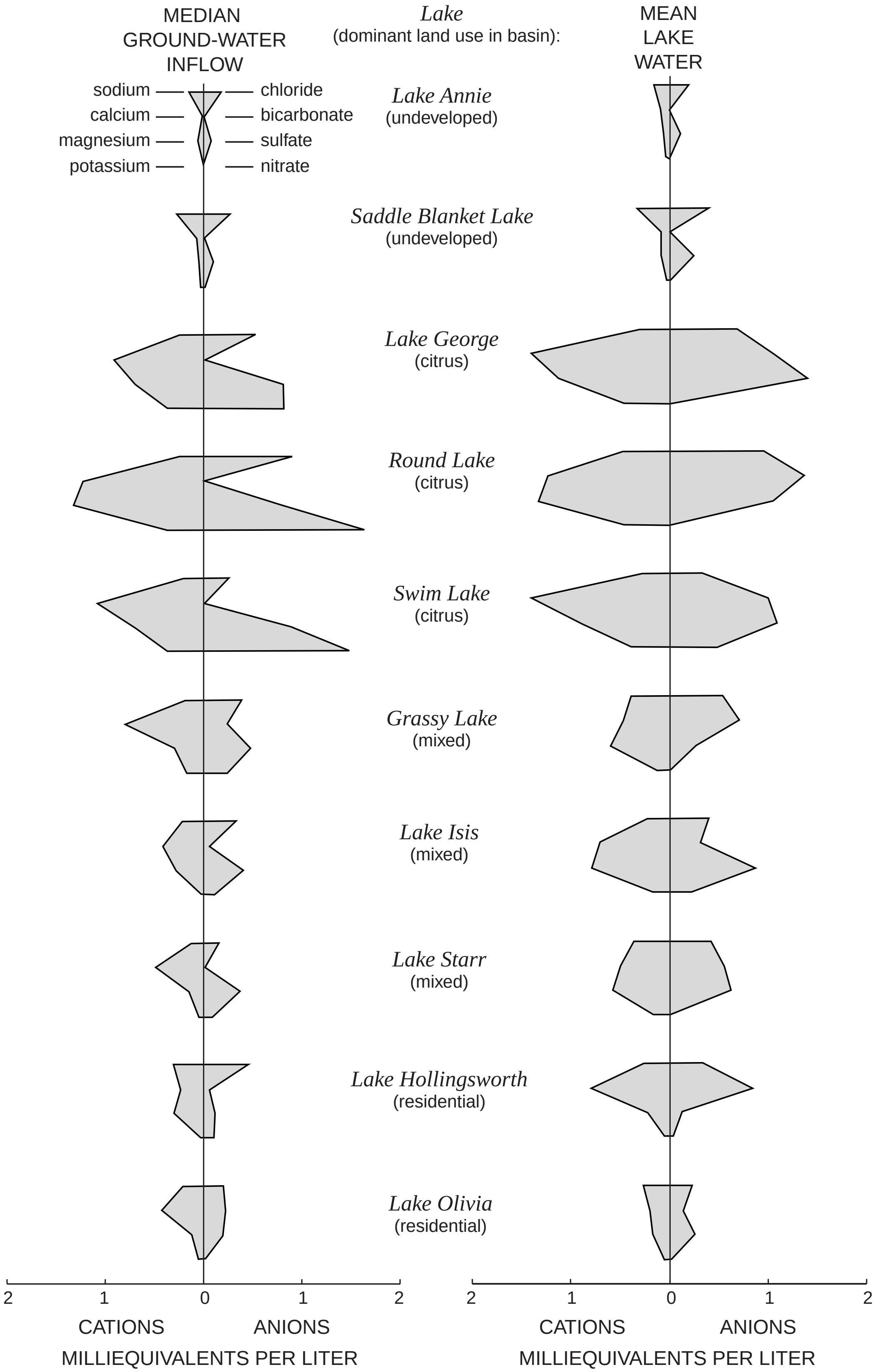


Figure 16. Chemical composition of ground-water inflow and lake water.

Waters from the shallow surficial aquifer system in areas of citrus agriculture had a distinct chemical composition (table 8 and fig. 16). These ground waters were highly enriched in calcium, magnesium, potassium, sulfate, and nitrate, as a result of fertilizer applications and possibly irrigation water. Chloride was sometimes, but not always, enriched because chloride salts are not uniformly applied to all groves. The amount of solute enrichment varied widely and is probably related to differences in grove management practices and the well locations relative to groves and ground-water flow paths. Specific conductance was typically high (greater than 250 μS/cm) because of solute enrichment from fertilizers and possibly irrigation water, and pH values were typically low (less than 5). It is interesting to note that the water is not buffered by the addition of calcium and magnesium, probably because nitrification reactions (whereby ammonia from fertilizers is converted to nitrate) produces H^+ ions (Stumm and Morgan, 1981). Nitrate concentrations in ground water were almost always greater than 10 mg/L as nitrogen (N), and were greater than 50 mg/L in water from several wells in upper parts of lake basins (Tihansky and Sacks, 1997).

Ground-water composition in residential areas or areas of mixed land use was highly variable and probably depended on a number of factors, such as homeowner and agricultural fertilizer practices, the presence of septic tanks, and upgradient land use. Enriched sodium and chloride concentrations probably are related to septic-tank leachate (Cogger and others, 1988; Alhajjar and others, 1989; Alhajjar and others, 1990). Acid neutralizing capacity and pH values were sometimes higher than in undeveloped and citrus-growing areas. Nitrate concentrations typically were much lower than in citrus-growing areas, but in places were above background levels (table 8).

In areas of the basin that received ground-water outflow from the lake (determined from head measurements), ground water typically had sodium and chloride concentrations more similar to the lake water than the surrounding ground water. However, this was not always the case, probably because recharge between the lake and the well site can dilute the lake water, and land-use practices (such as citrus agriculture) can overwhelm the lake-water signature. Ground-water outflow was sampled for δD and $\delta^{18}O$ at only three lake basins (Grassy Lake, Round Lake, and Lake Starr). At two of these, lake water could be distinguished in the ground water because of enrichment of δD and $\delta^{18}O$ (fig. 17). Similar isotopic enrichment has been noted in areas of ground-

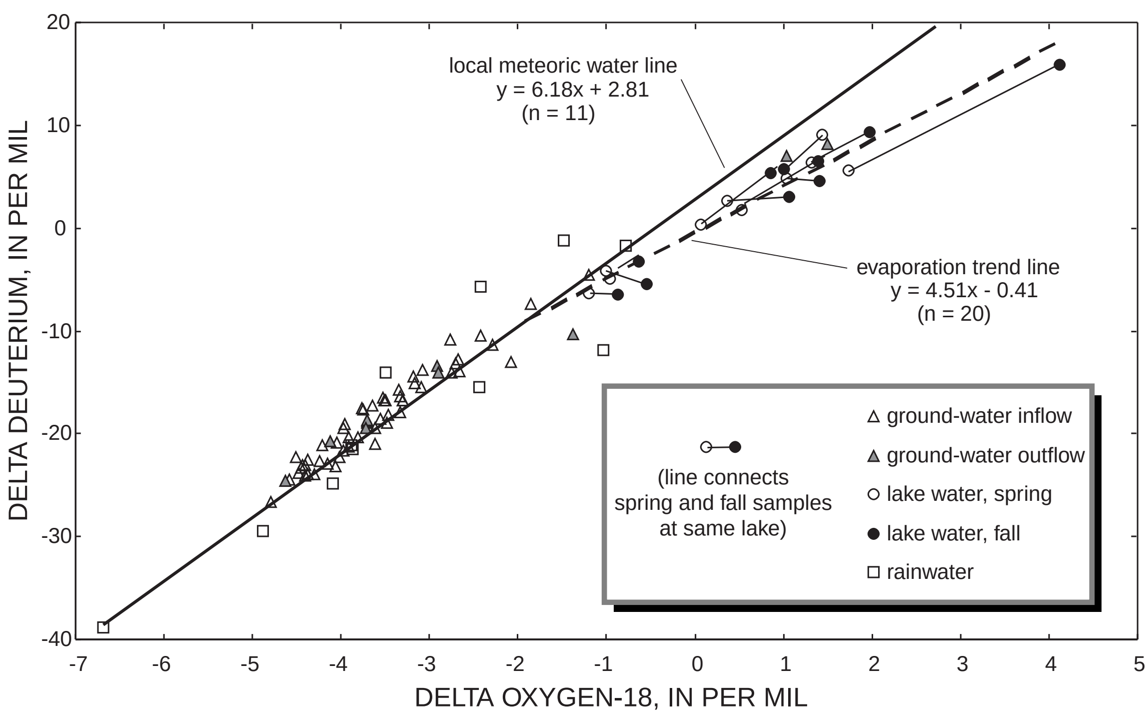


Figure 17. Relation between delta deuterium and delta oxygen-18 in ground water, lake water, and rainwater.

water outflow in other studies (Krabbenhoft and others, 1990; Sacks and others, 1992b; Katz and others, 1995). In contrast, ground-water inflow not in contact with lake water had isotopically lighter values and plots near the meteoric water line (fig. 17).

When using the chemical mass-balance approach (equation 5), the tracer concentration of ground-water inflow to each lake has to be estimated. Major-ion concentrations in ground water typically varied both temporally and spatially within a lake basin. In undeveloped lake basins, spatial and temporal variability were similar. However, in the other lake basins, spatial variability was always more than twice that of the temporal variability, and solute concentrations could vary spatially by more than 100 percent in a given lake basin. The ground-water tracer concentration used in equation 5 was the median concentration of water from near-shore wells with a ground-water inflow gradient for more than half the time (table 8). Sensitivity of the calculations to uncertainties in the ground-water inflow tracer concentration are discussed in a later section. In contrast to solute tracers, δD and $\delta^{18}O$ ratios in ground-water inflow were more uniform.

Lake Water

Lakes in ridge areas of Florida are naturally acidic due to low base cation concentrations and low acid neutralizing capacity in water from the surficial aquifer system (Canfield, 1983; Brenner and others, 1990; Pollman and Canfield, 1991). The study lakes in pristine areas (Lake Annie and Saddle Blanket Lake) had the lowest pH values (less than 6) (table 9). These lakes were dilute (specific conductance generally less than 100 µS/cm) and dominated by sodium and chloride ions (table 9 and fig. 16). Calcium and sulfate concentrations were depleted relative to atmospheric deposition.

Table 9. Mean water-quality and isotopic data and principal land use for the study lakes

[All units in milligrams per liter unless noted; undev, undeveloped; res., residential; sp. cond., specific conductance; µS/cm, microsiemens per centimeter at 25 degrees Celsius; ANC, acid neutralizing capacity; δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; <, less than; >, greater than; N, nitrogen; $CaCO_3$, calcium carbonate; ft, feet]

Lake	Principal land use in basin	Sp. cond., lab (µS/cm)	Field pH (standard units)	Calcium, dissolved	Magnesium, dissolved	Sodium, dissolved	Potassium, dissolved
Annie	undev.	42	5.57	1.7	0.7	3.6	0.7
George	citrus	354	8.10	28	14	6.8	18
Grassy	citrus, res.	172	7.75	9.5	7.3	8.8	4.8
Hollingsworth	res.	148	9.52	16	2.6	5.7	0.7
Isis	citrus, res.	216	7.10	14	9.6	5.3	6.6
Olivia	res.	81	7.10	4.0	2.0	6.1	1.8
Round	citrus	370	7.97	25	16	11	18
Saddle Blanket	undev.	105	4.13	1.5	1.0	7.3	0.5
Starr	citrus, res.	177	7.51	10	6.8	8.3	6.2
Swim	citrus	321	7.88	28	11	6.4	15

Lake	Chloride, dissolved	Sulfate, dissolved	ANC, total, as $CaCO_3$	Nitrate, dissolved as N[1]	Secchi depth (ft)	δD[2] (per mil)	$\delta^{18}O$[2] (per mil)
Annie	6.9	5.4	-0.34	<0.02	11	-4.1	-0.80
George	24	67	53	0.07	6	2.9	0.71
Grassy	19	13	35	<0.02	2	4.1	0.96
Hollingsworth	12	5.9	42	<0.02	0.7	7.5	1.23
Isis	14	42	16	3.1	17	-4.8	-0.78
Olivia	8.6	13	6.9	0.02	10	2.8	0.46
Round	34	50	68	<0.02	5	7.9	1.65
Saddle Blanket	14	12	-3.8	<0.02	> 9	10.8	2.93
Starr	15	30	28	<0.02	9	4.8	1.22
Swim	12	52	50	6.9	15	-6.5	-1.04

[1]To compute mean, less than values set to half the detection limit.
[2]Isotopes only sampled twice.

The chemical composition of lakes in basins dominated by citrus agriculture is markedly different than lakes in pristine areas. These lakes (Lake George, Round Lake, and Swim Lake) had pH values greater than 7 and specific conductance greater than 300 μS/cm. Major-ion concentrations were also distinctly different than concentrations in pristine lakes, with significant enrichment over background levels of calcium, magnesium, potassium, sulfate, bicarbonate, and sometimes chloride (depending upon grove management practices) (table 9 and fig. 16). This ion enrichment is consistent with other studies of lakes in citrus-impacted basins in Florida (Pfischner, 1968; Stauffer, 1991). Ion enrichment is direct evidence of ground water's influence on lake water quality. The increased loading of base cations from the ground water can increase the acid neutralizing capacity of a lake (Stauffer, 1991). These lakes also probably have greater loading of nitrate from ground water (table 8), and denitrification reactions and biological assimilation of nitrate during photosynthesis can increase lake acid neutralizing capacity and pH (Stumm and Morgan, 1981).

Lakes in basins with residential or mixed land use typically had specific conductance values between those in pristine and citrus-agriculture basins (less than 250 μS/cm). Values of pH were usually greater than 7. Lakes with mixed land use that have some citrus agriculture in the basin show enrichment of major ions similar to lakes in citrus areas, but the enrichment is less pronounced (fig. 16). At Lakes Starr and Isis, most of the citrus is in upper parts of the basins. Because water quality at these lakes reflects some enrichment from citrus land use, long ground-water flow paths from upper parts of their basins are probably intercepting the lake.

Two of the study lakes (Lakes Isis and Swim) had significant free nitrate in the water column (greater than 2 mg/L as N). The other lakes had nitrate concentrations less than, or very near, the laboratory detection limit (0.01 mg/L as N). These lakes with high nitrate concentrations also had the greatest clarity based on secchi depths (average of 17 ft at Lake Isis and 15 ft at Swim Lake), and fit into a category of lakes in Highlands County described by Stauffer (1991) as "clearwater citrus ponds." The presence of nitrate and the high clarity indicate that another nutrient might be limiting the biological activity in the lake. Orthophosphate concentrations in ground-water inflow was lower at these lakes (less than 0.01 mg/L as phosphorus, P) than at the other eight lakes (average of 0.18 mg/L as P), and indicates that phosphorous might be a limiting nutrient in Lake Isis and Swim Lake. Orthophosphate concentrations were less than the laboratory detection limit (0.01 mg/L as P) in all lakes. Net ground-water flow results indicated that ground water is a significant part of the water budgets of Lakes Isis and Swim, and this probably results in higher nitrate loading to these lakes compared to lakes with less ground-water inflow. At Swim Lake, ground water from near-shore wells (presumed to represent ground-water inflow) had a median concentration of 21 mg/L as N, and the lake is entirely surrounded by citrus groves. However, at Lake Isis, the median nitrate concentration in ground water from near-shore inflow wells was much lower (1.6 mg/L as N). Some of the ground-water inflow to Lake Isis could originate in upper parts of the basin in areas of citrus agriculture, where nitrate concentrations probably are higher. This water could then be transported to the lake along deeper flow paths, passing below the shallower near-shore wells.

In the chemical mass-balance calculations (equation 5), the mean solute concentration in the lake (table 9) was used to compute ground-water inflow. Major-ion concentrations in the lakes were much more uniform between samplings than in the ground water. Variability around the mean concentration was typically less than 10 percent. For lakes with historical water-quality data, solute concentrations during the study were generally consistent with data from previous samplings.

The isotopic composition of lake water differs from that of rainwater and ground water because evaporation enriches the lake water in δD and $\delta^{18}O$. Data from the lakes plot along an evaporation line that is offset from the meteoric water line (fig. 17). Lakes with little ground-water exchange are more highly evaporated, and should plot farther along the evaporation line; in contrast, lakes with high rates of ground-water exchange should plot closer to the meteoric water line (Krabbenhoft and others, 1994). The trend line for rainwater collected for this study had a lesser slope (6.2) than the global meteoric water line (slope of 8). It is possible that some of the rainwater samples were exposed to evaporation during collection. However, the trend line through the ground-water inflow samples had a very similar slope (6.0), suggesting that the local meteoric water line might indeed be different in central Florida than the global line. The lakes typically were more enriched in δD and $\delta^{18}O$ during the fall, following the summer months when evaporation rates are highest, than during the spring (fig. 17). Lake Hollingsworth is the exception, where lighter δD and $\delta^{18}O$ values in the fall are probably indicative of dilution from stormwater inflow (which is about 70 percent of rainfall) during the wet season. The average of the two lake samplings for stable isotopes was assumed to be representative of annual average conditions. Long-term data, however, were not available on the isotopic composition of the lakes, and whether these two samples are representative of long-term conditions is not known.

Chemical Mass-Balance Results

The following sections describe ground-water fluxes computed using solutes and stable isotopes of water (δD and $\delta^{18}O$). Ground-water inflow was calculated using equation 5 for the various tracers. The inflow estimates were then used to compute ground-water outflow as the residual to the steady-state water budget equation (1).

Solute Tracer

Ground-water inflow was computed using several different solutes: chloride, sodium, magnesium, calcium, potassium, and bromide (for selected lake basins). For a given lake, estimates of ground-water inflow typically were considerably different for different tracers, which is not unusual when using multiple solute tracers (for example, LaBaugh and others, 1997; Katz and others, in press). In some cases, computed ground-water inflow or outflow was less than zero, which is an invalid numerical solution. About half the calculations using magnesium, calcium, and potassium gave invalid numerical solutions, indicating that these solutes are probably not conservative. Chloride (Cl) and sodium (Na) were the most successful tracers, based on the more frequent occurrence of valid solutions.

Bromide was sampled at several lakes to investigate its usefulness as a tracer because it is generally considered to be conservative. However, concentrations of bromide were too low in the lakes and rainfall (typically less than the laboratory detection limit of 0.001 mg/L) to be used as a tracer for this study. Bromide concentrations in ground water typically were above detection limits. However, they were spatially variable in a given lake basin, like the major ions. Thus, even if analytical detection limits were improved, bromide is probably not a better tracer than chloride or sodium.

Ground-water inflow results using Cl and Na are shown in table 10. The lake with the highest computed ground-water inflow was Lake Annie, followed by Lake Hollingsworth (about 240 and 110 in/yr, respectively, using the average of Cl and Na tracers). The high inflow computed for these lakes is relatively consistent with, but slightly lower than, estimates from previous studies, which estimated that ground-water inflow was 345 in/yr at Lake Annie (Battoe, 1987) and about 240 in/yr at Lake Hollingsworth (Romie, 1994). High ground-water inflow at Lake Annie is also consistent with net ground-water flow results (table 4). Lakes with the lowest computed ground-water inflow using Cl as a tracer were Grassy Lake and Lake Starr, and using Na as a tracer were Grassy Lake, Lake Isis, and Round Lake (table 10).

Invalid numerical solutions for Lake George and Lake Isis using Cl as a tracer might have been a result of not accurately defining the tracer concentration in ground-water inflow. Computed ground-water outflow was less than zero for Lake George using both Cl and Na, and computed inflow for this lake was significantly lower than 1996 net ground-water flow (tables 5 and 9). These results indicate that solute concentrations in average ground-water inflow are probably higher than the median concentrations used in these calculations; higher ground-water inflow and positive ground-water outflow were computed using the higher range of Cl and Na concentrations measured in ground-water inflow (table 8). Alternatively, surface-water outflow during 1996 might have been significantly greater than steady-state conditions (even after considering the uncertainty in the 1996 estimate).

For Lake Isis, the negative ground-water inflow and outflow computed using Cl as a tracer implies that the median Cl concentration from near-lake inflow wells was not representative of ground water flowing into the lake. In order to arrive at a valid numerical solution, the Cl concentration of ground-water inflow would need to be higher, but still within the range of measured ground-water inflow concentrations. Significant amounts of ground-water inflow might originate in upper parts of the Lake Isis basin, where citrus agricultural practices can contribute Cl to the ground water. This water might then follow deeper flow paths that intercept the lake at points deeper than the near-lake wells.

Table 10. Computed ground-water inflow to the study lakes using various tracers, and sensitivity of inflow calculations to concentrations of chloride and sodium in ground-water inflow

[Units in inches per year; gw, ground water; conc., concentration; %, percent; δD, delta deuterium, $\delta^{18}O$, delta oxygen-18; δ_a, isotopic composition of atmospheric moisture; n/a, numerically invalid solution; Cl, chloride]

Lake	Computed ground-water inflow						
	Using chloride		Using sodium		Using δD		Using $\delta^{18}O$
	median gw inflow conc.	minus - plus 25 % of median conc.	median gw inflow conc.	minus - plus 25 % of median conc.	assuming δ_a in equilibrium with rainwater	δ_a backcalculated from Starr Cl results	δ_a backcalculated from Starr Cl results
Annie	180	[1]28 - n/a	293	[1]30 - n/a	[1]90	[1]78	[1]100
George	[1]8	[1]4 - 51	[1]19	[1]9 - n/a	54	[2]31	[2]33
Grassy	15	9 - 49	8	7 - 11	30	15	19
Hollingsworth	90	n/a - 45	123	n/a - 52	n/a	n/a	n/a
Isis	n/a	n/a - 61	8	2 - n/a	101	90	95
Olivia	57	24 - n/a	33	18 - 166	33	22	37
Round	48	10 - n/a	8	6 - 11	6	n/a	n/a
Saddle Blanket	21	14 - 42	42	19 - n/a	n/a	n/a	n/a
Starr	11	9 - 13	10	9 - 11	23	[3]11	[3]11
Swim	29	16 - 122	29	17 - 116	183	155	160

[1]Negative ground-water outflow computed, which cannot be explained by uncertainty in 1996 surface-water ouflow estimate.
[2]Negative ground-water outflow computed, but within uncertainty of 1996 surface-water outflow estimate.
[3]Not independently computed.

The biggest uncertainty in applying the chemical mass-balance method is in defining the solute concentration of ground water inflow. As discussed earlier, Cl and Na concentrations can vary widely in a given lake basin. This uncertainty in the inflow concentration is even more significant when the solute concentration in the lake water is similar to that in the ground water because the denominator in equation 5 becomes very small (Stauffer, 1985). This occurs when ground-water inflow is high, resulting in lake water more similar in composition to ground water than to evaporated rainwater. In this situation, small uncertainties in the tracer concentration of ground-water inflow can result in large changes in the computed ground-water inflow. For example, figure 18 shows the relation between computed ground-water inflow and the assumed value of Cl concentration in ground-water inflow for two lakes. The median Cl concentration of ground-water inflow is bounded by a 25 percent range of uncertainty. For Lake Starr, which has ground-water and lake-water Cl concentrations that are distinctly different, a 25 percent increase in the ground-water Cl concentration results in a 19 percent increase in the computed inflow. In contrast, Swim Lake has a Cl concentration more similar to that of ground water, and a 25 percent increase in the Cl concentration of ground-water inflow causes a 300 percent increase in computed ground-water inflow. The range of ground-water inflow, given a 25 percent uncertainty in the median Cl and Na concentrations of ground-water inflow, is shown for all the lakes in table 10.

If a transient formulation of the chemical mass-balance approach is to be used to estimate ground-

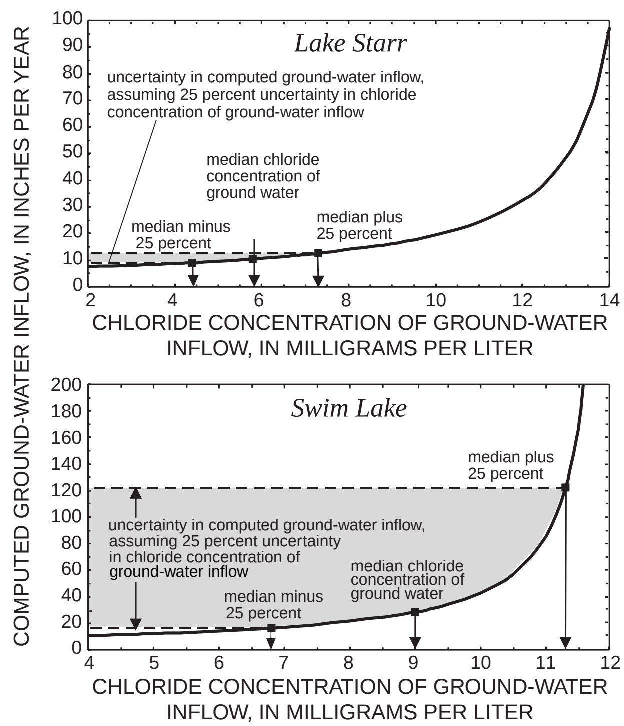


Figure 18. Relation between computed ground-water inflow and assumed chloride concentration of ground-water inflow for Lake Starr and Swim Lake.

water inflow on a short-term basis (for example, monthly or semiannually), more detailed data collection would be needed. The data needed include more accurate quantification of the solute concentration of ground water seeping into the lake, better analytical precision in lake solute concentrations (so that change in mass can be computed more accurately), sampling of rainfall at each lake, and a better estimate of short-term lake evaporation rates. A transient formulation of the chemical mass-balance approach is even more sensitive to uncertainties in terms such as the solute concentration of ground-water inflow, than is the steady-state approach (Pollman and Lee, 1993).

Isotope Tracer

Ground-water inflow was also computed using the stable isotopes of water (δD and $\delta^{18}O$). Some of the biggest drawbacks to using a solute tracer are avoided when using these isotopes. For example, the isotopic composition of ground-water inflow is much more uniform than the solute concentrations. In addition, there is always a big difference between the isotopic composition of ground-water inflow and lake water because evaporation enriches the lake water in heavier isotopes. Therefore, relatively large values are always in the denominator of equation 5, which makes the solution much more stable. The biggest difficulty in using the isotope method is the need for estimating the isotopic composition of evaporating water, which is not necessary when using a solute tracer.

For this study, the isotopic composition of atmospheric moisture (δ_a) was estimated two ways for both deuterium and oxygen-18. The first method assumed that δ_a was in isotopic equilibrium with rainwater (table 7). The second method back-calculated δ_a, using ground-water inflow estimated for Lake Starr using Cl as a tracer; this estimate of ground-water inflow for Lake Starr was relatively insensitive to the assumed ground-water inflow concentration (fig. 18 and table 10).

Ground-water inflow estimated from these two methods using δD as a tracer were relatively consistent (table 10), although the inflow estimates using δ_a back-calculated from the Lake Starr water budget were slightly lower. In contrast, when using $\delta^{18}O$ and assuming that δ_a was in isotopic equilibrium with rainwater, unrealistically high ground-water inflow (greater than 100 in/yr) was computed for most of the lakes; therefore, results are not presented in table 10. These high computed inflow rates probably indicate that $\delta^{18}O$ content of atmospheric moisture is not in isotopic equilibrium with rainwater, and that additional kinetic fractionation occurs. A more accurate definition of δ_a (for example, from direct data collection, which was beyond the scope of this study) could resolve this discrepancy. Ground-water inflow computed using $\delta^{18}O$ as a tracer, with δ_a back-calculated from the Lake Starr results, was very similar to results using δD (table 10).

Ground-water inflow computed with isotope tracers was highest for Swim Lake and Lake Isis (about 170 and 95 in/yr, respectively, using the average of the isotope tracers in table 10). These high inflow rates are supported by net ground-water flow results. Swim Lake and Lake Isis both had some months with very positive or very negative net ground-water flow, indicating that ground water is a significant part of their water budgets (figs. 9 and 10). Further, annual ground-water inflow estimated using the water-budget approach was highest for Swim Lake and third highest for Lake Isis (table 4). The presence of nitrate in the water column of these two lakes (table 9) could also be evidence that ground-water inflow is high, resulting in very high nitrate loading rates from the ground water. The high ground-water inflow rates computed using δD and $\delta^{18}O$ are not consistent with results using Cl and Na as tracers (table 10). This is probably due to large uncertainties in the Cl and Na inflow estimates because concentrations in lake water and ground water were similar (table 10).

Ground-water inflow calculated at Lake George using isotope tracers was consistent with net ground-water flow results (tables 5 and 10), and probably is between 30 and 60 in/yr. Although negative ground-water outflow was calculated for the isotope tracers when δ_a was back-calculated from the Lake Starr water budget, ground-water outflow was positive when surface-water outflow was reduced to within the range of uncertainty in this estimate. When Cl or Na tracers were used, ground-water inflow was too low, causing negative ground-water outflow to be computed. Cl and Na concentrations in water from wells at Lake George might not be representative of all ground-water inflow sources.

For four of the study lakes (Grassy Lake, Lake Olivia, Round Lake, and Lake Starr), ground-water inflow computed using isotope tracers was relatively consistent with inflow computed using either Cl or Na as tracers (table 10). Ground-water inflow at Lake Olivia is probably slightly greater (between 20 and

40 in/yr) than at Grassy Lake and Lake Starr (between 10 and 30 in/yr). Ground-water inflow to Round Lake is probably lowest (less than 10 in/yr). For Round Lake, results using δD, assuming δ_a is isotopic equilibrium with rainwater, were consistent with results using Na as a tracer (table 10). Ground-water inflow computed using Cl as a tracer, however, was much higher. Cl was enriched to varying degrees in the ground water in this citrus-agricultural basin because of fertilizer application. Na was not as enriched and, therefore, was probably the better tracer. Results for Round Lake, using δ_a back-calculated from the Lake Starr water budget, resulted in negative ground-water inflow and outflow. However, slight changes in δ_a resulted in positive, but very low, ground-water inflow. (For example, a 3 percent decrease in δ_a will cause inflow to increase to 6 in/yr).

Valid results were not obtained using δD and $\delta^{18}O$ for three of the study lakes (Lake Annie, Lake Hollingsworth, and Saddle Blanket Lake). Results using solute tracers indicated that ground-water inflow was a very significant part of the water budgets of Lakes Annie and Hollingsworth (about 240 and 110 in/yr at Lake Annie and Lake Hollingsworth, respectively, using the average of Cl and Na tracer results). For Lake Annie, ground-water inflow calculated from isotope tracers was too low, causing negative ground-water outflow to be computed. For Lake Hollingsworth, negative ground-water inflow and outflow were computed. The only term in equations 5 and 6 that can account for these low computed values is δ_a, which would need to be at least 20 percent greater for positive ground-water inflow and outflow to be computed. Lakes Annie and Hollingsworth are farther away from the other study lakes (fig. 1), and could be exposed to atmospheres with different isotopic compositions. Lake Annie is the farthest south of the study lakes, and is probably influenced by a more tropical south Florida climate. Swart and others (1989) determined that δ_a of deuterium in Florida Bay in south Florida was -75 per mil; using this δ_a value for Lake Annie results in a ground-water inflow estimate (240 in/yr) that is consistent with the average inflow estimate using Cl and Na (table 10). Lake Hollingsworth is farthest west, and closer to the Gulf of Mexico than the other lakes. It might be influenced by coastal atmospheric moisture. For future studies, atmospheric moisture or rainfall should be collected in several locations to assess the geographic variability in δ_a.

For Saddle Blanket Lake, negative ground-water inflow and outflow were computed using the isotope tracers (table 10). The period sampled for this small, shallow lake might not have been representative of steady-state conditions. Between the spring and fall 1996 samplings, 28 percent of the lake volume was lost due to evaporation and ground-water outflow. This did not significantly affect the solute concentrations in the lake, but δD and $\delta^{18}O$ values were significantly enriched between the first and second samplings because of fractionation due to evaporation. The isotopic composition of the lake (δ_L) is an important term in estimating the isotopic composition of evaporating water (δ_E) in equation 6. If the lake's isotopic composition from only the spring sampling is used to estimate δ_E, computed ground-water inflow is 16 in/yr. Thus, the isotopic composition of Saddle Blanket Lake in the fall of 1996 might not have reflected steady-state conditions, which particularly affects the δ_E computed using equation 6.

Estimating Ground-Water Exchange

Reasonable estimates of ground-water inflow were made for seven of the study lakes using deuterium, assuming that δ_a is in isotopic equilibrium with rainwater (table 11). The isotope tracers were more robust than the solute tracers because there was always a distinct difference between the isotopic composition of lake water and ground water, and because the isotopic composition of ground water was more spatially uniform than concentrations of solutes in the shallow ground water. Thus, results for these seven lakes were assumed to be good estimates of annual ground-water inflow (table 11). Ground-water outflow computed from the inflow estimates are also shown in table 11. Uncertainties in these inflow and outflow values were computed by estimating an uncertainty associated with each term used in equation 5 (for inflow) or equation 1 (for outflow), following methods described by Lee and Swancar (1997). For the three lakes where the isotope approach did not work because of difficulties defining δ_E (Lake Annie, Lake Hollingsworth, and Saddle Blanket Lake), the best estimate for ground-water inflow and outflow were assumed to be the average values computed using Cl and Na as tracers (table 11).

Table 11. Estimate of ground-water inflow and outflow and uncertainty using the most successful tracer

[units in inches per year, rounded to two significant figures; ground-water inflow estimated using deuterium as tracer and assuming atmospheric moisture in isotopic equilibrium with rainwater unless otherwise noted; G_i, ground-water inflow; e_{Gi}, uncertainty or error in ground-water inflow estimate; G_o, ground-water outflow; e_{Go}, uncertainty in ground-water outflow estimate]

Lake	G_i	e_{Gi}	G_o	e_{Go}
Annie	[1]240	120	66	120
George	54	33	17	36
Grassy	30	16	28	17
Hollingsworth	[1]110	55	92	60
Isis	100	37	100	38
Olivia	33	18	29	19
Round	6	10	2	12
Saddle Blanket	[1]30	15	26	16
Starr	23	12	19	13
Swim	180	61	180	61

[1]Average of Cl and Na tracers, error assumed to be 50 percent.

Ground-water flow results using the best tracer from the chemical mass-balance approach (table 11) were typically similar in magnitude to those computed using the water-budget approach (table 4). For example, Lake Annie, Lake Hollingsworth, Lake Isis, and Swim Lake had the most ground-water inflow using either method. Inflow and outflow estimates for these lakes, however, were lower for the water-budget approach, compared to the chemical mass-balance approach. The water-budget approach underestimated ground-water inflow and outflow for lakes with large amounts of ground-water exchange because it was assumed that the month with the most negative net ground-water flow had predominantly ground-water outflow and had minimal ground-water inflow. For lakes with large amounts of ground-water exchange, ground-water inflow is probably always significant. The water-budget approach, however, might produce a good approximation for lakes with lesser amounts of ground-water exchange. Ground-water inflow and outflow computed using the water budget approach were within the uncertainty bounds of values computed using the chemical mass-balance approach for most lakes (tables 4 and 11). Other differences in ground-water exchange between the two approaches are probably related to differences in hydrologic stresses during the 1996 water-budget period or seasonality of ground-water outflow. For example, lakes with below normal rainfall during 1996 could have had lower ground-water inflow because of reduced recharge and higher ground-water outflow because of greater ground-water pumping for irrigation, compared to the 10-year average conditions used in the chemical mass-balance approach.

Differences in ground-water exchange between the 10 study lakes illustrate the wide spectrum of ground-water/lake interactions for lakes in ridge settings of Florida. Ground-water inflow and outflow ranged over an order of magnitude at the study lakes, from less than 10 to greater than 150 in/yr. For seepage lakes, ground-water outflow is very similar to ground-water inflow on a long-term basis because long-term average precipitation and evaporation rates are very similar in the study area. Thus, a seepage lake with a large ground-water inflow component also has a correspondingly large ground-water outflow component. Extended periods of below normal rainfall can reduce recharge and ground-water inflow, resulting in large stage reductions because net precipitation (precipitation minus evaporation) and ground-water inflow decline but outflow does not. Outflow can actually increase during these periods because increased ground-water pumping can increase vertical ground-water outflow, and possibly because a greater part of the lake perimeter experiences lateral ground-water outflow. The opposite is true for wet periods, and the stage of lakes with large ground-water exchange can oscillate more widely between wet and dry years than the stage of lakes with lesser amounts of ground-water exchange.

Differences in stage fluctuations are inherently related to the ground-water exchange characteristics at individual lakes, which, in turn, are related to the lake's physical and hydrogeologic setting. Physical characteristics of the lake are important in controlling how much interaction the lake has with the ground-water system. For example, the deepest study lakes (Lakes Annie and Isis) had high rates of ground-water inflow. Results from this study indicate that lakes can be classified according to their amount of ground-water exchange; however, the number of lakes studied was insufficient to establish that physical characteristics of the lakes can be used to predict how much a lake's stage would respond to climatic extremes or increased ground-water pumping.

The isotopic composition of lakes in a similar geographic area can provide valuable information about the relative amount of ground-water inflow that a lake receives (Krabbenhoft and others, 1994). Equation 5 was rearranged to calculate C_L (the isotopic composition of the lake), assuming different amounts of ground-water inflow. This was done using parameters from one of the study lakes (Lake Starr) as an example, in a manner referred to as the "index lake method" (Krabbenhoft and others, 1994); results were plotted along with the mean isotopic composition of the other study lakes (fig. 19). Lakes become isotopically enriched (more positive) through evaporation; thus, a more positive isotopic composition indicates that evaporation is a greater part of the water budget of the lake. The isotopic composition of lakes plot within different ranges of calculated ground-water inflow. For example, the composition of Lake Isis and Swim Lake are isotopically depleted and plot in the high range of ground-water inflow (greater than 100 in/yr). These lakes have a greater amount of ground-water exchange compared to evaporation. In contrast, the composition of Round Lake is isotopically enriched and plots at the low range of computed ground-water inflow (fig. 19), indicating that evaporation is a greater part of its water budget and ground-water exchange is less important. For Lake Annie, Lake Hollingsworth, and Saddle Blanket Lake, the isotope approach did not work because of difficulties defining δ_E. The isotopic composition of these three lakes plot in ranges of less ground-water inflow (or off the scale, in the case of Saddle Blanket Lake) than would be expected based on results in table 11 (fig. 19). For Lake Hollingsworth, the isotopic composition of surface-water inflows are also not accounted for using this approach. Interestingly, the composition of Lake Annie is isotopically depleted enough to still plot in the high range of ground-water inflow (greater than 100 in/yr), even though actual ground-water inflow (table 11) is even greater than where its isotopic composition plots on figure 19.

These results reveal that the isotope approach is a promising method for evaluating the ground-water flow regime for numerous lakes in geographic proximity in Florida. The isotopes δD and $\delta^{18}O$ were used as tracers for this study in a reconnaissance manner. This is the first study to use this approach to quantify ground-water inflow to Florida lakes. Limitations exist in applying this approach because the lack of long-term data on the isotopic composition of lake water, atmospheric moisture, and rainwater. More information on spatial variability of the isotopic composition of rainwater and atmospheric moisture, and of climatic variables would also help define geographic variability and appropriate geographic range when applying this method in Florida.

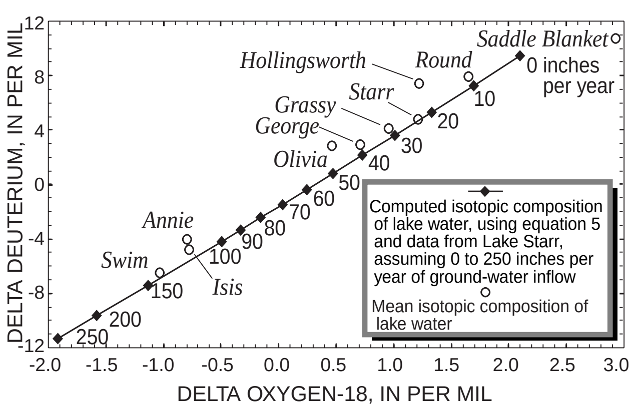


Figure 19. Relation between delta deuterium and delta oxygen-18 for mean lake water and lake water computed theoretically using equation 5.

SUMMARY AND CONCLUSIONS

Lakes can vary in their stage response to climatic conditions because of differences in the amount of ground water in their water budgets. Quantifying ground-water fluxes independently at an individual lake is time-consuming and costly, and results often cannot be extrapolated to a larger population of lakes in the region because of differences in hydrogeologic settings. Simpler techniques were used to understand ground-water exchange with Florida lakes on a more regional scale. Water budget and chemical mass-balance approaches were used to estimate ground-water exchange with 10 lakes in ridge areas of Polk and Highlands Counties. At each of the lakes, heads were monitored in the surficial aquifer system and deeper Upper Floridan aquifer, lake stage and rainfall were measured continuously, and lakes and wells were sampled three times between October 1995 and December 1996.

The study lakes were all in flow-through settings with respect to the surficial aquifer system during some of the study period. Ground water enters a lake along part of its perimeter, and the lake loses water to the aquifer along another part of its perimeter. Ground-water flow patterns do not necessarily follow topography. Several lakes exhibited ground-water flow reversals due to transient water-table mounding following periods of high recharge. Heads in the surficial aquifer system and lake stages were consistently higher than those in the underlying Upper Floridan aquifer, indicating a consistent potential for downward flow from the shallow system to the Upper Floridan aquifer.

The water-budget approach computes net ground-water flow (ground-water inflow minus outflow) as the residual of the monthly water-budget equation. Net ground-water flow varied seasonally at each of the 10 lakes and was notably different between lakes, illustrating short-term differences in ground-water fluxes. Net ground-water inflow typically occurred during the wet season, and net ground-water outflow typically occurred during the dry season. On an annual basis, seepage lakes experiencing below average rainfall had net ground-water outflow, whereas those with above average rainfall had net ground-water inflow. Estimates of ground-water inflow and outflow were made by assuming that the month with the most negative net ground-water flow had predominantly ground-water outflow and that this outflow was relatively constant throughout the year. Using this approach, the study lakes exhibited large differences in the annual estimate of ground-water inflow and outflow, which varied by more than a factor of three between lakes.

Monthly patterns in net ground-water flow were related to monthly patterns of other hydrologic variables, such as rainfall, ground-water flow patterns, and head differences between the lake and the Upper Floridan aquifer. Important factors influencing ground-water flow are lateral head gradients between the lake and surficial aquifer system and vertical head gradients between the lake and the Upper Floridan aquifer. Lakes in shallow topographic basins are more susceptible to transient water-table mounding following rainy periods, which increases net ground-water flow. Lakes in steeper topographic basins have more delayed responses to recharge, and net ground-water flow responds more seasonally. Artificial lowering of a lake's stage can induce additional ground-water inflow and affect ground-water flow patterns around the lake. Vertical ground-water outflow is influenced by the vertical head difference between the lake and the Upper Floridan aquifer. Much stronger relations were found between net ground-water flow and this head difference when computed using an Upper Floridan well with continuously recorded head data, compared to a well with single monthly head measurements. More direct evidence of the effects of pumping from the Upper Floridan aquifer on ground-water outflow was illustrated by large daily declines in lake stage that occurred when agricultural pumping was at a maximum to protect crops during potential freezes.

The chemical mass-balance approach combines the water-budget and solute or isotope mass-balance equations, and assumes steady-state conditions. The tracers were naturally occurring solutes and the stable isotopes of water (deuterium and oxygen-18). In order to use this technique, the chemical composition of the ground water and lake water were defined. Ground-water and lake-water quality were influenced by land use. Ground water and lake water in undeveloped areas were dilute and dominated by sodium and chloride ions. Ground water beneath citrus groves was enriched in most major ions and nitrate because of fertilizer use; this ground water subsequently enriches major-ion concentrations in lakes dominated by citrus agriculture. Ground-water composition in residential areas or areas of mixed land use was highly variable and probably depends on local fertilizer use, the presence of septic tanks, and upgradient land use; lakes in residential or mixed land use areas were less enriched in major ions than basins dominated by citrus agriculture.

Estimates of ground-water inflow computed using the chemical mass-balance approach varied depending on the tracer used. Chloride and sodium were the most successful solute tracers. However, chloride and sodium concentrations in ground water typically varied spatially, and in places were similar to that in lake water, limiting their sensitivity as tracers. In contrast, the isotopes were more robust tracers because the isotopic composition of ground water was relatively uniform and was distinctly different from the composition of lake water. Ground-water inflow computed using isotope tracers is sensitive to the isotopic composition of atmospheric moisture, and isotope tracers could be used more accurately if this term were measured.

Ground-water inflow varied significantly between lakes. It ranged from less than 10 to more than 150 in/yr at the 10 lakes. These results underscore how variable ground water can be in the water budget of Florida lakes and the unique nature of ground-water exchange at individual lakes. Both net ground-water flow and chemical mass-balance approaches had limitations, but the multiple lines of evidence helped better explain ground water's role in lake-water budgets. Although the lakes encompass a range of sizes and shapes that are representative of the Central Lakes District, 10 lakes were an insufficient number to establish regional classifications of lakes based on readily identifiable features. The isotope mass-balance approach is a promising method that could be applied to a larger number of lakes in the region to classify ground-water exchange for a larger population of lakes. This could help water managers and residents understand the impacts of climatic variability and aquifer pumping on lake water resources.

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Appendix

Appendix. Monthly water-budget terms, computed net ground-water flow, and estimated uncertainty in net ground-water flow for the study lakes between October 1995 and December 1996

[Units in inches per month; P, precipitation; E, evaporation; S_i, surface-water inflow; S_o, surface-water outflow; ΔV, change in lake volume; G_{net}, net ground-water flow (ground-water inflow minus outflow); e_{Gnet}, uncertainty or error in net ground-water flow; --, not applicable; <, less than]

Month	Year	P	E	S_i	S_o	ΔV	G_{net}	e_{Gnet}
Lake Annie:								
October	1995	7.7	6.7	8.0	37.7	0.5	29.2	5.8
November	1995	0.3	4.8	1.0	21.8	-3.9	21.4	3.0
December	1995	0.6	3.8	--	15.3	-0.6	17.9	2.6
January	1996	1.9	1.5	--	17.4	0.0	17.0	2.6
February	1996	1.5	1.5	--	12.8	-0.9	11.9	2.3
March	1996	5.3	2.8	--	12.7	2.7	12.9	2.4
April	1996	1.2	3.9	--	14.3	-2.7	14.3	2.5
May	1996	8.2	4.6	--	12.4	3.8	12.6	2.5
June	1996	7.2	4.6	--	23.5	-1.1	19.8	3.1
July	1996	6.2	5.4	0.5	22.8	-1.8	19.7	3.1
August	1996	4.4	6.3	< 0.1	19.0	0.0	20.9	3.0
September	1996	1.7	7.0	--	12.1	-1.4	16.0	2.7
October	1996	3.6	6.3	--	13.2	0.7	16.6	2.7
November	1996	0.3	5.3	--	6.3	-1.7	9.6	2.3
December	1996	1.6	4.1	--	6.1	0.2	8.8	2.3
Lake George:								
October	1995	5.9	4.3	--	5.4	-0.5	3.3	1.4
November	1995	1.2	3.1	--	3.6	-2.1	3.4	1.2
December	1995	0.5	2.1	--	2.1	-1.4	2.3	1.1
January	1996	5.8	2.3	--	4.4	1.8	2.7	1.2
February	1996	3.3	2.4	--	2.9	-0.2	1.8	1.1
March	1996	6.5	4.0	--	2.9	2.1	2.5	1.3
April	1996	1.3	5.3	--	2.7	-3.5	3.2	1.4
May	1996	2.3	5.4	--	0.5	-2.4	1.2	1.5
June	1996	7.1	5.4	--	0.9	3.6	2.8	1.5
July	1996	3.9	6.2	--	3.0	-2.1	3.2	1.6
August	1996	7.7	5.3	--	2.9	3.2	3.7	1.5
September	1996	5.3	6.2	--	3.9	0.5	5.3	1.6
October	1996	4.5	4.1	--	5.2	0.8	5.6	1.3
November	1996	0.6	3.5	--	3.5	-2.6	3.8	1.2
December	1996	4.1	2.3	--	4.1	1.0	3.3	1.1
Grassy Lake[1]:								
October	1995	7.2	4.3	--	--	4.4	1.5	1.0
November	1995	3.7	3.1	--	19.6	-12.9	6.1	1.3
December	1995	0.6	2.1	--	20.9	-19.0	3.4	1.5
January	1996	6.0	2.3	--	--	9.3	5.6	0.7
February	1996	2.7	2.4	--	--	2.5	2.2	0.5
March	1996	7.7	4.0	--	--	6.3	2.6	0.9
April	1996	1.8	5.3	--	--	-1.0	2.5	1.1
May	1996	2.8	5.4	--	--	-2.9	-0.3	1.1
June	1996	6.3	5.4	--	--	1.3	0.4	1.1
July	1996	5.2	6.2	--	--	-0.2	0.8	1.3
August	1996	6.4	5.3	--	--	1.8	0.7	1.1
September	1996	9.9	6.2	--	--	6.4	2.7	1.4
October	1996	3.2	4.1	--	--	0.4	1.3	0.8
November	1996	0.7	3.5	--	--	-4.2	-1.4	0.7
December	1996	2.2	2.3	--	--	-1.0	-0.9	0.5

Appendix. Monthly water-budget terms, computed net ground-water flow, and estimated uncertainty in net ground-water flow for the study lakes between October 1995 and December 1996 (Continued)

[Units in inches per month; P, precipitation; E, evaporation; S_i, surface-water inflow; S_o, surface-water outflow; ΔV, change in lake volume; G_{net}, net ground-water flow (ground-water inflow minus outflow); e_{Gnet}, uncertainty or error in net ground-water flow; --, not applicable; <, less than]

Month	Year	P	E	S_i	S_o	ΔV	G_{net}	e_{Gnet}
Lake Hollingsworth[2]:								
January	1996	5.4	2.3	6.7	8.0	0.6	-1.2	3.2
February	1996	2.8	2.4	2.4	4.1	-1.8	-0.5	1.4
March	1996	7.4	4.0	6.3	4.6	1.6	-3.5	2.2
April	1996	2.2	5.3	1.9	4.3	-4.7	0.8	1.7
May	1996	4.1	5.4	3.6	4.0	-1.8	-0.1	1.8
June	1996	7.5	5.4	6.3	4.0	2.6	-1.8	2.3
July	1996	5.5	6.2	5.1	4.5	0.8	0.9	2.2
August	1996	7.3	5.3	8.7	18.1	-2.1	5.3	3.5
September	1996	7.5	6.2	6.6	6.5	6.0	4.6	2.3
October	1996	4.0	4.1	4.3	6.1	-0.2	1.7	1.5
November	1996	1.1	3.5	0.8	5.4	-3.9	3.1	0.9
December	1996	2.5	2.3	2.1	2.6	1.1	1.4	0.8
Lake Isis[3]:								
October	1995	7.8	6.7	1.6	0.1	8.4	5.8	1.5
November	1995	2.4	4.8	0.5	0.2	0.2	2.3	1.0
December	1995	0.6	3.8	0.1	0.2	-6.8	-3.5	0.9
January	1996	3.6	1.5	0.7	0.2	-1.9	-4.5	0.5
February	1996	1.2	1.5	0.2	0.2	-7.3	-7.0	0.5
March	1996	4.8	2.8	1.0	0.2	-2.7	-5.5	0.7
April	1996	1.7	3.9	0.3	0.2	-6.9	-4.8	0.9
May	1996	5.4	4.6	1.1	0.2	-5.1	-6.8	1.1
June	1996	5.8	5.4	1.2	0.2	-1.2	-2.6	1.2
July	1996	1.9	6.0	0.4	0.3	-6.7	-2.7	1.3
August	1996	4.6	6.2	0.9	0.2	-3.2	-2.3	1.5
September	1996	5.7	7.0	1.1	0.2	-1.0	-0.6	1.5
October	1996	4.4	6.3	0.9	0.2	0.2	1.4	1.3
November	1996	0.3	5.3	0.1	0.3	-11.5	-6.3	1.2
December	1996	1.9	4.1	0.4	0.2	-4.4	-2.4	0.9
Lake Olivia:								
October	1995	6.8	4.3	--	--	4.7	2.2	1.0
November	1995	2.0	3.1	--	--	-1.4	-0.3	0.6
December	1995	1.2	2.1	--	--	-4.5	-3.6	0.5
January	1996	3.7	2.3	--	--	0.2	-1.2	0.5
February	1996	1.1	2.4	--	--	-4.8	-3.5	0.5
March	1996	3.8	4.0	--	--	-2.6	-2.4	0.8
April	1996	1.4	5.3	--	--	-6.2	-2.3	1.1
May	1996	5.1	5.4	--	--	-2.4	-2.1	1.1
June	1996	6.1	6.2	--	--	1.8	1.9	1.3
July	1996	2.9	6.8	--	--	-2.8	1.1	1.4
August	1996	3.6	6.3	--	--	-2.9	-0.2	1.3
September	1996	4.3	6.2	--	--	-1.6	0.3	1.3
October	1996	5.2	4.1	--	--	1.8	0.7	0.9
November	1996	0.5	3.5	--	--	-6.4	-3.4	0.8
December	1996	1.6	2.3	--	--	-3.4	-2.7	0.5

Appendix. Monthly water-budget terms, computed net ground-water flow, and estimated uncertainty in net ground-water flow for the study lakes between October 1995 and December 1996 (Continued)

[Units in inches per month; P, precipitation; E, evaporation; S_i, surface-water inflow; S_o, surface-water outflow; ΔV, change in lake volume; G_{net}, net ground-water flow (ground-water inflow minus outflow); e_{Gnet}, uncertainty or error in net ground-water flow; --, not applicable; <, less than]

Month	Year	P	E	S_i	S_o	ΔV	G_{net}	e_{Gnet}
Round Lake[1]:								
October	1995	5.1	4.3	--	--	2.4	1.6	0.9
November	1995	3.3	3.1	--	--	0.9	0.7	0.6
December	1995	0.8	2.1	--	--	-3.7	-2.4	0.5
January	1996	5.0	2.3	--	--	3.3	0.6	0.5
February	1996	1.2	2.4	--	--	-3.5	-2.3	0.6
March	1996	6.0	4.0	--	--	1.1	-0.9	1.0
April	1996	0.8	5.3	--	0.8	-5.9	-0.6	1.1
May	1996	3.4	5.4	--	0.8	-5.2	-2.4	1.1
June	1996	9.4	5.4	--	--	4.9	0.9	1.2
July	1996	4.2	6.2	--	0.3	-0.2	2.1	1.3
August	1996	4.2	6.3	--	--	-1.0	1.1	1.3
September	1996	6.2	6.2	--	--	1.2	1.2	1.3
October	1996	1.9	4.1	--	--	-3.9	-1.7	0.8
November	1996	0.8	3.5	--	0.5	-6.4	-3.2	0.8
December	1996	2.8	2.3	--	--	-1.5	-2.0	0.5
Saddle Blanket Lake:								
October	1995	6.0	4.3	--	--	6.6	4.9	1.0
November	1995	1.2	3.1	--	--	-2.7	-0.8	0.6
December	1995	0.9	2.1	--	--	-3.8	-2.6	0.5
January	1996	3.7	2.3	--	--	0.9	-0.5	0.5
February	1996	1.3	2.4	--	--	-4.1	-3.0	0.5
March	1996	5.0	4.0	--	--	-1.5	-2.5	0.9
April	1996	1.7	5.3	--	--	-5.9	-2.3	1.1
May	1996	5.1	5.4	--	--	-3.3	-3.0	1.1
June	1996	6.0	6.2	--	--	0.2	0.4	1.3
July	1996	2.8	6.8	--	--	-4.6	-0.6	1.4
August	1996	2.0	6.5	--	--	-6.1	-1.6	1.3
September	1996	3.7	6.2	--	--	-4.4	-1.9	1.3
October	1996	4.3	4.1	--	--	-0.3	-0.5	0.8
November	1996	0.7	3.5	--	--	-6.5	-3.7	0.8
December	1996	1.7	2.3	--	--	-4.7	-4.1	0.5
Lake Starr:								
October	1995	3.5	4.3	--	--	1.7	2.5	0.9
November	1995	2.8	3.1	--	--	2.2	2.5	0.7
December	1995	0.5	2.1	--	--	-1.6	0.0	0.4
January	1996	5.0	2.3	--	--	3.6	0.9	0.5
February	1996	0.6	2.4	--	--	-3.5	-1.7	0.5
March	1996	7.2	4.0	--	--	2.9	-0.3	0.9
April	1996	1.1	5.3	--	--	-4.8	-0.6	1.1
May	1996	1.9	5.4	--	--	-5.6	-2.1	1.1
June	1996	11.7	5.4	--	--	8.1	1.8	1.3
July	1996	5.5	6.2	--	--	0.6	1.3	1.3
August	1996	9.2	5.3	--	--	6.8	2.9	1.2
September	1996	4.8	6.2	--	--	1.9	3.3	1.3
October	1996	3.5	4.1	--	--	0.8	1.4	0.8
November	1996	1.3	3.5	--	--	-4.1	-1.9	0.7
December	1996	3.0	2.3	--	--	0.8	0.1	0.5

Appendix. Monthly water-budget terms, computed net ground-water flow, and estimated uncertainty in net ground-water flow for the study lakes between October 1995 and December 1996 (Continued)

[Units in inches per month; P, precipitation; E, evaporation; S_i, surface-water inflow; S_o, surface-water outflow; ΔV, change in lake volume; G_{net}, net ground-water flow (ground-water inflow minus outflow); e_{Gnet}, uncertainty or error in net ground-water flow; --, not applicable; <, less than]

Month	Year	P	E	S_i	S_o	ΔV	G_{net}	e_{Gnet}
Swim Lake:								
October	1995	4.1	4.3	--	--	1.2	1.4	0.9
November	1995	2.9	3.1	--	--	-2.5	-2.3	0.7
December	1995	0.6	2.1	--	--	-8.6	-7.1	0.6
January	1996	5.0	2.3	--	--	5.6	2.9	0.6
February	1996	0.6	2.4	--	--	-6.6	-4.8	0.6
March	1996	6.8	4.0	--	--	0.7	-2.1	0.9
April	1996	3.8	5.3	--	--	2.1	3.6	1.1
May	1996	3.9	5.4	--	--	-0.1	1.4	1.1
June	1996	11.7	5.4	--	--	15.7	9.4	1.5
July	1996	1.7	6.2	--	--	-2.6	1.9	1.3
August	1996	8.0	5.3	--	--	6.2	3.5	1.2
September	1996	4.2	6.2	--	--	-2.0	0.0	1.3
October	1996	2.2	4.1	--	--	-7.0	-5.1	0.9
November	1996	0.7	3.5	--	--	-5.0	-2.2	0.7
December	1996	3.0	2.3	--	--	-1.1	-1.8	0.5

[1]For Grassy Lake and Round Lake, S_o is direct pumping from lake.
[2]For Lake Hollingsworth, S_i is stormwater inflow plus surface-water inflow.
[3]For Lake Isis, S_i is stormwater inflow and S_o is direct pumping from lake.