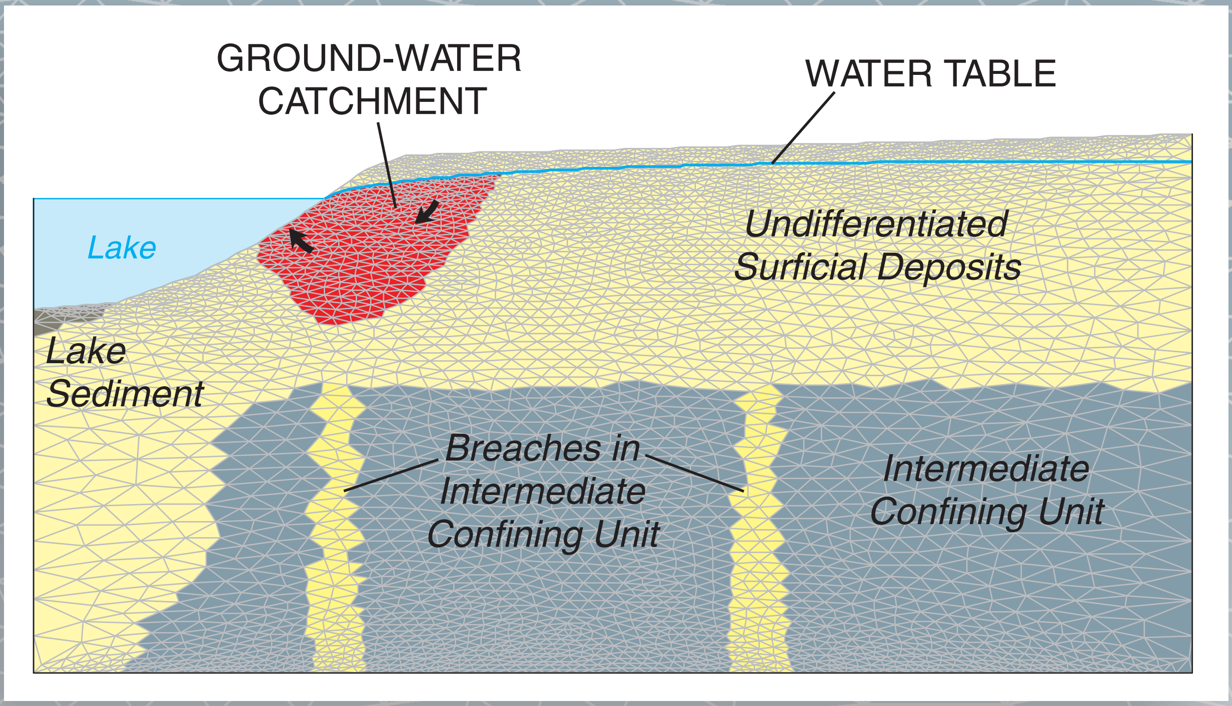
Factors Affecting Ground-Water Exchange and Catchment Size for Florida Lakes in Mantled Karst Terrain

Water-Resources Investigations
Report 02-4033



U.S. Geological Survey

Prepared in cooperation with the
Southwest Florida Water Management District
and the
St. Johns River Water Management District

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By T.M. Lee

U.S. GEOLOGICAL SURVEY
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SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT
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ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

science for a changing world

Tallahassee, Florida
2002

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Conversion Factors and Vertical Datum

Multiply	By	To obtain
inch (in.)	2.54	centimeter
inch per year (in/yr)	25.4	millimeter per year
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day
mile (mi)	1.609	kilometer
acre	4,047	square meter
acre	0.4047	hectare
cubic foot per day (ft^3/d)	0.02832	cubic meter per day

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 ABBREVIATIONS

R	Radius
SJRWMD	St. Johns River Water Management District
SWFWMD	Southwest Florida Water Management District
USGS	U.S. Geological Survey

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ABSTRACT

In the mantled karst terrain of Florida, the size of the catchment delivering ground-water inflow to lakes is often considerably smaller than the topographically defined drainage basin. The size is determined by a balance of factors that act individually to enhance or diminish the hydraulic connection between the lake and the adjacent surficial aquifer, as well as the hydraulic connection between the surficial aquifer and the deeper limestone aquifer. Factors affecting ground-water exchange and the size of the ground-water catchment for lakes in mantled karst terrain were examined by: (1) reviewing the physical and hydrogeological characteristics of 14 Florida lake basins with available ground-water inflow estimates, and (2) simulating ground-water flow in hypothetical lake basins. Variably-saturated flow modeling was used to simulate a range of physical and hydrogeologic factors observed at the 14 lake basins. These factors included: recharge rate to the surficial aquifer, thickness of the unsaturated zone, size of the topographically defined basin, depth of the lake, thickness of the surficial aquifer, hydraulic conductivity of the geologic units, the location and size of karst subsidence features beneath and onshore of the lake, and the head in the Upper Floridan aquifer.

Catchment size and the magnitude of ground-water inflow increased with increases in recharge rate to the surficial aquifer, the size of the topographically defined basin, hydraulic conductivity in the surficial aquifer, the degree of confinement of the deeper Upper Floridan aquifer, and the head in the Upper Floridan aquifer. The catchment size and magnitude of ground-water inflow increased with decreases in the number and size of karst subsidence features in the basin, and the thickness of the unsaturated zone near the lake. Model results, although qualitative, provided insights into: (1) the types of lake basins in mantled karst terrain that have the potential to generate small and large amounts of ground-water inflow, and (2) the location of ground-water catchments that could be managed to safeguard lake water quality. Knowledge of how ground-water catchments are related to lakes could be used by water-resource managers to recommend setback distances for septic tank drain fields, agricultural land uses, and other land-use practices that contribute nutrients and major ions to lakes.

INTRODUCTION

Ground-water interactions with lakes in mantled karst terrain are a fundamental concern to water managers interested in protecting and developing water resources. In Florida, more than 7,000 lakes are situated in a layer or mantle of sand and clay that blankets an extensive and highly productive limestone aquifer, the Upper Floridan aquifer. Many are seepage lakes with basins that lack natural streams, and all rely to varying degrees on ground water to convey inflow and outflow between the lake and surrounding aquifers. Understanding the location and size of the catchment contributing ground-water inflow to lakes is particularly important because all of the ground water within the catchment eventually flows into the lake. Ground water from the surficial aquifer system flows into the lake and helps to sustain lake stage by replacing the lake water that leaks to the deeper limestone aquifer. Ground-water inflow also helps offset lake evaporation losses, which can exceed rainfall in west-central Florida lakes (Swancar and others, 2000). Fertilizers and other solutes applied within catchment areas can enter the lakes through ground-water inflow and have a measurable effect on the water quality of lakes in Florida (Eilers and others, 1988; Lee and Sacks, 1991; Pollman and others, 1991; Stauffer, 1991; Sacks and others, 1998).

Results of water, solute, and isotope mass balance studies of 14 lakes in Florida suggest that the amount of annual ground-water inflow to lakes can vary widely, even for lakes of similar size and apparent physical setting (Pollman and others, 1991; Sacks and others, 1998). In addition, the size of ground-water catchments can vary substantially from lake to lake (Grubbs, 1995; Lee, 1996; Amy Swancar and T.M. Lee, USGS, written commun., 2002). The effects of physical setting on ground-water exchange have been described in detail in a few basin-scale lake studies that combine hydrogeologic descriptions with water budgets and ground-water flow modeling (Lee and others, 1991; Grubbs, 1995; Lee and Swancar, 1997, Swancar and others, 2000). However, a more general quantitative framework is needed to anticipate the ground-water interactions in the larger population of lakes.

Modeling the distinctive settings of Florida lakes can aid in characterizing the principle types of flow regimes within the overall lake population. Numerical modeling studies of hypothetical lake basins have been used to characterize the ground-water flow regimes of lakes in the glacial terrain of North America (Winter, 1976, 1978; Anderson and Munter, 1981; Winter and Pfannkuch, 1984), and the coastal plain near Perth, Western Australia (Nield and others, 1994; Townley and Trefry, 2000). Because of essential differences in geology and climate, however, it can be difficult or impossible to extrapolate these results to Florida lakes in mantled karst terrain. The U.S. Geological Survey began a study in 1998 in cooperation with the Southwest Florida Water Management District and the St. Johns River Water Management District to examine the effect of recharge and basin hydrogeologic characteristics on the magnitude of ground-water exchange and catchment sizes for lakes in the mantled karst terrain of Florida.

Purpose and Scope

This report presents the results of numerical ground-water flow modeling of hypothetical lake basins with a range of basin characteristics typical of mantled karst terrain. In this report, steady-state and transient ground-water flow modeling is used to simulate how recharge, hydrogeologic setting, and basin geometry affect the size of the ground-water catchment and the magnitude of ground-water inflow. Modeling results are summarized and used to make generalizations about the potential for different archetypal lake basins to generate ground-water inflow to Florida lakes.

Ground-water flow is simulated using a variably saturated flow model. Most of the model simulations assume steady-state conditions, but transient simulations are used to explore how the timing of recharge fluxes may affect ground-water interactions with the lake. The idealized lake basin geometries and hydrogeologic data used in the modeling relied on physical characteristics summarized for 14 lake basins in ridge areas of Florida. Estimates of the ground-water inflow to these lakes and data on their hydrogeologic settings are available in published reports. Model simulations of hypothetical lakes examine the effect of the following characteristics on the ground-water exchange and catchment size: recharge rate, topographically defined basin size, surficial aquifer conductivity, intermediate confining unit integrity, lake sediment, Upper Floridan aquifer boundary condition, lake stage, and lake depth.

Acknowledgments

This study was conducted by the U.S. Geological Survey (USGS) in cooperation with the Southwest Florida Water Management District (SWFWMD) and the St. Johns River Water Management District (SJRWMD), two agencies committed to providing a better understanding of lake hydrology in Florida. The author is grateful to Kathleen Hammett (USGS) for her steadfast support during the study; Angel Martin, Laura Sacks, and Amy Swancar (USGS) for helpful discussions on Florida lakes and preliminary reviews of the manuscript; and Richard Schultz (SWFWMD) for perspectives on water management in west-central Florida.

Background

Previous modeling investigations have explored the effect of physical and hydrological settings on ground-water interactions in hypothetical lakes (Nield and others, 1994; Townley and Davidson, 1988; Townley and Trefry, 2000; Winter 1976, 1978, 1983; Winter and Pfannkuch, 1984). In these modeling studies, the lake and underlying aquifers were underlain by an impervious no-flow boundary. For this reason, all of the recharge to the model (or influx from a lateral model boundary) eventually discharged to one or more lakes, or exited the model as lateral flow. The considerable vertical ground-water flow occurring in many Florida lake basins was not represented. Winter probably made the earliest applicable simulations of hypothetical Florida lake basins to aid discussions with a Florida colleague (T.C. Winter, USGS, Denver, Colo., written commun. to G. H. Hughes, USGS, Tallahassee, FL, 1977). Although not published, the conceptual framework contained in these simulations provided the USGS a departure point for modeling ground-water and lake interactions in Florida.

In the mantled karst terrain of central Florida, flow in the surficial aquifer is predominantly downward and massive amounts of recharge flow vertically to the deeper Upper Floridan aquifer across an intermediate confining unit. The comparatively smaller amount of lateral ground-water flow intercepted by lakes depends upon boundary fluxes and head conditions and the hydrogeologic framework. Small-scale features of the geologic framework within lake basins are important. The intermediate confining unit below the lake typically differs from that in the surrounding basin due to the sinkhole processes that formed the lake. Further, the head difference between the two aquifers that causes the downward flow can be highly dynamic, subject to changes due to the seasonal climate and withdrawals from the Upper Floridan aquifer. Thus, modeling assumptions about boundary conditions and the hydrogeologic framework should be specific to each lake basin simulated.

Many lakes in Florida are situated within sand hills and ridges along the central peninsula, referred to as the Central Lake District (Brooks, 1981). Other lakes are concentrated in smaller ridge areas in the panhandle and west-central part of the peninsula (Griffith and others, 1997). The general hydrogeologic setting of many of the ridge lake basins is similar (fig. 1), although the exact geometry and conductivity of the hydrogeologic units can vary widely (Geraghty and Miller, Inc., 1980; Tihansky and others, 1996; Schiffer, 1998).

Most ridge lakes occupy topographic depressions resulting from the piping and subsidence of surficial sand and clay deposits into solution cavities in the underlying limestone (Tihansky, 1999). In peninsular Florida, clay-rich beds of the Hawthorn Group make

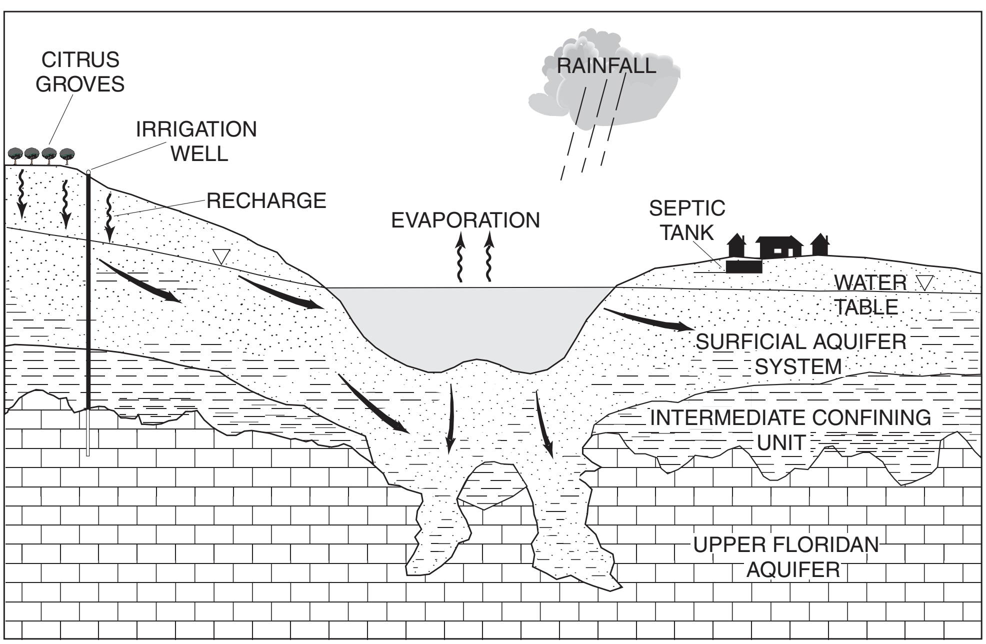


Figure 1. Generalized hydrogeologic section through a Florida ridge lake in a flow-through setting (modified from Tihansky and Sacks, 1997).

up the intermediate confining unit that separates the limestone Upper Floridan aquifer system from the overlying surficial aquifer system (fig. 1 and table 1). In the basin surrounding a lake, the intermediate confining unit may be relatively intact. Beneath the lake, however, the confining unit has been disrupted to varying degrees by sinkhole formation. Because the intermediate confining unit only slows down vertical flow, ground water in the surficial aquifer flows laterally and downward. Near the lake, ground water flowing in a predominantly lateral direction enters the shallow lake bottom. Lake water can leak out laterally near the shoreline when the water table in the surficial aquifer slopes away from the lake. Along the deeper lake bottom, lake water leaks vertically downward. Ultimately, all of the lake leakage and ground water in the deeper surficial aquifer flow downward across the intermediate confining unit to recharge the Upper Florida aquifer (fig. 1).

The subsidence structure beneath sinkhole lakes substantially affects vertical leakage losses. High-resolution seismic reflection surveys have provided insights into the shape and geologic structure of collapse features beneath lakes in north-central Florida (Subsurface Detection Investigations, Inc., 1992; Kindinger and others, 1994) and west-central Florida (Tihansky and others, 1996). The hydraulic conductivity distribution beneath these lakes, however, cannot be similarly inferred.

The hydraulic conductivity below lakes is not known but has been estimated from water budget studies. For example, by assuming that all lake leakage derived from lake water budgets was vertical, average leakance values (K_v/b) were derived for the column of material between the lake bottom and the Upper Floridan aquifer (Motz, 1998). In modeling studies, individual hydraulic conductivity values were assigned to organic lake sediment, surficial sediments, and remnants of the intermediate confining unit filling the collapse features below lakes (Lee and Swancar, 1997; Amy Swancar and T.M. Lee, USGS, written commun., 2002). For example, in simulations of Lake Starr in Polk County, sediments collapsed into the sinkhole beneath the lake were 12.5 times more conductive than the intermediate confining unit they replaced (Amy Swancar and T.M. Lee, USGS, written commun., 2002).

Lake leakage also depends on the potentiometric surface of the Upper Floridan aquifer, which is affected by pumping and recharge rates (Yobbi, 1996).

Table 1. Relation of stratigraphic and hydrogeologic units in central Florida

<table>
<tr><th colspan="2">LITHOSTRATIGRAPHIC UNIT</th><th colspan="2">HYDROSTRATIGRAPHIC UNIT</th><th>GENERALIZED LITHOLOGY</th></tr>
<tr><td colspan="2">Undifferentiated sand, shell, and clay (UDSC)</td><td colspan="2">Surficial Aquifer System (SAS)</td><td>Highly variable lithology ranging from unconsolidated sands to clay beds with variable amounts of shell fragments, gravel-sized quartz grains and reworked phosphate</td></tr>
<tr><td rowspan="2">Hawthorn Group</td><td>Peace River Formation</td><td colspan="2" rowspan="2">Intermediate Aquifer System and/or Intermediate Confining Unit (IAS - ICU)</td><td>Interbedded sands, clays and carbonates with siliciclastic component being dominant and variably mixed; moderate to high phosphate sand/gravel content</td></tr>
<tr><td>Arcadia Formation</td><td>Arcadia Formation is a fine-grained carbonate with low to moderate phosphate and quartz sand, variably dolomitic</td></tr>
<tr><td colspan="2">Suwannee Limestone</td><td rowspan="2">Floridan Aquifer System</td><td rowspan="2">Upper Floridan Aquifer (UFA)</td><td>Suwannee Limestone is a fine- to medium-grained packstone to grainstone with trace organics and variable dolomite and clay content</td></tr>
<tr><td colspan="2">Ocala Limestone</td><td>Ocala Limestone is a chalky, very fine- to fine-grained wackestone/packstone varying with depth to a biogenic medium- to coarse-grained packstone grainstone; trace amounts of organic material, clay, and variable amounts of dolomite</td></tr>
</table>

As the head in the underlying aquifer drops, the downward head gradient controlling lake leakage increases. For example, the estimated monthly leakage from Lake Lucerne was 1.8 inches (in.) in May 1986, when pumping increased the (daily average) downward head difference between the lake and the Upper Floridan aquifer head to about 13 feet (ft). During September 1986, when this head difference was only 5 ft, lake leakage was 0.7 in. (Lee and Swancar, 1997). The Upper Floridan aquifer head also has a large effect on the size of the ground-water catchment and the magnitude of ground-water inflow; however, few previous studies have examined this relation.

Annual recharge to the surficial aquifer affects the annual ground-water inflow to lakes. For example, when rainfall was about 25 percent above average in 1989 at Lake Five-O near Panama City, Fla., ground-water inflow appreciably exceeded lake leakage. In 1990, however, rainfall was about 25 percent below average, and lake leakage greatly exceeded inflow (Grubbs, 1995).

The timing of rainfall (winter or summer) affects how much of the rainfall becomes recharge. Annual rainfall averages about 50 inches/year in central Florida (National Oceanic and Atmospheric Administration, 1996); however, it varies widely between years and can differ substantially at different lake basins within a geographic area for the same year (Sacks and others, 1998). The annual rainfall was similar in two consecutive years of study at Lake Starr near Lake Wales, Fla. Yet recharge to the surficial aquifer and ground-water inflow to the lake were substantially greater in the second year (August 1997 - July 1998), because most of the annual rainfall fell in the winter and spring when evapotranspiration was low. Annual recharge to the surficial aquifer in ridge areas of central Florida has been estimated to range from 30 to 53 percent of average annual rainfall (Knowles, 1996; Sumner, 1996).

Topographic relief in lake basins also affects ground-water inflow to lakes. Near the lake shoreline, where the unsaturated zone is typically thinnest, recharge to the water table can be rapid and cause the formation of transient water-table mounds that can increase the ground-water inflow (Winter, 1983; Lee, 2000). Higher land-surface elevation increases the thickness of the unsaturated zone above the water table and increases the time between rainfall and aquifer recharge. As a result of the slower, more prolonged recharge process, elevation gradients in the water table are lower, resulting in less lateral flow. Variably saturated flow modeling was first used by Lee (2000) to simulate the effects of topography and transient recharge on the magnitude of ground-water inflow to a lake in mantled karst terrain. Saturated ground-water flow models typically overlook these processes. Recently, the results of one-dimensional unsaturated ground-water flow modeling were combined with a three-dimensional saturated flow model to improve the estimates of ground-water flow to Lake Starr, in central Florida (Amy Swancar and T.M. Lee, USGS, written commun., 2002).

PHYSICAL CHARACTERIZATION OF LAKE BASINS

The physical settings of 14 lakes helped to define a range of basin characteristics that potentially affect ground-water interactions with lakes in Florida (fig. 2). These physical settings provided concepts for the numerical modeling of hypothetical lakes. Eleven of the lakes are located in Polk and Highlands Counties (Sacks and others, 1998; Lee and others, 1991). Lake Five-O, in Bay County, is in the panhandle of Florida and its hydrogeologic setting is described in Andrews and others (1990). Lake Barco is in Putnam County in north-central Florida, and is described by Sacks and others (1992). Halfmoon Lake, in Hillsborough County, is in a physiographic region called the Northern Gulf Coast Lowlands (White, 1970). The hydrogeologic setting and water budget of Halfmoon Lake are described by Metz and Sacks (2002).

The annual ground-water inflows to all 14 lakes were estimated in previous studies. Sacks and others (1998) estimated the steady-state ground-water inflow rates to 10 of the lakes using a combination of water-balance and chemical mass-balance approaches. Five of the 14 lakes (including one of the 10 lakes described above) were the subjects of detailed basin-scale modeling studies. Ground-water inflow and lake-water leakage at Lakes Lucerne, Barco, Five-O, Starr, and Halfmoon were estimated using a combination of water-balance and numerical modeling approaches (Grubbs, 1995; Lee, 1996; Lee and Swancar, 1997; Swancar and others, 2000; Metz and Sacks, 2002; Amy Swancar and T.M. Lee, USGS, written commun., 2002; and R.Yager, USGS, Ithaca N.Y., personal commun., July 2001). The information in the following sections is taken from these sources, unless another reference is cited.

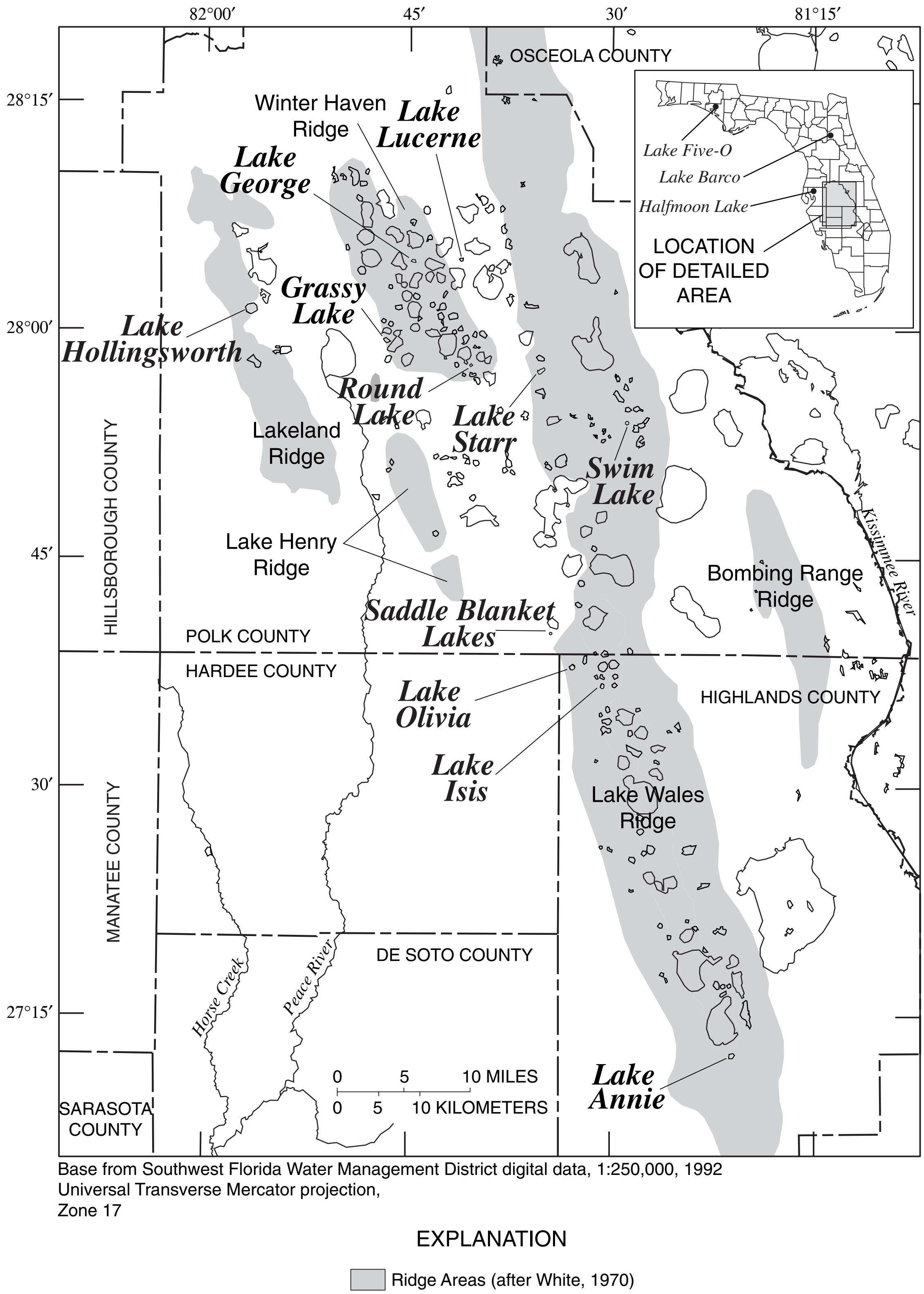


Figure 2. Locations of the study lakes in Florida (modified from Sacks and others, 1998).

Methods

The physical basin characteristics compiled during the previous studies included: the size and depth of each lake, the thickness of the surficial aquifer encompassing the lake, the slope of the water table, and the thickness of the intermediate confining unit separating the surficial aquifer from the underlying Upper Floridan aquifer (table 2). In addition, the thickness of the unsaturated zone and the size of the topographically defined basin were described for each lake.

Detailed hydrogeologic information is available for the five lakes that were the subject of basin-scale modeling studies (Lucerne, Barco, Five-O, Starr, and Halfmoon Lakes). Generalized hydrogeologic information is available for the remaining nine lake basins and was taken from regionalized lithologic maps (Buono and Rutledge, 1978; Buono and others, 1979; Tihansky and others, 1996). Information on lake bathymetry, basin topography, and geology was available on all 14 of the lakes. With the exception of Swim Lake and Lake Five-O, aerial photos (scale 1 in. = 200 ft) with topographic contours at 1-ft intervals were used during this study to describe elevations along hillsides in the lake basins. Topographic maps (scale 1 in. = 24,000 in.) were used to describe the land elevation around Swim Lake and Lake Five-O.

Ground-water elevations were available in the basins of all 14 lakes. Monthly water levels measured during the previous studies of each lake were used to characterize the direction of ground-water flow in the basin, and high and low water-table conditions. Daily lake-stage data and monthly or biweekly water-table measurements typically were available. The slope of the water table was computed between adjacent monitor wells located along a head gradient into or out of the lake.

The potentiometric level of the Upper Floridan aquifer was measured in the nearest available observation well or from wells drilled onsite for the study. The head difference between the lake and the Upper Floridan aquifer was the mean of wet- and dry-season observations (typically made during May and September, respectively) (table 3). Because ground-water pumping effects are minimal in the Lake Five-O and Lake Barco basins, periodic measurements of head in the Upper Floridan aquifer generally were representative of monthly conditions. In contrast, periodic measurements typically made a poor surrogate for the average monthly head

Table 2. Physical characteristics of selected lake basins in Florida

[R, principal radius; r, secondary radius; ft, msl, feet above mean sea level; max, maximum; min, minimum; GW Inflow (in/yr), estimated annual ground-water inflow to lake expressed as inches per year above the lake surface area]

Lake name	Surface area (acres)	Lake stage (ft msl)		Estimated lake radius (feet)		Basin dimension		Distance to closest lake	Lake bed slope (percent)		Water table[1] wet season slope (percent)		Water table dry season slope (percent)		GW inflow (in/yr)
		Wet season	Dry season	r	R	Min	Max	R	Mean	Max	Min	Max	Min	Max	
Annie	92	110.5	109.8	500	1,000	0.2R	6.0R	4.5R	6	11	-0.1	0.5	-0.1	0.3	240
Barco	29	88.0	83.6		640	0.7R	4.0R	1.2R	3	10	-1.1	2.3	-0.7	2.2	8
Five-O	27	50.2	45.1		650	1.0R	7.0R	1.2R	7	14	0.3	1.5	0.3	1.4	237
George	59	130.5	130.0		800	0.1R	2.0R	2.0R	2	5	-0.5	1.1	-0.6	0.5	54
Grassy	76	130.9	129.7		1,000	0.8R	2.2R	1.5R	2	6	0.1	0.3	0.3	0.2	30
Halfmoon	33	42.0	40.7	300	500	0.5R	2.0R	2.0R	9	11	0.0	2.6	0.0	0.7	23[2]
Hollingsworth	356	131.3	130.5		2,250	0.3R	1.3R	0.5R	0.2	0.8	0.5	1.8	0.5	1.8	110
Isis	50	108.7	109.5	600	650	0.5R	7.0R	2.5R	9	14	-0.6	1.8	-1.2	1.4	100
Lucerne	38	126.0	124.8		860	1.0R	2.0R	0.8R	2	5	0.5	0.6	0.1	0.3	24
Olivia	86	114.5	114.7		800	0.3R	3.5R	1.0R	5	13	-0.4	0.7	-0.4	0.6	33
Round	31	131.4	130.8		650	0.7R	1.7R	1.2R	4	11	0.4	1.0	0.1	0.3	6
Saddle Blanket	6	116.9	117.7		330	1.0R	7.0R	1.0R	3	7	-0.2	0.7	-0.6	0.4	30
Starr	134	103.9	104.2	650	1,000	1.0R	2.0R	2.2R	3	9	-0.2	0.2	-0.2	0.2	23
Swim	5	96.8	96.2		240	1.0R	3.0R	2.0R	12	20	-0.1	0.8	-0.1	0.9	180
										mean		1.1		0.8	
										median		0.9		0.6	

[1]Negative values indicate water table sloping away from lake.

[2]Average of 3 years, including year with rainfall 34 inches above normal.

conditions for basins in Polk and Highlands Counties, where ground-water pumping could cause considerable hour-to-hour variation in head. For this reason, heads presented in table 3 provide only ageneral indication of the aquifer conditions near these lakes.

Physical Characteristics

Although the 14 lakes surveyed represent a tiny proportion of the thousands of lakes located in the Central Lake District, they exhibit a wide range of physical characteristics (tables 2 and 3). The lakes range in size from 5 (Lake Swim) to 356 acres (Lake Hollingsworth). Most of the lakes are less than 100 acres in size (table 2), and are roughly circular in shape (figs. 3-14), except Halfmoon Lake in Hillsborough County which is least circular and more segmented than the other 13 lakes (fig. 7). The topographically defined basins surrounding the lakes can be roughly circular (for example, George (fig. 6), Grassy (fig. 6), Hollingsworth (fig. 8), and Round Lakes (fig. 12)). More commonly, the drainage divide extends a considerable distance from the lake along one axis, where as in other areas, the divide is relatively close to the lake margin (Barco (fig. 4), Five-O (fig. 5), Isis (fig. 9), Olivia (fig. 11), Saddle Blanket (fig. 12), and Swim Lakes (fig. 14)). Following the convention of Sacks and others (1998), the Saddle Blanket Lake referred to in this report is the larger of the two lakes named together as Saddle Blanket Lakes (fig. 12).

Table 3. Hydrogeologic characteristics of selected lake basins in Florida

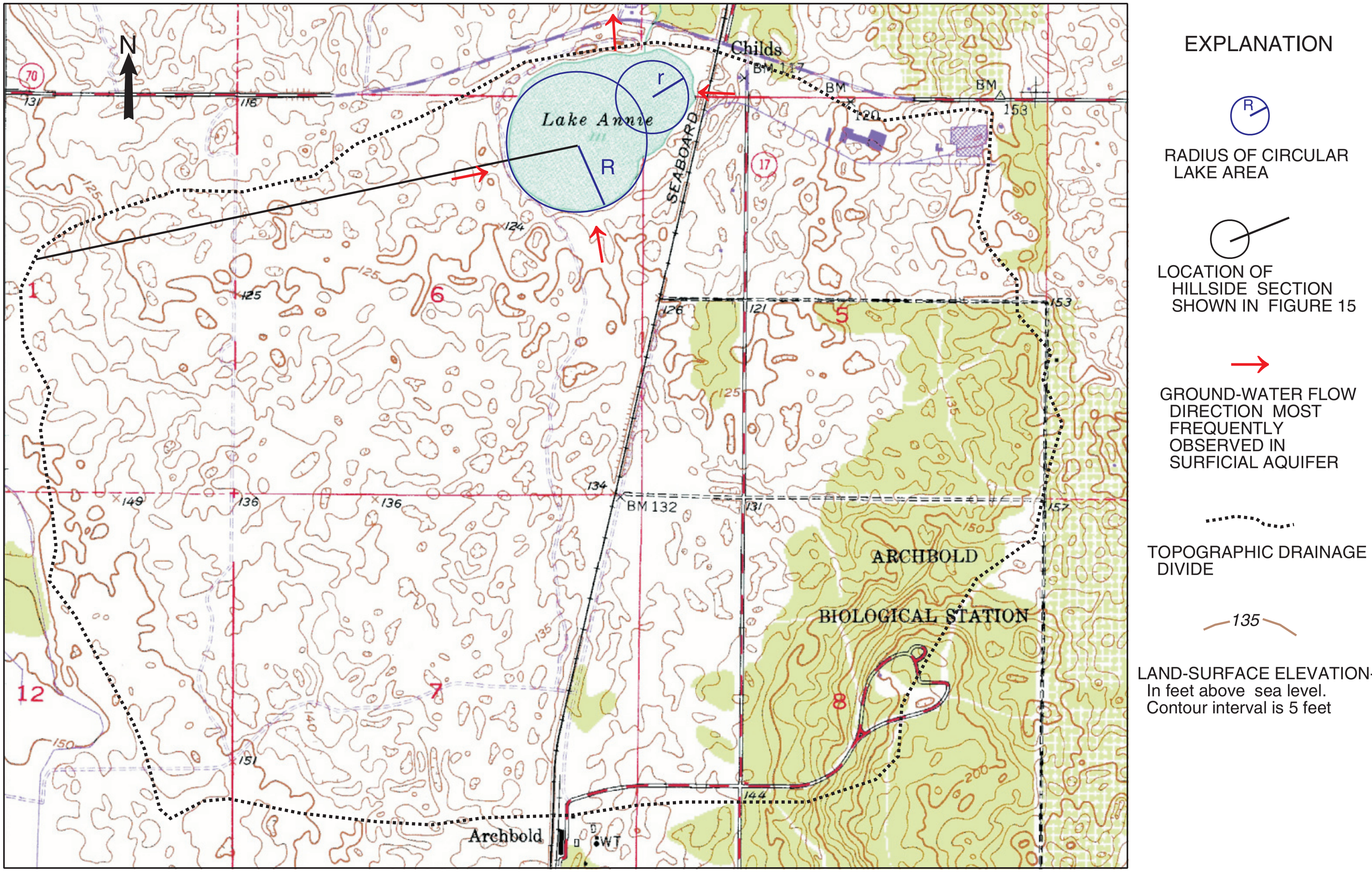
[USD, undifferentiated surficial deposits; UFA, Upper Floridan aquifer; Mean vertical head difference equal to lake stage minus the mean head in the UFA; ft, msl, feet above mean sea level]

Lake name	County	Reference stage[1] (ft msl)	Lake depth maximum (feet)	Thickness USD (feet)	Thickness Hawthorn[2] formation (feet)	Thickness mantle total (feet)	Thickness mantle sublake (feet)	Hydraulic head Upper Floridan aquifer (ft msl)		Mean vertical head difference lake to UFA (feet)
								Wet season	Dry season	
Annie	Highlands	110.0	65	300	250	550	485	52.6	49.8	59
Barco	Putnam	88.0	22	40	60	100	78	83.2	78.4	7
Five-O	Bay	47.0	48	23	37	60	12	44.7	39.8	5
George	Polk	130.0	15	55	75	130	115	122.9	119.1	9
Grassy	Polk	130.0	23	80	100	180	157	107.5	101.0	26
Halfmoon	Hillsborough	41.4	22	35	7	42	20	30.2	27.3	13
Hollingsworth	Polk	131.0	6	10	210	220	214	81.2	73.3	54
Isis	Highlands	109.0	64	230	200	430	366	88.3	83.1	23
Lucerne	Polk	125.0	22	50	90	140	118	120.2	112.9	9
Olivia	Highlands	114.5	47	230	200	430	383	75.3	74.8	39
Round	Polk	131.0	28	55	100	155	127	112.3	105.1	21
Saddle Blanket	Polk	117.0	11	150	200	350	339	79.6	72.2	41
Starr	Polk	104.0	33	50	40	90	57	103.0	100.5	2
Swim	Polk	96.5	30	100	100	200	170	88.6	84.8	10
Crooked Lake[3]	Polk	108.5	13	100	150	250	237			49
Clinch	Polk	104.0	29	140	160	300	271			33
Lotela	Highlands	101.8	25	140	290	430	405			43
Jackson	Highlands	101.4	26	120	380	500	474			49
Letta	Highlands	91.0	9	140	360	500	491			37
Placid	Highlands	90.8	57	200	400	600	543			44
Reedy	Polk	78.0	no data	180	160	340	no data			11
June-in-Winter	Highlands	73.7	35	130	420	550	515			24
Hamilton	Polk	120.0	12.5	90	100	190	177.5			11

[1]Reference stage used to calculate the vertical head difference with the Upper Floridan aquifer.

[2]Thickness of the Hawthorn formation is assumed equivalent to the thickness of the intermediate confining unit.

[3]Data for the nine additional lakes at the bottom of table 3 are from Geraghty and Miller (1980) and Barcelo and others (1990), and are used in figure 21a.



Base from U.S. Geological Survey digital data, 1:24,000,1972
Universal Transverse Mercator projection,
Zone 17
Childs quadrangle 1953 (1972)

0 1,000 2,000 FEET
0 300 600 METERS

Figure 3. Topographic setting and general direction of ground-water flow in the surficial aquifer around Lake Annie.

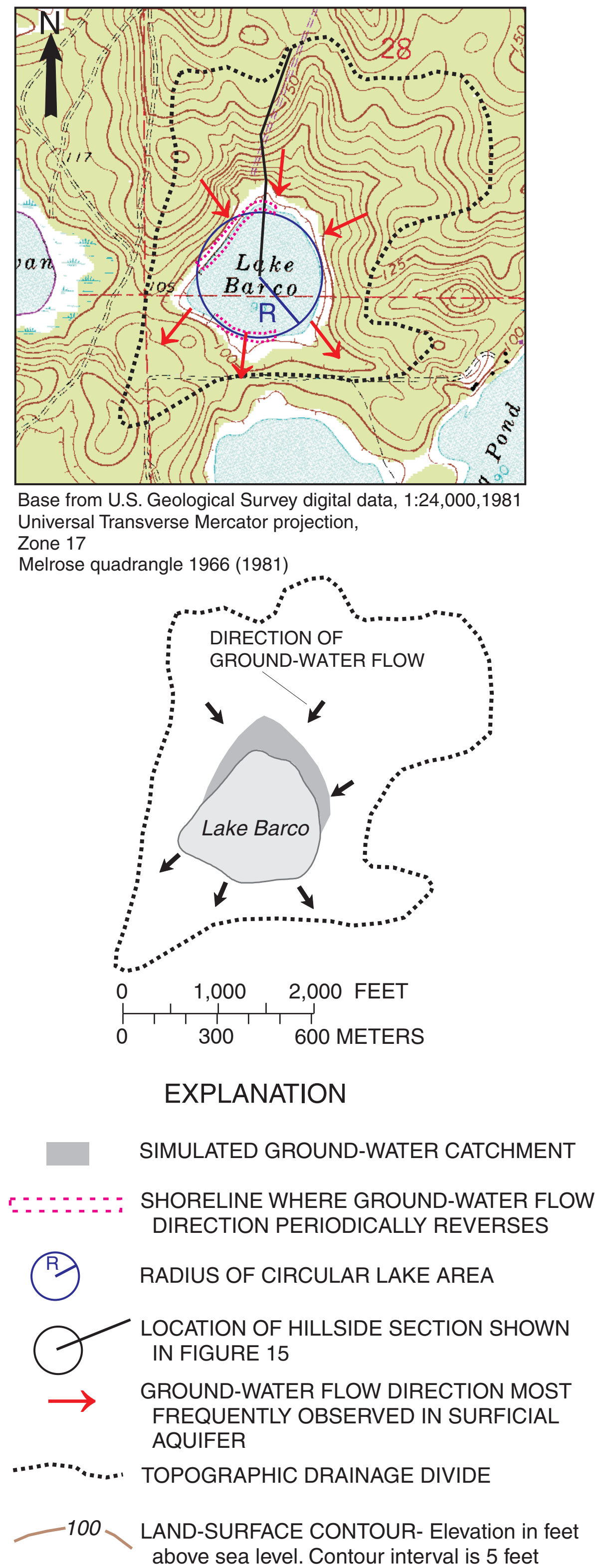


Figure 4. Topographic setting of Lake Barco, general direction of ground-water flow in the surrounding surficial aquifer, and the simulated steady-state ground-water catchment (modified from Lee, 1996).

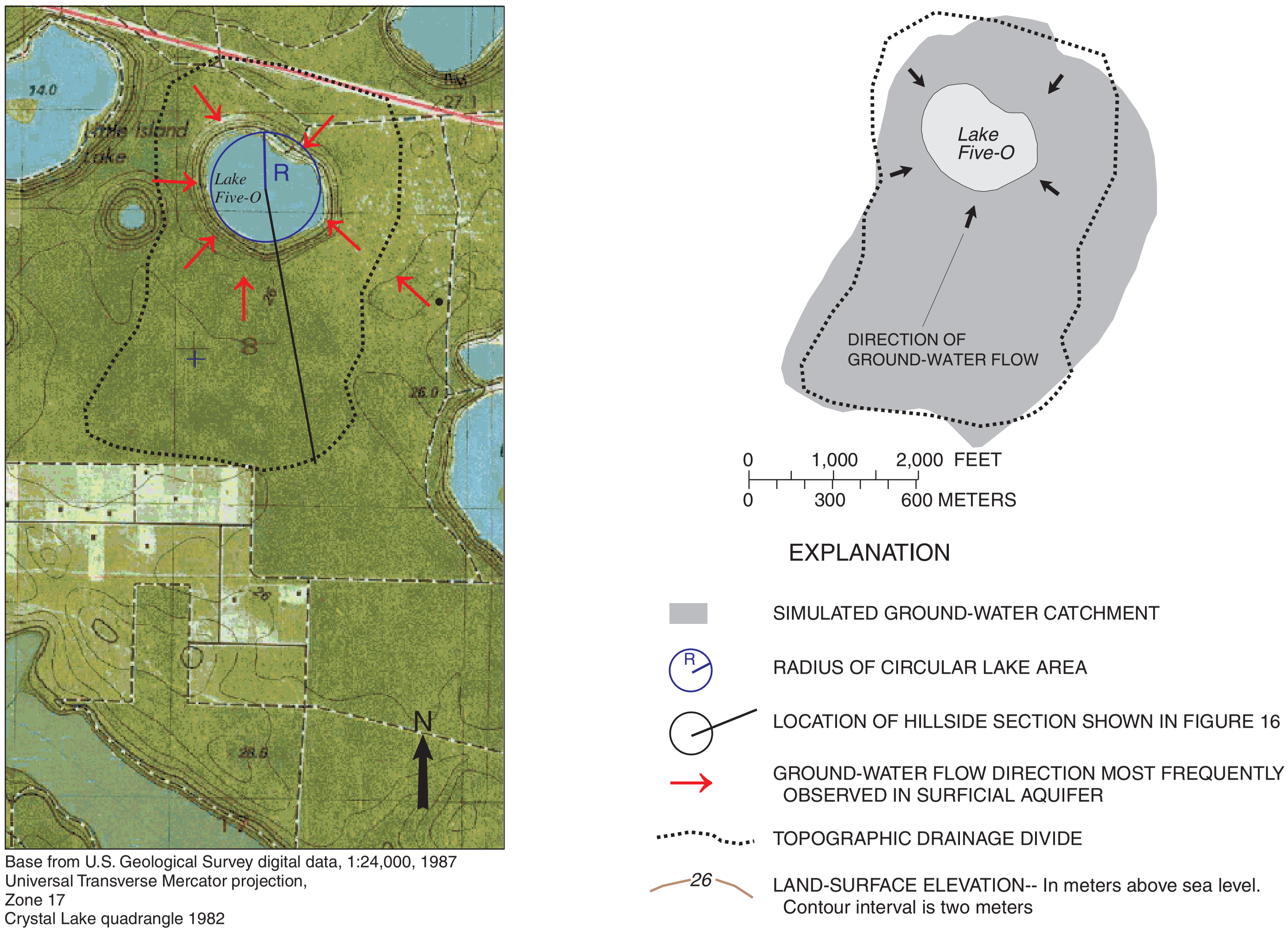
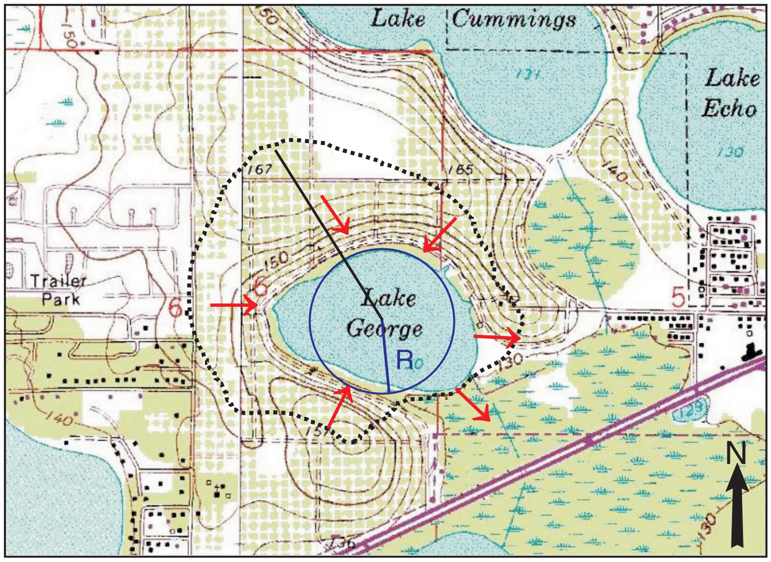
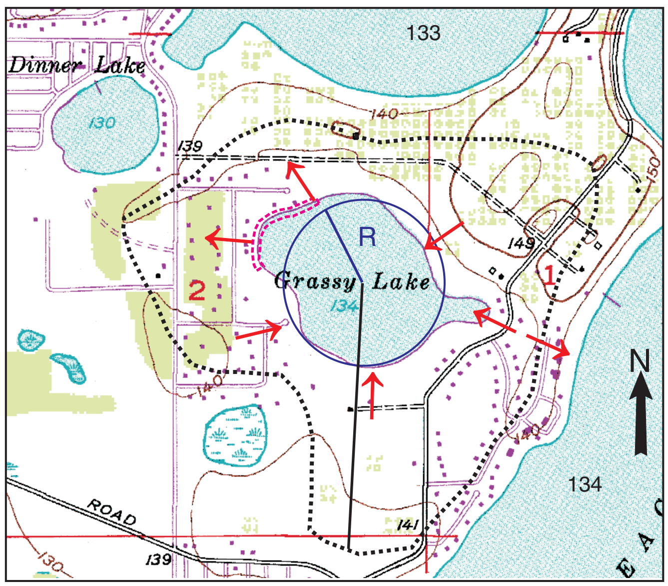


Figure 5. Topographic setting of Lake Five-O, general direction of ground-water flow in the surrounding surficial aquifer, and the simulated steady-state ground-water catchment (modified from Grubbs, 1995). Note the simulated ground-water catchment extends beyond the topographic drainage divide east of the lake.



Base from U.S. Geological Survey digital data, 1:24,000, 1980, 1988
Universal Transverse Mercator projection,
Zone 17
Winter Haven quadrangle 1959 (1980)

0 1,000 2,000 FEET
0 300 600 METERS



Base from U.S. Geological Survey digital data, 1:24,000, 1987
Universal Transverse Mercator projection,
Zone 17
Bartow quadrangle 1949 (1987)

EXPLANATION

SHORELINE WHERE GROUND-WATER FLOW DIRECTION PERIODICALLY REVERSES

RADIUS OF CIRCULAR LAKE AREA

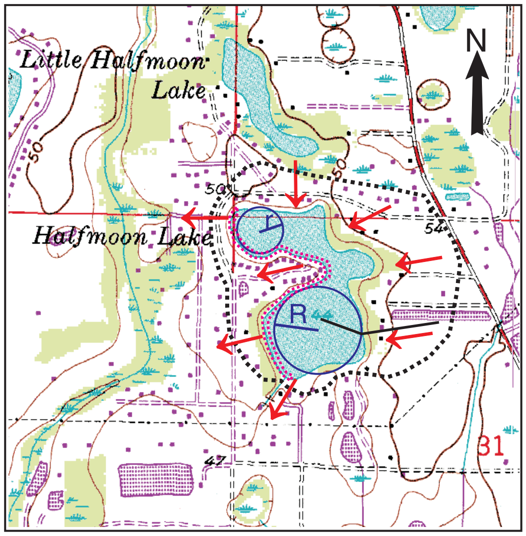
LOCATION OF HILLSIDE SECTION SHOWN IN FIGURE 16

GROUND-WATER FLOW DIRECTION MOST FREQUENTLY OBSERVED IN SURFICIAL AQUIFER

TOPOGRAPHIC DRAINAGE DIVIDE

130 LAND-SURFACE ELEVATION--In feet above sea level. Contour interval is 5 feet at Lake George and 10 feet at Grassy Lake

Figure 6. Topographic setting and general direction of ground-water flow in the surficial aquifer around Lake George and Grassy Lake.



Base from U.S. Geological Survey digital data,1:24,000, 1987
Universl Transverse Mercator projection,
Zone 17
Citrus Park quadrangle 1956 (1987)

0 1,000 2,000 FEET
0 300 600 METERS

EXPLANATION

SHORELINE WHERE GROUND-WATER FLOW DIRECTION PERIODICALLY REVERSES

R — RADIUS OF CIRCULAR LAKE AREA

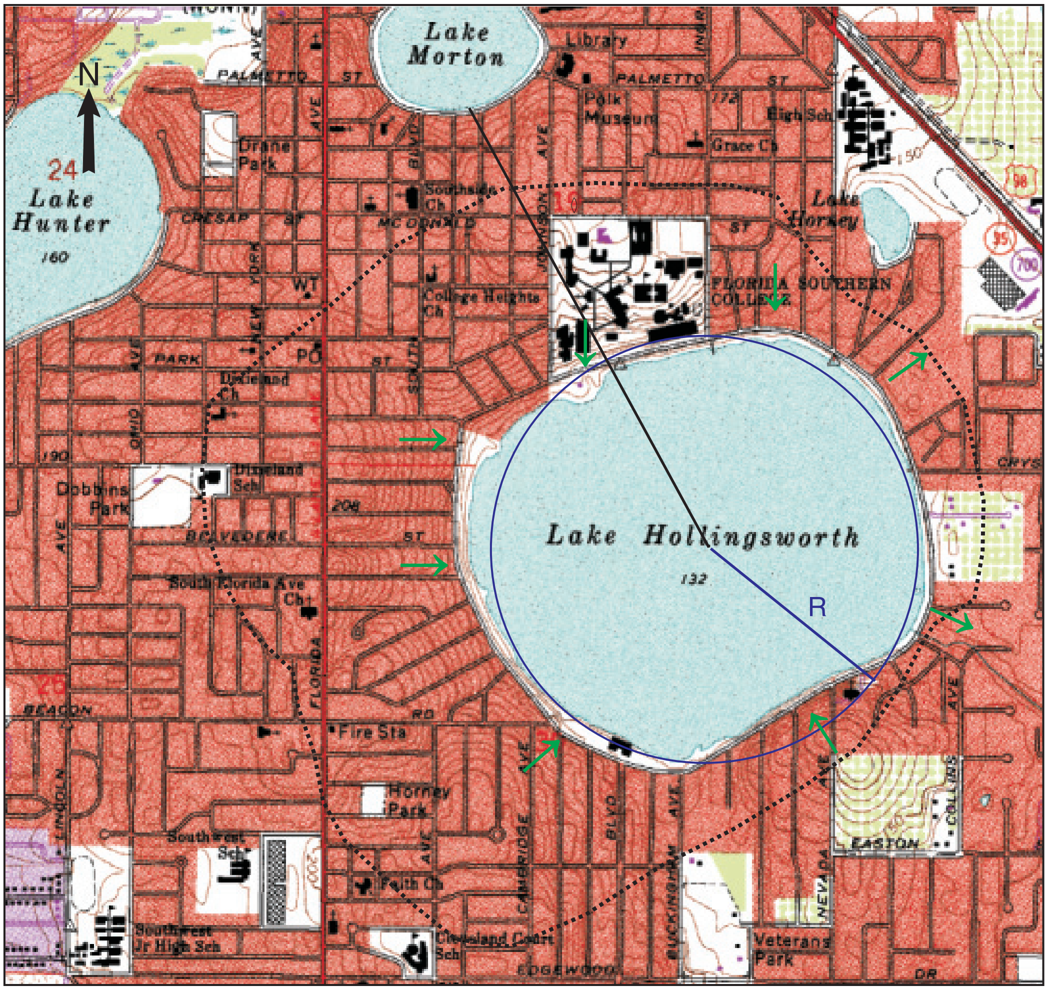
LOCATION OF HILLSIDE SECTION SHOWN IN FIGURE 16

GROUND-WATER FLOW DIRECTION MOST FREQUENTLY OBSERVED IN SURFICIAL AQUIFER

TOPOGRAPHIC DRAINAGE DIVIDE

50 — LAND-SURFACE ELEVATION-- In feet above sea level. Contour interval is 5 feet

Figure 7. Topographic setting and general direction of ground-water flow in the surficial aquifer around Halfmoon Lake.



Base from U.S. Geological Survey digital data, 1:24,000, 1987
Universal Transverse Mercator projection,
Zone 17
Lakeland quadrangle 1975 (1987)

0 1,000 2,000 FEET

0 300 600 METERS

EXPLANATION

RADIUS OF CIRCULAR LAKE AREA

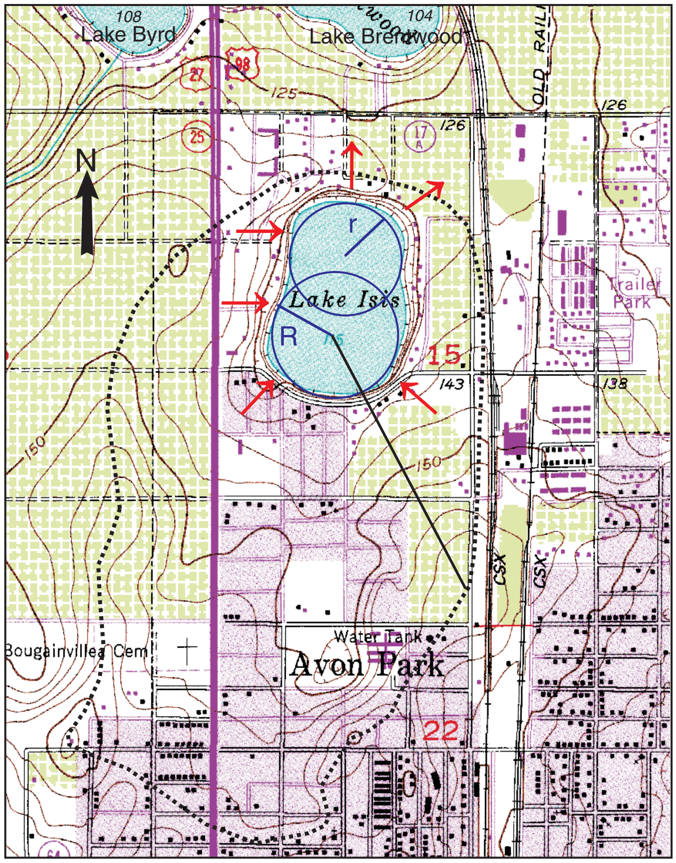
LOCATION OF HILLSIDE SECTION SHOWN IN FIGURE 17

GROUND-WATER FLOW DIRECTION MOST FREQUENTLY OBSERVED IN SURFICIAL AQUIFER

TOPOGRAPHIC DRAINAGE DIVIDE

200 LAND-SURFACE ELEVATION-- In feet above sea level. Contour interval is 5 feet

Figure 8. Topographic setting and general direction of ground-water flow in the surficial aquifer around Lake Hollingsworth.



Base from U.S. Geological Survey digital data, 1:24,000, 1987
Universal Transverse Mercator projection,
Zone 17
Avon Park quadrangle 1953 (1987)

0 1,000 2,000 FEET
0 300 600 METERS

EXPLANATION

R — RADIUS OF CIRCULAR LAKE AREA

LOCATION OF HILLSIDE SECTION SHOWN IN FIGURE 17

GROUND-WATER FLOW DIRECTION MOST FREQUENTLY OBSERVED IN SURFICIAL AQUIFER

TOPOGRAPHIC DRAINAGE DIVIDE

150 — LAND-SURFACE ELEVATION-- In feet above sea level. Contour interval is 5 feet

Figure 9. Topographic setting and general direction of ground-water flow in the surficial aquifer around Lake Isis.

Base from U.S. Geological Survey digital data, 1:24,000, 1980
Universal Transverse Mercator projection,
Zone 17
Winter Haven quadrangle 1959 (1980)

0 1,000 2,000 FEET
0 300 600 METERS

EXPLANATION

R — RADIUS OF CIRCULAR LAKE AREA

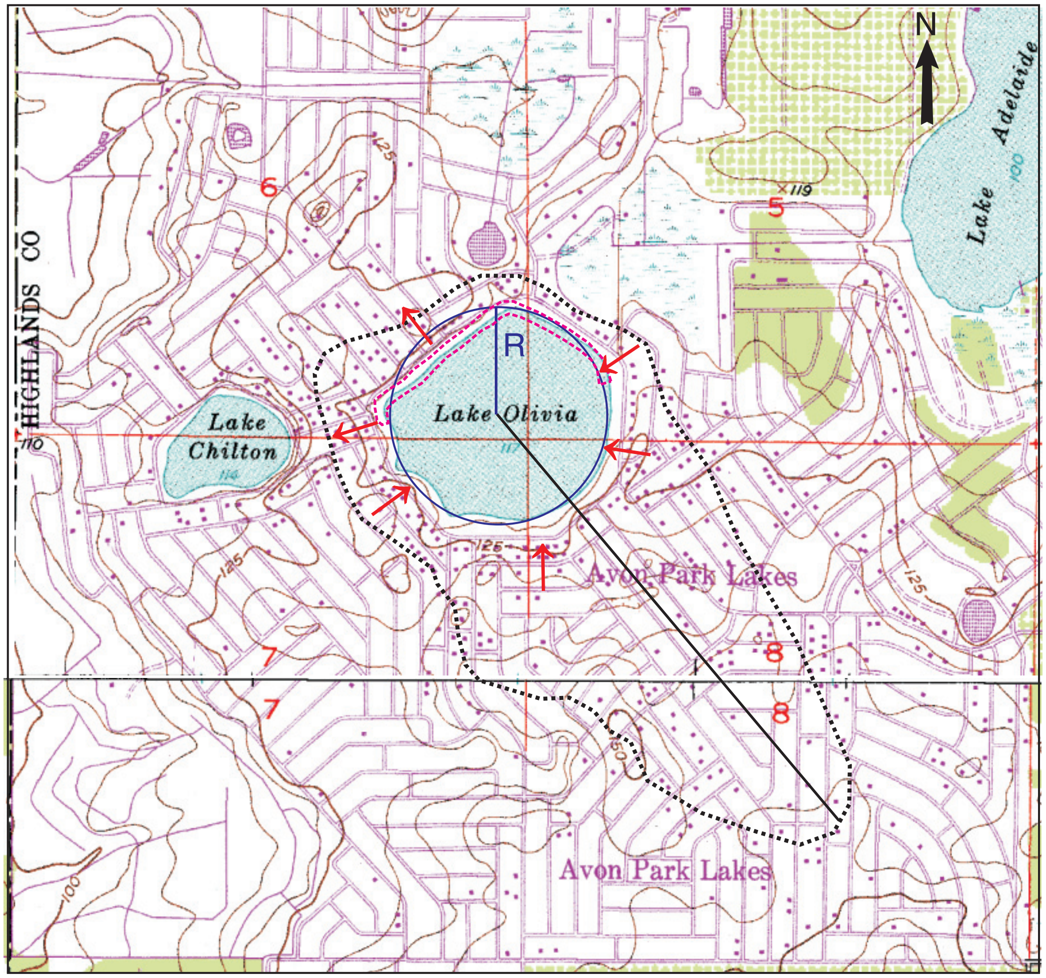
LOCATION OF HILLSIDE SECTION SHOWN IN FIGURE 18

GROUND-WATER FLOW DIRECTION MOST FREQUENTLY OBSERVED IN SURFICIAL AQUIFER

TOPOGRAPHIC DRAINAGE DIVIDE

150 — LAND-SURFACE ELEVATION-- In feet above sea level. Contour interval is 5 feet

Figure 10. Topographic setting and general direction of ground-water flow in the surficial aquifer around Lake Lucerne.



Base from U.S. Geological Survey digital data, 1:24,000, 1972, 1987
Universal Transverse Mercator projection,
Zone 17
Avon P ark quadrangle 1953 (1987)
Frostproof quadrangle 1953 (1972)

0 1,000 2,000 FEET
0 300 600 METERS

EXPLANATION

SHORELINE WHERE GROUND-WATER FLOW DIRECTION PERIODICALLY REVERSES

R RADIUS OF CIRCULAR LAKE AREA

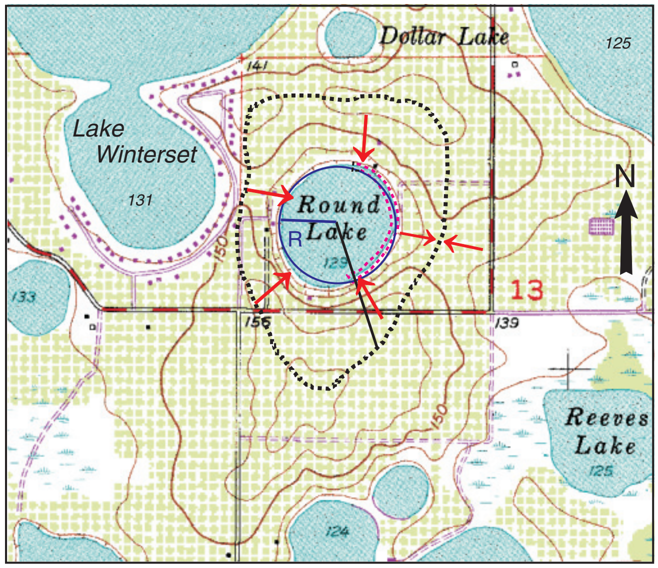
LOCATION OF HILLSIDE SECTION SHOWN IN FIGURE 18

GROUND-WATER FLOW DIRECTION MOST FREQUENTLY OBSERVED IN SURFICIAL AQUIFER

TOPOGRAPHIC DRAINAGE DIVIDE

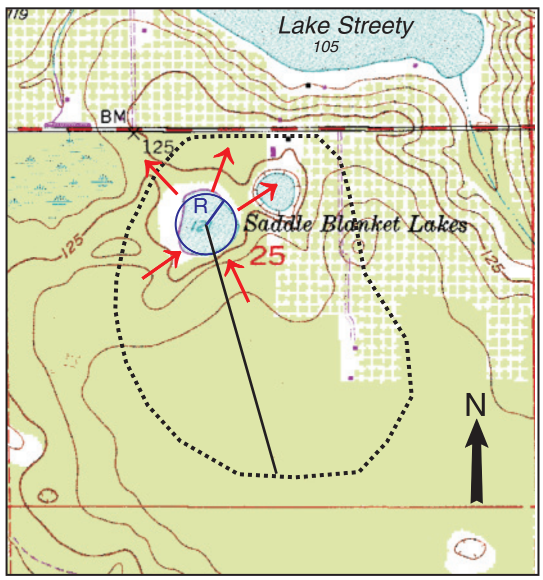
100 LAND-SURFACE ELEVATION-- In feet above sea level. Contour interval is 5 feet

Figure 11. Topographic setting and general direction of ground-water flow in the surficial aquifer around Lake Olivia.



Base from U.S. Geological Survey digital data, 1:24,000, 1987
Universal Transverse Mercator projection,
Zone 17
Eloise quadrangle 1955 (1987)

0 1,000 2,000 FEET
0 300 600 METERS



Base from U.S. Geological Survey digital data, 1:24,000, 1972
Universal Transverse Mercator projection,
Zone 17
Frostproof quadrangle 1953 (1972)

EXPLANATION

SHORELINE WHERE GROUND-WATER FLOW DIRECTION PERIODICALLY REVERSES

GROUND-WATER FLOW DIRECTION MOST FREQUENTLY OBSERVED IN SURFICIAL AQUIFER

R RADIUS OF CIRCULAR LAKE AREA

TOPOGRAPHIC DRAINAGE DIVIDE

LOCATION OF HILLSIDE SECTION SHOWN IN FIGURE 19

125 LAND-SURFACE ELEVATION-- In feet above sea level. Contour interval is 10 feet at Round Lake and 5 feet at Saddle Blanket Lake

Figure 12. Topographic setting and general direction of ground-water flow in the surficial aquifer around Round Lake and Saddle Blanket Lakes.

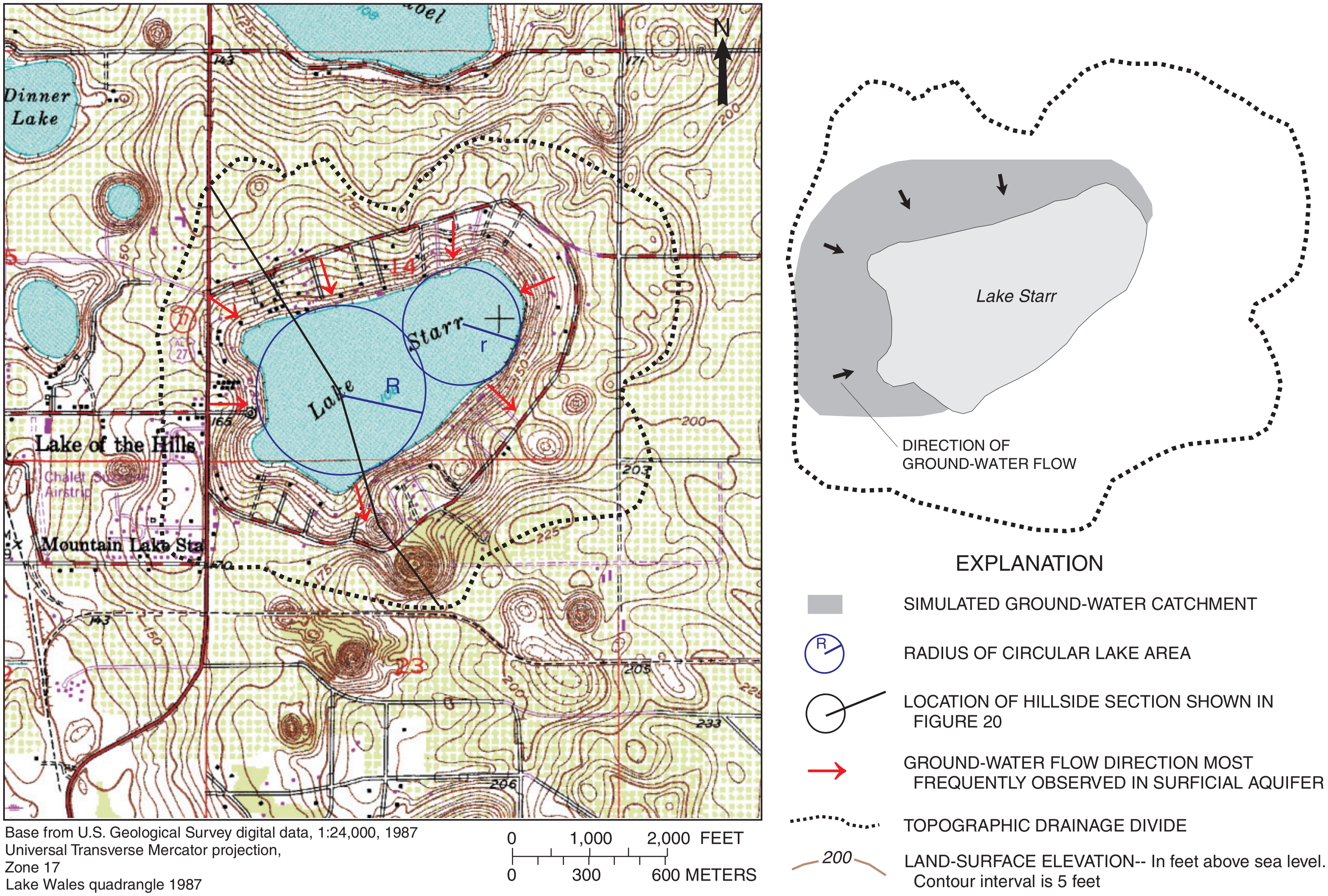
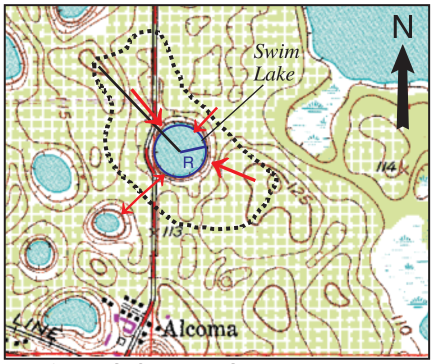


Figure 13. Topographic setting of Lake Starr, general direction of ground-water flow in the surrounding surficial aquifer, and the simulated steady-state ground-water catchment.



Base from U.S. Geological Survey digital data, 1:24,000, 1972
Universal Transverse Mercator projection,
Zone 17
Hesperides quadrangle 1952 (1972)

0 1,000 2,000 FEET
0 300 600 METERS

EXPLANATION

RADIUS OF CIRCULAR LAKE AREA

LOCATION OF HILLSIDE SECTION SHOWN IN FIGURE 20

GROUND-WATER FLOW DIRECTION MOST FREQUENTLY OBSERVED IN SURFICIAL AQUIFER

TOPOGRAPHIC DRAINAGE DIVIDE

110 LAND-SURFACE ELEVATION-- In feet above sea level. Contour interval is 5 feet

Figure 14. Topographic setting and general direction of ground-water flow in the surficial aquifer around Swim Lake.

As an approximation, the surface areas of the lakes can be represented as circular in shape (figs. 3-14). Representing the lake geometry in this manner provides a conceptual framework used in this report for modeling lake basins in radial section. The assumptions of a nearly circular lake and radial symmetry in the surrounding basin were used by Lee (2000) to simulate lake and ground-water interactions using a two-dimensional variably saturated flow model. The principle radius (R) describing the largest circular area of each lake ranged from about 240 ft in length for Swim Lake to about 1,000 ft for three of the larger lakes (Lakes Annie, Grassy, and Starr) (figs. 3-14 and table 2). The lake with the largest radius was Lake Hollingsworth (R = 2,250 ft). The distance from each lake margin to another point in the basin can be expressed as a multiple of the radius of the lake. For example, the longest hillside in the Lake Olivia basin is about 3.5R (2,800 ft) in length, the shortest is about 0.3R (240 ft) (fig. 11).

Topography and Ground-Water Flow Patterns

The areas of a lake basin capable of generating ground-water inflow from a surficial aquifer cannot be accurately determined by topography alone. When the typical direction of ground-water flow in the basins of the 14 lakes was superimposed onto the basin topography, however, some general tendencies became apparent (figs. 3-14).

Most of the lakes were in a "flow-through" setting during some part of the year, with ground water flowing into the lake along part of the perimeter and lake water flowing out along another. Flow reversals, when the typical ground-water flow direction temporarily reverses, were routinely observed in the basins of Lakes Barco, Grassy, Halfmoon, Olivia, and Round. Often, during rainy months, recharge was sufficient to raise the water table above lake stage along much of the shoreline, increasing the inflow. For example, the northern perimeter of Lake Olivia (fig. 11) received ground-water inflow only during June, July, and August 1996. After the rainy season ended, the water table again sloped away from the lake in this area, and inflow decreased substantially (Sacks and others, 1998). In other basins, drought conditions coupled with poor confinement of the Upper Floridan aquifer cause the adjacent water table to fall below lake stage, resulting in lateral leakage along parts of the perimeter that typically receive inflow. The Lake Barco basin provides an example of this effect (Sacks and others, 1992).

In general, sustained ground-water inflow arrived from the areas of the basins with the highest ridges. Lateral leakage and flow reversals typically occurred on the side of the lake with the lowest basin elevations (figs. 3-14). Lateral lake leakage appeared more likely where the drainage divide was close to the lake margin, for example, south of Lake Barco (fig. 4), southeast of Lake George (fig. 6), west of Halfmoon Lake (fig. 7), north of Lake Isis (fig. 9), and northwest of Lake Olivia (fig. 11). Lake Starr was somewhat atypical as it leaked toward the southeast, in the direction of the highest topographic ridge. However, this also was the area of the basin characterized by conspicuous sinkhole depressions (fig. 13).

Proximity to other lakes also may affect the pattern of ground-water flow around the 14 lakes. Thirteen of the 14 lakes were within 2.5R of one or more lakes, and 8 were within 1.5R (table 2). Lake Annie was farthest from any lake (about 4.5R). The tendency for ground water from the intervening basin to enter the lake is affected by whether the adjacent lake is higher or lower. For example, lake water typically leaked out laterally through the eastern shoreline of Round Lake toward a region of the eastern basin with low topography and a short hillside (fig. 12). Although the basin topography is similar on the western side of the lake, the lake consistently received ground-water inflow in this area. This may be because nearby Lake Winterset, which had a slightly higher stage than Round Lake, kept the adjacent water table elevated (fig. 12).

Ground-water catchments were simulated in previous studies for Lakes Barco, Five-O, and Starr using three-dimensional, finite-difference, saturated ground-water flow modeling combined with particle tracking. The models resolved steady-state flow-field velocities to determine the pathlines of ground water entering the lake. The extent of these pathlines defined the catchment. All of the ground water within the simulated ground-water catchment eventually flows into the lake. The sizes of the ground-water catchments for Lakes Barco, Five-O, and Starr differed substantially. The ground-water catchments to Lakes Barco and Starr reached about 0.3R and 1.0R from their respective lake margins, but both catchments were much smaller than their topographically defined basins (figs. 4 and 13). In contrast, at Lake Five-O, the ground-water catchment encompassed most of the topographic basin (fig. 5).

Hydrogeologic Framework

The size of ground-water catchments depends upon the hydrogeologic framework of the lake basin as well as basin topography. Hillside views of the basins reveal differences and similarities in the physical and geologic settings of the 14 lakes (see figs. 15-20). Hillside views are the perspective used in the two-dimensional modeling in the next section. The location of each hillside is shown on basin maps (figs. 3-14). Hillsides begin in the lake center at the lowest land-surface elevation (lake bottom), and end at the hilltop of the topographic drainage divide. Hillside views plotted at the same horizontal and vertical scale show the depth and slope of the lakebeds, basin radius and elevation, the thickness of the surficial aquifer and the intermediate confining unit, as well as the thickness of the unsaturated zone (figs. 15-20). The bottom elevation of each cross section is the approximate top of the Upper Floridan aquifer in the basin.

The thickness of the surficial deposits within the basins ranged widely from about 10 ft at Lake Hollingsworth to about 300 ft at Lake Annie (table 3). Although the hydraulic conductivity of the surficial aquifer was not known for all of the 14 basins, in the 5 intensively studied basins, the surficial aquifer conductivity ranged over an order of magnitude. The representative horizontal hydraulic conductivity (K_h) in the *shallow* surficial aquifer was about 60 feet per day (ft/d) at Five-O, 30 ft/day at Lake Starr, 8 ft/d at Lake Lucerne, 5 ft/d at Halfmoon Lake, and 3 ft/day at Lake Barco. Anisotropy was not directly determined in any of the basins, but the surficial deposits were heterogeneous and K_h typically decreased with depth in the surficial aquifer.

The depth of the water table below land surface also varied considerably among basins. Along the southern extent of the Lake Starr basin, the water table was overlain by nearly 120 ft of unsaturated material (fig. 20). At Lake Annie, the maximum unsaturated thickness was about 10 ft (fig. 15). Unsaturated zone thickness was affected more by topography than by the slope of the water table, which by comparison was relatively flat. At the end of a wet season, the maximum water-table slope found on the inflow side of the lakes ranged from 0.2 to 2.6 percent (2.6 ft vertical change per 100 ft horizontal distance). The maximum slope measured was less than 1 percent at Lakes Annie, Grassy, Lucerne, Olivia, Saddle Blanket, Starr, and Swim. The maximum water-table slope was greater than 1 percent at Lakes Barco, Five-O, George, Halfmoon, Hollingsworth and Isis. Lakes Barco and Isis, which were flow-through lakes, also had the largest negative water-table slopes on their outflow sides (table 2).

The lakes ranged in depth from 6 ft (Hollingsworth) to 65 ft (Annie) (figs. 15 and 17, and table 3). Four of the 14 lakes were considered deep, with a maximum depth greater than 45 ft (Annie, Five-O, Isis, and Olivia). The beds of these lakes also had steep slopes (maximum bed slope greater than 10 percent). Swim Lake, with a maximum depth of 30 ft but a small surface area (5 acres) had the steepest bed slope (maximum about 20 percent). Of the five lakes estimated to receive the highest ground-water inflow, four also had a steep bed slope (Annie, Five-O, Isis,

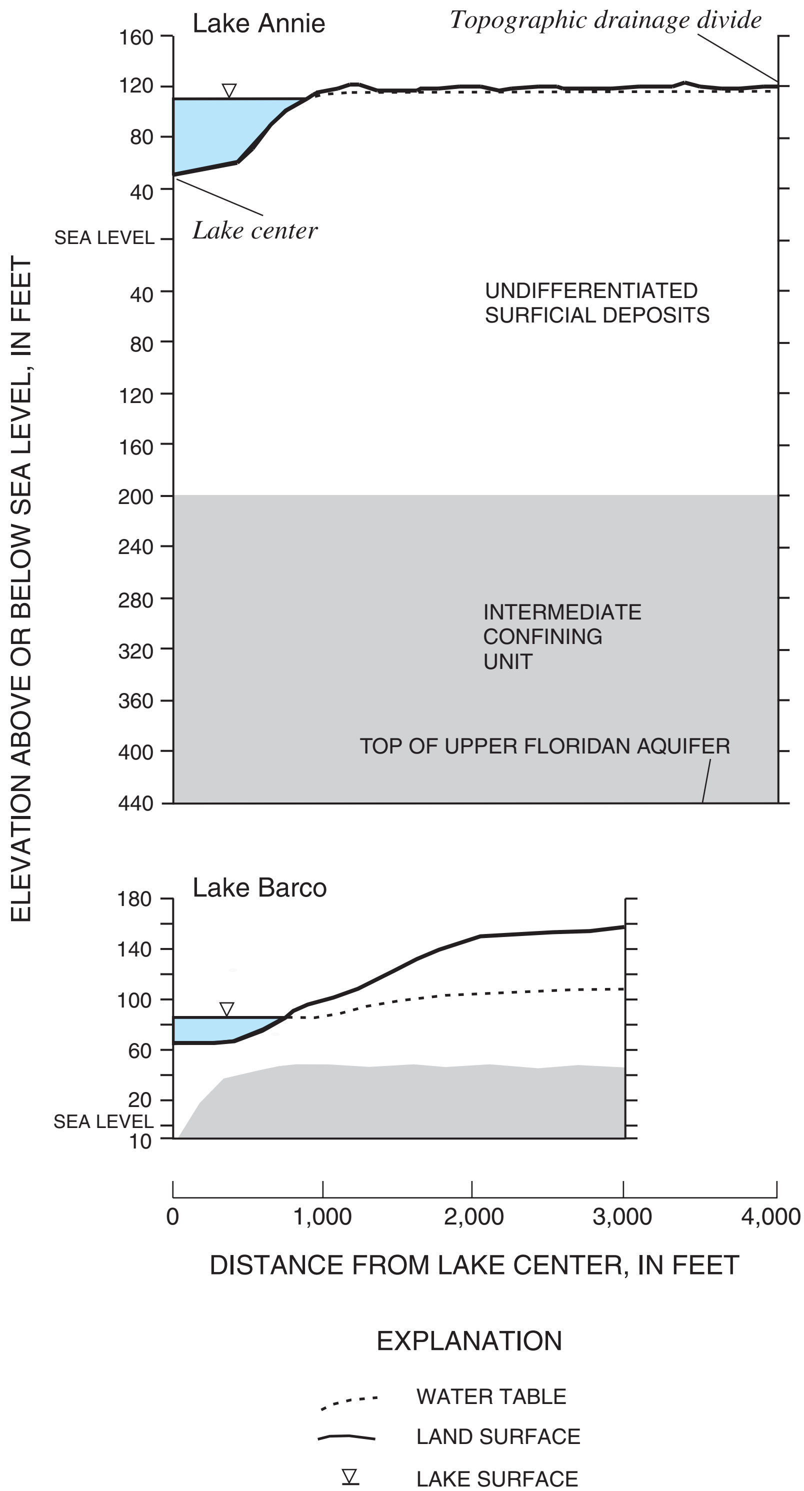


Figure 15. Simplified hydrogeologic sections along hillsides in the topographic basins of Lake Annie and Lake Barco. Section locations are shown in figures 3 and 4.

and Swim Lakes (table 2)). The large ground-water inflow estimated for Lake Hollingsworth, with its flat bottom, is probably attributable to other basin characteristics. Three of the four deep lakes were in Highlands County where the surficial deposits were greater than 200 ft thick (Lakes Annie, Isis, and Olivia) (figs. 15, 17, and 18). The fourth, Lake Five-O in the Florida panhandle, penetrated the entire thickness of a comparatively thin surficial aquifer (about 27 ft thick) (fig. 16).

The Hawthorn Group comprises the intermediate aquifer/confining unit below all of the lakes except Lake Five-O (Buono and others, 1979). The Hawthorn Group is composed of several formations that confine the Upper Floridan aquifer to varying degrees. For example, at Lake Lucerne and Lake Starr in Polk County, detailed lithology and hydraulic head data indicated that the lower part of the Hawthorn Group (Arcadia Formation) is connected hydraulically to the Upper Floridan aquifer. The upper part of the Hawthorn Group (the Peace River Formation) provides the confinement. Similarly, at Lake Five-O, in the panhandle of Florida, the Jackson Bluff Formation is considered the intermediate confining unit, and is about 40-ft thick in the basin (fig. 16). A dense, black, shelly clay less than 10 ft thick present at the base of the Jackson Bluff Formation, however, provides most of the confinement (Andrews and others, 1990). Because detailed lithology is not available for all of the basins, the convention of Buono and others (1979) is used in this report, wherein the entire thickness of the Hawthorn Group (or Jackson Bluff Formation) is referred to as the intermediate confining unit.

In the lake basins surveyed, the intermediate confining unit ranged in thickness from a minimum of about 5-10 ft at Halfmoon Lake to a maximum of about 250 ft at Lake Annie. The intermediate confining unit was greater than 200 ft thick in the southern range of the

Central Lake District (southern Polk and Highlands Counties), and typically less than 150 ft thick in central and northern Polk County. Subsidence features breaching the intermediate confining unit were identified beneath all five intensively studied lakes based on seismic reflection surveys (Lakes Barco, Five-O, Halfmoon, Lucerne, and Starr). Breaches in the confining unit were also documented in the basins surrounding Lakes Barco and Starr. Although represented as being flat in the hillside figures, the intermediate confining unit surface and thickness is uneven with variability in altitude of tens of feet over distances of hundreds of feet (Tihansky and others, 1996). The contour interval used to map the thickness of this unit in regional maps was 50 ft (Buono and others, 1979).

Soft lake sediment was described in the intensively studied lake basins. Sediment covered over two-thirds of the bottom of Lake Barco and was about 12 ft thick at the center (Sacks and others, 1992, fig. 8). Soft sediments were thinner at Lake Starr, (maximum thickness about 4 ft) and occupied less than half of the lake bottom area (Swancar and others, 2000, fig. 10). Thin and discontinuous sediments were reported for Lake Five-O by scuba divers (Roger Sweets, University of Kentucky, written commun., 1996). Sediment cores indicated that sediment was present mostly in the deepest areas of Lake Lucerne and generally was less than 3 ft thick (Lee and Swancar, 1997). Similarly, soft sediment was zero to 4 ft thick in the center of Halfmoon Lake (Metz and Sacks, 2002).

The downward head difference between the lake and the Upper Floridan aquifer varied from about 2 to 59 ft in the 14 lakes surveyed in this study (table 3). Due to differences in hydrogeology, the head difference typically was greater in lake basins in southern Polk County and Highlands County than in central and northern Polk County (table 3). The limestone of the Upper Floridan aquifer becomes deeper and the head in the Upper Floridan aquifer decreases toward the south, whereas the overlying surficial deposits, surficial aquifer, and intermediate aquifer/confining unit thicken (Tihansky and others, 1996).

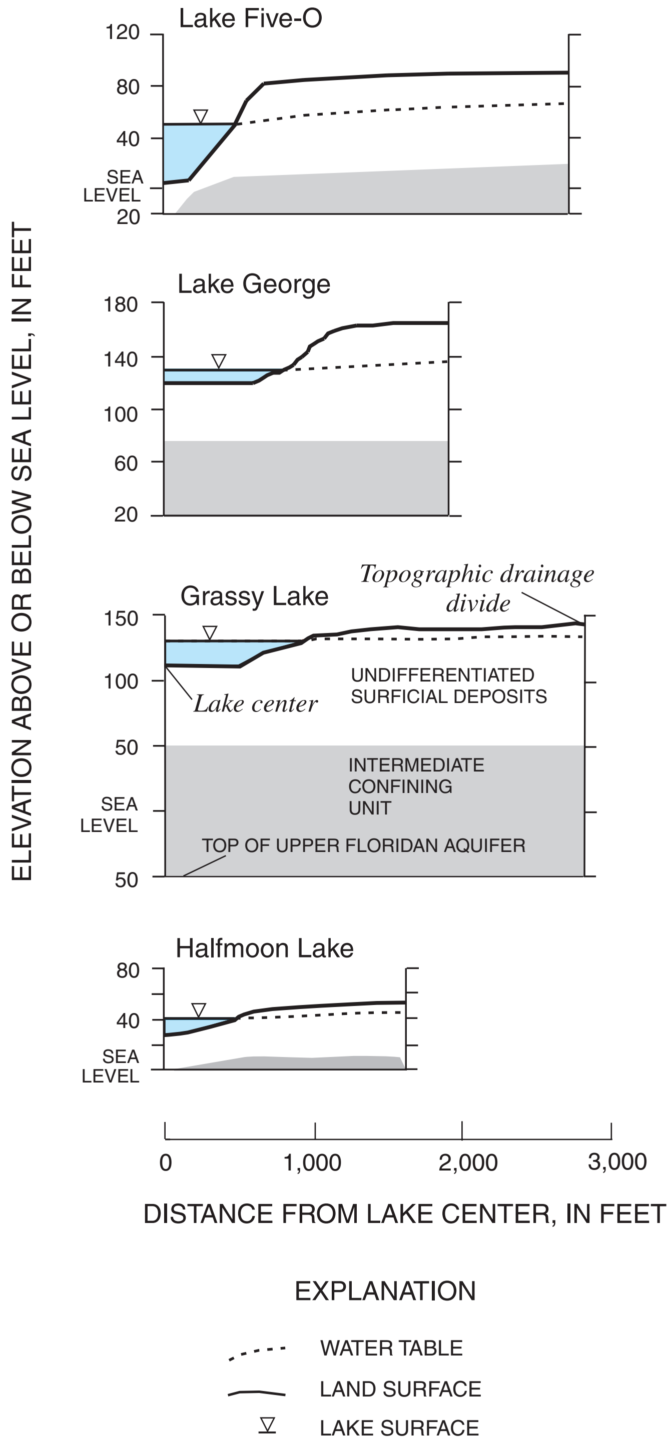


Figure 16. Simplified hydrogeologic sections along hillsides in the topographic basins of Lake Five-O, Lake George, Grassy Lake, and Halfmoon Lake. Section locations are shown in figures 5, 6, and 7.

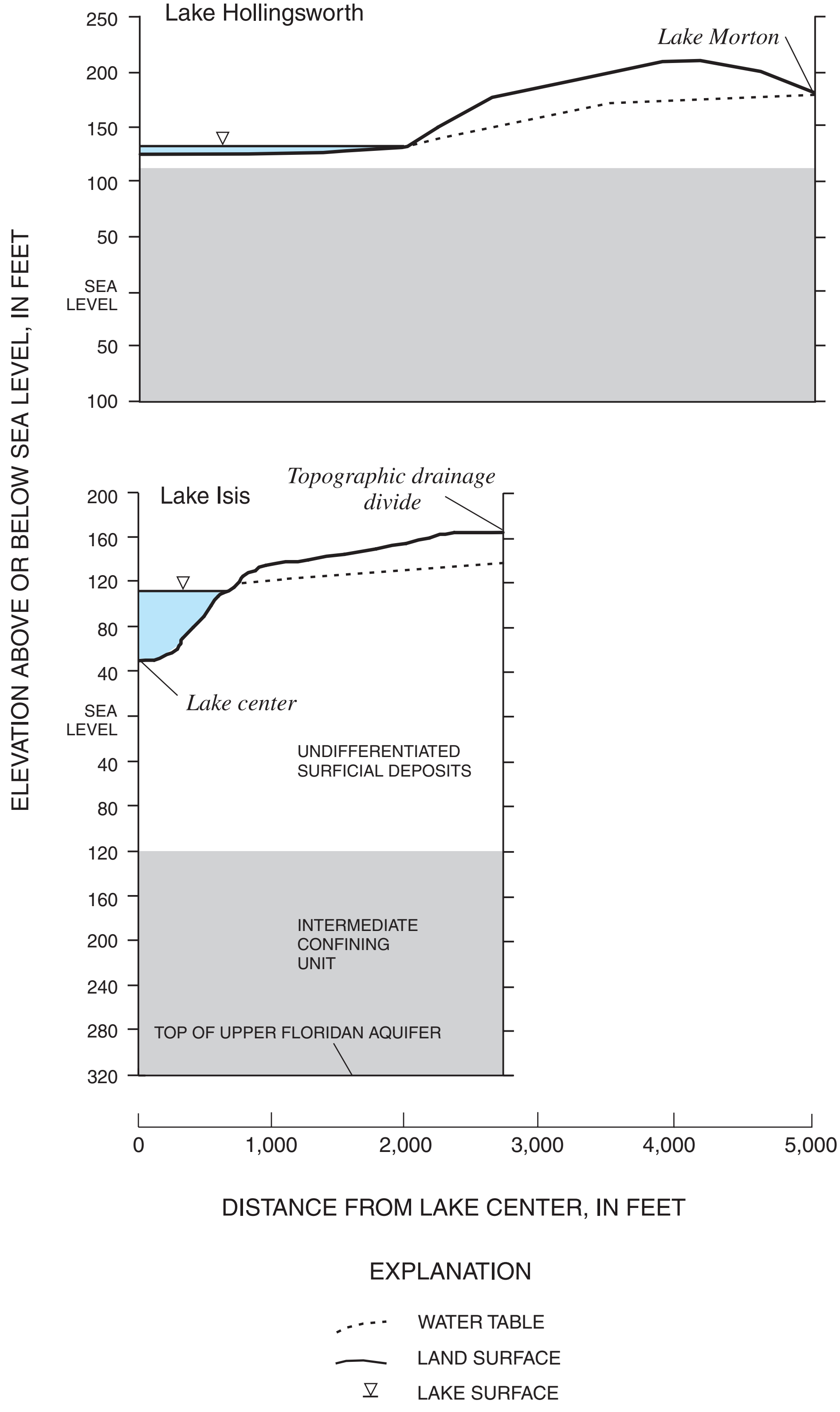


Figure 17. Simplified hydrogeologic sections along hillsides in the topographic basins of Lake Hollingsworth and Lake Isis. Section locations are shown in figures 8 and 9.

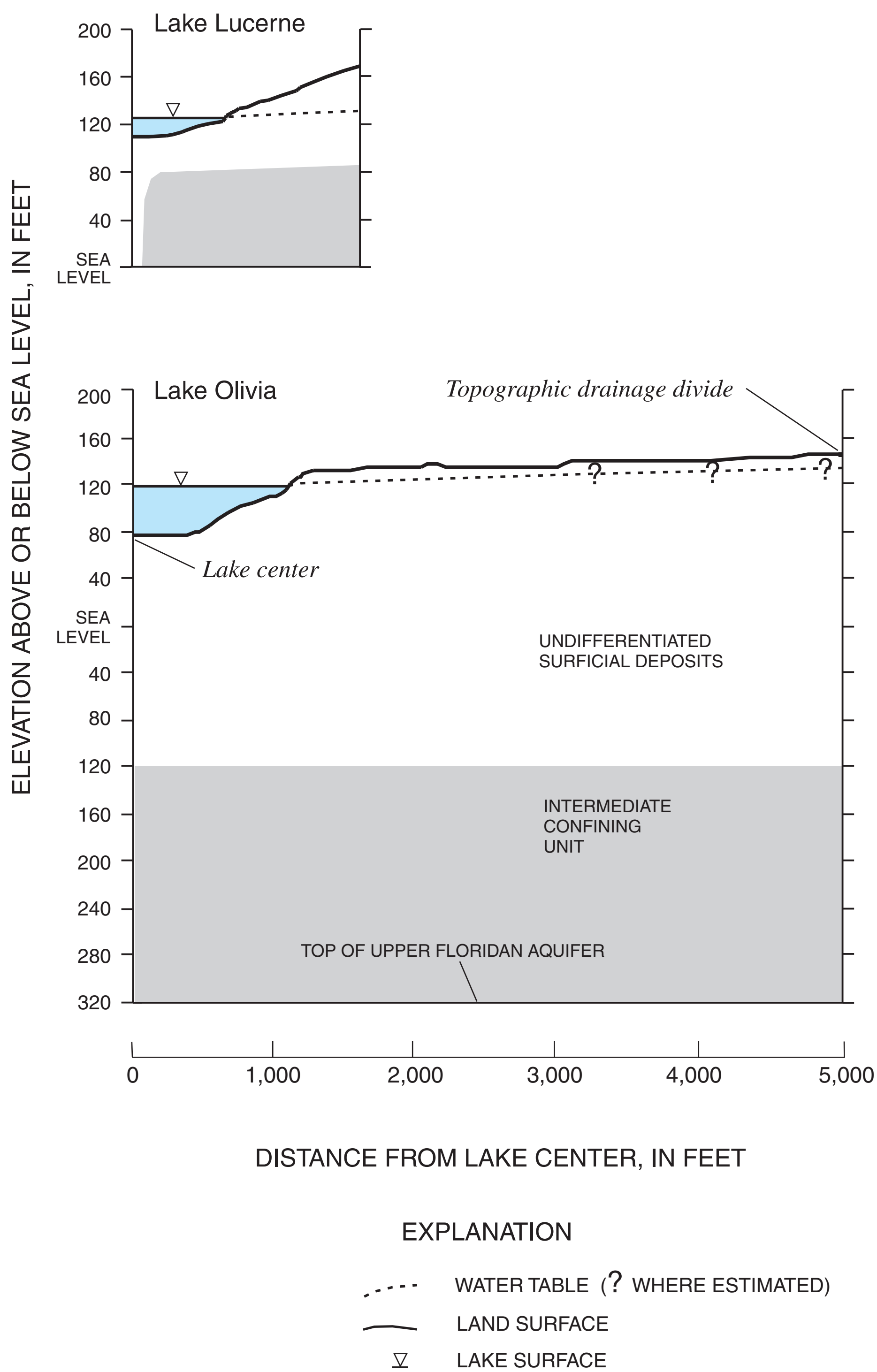


Figure 18. Simplified hydrogeologic sections along hillsides in the topographic basins of Lake Lucerne and Lake Olivia. Section locations are shown in figures 10 and 11.

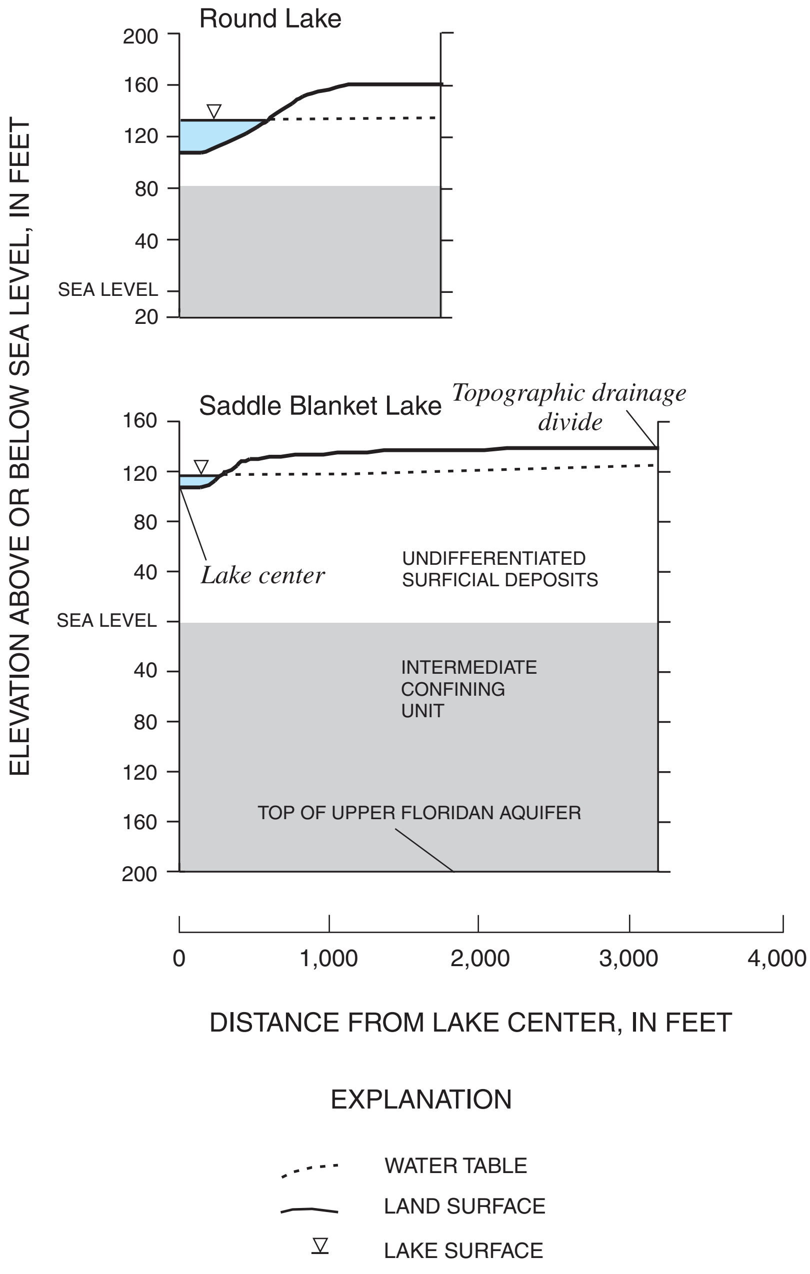


Figure 19. Simplified hydrogeologic sections along hillsides in the topographic basins of Round Lake and Saddle Blanket Lakes. Section locations are shown in figure 12.

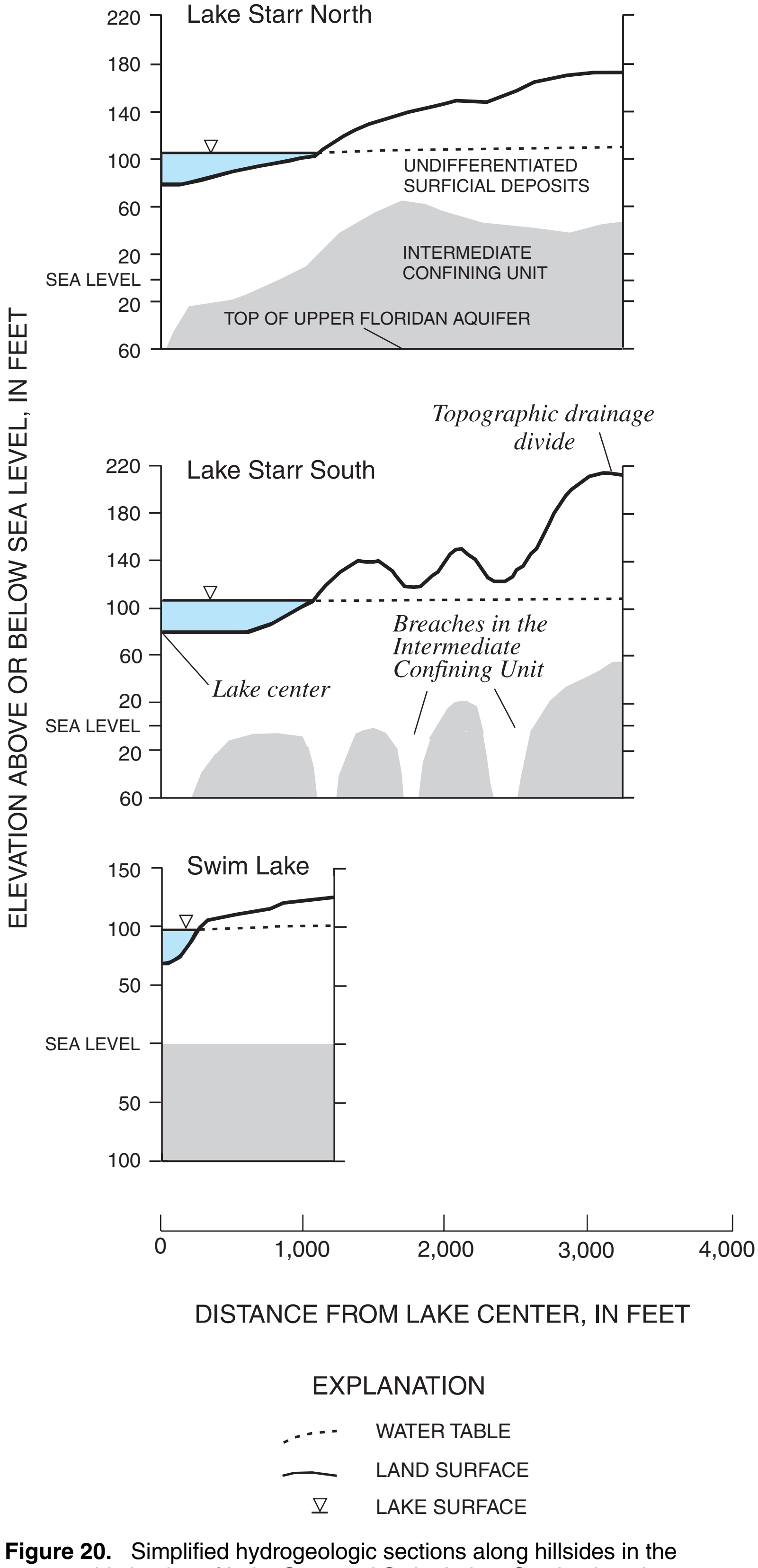


Figure 20. Simplified hydrogeologic sections along hillsides in the topographic basins of Lake Starr and Swim Lake. Section locations are shown in figures 13 and 14.

Regressions were used to examine relations between head difference and physical setting. Nine lakes described in two earlier investigations of lakes in the Highlands Ridge were included with the 14 lakes presented in this report (Geraghty and Miller, 1980; Barcelo and others, 1990) (table 3). In all cases, head differences were assumed to reflect steady conditions (no change in head with time). The head differences below these 23 lakes were significantly correlated to the mantle thickness (sum of surficial deposits and intermediate confining unit) in the basin (fig. 21a), but not to the elevation of the lakes, as suggested by Geraghty and Miller (1980) (fig. 21b). Most of the variation in head difference was explained by the thickness of the intermediate confining unit (R^2=0.43 for intermediate confining unit thickness alone, compared with R^2=0.27 for surficial aquifer thickness alone).

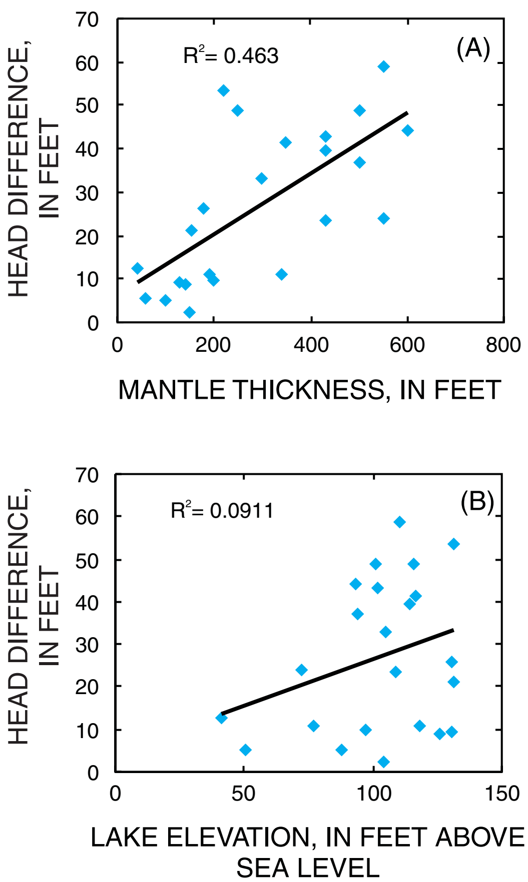


Figure 21. Relation of head difference between the lake and Upper Floridan aquifer to (A) mantle thickness near lake and (B) lake elevation. (Mantle thickness is the combined thickness of the surficial deposits and intermediate confining unit.)

NUMERICAL MODELING OF GROUND-WATER FLOW

Numerical modeling was used to simulate the potential effects of the physical setting of lake basins on the ground-water inflow to lakes. Ground-water flow beneath a series of conceptualized lake basins was simulated using a two-dimensional variably saturated flow model. The model was applied along a radial transect (hillside) through a series of hypothetical, circular lake basins. None of the lakes surveyed displayed complete radial symmetry in their interactions with the adjacent surficial aquifer, although ground-water interactions can be symmetric along some arc of a lake perimeter. Assuming radial symmetry for the entire lake basin is an oversimplification made for purposes of numerical modeling.

Methods

Variably saturated flow was simulated using the HYDRUS-2D flow modeling software (Šimůnek and others, 1996). At the core of HYDRUS-2D is the computer program SWMS_2D, a two-dimensional, finite-element model code that numerically solves the Richards' equation for unsaturated-saturated water flow in porous media and the Fickian-based convection-dispersion equation for solute transport (Šimůnek, et al., 1992). HYDRUS-2D unites this modeling code with a sophisticated graphical user interface. The model simulates two-dimensional, isothermal, Darcian flow of water in a variably saturated rigid porous media. Air flow is assumed to be insignificant. The governing flow equation for variably saturated flow is Richards' equation as applied in Šimůnek and others (1996):

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^A\frac{\partial h}{\partial x_j} + K_{iz}^A\right)\right] - S, \qquad (1)$$

where:

θ is the volumetric water content $[L^3 L^{-3}]$,

h is the pressure head [L],

S is a sink term $[T^{-1}]$,

x_i (i=1,2) are the spatial coordinates [L],

t is time [T], and

K_{ij}^A are the components of a dimensionless anisotropy tensor K^A used to account for an anisotropic medium.

K is the unsaturated hydraulic conductivity function [LT^{-1}] given by

$$K(h,x,z,t) = K_s(x,z)K_r(h,x,z,t), \qquad (2)$$

where:

K_s is saturated hydraulic conductivity and

K_r is relative hydraulic conductivity [$L\,T^{-1}$].

If equation (1) is applied to planar flow in a vertical cross section, $x_1 = x$ is the horizontal dimension and $x_2 = z$ is the vertical dimension, assumed positive upward. For flow in an axisymmetric system, $x_1 = r$, where r is the radial distance from the center line. Model simulations were performed using metric units, but are expressed in English units for this report.

Radial Models

Ground-water flow was simulated for a radial section that represents a hillside taken from a circular basin. The catchment size was delineated using the simulated ground-water velocity vectors. The catchment size also was derived using the modeled ground-water inflow rate and with the recharge flux along the hillside. Both methods gave comparable estimates of the length of the catchment along the hillside.

The model described in figure 22, without the breaches in confining unit onshore of the lake, was the starting point for most of the steady-state simulations. Variations on this original case were made for successive simulations. The lake had a radius of 656 ft (200 m), and a maximum depth of 24.6 ft (7.5 m). The hillside extended 1,968 ft (600 m) or 3R from the edge of the lake to the topographic drainage divide. The vertical relief from the deepest point on the lake bottom to the hilltop was 39 ft (12 m). The conceptual basin was analogous to a circular lake with a surface area of 31 acres surrounded by a 465-acre basin with low topographic relief. The hypothetical lake is similar in size to Lakes Lucerne, Barco, and Round (table 2).

The model domain represented the lake and the mantle deposits overlying the Upper Floridan aquifer.

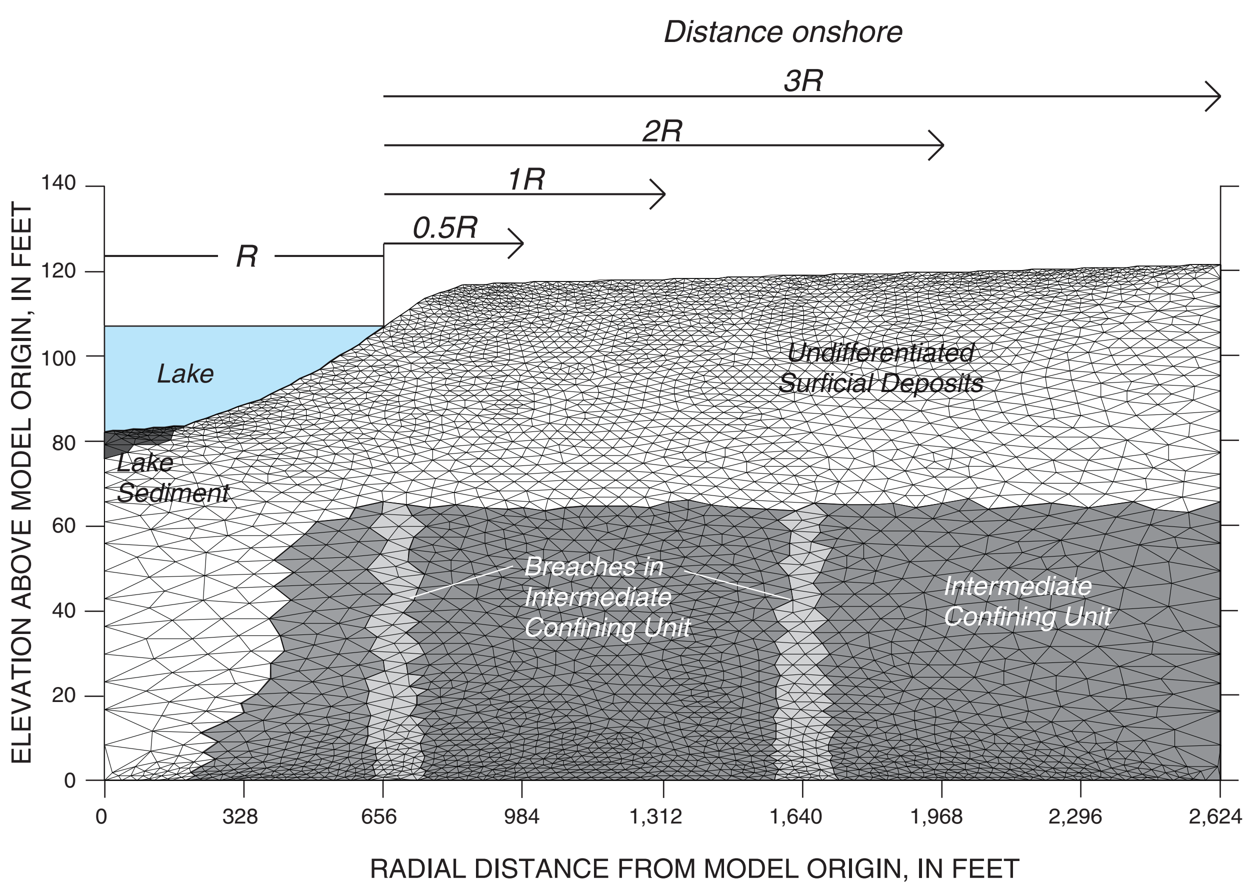


Figure 22. Schematic of the initial lake basin model. Breaches in the intermediate confining unit around the lake were not included in the initial lake basin model, but were used in subsequent simulations.

The intermediate confining unit, in the lower part of the model, was 65 ft thick. Directly below the lake, the intermediate confining unit has been breached by a sinkhole structure and replaced with surficial deposits. Surficial sand and clay deposits ranging in thickness from 40 to 60 ft overlie the intermediate confining unit. Lake sediment underlies the lake, and this sediment has a much lower hydraulic conductivity than the encompassing surficial deposits.

The hydraulic characteristics of the hydrogeologic units used in the model are shown in table 4 and are loosely adapted from the Lake Barco basin. The unconsolidated surficial deposits were assumed to be predominantly sand with a hydraulic conductivity of 3 ft/d. The daily flux of water entering the hillside was based on 35 percent of the average annual rainfall rate of 52 in/yr. The head in the Upper Floridan aquifer was 4.9 ft below the lake stage. With these hydraulic parameters set, the K_h of the intermediate confining unit was adjusted until the overall water-table slope between the lake and hilltop was about 0.5 percent. The highest incremental water-table slope simulated in the basin model (about 1.5 percent near the lake) was similar to the maximum values in the 14 surveyed lakes (table 2). The resulting saturated horizontal hydraulic conductivity (K_h) for the intermediate confining unit was 0.2 ft/d, and was comparable to values determined in field studies (for example, Amy Swancar and T.M. Lee, USGS, written commun., 2002).

Table 4. Hydraulic parameters used in the initial lake basin model

[ft-1, per foot; m^{-1}, per meter; m/d, meters per day]

Unsaturated Hydraulic Parameters[1]		
Saturation moisture content	0.32	
Residual moisture content	0.034	
Alpha[2]	1.0 ft^{-1}	(3.27 m^{-1})
N[2]	4.68	
Saturated Horizontal Hydraulic Conductivity[1]	**(foot per day)**	**(meters per day)**
Surficial aquifer	3	(0.91)
Intermediate confining unit	0.2	(0.06)
Organic sediment	0.03	(0.009)
Upper Floridan aquifer[3]	833	(254)

[1]All initial values were taken from a simulation of Lake Barco by Lee (2000). Unsaturated zone is within the undifferentiated surficial deposits only.

[2]Alpha and N are curve-fitting parameters developed by van Genuchten and others (1991).

[3]Boundary nodes only.

For transient simulations, the hillside shown in figure 22 was changed to test the effect of the topography on the simulated inflow to the lake. The initial lake basin model simulated a hillside with relatively low relief above the lake surface. In a variation on the initial lake basin model, the land surface close to the lake shore was lowered to reduce the unsaturated zone thickness in the near shore region (fig. 23a). The hillside of the initial lake basin model was then raised, increasing the unsaturated zone thickness at the top of the hill from about 7 to 50 ft (fig. 23b). The near shore region of the high hillside was also lowered (fig. 23b).

The unsaturated soil characteristics used in the model were from a Candler series sand (deeply weathered, acidic, uncoated, Typic Quartzipsamments) collected at a site in Orange County, in the Central Lake District (Lee, 2000; Sumner, 1996). This soil was used to simulate the shallow surficial deposits in the model. Below the elevation of the lake water surface, porous media in the model typically were saturated, and K_h and anisotropy were the only soil parameters required. The anisotropy in the saturated zone (K_h/K_v) was assumed to be 10. An anisotropy of one was assumed in the unsaturated zone.

Changing the geometry of the model domain by changing the contour of the lake bottom or hillside, or the overall height or length of the section, required a new model with a new finite-element mesh. To prevent changes in modeled fluxes from becoming an artifact of differences in the finite-element meshes used in simulations, the triangular elements used in the meshes were kept as small as practical, and the size of triangular elements used in different model variations was kept comparable. The dimensions of mesh elements were reduced in preliminary model runs until consistent lake fluxes could be produced using a variety of meshes with the same tolerances on mesh design. The dimensions of the mesh elements then were kept comparable between models by keeping the spacing between boundary nodes similar.

The model has a mesh generator algorithm that constructs the finite-element mesh based on user-defined parameters. The dimensions of the finite-element grid were smallest in the shallow surficial deposits and along the lake bottom, where the heights of the triangles (measured vertically),

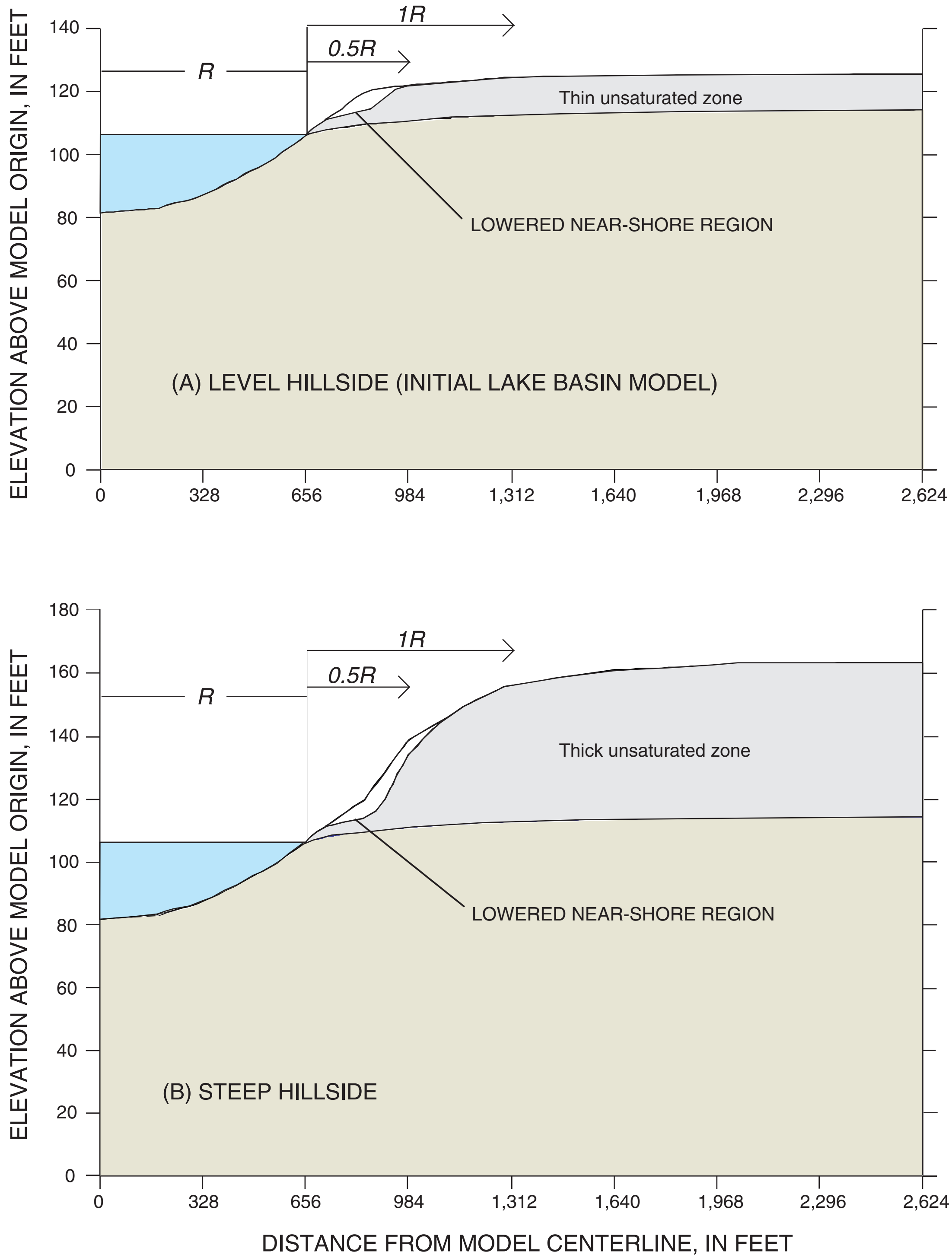


Figure 23. Schematic of the hillsides used for transient simulations.

Δz, were less than or equal to ($\leq$) 0.82 ft and the widths of the triangles, Δr, were $\leq$ 16.4 ft. The largest mesh dimensions ($\Delta z \leq$ 6.6 ft, $\Delta r \leq$ 131 ft) were generated in the intermediate confining unit beneath the hilltop. All models used a mesh distortion variable of 0.04 or 0.05. This variable gives the mesh a vertical to horizontal ratio of 1 to 20 or 1 to 25. All of the simulations with a long hillside (radial distance 2,624 ft or 800 m) used 220 boundary nodes. In shorter basins (discussed in the following section on Effect of Basin Size), the number of boundary nodes was reduced to maintain a comparable mesh density (number of triangular elements).

Model Boundaries

In all simulations, lateral model boundaries were located beneath the center of the lake and beneath the topographically defined drainage divide (figs. 22 and 23). At these boundaries, the flow in the unsaturated and saturated zones was assumed to be predominantly vertical, as observed in field studies. Thus, no flow occurred across these lateral boundaries. The lower model boundary represented the Upper Floridan aquifer, and was assigned a specified pressure head to reflect the potentiometric head in the aquifer. The total head along this boundary was assumed to be 4.9 ft below the lake stage for the initial model run, and was varied in subsequent runs. Where the lake submerges the lowest part of the hillside, the boundary was a specified pressure head distributed along the lake bottom to reflect hydrostatic conditions of the lake stage. The lake stage was assumed to be 106.63 ft (32.5 m) above the model origin for most simulations.

The water flux rate along the hillside differed in the steady-state and transient model simulations. In the steady-state simulations, the hillside received a constant flux of water. Losses to evaporation and transpiration were not simulated but were subtracted directly from the flux rate applied to the hillside. For most of the steady-state simulations, this net recharge rate (flux) was assumed to equal 0.0496 inches per day (in/d), and was equivalent to 35 percent of an average annual rainfall rate of 52 inches per year, based upon recharge estimates at Lake Barco (Lee, 1996). This flux was applied to the land surface and traveled through the unsaturated zone before arriving at the water table as a net recharge rate. There is no change in storage in the unsaturated zone under steady-state conditions, therefore the flux into the land surface at any time equaled the flux at the water table. For this reason, the hillside topography had no affect on the water-table configuration for steady-state simulations.

Transient simulations used a time-variable specified flux along the hillside to reflect the seasonal variability of recharge. A flux rate approximating net daily recharge was applied to the land surface each day for a representative 273-day period (October 1, 1997 - June 30, 1998). The daily recharge rates applied to the land surface were those used by Amy Swancar and T.M. Lee, USGS, written commun., 2002, to simulate the saturated ground-water flow at Lake Starr, in Polk County. Daily recharge was computed as a variable percentage of the daily net precipitation in a manner referred to as the "threshold" method. With this method, the annual total recharge equaled about 50 percent of the average annual rainfall (Amy Swancar and T.M. Lee, USGS, written commun., 2002). This recharge rate was higher than the 35 percent rate applied to the initial steady-state model, but comparable to the higher recharge cases considered in the steady-state simulations. The last 150 days or 5 months of the simulation provided the results for the transient analysis. The first 4 months (123 days) of the simulation were used to distance the model results from the effects of the initial conditions. Within the latter 5 months, the first 2 months had above average rainfall and the last 3 months were drier.

Unlike the steady-state model, the transient model simulates the arrival time and rate of recharge to the water table at different locations under the hillside (fig. 23). The flux arriving at the water table, and thus the *transient* water-table response, is affected by the daily recharge flux, the moisture storage in the unsaturated zone, the depth of the water table below land surface, and the soil moisture characteristics (table 4). The initial pressure-head distribution for transient simulations was the simulated steady-state pressure-head distribution for the model.

Limits to Hypothetical Steady-State Simulations

Hypothetical steady-state modeling results were compared to explore the effect of physical and hydrogeological factors on the magnitude of ground-water inflow and catchment size. For example, consider two identical hypothetical lake basin models. If a single physical factor in one of the two basin models is altered, the effect it has on the simulated ground-water flow can be compared to the unaltered model.

Properly interpreting the model results, however, requires considering the effect of the lake stage boundary on model simulations. In steady-state model simulations, the lake stage remains fixed regardless of the magnitude of fluxes simulated to enter or leave the lake. This is a feature of the specified head model boundary representing the lake and a necessary constraint of using a two-dimensional radial model. The hypothetical setting represented by the model can be thought of as a lake with inflow and outflow streams that deliver and remove the amount of water necessary to maintain a constant lake stage. If the model simulates ground-water inflow greater than lake leakage, then the outflow stream carries away the excess. If the model simulates lake leakage greater than ground-water inflow, then an inflow stream brings in the water necessary to keep the stage from falling.

Alternatively, modeling results could reflect ground-water interactions along some limited arc of the lake perimeter. Along this arc, either net ground-water inflow (that is, ground-water inflow in excess of the lake leakage) occurs, or net leakage (leakage in excess of ground-water inflow) occurs; however, the sum of these fluxes along the entire perimeter equals zero. For example, net ground-water inflow was simulated along the northern shore of Lake Barco, whereas net leakage was simulated along the southern shore (Lee, 2000).

Recognizing the effect of the lake stage boundary provides the basis for interpreting the model simulation results. In simulations that increase ground-water inflow, keeping lake stage fixed tends to exaggerate increases in inflow. Imagine two lake basins in west-central Florida. Assume they are identical in all respects except that the intermediate confining unit in the basin surrounding one of the two lakes leaks more than the intermediate confining unit around the other. (Assume confinement directly *beneath* each lake is the same.) Under steady-state conditions, the lake in the well-confined basin will receive a higher rate of ground-water inflow than the lake in the leakier basin, the stage will be higher, and lake leakage will be higher (three-dimensional lake basin simulations provided by A. Swancar, USGS, Tampa, Fla., written commun. June 2001). However, keeping the lake stage constant as ground-water inflow increases, instead of allowing it to rise, will tend to exaggerate the steady-state ground-water inflow received by the lake in the well-confined setting. Conversely, in simulations that increase lake leakage, keeping lake stage fixed tends to exaggerate the increase in leakage rates instead of increasing lake leakage *and* lowering the lake stage.

For these reasons, the changes in inflow and lake leakage within a suite of simulations are not meant to convey quantitatively the changes in the magnitude of inflow and leakage to an actual lake. Instead, model results should be compared qualitatively for whether the factor considered tended to increase or decrease the simulated ground-water inflow rate and catchment size, whether these changes were large or small, and why. Model results also were used to investigate the potential limits to catchment size in mantled karst terrain, explore whether factors affected mostly inflow or leakage, and describe the effect of various factors on the distribution of inflow and leakage along the lake bottom.

Limits to Hypothetical Transient Simulations

The thickness of the unsaturated zone affects the time for recharge to reach the water table, and this affects the timing and magnitude of the consequent ground-water inflow to the lake. Transient simulations were used to show the potential effects of the unsaturated zone thickness in a given basin on the timing and magnitude of ground-water inflow. Short time-scale responses (days) of the water table and simulated ground-water inflow also were affected by the assumption of constant lake stage during the 9-month simulation period (see discussion). Still, the transient simulations provide insight into the overall response of the flow field to transient recharge, how topography affects the transient recharge in basins, and whether this response tended to increase or decrease the ground-water inflow and catchment size. Short-term responses seen in the basins also were affected by the assumed soil characteristics, the saturated hydraulic conductivity, and the time interval over which recharge was applied at the land surface. These and other considerations for ground-water inflows from transient simulations with a variably saturated flow model are discussed in Lee (2000).

Steady-State Simulation Results

Initial Lake Basin Model

The initial lake model results describe the exchange of water between the lake and the surrounding aquifer, and define the ground-water catchment. The simulated catchment in the initial lake model extended 374 ft (0.56R) onshore (figs. 24a and b). This distance onshore, when converted to an area ringing the

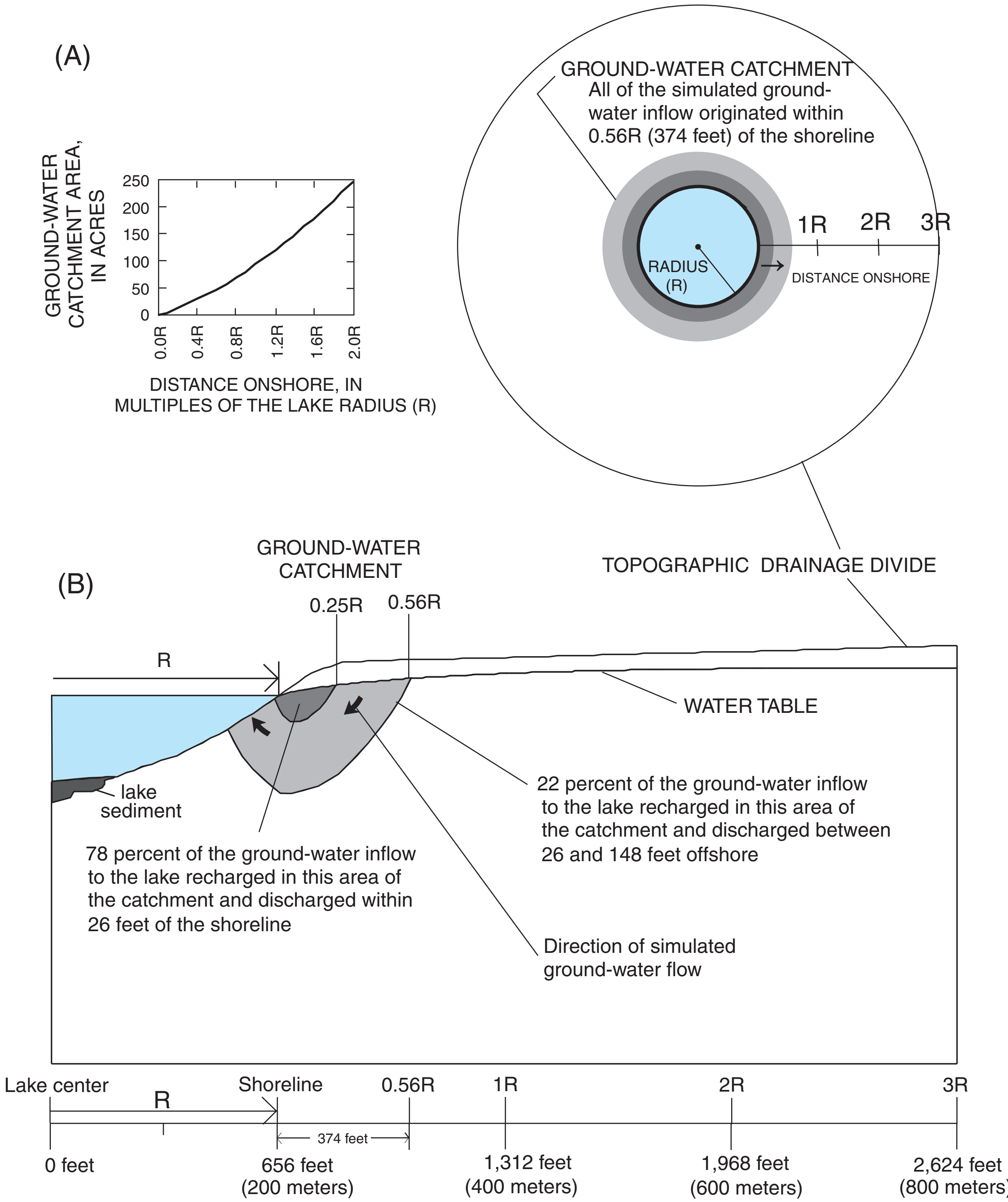


Figure 24. Simulation results for the initial lake basin model: (A) areal view of basin showing the location of the ground-water catchment to the lake, and (B) radial view showing the simulated water table and location of the ground-water catchment.

lake, described the size of the catchment. The catchment area increases as the square of the catchment distance onshore (fig. 24a). Ground water entering the shallow lake bottom originated as recharge in the near shore region of the catchment. Ground water entering the deeper regions of the lake bottom originated as recharge farther up the hillside (fig. 24b). For the initial model simulation, the ground-water inflow rate exceeded the lake leakage rate (8,470 and 4,940 ft^3/d/360 degrees, respectively) and the excess was equivalent to a 27.5-in/yr rise over the lake area. Variations on this initial simulation could seem to produce more realistic results, with balanced leakage and inflow. In this analysis, however, no one simulation is necessarily better than another, as all provide a measure of the tendency of the flow field to generate inflow or leakage under different physical conditions.

The velocity of the ground-water inflow was highest at the water's edge, and decreased with distance offshore (fig. 25). Inflow stopped about 148 ft offshore, where the velocity vectors reversed from inflow to leakage. Leakage velocity increased from this point toward the lake center and peaked just before reaching the lake sediment. The radial model simulated a large volume of ground water entering the lake near the shoreline for two reasons. First, the ground-water velocity was high in this part of the lake, and second, the area of inflow was large; that is, the area of the lake bottom near the shoreline occupied a relatively large fraction of the total lake bottom area (fig. 25).

Effect of Recharge Rate

Simulated ground-water inflow to the lake approximately tripled when the steady-state recharge rate was increased from 25 percent to 45 percent of the annual rainfall (fig. 26). Greater recharge also increased the radius of the ground-water catchment. The catchment extended about 290 ft onshore of the lake (0.44R) when the recharge was 25 percent of the annual rainfall. It reached 440 ft onshore (0.66R) when recharge was 45 percent of the annual rainfall. For the lake basin dimensions used in this model, this translates into an increase in the catchment area from 33 to 54 acres or a 60 percent increase in size.

Under the assumption of constant lake stage, the simulated lake leakage decreased only slightly (<10 percent) in response to the increased recharge (fig. 26).

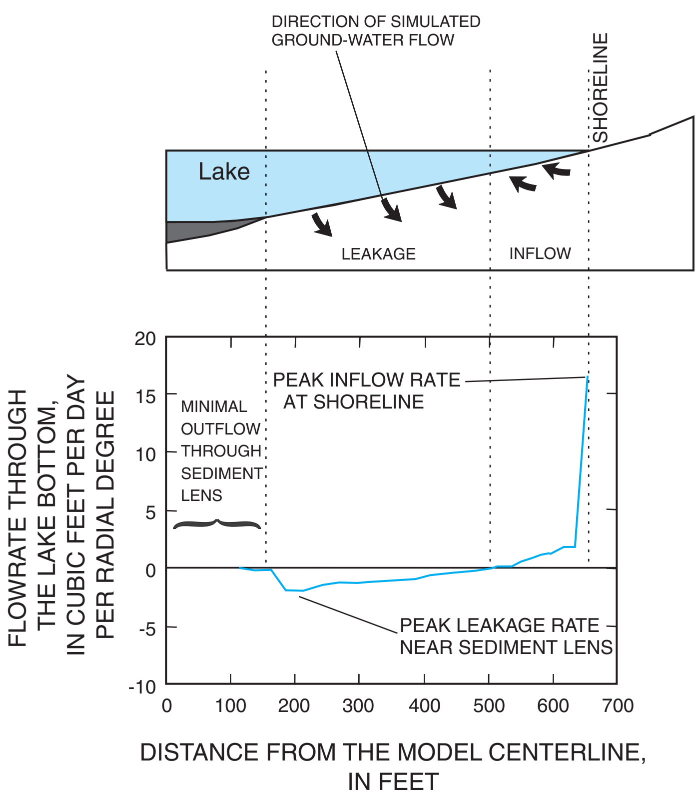


Figure 25. Ground-water flow distribution along the lakebed for the initial lake basin model. Arrows show ground-water flow direction.

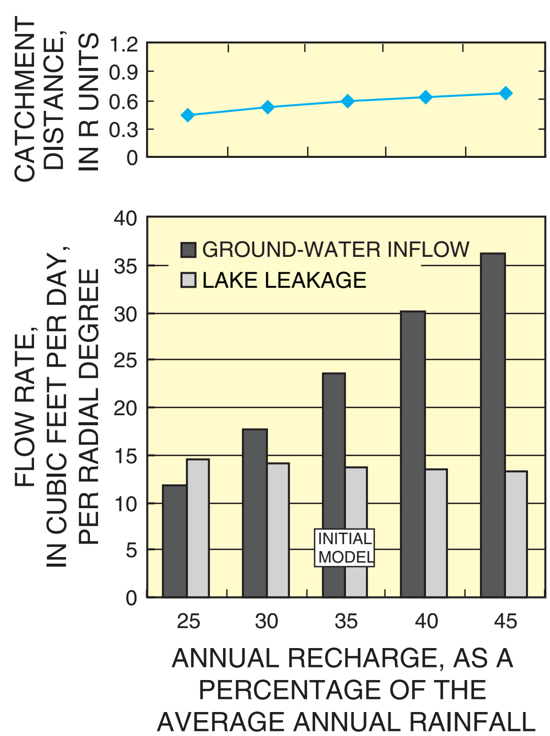


Figure 26. Simulated ground-water inflow and leakage rates, and catchment sizes for modeled lakes with different recharge rates.

This small decrease occurred because at the higher of the two recharge rates, ground water entered the lakebed farther offshore (172 ft compared to 101 ft), reducing the area of lake bottom that leaked. The reduction in leakage was relatively small, however, because velocities were low in the area of the lake bottom where this transition from leakage to inflow occurred. The greatest increase in ground-water inflow was near the lake margin where velocity increased because of the increased water-table slope.

Greater recharge typically is coupled with a rise in the potentiometric surface of the Upper Floridan aquifer, particularly in basins where greater rainfall would lessen ground-water pumping for irrigation. Both effects, when sustained, would tend to raise lake stage, and increase the magnitude of ground-water inflow and catchment size. The steady-state losses from the lake would rise accordingly (see section Effect of Upper Floridan Aquifer Boundary Condition).

Effect of Basin Size

For lake basins in which all other basin characteristics are equal, differences in the size of the topographically defined basin can affect the magnitude of ground-water inflow and catchment size. In successive simulations, the lateral model boundary was set at distances from the lakeshore ranging from 0.5R to 3.0R. The dimensions of the modeled basins are shown on figure 22. Increasing the basin size from 0.5R to 1R approximately doubled the simulated ground-water inflow (fig. 27) and increased the ground-water catchment size from 0.24R to 0.44R. Increasing the size of the basin from 1R to 2R increased the steady-state inflow again but by about 35 percent and increased the catchment size to 0.56R. Increasing the basin size from 2R to 3R resulted in only a 6 percent increase in the simulated inflow, suggesting that successive increases in basin size would generate little additional inflow for this setting (fig. 27).

The shape of the steady-state water table was independent of the slope of the land surface or the unsaturated zone thickness. The shape depended only on the boundary conditions, the distribution of hydraulic conductivity in the model, and basin size. Increasing the size of the basin increased the simulated water-table elevation at the drainage divide by moving the divide beyond the region where the water table was deformed by ground-water discharge to the lake. The higher water table at the divide, in turn, increased the water-table gradient near the lake, which increased

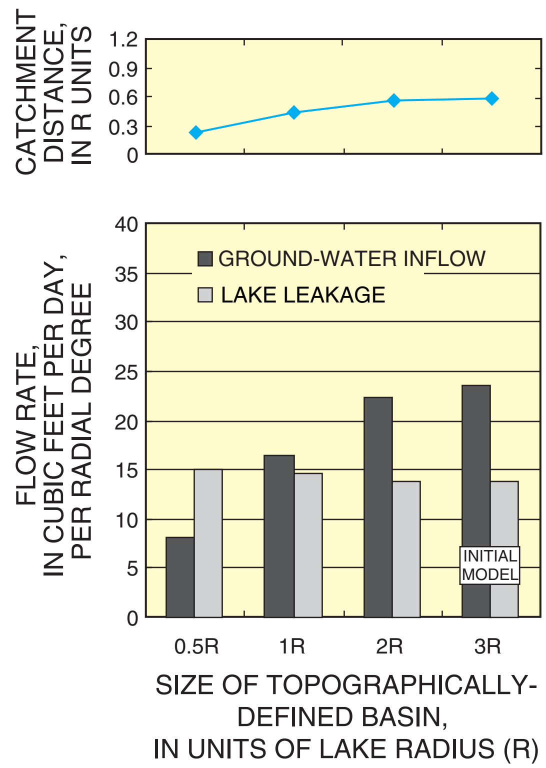


Figure 27. Simulated ground-water inflow and leakage rates, and catchment sizes for modeled lakes with different size basins.

inflow. For simulations beyond 2R, the rise in the simulated water table at the drainage divide was relatively small for each additional R of basin size. As a result, ground-water inflow only increased marginally as basin radius was increased beyond 2R.

Increasing basin size also slightly decreased the tendency for the simulated lakes to leak. Because greater basin size tended to increase ground-water inflow, it also tended to reduce the area of the lakebed through which leakage occurred. Leakage was minimally responsive to basin radius, decreasing by about 8 percent as basin radius increased from 0.5R to 3R.

Each of the 14 lakes described had within its basin a shortest hillside ≤ 1R in length (table 2). A nearby lake can shorten the distance to the basin drainage divide along a hillside, potentially limiting the size of the ground-water catchment and ground-water inflow. If the adjacent lake were at a higher stage, however, it could increase the catchment size relative to a short hillside with no lake. An upgradient lake does not imply lateral ground-water flow between the lakes. Instead, the water table below the hillside may be maintained higher than it would be beneath a short hillside with no upgradient lake. This higher water table would extend the size of the ground-water catchment on this side of the basin. In contrast, a small ground-water catchment, or lateral leakage, could result if the adjacent lake were lower than the principal lake.

Effect of Surficial Aquifer Conductivity

Of the basin characteristics simulated, surficial aquifer K_h had the most direct effect on the size of the contributing ground-water basin and magnitude of the simulated ground-water inflow. Simulations began with the initial model conditions shown in table 4. Varying K_h in the initial model from 1 to 20 ft/day changed the ground-water inflow to the lake by a factor of about 6 (fig. 28), and altered the radius of the contributing ground-water basin by a factor of about 4 (from 0.33R to 1.33R) (table 5). The basin with the lowest surficial aquifer K_h had the smallest catchment (0.33R) and generated the least amount of ground-water inflow. However, the water table in this basin had the steepest slope toward the lake (table 5). The water table was 5.7 ft higher at the drainage divide than the basin with the largest K_h.

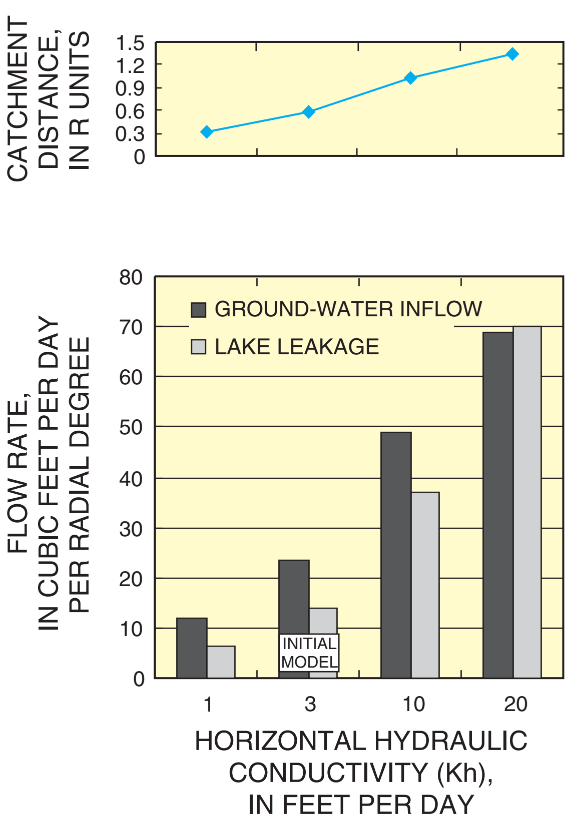


Figure 28. Simulated ground-water inflow and leakage rates, and catchment sizes for modeled lakes with different horizontal hydraulic conductivity (K_h) values in the surficial aquifer.

Table 5. Simulated water-table slopes and catchment sizes resulting from varying horizontal hydraulic conductivity (K_h) in the surficial aquifer

[R, catchment size in units of lake radius]

K_h (feet per day)	Catchment size	Slope[1] (percent)	Slope[2] (percent)
1	0.33R	0.5	1.0
3	0.58R	0.4	0.8
10	1.0R	0.3	0.6
20	1.33R	0.2	0.4

[1]Water-table slope between the lake and drainage divide.
[2]Water-table slope between the lake and the basin at 1.5R.

In a highly conductive surficial aquifer, steady-state ground-water inflow and lake leakage would both be large. In nature, however, one process typically dominates over the other at any given time. For example, at Lake Five-O, in Bay County, the surficial aquifer was conductive with a median K_h determined from slug tests to be 62 ft/d (19 m/d) (Andrews and others, 1990). Both inflow and leakage were large but they alternated in importance at different times. Ground-water inflow substantially exceeded leakage during 1989, when recharge was above average. Leakage far exceeded inflow during 1990, when recharge was below average (Grubbs, 1995).

Within ridge areas of Florida (fig. 2) the undifferentiated surficial deposits are principally sand with smaller fractions of silt and clay, and the clay content commonly increases with depth (Stewart, 1966). To explore the effect of contrasts in surficial aquifer conductivity on ground-water inflow, the lower part of the surficial aquifer as represented in the model, was made less conductive than the upper part. K_h in the surficial aquifer was 10 ft/day above an elevation of 88.6 ft, and 3 ft/day below that elevation. Simulating the two layers in the surficial aquifer (compared to the entire surficial aquifer having a K_h of 10 ft/d) reduced ground-water inflow slightly (by 14 percent) and resulted in a slightly smaller and shallower catchment. The presence of low-conductivity deposits in the collapse feature below the lake, however, reduced lake leakage by nearly 60 percent, which more than made up for the lost inflow. In a similar manner, doubling the anisotropy in the surficial aquifer (in effect, halving K_v) caused a relatively small decrease in inflow (6 percent), but a large decrease in lake leakage (52 percent).

Effect of Intermediate Confining Unit

The conductivity of the intermediate confining unit surrounding the lake affected the size of the ground-water catchment and the magnitude of ground-water inflow (fig. 29). In these simulations, the range in confining unit K_v was approximately one order of magnitude (0.010 ft/d to 0.098 ft/d). Where the intermediate confining unit was least permeable, and K_v was at the lowest simulated value (0.01 ft/d), the catchment extended 1.1R onshore and contributed slightly more than twice the inflow as in the initial model simulation. For this simulation, about 22 percent of the recharge entering the hillside discharged into the lake as ground-water inflow. As the conductivity of the intermediate confining unit increased, more of the recharge went to the Upper Floridan aquifer, and less discharged into the lake. For example, increasing the K_v of the intermediate confining unit from 0.0164 to 0.023 ft/day (about 40 percent increase) reduced ground-water inflow by 38 percent (fig. 29), and reduced the size of the ground-water catchment from 0.71R to 0.48R.

Moderately increasing the K_v of the intermediate confining unit in the basin (from 0.01 to 0.023 ft/day) reduced ground-water inflow by a factor of about 3, but caused only a small increase in lake leakage (13 percent) (fig. 29). The decreased inflow caused the lake leakage to advance closer to shore (from 195 ft to 124 ft offshore). However, the area of the lake bottom where leakage replaced inflow was where the flow field had the lowest velocities. As a result, the shoreward advance of the area of lake leakage with increasing K_v in the basin had a relatively small effect on total lake leakage. Inflow was still occurring, although at a lesser rate, in a large area concentric to the shoreline where the velocity and incremental bottom area were relatively large. Total lake leakage was still affected primarily by the head difference between the lake and the Upper Floridan aquifer and the K_v directly beneath the lake, neither of which had changed from the initial model conditions.

When the K_v in the basin was increased further, leakage increased substantially, because it began to occur not just through the deeper lakebed but closer to the shoreline. For example, when the K_v of the intermediate confining unit was raised to 0.066 ft/d, the water table fell 0.3 ft below the lake stage at the drainage divide, causing a small outflow slope in the water table (-0.03 percent). Thus, lake leakage replaced ground-water inflow along the lake margin. Further

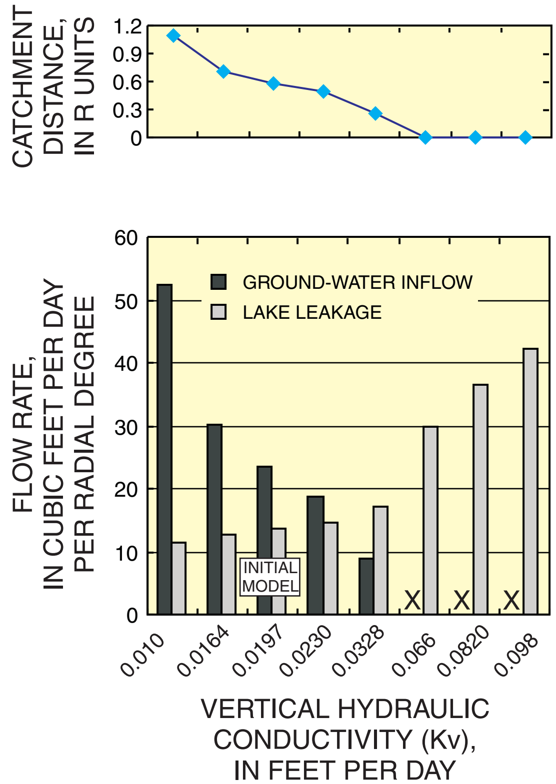
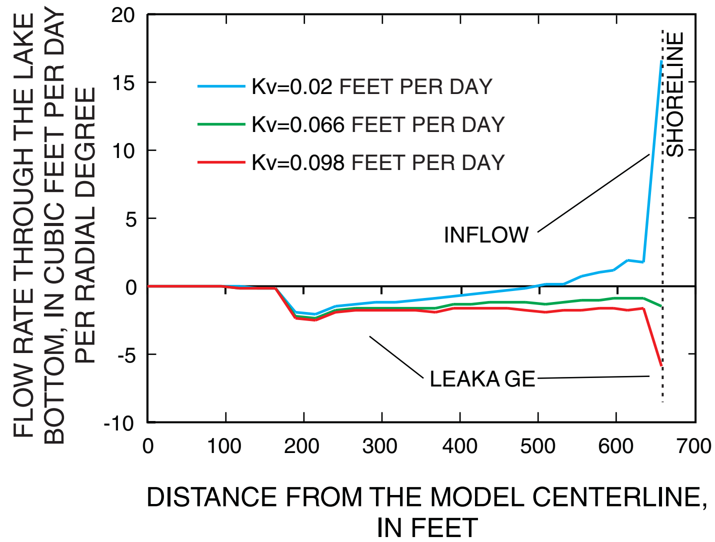


Figure 29. Simulated ground-water inflow and leakage rates, and catchment sizes for modeled lakes with different vertical hydraulic conductivity (K_v) values in the intermediate confining unit surrounding the lake. X indicates zero ground-water inflow.

increases in the K_v of the intermediate confining unit increased the total lake leakage by increasing leakage near the shoreline (fig. 29). Only slight increases in leakage occurred in the deeper lakebed (fig. 30).

Changing the confinement in the surrounding basin affected both ground-water inflow and leakage fluxes through the shallow lakebed. Changing confinement directly beneath the lake, however, affected lake leakage more than ground-water inflow. Larger breaches in the intermediate confining unit directly beneath the lake increased the simulated leakage from the deeper areas of the lakebed (figs. 31 and 32). Increases in leakage had relatively little effect on the inflow until the breach became large enough to intercept inflow occurring nearer the shoreline (for example, 330-ft opening, figs. 31 and 32). The shape as well as the size of the opening in the intermediate confining unit also affected the simulated ground-water exchange. When the top of the breach was widened, the simulated leakage increased moderately (24 percent) (fig. 32, compare “185-ft opening” with “185 ft opening, wider top”).

Figure 30. Ground-water flow distribution along the lakebed for different vertical hydraulic conductivity (K_v) values in the intermediate confining unit surrounding the lake.



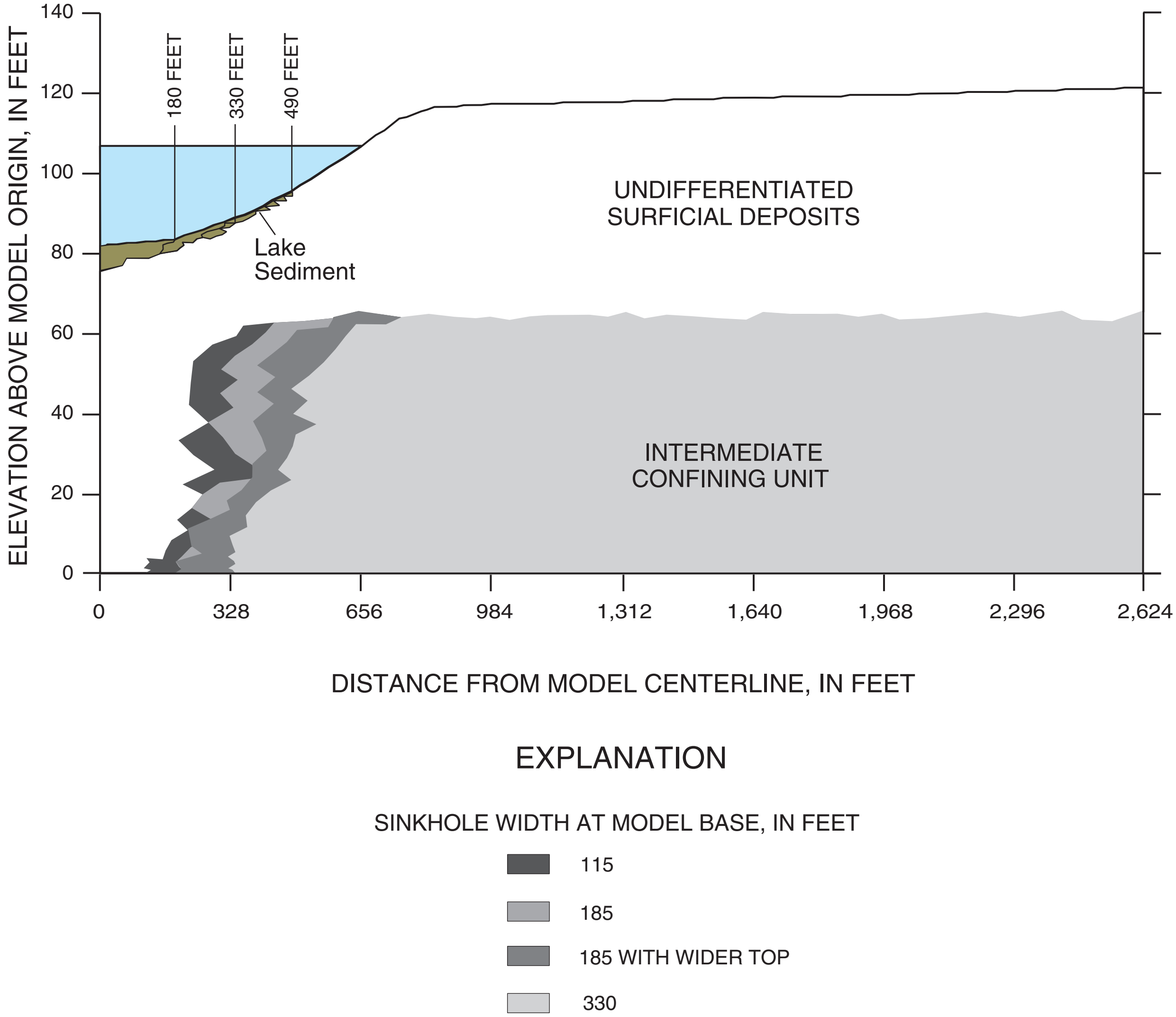


Figure 31. Different size collapse features beneath lake and various arrangements of lake sediment used in ground-water flow simulations.

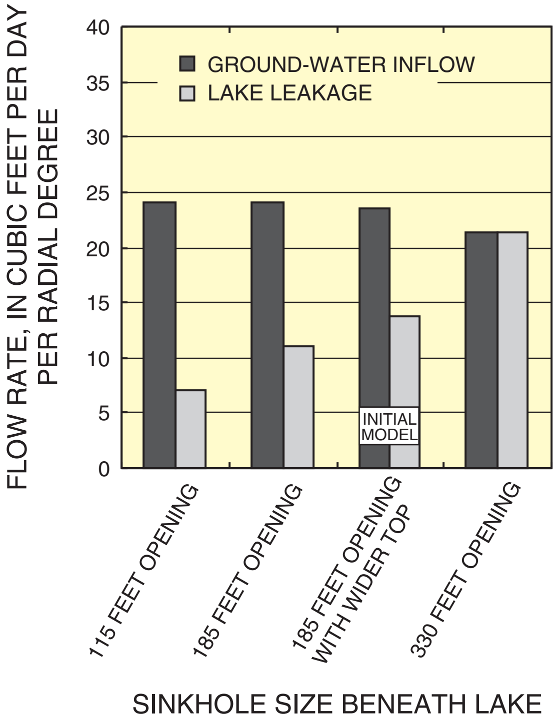


Figure 32. Simulated ground-water inflow and leakage rates for modeled lakes with different size collapse features beneath the lake.

The size of collapse features below any individual lake can be assumed to remain constant, however, lake surface area can change producing a similar effect. For example, as lake stage decreases, the decreasing surface area of the lake can change the proximity of the breach to the lakeshore. Thus, karst features below a lake could affect lake/ground-water interactions differently as the lake stage and surface area change.

Breaches in the intermediate confining unit surrounding lakes also affect the ground-water interactions with lakes. Breaches can lower the water table in an area of the basin by increasing the localized recharge rate to the Upper Floridan aquifer. Breaches in the confining unit have been documented near the shorelines and in the basins surrounding numerous Florida lakes. For example, karst subsidence features onshore of the lake have been described at Lakes Brooklyn and Barco in north-central Florida (Clark and others, 1963; Sacks and others, 1992) and at Crooked Lake and Lake Starr in west-central Florida (Evans and others, 1994; Swancar and others, 2000).

Simulating a sinkhole feature within a radial model implies the lake is surrounded by a doughnut-shaped breach in the confining unit. The assumption of radial symmetry with respect to breaches is largely unrealistic. Recognizing this limitation, however, the modeling results are still instructive when viewed as describing one region of the basin. Sands infilling the sinkholes were assumed to be about one-third as conductive as the surficial aquifer and about 4 times more conductive than the intermediate confining unit. The physical setting was otherwise the same as the initial lake basin model (fig. 22).

A single breach in the intermediate confining unit located about 1.5R onshore of the lake reduced ground-water inflow by about 23 percent compared to initial model and lowered the water-table elevation at the drainage divide by 1.3 ft (fig. 33). The breach caused minimal change in the lake leakage. When the sinkhole was simulated near the edge of the lake (fig. 22), ground-water inflow decreased by about

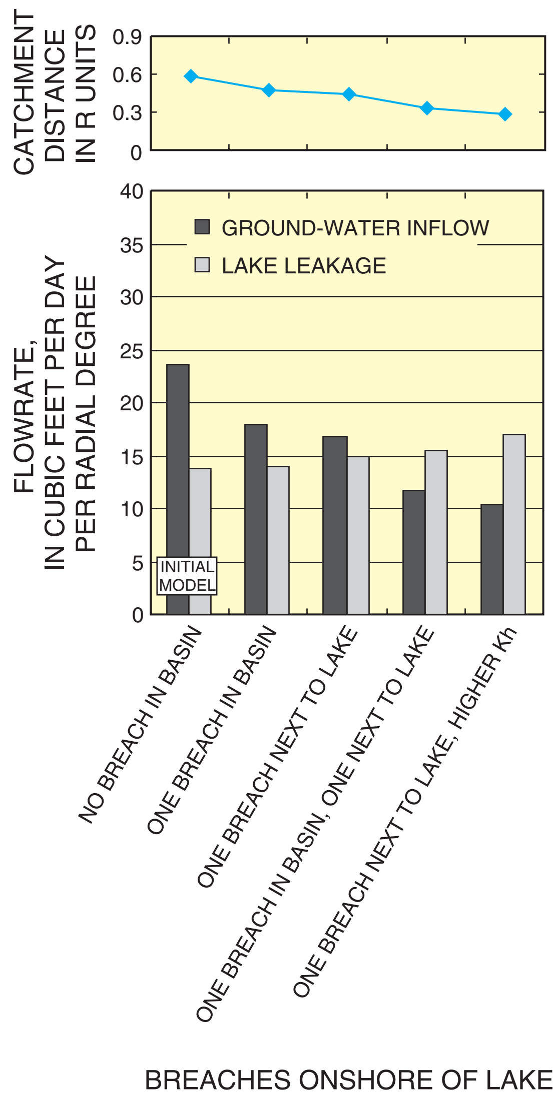


Figure 33. Simulated ground-water inflow and leakage rates, and catchment sizes for modeled lakes with breaches in the intermediate confining unit surrounding the lake.

30 percent and lake leakage increased by about 8 percent. This sinkhole lowered the water-table elevation near the lake, but not near the drainage divide. Simulating both sinkholes in the basin halved the rate of ground-water inflow compared with the initial basin model and reduced the ground-water catchment size from 0.57R to 0.32R. Thus, the ability of catchments to deliver ground-water inflow to lakes could vary widely depending upon the size and location of the breaches, and the conductivity of the material infilling them.

Effect of Lake Sediment

The hydraulic conductivity of organic lake sediment and the mineralized deposits that grade away from them can be very low (Winter, 1978). Thus, a lake with a thicker and more extensive area of organic sediment should leak more slowly than an identical lake with thinner, patchier, or more conductive sediments.

To test the effect of lake sediment on lake and ground-water interactions, the K_h of the sediment lens in the initial model (0.029 ft/day) was varied by greater than 2 orders of magnitude from 0.0148 ft/d to 2.98 ft/d. Increasing the sediment K_v increased the flow velocity and leakage through the sediment lens, but added little to the total leakage simulated for the lake because of the small size of the sediment lens. In the initial model setting, the sediment lens extended about 180 ft from the model centerline and covered an area equivalent to about 8 percent of the lake surface area. The lens was about 6.6 ft thick at the center of the lake and thinned with distance from the center (fig. 22). Removing the small sediment lens altogether made little difference to the total leakage. Almost all of the lake leakage occurred in the area concentric to the sediment lens (from 164 to 328 ft from the centerline of the lake) which covered roughly 56 percent of the lake bottom area.

The size of the sediment lens had a greater effect on leakage than the conductivity of the small, initial sediment lens. When the sediment lens was extended to 330 ft and 490 ft from the centerline, lake leakage was reduced by about 20 percent and 30 percent, respectively (figs. 31 and 34). When the edge of the 490-ft sediment lens was made 1-2 ft thicker, leakage decreased by an additional 15 percent (fig. 34). Increasing the size of the sediment lens tended to slightly reduce ground-water inflow (3 percent reduction between the 180-ft and 490-ft simulation), but loss of inflow was small compared with the diminished leakage (fig. 34).

Effect of Upper Floridan Aquifer Boundary Condition

In steady-state simulations, the model boundary representing the potentiometric level (head) of the Upper Floridan aquifer greatly affected the size of the ground-water catchment and magnitude of ground-water inflow to the lake, as well as the magnitude of lake leakage (fig. 35). Raising the head in the Upper Floridan aquifer in the initial model by 3.3 ft, from 101.7 to 105 ft, reduced the head difference between the lake and the Upper Floridan aquifer from 4.9 ft to 1.6 ft. The higher head in the Upper Floridan aquifer increased the simulated ground-water inflow by about 50 percent, and increased the catchment size from 0.56R to 0.82R (fig. 35). Raising the head in the Upper Floridan aquifer also reduced lake leakage to about one-third of the amount in the initial lake basin model. Lowering the Upper Floridan aquifer head to 98.4 ft, or 3.3 ft below the initial model condition, halved the amount of ground-water inflow to the lake compared to the initial model and reduced the ground-water catchment size from 0.58R to 0.35R. Leakage losses, in turn, almost doubled (factor of 1.8). Lowering the Upper Floridan aquifer head boundary further

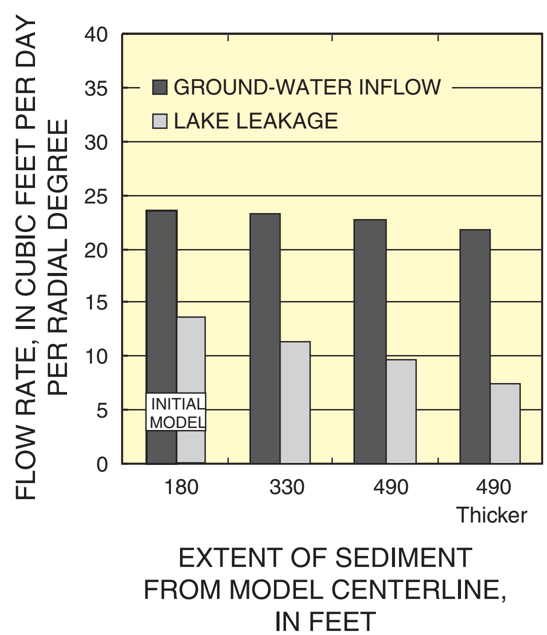


Figure 34. Simulated ground-water inflow and leakage rates for modeled lakes with different arrangements of lake sediment.

to 95.1 ft, or 11.5 ft below lake stage, reduced the ground-water inflow to 16 percent of the initial amount and reduced the catchment size to 0.12R. Leakage increased by a factor of 2.7 from the initial simulation.

Lowering the head of the Upper Floridan aquifer caused lake leakage to increase and extend closer to the shoreline. When the head in the Upper Floridan aquifer was at 1.6 ft below lake stage, 56 percent of the overall lakebed received ground-water inflow and the remaining 44 percent leaked. When the head was 11.5 ft below lake stage, inflow occurred through only 6 percent of the lakebed, and 94 percent of the lakebed leaked. Lowering the head in the Upper Floridan aquifer reduced ground-water inflow to the lake by inducing greater flow between the surficial and Upper Floridan aquifers and thus lowering the water-table elevation. Further reductions in the head, therefore, would lower the water table below the (constant) lake stage resulting in leakage through 100 percent of the lake bottom.

In actual lake basins, the potentiometric level of the Upper Floridan aquifer is rarely steady. In areas

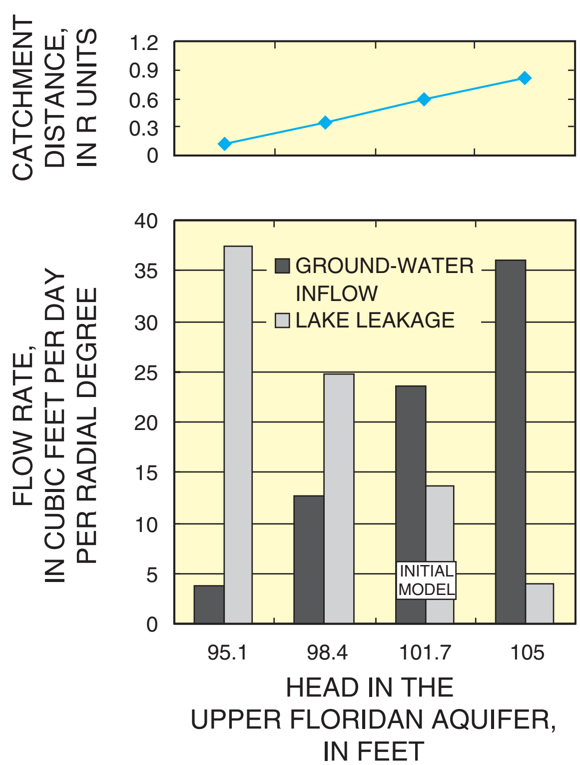


Figure 35. Simulated ground-water inflow and leakage rates, and catchment sizes for modeled lakes with different head values in the Upper Floridan aquifer.

with pumping, the Upper Floridan aquifer head is often substantially lowered for periods of weeks or months during the dry spring season, but rises during the rainy summer. For example, the daily average head of the Upper Floridan aquifer was between 5 and 7 ft below the level of Lake Lucerne for most of the 1986 water year. During April and May 1986, and as a result of local pumping for citrus irrigation, daily heads averaged 10 to 12 ft below lake stage, with daily maximum values of 14 ft. During June and with the onset of the rainy season, the downward head difference averaged 9 ft. Although the lowest head conditions lasted only about 2 months, the lake and surrounding ground-water system had time to respond to the stress. The heads were lowered not only in the Upper Floridan aquifer but also around and beneath the lake, and monthly leakage nearly doubled during April and May compared with February and March of 1986 (Lee and Swancar, 1997).

Effect of Lake Stage

Lake levels can be raised artificially by damming surface-water outflows or by adding water from other sources. For example, a lake level can be augmented using storm drainage, water diverted from an upgradient lake, or ground water pumped from an underlying aquifer. Lake levels can be lowered artificially using an outflow ditch, or by pumping water directly from a lake. For two hypothetical lakes situated in otherwise identical settings, differences in the level that lake stage is maintained would cause differences in the lake and ground-water interactions. The following model simulations illustrate the principle.

When the boundary condition representing lake stage was raised 1.6 ft above the level in the initial lake basin model, ground-water inflow to the lake decreased by 20 percent and the catchment size decreased about 15 percent (fig. 36). Less ground-water inflow occurred because the higher lake level caused the water table to flatten near the lake and reduced the inflow head gradient. The change in lake stage did not affect the water-table elevation at the drainage divide (4R), but did affect it to a distance of about 2.5R. Raising the lake stage by 1.6 ft also increased lake leakage by 42 percent. The lake leaked more because of the increased downward head gradient between the lake and the Upper Floridan aquifer. Leakage also increased because, due to the decreased inflow, more of the lake bottom was available to leak (the boundary between

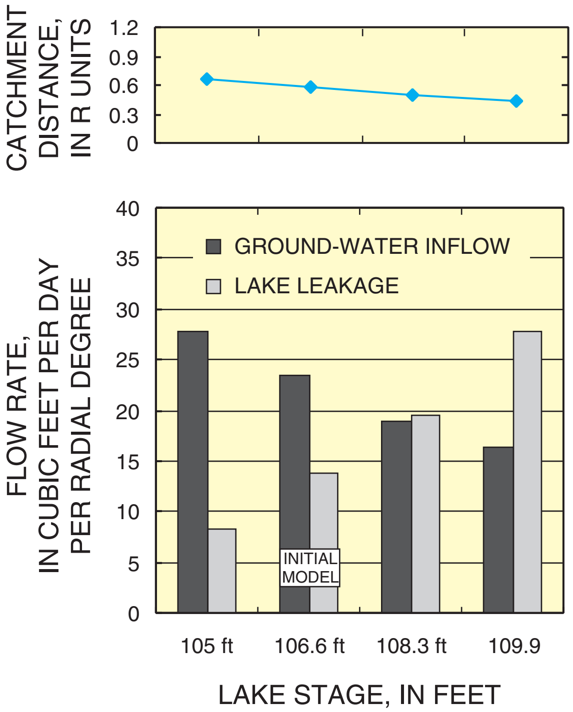


Figure 36. Simulated ground-water inflow and leakage rates, and catchment sizes for modeled lakes maintained at different lake stages.

leakage and ground-water inflow moved shoreward 47 ft). As a result, simulated lake leakage approached the magnitude of the ground-water inflow, instead of ground-water inflow exceeding the outflow.

When lake stage was lowered by 1.6 ft, the ground-water inflow to the lake increased by 18 percent relative to the initial simulation, and lake leakage decreased by 39 percent (fig. 36). A monthly water budget for Grassy Lake in Polk County demonstrated this effect (Sacks and others, 1998). When high lake levels flooded nearshore homes, water was pumped out of the lake over a 2-month period. For this period, monthly net ground-water inflow (the net amount of ground-water inflow after subtracting lake leakage) increased by a factor of 2 to 3 compared with the previous month.

Most factors that cause lake levels to decline will not be accompanied by a sustained increase in ground-water inflow. For example, low recharge or lowering the head in the Upper Floridan aquifer typically lower both the lake and the water table in the surrounding basin, resulting in less not more potential for ground-water inflow. In the short term, however, environmental stresses (such as ground-water pumping from the Upper Floridan aquifer or rainfall deficit) can lower lake stage more quickly than the surrounding water table. A delay in the drop of the water table can temporarily increase the ground-water inflow to a lake. For example, an increase in the net ground-water inflow was observed at Lake Lucerne, in Polk County, for a month when the lake stage dropped substantially due to increased lake leakage and lake evaporation losses. However, the next month when ground-water levels equilibrated with the lake, net ground-water inflow dropped as well (Lee and Swancar, 1997).

Occasionally, lake levels are augmented well above the elevation of the adjacent water table. For example, Round Lake in Hillsborough County (not to be confused with Round Lake in Polk County) is typically maintained at an elevation 5 to 9 ft above the surrounding water-table. The resulting ground-water flow field causes the entire lake bottom to leak and imposes steep lateral outflow head gradients around the shoreline (Metz and Sacks, 2002). For a lake in homogeneous surficial deposits, leakage velocities would peak near the shoreline where lateral head gradients are at a maximum, and would peak again in the deepest areas of the lake where the vertical head gradient is highest (fig. 25). If anisotropy in the surficial aquifer substantially favored horizontal flow over vertical flow, then leakage outflow could be focused near the shoreline, where outflow head gradients and the bottom area of the lake are both large.

Effect of Lake Depth

The effects of lake depth and bed slope on ground-water inflow and lake leakage were examined by altering the bottom configuration of the lake from the initial lake basin model. Maximum lake depth was simulated to be 8.5, 15, 24.6, and 41 ft (fig. 37a). Changing the maximum depth of the hypothetical lake from 8.5 to 41 ft, and shallow bed slope from about 4 to 20 percent, caused only a slight increase (7 percent) in the amount of ground-water inflow to the lake (fig. 38a). Increasing the shallow bed slope from 6.7 to 15 percent in the 24.6-ft-deep lake did not increase inflow, suggesting that inflow was less sensitive to slope than lake depth. The small but incremental increases in the ground-water inflow as lake depth increased were due to the lake bottom intercepting slightly deeper flow lines in the surficial aquifer. The contribution of inflow at greater depth, however, was minor compared to the shallow inflow. Because the surficial aquifer was relatively thin (41 ft thick at the shoreline) and had a relatively large downward velocity component, inflow was focused near the shoreline where the water table imposed the highest inflow head gradients. Thus, the shallowest lake captured almost equivalent inflow as the deepest lake.

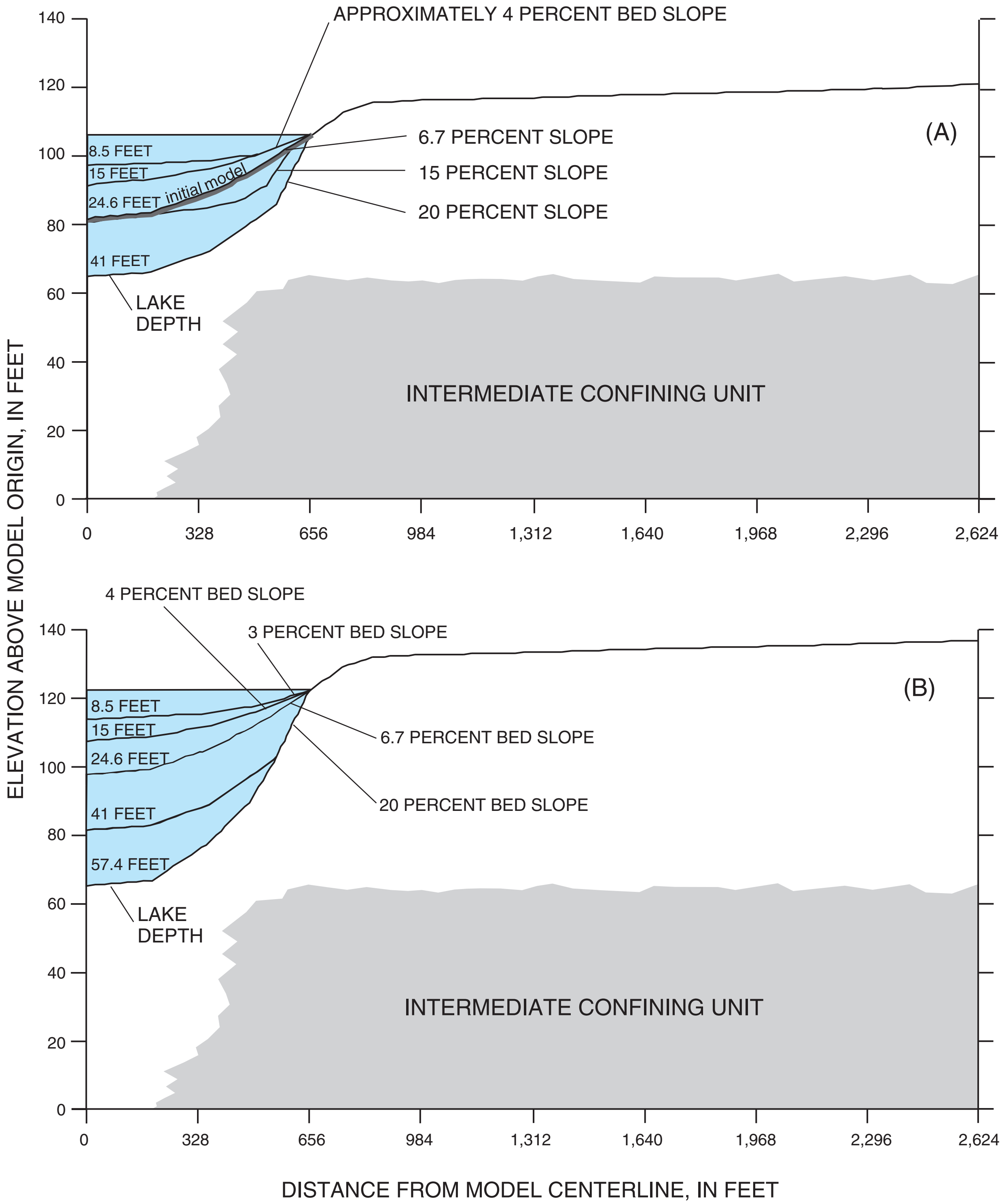


Figure 37. Different lake depths and surficial aquifer thicknesses used in model simulations. Surficial aquifer thickness near lake is: (A) 41 feet and (B) 57.4 feet.

Lake leakage increased more than inflow as lake depth changed from 8.5 to 41 ft (36 percent) (fig. 38a). Leakage increased because the downward head gradient below the lake increased as the vertical distance between the top of the Upper Floridan aquifer and the lake bottom decreased. Changing the bottom profile of the 24.6-ft- deep lake to make the shallow bed slope steeper increased lake leakage slightly (4 percent), possibly because it broadened the deepest area of the lake bottom exposed to these vertical head gradients (fig. 37a and 38a).

The surficial aquifer thickness in the model was increased from 41 to 57.4 ft so that deeper lakes with steeper bed slopes could be simulated (fig. 37b). In these simulations, ground-water inflow was comparable among the three shallower lakes with depths of 8.5, 15, and 24.6 ft, and bed slopes of 3 to 6.7 percent (fig. 38b). The small (≤ 3 percent difference) decrease in ground-water inflow between 8.5 ft and 15 ft depths was not considered a significant change. Ground-water inflow increased by 16 percent, however, when the lake depth was increased from 24.6 to 57.4 ft, and bed slope increased from 6.7 to 20 percent (fig. 38b). Similarly, when the surficial aquifer thickness was simulated as being 73.8 ft thick, increasing lake depth from 24.6 to 57.4 ft increased the ground-water inflow by 14 percent. These results indicate that greater lake depth and greater surficial aquifer thickness may act together to increase ground-water inflow to lakes.

Deep lakes in Florida generally are more common where the surficial aquifer is thicker such as in southern Polk and Highlands Counties (table 3). Because surficial deposits thicken toward the south, deeper lakes may be more common in the southern than northern end of the Lake Wales Ridge (fig. 2). For example, in Highlands County, in the southern part of the Lake Wales Ridge, about 23 percent of the lakes surveyed had a maximum depth over 50 ft, whereas in Polk County to the north, this percentage decreased to about 4 percent (written commun., Richard Gant, Southwest Florida Water Management District, Brooksville, Fla., 2001). None of the lakes in Highlands County penetrate the entire thickness of the surficial aquifer. In contrast, Lake Five-O, a deep lake in Bay County, penetrates the entire thickness of the relatively thin surficial deposits overlying the confined Upper Floridan aquifer.

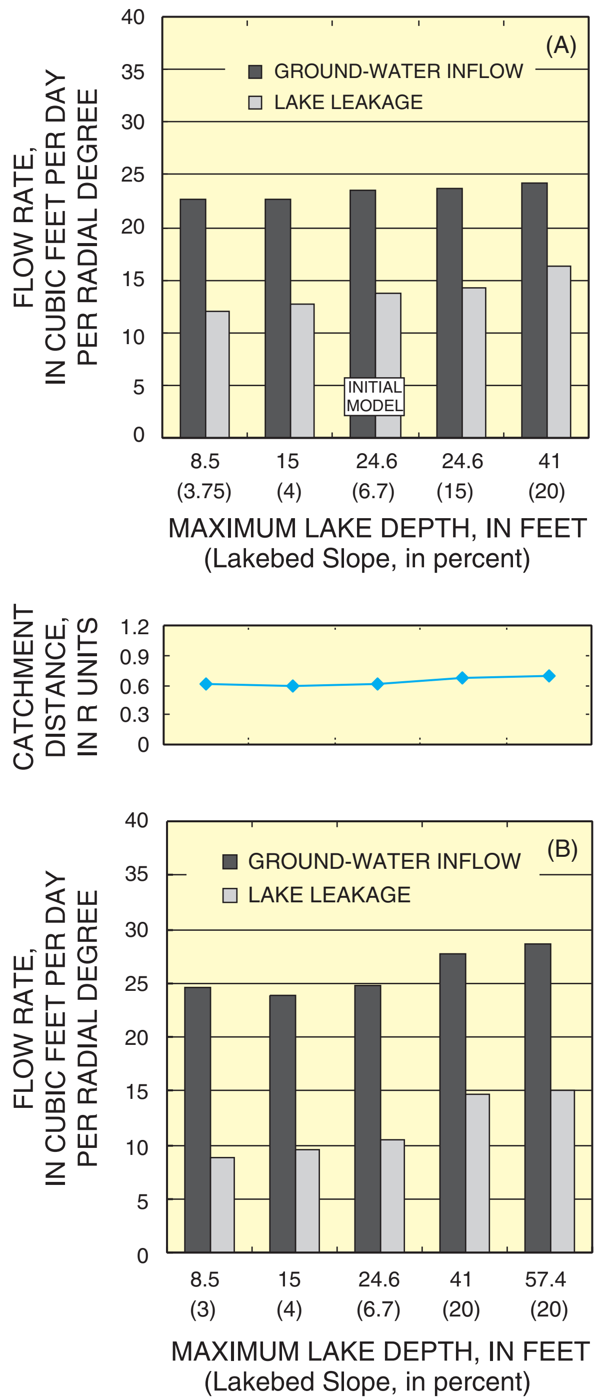


Figure 38. Simulated ground-water inflow and leakage rates, and catchment sizes for modeled lakes of different depths with the surficial aquifer thickness near lake equal to: (A) 41 feet and (B) 57.4 feet.

In model simulations, hydrogeologic factors that slow the movement of water to the Upper Floridan aquifer increase the saturated thickness of the surficial aquifer. For example, lowering the conductivity of the intermediate confining unit, raising the head in the Upper Floridan aquifer, decreasing K_h, or increasing the anisotropy in the surficial aquifer increases the saturated thickness of the surficial aquifer. Greater recharge also can raise the level of the surficial aquifer. These same factors, however, affect the vertical head gradient and flow lines within the surficial aquifer in different ways, changing the flow lines that are intercepted by the lake. Factors that promote lateral over vertical flow in the surficial aquifer can allow a deeper lake to intercept more ground-water inflow than a shallower lake. If most of the vertical head loss between a lake and the Upper Floridan aquifer occurs in the deeper surficial aquifer and through the confining unit, then lateral flow can predominate in the shallow surficial aquifer, enhancing ground-water inflow. If a substantial amount of vertical head loss occurs throughout the surficial aquifer, and flowlines in the surficial aquifer become more vertical, then deeper lakes may have little advantage over shallow lakes for intercepting lateral flow.

Transient Simulation Results

Four transient simulations were made to examine the potential effects of transient recharge and basin topography on the magnitude and timing of ground-water inflow to lakes. In steady-state simulations, recharge boundary fluxes to the model are constant and the water table achieves the same equilibrium position irrespective of the hillside topography. In reality, rainfall on the basin is variable during days, seasons, and years, and the water table responds constantly to the recharge rate arriving from the unsaturated zone. Differences in hillside topography largely control the thickness of the unsaturated zone above the water table, given that other aspects of the hydrogeologic setting are comparable. This thickness, as well as the moisture status and unsaturated hydraulic properties of the soil, affect the time required for recharge to arrive at the water table. Because topography affects the timing and recharge rate to the water table, it also affects the transient water-table position, and thus ground-water flow.

One of the simulated hillsides was relatively low and level, and the unsaturated zone was thin (maximum thickness 10 ft) (fig. 23). The other hillside was steeper, reaching a higher elevation at the basin drainage divide. The maximum unsaturated zone thickness in the steeper hillside models was about 49 ft (fig. 23). Transient simulations first were generated for each of the two hillsides. Then, the land surface nearby each lake was lowered to examine the effect of variable topography on the water-table configuration and inflow to the lake. The elevation of the hillside was altered most within a distance 0.5R onshore of the lake, in the area that most likely comprises much of the ground-water catchment.

The level hillside generated more ground-water inflow to the lake over the 5-month simulation period than the steeper hillside (table 6). The level hillside with the lowered nearshore region generated the most inflow: about 32.3 ft^3/d/degree or about 8 percent more than either of the steep hillside basins.

Table 6. Simulated ground-water inflow to lakes adjacent to level and steep hillsides

	Daily Average Ground-Water Inflow (cubic feet per day per radial degree)[1]		
Hillside	**Total period**	**Wet season**	**Dry season**
Level	31.4	34.5	30.2
Level with low nearshore region	32.3	37.3	30.0
Steep	30.4	33.4	29.1
Steep with low nearshore region	30.0	34.6	28.1

[1]Ground-water inflow computed in the radial model is divided by 360 degrees and reported here as flux per degree.

For the level hillside model, more ground-water inflow was generated with the lowered nearshore region. Most of this additional inflow occurred during the rainy period, in the first third of the simulation (fig. 39). The inflow generated during the dry season was comparable but slightly less for the level hillside with the low nearshore region.

For the steep hillside, lowering the nearshore region generated slightly more ground-water inflow during the wet season compared with the unaltered steep basin, however, the increase was less than for the level basin. During the dry season, the lake received less inflow than it would have if the elevation of the nearshore region remained high. As a result, the steep basin with the lower hillside generated slightly less ground-water inflow over the total simulation period than the unaltered steep hillside.

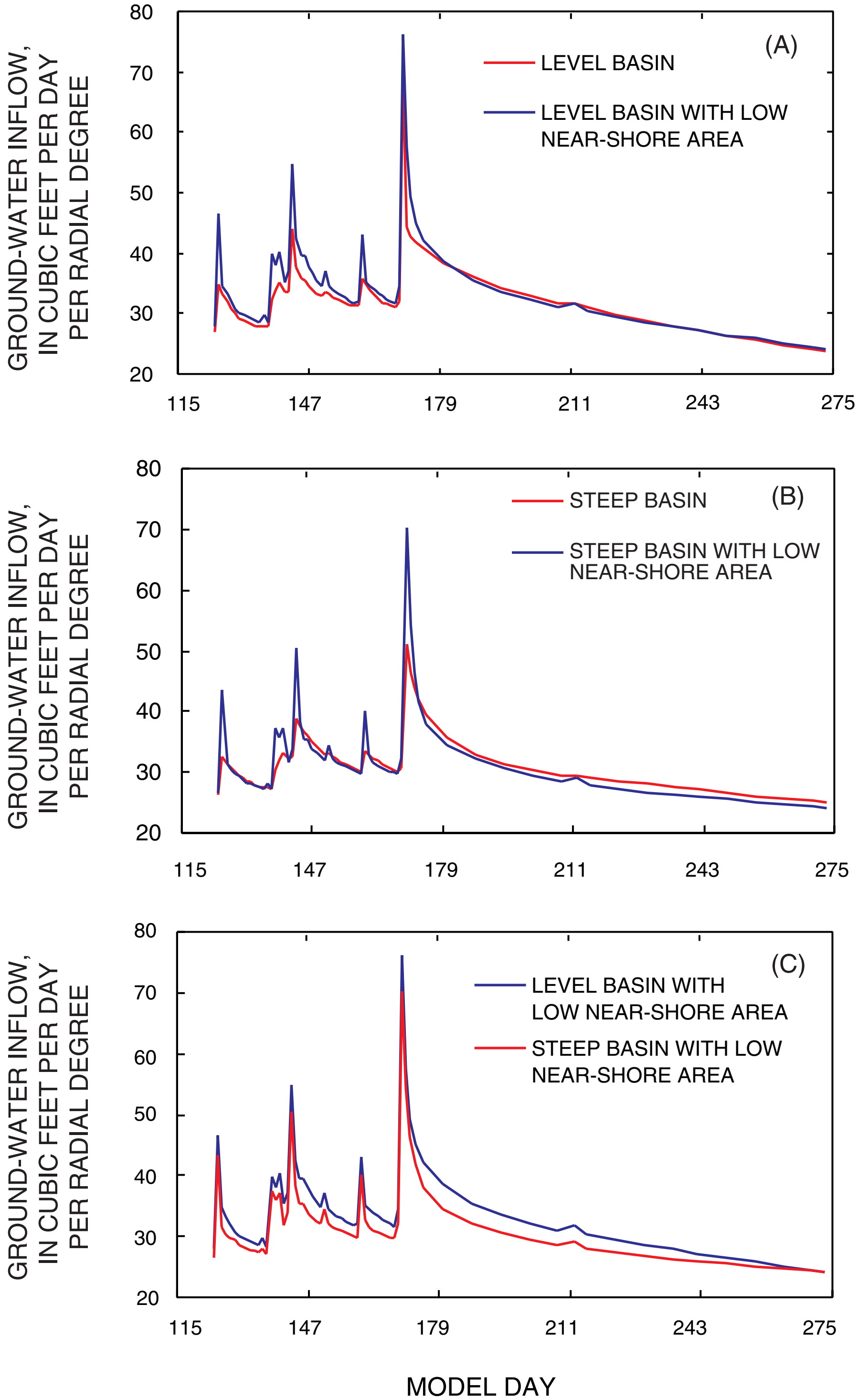


Figure 39. Transient ground-water inflow to modeled lakes for basins with different unsaturated zone thicknesses.

FACTORS AFFECTING GROUND-WATER EXCHANGE AND CATCHMENT SIZE

Ground-water flow modeling was used to examine the factors affecting ground-water inflow, catchment size, and lake leakage for lakes in mantled karst terrain. Changes to individual basin characteristics were simulated in the numerical modeling, however, ground-water inflow to a given lake is affected by a combination of basin characteristics that act to increase or diminish catchment size. The variety of combinations can result in a wide range of ground-water inflow values in actual lakes (table 2). Modeling results, however, suggest that by defining lake basin characteristics, we can begin to infer whether the inflow potential for a given lake is low or high.

In some settings, hydrogeologic characteristics can have an additive effect increasing the potential for a lake to receive inflow. In other settings, the cumulative effect of these characteristics can greatly decrease the potential for ground-water inflow. For example, multiple basin characteristics tend to enlarge the catchment at Lake Five-O and increase the amount of ground-water inflow. The basin is large (7R maximum), and the lake is deep (about 50 ft). Heads in the Upper Floridan aquifer showed little effects of pumping. The K_h of the surficial aquifer is high (about 60 ft/d), whereas the intermediate confining unit surrounding the lake is low (K_v about 0.0001 ft/d). As a result, the lake consistently receives inflow along its entire perimeter (Grubbs, 1995). Further, the soils in the basin are highly permeable, the topography is level, and the unsaturated zone throughout the basin is relatively thin (maximum thickness about 25 ft). Annual average rainfall in the Lake Five-O basin, in the panhandle of Florida, is higher than in the Central Highlands, which would increase the size of the catchment and the inflow contribution, due to transient recharge phenomena (fig.16).

The comparably large leakage losses from Lake Five-O could result from the presence of conductive material in the collapse feature beneath the lake (derived from the conductive surficial deposits), the depth of the lake, and the absence of an extensive sediment lens.

In contrast to Lake Five-O, a combination of basin characteristics tend to diminish the size of the ground-water catchment at Lake Barco (Lee, 1996). The lake is shallow (about 20 ft deep), the K_h of the surficial aquifer is relatively low (1-3 ft/d), and the intermediate confining unit surrounding the lake is leaky—2 to 3 orders of magnitude more conductive than at Lake Five-O. The topographic basin is large and steep toward the north (maximum distance 4R) where the catchment lies, but a subsidence feature located within the catchment reduces the ground-water inflow entering the lake. The southern side of the lake basin is smaller (0.7 R) and the water table is frequently lower than the lake in this area, resulting in lateral leakage along the southern shoreline.

Several basin characteristics slow leakage from Lake Barco. Heads in the Upper Floridan aquifer showed little evidence of pumping. The lake is relatively shallow (maximum depth about 20 ft) and has a thick sediment lens covering over two-thirds of the lake bottom. The combination of sediment and geologic material beneath Lake Barco was estimated to be 2 to 3 orders of magnitude *less* conductive (tighter) than at Lake Five-O. Surficial deposits at Lake Barco were less conductive compared to Lake Five-O, and this slowed the rate of both lateral and vertical leakage losses. Flow reversals due to transient recharge phenomena also slowed lake leakage. For example, for days to weeks after large rainfall events, the water table along the southern shoreline mounded above lake stage. The temporary flow reversal generated ground-water inflow and inhibited lateral lake leakage (Lee, 2000). At Lakes Five-O and Barco, the thickness of the surficial aquifer near the lakeshore was comparable (about 40 to 50 ft), and the vertical head difference between the lakes and the Upper Floridan aquifer was comparable (about 5 ft).

When taken as a group, the 14 lakes with ground-water inflow estimates provided indirect support for two of the simulated basin characteristics controlling inflow: lake depth and topographic basin size. Lakes in table 2 fell roughly into two groups: lakes with high ground-water inflow $\geq$ 100 in/yr, and lakes with low ground-water inflow $\leq$ 50 in/yr. Lake George (54 in/yr) is grouped in the latter group. When Lake Hollingsworth is omitted, all of the high inflow lakes had maximum lake depths of 30 ft or more, and all had maximum basin dimensions that were $\geq$ 3R. None of the lakes with shallower lake depths or smaller (maximum) basin lengths were in the high ground-water inflow group.

These two traits alone did not ensure the higher amount of ground-water inflow from the catchment.

Lake Olivia was deep (47 ft) and the maximum basin length was large (3.5R), but the estimated inflow was low (33 in/yr), suggesting that recharge or other basin characteristics limited catchment size. For instance, the maximum basin length characterizes only a small part of the basin. Approximately half of the Lake Olivia perimeter is bordered by a short topographic basin, (0.3R), and the lake periodically leaks along this shoreline (table 2 and fig. 11) (Sack and others, 1998). In a later study estimating ground-water inflow to lakes, Lake Olivia was grouped into the “high” ground-water inflow group. This change may have been related to the higher recharge rates found in the later study compared to drier-than-average conditions documented in the initial study (Sacks, L.A., U.S. Geological Survey, written commun., June 2001, Tampa Fla.).

Catchment Size in Mantled Karst Terrain

Results of the steady-state modeling suggest that ground-water catchments in mantled karst terrain often are found within 2R of lakes. For this reason, studies of the physical characteristics and water quality of ground-water catchments should focus on this region of the topographic basins to lakes. Larger catchments could occur where the K_h of the surficial aquifer exceeds the values used in these models (and where the intermediate confining unit is tight). Simulated catchments were most often smaller than 2R, between 0.5R and 1.0R, and transient modeling results suggest that the topography and hydrogeologic characteristics of the catchment within 0.5R of the lake can affect the inflow. Transient modeling results also suggest that basins with high topography and very thick unsaturated zones may generate less inflow to lakes than basins with lower topography and thinner unsaturated zones, given all other basin characteristics are equal.

To better define ground-water catchment sizes to lakes, the hydraulic conductivity of the surficial aquifer, including its variability with depth, needs to be described for different lake regions of Florida. The vertical distribution of hydraulic properties and head in the surficial aquifer is particularly important in the southern part of the Lake Wales Ridge (Highlands County) where the surficial aquifer can be 200-300 ft thick. Inferring catchment size from the surficial aquifer hydraulic conductivity can be useful for safeguarding lake-water quality. Numerous lakes in the ridge areas of central Florida are enriched in major ions due to land-use practices occurring in the ground-water catchment (Stauffer, 1991; Lee and Sacks, 1991; Sacks and others, 1998). If septic tanks and fertilizer applications were limited within the ground-water catchment, then the natural lake-water quality could be restored.

In model simulations, ground-water inflow to lakes was highest directly offshore, and decreased steeply with increased distance offshore. For this reason, ground-water inflow and leakage occurring through the shallow lakebed (near the shoreline) should have a relatively greater affect on the water budget of small lakes than large lakes, given all other factors are equal. As lake surface area decreases (or the shoreline becomes more scalloped), the shoreline to area ratio increases causing a larger percentage of the total lakebed area to experience lateral flow (Millar, 1971). For example, simulated ground-water inflow typically entered the hypothetical lakebed within 50 to 200 ft of the shoreline. Assuming these same inflow distances but reducing the lake radius from 1,200 to 600 ft would increase the percentage of the total lakebed with ground-water inflow by about 80 percent, leaving less of the lakebed to leak (fig. 40). Alternatively, if lateral leakage were occurring along the shoreline, then more of the total leakage would be lateral leakage in a smaller lake. In larger lakes, vertical leakage losses should have a greater effect on the water budget because of the comparatively greater area of lakebed (away from the shoreline) that is available to leak.

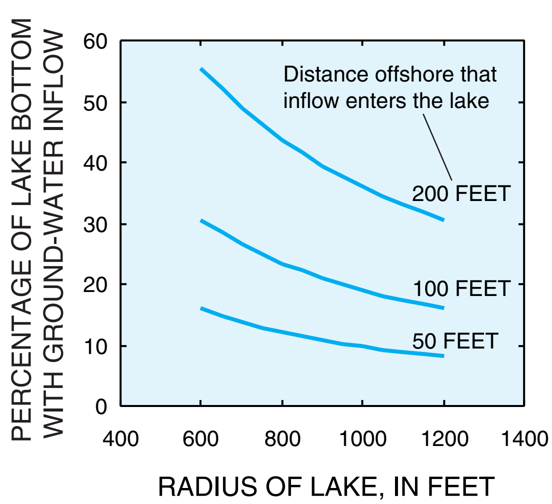


Figure 40. Relation between lake size, the distance offshore that ground-water inflow occurs, and the percentage of the lakebed receiving ground-water inflow.

Hydrogeologic Controls on Ground-Water Exchange

The geology directly below lakes in mantled karst terrain is often distinctly different from that of the surrounding basin. In model simulations, the geologic framework underlying lakes, and its effect on downward leakage, acted largely independently of the geologic factors that regulated ground-water inflow to lakes. For example, simulated ground-water inflow was only moderately affected by changes in the sub-lake geology, unless the size of the sinkhole approached the size of the lake. Ground-water inflow responded mostly to factors affecting the water-table elevation in the surrounding basin, such as recharge rate or the degree of confinement in the basin. But these changes had little effect on the simulated lake leakage. The twofold nature of the karstic hydrogeologic setting does tend to decouple ground-water inflow processes from lake leakage in the short term. For example, short-term increases and decreases in ground-water inflow can have a relatively small effect on the concurrent lake leakage, assuming the leakage is occurring through the deeper lake bottom. (Short-term reversals of ground-water flow direction along the shoreline *can* greatly affect leakage.) Minimal short-term feedback between inflow and leakage has been described in transient simulations of saturated ground-water flow at Lakes Barco, Five-O and Starr, in which the short term changes in lake stage were represented (Lee, 1996, Grubbs, 1995; Swancar and others, 2000). Over longer time periods, inflow and leakage tend toward equilibrium through the feedback mechanism provided by lake stage.

Unlike the two fold effect of the geologic settings, ground-water inflow and lake leakage responded in comparable measure to changes in the head in the Upper Floridan aquifer, changes in the imposed lake stage, and changes in the surficial aquifer hydraulic conductivity. Changes to the surficial aquifer hydraulic conductivity either increased or decreased both ground-water inflow and lake leakage. Changes in the head of the Upper Floridan aquifer, or the imposed lake stage, were the only basin characteristics that caused a direct decrease in the catchment size and ground-water inflow, and a commensurate increase in lake leakage. Conversely, a higher head in the Upper Floridan aquifer, or artificially lowered lake stage, resulted in an increase in ground-water inflow and decrease in lake leakage. Because of the opposing effect on inflow and leakage, changes in these two head conditions have an appreciable effect on the net ground-water flow to the lake.

The constant lake stage used in the steady-state model tended to exaggerate the change in steady-state leakage or ground-water inflow instead of causing a decrease or increase in lake stage. Because the models oversimplified the representation of actual lakes, modeling results were considered qualitative. Simulated lakes were assumed to be circular with radial symmetry throughout the basin, with characteristics only partly represented in the 14 actual lake basins. Despite simplifications, modeling results provided insights into the factors controlling ground-water inflow to lakes from different types of lake basins.

In transient model simulations, differences in hillside topography caused spatially variable recharge to the water table of the four basins, even though identical net precipitation rates were applied at land surface. The spatial differences in recharge below the four hillsides were due to the differences in the travel times through the unsaturated zones, caused by differences in the thickness and soil moisture content of the unsaturated zones. In general, a thinner unsaturated zone and more rapid recharge to the water table adjacent to the lake tended to increase the percentage of the net precipitation that became ground-water inflow to the lake during the wet season. Within the catchment area, topography and its effect on temporal and spatial recharge may enhance ground-water inflow to some lakes relative to others.

SUMMARY AND CONCLUSIONS

A variety of basin characteristics affect the amount of annual ground-water inflow to lakes in the mantled karst terrain of Florida. Differences in the karstic hydrogeologic setting, head in the Upper Floridan aquifer, and topography cause some lakes to be hydraulically well connected to their ground-water catchments and others to be weakly linked to their potential catchments. As a result, the ground-water catchment size, which is directly related to the recharge rate and basin hydrogeologic characteristics, can vary widely.

Steady-state, finite-element ground-water flow modeling was used to simulate the effect of various basin characteristics on the ground-water inflow, lake leakage, and catchment size of hypothetical lakes. Realistic basin characteristics were derived from the basins of 14 lakes with available ground-water inflow estimates. Eleven of the lakes were located in Polk and

Highlands Counties, the remaining three lakes were in Bay, Hillsborough and Putnam Counties. Physical and hydrogeologic characteristics such as annual average recharge rate, lake depth, basin size, and head in the Upper Floridan aquifer were altered in steady-state model simulations. Transient simulations using daily recharge were used to examine the effect of the unsaturated zone thickness on ground-water inflow. Model results indicate:

1. An increase in the following basin characteristics increased the size of the simulated steady-state ground-water catchment, the magnitude of ground-water inflow, and the depth and distance over which inflow entered the lake:
   - Recharge rate to the surficial aquifer
   - Size of the topographic basin
   - (Horizontal) hydraulic conductivity of the surficial aquifer
   - Lake depth/bed slope
   - Potentiometric surface of the Upper Floridan aquifer
2. Ground-water inflow increased as the following characteristics decreased:
   - Hydraulic conductivity of the intermediate confining unit around the lake
   - Number of sinkholes in the basin surrounding the lake
   - Vertical velocity in the surficial aquifer
   - Unsaturated zone thickness in the basin and near the lakeshore
   - Lake stage
3. Lake leakage flowed vertically downward out of the deeper areas in all of the simulated lakes. Vertical leakage increased with increases in the following characteristics:
   - Permeability of the organic sediments
   - Size of the sinkhole feature in the sublake region
   - Lake depth
   - (Vertical) hydraulic conductivity of the surficial aquifer
   - Lake stage
4. Vertical leakage increased with decreases in the following basin characteristics:
   - Potentiometric surface of the Upper Floridan aquifer
   - Size of the organic sediment lens
5. In addition to vertical leakage, lateral leakage also occurred near the shoreline for certain hydrogeologic conditions in the basin. Lateral lake leakage occurred where the water table sloped away from the lake, and these losses had the potential to exceed vertical leakage losses, especially for some small lakes. The potential for lateral leakage increased with increases in the following characteristics:
   - Hydraulic conductivity of the intermediate confining unit around the lake
   - Lake stage
   - Sinkholes peripheral to the lake
   - Size of the sublake collapse feature relative to the lake area
6. Lateral leakage increased with a decrease in the following characteristics:
   - Potentiometric surface of the Upper Floridan aquifer
   - Recharge

Actual lake basins show a combination of characteristics that tend to diminish or enlarge the size of the ground-water catchment, and diminish or enhance lake leakage. Only one hydrogeologic characteristic simulated, the surficial aquifer hydraulic conductivity, simultaneously increased (or decreased) both ground-water inflow and lake leakage. The two hydraulic boundary conditions most likely to be altered by human activities, lake stage and the potentiometric surface of the Upper Floridan aquifer, affected ground-water inflow and lake leakage in opposing ways. As a result, lowering heads in the Upper Floridan aquifer or augmenting lake stage affects lake levels by decreasing the ground-water inflow and catchment size, and increasing lake leakage. A third hydraulic boundary condition, recharge, mostly affected ground-water inflow but would eventually indirectly affect lake leakage by changing the head in the Upper Floridan aquifer. Transient simulations of lakes in different geologic settings would be required to determine the cumulative effect of short-term fluctuations in these boundary conditions.

Modeling hypothetical lake basins provides a qualitative way to examine the effect of basin characteristics on ground-water exchange with actual lakes. By identifying the suite of controlling factors, lakes can be categorized by their physical and hydrogeologic settings and by their potential to exchange either high or low amounts of ground-water inflow and leakage. Understanding the relation between ground-water catchments and lakes also is an essential step toward managing lake-water quality. Knowledge of how ground-water catchments are related to lakes can be used by resource managers to recommend setback distances for septic tank drain fields, agricultural land uses, and other land-use practices that contribute nutrients and major ions to lakes.

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