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Hydrogeologic Setting, Water Budget, and Preliminary Analysis of Ground-Water Exchange at Lake Starr, a Seepage Lake in Polk County, Florida

Water-Resources Investigations Report 00-4030

Prepared in cooperation with the
SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT

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

Cover photograph: Lake Starr from
east side, September 8, 1999.
(Amy Swancar, U.S. Geological Survey)

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

°C = (°F–32)/1.8.

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

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Abstract

Lake Starr, a 134-acre seepage lake of multiple-sinkhole origin on the Lake Wales Ridge of central Florida, was the subject of a detailed water-budget study from August 1996 through July 1998. The study monitored the effects of hydrogeologic setting, climate, and ground-water pumping on the water budget and lake stage.

The hydrogeologic setting of the Lake Starr basin differs markedly on the two sides of the lake. Ground water from the surficial aquifer system flows into the lake from the northwest side of the basin, and lake water leaks out to the surficial aquifer system on the southeast side of the basin. Lake Starr and the surrounding surficial aquifer system recharge the underlying Upper Floridan aquifer. The rate of recharge to the Upper Floridan aquifer is determined by the integrity of the intermediate confining unit and by the downward head gradient between the two aquifers. On the inflow side of the lake, the intermediate confining unit is more continuous, allowing ground water from the surficial aquifer system to flow laterally into the lake. Beneath the lake and on the southeast side of the basin, breaches in the intermediate confining unit enhance downward flow to the Upper Floridan aquifer, so that water flows both downward and laterally away from the lake through the ground-water flow system in these areas.

An accurate water budget, including evaporation measured by the energy-budget method, was used to calculate net ground-water flow to the lake, and to do a preliminary analysis of the relation of net ground-water fluxes to other variables. Water budgets constructed over different timeframes provided insight on processes that affect ground-water interactions with Lake Starr. Weekly estimates of net ground-water flow provided evidence for the occurrence of transient inflows from the nearshore basin, as well as the short-term effects of head in the Upper Floridan aquifer on ground-water exchange with the lake. Monthly water budgets showed the effects of wet and dry seasons, and provided evidence for ground-water inflow generated from the upper basin. Annual water budgets showed how differences in timing of rainfall and pumping stresses affected lake stage and lake ground-water interactions.

Lake evaporation measurements made during the study suggest that, on average, annual lake evaporation exceeds annual precipitation in the basin. Rainfall was close to the long-term average of 51.99 inches per year for the 2 years of the study (50.68 and 54.04 inches, respectively). Lake evaporation was 57.08 and 55.88 inches per year for the same 2 years, making net precipitation (rainfall minus evaporation) negative during both years. If net precipitation to seepage lakes in this area is negative over the long-term, then the ability to generate net ground-water inflow from the surrounding basin plays an important role in sustaining lake levels.

Evaporation exceeded rainfall by a similar amount for both years of the study, but net ground-water flow differed substantially between the 2 years. The basin contributed net ground-water inflow to the lake in both years, however, net ground-water inflow was not sufficient to make up for the negative net precipitation during the first year, and the lake fell 4.9 inches. During the second year, net ground-water inflow exceeded the difference between evaporation and rainfall and the lake rose by 12.7 inches. The additional net ground-water inflow in the second year was due to both an increase in the amount of gross ground-water inflow and a decrease in lake leakage (ground-water outflow). Ground-water inflow was greater during the second year because more rain fell during the winter, when evaporative losses were low, resulting in greater ground-water recharge. However, decreased lake leakage during this year was probably at least as important as increased ground-water inflow in explaining the difference in net ground-water flow to the lake between the 2 years. Estimates of lake leakage based on a relation between net ground-water flow and head in the Upper Floridan aquifer could easily account for the differences in net ground-water exchange with the lake in the 2 years of the study. The relation between net ground-water flow and head in the Upper Floridan aquifer implied that an estimated 1-foot increase in the average Upper Floridan aquifer head from the first to the second year could account for reduced leakage of about 8.5 million cubic feet of water from Lake Starr, or an additional 17 inches of lake stage over a year.

The first year of the study was representative of typical rainfall patterns, where most of the rainfall occurs during the summer. If rainfall and lake evaporation in the first year reflect long-term average conditions, the stage of Lake Starr will decrease unless ground-water inflow increases, or leakage decreases, compared to that year.

INTRODUCTION

The intrinsic beauty, ecological diversity, and multiple uses of lakes make them an important water resource. Properly managing lake water levels and water quality requires a thorough understanding of water fluxes into and out of lakes and the factors that affect these fluxes. Recognition of this need has led to studies that have increased the understanding of lake hydrology in Florida, as well as nationwide in recent years (Anderson and Munter, 1981; Winter, 1981; Krabbenhoft and others, 1994; Winter, 1995). In the karst terrain of central Florida, lake hydrology is complicated by the integral connection between surface and ground water (Brenner and others, 1990; Lee and Swancar, 1997; Winter and others, 1998). Because of this connection, lake levels can be affected by ground-water pumping from underlying aquifers, as well as naturally occurring extremes in climate (Chen and Gerber, 1990; Southwest Florida Water Management District, 1996; Yobbi, 1996). Ground-water interactions are further controlled by the hydrogeologic setting of lakes, which can be greatly affected by karst subsidence features within the immediate basin. Hydrogeologic features within a lake basin can transform the regional effects of rainfall, evaporation, or ground-water pumping into distinctive lake level responses.

Lake water-budget data for multiple years are needed to learn more about the potential range of lake and ground-water interactions under different climatic conditions (Winter and Rosenberry, 1995), and to discern annual trends and variability in individual water-budget terms. Because the residence time of water in seepage lakes is usually measured in years (Nace, 1971), lake levels and particularly lake water quality may reflect a “running average” of basin conditions over successive years. At present, there is little information about how one of the largest water losses from Florida lakes, evaporation, varies temporally. Yet uncertainty in evaporation measurements directly affects our ability to quantify lake leakage, the budget term most affected by ground-water pumping.

Short-term changes in climate and ground-water pumping also may affect the lake water budget. For example, transient water-table mounding near the edge of lakes is one mechanism contributing ground-water inflow to lakes for periods of days or weeks (Lee, in press). To isolate the effects of both short-term and long-term environmental conditions on ground-water inflows and outflows to the lake, water budgets need to be resolved for weekly time intervals, as well as for multiple years.

Three intersecting lines of evidence are useful to investigate the dynamics of lake-ground-water interactions in Florida: a description of the local hydrogeologic setting of lakes, detailed lake water-budget studies, and numerical modeling studies of ground-water flow in lake basins. Numerous studies have looked at the hydrogeologic setting of lakes in the karst terrain of central Florida (Clarke and others, 1963; Lee and others, 1991; Sacks and others, 1992; Kindinger and others, 1994; Tihansky and others, 1996). Others have computed water or chemical budgets of lakes (Deevey, 1988; Pollman and others, 1991; Lee and Swancar, 1997), or simulated lake/ground-water interactions with numerical ground-water flow models (Grubbs, 1995; Lee, 1996; Lee and Swancar, 1997). Few studies have incorporated all three approaches (Grubbs, 1995; Lee, 1996; Lee and Swancar, 1997). Previous studies of lake water budgets in Florida that have combined these three approaches have looked in detail at periods of 12 to 20 months. While these studies have defined important processes affecting lake levels, their timeframes prevented comparisons of how components of the water budget change over multiple years.

In 1996, the U.S. Geological Survey (USGS) and the Southwest Florida Water Management District began a 4-year study of Lake Starr. The first goal of this cooperative project was to select a “benchmark” lake, one considered to be representative of the surrounding population of lakes, and to instrument the lake and basin for long-term hydrologic monitoring. The second goal was to investigate the effects of evaporation, rainfall, recharge, hydrogeologic setting, and pumping from the underlying aquifer on the water budget of Lake Starr, and to describe lake/ground-water interactions.

Purpose and Scope

The purpose of this report is to describe the hydrogeologic setting of Lake Starr, and present a lake water budget computed at weekly, monthly, and annual time intervals covering the 2-year period from August 1996 through July 1998. Also, a preliminary analysis of the ground-water exchange with the lake at different time scales, from weekly to annually, is discussed.

The report describes the geology, ground-water levels, and ground-water flow patterns around Lake Starr, including highly transient ground-water flow patterns close to the lake. Climate data to calculate lake evaporation by the energy-budget method are presented (see appendix), and the water budget is summarized. Methods used to quantify lake water-budget components were chosen to minimize errors associated with water-budget components.

Net ground-water flow was calculated as a residual to the water budget over different time intervals. The estimates of weekly net ground-water flow presented in this report are the first of their kind for any lake in the United States. Weekly estimates of net ground-water flow are informative about factors that affect the short-term ground-water exchange with the lake. The preliminary analysis of ground-water exchange with Lake Starr presented in this report will be used to assist development of a 3-dimensional transient numerical ground-water flow model of the lake basin.

Acknowledgments

The authors are grateful to the Lake of the Hills community, which surrounds Lake Starr, for accommodating and assisting in the project activities. We especially thank the officers and members of the Lake of the Hills Community Club, who allowed placement of two climate stations on their property. Many land owners allowed installation of monitoring wells on their property, with special thanks to Francis K. Hart, Jr. and Vicki Hart, Frances Saxon, and Jeanette Coffey. Local residents John and Barbara Hodgkinson, Mark Estes, Robert Draudt, Greg Esteve, and Jackie Olsen provided invaluable assistance by acting as site observers during the study. Geologic logs written by drillers at Crosby Well Drilling of Lake Wales, Florida, were very useful in describing the area geology.

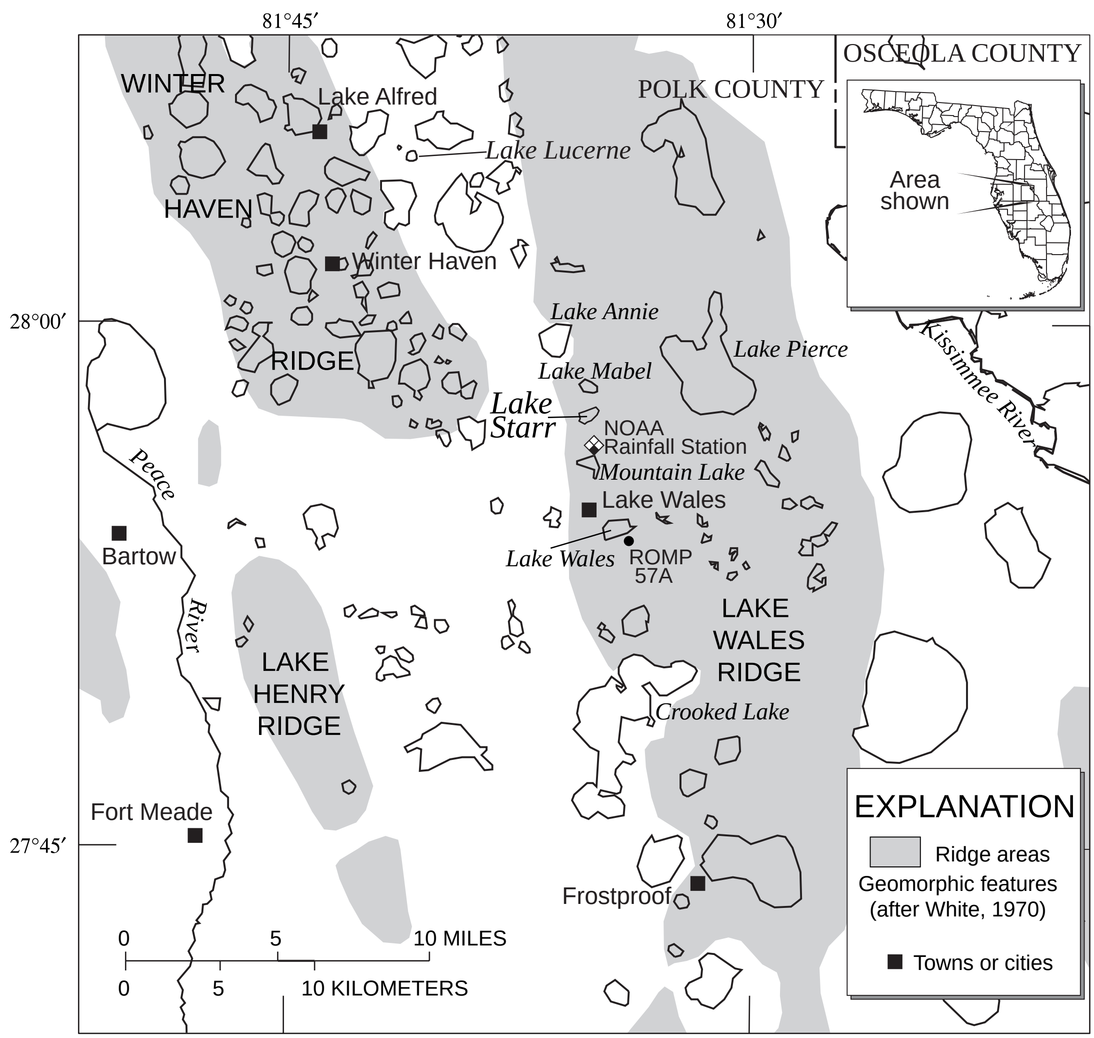
Description of the Study Area

Lake Starr is a 134-acre seepage lake located on the Lake Wales Ridge approximately 4 miles north of the city of Lake Wales, in central peninsular Florida (fig. 1). Lakes are prominent features of the Lake Wales Ridge, a north-south trending ridge that is part of the Central Lake District (Brooks, 1981). In Polk County, land surface elevations on the ridge exceed 200 feet (ft) above sea level; these are the highest elevations in the southern half of the state.

Lake Starr has an elongated shape in a southwest to northeast direction (fig. 2). Three shallow coves on the west side of the lake provide the explanation for the lake’s name; at higher water levels, the coves look like the radiating points of a star. The north and southeast shores of the lake are roughly linear. The maximum lake depth is about 32 ft at an altitude of 104 ft above sea level. The lake is deepest in the center of the western side, but much of the center of the lake is greater than 25 ft deep. While the lake depth increases quickly away from the shore, the deepest parts are relatively flat, partly because this is where lake sediments accumulate.

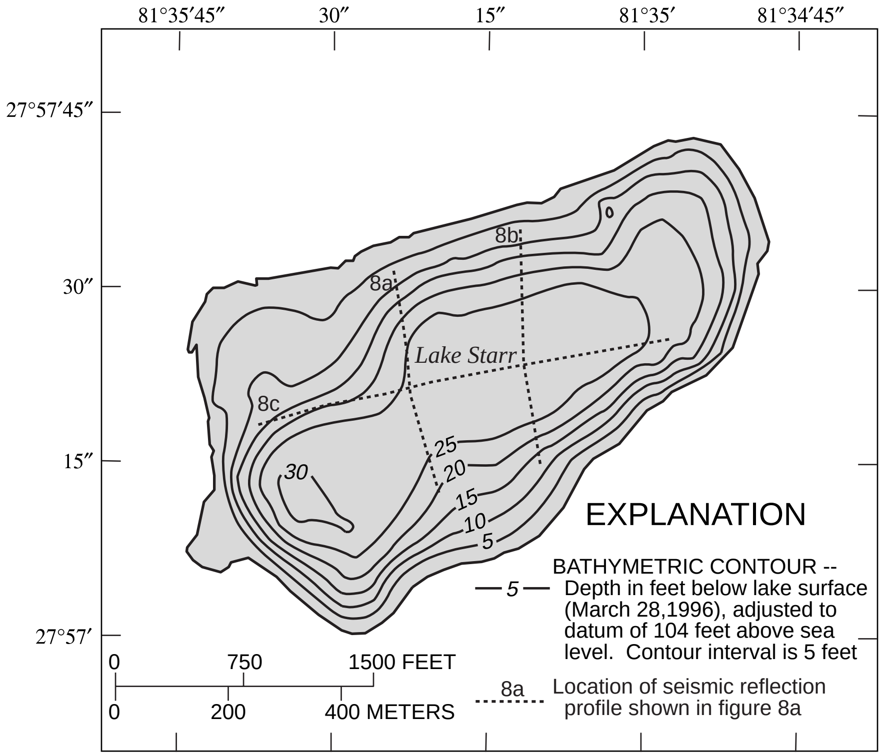
The thermal regime of Lake Starr is warm monomictic (Wetzel, 1975). The lake thermally stratifies in the summer, when it has a persistent thermocline at around 25 ft. Gradual warming of bottom layers through the summer combined with increased wind in the fall cause the lake to mix, and it remains thermally mixed through the winter.

The topographic basin for Lake Starr is estimated to be 1.15 square miles, and sandy ridges between 150 and 225 ft above sea level delineate the basin divide (fig. 3). Lake Starr is located in a mantled karst region, where buried carbonate rocks are subject to dissolution and eventual collapse, producing prominent features such as sinkholes (Sinclair and others, 1985). The lakes in this region were formed by limestone collapse and subsequent infilling of the voids by overlying material. Partly because of karst features, the topography is relatively steep for Florida, with slopes up to 0.25. Because the sand ridges surrounding the lake are extremely porous and permeable, most rainfall seeps into the ground quickly. With the exception of the extreme nearshore parts of the basin, soils around Lake Starr are Candler sands, an excessively drained upland soil with a deep water table. Smyrna and Myakka fine sands are found adjacent to the lake in



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

Figure 1. Location of Lake Starr, Polk County, Florida.



Base from Southwest Florida Water Management District
Sheet No 15-29-27, Aerial Photography with contours, January 1987

Figure 2. Bathymetry of Lake Starr and location of seismic profiles.

poorly drained areas that are periodically flooded (Soil Conservation Service, 1990).

The Lake Starr basin was originally developed in the 1910's, and the current Lake of the Hills Community Club house, built in 1929, continues to be a center of local activities (Kaucher, 1976). Areas immediately surrounding the lake are mostly 1- to 4-acre residential lots leading up to a perimeter road. Cattail (*typha domingensis*) and panic grass (*Panicum sp.*) dominate nearshore vegetation (D. Richters, Southwest Florida Water Management District, written commun., 1995). Many of the nearshore lots also contain small citrus groves. Upper parts of the basin have historically been used for commercial citrus cultivation. Many of the citrus trees in this part of the state were killed by below freezing temperatures in the 1980's. Some of the groves in the basin have been replanted, but many acres have been converted to residential lots or left fallow.

Water for residential use and for citrus irrigation in the Lake Starr basin comes mainly from deep private wells drilled into carbonate rock (cased to a minimum depth of 100-200 ft). A few homeowners use shallower wells drilled into sand (less than 100 ft deep) for residential supply, and five are known to use lake water directly for irrigation. Each residential lot generally has its own well and septic tank. In the 6 square miles surrounding Lake Starr, 14 large-capacity, deep wells are permitted to pump ground water from the intermediate and Upper Floridan aquifers at average rates from 100,000 to 284,600 gallons per day (gpd) per well (J. Whalen, Southwest Florida Water Management District, written commun., 1999). Thirty-six permits for ground-water withdrawals averaging less than 100,000 gpd also exist in this area. There are no permits to withdraw water directly from the lake, but permits are not required for lake withdrawals less than 100,000 gpd (Southwest Florida Water Management District, oral commun., 1999).

The climate at Lake Starr is humid subtropical, with hot, humid summers (May through September) and mild, drier winters (December through February). Monthly average air temperatures range from 61.0 ^{o}F (16.1 ^{o}C) in January to 81.8 ^{o}F (27.7 ^{o}C) in August (National Oceanic and Atmospheric Administration

(NOAA), 1997). Long-term average annual rainfall for the area is 51.99 inches based on 71 years of data from the Mountain Lake National Weather Service (NWS) station (fig. 4), which is about 1 mile south of Lake Starr (NOAA, 1998) (fig. 1). The 30-year average annual rainfall (1961-1990) at Mountain Lake (48.21 inches) is lower than the long-term average because of recent droughts in central Florida (NOAA, 1999). Based on the 71-year record, average monthly rainfall varies between less than 2 inches (November and December) to greater than 7 inches per month (June, July, and August).

Because central Florida is at low latitude, solar radiation is high, and therefore, evaporation is high. Despite high humidity, evaporation in Florida is higher than most of the country except for the arid southwest

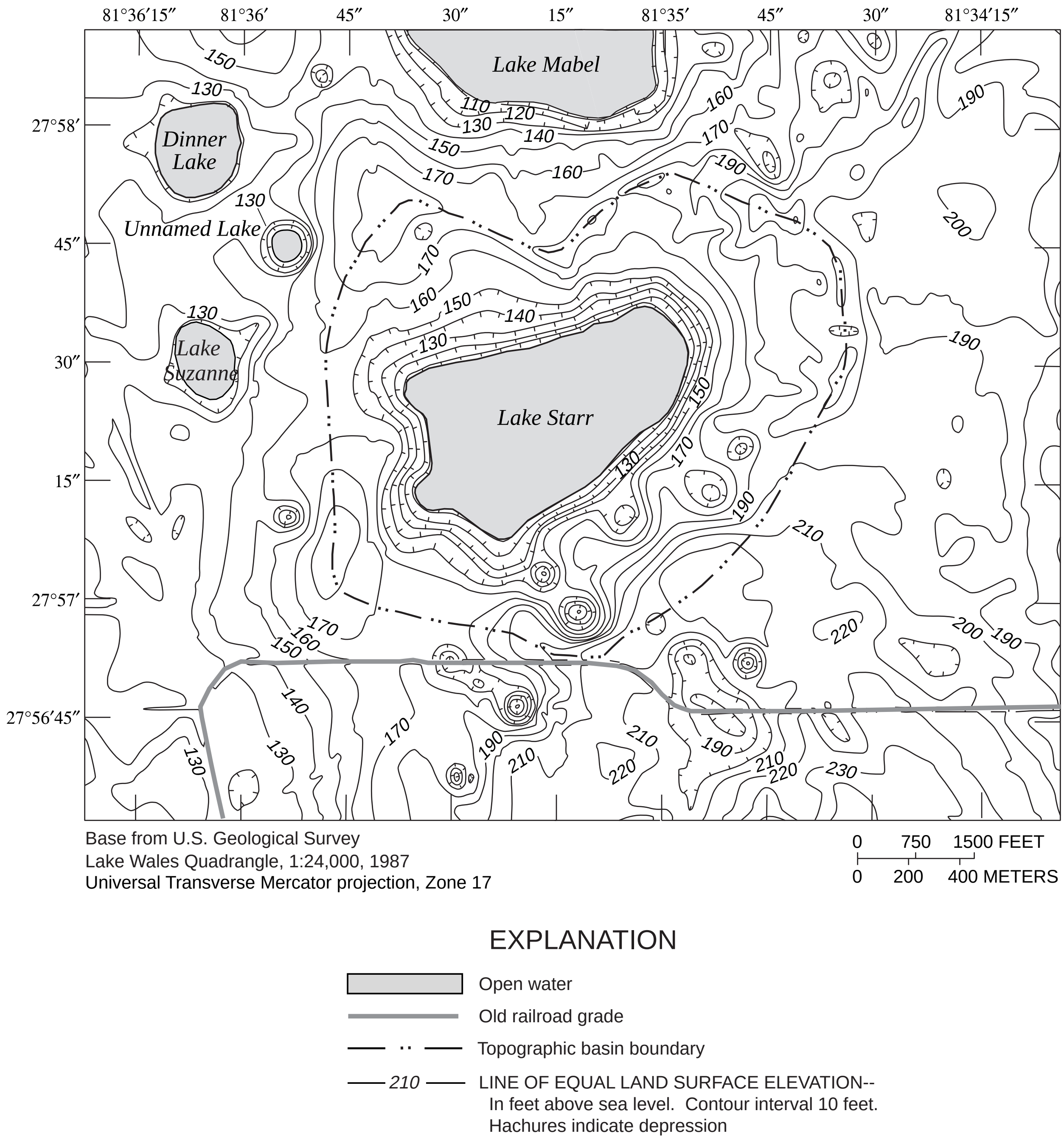


Figure 3. Topography of Lake Starr basin.

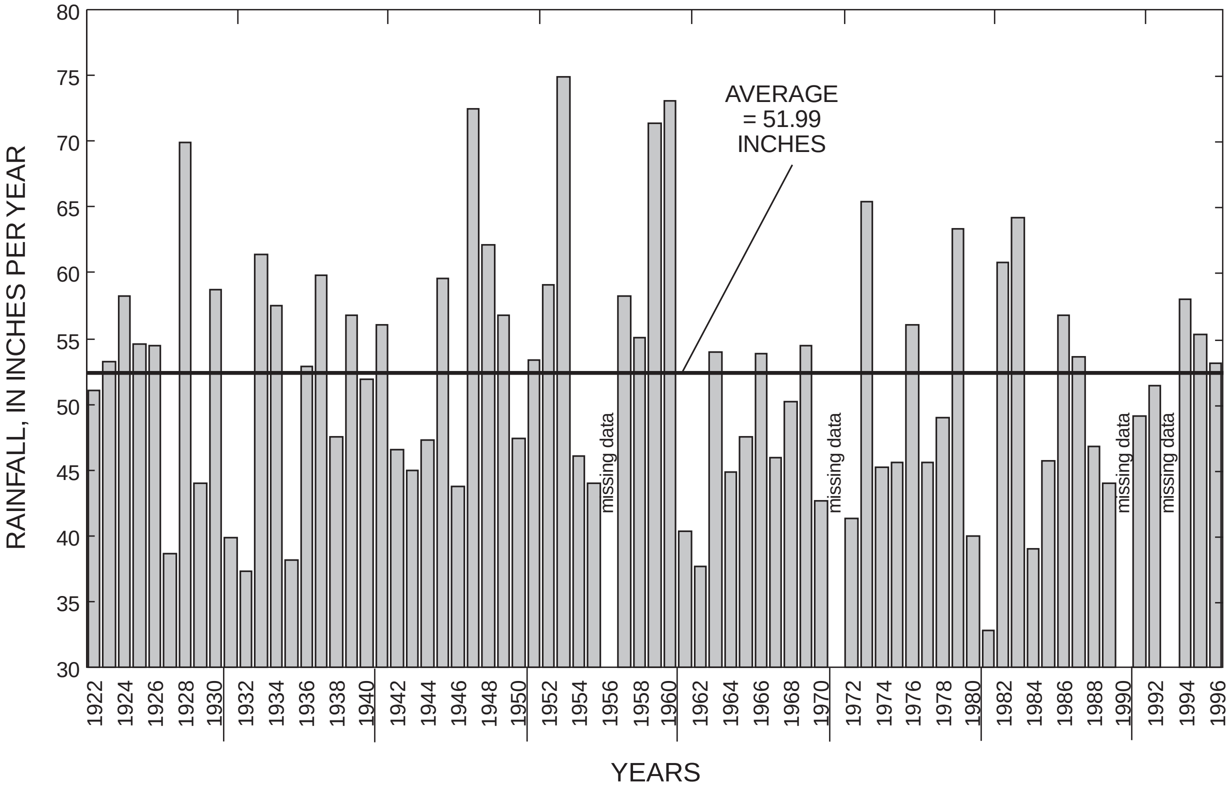


Figure 4. Long-term annual rainfall at Mountain Lake National Weather Service station, Florida for 1922-1996 (NOAA, 1999). 71 years of complete data; missing 1956, 1971, 1990, and 1993.

(Farnsworth and others, 1982). Long-term estimates of annual shallow lake evaporation, based on evaporation pan data, are lower than rainfall in central Florida (48 inches of evaporation compared to 52 inches of rainfall) (Farnsworth and others, 1982; NOAA, 1999). More recent studies indicate that annual lake evaporation in Florida can be as high as 59 inches, particularly during droughts (Sacks and others, 1994; Lee and Swancar, 1997).

Lake Starr was at a relatively high stage during this study compared to the previous 12 years of existing record (M. Barcelo, Southwest Florida Water Management District, written commun., 1995). The lowest recorded stage was 97.68 ft above sea level on February 26, 1991, and the highest was 106.56 ft above sea level on April 2-4, 1998. Even though there are no documented data available before 1983, many long-term lake residents have noted that the lake had not been this high in more than 30 years, although historically the lake level had been much higher than 106.56 ft above sea level. Estimates based on accounts of residents indicate that the lake has been as high as 115 ft above sea level since the 1930’s. Locations of the oldest houses and docks indicate that the lake was much higher when the area was first developed. Currently, the lowest house slab is at about 117 ft above sea level (D. Richters, Southwest Florida Water Management District, written commun., 1995). There is a noticeable break in slope around the basin, typically between 107 and 109 ft above sea level, which may correspond to a stable historical lake stage.

HYDROGEOLOGIC SETTING

Hydrogeology

Some aspects of the hydrogeology at Lake Starr are regional in nature and have been studied extensively, such as flow in the Upper Floridan aquifer, which underlies almost the entire peninsula of Florida. Other aspects are local and affect the lake basin in addition to regional patterns. Local aspects include the location of karst features such as sinkholes. While regional hydrogeology determines the general ground-water flow around the basin, local differences from the regional pattern are important within the scale of the lake basin and may strongly influence flow to and from the lake.

Regional Lithology and Hydrogeology

The lithology and hydrogeology of the region around Lake Starr basin are typical of the Lake Wales Ridge, as described by Tihansky and others (1996) (table 1). The general order of rocks in this region is a thick sequence of carbonates overlain by siliciclastic sand and clay sediments (units containing silica that were formed from fragments of other rocks; for example, quartz sand). Rocks and sediments were deposited during periods when sea level was high and parts of the peninsula were submerged. During low sea levels, rocks and sediments were eroded or reworked. In general, geologic units that remain in this region thicken to the south, west, and east (Miller, 1986; Scott, 1988).

The bottom-most geologic unit of interest to the study of the lake is the upper Eocene Ocala Limestone (table 1). The upper Ocala Limestone is a white, loosely bound, porous rock unit composed of large remains and broken fragments of fossils and shells (Applin and Applin, 1944). The altitude of the top of the Ocala Limestone in the region around the study area ranges from 50 to 150 ft below sea level, and the unit averages 300 ft in thickness (Tihansky and others, 1996). The Suwannee Limestone, which commonly overlies the Ocala Limestone, is absent in the study area, although it occurs to the west (Scott, 1988; Tihansky and others, 1996).

The Hawthorn Group of Oligocene to Pliocene age unconformably overlies the Ocala Limestone near the study area. The distinguishing characteristic of the Hawthorn Group is the presence of phosphate grains that may occur as sand- to gravel-sized particles. The Hawthorn Group is characterized by two lithologies: a dominantly calcareous (calcium carbonate) lower unit called the Arcadia Formation and a siliciclastic upper unit called the Peace River Formation (Scott, 1988). According to Scott (1988), the top of the Arcadia in the region around the study area ranges from 0 to 50 ft above sea level and the unit averages 50 ft in thickness. The Peace River Formation also has a surface altitude between 0 and 50 ft above sea level, with a thickness of less than 50 ft (Scott, 1988). Lithologies of these units are described in table 1.

Sediments overlying the Hawthorn Group in the study area are lumped together as a single unit (undifferentiated sand, shell and clay) (table 1). The lithol-

Table 1. Relation of stratigraphic and hydrogeologic units near the study area. Dashed where hydrostratigraphic contact varies (modified from Tihansky and others, 1996; Missimer and others, 1994; Scott and others, 1994; Wingard and others, 1994; Covington, 1993)

<table>
<tr><th>System</th><th>Series</th><th colspan="2">Lithostratigraphic unit</th><th colspan="2">Hydrostratigraphic unit</th><th>Generalized lithology</th></tr>
<tr><td>QUATERNARY</td><td>PLEISTOCENE</td><td colspan="2" rowspan="2">UNDIFFERENTIATED SAND, SHELL, AND CLAY (UDSC)</td><td colspan="2" rowspan="2">SURFICIAL AQUIFER SYSTEM (SAS)</td><td rowspan="2">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="7">TERTIARY</td><td rowspan="2">PLIOCENE</td></tr>
<tr><td rowspan="4">HAWTHORN GROUP</td><td rowspan="2">PEACE RIVER FORMATION</td><td colspan="2" rowspan="3">INTERMEDIATE AQUIFER SYSTEM AND/OR INTERMEDIATE CONFINING UNIT (IAS -ICU)</td><td rowspan="2">INTERBEDDED SANDS, CLAYS AND CARBONATES WITH SILICICLASTIC COMPONENT BEING DOMINANT AND VARIABLY MIXED; MODERATE TO HIGH PHOSPHATE SAND/GRAVEL CONTENT</td></tr>
<tr><td rowspan="2">MIOCENE</td></tr>
<tr><td rowspan="2">ARCADIA FORMATION</td><td rowspan="2">FINE-GRAINED CARBONATE WITH LOW TO MODERATE PHOSPHATE AND QUARTZ SAND, VARIABLY DOLOMITIC</td></tr>
<tr><td rowspan="2">OLIGOCENE</td><td rowspan="3">FLORIDAN AQUIFER SYSTEM</td><td rowspan="3">UPPER FLORIDAN AQUIFER (UFA)</td></tr>
<tr><td colspan="2">SUWANNEE LIMESTONE</td><td>FINE-TO MEDIUM-GRAINED PACKSTONE TO GRAINSTONE WITH TRACE ORGANICS AND VARIABLE DOLOMITE AND CLAY CONTENT</td></tr>
<tr><td>EOCENE</td><td colspan="2">OCALA LIMESTONE</td><td>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>

ogy of this unit is highly variable, but along the Lake Wales Ridge it consists mainly of quartz sand with minor amounts of clay. The top of this unit coincides with land surface, and the thickness varies from 70 to 300 ft along the ridge.

This report will focus on the uppermost hydrogeologic units because these units are the ones that interact with the lake. The regional ground-water system in the area around Lake Starr consists of two aquifers, an upper unconfined (water-table) aquifer and a lower confined aquifer. These two aquifers are separated by a confining unit that isolates the two aquifers. Farther south, the confining unit thickens and the system becomes more complex with multiple aquifers and confining units. The confining unit is absent to the north, and the confined aquifer becomes unconfined in this direction.

The upper unconfined aquifer is called the surficial aquifer system, and it occurs in the undifferentiated sand and clay sediments that start at land surface. This system is recharged by rainfall that infiltrates these permeable sediments and percolates downward to the water table. The ground water then either migrates laterally to discharge points, where it augments surface-water bodies, or it continues downward, eventually recharging the lower aquifer. Water levels in the surficial aquifer system follow topography in a very broad sense, with levels highest under the ridges in the center of the State and lowest at the coast. Within more localized settings, topographic highs may be underlain by water-table lows. Lake levels reflect the local water level of this aquifer, and along with wells, lake levels can be used to construct water-table maps (Yobbi, 1996). In the Lake Wales Ridge, the thickness of the surficial aquifer system varies from 50 to 300 ft (Yobbi, 1996). Published hydraulic conductivity values for the surficial aquifer system in this area range from 2 to 38 ft per day (ft/d) (Pride and others, 1966; Southwest Florida Water Management District, 1994; Lee and Swancar, 1997).

The intermediate aquifer system, or intermediate confining unit, includes all water-bearing and confining units between the base of the surficial aquifer system and the top of the Upper Floridan aquifer (Southeastern Geological Society, 1986). In the northern part of Polk County, including the area encompassing Lake Starr, these hydrogeologic units act only as a confining unit, so they are called the intermediate confining unit. Farther south, where the Hawthorn Group becomes thicker and more complex, these hydrogeologic units are called the intermediate aquifer system, and are an important regional water supply comprised of one or more aquifers and confining units (Mattie and others, 1996a; Yobbi, 1996). In this report, the intermediate confining unit is commonly referred to simply as the confining unit.

The Upper Floridan aquifer lies beneath the intermediate confining unit or aquifer system, and is the principal source of freshwater in west-central Florida (Ryder, 1985; Miller, 1986; Tibbals, 1990). The potentiometric surface of the Upper Floridan aquifer is highest along the Winter Haven and Lake Wales Ridges (fig. 1), and decreases toward the southwest, south, and southeast. Heads in the Upper Floridan aquifer along the Lake Wales Ridge range from greater than 120 ft above sea level to less than 50 ft above sea level (Mattie and others, 1996b). Yobbi (1996) derived average transmissivity values of 40,000 to 60,000 ft squared per day (ft^2/d) for the Upper Floridan aquifer in the study area through aquifer model development and calibration.

The mantled karst region that includes Lake Starr has limited surface-water drainage (Sinclair and others, 1985). Instead, the area is internally drained with relatively high recharge rates to the Upper Floridan aquifer (greater than 10 inches per year) (Aucott, 1988). Limestone bedrock dissolves gradually as acidic rain and soil water flow downward. Dissolution occurs along fractures in the rock, which enlarge over time. Eventually the process of dissolution reduces the strength of the rock to the point where it can no longer bear the weight of overlying sediments, and collapse or subsidence occurs.

Surface expressions and shapes of features produced by dissolution in central Florida range from small (less than 5 ft wide), shallow depressions to large dramatic collapses (Sinclair and others, 1985). Subsurface carbonate dissolution is a process that occurs over thousands of years (White, 1988), so that the resulting surface expression depends more on the nature of overlying materials than the rate of dissolution. When the overlying clays and sands are thick, the solution void can grow large before the overburden collapses. Catastrophic collapses typically occur in areas where support fails abruptly (Sinclair and others, 1985). Thinner or discontinuous clay units overlain by sands are more likely to result in "piping" or "raveling" sinks that fill in gradually as support is reduced.

Basin Lithology and Hydrogeology

Geologic and hydrologic data were collected from wells that were drilled for the study and from existing wells. A total of 39 observation wells were installed in the Lake Starr basin to monitor ground-water levels and to record geology (fig. 5, table 2). Both existing wells and deeper wells drilled for this study were used to construct geologic sections across the basin (fig. 6). Existing wells whose geologic logs were submitted by private drilling contractors to the Southwest Florida Water Management District were reviewed, and those that were judged to be accurate were included in geologic sections.

Geologic descriptions of rocks and sediments in the Lake Starr basin came from drillers' logs and analyses of drill cuttings from all wells drilled for the study, including split-spoon samples from the two deepest wells. Additional geologic information came from natural-gamma geophysical logs completed for 21 wells. Sublake geology was determined using seismic stratigraphy, and lake-bottom sediment thickness was measured by probing.

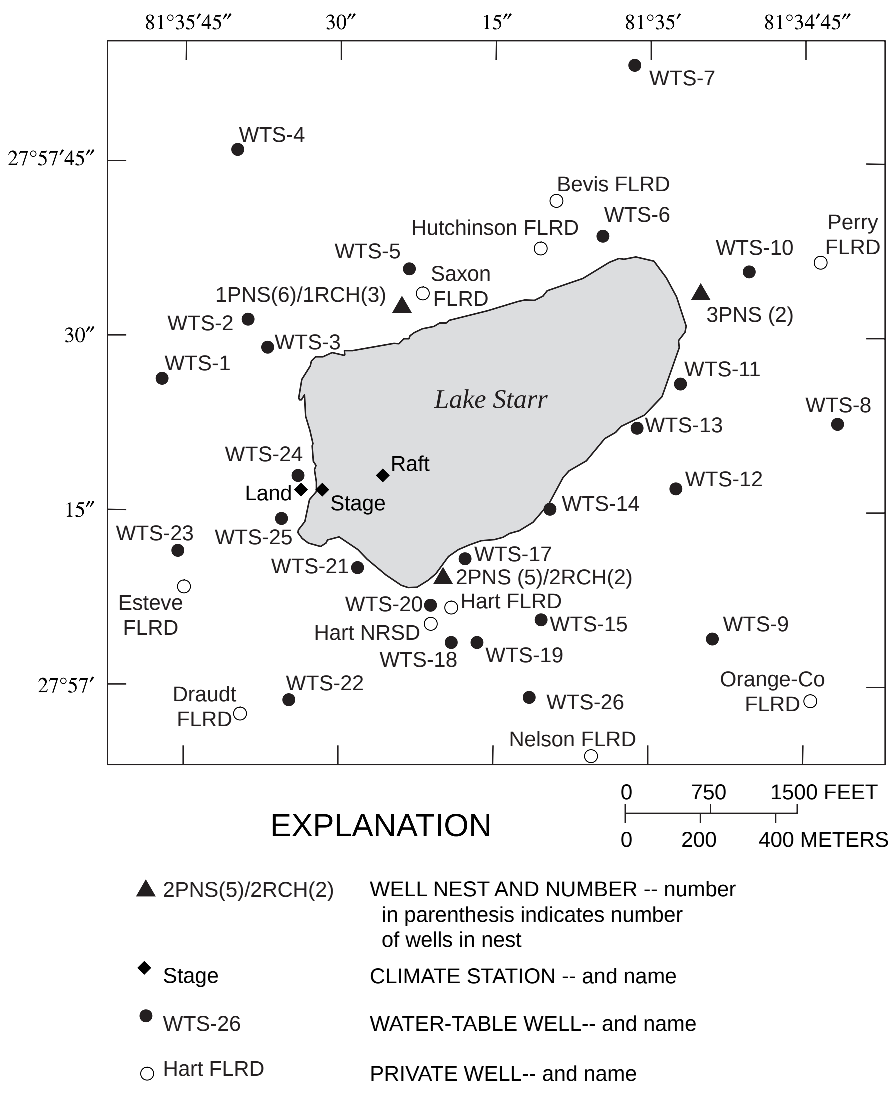


Figure 5. Location of water-level monitoring wells and climate stations in the Lake Starr basin.

Table 2. Description of observation wells in the basin surrounding Lake Starr

[Alt name, alternate name from Sacks and others, 1998; FLRD, Upper Floridan aquifer; NRSD, nonartesian sand aquifer; nd, no data]

Well number	Alt name	Latitude	Longitude	Well depth in feet below land surface	Altitude of top of casing in feet above sea level
Water table wells[1]					
WTS-1		275726	813547	50	153.98
WTS-2	STUNW	275731	813540	35	134.21
WTS-3	STLNW	275729	813537	13	111.38
WTS-4		275749	813540	80	181.63
WTS-5	STUN	275736	813523	35	130.27
WTS-6	STLNE	275739	813504	25	115.89
WTS-7		275753	813502	90	191.22
WTS-8		275723	813442	102	200.78
WTS-9		275704	813454	130	230.39
WTS-10	STUE	275737	813451	74	166.92
WTS-11		275726	813457	20	120.95
WTS-12	STUSE	275717	813458	80	178.57
WTS-13	STLSE	275721	813503	11	108.22
WTS-14		275715	813510	10	111.49
WTS-15		275706	813510	75	172.82
WTS-17		275711	813518	8	111.11
WTS-18	STUS	275704	813519	50	142.72
WTS-19		275704	813517	15	118.48
WTS-20	STLS	275708	813520	22	113.91
WTS-21		275710	813528	20	118.16
WTS-22		275659	813535	65	163.72
WTS-23		275712	813546	85	182.43
WTS-24	STLW	275719	813534	19	116.34
WTS-25		275714	813536	13	114.69
WTS-26		275659	813512	24	118.27
1RCH-A		275732	813524	5	108.36
1RCH-B		275732	813524	8	107.84
1RCH-C		275732	813524	7	110.26
2RCH-A		275709	813520	5	107.36
2RCH-C		275709	813520	16	114.36
Nested wells[2]					
1PNS-15	STLN	275734	813523	15	112.99
1PNS-25		275732	813524	25	112.70
1PNS-50		275732	813524	50	112.84
1PNS-75		275732	813524	75	112.98
1PNS-100		275732	813524	100	112.42
1PNS-125		275732	813524	125	113.87
2PNS-10	[3]2RCH-B	275709	813520	10	108.51
2PNS-27		275709	813520	27	108.71
2PNS-51		275709	813520	51	108.93
2PNS-101		275709	813520	101	109.08
2PNS-156		275709	813520	156	109.64
3PNS-20	STLE	275734	813455	20	120.19
3PNS-40		275734	813455	40	120.63

Table 2. Description of observation wells in the basin surrounding Lake Starr (Continued)

[Alt name, alternate name from Sacks and others, 1998; FLRD, Upper Floridan aquifer; NRSD, nonartesian sand aquifer; nd, no data]

Well number	Alt name	Latitude	Longitude	Well depth in feet below land surface	Altitude of top of casing in feet above sea level
Private wells[4]					
Esteve FLRD		275708	813545	460	183.52
Saxon FLRD		275734	813522	150	122.88
Hutchinson FLRD		275738	813511	347	132.45
Bevis FLRD		275742	813509	190	159.91
Hart FLRD		275707	813519	nd	137.71
Hart NRSD		275706	813521	80	130.76
Draudt FLRD		275658	813540	480	163.55
Perry FLRD		275737	813444	450	192.72
Orange-Co FLRD		275659	811444	495	220.14
Nelson FLRD		275654	813506	300	213.43

[1]Water table wells have 5-foot screens

[2]Nested wells have 2.5-foot screens except for 1PNS-15 and 3PNS-20, which have 5-foot screens

[3]Alternate name because well used in 2RCH transect

[4]Casing depths of private wells in feet are as follows: Esteve, 160; Saxon, 140; Hutchinson, 203; Bevis, 176; Hart FLRD, nd; Hart NRSD, 60; Draudt, 162; Perry, 256; Orange-Co, 213; Nelson, 215

Undifferentiated surficial sediments that make up the surficial aquifer system around Lake Starr consist largely of fine to medium sands with minor silt and clay fractions. Surficial deposits are very consistent in character throughout the basin. A layer of coarser sands exists at depth in some areas, typically overlying the confining clays. Grain-size analyses of samples from wells drilled for this study indicate that the silt and clay content of surficial deposits is very low (less than 2 percent). Sands range in color from brown to orange, yellow, and white, while clays range from red to orange and yellow. Some anomalous purple clay occurs in deeper parts of the surficial aquifer system on the southwest side of the lake. In areas of the basin not disrupted by development of sinkholes, surficial deposits range from 90 to 200 ft thick, with the greatest thickness occurring under the ridges on the southeast side of the lake.

The contact between the surficial deposits and the Hawthorn Group was difficult to determine from drillers' logs of existing wells. The contact was found in one of the two deep wells drilled for this study (1PNS-125). Generally, this contact is distinguished by gradually increasing amounts of clay and phosphate and a color change of the clays to olive-green and blue-gray (Scott, 1988). However, this color change is not consistent over the basin; in many logs for existing wells the contact was interpreted to be at the top of a prominent layer of red clay above the carbonate section.

Natural-gamma geophysical logging was useful in determining the contact between the Peace River Formation of the Hawthorn Group and the overlying surficial deposits (fig. 7). The Hawthorn Group has a substantial increase of natural-gamma radiation compared with the surficial deposits due to uranium-bearing phosphate minerals that occur throughout the unit (Scott, 1988). Natural-gamma logs were made on the two deepest nest wells (1PNS-125 and 2PNS-156), and on 19 existing wells drilled on vacant lots on the south side of the lake. Wells on vacant lots were easily logged because pumps were not installed. Interpretation of natural-gamma logs was based on a comparison of the gamma signature with the lithology from the 1PNS-125 well. Gamma logs indicated that the contact between the surficial deposits and the Peace River Formation was gradational. The highest gamma radiation counts occurred deeper in the Hawthorn Group at the contact between the Peace River and Arcadia Formations.

Geophysical and drillers' logs indicate that the elevation of the top of the Peace River Formation ranges from 9 ft below sea level to 68 ft above sea level in the area around Lake Starr, and the thickness ranges from 15 to 51 ft. The Peace River Formation is generally highest and thickest under the ridges that define the surface drainage basin and thinnest or absent near the lake. The occurrence and thickness of the Peace River Formation are important because this formation acts as the confining unit to the Upper Floridan aquifer, and therefore determines the degree of interaction between the surficial and the Upper Floridan aquifers.

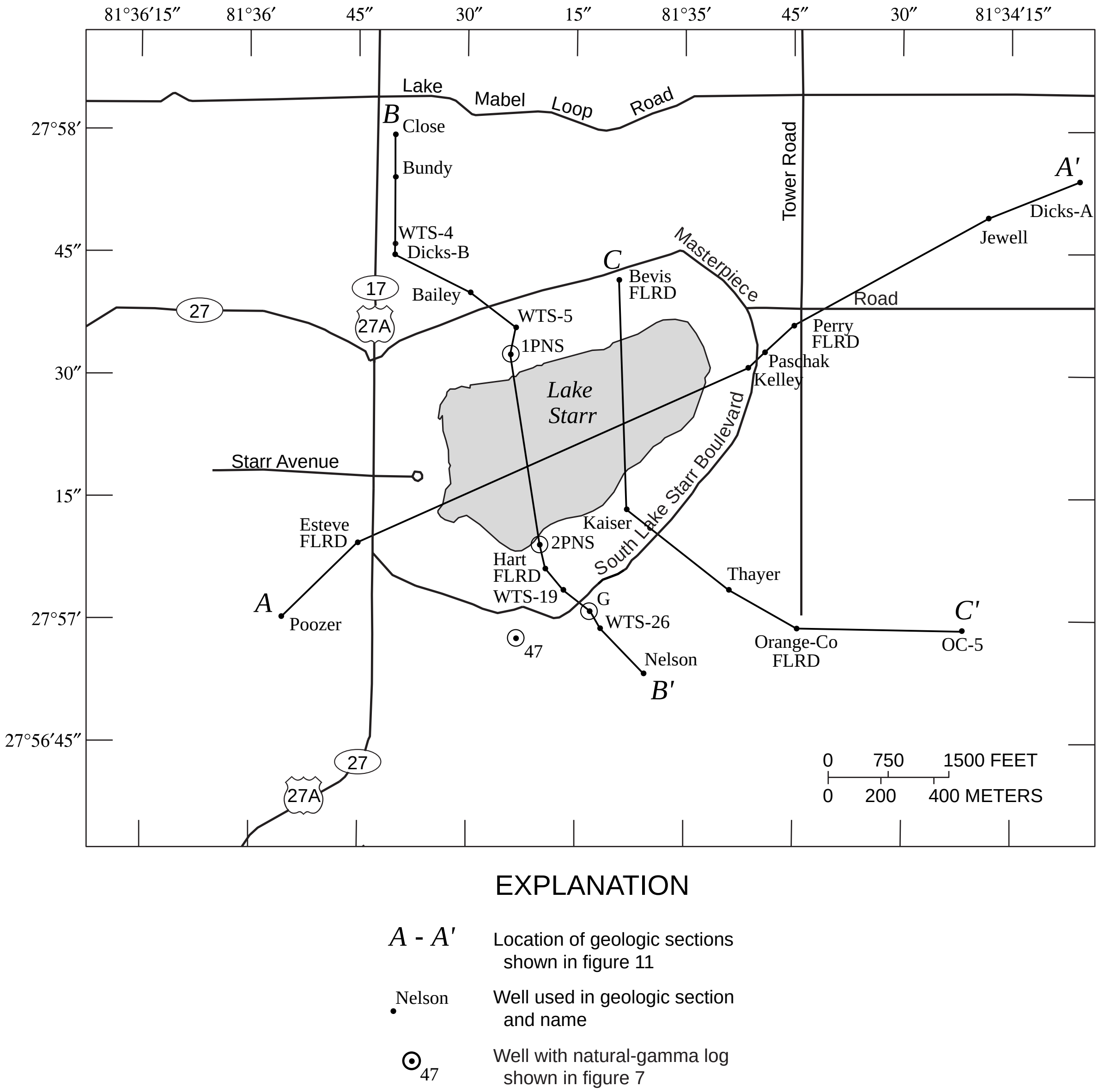


Figure 6. Location of geologic sections and wells with natural-gamma logs.

The Arcadia Formation of the Hawthorn Group is the uppermost producing zone of the Upper Floridan aquifer in the study area, and most domestic and irrigation wells are open to this unit. Drillers' logs indicate a range of elevations for the top of the Arcadia Formation in the study area from 20 ft below sea level to 50 ft above sea level. Wells that completely penetrate the Arcadia and continue down into the Ocala Limestone provide a record of thickness for the Arcadia ranging from 55 to 143 ft. No evidence of the presence of the Suwannee Limestone was found in the study area, but many lithologic logs of existing wells are not detailed enough to distinguish formation changes.

Evidence of Karst Features in the Lake Starr Basin

Two types of sinkholes are found in the Lake Starr basin. Steep, areally limited "piping" sinkholes, also called cover-subsidence sinkholes, are the dominant form of subsidence. A second type of sinkhole, a cover-collapse sinkhole, is probably responsible for larger features in the basin, including the deeper parts of the lake. Snyder and others (1989) described this type of sinkhole in Crooked Lake, a large lake farther south along the Lake Wales Ridge (fig. 1).

Subsurface geologic processes are reflected in the basin topography at Lake Starr. On the south side

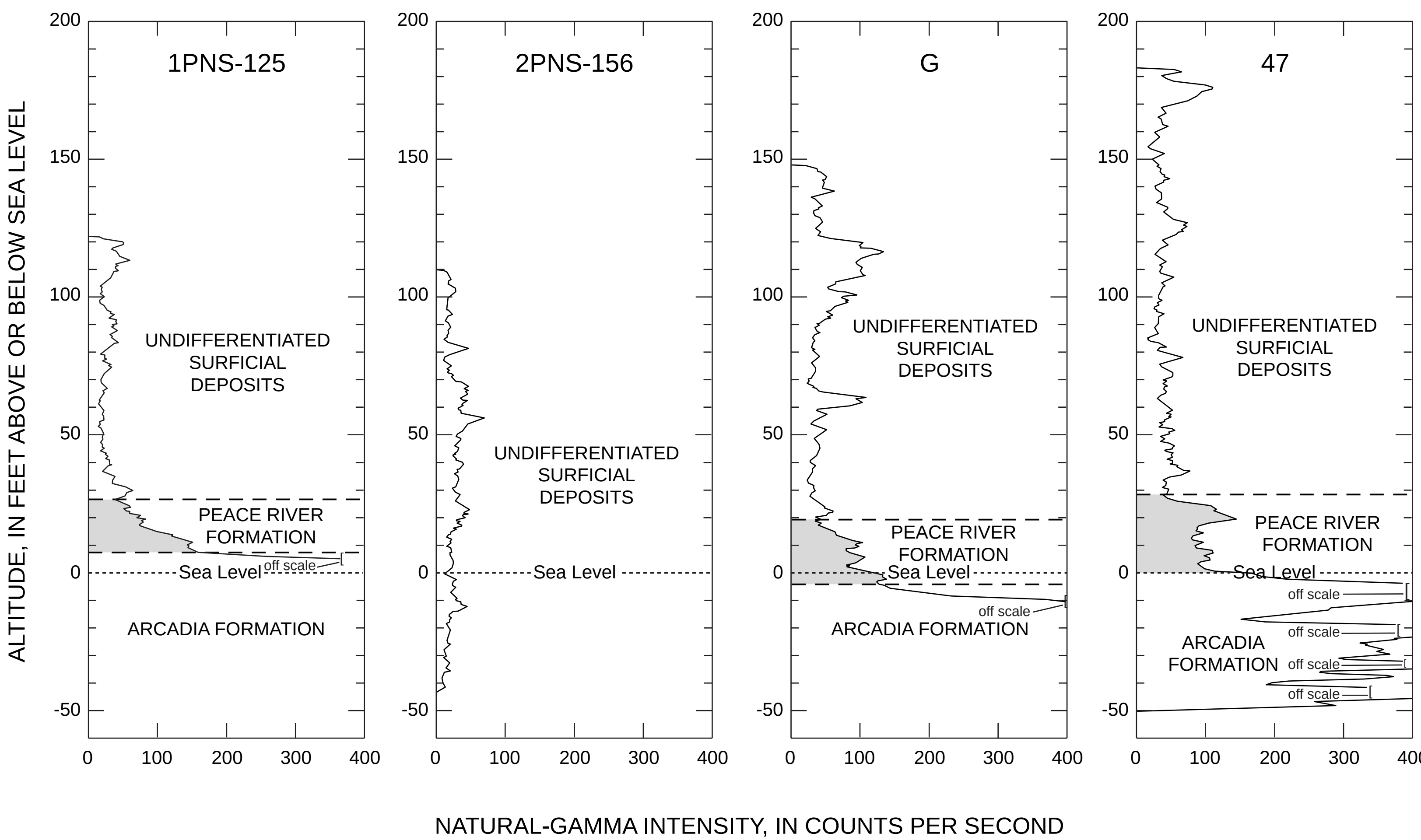


Figure 7. Natural-gamma radiation logs from selected wells. (Well locations shown in figure 6).

of the lake are two prominent sinkholes, each about 50 ft deep and 500 ft wide (fig. 3). The geophysical log of a well located between the two sinkholes shows that the confining unit is intact in this small area (fig. 7, well G), reflecting the localized nature of cover-subsidence sinkholes (Tihansky and others, 1996).

Lack of confinement due to karst processes may not be obvious at the land surface, however. Geologic logs of existing wells in the area show that there is not always a surface expression of subsurface disturbance. Older sinks may be inactive, and may have been buried over time by overlying sands. Boreholes drilled approximately 3,200 ft east of the Orange-Co FLRD well and at Hart's NRSD well (fig. 5) did not find carbonate rock at the expected depths. Neither of these locations appears to be different at the surface from nearby areas where well logs show that the confining unit and underlying rock are intact. The 2PNS nest of wells also was located in a collapse area near the lakeshore where carbonate rocks were not found to a total depth of 156 ft. This depth is equivalent to 46 ft below sea level; the contact with carbonates elsewhere in the basin was not deeper than 20 ft below sea level.

Sublake Geology

Understanding the sublake geology is critical to understanding the interactions between the lake and ground-water system. The local hydrogeologic setting controls the amount of water that flows out of the lake (lake leakage or ground-water outflow) to the ground-water system, and varies between lakes. Regionally, the Lake Wales Ridge provides recharge to the Upper Floridan aquifer because elevations of lakes and the water table are higher than elevations of the potentiometric surface of the Upper Floridan aquifer. Lakes are expected to have better connections to the Upper Floridan aquifer because of their origin as subsidence features. The amount of vertical leakage from Florida lakes depends on the degree of sublake confinement and the downward head gradient between the lake and the Upper Floridan aquifer (Motz, 1998).

A geophysical method called high-resolution seismic reflection was used at Lake Starr to learn about variations in sublake geology (Locker and others, 1988; Snyder and others, 1989; Kindinger and others, 1994; Tihansky and others, 1996). Tihansky and others (1996) present a thorough discussion of this method and how it has been applied on the Lake Wales Ridge. Seismic reflection surveys at Lake Starr in July 1996 consisted of 23 transects and a lake perimeter survey. The interpretation of sublake geology at Lake Starr is based on the work of Tihansky and others (1996) at Lake Wales, which is approximately 4 miles south of Lake Starr (fig. 1). Seismic data were converted to depths by assuming an acoustic velocity of 1,800 meters per second (m/s), and interpretations are consistent with land-based depths to geologic contacts determined from logs of wells in the lake basin.

Seismic data collected at Lake Starr were of average quality (fig. 8). The seismic signal can be attenuated or disrupted by both the thick, fine surficial sands and the lake sediments that occur beneath the lake (Locker and others, 1988; J. Flocks, USGS, oral commun., 1996). Surveys of the western two-thirds of the lake were best. Data collected from the eastern third of the lake and along the lake perimeter were of poor quality.

Three prominent reflectors were identified in the seismic profiles at Lake Starr. The deepest reflector was interpreted to be the limestone surface that constitutes the top of the Arcadia Formation, which also is the top of the Upper Floridan aquifer in the study area (figs. 8a, 8c, and 9). This reflector was typically high-amplitude (dark or prominent) with an irregular surface, and it appeared at a depth between 50 ft below sea level and 10 ft above sea level. The top of this reflector was deepest near subsidence features, and the irregular surface is typical of karst weathered carbonate units (Tihansky and others, 1996). The margins of the subsidence feature on the southwest side of the lake, which corresponds to the area of greatest water depth, were delineated by the changes in this reflector. This reflector also was evident in a shallower area of the lake from south to north across the center of the lake (fig. 9). The carbonate rock was intact beneath this part of the lake, forming a "saddle" in the rock surface and the bathymetry (figs. 2 and 9).

The second reflector "package" that was identified at Lake Starr was a group of continuous high-amplitude concordant parallel reflectors that exhibit sags (figs. 8b and 8c). Tihansky and others (1996) interpreted this type of reflector as "clays or other units capable of deformation in response to loss of support at depth." This loss of support was assumed to be due to collapse in the underlying limestone units. In the Lake Starr basin, these reflectors corresponded to clays at the top and within the Peace River Formation. This reflector package was most prominent in the eastern, deeper part of the lake (figs. 2, 8b, and 8c). The clays seem to drape into areas of subsidence located on the south

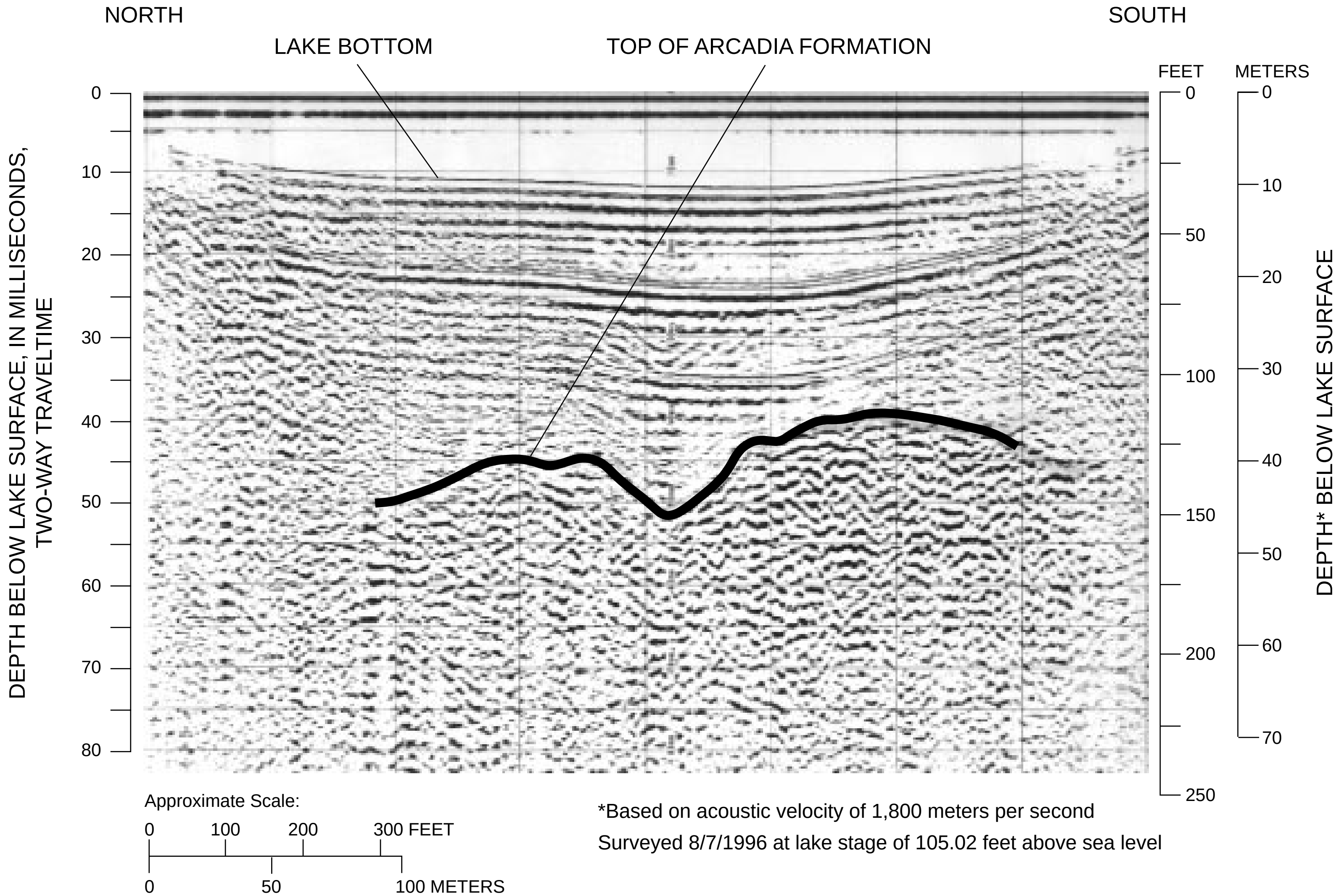


Figure 8a. Seismic-reflection profile 8a and interpretation of sublake geology for Lake Starr (profile location shown in figure 2).

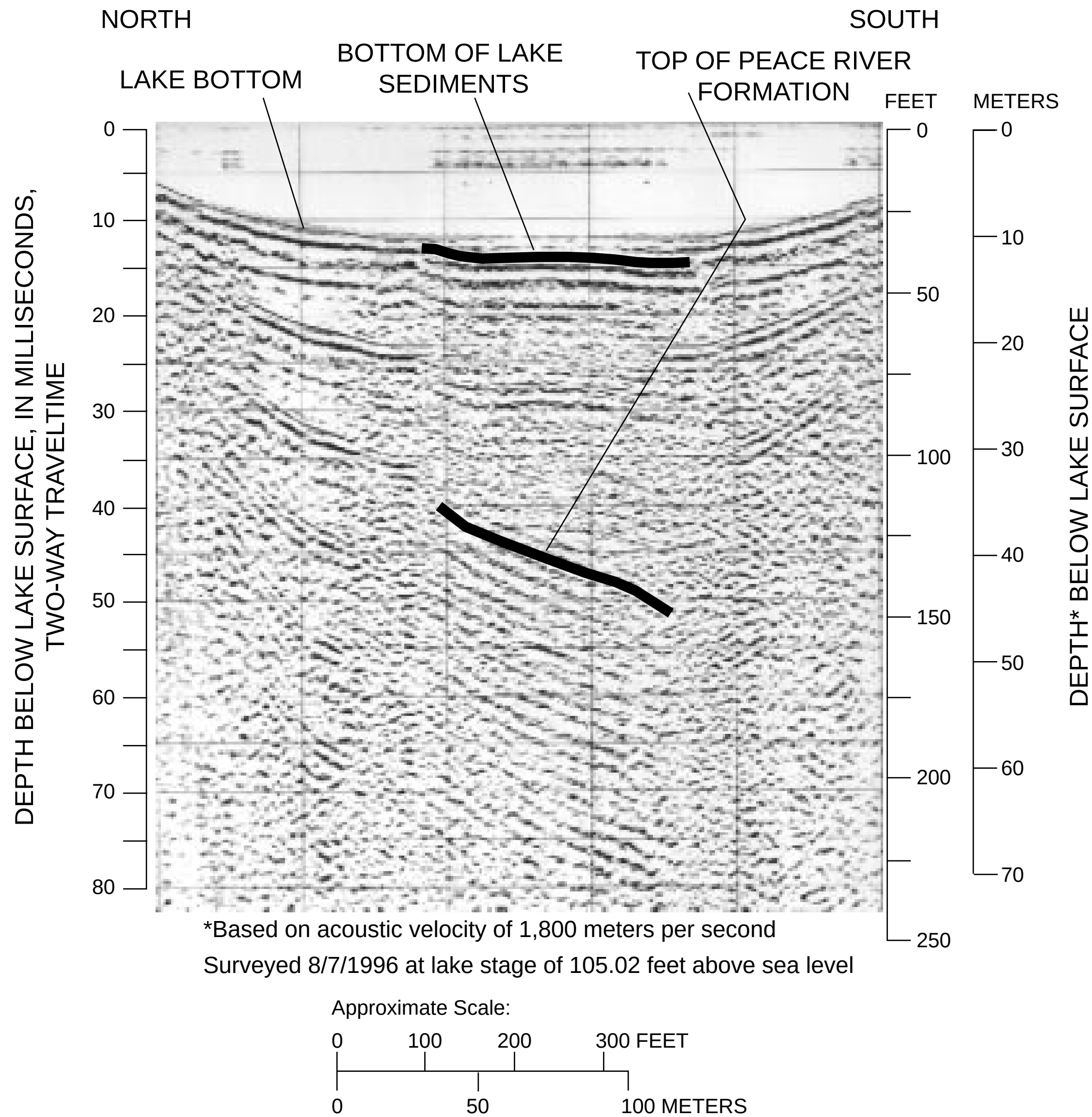


Figure 8b. Seismic-reflection profile 8b and interpretation of sublake geology for Lake Starr (profile location shown in figure 2).

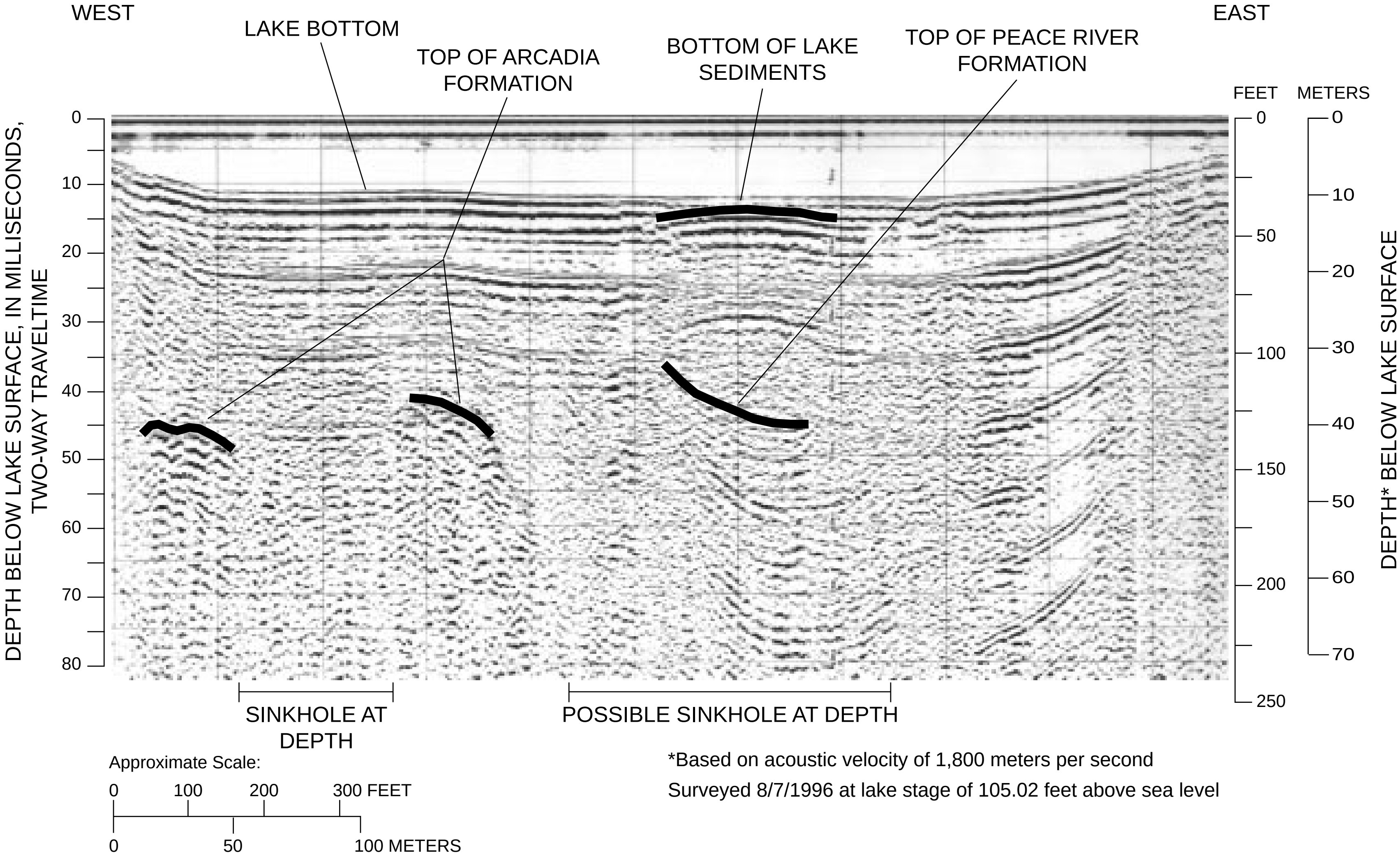
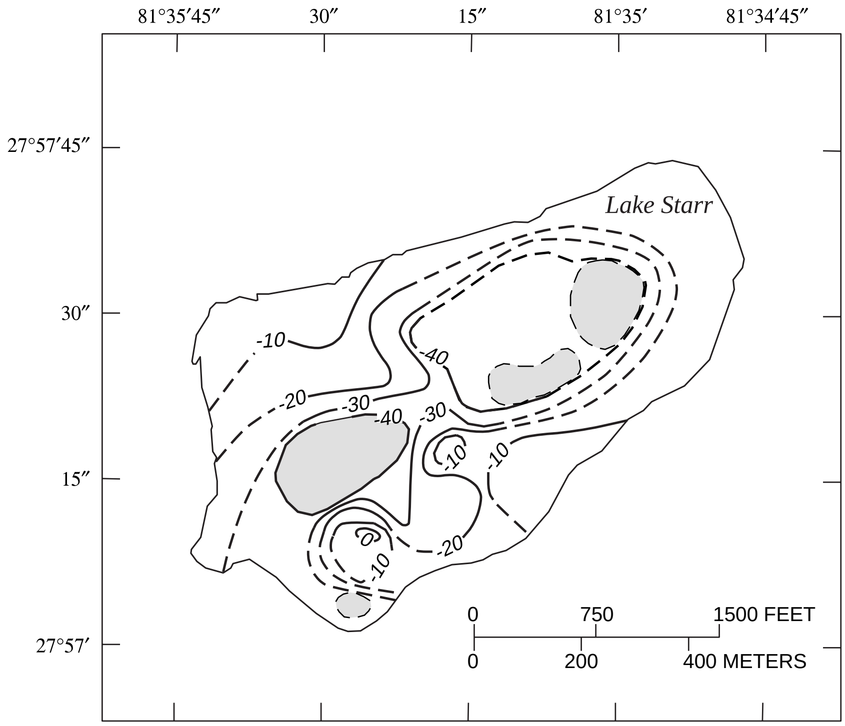


Figure 8c. Seismic-reflection profile 8c and interpretation of sublake geology for Lake Starr (profile location shown in figure 2).



EXPLANATION

-10 — — LINE OF EQUAL ELEVATION OF LIMESTONE REFLECTOR SURFACE-- In feet above sea level. Contour interval 10 feet. Dashed where inferred from trends in seismic data and geologic logs. Two-way traveltime converted to depth assuming acoustic velocity of 1,800 meters per second

Region underlain by subsidence feature

Figure 9. Structural contours of the limestone surface below Lake Starr interpreted from seismic-reflection profiles.

margin of the eastern bathymetric low and in a line extending north from the south margin.

The third reflector was a shallow, low amplitude reflector corresponding to lake bottom sediments. Lake sediments are an important hydrogeologic feature because they impede lake leakage. The map of this reflector was compared with data collected by probing the lake bottom to determine sediment thickness; these two datasets were used to generate the map of lake sediments shown in figure 10. Lake-bottom sediments were soft, gelatinous, and black/brown in color. Lake-bottom sediments at Lake Starr were relatively thin (less than 5 ft thick) and occurred only in the deepest parts of the lake. In areas where the sediments were thinner, they also were sandy. Although the distribution of sediments was similar in the two datasets, the sediments seemed to be twice as thick in the seismic record using the 1,800 m/s acoustic velocity. Probed depths were assumed to be more accurate because sediment thickness was not great and the probe could not be driven more than a few inches beyond the sediment/sand interface. It is likely that the transition between the sediment and water or the nature of the sediments affected the seismic response. Acoustic velocities through the lake sediments of about one-half of that assumed also would account for this discrepancy.

The overall interpretation of the sublake geology and the presence of collapse features at Lake Starr were based on previous studies, as well as the data collected for this study. The presence of sinkholes and other collapse features in Florida lakes has been documented (Snyder and others, 1989; Lee and others, 1991;

Kindinger and others, 1994; Tihansky and others, 1996). The presence of dry sinkholes in upper parts of the lake basin indicates that these features exist in the study area. Collapse features, by their nature, are the absence of original geologic structures. Therefore, they are not easily visible as seismic reflectors. While collapse features were not directly visible in the seismic data, the evidence of their location has been inferred from discontinuous and sagging reflectors that were visible.

Information on sublake geology was incorporated into geologic sections to determine basin-wide geologic trends (fig. 11). Looking at the basin as a whole, and neglecting the overprint of subsidence features, the limestone/carbonate surface had a slope of about 30 ft from west (high) to east (low). The elevation of the top of the Peace River Formation (Hawthorn Group) was extremely variable. The top of the formation was at a higher elevation in upper parts of the basin, indicating that erosion and subsidence have affected the continuity of the formation, which also acts as the confining unit to the Upper Floridan aquifer. The Peace River Formation was generally intact where the underlying units were intact because of the localized nature of most subsidence features. However, in a few locations, Peace River clays were absent where the underlying carbonate unit was intact. Sinkholes located beneath Lake Starr and on the south shore tend to dominate the geology shown in the cross sections. These features are expected to have a substantial effect on ground-water flow patterns near the lake.

Ground-Water Flow Patterns in the Lake Starr Basin

Interpretation of the ground-water flow system at Lake Starr was based on water levels measured in a network of 53 existing and installed wells distributed throughout the lake basin (fig. 5 and table 2). Ground-water levels were typically measured every other week to provide a picture of the subsurface head distribution at many points in time (Coffin and Fletcher, 1999). Most wells were finished 5 to 10 ft below the top of the water table in the surficial aquifer system. Water-table elevations at the WTS (“water-table Starr”) wells in table 2 were used to interpret areal patterns of ground-water flow in the basin. Most of these wells were located farther than 50 ft from the shoreline where the unsaturated zone was greater than 5 ft thick.

At two sites, additional wells were drilled close to the lakeshore where the unsaturated zone is thin and rainfall quickly recharges the surficial aquifer. These

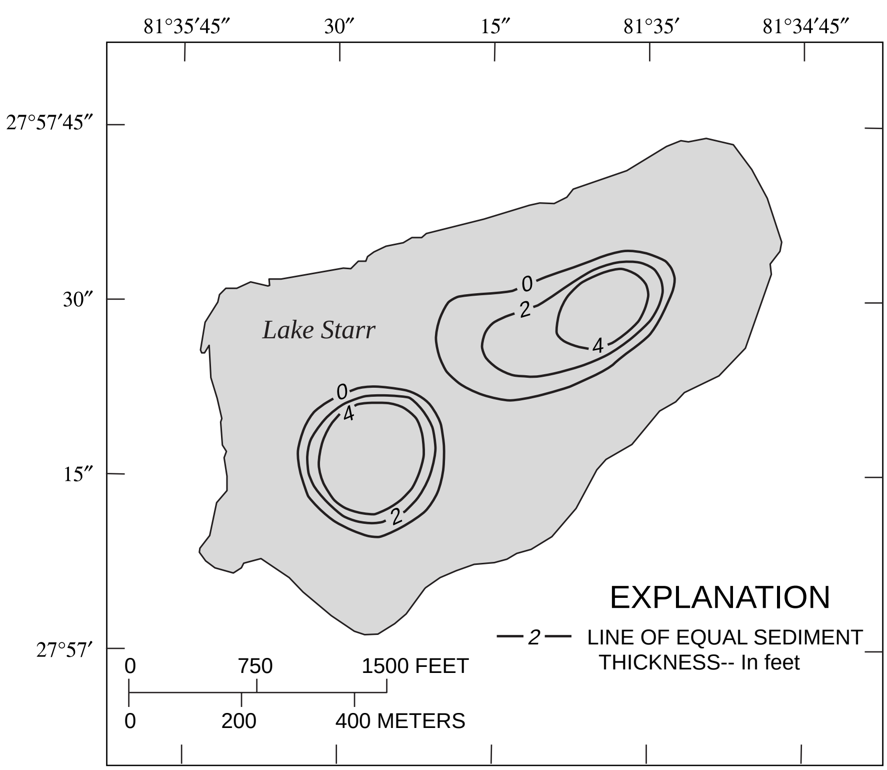


Figure 10. Thickness of lake-bottom sediments beneath Lake Starr.

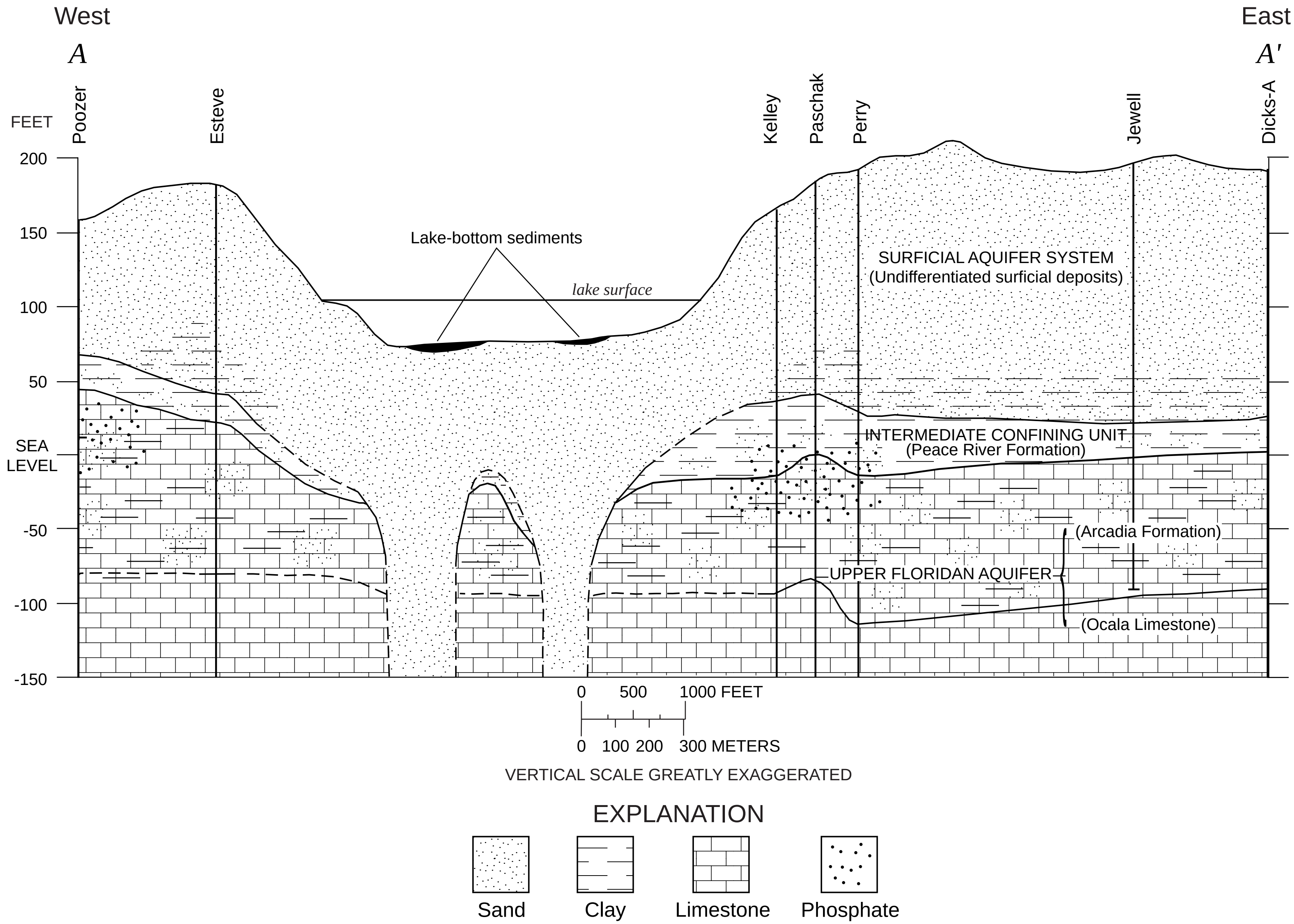


Figure 11a. Geologic section *A-A′* through Lake Starr (section location shown in figure 6).

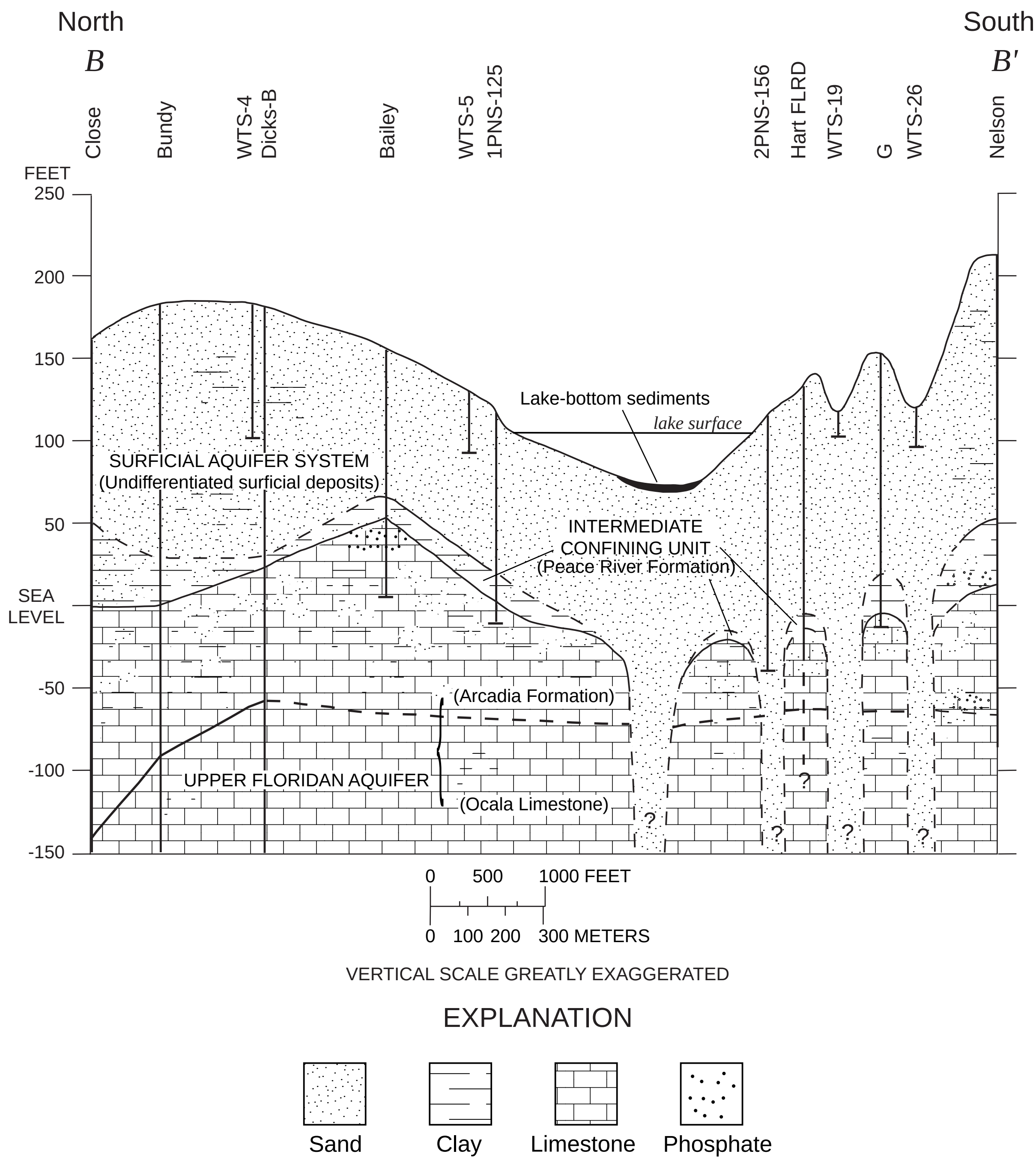


Figure 11b. Geologic section *B-B′* through Lake Starr (section location shown in figure 6).

wells were used to monitor the water-table response to rainfall and ground-water flow patterns near the lake. Short-term or transient flow patterns near the edge of lakes can temporarily increase the potential for ground-water inflow (Winter, 1983; Lee and Swancar, 1997; Lee, in press).

Site 1RCH ("recharge") was located adjacent to the first piezometer nest site (1PNS; "piezometer nest Starr") on the northern or inflow side of the lake (fig. 5). Site 2RCH was located on the southeastern or outflow side of the lake near the second piezometer nest (2PNS). At each RCH site, three shallow wells (A, B, and C) were drilled along a line perpendicular to the shoreline. The most distant well from the lake (C well) was typically within 100 ft of the shoreline. The unsaturated zone in the nearshore area was thicker at 2RCH than at 1RCH (fig. 12). At both sites, the thickness of the unsaturated zone and the distance between the wells

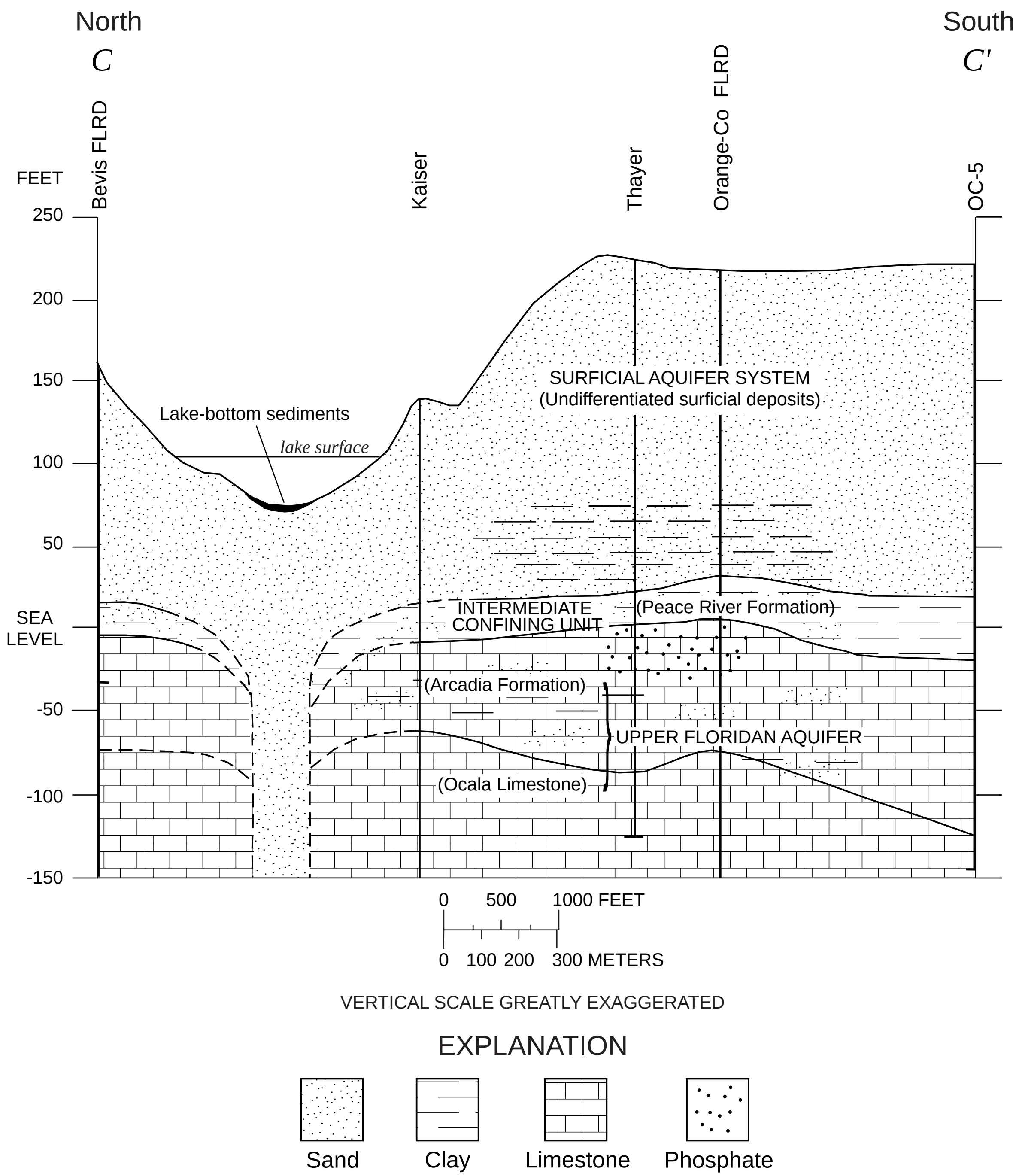


Figure 11c. Geologic section *C-C′* through Lake Starr (section location shown in figure 6).

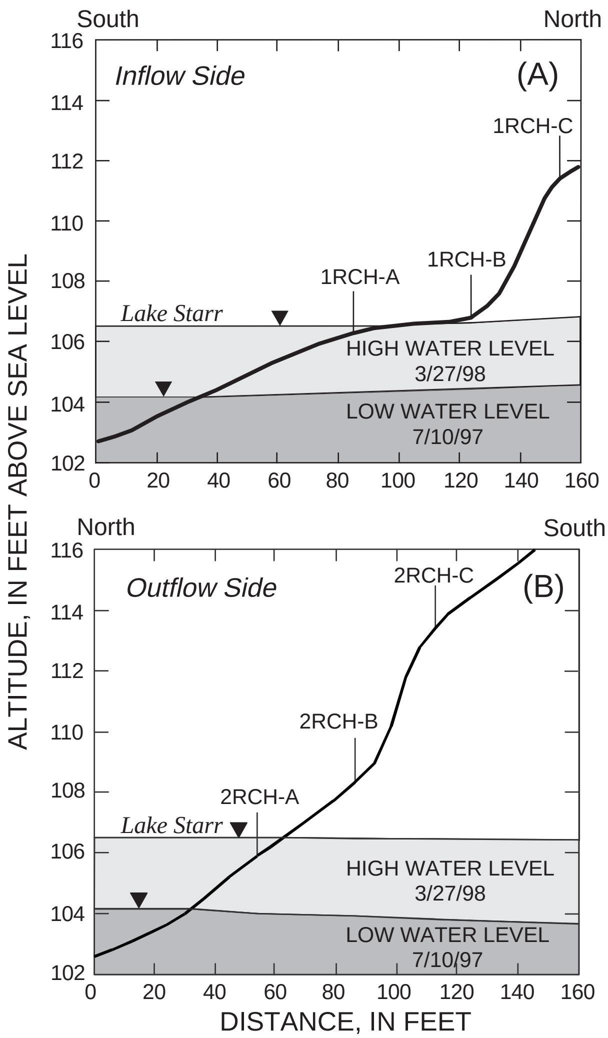


Figure 12. Shoreline profiles showing (A) inflow side of Lake Starr and the location of wells 1RCH-A, 1RCH-B, and 1RCH-C, and (B) outflow side of Lake Starr and the location of wells 2RCH-A, 2RCH-B, and 2RCH-C. The distance of the wells from the lake and water-table profiles are shown for high and low water levels.

and the shoreline varied as the level of the lake and adjacent water table rose and fell (fig. 12a and b). Water levels in these wells were measured every 15 minutes with pressure transducers between July 1997 and September 1998. Measurements were typically accurate to 0.02 ft.

Water-level measurements at three piezometer nest sites (1PNS, 2PNS and 3PNS) provided information on vertical head gradients between the water table and Upper Floridan aquifer (fig. 5 and table 2). Nested wells were drilled on the north, south, and east shores of the lake to provide information on vertical ground-water flow patterns near the lake. Well nests consisted of adjacent wells with small screened intervals that were drilled to different depths between the water table and Upper Floridan aquifer. Differences in water level at different depths determined the gradient and direction of ground-water flow. For the well that was drilled through the confining unit, the well screen was isolated by placing a bentonite seal in the annular space above the screen.

Measurements from Upper Floridan wells were used to map the areal head distribution in the Upper Floridan aquifer and to document the effects of ground-water pumping in the basin. After an initial period of measurements, water levels in two wells were estimated by establishing linear relations to other Upper Floridan aquifer wells. Water levels in the Hutchinson and Draudt Upper Floridan aquifer wells were estimated from relations with the 1PNS-125 ($r^2 = 0.98$) and Esteve Upper Floridan aquifer wells ($r^2 = 0.99$), respectively.

Areal Ground-Water Flow Patterns

Basin-Wide Flow Patterns

Basin-wide shallow ground-water flow patterns deviate somewhat from the regional water table pattern. The regional water table encompassing Lake Starr slopes to the east (Yobbi, 1996). For example, the stage of Dinner Lake, located about 0.5 mile to the northwest (see fig. 3), is approximately 9 ft higher than Lake Starr (Southwest Florida Water Management District, 1994), whereas a water-table well 1.2 miles east of Lake Starr is approximately 9 ft lower than the lake (St. Helena Rd. well, Southwest Florida Water Management District Ambient Ground-Water Quality Monitoring Program, written commun., 1997). However, detailed mapping of the water table within the Lake Starr basin showed that flow lines deviated from the regional west to east flow pattern and bent towards the south-southeast (fig. 13).

Lake Starr is a ground-water “flow-through” lake. About two-thirds of the lake perimeter receives ground-water inflow and the remainder loses water to the ground-water system. Ground-water levels in the surficial aquifer system were consistently higher than the lake on the west, north, and northeast sides of the lake, allowing ground water to flow in along the northern and western lake margins. Toward the south and southeast, despite the higher land surface elevations on this side of the basin, the water table sloped away from the lake, allowing lake water to leak into the adjacent surficial aquifer system (fig. 13). The tendency for shallow ground water to flow southward, as well as eastward across the Lake Starr basin may be partly

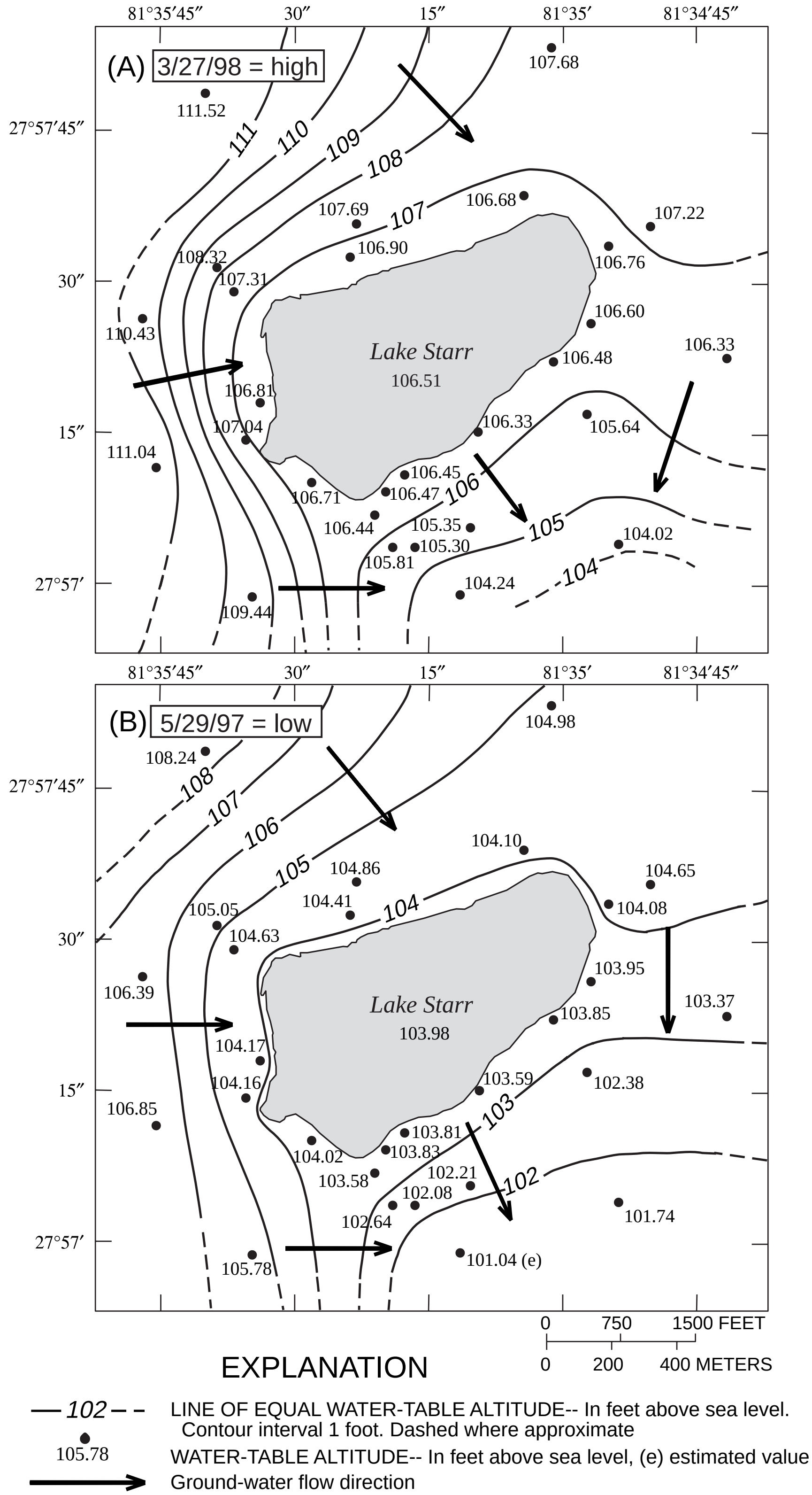


Figure 13. Water-table configurations at Lake Starr for representative (A) high water-level conditions (March 27, 1998) and (B) low water-level conditions (May 29, 1997).

attributed to collapse features (sinkholes) in the southern basin, which enhance downward recharge to the Upper Floridan aquifer in this part of the basin.

Basin wide, the highest water-table elevations during the study were measured for the period late March through April 1998. The lowest water-table elevations occurred between May and July 1997, despite normal rainfall during these months. Representative water-table maps for these two periods are shown in figure 13. The water table under the northwest topographic divide (well WTS-4; fig. 5) ranged from 3.38 to 5.84 ft higher than the lake, and averaged 4.52 ft higher. To the south, beneath the topographic drainage divide southeast of the lake (WTS-9; fig. 5), the water table ranged from 0.24 to 3.38 ft lower than the lake, and averaged 2.07 ft lower. However, in karst lake basins in recharge areas, ground-water flow is dominantly vertical, so that the contributing ground-water basin to the lake probably occurs much closer to the lake than the topographic divide (Lee, 1996).

Ground-water levels in the Lake Starr basin rose in response to rainfall differently depending upon the thickness of the overlying unsaturated zone. The unsaturated zone in the basin ranges in thickness from 0 ft at the edge of the lake to greater than 120 ft in the upper basin (for example, at well WTS-9) (fig. 5). Because the unsaturated zone delays recharge, the water table in the upper basin responded up to 2 months later than the water table in the lower basin. For the purposes of this report, the upper basin was defined to be wherever the depth to water was greater than 15 ft. This area also can be roughly defined as the part of the basin above the 120-ft land-surface elevation contour (fig. 3).

During 1998, surficial aquifer water levels in the lower basin were highest around mid-March (see wells WTS-3 and WTS-14 on figure 14). At higher land-surface elevations in the basin, surficial aquifer water levels peaked during April and May, 6 to 8 weeks later than the lower basin. Sometimes the water-table responses in the upper and lower basin were sufficiently out of phase that peaks in the upper basin coincided with declines in the lower basin (see well WTS-

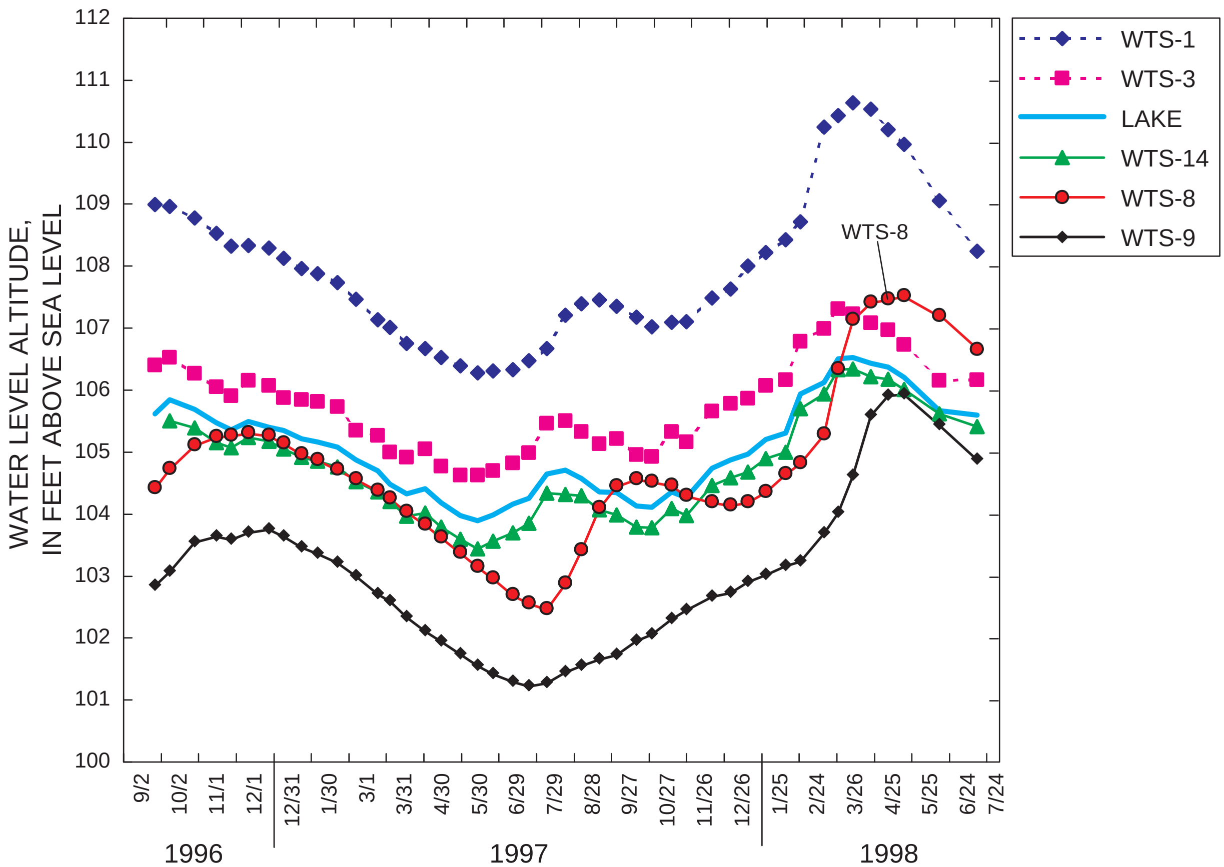


Figure 14. Hydrographs of selected water-table wells near Lake Starr and Lake Starr stage.

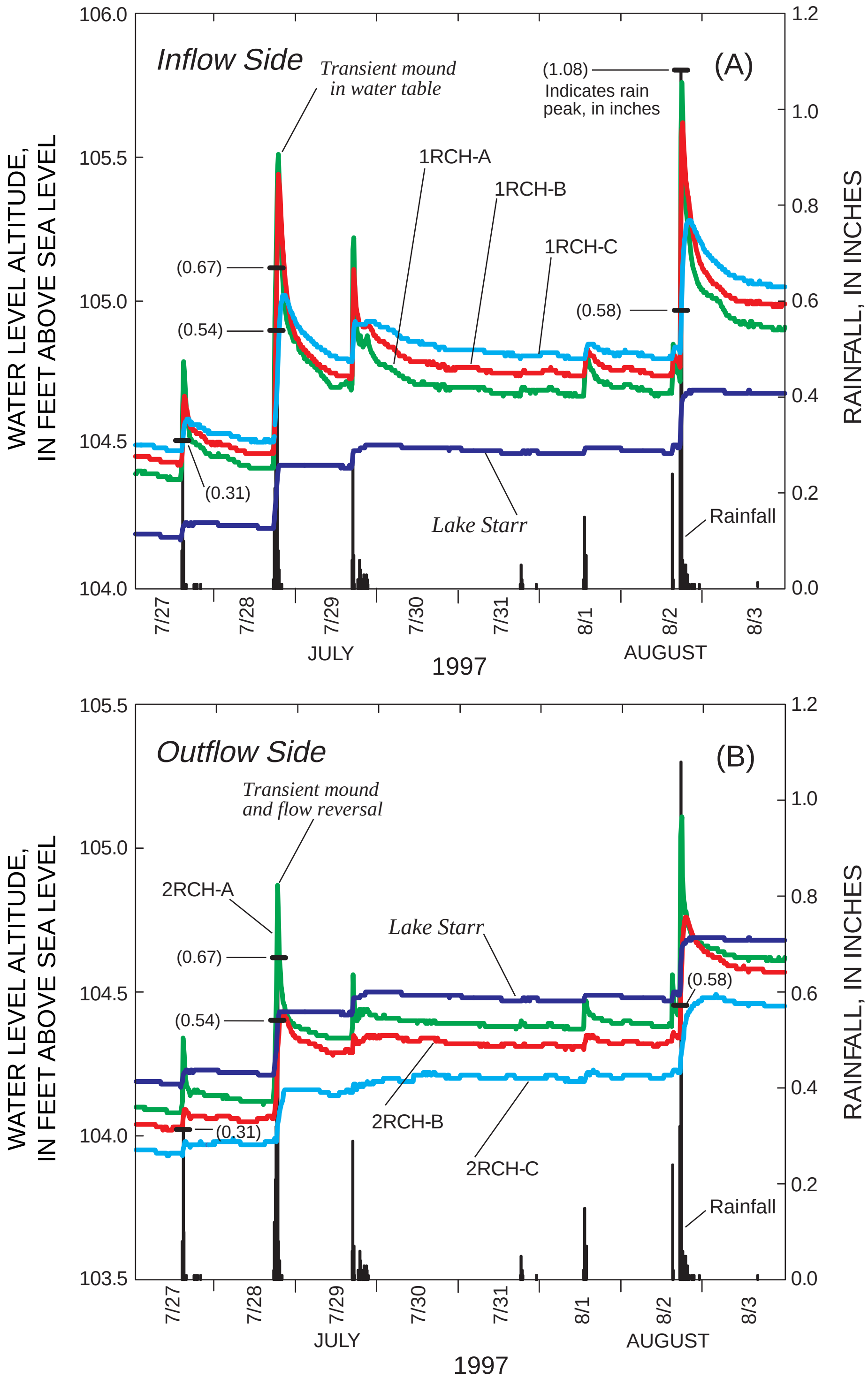


Figure 15. Ground-water levels and rainfall totals at the (A) inflow and (B) outflow side of Lake Starr for July 27 to August 3, 1997. Measurements were made every 15 minutes and tick marks are shown at 0000 hours.

8 on figure 14). For this reason, it was not possible to construct a single map of the water-table that captured peak or low water levels in both the upper and lower parts of the basin.

Nearshore Flow Patterns

Recharge was rapid and efficient in the nearshore region and caused the water table to mound, which temporarily changed the pattern of ground-water flow near the lake. For example, prior to rainfall, inflow head gradients were always observed at site 1RCH on the northern or inflow side of the lake (figs. 15-17). Recharge created steep, transient water-table mounds that enhanced ground-water inflow rates by increasing the inflow head gradient near the lake. Rainfall events on July 28 and August 2, 1997, each caused a water-table mound centered near the 1RCH-A well, or about 40 ft onshore (figs. 12a and 15a). In response to each event, the water table at 1RCH-A rose from about 0.2 ft above the lake before the rainfall to about 1.1 ft above the lake after rainfall (fig. 15a). The water table at 1RCH-B peaked slightly lower, and water levels were lower still at 1RCH-C, allowing for a brief period where ground water could flow from 1RCH-A toward 1RCH-B and C. However, as the mound redistributed and recharge arrived at the water table further onshore, the RCH water levels recovered to an inflow head gradient that was higher than before the rainfall.

On the southern or outflow side of the lake, water levels in the 2RCH wells typically showed an outflow head gradient consistent with basin-wide water levels (figs. 15-17). However,

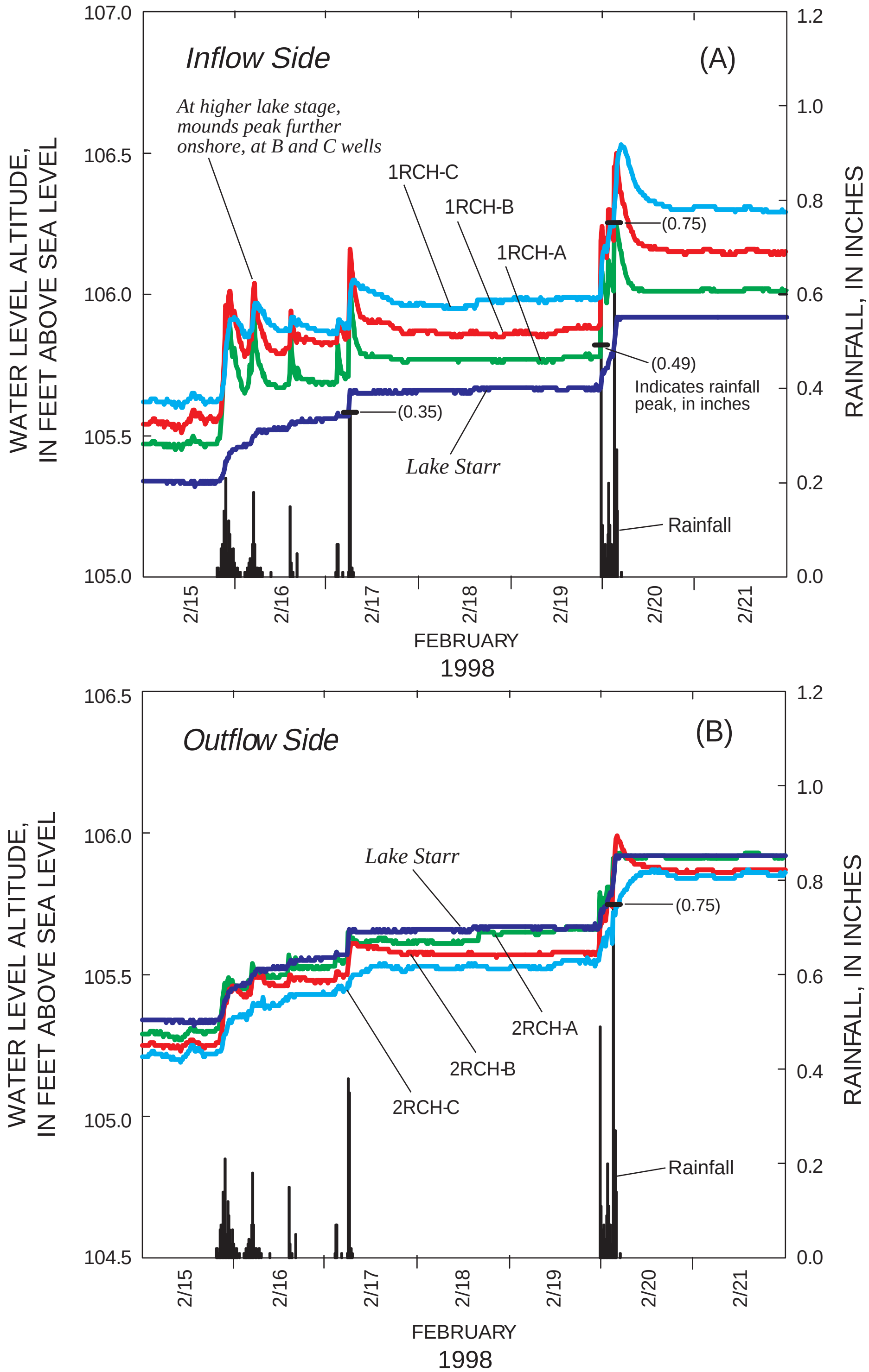


Figure 16. Ground-water levels and rainfall totals at the (A) inflow and (B) outflow side of Lake Starr for February 15 to February 21, 1998. Measurements were made every 15 minutes and tick marks are shown at 0000 hours.

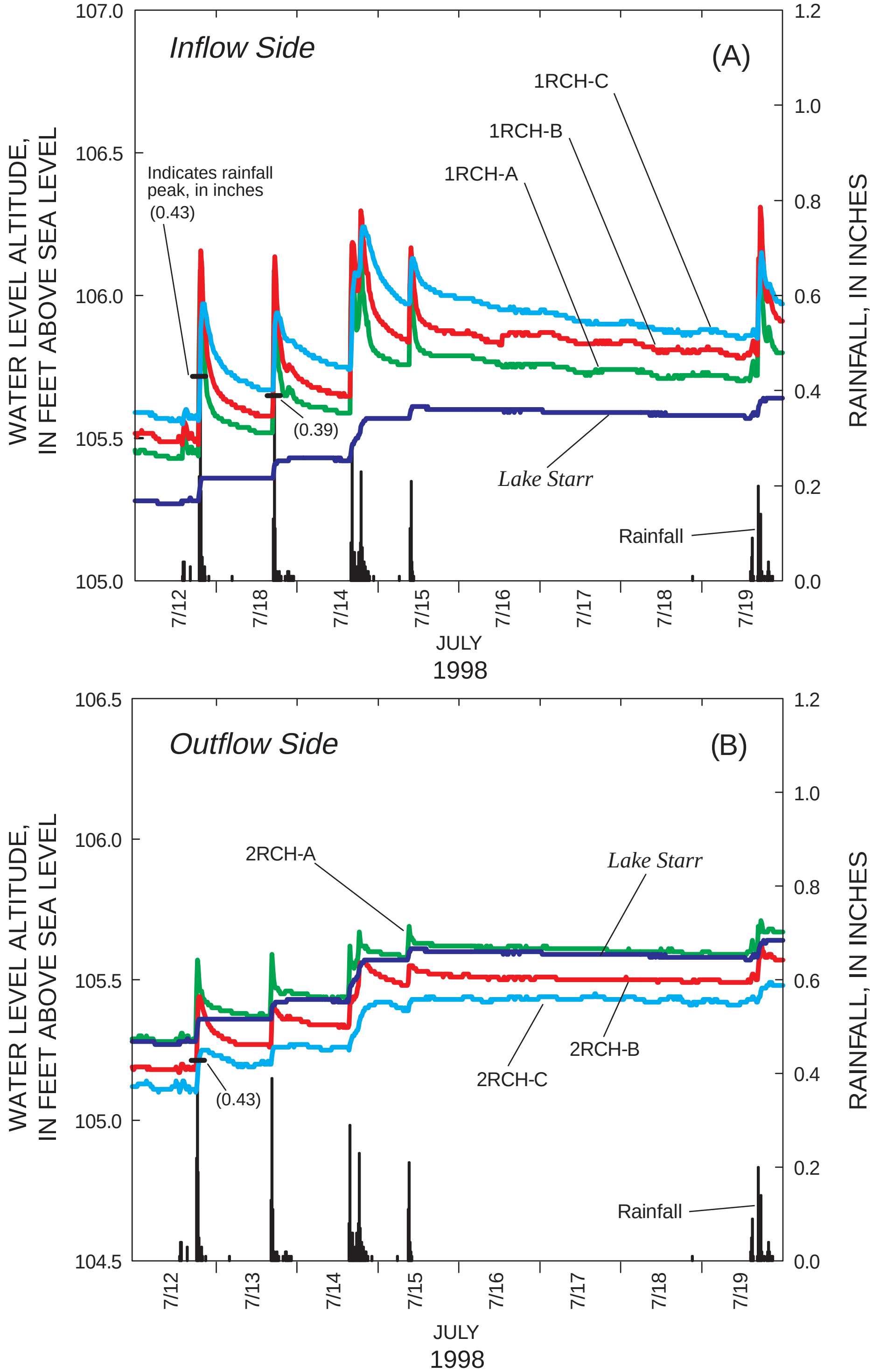


Figure 17. Ground-water levels and rainfall totals at the (A) inflow and (B) outflow side of Lake Starr for July 12 to July 19, 1998. Measurements were made every 15 minutes and tick marks are shown at 0000 hours. (Note: Water levels in 2RCH-A are equivalent to lake stage (within the measurement precision) for the period July 16 to July 19, 1998).

rainfall routinely raised the water table at 2RCH-A above the lake, and temporarily reversed the direction of ground-water flow from outflow to inflow. For example, five separate rainfall events during the week of July 27 to August 3, 1997, raised the water table at 2RCH-A, located about 20 ft onshore, higher than the lake. For the largest daily rainfall during this week (2.42 inches on August 2), the water table rose from about 0.1 ft below to more than 0.5 ft above the lake level (fig. 15b). The water table at the 2RCH-B well, about 50 ft from the lake, also rose from about 0.15 ft below to 0.08 ft above the lake level. However, the thicker unsaturated zone at 2RCH-B and C slowed recharge to the water table, and water levels at these sites always remained downgradient of the peak at 2RCH-A (fig. 12). Smaller rainfall events produced smaller, briefer episodes of mounding at 2RCH-A, but still reversed ground-water flow direction from outflow to inflow (see the 0.42-inch event on July 27). For the smallest event, a 0.29-inch rainfall on August 1, the water level at 2RCH-A peaked below the lake level so that no flow reversal occurred.

Flow reversals at 2RCH did not last long, generally from 2 to 6 hours, but suggest the potential for ground-water inflow to be contributed from what is normally the outflow side of the lake. In addition to briefly generating ground-water inflow, transient water-table mounding on the outflow side of the lake also temporarily reduced the lateral outflow head gradients controlling leakage. Mounding on the inflow side lasted longer, but inflow head gradients were generally restored to pre-storm conditions within 24 hours (figs. 15-17). The water-table response was consistently greater on the inflow side compared to the outflow side, probably due to differences in saturated hydraulic conductivity and the physical properties of the soil at the two sites. The relatively rapid dissipation of water-table mounds at both sites was indicative of high conductivity (for example, greater than 10 ft/d) in the surficial aquifer (Lee, in press).

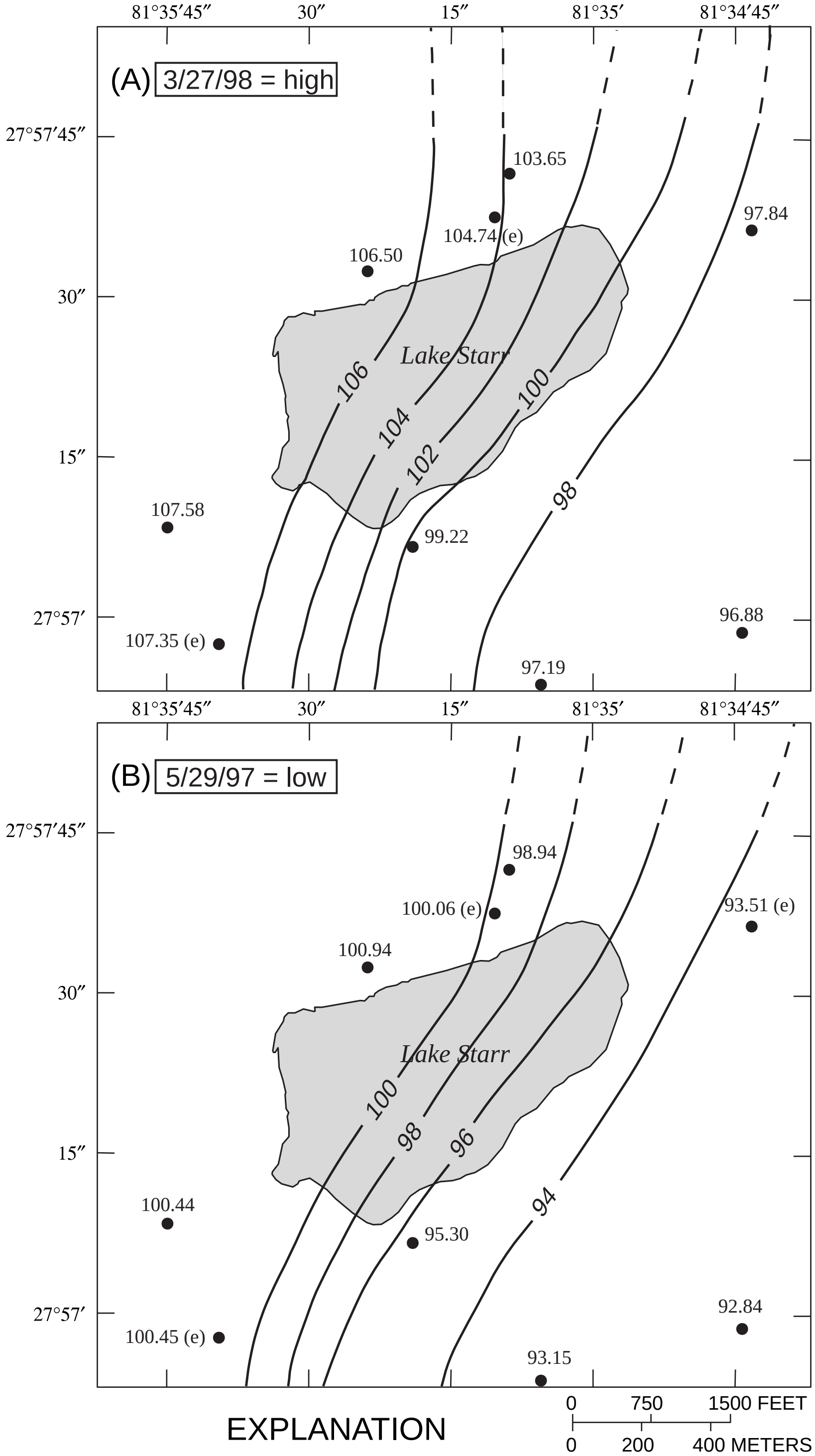
The level of the lake, the profile of the unsaturated zone beneath the adjacent hillside, and the magnitude of the rainfall event all determine the location of the center of the transient mounds. For example, the wetter conditions and higher lake levels experienced during the winter of 1998 caused transient mounds to be positioned farther inland compared with the summer of 1997. For example, for a 2.02-inch rainfall on February 20, 1998, water levels on the inflow side peaked at 1RCH-C instead of 1RCH-A. On the outflow side, peak water levels occurred at 2RCH-B instead of 2RCH-A (figs. 12b and 16). For large storms during the summer of 1998, lower lake levels caused the mounds to shift slightly lakeward at both sites. For July 12-19, 1998, mounds were centered nearer the 1RCH-B well on the inflow side, and moved back to 2RCH-A on the outflow side (fig. 17).

Evaporation and transpiration losses occur from the ground water near Lake Starr, but continuous water-level measurements in the nearshore wells provided little evidence of their effect. Evapotranspiration effects were probably responsible for a small but consistent diurnal fluctuation of ±0.02 ft in the water levels in well 1RCH-C during several dry weeks at the beginning of June 1998. The timing of the water-level oscillation was consistent with evapotranspiration effects, with the highest water levels occurring between midnight and 6 a.m. and the lowest between noon and midnight. However, the amplitude of water-level change was small and close to the precision of the pressure transducer (±0.01 ft). During this period, the water table was about 5 ft beneath land surface at 1RCH-C. No fluctuation in water levels was seen at either 1RCH-A or B. Water levels in the three 2RCH wells showed no evidence of diurnal fluctuations. This could imply that water lost to evapotranspiration was readily replaced by lateral ground-water flow.

Upper Floridan Aquifer Flow Patterns

Heads in the Upper Floridan aquifer decreased from west to southeast across the lake basin similar to the pattern in the water table. The lowest heads occurred in the southeast part of the basin (fig. 18). Stewart's (1966) potentiometric surface map of the Upper Floridan aquifer in Polk County also showed a localized area of low heads southeast of Lake Starr for the period October 1959 to February 1960. These local lows are not reflected in the regional potentiometric surface map (Metz and others, 1997), but this is probably due to a lack of spatial resolution.

Heads in the Upper Floridan aquifer rise and fall more steeply than heads in the surficial aquifer system, and are strongly affected by local and regional irrigation pumping for citrus cultivation (Yobbi, 1983; Lee and others, 1991; Sacks and others, 1998) (fig. 19). During the study, the highest heads occurred in March 1998 following an unusually wet winter, and lowest heads occurred in the spring and early summer months (April-June) of 1997 and 1998. On the west and northwest sides of the lake basin, heads in the Upper Floridan aquifer from December 1997 through March 1998 were higher than the lake, and approached the head in the surficial aquifer system near the lake. As a result, there was very little potential for downward flow between the surficial aquifer system and Upper Floridan aquifer along the western and northern lake margin during these months. On the other sides of the lake, the lake level was always higher than the head in the Upper Floridan aquifer.



EXPLANATION

—100— — POTENTIOMETRIC CONTOUR-- Showing altitude at which water would have stood in tightly cased wells, in feet above sea level. Contour interval 2 feet. Dashed where approximate

100.45 ● ALTITUDE OF WATER LEVEL IN THE UPPER FLORIDAN AQUIFER-- In feet above sea level, (e) estimated value

Figure 18. Potentiometric surface of the Upper Floridan aquifer in the Lake Starr basin for representative (A) high head conditions (March 27, 1998) and (B) low head conditions (May 29, 1997).

Heads in the Upper Floridan aquifer in different parts of the lake basin responded differently to ground-water pumping. Levels at the 1PNS-125 well and other Upper Floridan aquifer wells on the northwest side of the lake showed steep rises and drops in response to pumping, whereas the Hart FLRD well and other wells on the southeast side showed a more moderate response (fig. 19). The difference in response is probably due to differences in the degree of confinement of the Upper Floridan aquifer between the northwest and southeast sides of the basin. Many sinkholes on the southeast side of the lake, and particularly near the Hart FLRD well, indicate breaches in the intermediate confining unit that should enhance recharge from the surficial aquifer system to the Upper Floridan aquifer.

Vertical Flow Patterns

Vertical flow patterns were determined by comparisons of water levels in wells open to different depths. In figure 20, a section through the two piezometer nests shows how lines of equal water level were drawn across the basin. Some of the equipotential lines in figure 20 were inferred from preliminary results of the steady-state ground-water flow model of the lake. At the 1PNS well nest on the north side of the lake, the downward head difference within the surficial aquifer system was small, typically less than 0.1 ft, and indicated a dominantly lateral flow direction on this side of the lake. Very small upward head differences were sometimes measured between surficial aquifer system wells in the 1PNS well nest (fig 20 and 21). Heads were considerably lower in the underlying Upper Floridan aquifer (well 1PNS-125), particularly when they were affected by ground-water pumping. As a result, a large head drop was evident across the intermediate confining unit most of the time. The head difference across the confining unit ranged from –7.92 to +0.10 ft (positive taken as upward). Small upward head differences were measured in January and February 1998, a rainy period when little ground-water pumping for irrigation occurred.

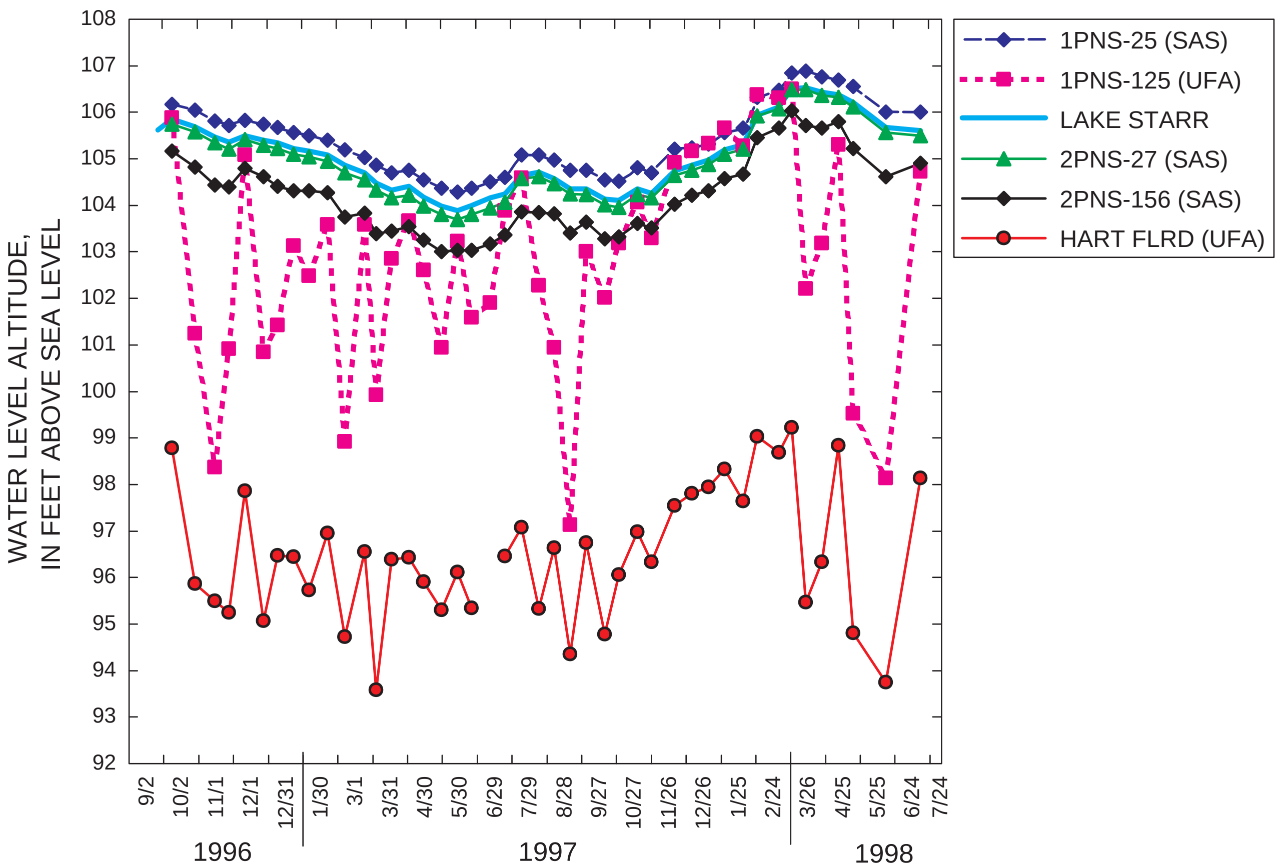
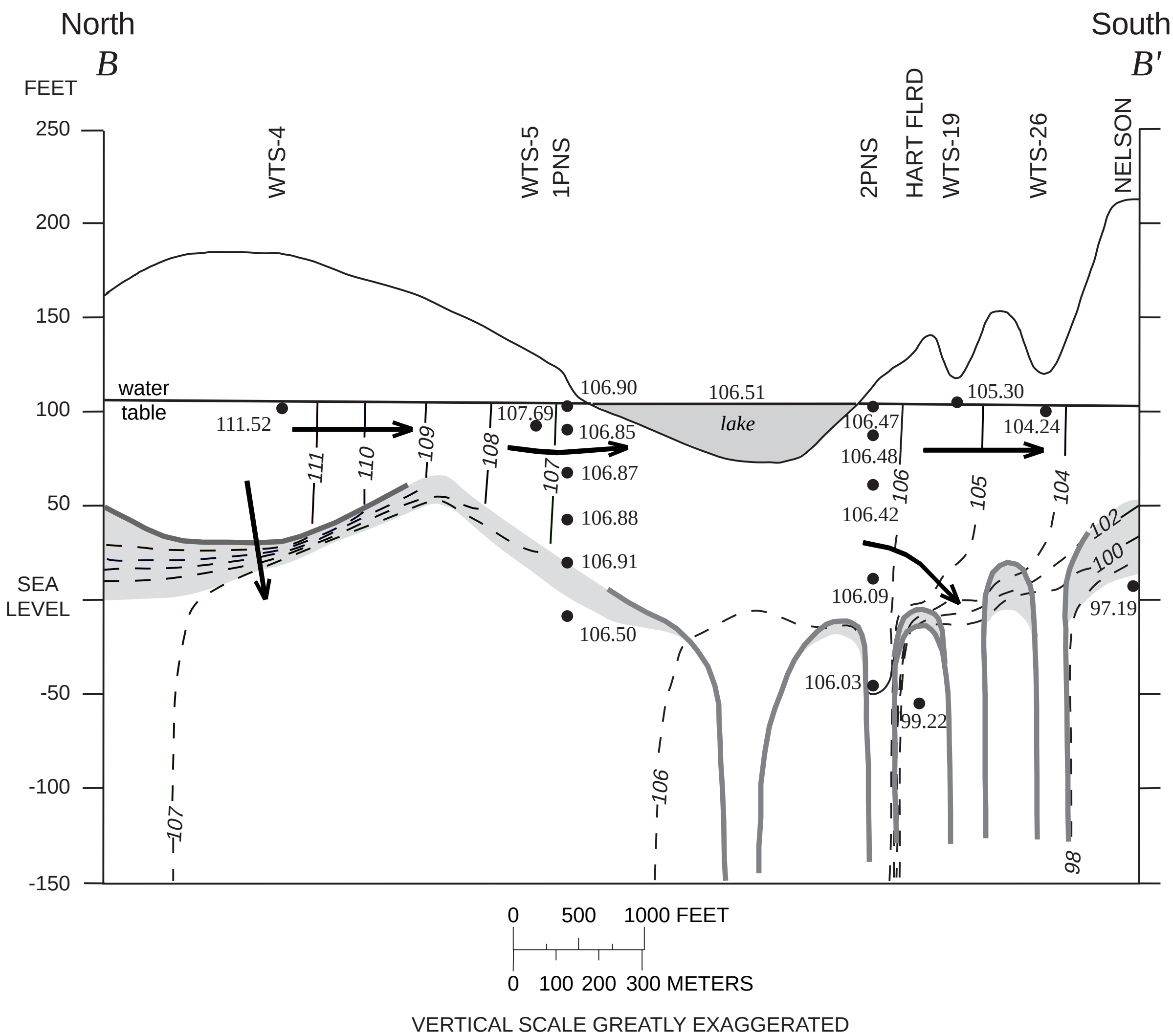


Figure 19. Hydrographs of selected piezometer nest wells and Upper Floridan aquifer wells near Lake Starr and Lake Starr stage.



EXPLANATION

Intermediate confining unit

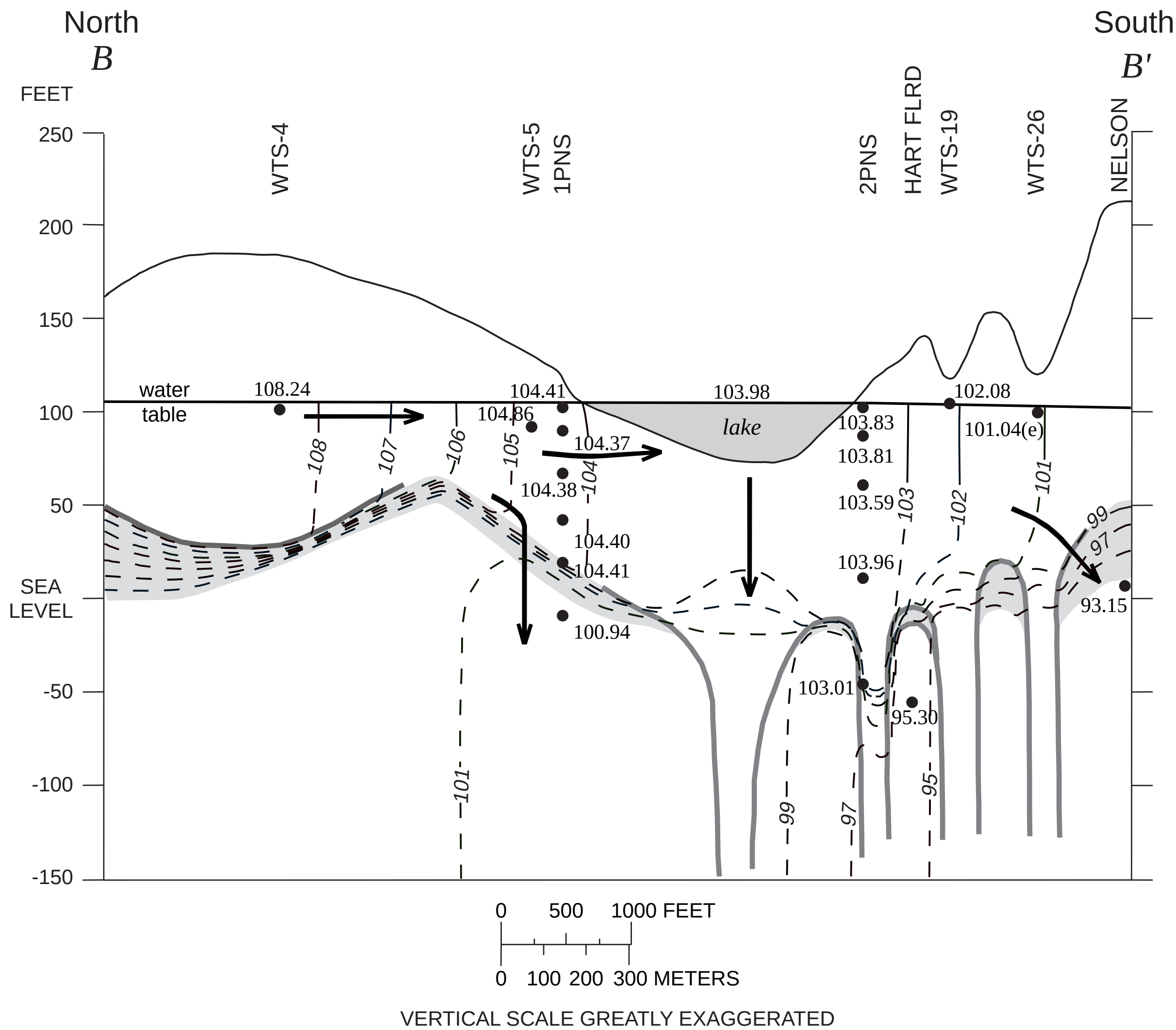
Inferred geologic contact

100 LINE OF EQUAL WATER LEVEL-- In feet above sea level. Contour interval 1 and 2 feet. Dashed where approximate

• 106.50 HYDRAULIC HEAD VALUE-- In feet above sea level

Ground-water flow direction

Figure 20a. Vertical head distribution along section *B-B′* for representative high water-level conditions (March 27, 1998). (Section location shown in figure 6).



EXPLANATION

Intermediate confining unit

Inferred geologic contact

—*100* — — LINE OF EQUAL WATER LEVEL-- In feet above sea level. Contour interval 1 and 2 feet. Dashed where approximate

•101.90 HYDRAULIC HEAD VALUE-- In feet above sea level

Ground-water flow direction

Figure 20b. Vertical head distribution along section *B-B′* for representative low water-level conditions (May 29, 1997). (Section location shown in figure 6).

The 2PNS nest was constructed in a karst subsidence feature, and hydrogeologic units that occur elsewhere in the basin were absent at the expected depth range. The two deepest wells (2PNS-101 and 2PNS-156) were expected to be in the intermediate confining unit and Upper Floridan aquifer, respectively. Instead, these wells were screened in sandy surficial sediments, which together with clays of the intermediate confining unit, probably migrated downward to fill a solution void in the deeper limestone. Because the subsidence feature breaches the intermediate confining unit, the deeper wells in the nest are part of the surficial aquifer system.

Downward head differences in the surficial aquifer system were larger at the 2PNS site than at 1PNS. Downward head differences in the 2PNS nest ranged from -0.42 to -0.95 ft. The downward head difference between 2PNS-51 and 2PNS-156 in the lower surficial aquifer system at the 2PNS site was related to head at the Hart FLRD well ($r^2 = 0.74$). In contrast, at 1PNS, the downward head difference between the deepest surficial aquifer system wells, 1PNS-50 and 1PNS-75, had no relation to head in the Upper Floridan aquifer at 1PNS-125 ($r^2 = 0.03$). The better relation between downward head difference in the surficial aquifer system and head in the Upper Floridan aquifer near 2PNS suggests a greater hydraulic connection between the surficial aquifer system and the Upper Floridan aquifer at 2PNS compared with 1PNS. Similar evidence was reported at Lake Lucerne, also in Polk County (fig. 1), where the head difference between a mid-lake well and the lake showed a good linear relation to head in an Upper Floridan aquifer well (Lee and others, 1991).

Areas of inflow and outflow to Lake Starr can be inferred from the vertical and horizontal head distributions. Inflow occurs across the part of the lake bottom that intersects horizontal flow paths in the surficial aquifer system on the northwest side of the lake. Some upward flow to the lake also may occur when heads in the Upper Floridan aquifer and surficial aquifer system on this side of the basin are higher than the lake. On the southeast side of the lake and beneath the rest of the lake, outflow probably occurs across most of the lake bottom where it is not impeded by lake sediments. Minimal exchange between the surficial aquifer system and the lake on the east side of the lake is expected to occur because ground-water flow lines on this side of the lake are parallel to the lake shore.

WATER BUDGET

Lake water budgets are important tools for understanding lake/ground-water interactions. While water-level data give information on ground-water flow direction, flow volumes are more difficult to quantify. The seepage lake water budget is commonly used to estimate net ground-water flow. When net ground-water flow is calculated as a residual to the water budget, the accuracy of the water budget and the relative magnitudes of water-budget components determine the validity of the estimate.

Methods

The sum of inflows to and outflows from a lake must equal the change in volume. For a seepage lake that has no surface-water flow, the water-budget equation is:

$$\text{delta S} \pm e_{\text{delta S}} = P - E + G_i - G_o - Q \pm e_P \pm e_E \pm e_{Gi} \pm e_{Go} \pm e_{Q}, \qquad (1)$$

where delta S is change in volume, P is precipitation, E is evaporation, G_i is ground-water inflow, G_o is ground-water outflow, and Q is direct pumping from the lake; other terms are errors associated with each component. Seepage lakes are defined by having no surface-water flow. Ground-water outflow also is referred to as "lake leakage" in this report, to reflect that it is lake water that is moving into the ground-water system. Change in volume and precipitation can be measured directly, while evaporation and ground-water fluxes require more complex methods to calculate. P and E are typically the largest water gain and loss, respectively, from seepage lakes in Florida. However, ground-water fluxes have been found to exceed P and E in the water budget of some lakes (Grubbs, 1995; Sacks and others, 1998).

Net ground-water flow (ground-water inflow minus outflow) can be calculated as a residual to the water budget using the equation:

$$\text{Net GW} = G_i - G_o = \text{delta S} - P + E + Q. \qquad (2)$$

Although inflow and outflow cannot be separated when net ground-water flow is calculated as a residual, the water budget provides a limit to the sum of inflow and outflow. Net ground-water flow calculated as a residual, however, incorporates all of the water-budget errors. The overall error is the square root of the sum of the individual errors squared (Winter, 1981):

$$e_{net\ GW} = [(e_{delta\ S})^2 + (e_P)^2 + (e_E)^2 + (e_Q)^2]^{1/2}. \quad (3)$$

Errors in monthly water-budget terms are assumed as follows: precipitation, 5 percent; evaporation, 15 percent; change in stage, 5 percent; direct pumping from the lake, 100 percent. With the exception of the lake pumping term, the uncertainty in water-budget components was taken from previous studies (Winter, 1981; Lee and Swancar, 1997; Sacks and others, 1998). Uncertainty, or error, is generally higher when components are measured over shorter periods because errors are more significant as a percentage of the measured quantity. For example, an error of 0.01 ft in the measurement of lake stage may be 30 percent of the daily change in stage, but only 2 percent of the monthly change. The following errors were used in weekly water budgets: change in stage, 10 percent; precipitation, 5 percent; evaporation, 15 percent; and lake pumping, 100 percent. For the annual water budget, the evaporation error is reduced to 10 percent and all others are the same as monthly errors. Energy-budget evaporation is sensitive to errors in some energy-budget components, particularly radiation fluxes (Sacks and others, 1994; Lee and Swancar, 1997). Missing data were a small source of error in evaporation at Lake Starr. For the relatively small amount of missing data that had to be substituted to calculate evaporation, methods used were similar to Lee and Swancar (1997).

Water-budget components are expressed as both linear units (inches) over the lake surface, and as volumes (cubic feet) in the discussion. It is generally easier to conceive of some processes, such as rainfall and evaporation, in linear units. However, the use of linear units can add error to the analysis because a given linear unit is not the same volume of water at one lake level as it is at another. Because determining ground-water fluxes is one goal of the study, the final water budget is expressed in volumes, but discussions of both rainfall and evaporation are initially expressed in linear units. To convert linear units to volumes, we rely on a known stage to surface area relation based on data collected by Sacks and others (1998). Average surface areas are included in water-budget tables to simplify conversions.

The potential for stormwater runoff into Lake Starr adds a small additional uncertainty to the water budget, but runoff is inferred to be negligible. The paved area is small compared to the permeable area of the basin, probably not exceeding 10 percent of the basin. Where present, storm drain outfalls were generally greater than 50 ft from the lake shore, allowing stormwater to infiltrate into the intervening sandy soils. In addition, 15-minute changes in lake stage and rainfall compared closely even during high-intensity storms (greater than 0.40 inch of rain in 15 minutes), giving no evidence of any substantial contribution from stormwater.

Pumping directly from the lake for lawn and citrus irrigation is another source of uncertainty in the water budget. The estimated volume of water withdrawn directly from the lake represents a minor water loss from Lake Starr for most months. During dry periods, the loss becomes significant to the water budget when lake pumping continues for periods of a month or more.

Climate Stations

Three climate stations continuously measured parameters needed to quantify the water budget, and data were recorded hourly (fig. 5). Lake stage and rainfall also were recorded at 15-minute intervals during the second year of the study to correspond to readings from pressure transducers in nearshore wells. In addition to measuring lake stage and rainfall, the stage station located on the west shore of the lake contained instruments to measure reflected solar radiation and the sum of reflected and emitted longwave radiation. A land station located uphill from the stage station contained instruments to measure incoming solar and longwave radiation, wind speed, relative humidity, air temperature, pan evaporation, and rainfall. A floating raft station was located near the deepest part of the lake; it contained instruments to measure wind speed, relative humidity, air temperature, and water temperature at 1-ft depth intervals.

Methods and instrumentation used for this study were similar to those used at Lake Lucerne in Polk County (Lee and others, 1991) and at Lake Barco in Putnam County in north Florida (Sacks and others, 1992). Equipment used at Lake Starr to measure water-budget components was the same as that listed in Sacks and others (1992) with the following exceptions; relative humidity sensors at Lake Starr were Vaisala model HMP35; a Campbell Scientific, Inc. AM416 multiplexer was used for processing signals from the raft thermocouple strings; and reflected radiation terms were measured directly using Eppley radiometers. Measurements at all climate stations were processed by Campbell Scientific, Inc. CR10 dataloggers.

Precipitation

Precipitation was measured continuously and recorded hourly using a tipping-bucket rain gage at the stage climate station (fig. 5). An observer also recorded rainfall daily from a storage rain gage at the land climate station. Another observer recorded rainfall at weekly or lesser intervals from a storage rain gage at well WTS-3 (fig. 5). Because tipping-bucket rain gages underestimate actual rainfall, especially during intense storms (Sacks and others, 1992; Bidlake and Boetcher, 1996), tipping-bucket rain data were corrected upward for all events by using a linear relation between the tipping-bucket and storage rain gage readings as described in Sacks and others (1992). The two tipping-bucket gages used sequentially at Lake Starr underestimated storage gage rainfall by an average of about 9 percent.

Evaporation

The energy-budget method was used to measure evaporation at Lake Starr. This method was developed to quantify evaporation from western reservoirs in the 1950's (Anderson, 1954), and has been used by the USGS on a number of long-term lake studies (Sturrock and Rosenberry, 1992; Rosenberry and others, 1993). The energy-budget method is the most accurate method for measuring lake evaporation (Winter, 1981). Use of the energy-budget method requires a large amount of data collection, but the effort is important because accurate measurements of lake evaporation are rare. Evaporation data provided by this study can be extrapolated to other lakes in central Florida.

An energy budget is similar to a water budget in that the change in stored energy is equal to the fluxes in and out of the system. Energy drives the process of evaporation because the water at the surface of the lake must absorb a certain amount of energy (latent heat of vaporization; approximately 580 calories per gram) before the water will evaporate. After some derivation, the following equation is used to calculate evaporation from the lake system (Anderson, 1954):

$$EEB = \frac{(Qs - Qr + Qa - Qar - Qbs + Qv - Qx)}{[L(1 + BR) + T_0]}, \qquad (4)$$

where EEB is energy-budget evaporation, Qs is incoming solar (short-wave) radiation, Qr is reflected solar radiation, Qa is incoming atmospheric longwave radiation, Qar is reflected longwave radiation, Qbs is emitted (back-scattered) longwave radiation, Qv is net energy advected to the body of water, Qx is change in stored heat, L is latent heat of vaporization, BR is the Bowen ratio, and T_0 is water-surface temperature (^oC). Units for energy terms are calories per square centimeter per day ($cal/cm^2/d$). Qs, Qr, Qa, and the sum of Qar and Qbs are measured quantities. The remaining components are calculated from other climatic data. Qv is calculated by multiplying the daily rainfall in centimeters by the air temperature in ^oC. Latent heat is calculated from the water-surface temperature using the equation:

$$L = (T_0 - 1083.6364)/(-1.8182). \qquad (5)$$

The Bowen ratio (ratio of sensible heat (Qh) to energy used for evaporation (Qe)) is calculated from the following equation (Bowen, 1926):

$$BR = Qh/Qe = 0.00061P(T_0 - T_a)/(e_0 - e_a), \qquad (6)$$

where P is barometric pressure (millibars), T_a is air temperature (^oC), e_0 is saturation vapor pressure at the water-surface temperature (millibars), and e_a is ambient vapor pressure at air temperature (millibars). Relative humidity (RH) is converted to vapor pressure using the following relations (Rosenberg and others, 1983):

$$RH = (e_a/e_s) \times 100, \text{ and} \qquad (7)$$

$$e_s = 6.1078 \exp((17.269\, T_a)/(T_a + 237.3)), \qquad (8)$$

where e_s is saturation vapor pressure at air temperature (millibars).

Temperature and vapor pressure gradients over the lake are incorporated into the Bowen ratio in the energy-budget equation. The energy-budget method is sensitive to the values of both the temperature and vapor pressure gradients when evaporation is very low because the Bowen ratio equation can be unstable under these conditions (Lee and Swancar, 1997). Wind speed data also were collected at Lake Starr to compare alternative methods for calculating evaporation with the energy budget.

Weekly thermal surveys of the lake were made to calculate the change in stored heat (Qx) and to compare readings at multiple points with readings at the raft. These surveys consisted of temperature profiles taken at 1-ft intervals at seven regular points around the lake. Data were averaged by layer and compared with the continuous raft temperature profiles. Because layer temperatures measured at the raft were equivalent to the average layer temperature measured during thermal surveys, total stored heat in Lake Starr was calculated from the raft water temperature sensors. Therefore, the lake temperature is laterally well mixed.

Stored heat was calculated by multiplying the 1-ft-layer temperature by layer volume and summing all the layers. Then the total was normalized to the lake area. Because the volume changes as the lake stage changes, all calculations were referenced to the stage/volume/area relations for the lake.

Energy-budget evaporation is calculated over a period defined by the change in stored heat in the same way that a water budget is defined by the change in stage over a period of time. The method can be used for time intervals less than a week with the understanding that errors in the stored heat term are magnified and may result in a much larger error in evaporation. Energy-budget evaporation was calculated on a daily, weekly, and monthly basis. “Weekly” periods were sometimes different from 7 days in length to account for missing stored heat data.

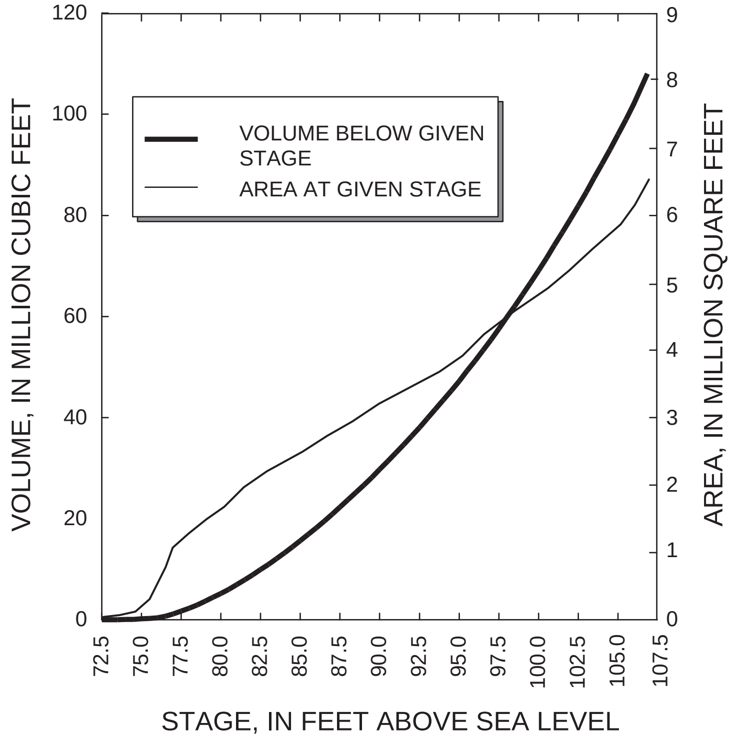


Figure 21. Stage-volume-area relations for Lake Starr.

Pan evaporation is a direct method for measuring evaporation that can be compared to the more accurate energy-budget method. Pans are expected to overestimate lake evaporation because the standard class-A pan is a shallow metal cylinder that gets much hotter than a lake. Pan evaporation is adjusted for these effects by multiplying pan data by a pan coefficient that is less than 1 on an annual basis (Kohler and others, 1955; Doorenbos and Pruitt, 1977; Farnsworth and others, 1982). A local observer measured pan evaporation daily at Lake Starr for 22 months during the 2-year study. The pan was located at the land climate station (fig. 5), an area of sparse grass cover about 50 ft from the lake.

Change in Volume

The volume of Lake Starr was calculated from a bathymetric survey of the lake conducted by the USGS in 1995 (Sacks and others, 1998). Stage-volume and stage-area relations were generated from bathymetric data (fig. 21). Stage was recorded hourly to the nearest 0.01 ft in a stilling well using a float connected to a potentiometer at the stage climate station (fig. 5). An observer also recorded stage daily to the nearest 0.02 ft from a staff gage near the stilling well.

Lake Pumping

Pumping from Lake Starr to irrigate landscaped areas and residential citrus groves was a small but significant component of the water budget at Lake Starr. A liberal estimate of the acreage irrigated with lake water was made by doubling the total area of properties where lake pumping was either known to occur or where pumps were observed, allowing for a margin of error that would account for unknown users. Irrigation of 1 inch of water over this 18-acre area is equivalent to 0.13 inches (0.01 ft) of stage over the 134-acre lake. In central Florida when the grass shows signs of stress from lack of water, the recommended amount of irrigation for lawns is 0.75 to 1 inch of water (Cisar and others, 1995). Direct pumping from the lake was estimated by assuming that 0.14 inches of water was applied as irrigation over this area each day (1 inch per week) if less than 0.25 inch of rain fell during the previous seven days. This amount is equivalent to 0.01 ft in lake stage over a week with no rain.

This amount (0.01 ft) also is within the error of the stage measurement, and over short periods (days or weeks), direct pumping from the lake is probably an unimportant water-budget term. There is no evidence of direct pumping effects in the lake stage record, and considering the estimated volumes, one would not be expected. The cumulative effects of direct withdrawals of water from the lake are significant over longer periods, however, especially during droughts. For example, if this amount were withdrawn from the lake 20 times a year for 5 years, it would represent a 1-foot drop in the lake level.

Water Budget Results

Precipitation

Annual rainfall at Lake Starr during the study was close to the 71-year average at Mountain Lake, and monthly rainfall was much higher than long-term averages during the winter of 1997-1998 (fig. 22). Total rainfall for the 24-month study period (August 1996-July 1998) was 104.72 inches. This amount was 0.74 inches higher than the 71-year average and 8.30 inches higher than the 30-year average at Mountain Lake NWS station (NOAA, 1997, 1998). Annual rainfall totals were 50.68 and 54.04 inches for August 1996 through July 1997 and for August 1997 through July 1998, respectively.

Short, intense storms account for much of the rainfall in central Florida; at Lake Starr, 60 percent of the rain fell on 48 days (7 percent of 730 days) with rainfall totals of 0.50 inch or greater. During the study, the largest daily total rainfall was 3.99 inches on March 19, 1998, and the largest individual storm produced 2.66 inches of rain in 4.5 hours on February 19 and 20, 1998.

Evaporation

Weekly energy-budget evaporation ranged from zero to 0.25 inches per day, with the highest evaporation in the summer (June-August) and the lowest in the winter (December-February)(fig. 23). Calculated negative evaporation is an artifact of measurement errors that affect the calculation when evaporation is low (Lee and Swancar, 1997); for water budgets, negative weekly evaporation rates were set to zero. Monthly evaporation followed a pattern similar to, but smoother than, weekly evaporation (fig. 23). Weekly and monthly energy-budget results are listed in the appendix, which also includes graphs of many components of the energy-budget equation.

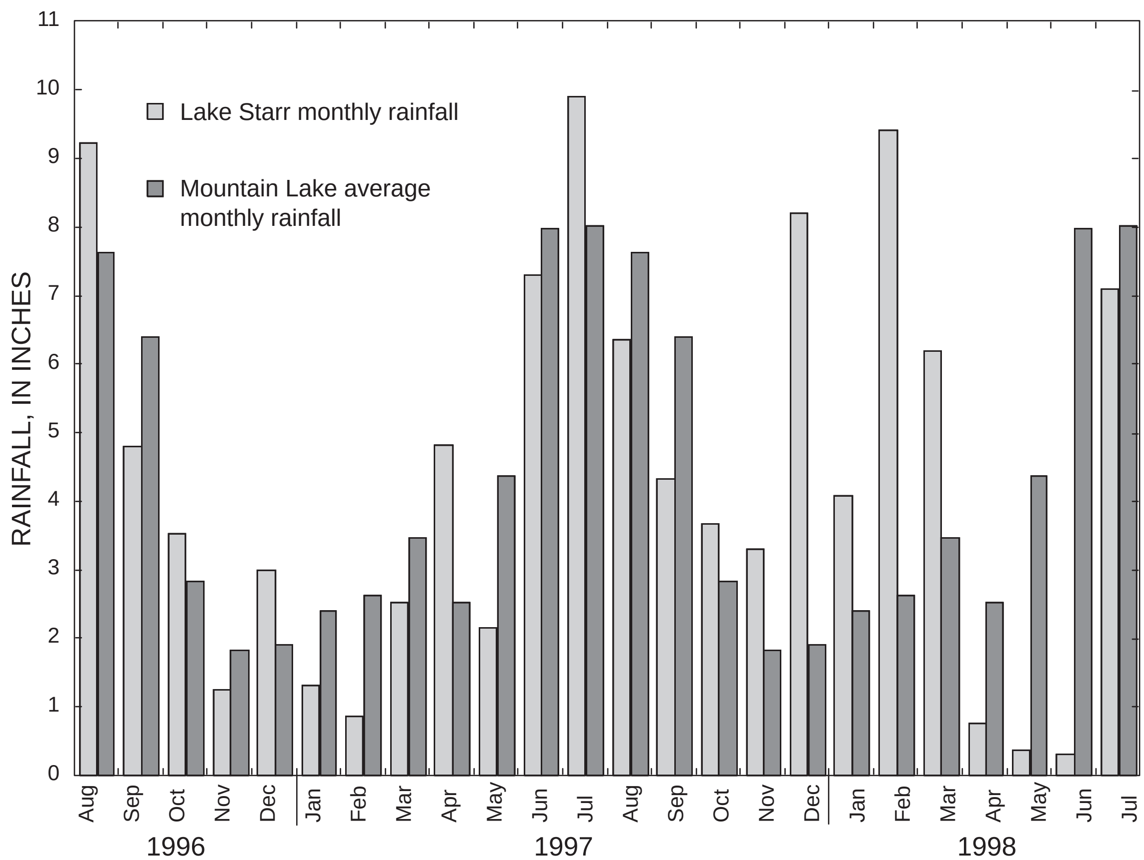


Figure 22. Monthly rainfall at Lake Starr and long-term average monthly rainfall at Mountain Lake (NOAA, 1999).

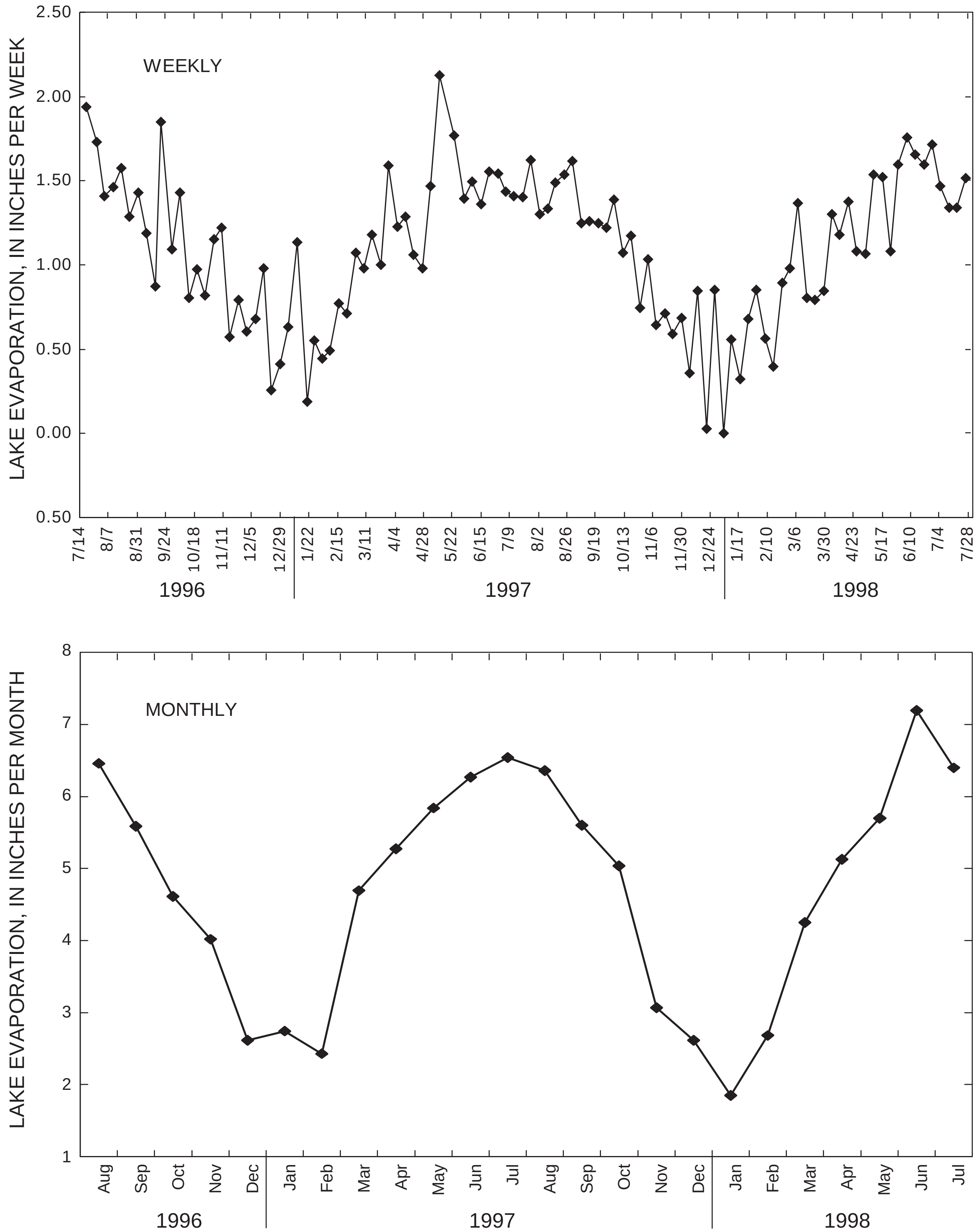


Figure 23. Weekly and monthly energy-budget evaporation at Lake Starr.

In the past, reflected radiation terms (Qr and Qar) in the energy-budget equation have been estimated as a percentage of the incoming radiation (Anderson, 1954; Ficke, 1972; Sacks and others, 1992). These terms were measured directly at Lake Starr. Reflected solar radiation at Lake Starr was approximately 4.6 percent of incoming solar radiation, but the relation between the variables was not good (r^2 = 0.44, standard error = 4.38 cal/cm^2/d). A better relation existed between these variables at Lake Lucerne (approximately 15 miles northwest of Lake Starr) with reflected solar radiation equal to 4 percent of incoming solar radiation (r^2 = 0.81, standard error = 2.63 cal/cm^2/d)(Lee and Swancar, 1997). The better relation at Lake Lucerne may have been due to less wave action on this smaller lake (43 acres compared to 134 acres for Lake Starr). Reflected longwave radiation has been assumed to be equal to 3 percent of incoming longwave radiation (Anderson, 1954). At Lake Starr, the sum of reflected (Qar) and emitted (Qbs) longwave radiation was measured using a single sensor, and Qar was calculated by subtracting Qbs (calculated from the Stefan-Boltzmann law) from the total. This estimate of Qar was related to measured incoming longwave radiation by the equation Qar = 0.1072 Qa –55.789 (r^2 = 0.50, standard error = 9.08 cal/cm^2/d). Although negative values resulted 4 percent of the time using this equation, the linear relation including an intercept term provided a better fit to the data than using 3 percent of incoming longwave to calculate reflected longwave radiation.

Annual evaporation at Lake Starr compared well with other recent measurements of open-water evaporation in Florida, but was higher than a commonly used estimate based on evaporation pan data. Annual evaporation between two open-water sites should be comparable if the change in stored heat is negligible. Annual energy-budget evaporation at Lake Starr was 57.08 and 55.88 inches per year for August 1996 through July 1997 and for August 1997 through July 1998, respectively. Annual evaporation calculated using the energy budget was 57.87 inches at Lake Lucerne in Polk County for October 1985 through September 1986 (Lee and Swancar, 1997), 59.52 inches at Lake Barco in north-central Florida in 1990, and 50.24 inches at Lake Five-O in the Florida panhandle in 1990 (Sacks and others, 1994). Mean annual open-water evaporation measured using a Bowen-ratio method was 55.54 inches per year in south Florida in 1997 and 1998 (German, 1999). Long-term average annual free water surface evaporation based on NWS evaporation pan data for the period 1956-1970 was 48 inches in central Florida (Farnsworth and others, 1982). Free water surface is a term used when the change in stored heat is negligibly small. Energy-budget methods indicate that open-water evaporation is probably higher than 48 inches per year even during years with average or above average rainfall.

Monthly pan evaporation measured at Lake Starr ranged from 2.57 inches per month in December 1996 to 8.50 inches per month in June 1998 for the 22 months when pan evaporation data were collected (table 3). Table 3 also shows the monthly pan evaporation at the nearest NWS site at Lake Alfred and the energy-budget evaporation for comparison. The monthly pan coefficient, defined as the ratio of energy-budget evaporation to pan evaporation, ranged from 0.58 to 1.15 for the pan at Lake Starr and from 0.53 to 0.88 for the pan at Lake Alfred.

Pan coefficients are often used to estimate evaporation. In central Florida, an annual pan coefficient of 0.74 is suggested for converting annual pan evaporation to lake evaporation (Farnsworth and others, 1982). The 0.74 coefficient is calculated from data collected only at the pan, however, rather than from a comparison with energy-budget evaporation. Lee and Swancar (1997) found similar annual coefficients using pan measurements at Lake Lucerne and Lake Alfred compared to energy-budget evaporation measured at Lake Lucerne (0.75 and 0.69, respectively). Sacks and others (1994) calculated an annual coefficient of 0.88 for Lake Barco and 0.80 for Lake Five-O (both in north Florida) using pan data from the nearest NWS site and energy-budget evaporation. The annual pan coefficients for the Lake Starr pan and the Lake Alfred pan, computed by using energy-budget evaporation at Lake Starr, were 0.89 and 0.73, respectively.

Differences in pan evaporation caused by differences in exposure, instrumentation, and maintenance are probably important, and pan exposures should be considered if they are to be used to estimate lake evaporation. Ideally, individual pans should be calibrated against independent measurements of lake evaporation, such as the energy budget, to develop an understanding of the effect of exposure on the pan to lake coefficient. Differences in exposure can effect evaporation because of changes in microclimate caused by differences in wind speed, land-surface radiative characteristics, and relative humidity. The range of pan to lake coefficients may be as broad as pan to crop evapotranspiration coefficients in different microclimates presented in Doorenbos and Pruitt (1977), which range from 0.40 to 0.85. The pan at Lake Starr may have been affected by its location close to and on the dominant downwind side of the lake, and sheltered somewhat from the wind on the west side by the hillside and vegetation. The combined effect of higher relative humidity and wind off the lake associated with this exposure could have caused the higher pan coefficient.

Based on the data from this study and the Lake Lucerne study (Lee and Swancar, 1997), the annual pan coefficient to convert Lake Alfred pan evaporation to lake evaporation is between 0.69 and 0.73. This annual coefficient may be applicable for similar Polk County lakes. Monthly coefficients varied considerably from year to year during these two studies, especially during the winter. A total of 3 years of monthly data (except 2 years for December) from the two studies were used to calculate an average monthly pan coefficient (table 3). The error associated with using monthly pan evaporation to estimate lake evaporation can be calculated by comparing energy-budget evaporation to lake evaporation calculated from the Lake Alfred pan using a monthly average pan coefficient. Multiplying this average by monthly pan evaporation at Lake Alfred produced errors in this estimate of lake evaporation compared to energy-budget evaporation ranging from –8 to +12 percent, averaging less than 1 percent.

Table 3. Monthly pan evaporation and pan coefficients

[in/mo, inches per month; EEB, energy-budget evaporation; ***7.45,*** number in italics means some data estimated; ***, missing data; Lake Alfred data from NOAA (1996, 1997, 1998)]

Month/Year	Lake Starr pan evaporation (in/mo)	Lake Alfred pan evaporation (in/mo)	Energy-budget evaporation (in/mo)	EEB/Starr pan coefficient (unitless)	EEB/Alfred pan coefficient (unitless)
Aug-1996	***6.33***	***7.36***	6.46	1.02	0.88
Sep-1996	***4.89***	***7.48***	5.59	0.99	0.75
Oct-1996	***	***5.59***	4.61	***	0.83
Nov-1996	***	4.67	4.02	***	0.86
Dec-1996	***2.57***	3.61	2.61	0.92	0.72
Jan-1997	3.60	4.42	2.74	0.76	0.62
Feb-1997	4.17	***4.57***	2.43	0.58	0.53
Mar-1997	6.14	***6.87***	4.69	0.76	0.68
Apr-1997	***5.59***	7.55	5.28	0.85	0.70
May-1997	***5.02***	8.38	5.84	1.09	0.70
Jun-1997	***6.25***	9.49	6.27	0.87	0.66
Jul-1997	7.71	9.01	6.54	0.85	0.73
Aug-1997	***5.51***	***8.85***	6.36	1.15	0.72
Sep-1997	5.66	***6.82***	5.60	0.99	0.82
Oct-1997	4.84	6.75	5.04	1.04	0.75
Nov-1997	***3.05***	***4.01***	3.07	1.01	0.76
Dec-1997	2.78	***	2.62	0.94	***
Jan-1998	2.59	***3.51***	1.85	0.71	0.53
Feb-1998	***3.75***	5.30	2.68	0.72	0.51
Mar-1998	***5.33***	***6.00***	4.25	0.80	0.71
Apr-1998	6.14	7.70	5.13	0.84	0.67
May-1998	***7.16***	9.02	5.70	0.80	0.63
Jun-1998	8.50	11.07	7.20	0.85	0.65
Jul-1998	6.92	8.49	6.40	0.92	0.75

Month	Average monthly pan coefficient (unitless)*
Jan	0.57
Feb	0.52
Mar	0.67
Apr	0.71
May	0.67
Jun	0.68
Jul	0.74
Aug	0.77
Sep	0.80
Oct	0.77
Nov	0.79
Dec	0.68

*Average monthly pan coefficient based on relation of Lake Lucerne and Lake Starr energy-budget evaporation to Lake Alfred pan. Average of 3 months for all months except December, which is 2 months. Periods of comparison are October 1985 to September 1986 (Lee and Swancar, 1997) and August 1996 to July 1998.

Change in Volume

The change in stage of Lake Starr was consistent with regional trends during the study period. In particular, the 1997-1998 winter in central Florida was influenced by a strong El Niño-Southern Oscillation warm event that produced unusually heavy rains, flooding, and high water levels. During the study, the stage of Lake Starr ranged from 103.85 (June 4-6, 1997) to 106.56 (April 2-4, 1998) ft above sea level (fig. 24). Overall, stage fell 4.9 inches during the first year of the study (August 1996 through July 1997), and rose 12.7 inches during the second year (August 1997 through July 1998). Stage increased through the fall of 1996 until October, and then fell over the winter and spring of 1997. Stage rose during early summer 1997, and then fell from mid-August to October 1997. Effects of El Niño began in November 1997 and continued through March 1998, generating a total stage increase of 29.0 inches for this period. April, May, and June 1998 were very dry and stage fell rapidly during these months.

Lake Pumping

Direct pumping from the lake was estimated to range from zero inches per month in June and July of 1997 to 0.5 inches per month in April and June 1998. Annually, direct pumping was estimated to be 2.3 and 2.9 inches per year for the first and second years of the study, respectively.

Net Ground-Water Flow

Net ground-water flow was derived from the measured and estimated components of the water budget by applying equation 2 over different time periods. Weekly and monthly net ground-water flows are presented in tables 4 and 5. Table 5 also shows annual totals of each budget term for each year of the study and for the overall 2-year period. Monthly net ground-water flow, calculated as a residual to the water budget, ranged from –1,166,000 (March 1997) to 2,584,000 cubic ft per month (ft^3/mo)(March 1998), or –2.40 to 4.93 in/mo (fig. 25). Errors in the net ground-water flow term ranged from 206,000 ft^3/mo in January 1998 (0.42 in/mo) to 640,000 ft^3/mo (1.26 in/mo) in June 1998. Uncertainty in the calculated net ground-water flow can be greater than net ground-water flow (see June 1997). However, in most months, the magnitude of the calculated value was greater than the error, so that net ground-water flow calculated as a residual was a meaningful quantity.

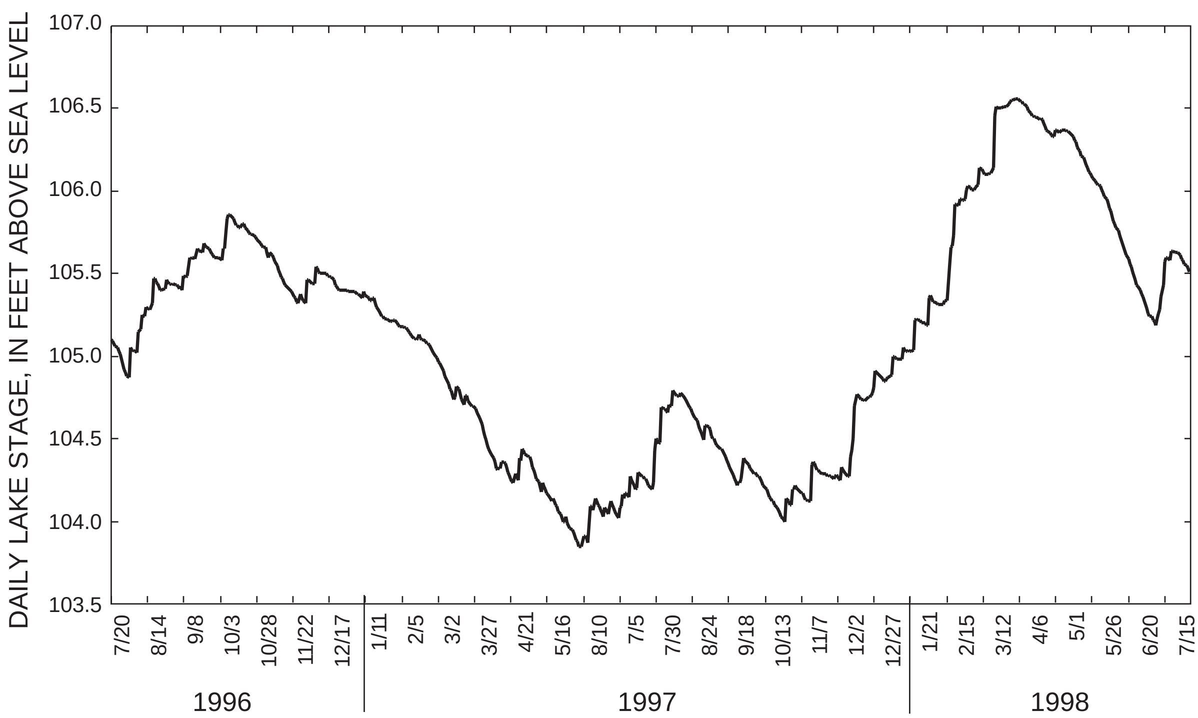


Figure 24. Daily stage of Lake Starr from July 20, 1996, to August 1, 1998.

Table 4. Weekly water budget for Lake Starr

[All units in thousands of cubic feet unless specified; some weekly periods are more or less than 7 days in length, net ground-water flow calculated as residual; negative evaporation set equal to zero; +/-, plus or minus]

Start date	Rain	Change in volume	Average surface area (feet^2 x 1,000)	Evaporation	Direct pumping	Net ground-water flow	Error in net ground-water flow (+/-)
7/20/96	11	-902	5,901	953	25	65	171
7/28/96	1,327	540	5,875	847	34	94	157
8/4/96	1,520	1,211	5,913	695	0	387	177
8/11/96	1,367	1,411	5,961	725	0	769	191
8/18/96	58	-370	6,004	787	9	368	124
8/25/96	324	185	6,004	643	9	512	100
9/1/96	765	309	6,000	715	9	268	118
9/8/96	914	683	6,035	596	0	365	121
9/15/96	374	250	6,059	440	0	315	73
9/20/96	351	-250	6,065	934	9	341	144
9/29/96	590	312	6,053	553	43	318	103
10/6/96	1,089	879	6,115	728	0	517	150
10/14/96	118	-63	6,110	411	44	274	76
10/20/96	0	-377	6,099	496	61	179	103
10/27/96	18	-376	6,079	416	61	83	95
11/3/96	210	-561	6,058	583	17	-172	106
11/10/96	0	-867	6,024	614	43	-210	134
11/17/96	0	-492	5,994	287	60	-145	89
11/24/96	398	-184	5,978	396	17	-169	67
12/1/96	1,477	1,356	6,003	303	0	182	161
12/8/96	0	-248	6,026	342	9	102	58
12/15/96	17	-494	6,015	491	60	40	107
12/22/96	0	-123	5,995	129	60	66	64
12/29/96	0	-123	5,992	205	60	142	68
1/5/97	329	-123	5,986	316	34	-102	62
1/12/97	156	-612	5,975	565	0	-202	105
1/21/97	34	-183	5,950	95	42	-80	48
1/26/97	138	-182	5,944	273	25	-21	52
2/2/97	34	-243	5,935	219	34	-24	53
2/9/97	148	-303	5,920	243	51	-157	70
2/16/97	240	-181	5,914	380	0	-41	61
2/23/97	6	-661	5,897	351	59	-257	103
3/2/97	0	-835	5,868	524	59	-253	129
3/9/97	749	-178	5,836	475	33	-418	89
3/16/97	383	-414	5,828	575	0	-223	98
3/23/97	90	-530	5,815	484	25	-111	93
3/30/97	0	-1,166	5,783	766	58	-343	174
4/6/97	296	-635	5,745	586	49	-296	120
4/13/97	454	-287	5,736	614	0	-127	99
4/20/97	1,157	576	5,720	505	16	-60	113
4/27/97	476	58	5,750	470	0	52	75
5/4/97	0	-1,034	5,731	702	49	-283	155
5/11/97	492	-853	5,699	1,008	33	-304	178
5/24/97	444	-564	5,669	835	8	-165	139
6/1/97	291	-617	5,648	657	0	-251	117
6/8/97	1,932	1,351	5,645	703	0	122	197
6/15/97	369	-113	5,687	645	0	162	99

Table 4. Weekly water budget for Lake Starr (Continued)

[All units in thousands of cubic feet unless specified; some weekly periods are more or less than 7 days in length, net ground-water flow calculated as residual; negative evaporation set equal to zero; +/-, plus or minus]

Start date	Rain	Change in volume	Average surface area (feet^2 x 1,000)	Evaporation	Direct pumping	Net ground-water flow	Error in net ground-water flow (+/-)
6/22/97	849	284	5,678	738	0	172	122
6/29/97	626	-170	5,681	730	0	-67	115
7/6/97	1,457	912	5,700	682	0	136	155
7/13/97	763	115	5,715	671	0	23	108
7/20/97	270	-458	5,717	667	0	-60	111
7/27/97	2,916	2,898	5,749	778	0	760	345
8/3/97	662	59	5,813	631	0	28	100
8/10/97	1,001	413	5,830	647	0	59	117
8/17/97	26	-649	5,822	722	17	65	127
8/24/97	77	-819	5,794	743	58	-96	150
8/31/97	689	-116	5,781	779	8	-18	123
9/7/97	159	-464	5,764	600	25	2	105
9/14/97	0	-807	5,742	602	57	-147	134
9/21/97	1,220	576	5,717	595	25	-25	125
9/28/97	5	-518	5,738	584	8	69	102
10/5/97	356	-401	5,722	663	0	-95	109
10/12/97	41	-570	5,701	509	33	-69	101
10/19/97	5	-623	5,680	556	57	-15	119
10/26/97	1,341	1,021	5,685	354	8	42	133
11/2/97	198	-228	5,705	492	0	66	78
11/9/97	1,312	1,145	5,706	307	33	173	144
11/16/97	0	-345	5,731	340	16	11	64
11/23/97	5	-115	5,723	282	57	220	72
11/30/97	474	115	5,724	327	33	1	65
12/7/97	2,238	2,384	5,738	169	0	315	265
12/14/97	456	177	5,826	412	0	133	68
12/21/97	807	1,068	5,830	15	42	319	122
12/28/97	31	-357	5,859	415	8	35	72
1/4/98	528	836	5,865	0	33	342	94
1/11/98	372	240	5,888	274	0	142	51
1/18/98	1,096	1,210	5,903	161	8	283	135
1/25/98	16	-243	5,943	337	17	95	59
2/1/98	1,045	793	5,967	424	8	181	115
2/8/98	189	123	5,971	280	34	248	56
2/15/98	2,998	3,621	6,059	200	0	822	393
2/22/98	510	574	6,158	458	0	521	93
3/1/98	66	128	6,185	507	9	577	78
3/8/98	746	449	6,212	709	9	420	122
3/15/98	2,424	2,604	6,258	422	27	629	295
3/22/98	0	132	6,366	422	18	572	67
3/29/98	23	264	6,382	450	64	755	97
4/5/98	0	-462	6,379	692	64	294	130
4/12/98	0	-329	6,351	626	63	360	118
4/19/98	45	-524	6,331	724	63	219	136
4/26/98	324	0	6,306	569	36	280	94
5/3/98	146	0	6,311	563	0	417	85
5/10/98	0	-716	6,295	805	54	143	150
5/17/98	0	-840	6,249	793	62	16	158

Table 4. Weekly water budget for Lake Starr (Continued)

[All units in thousands of cubic feet unless specified; some weekly periods are more or less than 7 days in length, net ground-water flow calculated as residual; negative evaporation set equal to zero; +/-, plus or minus]

Start date	Rain	Change in volume	Average surface area (feet^2 x 1,000)	Evaporation	Direct pumping	Net ground-water flow	Error in net ground-water flow (+/-)
5/24/98	39	-514	6,207	557	62	67	116
5/31/98	6	-893	6,176	822	62	-15	164
6/7/98	16	-1,074	6,122	896	61	-132	183
6/14/98	0	-1,062	6,070	839	61	-163	175
6/21/98	96	-990	6,019	801	60	-225	167
6/28/98	37	-980	5,976	854	34	-128	165
7/5/98	868	244	5,947	728	34	138	125
7/12/98	1,971	1,850	6,020	674	0	553	233
7/19/98	674	187	6,059	679	0	192	109
7/26/98	38	-745	6,040	762	52	31	146

Table 5. Monthly and annual water budget for Lake Starr

[All units in thousands of cubic feet unless specified; net ground-water flow calculated as residual; +/-, plus or minus]

Month	Rain	Change in volume	Average surface area (feet^2 x 1,000)	Evaporation	Direct pumping	Net ground-water flow	Error in net ground-water flow (+/-)
Aug-96	4,517	3,454	5,962	3,209	17	2,163	559
Sep-96	2,416	992	6,041	2,812	35	1,422	443
Oct-96	1,786	437	6,095	2,344	174	1,169	403
Nov-96	626	-2,167	6,017	2,014	155	-624	358
Dec-96	1,495	430	6,008	1,309	154	398	262
Jan-97	657	-1,101	5,970	1,364	136	-257	254
Feb-97	428	-1,329	5,919	1,198	135	-423	236
Mar-97	1,222	-2,369	5,836	2,283	142	-1,166	394
Apr-97	2,301	-1,047	5,743	2,526	107	-715	413
May-97	1,018	-2,567	5,703	2,775	90	-720	448
Jun-97	3,442	677	5,666	2,960	0	196	477
Jul-97	4,724	2,237	5,711	3,112	0	625	535
Aug-97	3,074	116	5,810	3,079	83	204	494
Sep-97	2,073	-810	5,750	2,685	107	-92	431
Oct-97	1,738	-917	5,702	2,394	106	-156	387
Nov-97	1,571	515	5,716	1,460	114	518	261
Dec-97	3,955	3,448	5,792	1,263	66	822	330
Jan-98	2,012	1,924	5,896	907	67	887	206
Feb-98	4,742	5,110	6,039	1,350	43	1,760	405
Mar-98	3,236	3,511	6,267	2,219	90	2,584	419
Apr-98	392	-1,184	6,349	2,714	263	1,401	489
May-98	190	-2,200	6,266	2,977	187	775	497
Jun-98	150	-4,323	6,083	3,648	252	-573	640
Jul-98	3,550	1,048	6,010	3,204	94	796	523
August 1996-July 1997 Total or average*	24,632	-2,352	5,889*	27,907	1,145	2,067	3,260
August 1997-July 1998 Total or average*	26,682	6,239	5,973*	27,899	1,472	8,928	3,439
2-year total or average*	51,315	3,887	5,931*	55,806	2,616	10,995	3,350

PRELIMINARY ANALYSIS OF GROUND-WATER EXCHANGE

Analysis of the lake water budget provides a preliminary understanding of ground-water flows to and from Lake Starr. The water budget, along with the data collected on the hydrogeologic setting, provide the foundation for a finite-difference saturated ground-water flow model of Lake Starr. While modeling provides a new way to look at factors affecting ground-water fluxes to and from the lake, and can be used to quantify inflow and outflows, much useful information can be derived from the water budget.

Seasonal Ground-Water Exchange

Ground-water inflow and outflow occur continually at Lake Starr. However, the relative importance of ground-water inflow and outflow in the water budget can be seen in seasonal shifts from positive to negative net ground-water flow (fig. 25). Positive net ground-water flow occurred mainly in months with positive net precipitation (precipitation minus evaporation), but also occurred in drier months that followed periods of high rainfall. For example, net ground-water flow continued to be positive into May 1998 in response to excess rain in November 1997 through February 1998, despite low rainfall in April and May 1998. Negative net ground-water flow typically occurred in drier months when net precipitation was negative. When monthly net ground-water flow is regressed against cumulative precipitation, it is found to have a better relation to the sum of rainfall in the current and previous 4 months of rainfall (r^2=0.51) than with rainfall in the current month (r^2 = 0.33). Sacks and others (1998) attributed this effect to longer ground-water flow paths in the Lake Starr basin compared to other lakes. This relation suggests that monthly net ground-water flow lags rainfall somewhat, and that changes from wet to dry seasonal conditions are reflected in the monthly water budget.

Ground-water exchange can be a large part of the water budget for individual months. Net ground-water inflow accounted for more than 40 percent of the total inflow to the lake (precipitation plus positive net ground-water flow) from March through May 1998, and was 80 percent of the total inflow in May 1998 (table 5). Net ground-water outflow accounted for more than 20 percent of total outflows from the lake (evaporation plus negative net ground-water flow plus lake pumping) in November 1996 and February through May 1997. Gross ground-water fluxes can be expected to be even higher percentages of total inflows and outflows.

The difference in timing of rainfall within the year had a noticeable effect on ground-water recharge and subsequent ground-water inflow to Lake Starr. In an average year in this area, like 1997, about one half of the annual total rain falls during the summer rainy season, in the 4 months from June through September (fig. 22). However, during the study, an equally wet season occurred in the winter (December 1997 to March 1998), which is atypical. Because evaporation is much higher in the summer, the differences in timing of rainfall produced a large difference in net precipitation. Net precipitation on the lake was five times greater between December 1997 and March 1998 than between June and September 1997 (8,210,000 and 1,480,000 ft^3/mo, respectively). Because lake evaporation is always greater than basin evapotranspiration, net precipitation is a conservative estimate of basin recharge. Recharge to the ground-water system for an equivalent amount of rain should be higher when rain falls in the winter months compared to summer months because evaporation and transpiration are lower during the winter months. Higher recharge to the basin has the potential to generate more ground-water inflow to the lake.

At the same time, differences in lake leakage also may account for some of the differences in seasonal net ground-water fluxes. Estimated heads in the Upper Floridan aquifer in the lake basin during the winter wet season averaged 2 ft higher than in the summer wet season. Thus, leakage was probably lower in wet winter months compared to wet summer months. Regulated water use for the 6 square miles around Lake Starr was 58 percent less in the winter wet season (December 1997-March 1998) compared to the summer wet season (June-September 1997) (J. Whalen, Southwest Florida Water Management District, written commun., 1999).

Transient Ground-Water Exchange

Weekly net ground-water flow showed similar patterns to monthly net ground-water flow within wet and dry seasons. Weekly net ground-water flow was generally negative (net outflow) during the dry winter and spring months of late 1996 and early 1997 (fig. 26). The summer wet season in 1997 mostly served to decrease outflow so that net ground-water flow was near zero between June and October. The unusually wet months between November 1997 and March 1998 consistently generated net inflow. This atypical wet period was followed by 3 months (April, May, June) that were exceptionally dry. Despite the lack of rain, a declining net inflow was sustained throughout April and into early May. The ground-water inflow respon-

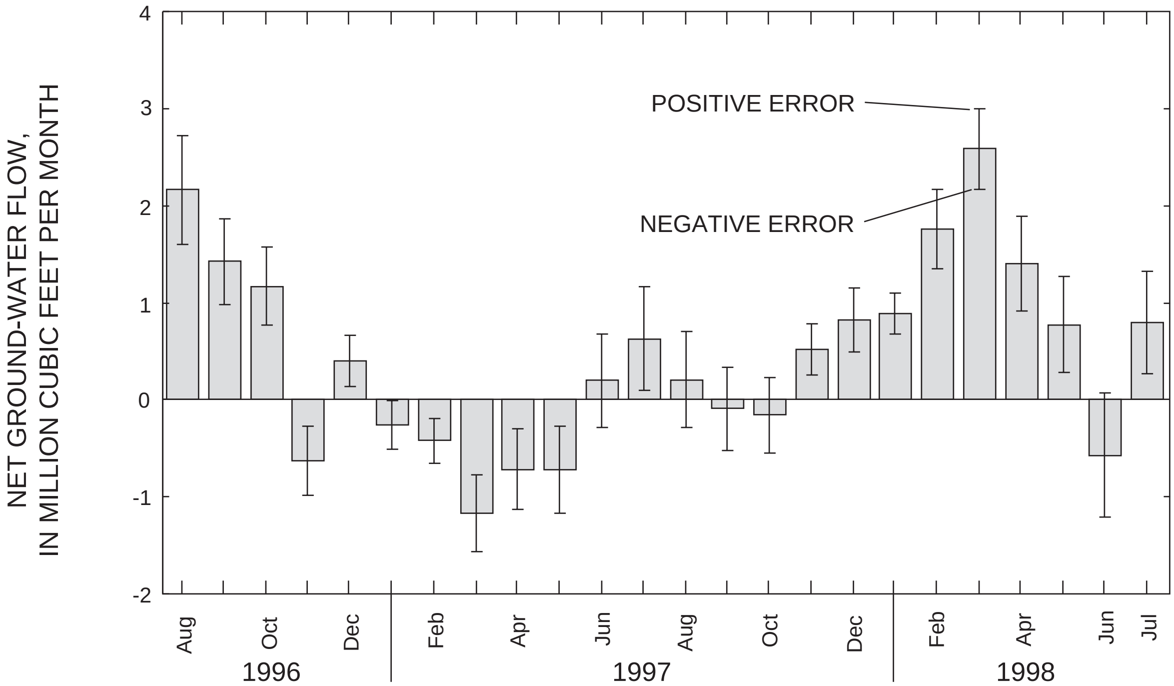


Figure 25. Monthly net ground-water flow and estimated error for Lake Starr, August 1996 through July 1998.

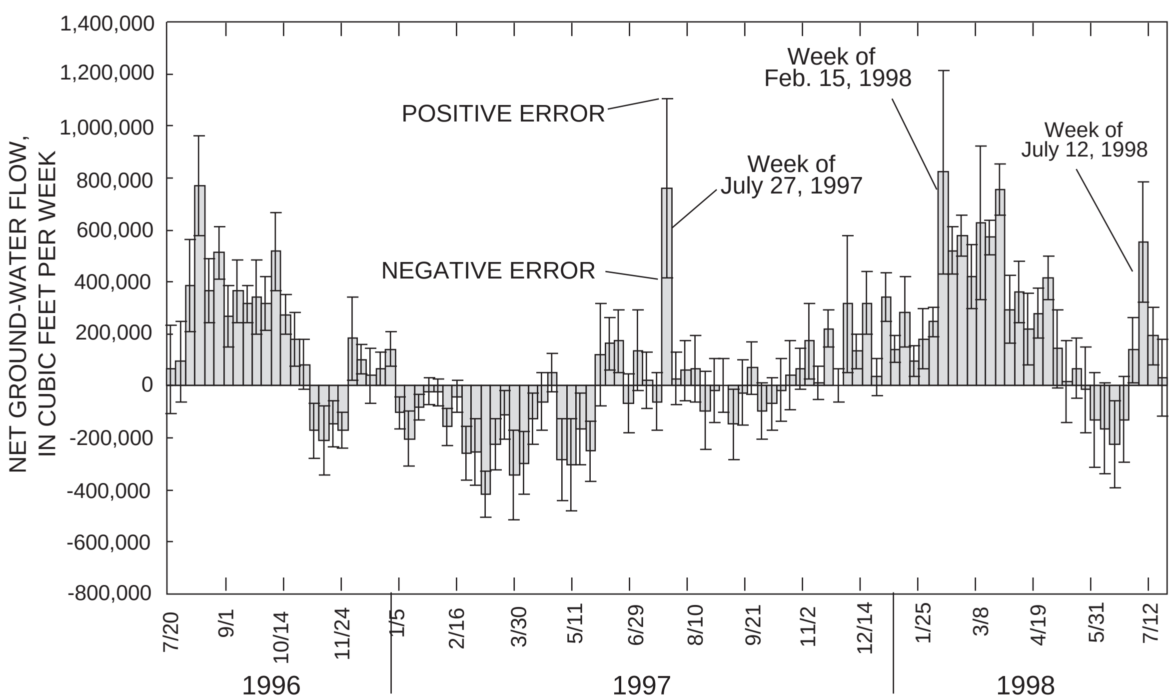


Figure 26. Weekly net ground-water flow and estimated error for Lake Starr, July 20, 1996 to August 1, 1998.

sible for sustaining this net inflow probably originated from areas of the basin where the travel times for flow to reach the lake would be about a month. Thereafter, during May and June, the weekly net ground-water exchange incrementally decreased to more net outflow.

Although the magnitude and direction of the net flows showed overall consistency within wet and dry periods, weekly values also changed substantially in response to the environmental conditions (primarily rainfall, but also shallow ground-water levels) within the week. Weekly fluctuations in net ground-water flows suggest that net ground-water exchange with a lake can be more transient than previously recognized. For example, a large amount of net ground-water inflow occurred the last week of July 1997 when total rainfall was 6.07 inches. The inflow was a reversal from the net outflow of the previous week (see week beginning July 27, 1997, on fig. 26). Then, during the following week, when rainfall was 1.37 inches, the ground-water exchange was reduced to a small net inflow. The rapid timing of this large net inflow suggests that ground water recharged and discharged rapidly from the nearshore region following the large rainfall events. Similar sharp increases in net inflow occurred for the weeks of February 15, 1998, and July 12, 1998, which were weeks when rainfall amounts also were large (5.94 and 3.94 inches, respectively) (fig. 26).

Continuously-recorded ground-water levels provided additional evidence for the rapid recharge and discharge of ground water in the nearshore area during these weeks. Water levels in the nearshore region rose rapidly during the large daily rainfall for July 28, 1997, causing steep inflow head gradients in the water table on both the inflow and outflow sides of the lake (see fig. 15). The water table responded similarly for weeks beginning February 15 and July 12, 1998 (figs. 16 and 17).

If the nearshore region was considered to be the area around the lake where the land surface was 5 ft or less above lake stage, the potential catchment of 670,000 ft^2 would be insufficient in size to provide the volume of inflow indicated during the week of July 27-August 2, 1997. For example, if recharge over this area was estimated to equal the weekly rainfall, the gross inflow volume generated from the nearshore area that week would be about 343,000 ft^3. By comparison, the net ground-water inflow to the lake estimated from the weekly water budget was about 760,000 ft^3 $\pm$ 345,000 ft^3. However, the net ground-water inflow provides only a minimum estimate of the <u>gross</u> ground-water inflow. The gross inflow would be 760,000 ft^3 <u>plus</u> the additional inflow needed to offset the lake leakage occurring this week. It is probable that the area contributing rapid ground-water inflow to Lake Starr extended further on shore and included areas of the basin where the unsaturated soils were thicker than 5 ft. For example, at Lake Barco in north central Florida, transient water-table mounds were occasionally observed in nearshore areas where the land surface was 6 to 10 ft above the water table (Lee, in press).

Although large weekly rainfall volumes apparently do affect weekly net ground-water inflow, the statistical relation between weekly rainfall (or net precipitation) and weekly net ground-water flow for all observations was poor, and explained less than 23 percent of the week-to-week variance in net ground-water flow (fig. 27). Instead, weekly net ground-water flow had a better linear relation to the weekly average head in the underlying Upper Floridan aquifer (fig. 28). Average Upper Floridan aquifer heads were estimated from hourly measurements at a well with recorded water levels (ROMP 57A) that were modified using a linear relation between instantaneous head measurements at a well on the outflow side of the lake (Hart FLRD well) and hourly readings from ROMP 57A. Estimates of average head in the Upper Floridan aquifer based on the linear relation with a recording well were needed because instantaneous measurements were not representative of average Upper Floridan aquifer heads. Instantaneous measurements can be affected by short-term pumping stresses (see Sacks and others, 1997, p. 26). The linear relation between weekly net ground-water flow and average Upper Floridan aquifer head explained about 59 percent of the variance in the net ground-water flow values with a standard error of about 170,000 ft^3. Heads in the Upper Floridan aquifer, in turn, are strongly controlled by ground-water pumping.

Analysis of these relations shows that over time periods as short as 1 week, the exchange of ground water with the lake can change substantially, and that these changes are linearly related to Upper Floridan aquifer heads in the basin (fig. 28). A decline in the weekly average Upper Floridan aquifer head from 96 to 94 ft corresponded to an increase in the weekly net outflow of about 340,000 ft^3. A good linear relation also existed between the monthly net ground-water flow and the monthly average head in the Upper Floridan aquifer (r^2 = 0.72, standard error = 525,000 ft^3). Transient inflow periodically generated by large rainfall events is still a noticeable process; however, it is less important overall than the Upper Floridan aquifer head in explaining net ground-water exchange with Lake Starr. Short-term Upper Floridan aquifer head conditions in lake basins may play a more important role in determining net ground-water exchange in lakes than previously realized.

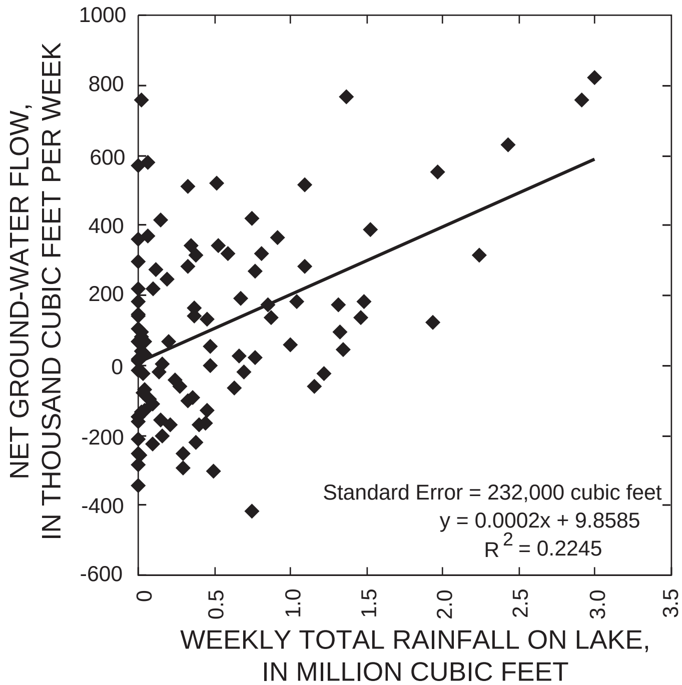


Figure 26. Relation between weekly net ground-water flow and rainfall at Lake Starr, July 20, 1996 to August 1, 1998.

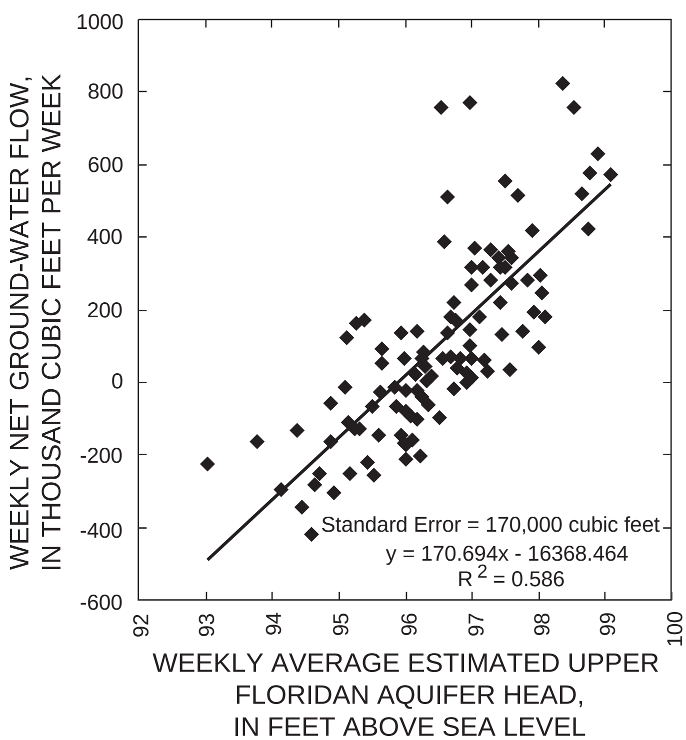


Figure 28. Relation between weekly net ground-water flow and weekly average estimated head in the Upper Floridan aquifer on the south side of Lake Starr, July 20, 1996 to August 1, 1998.

Annual Ground-Water Exchange

Annual lake water budgets can provide evidence of the magnitude of the long-term fluxes of ground water to and from lakes. By summing all the monthly net ground-water flows that are positive during the year, an estimate of the minimum annual contribution of ground water to the lake can be made. Using this approach, ground-water inflow contributed a minimum of 5,970,000 ft^3 to Lake Starr in the first year and 9,750,000 ft^3 in the second year of this study. Allowing for errors, this minimum estimate of ground-water inflow accounted for 13 to 26 percent of all inflows the first year and 19 to 34 percent the second year. Summing the negative monthly values of net ground-water flow, an estimate was made of the minimum ground-water outflow from the lake. Ground-water outflow was a minimum of 3,910,000 ft^3 in the first year and about one-fifth of this amount, 820,000 ft^3, in the second year. Allowing for errors, negative net ground-water flows were a minimum of 6 to 18 percent of total outflows during the first year and zero to 9 percent the second year of the study.

The role of net ground-water exchange in sustaining lake levels can be re-examined with our improved understanding of evaporative losses and net precipitation. Lake evaporation measurements made during the study suggest that, on average, annual lake evaporation exceeds annual precipitation in the basin. Rainfall was close to the long-term average of 51.99 inches per year for the 2 years of the study (50.68 and 54.04 inches, respectively). Lake evaporation was 57.08 and 55.88 inches per year for the same 2 years, making net precipitation (rainfall minus evaporation) negative during both years. If net precipitation to seepage lakes in this area is negative over the long term, then the ability to generate net ground-water inflow from the surrounding basin plays an important role in sustaining lake levels.

In both years of the study, the annual net ground-water flow that was calculated as a residual to the water budget was positive, indicating that inflows were greater than outflows. The water budget indicated net ground-water inflow of 2,067,000 ft^3 (3.9 inches) the first year and 8,928,000 ft^3 (17.5 inches) the second year.

Errors in both years were similar (3,260,000 and 3,439,000 ft^3 (6.7 and 6.9 inches) for the first and second years, respectively), and exceeded the magnitude of annual net ground-water flow in the first year (see table 5). Errors could potentially eliminate the difference between the annual net ground-water amounts if annual errors were in opposite directions (3.9 + 6.7 = 10.6 inches for the first year, and 17.5 - 6.9 = 10.6 inches in the second year). While it is unlikely that errors are this random, the calculation points out the problem with estimating net ground-water flow as a residual to the water budget.

Evaporation exceeded rainfall by a similar amount for both years of the study, but net ground-water flow differed substantially between the 2 years. The difference of 13.6 inches was due to both an increase in the amount of ground-water inflow and a decrease in lake leakage in the second year. Increase in ground-water inflow during the second year probably resulted from greater recharge to the ground-water basin. Recharge was probably much greater during the second year because half of the rainfall occurred in the winter when evapotranspiration losses were smaller. Assuming a minimum amount of annual ground-water inflow based on the sum of positive monthly net ground-water flows in a year, differences in ground-water inflow could account for a minimum of 7 inches of the difference between net ground-water flows in the 2 years.

Decreased lake leakage (ground-water outflow) during the second year was probably at least as important as increased ground-water inflow in explaining the difference in net ground-water flow to the lake between the 2 years. Decreased lake leakage was probably related to differences in the annual average potentiometric head in the Upper Floridan aquifer during the 2 years. The estimated annual average potentiometric surface was 1 ft higher in the second year than the first. Based on a linear relation of weekly net ground-water flow with the estimated head in the Upper Floridan aquifer, an average of 1 ft difference in head could account for as much as 18 inches (8,900,000 ft^3) of difference in leakage (fig. 28), which is much more than the difference in net ground-water flow between the 2 years. The higher potentiometric surface in the second year of the study should reflect reduced ground-water pumping during parts of the year. Many Upper Floridan aquifer wells in this region attained historical high levels in early 1998 (Coffin and Fletcher, 1999).

SUMMARY AND CONCLUSIONS

Lake Starr is a 134-acre seepage lake located on the Lake Wales Ridge in central Polk County, one of Florida’s principal lake districts. Lake Starr is located in a mantled karst setting, and the lake was formed from multiple sinkholes. Areally limited piping sinks are the primary type of sinkhole in the basin. The regional ground-water system in the area around Lake Starr consists of two aquifers, the upper unconfined (water table) surficial aquifer system, and the lower confined Upper Floridan aquifer. In the Lake Wales Ridge, water levels of lakes and the surficial aquifer system are higher than heads in the underlying Upper Floridan aquifer, so water flows downward, recharging the deeper confined aquifer. Breaches in the confining unit that separates the two aquifers are caused by sinkholes, and result in a lack of local confinement of the Upper Floridan aquifer. Lakes and the surficial aquifer system are more directly connected to the Upper Floridan aquifer in areas where sinkholes occur. Breaches in the intermediate confining unit occur beneath the lake and on the southeast side of the basin.

The hydrogeologic setting of the Lake Starr basin differs markedly on the two sides of the lake. Lake Starr is a flow-through lake with respect to the surficial aquifer system; about two-thirds of the lake perimeter receives ground-water inflow and the remainder loses water to the ground-water system. Ground water from the surficial aquifer system flows into the lake on its northwest side, and lake water flows out to the surficial aquifer system along the southeast side. Water-level responses to rainfall in the upper basin are lagged 1 to 2 months behind those in the lower basin because of the greater thickness of the unsaturated zone in the upper basin. Both the water table and the Upper Floridan aquifer slope to the east and southeast across the basin. The slope of the potentiometric surface of the Upper Floridan aquifer is steeper across the basin than the slope of the water table. On the northwest side of the lake, flow in the surficial aquifer system is largely horizontal near the lake. Ground-water flow in the surficial aquifer system on the southeast side of the lake is both downward and away from the lake. Below the lake and on the southeast side, breaches in the intermediate confining unit enhance downward flow to the Upper Floridan aquifer.

Water budgets were calculated on a weekly, monthly, and annual basis for the 2-year period August 1996 through July 1998. Annual rainfall for the 2 years of the study (August 1996-July 1997 and August 1997-

July 1998) was 50.68 and 54.04 inches, respectively. Rainfall during both years was within 2.1 inches of the 71-year annual average (51.99 inches), and was greater than the 30-year average (48.21 inches). Annual evaporation was 57.08 and 55.88 inches for the 2 years, respectively. Direct pumping from the lake was the smallest component of the water budget, accounting for losses of 2.3 and 2.9 inches from the lake for the 2 years, respectively. The lake lost water the first year (-4.9 inches) and gained water the second year (+12.7 inches).

Net ground-water flow was calculated as a residual to the water budget. The estimates of weekly net ground-water flow presented in this report are the first of their kind for any lake in the United States. These estimates were possible because accurate weekly evaporation losses computed by the energy-budget evaporation method were available. Net ground-water flow computed for different time intervals provided insight on processes that affect ground-water interactions with Lake Starr. Weekly estimates of net ground-water flow provided evidence for the occurrence of transient ground-water inflows, as well as the short-term effects of head in the Upper Floridan aquifer on ground-water exchange with the lake. Monthly water budgets showed the effects of wet and dry seasons on ground-water interactions with the lake and provided evidence for ground-water inflow generated from the upper basin. Annual water budgets showed how differences in timing of rainfall and pumping stresses affected lake stage and ground-water interactions.

Large weekly net ground-water inflows coincided with periods of heavy rain and transient nearshore ground-water flow reversals. Nearshore water levels showed ground-water mounds that lasted less than a day on both the inflow and outflow sides of the lake. Mounding temporarily reversed the flow direction on the outflow side of the lake to inflow. The nearshore area of the lake is defined as the part of the basin that is capable of generating ground-water inflow within a period of days in response to large rainfall events. The nearshore area would have to extend about 150 ft away from the lake shore to generate the volume of ground-water inflow that is calculated from the water budget during some weeks. Furthermore, transient inflows are probably generated in areas of the basin where the water table is within 10 ft of the land surface.

Although large weekly rainfall volumes apparently do affect weekly net ground-water inflow, the statistical relation between weekly rainfall and weekly net ground-water flow for all observations was poor, and explained less than 23 percent of the week-to-week variance in net ground-water flow. Instead, weekly net ground-water flow had a better linear relation to the estimated weekly head in the underlying Upper Floridan aquifer. These Upper Floridan aquifer heads, in turn, were strongly influenced by pumping from area wells.

Lake evaporation measurements made during the study suggest that, on average, annual lake evaporation exceeds annual precipitation in the basin. If net precipitation to seepage lakes is negative over the long term, the ground-water basin plays an important role in sustaining lake levels. Evaporation exceeded rainfall by a similar amount for both years of the study, but net ground-water flow differed substantially between the 2 years. Although annual net ground-water flow to Lake Starr was positive in both years, it was lower in the first year (3.9 inches) than in the second year (17.5 inches). Recharge to ground water was probably much greater during the second year because half of the rainfall occurred in the winter when evapotranspiration losses were smaller. Greater recharge during the second year generated more ground-water inflow. However, decreased lake leakage during the second year was probably at least as important as increased ground-water inflow in explaining the difference in net ground-water flow to the lake between the 2 years. Estimates of lake leakage based on a relation between net ground-water flow and head in the Upper Floridan aquifer could easily account for the differences in net ground-water exchange with the lake in the 2 years of the study. The effects of increasing ground-water inflow and reduced leakage were even more pronounced on a seasonal basis, particularly during the winter of 1997-1998.

Rainfall during the first year of the study was more representative of typical rainfall patterns, where most of the rainfall occurs during the summer. Despite 50.68 inches of rainfall in the first year (which is greater than the 30-year average but less than the 71-year average), the lake stage decreased because the lake lost more water than it gained. Even though net ground-water flow in the first year was positive, lake stage decreased in the first year because net ground-water inflow was smaller than the negative net precipitation. If we assume that rainfall and lake evaporation in the first year reflect long-term average conditions, the stage of Lake Starr will continue to drop unless ground-water inflow increases or leakage decreases compared to that year.

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APPENDIX

WEEKLY AND MONTHLY ENERGY-BUDGET COMPONENTS AND EVAPORATION CALCULATIONS

Table A1. Summary of weekly energy-budget components and evaporation calculations

[All weeks are not 7 days in length; all periods start at 0000 hours and end at 2400 hours on days given; all units are averages in calories per square centimeter per day unless noted; Qs, incident solar radiation; Qr, reflected solar radiation; Qa, incident longwave radiation; Qar, reflected longwave radiation; Qbs, emitted longwave radiation; Qv, advected energy; Qx, change in stored energy; BR, Bowen ratio; L, latent heat of vaporization; To, water surface temperature; ^{o}C, degrees celsius; EEB, energy-budget evaporation]

Start date	End date	Thermal survey period	Qs	Qr	Qa	Qar + Qbs	Qv	Qx	BR (unitless)	L (cal/gm)	To (^{o}C)	EEB (cm/day)	EEB (total inches)
7/20/96	7/27/96	1	590	20	855	973	0	38	0.11	579	31.7	0.62	1.94
7/28/96	8/3/96	2	532	22	858	968	27	-15	0.16	579	31.3	0.63	1.73
8/4/96	8/10/96	3	448	17	868	965	30	3	0.17	579	30.9	0.51	1.41
8/11/96	8/17/96	4	469	18	854	960	26	-7	0.17	579	30.5	0.53	1.46
8/18/96	8/24/96	5	516	24	838	959	1	-29	0.16	579	30.1	0.57	1.57
8/25/96	8/31/96	6	483	18	854	962	6	36	0.16	579	30.8	0.47	1.28
9/1/96	9/7/96	7	484	19	866	967	15	19	0.15	579	31.1	0.52	1.43
9/8/96	9/14/96	8	373	16	853	957	16	-42	0.20	579	30.3	0.43	1.19
9/15/96	9/19/96	9	431	20	852	958	10	7	0.15	579	30.0	0.44	0.87
9/20/96	9/28/96	10	438	22	811	942	5	-77	0.16	580	29.0	0.52	1.85
9/29/96	10/5/96	11	302	16	860	943	10	-74	0.20	580	28.4	0.40	1.10
10/6/96	10/13/96	12	332	19	797	912	17	-113	0.19	581	26.4	0.45	1.43
10/14/96	10/19/96	13	368	20	804	905	2	2	0.19	582	25.7	0.34	0.81
10/20/96	10/26/96	14	400	20	748	893	0	-15	0.17	582	25.4	0.35	0.98
10/27/96	11/2/96	15	357	18	805	909	0	30	0.15	582	26.2	0.30	0.82
11/3/96	11/9/96	16	346	23	736	886	3	-132	0.21	582	24.9	0.42	1.15
11/10/96	11/16/96	17	309	22	675	849	0	-222	0.25	584	22.1	0.44	1.22
11/17/96	11/23/96	18	296	19	738	847	0	20	0.17	584	21.3	0.21	0.57
11/24/96	11/30/96	19	283	20	723	840	5	-53	0.17	585	20.8	0.29	0.79
12/1/96	12/7/96	20	251	17	731	839	22	-10	0.19	585	20.6	0.22	0.61
12/8/96	12/14/96	21	315	24	646	814	0	-61	0.24	585	19.5	0.25	0.68
12/15/96	12/21/96	22	220	16	669	803	0	-217	0.32	586	18.5	0.36	0.98
12/22/96	12/28/96	23	256	12	725	803	0	104	0.08	586	17.6	0.09	0.26
12/29/96	1/4/97	24	287	14	762	845	0	87	0.14	584	21.2	0.15	0.41
1/5/97	1/11/97	25	297	19	731	842	5	4	0.20	584	21.1	0.23	0.63
1/12/97	1/20/97	26	292	21	626	793	1	-160	0.35	586	17.9	0.32	1.14
1/21/97	1/25/97	27	325	21	698	808	1	136	0.01	586	17.3	0.10	0.19
1/26/97	2/1/97	28	290	18	708	814	2	16	0.26	586	18.6	0.20	0.55
2/2/97	2/8/97	29	318	17	760	841	1	118	0.05	585	19.9	0.16	0.44
2/9/97	2/15/97	30	307	18	733	839	2	53	0.21	585	20.4	0.18	0.49
2/16/97	2/22/97	31	339	20	744	848	3	36	0.08	585	20.4	0.28	0.77
2/23/97	3/1/97	32	391	22	778	875	0	104	0.08	584	22.6	0.26	0.71
3/2/97	3/8/97	33	443	22	765	890	0	34	0.12	583	24.5	0.39	1.07
3/9/97	3/15/97	34	367	19	781	885	12	8	0.16	583	24.1	0.35	0.98
3/16/97	3/22/97	35	450	21	750	875	6	4	0.18	583	23.8	0.43	1.18

Table A1. Summary of weekly energy-budget components and evaporation calculations (Continued)

[All weeks are not 7 days in length; all periods start at 0000 hours and end at 2400 hours on days given; all units are averages in calories per square centimeter per day unless noted; Qs, incident solar radiation; Qr, reflected solar radiation; Qa, incident longwave radiation; Qar, reflected longwave radiation; Qbs, emitted longwave radiation; Qv, advected energy; Qx, change in stored energy; BR, Bowen ratio; L, latent heat of vaporization; To, water surface temperature; ^{o}C, degrees celsius; EEB, energy-budget evaporation]

Start date	End date	Thermal survey period	Qs	Qr	Qa	Qar + Qbs	Qv	Qx	BR (unitless)	L (cal/gm)	To (^{o}C)	EEB (cm/day)	EEB (total inches)
3/23/97	3/29/97	36	446	20	791	890	2	78	0.14	582	24.6	0.36	1.00
3/30/97	4/5/97	37	544	26	716	884	0	-55	0.16	582	24.6	0.58	1.59
4/6/97	4/12/97	38	428	21	790	889	5	9	0.13	583	24.2	0.44	1.22
4/13/97	4/19/97	39	376	18	752	865	6	-95	0.23	583	23.1	0.47	1.29
4/20/97	4/26/97	40	440	20	771	877	19	68	0.14	583	23.3	0.38	1.06
4/27/97	5/3/97	41	476	20	809	901	9	137	0.09	582	24.9	0.36	0.98
5/4/97	5/10/97	42	603	25	754	912	0	47	0.16	581	26.8	0.53	1.47
5/11/97	5/23/97	43	446	17	819	923	5	39	0.16	581	27.4	0.41	2.12
5/24/97	5/31/97	44	529	22	829	937	7	12	0.16	580	28.7	0.56	1.77
6/1/97	6/7/97	45	544	21	814	932	6	52	0.17	580	28.6	0.51	1.40
6/8/97	6/14/97	46	462	21	860	942	37	4	0.20	580	28.6	0.54	1.50
6/15/97	6/21/97	47	546	18	856	951	7	109	0.11	580	29.8	0.49	1.36
6/22/97	6/28/97	48	500	21	856	960	17	-11	0.18	579	30.6	0.57	1.56
6/29/97	7/5/97	49	514	18	871	967	13	24	0.15	579	31.2	0.56	1.54
7/6/97	7/12/97	50	479	19	856	962	28	9	0.18	579	30.9	0.52	1.44
7/13/97	7/19/97	51	479	21	861	964	16	9	0.17	579	31.0	0.51	1.41
7/20/97	7/26/97	52	528	22	870	969	6	52	0.17	579	31.4	0.51	1.40
7/27/97	8/2/97	53	481	21	874	965	57	-1	0.20	579	31.3	0.59	1.62
8/3/97	8/9/97	54	431	18	874	963	12	-6	0.20	579	30.9	0.47	1.30
8/10/97	8/16/97	55	477	18	883	973	20	47	0.17	579	31.7	0.48	1.33
8/17/97	8/23/97	56	502	21	870	977	1	0	0.14	578	32.0	0.54	1.49
8/24/97	8/30/97	57	501	23	837	966	2	-33	0.14	579	31.2	0.56	1.54
8/31/97	9/6/97	58	434	22	857	959	14	-94	0.17	579	30.3	0.59	1.62
9/7/97	9/13/97	59	447	21	831	949	3	-8	0.16	580	29.7	0.45	1.25
9/14/97	9/20/97	60	475	24	843	955	0	21	0.15	579	30.1	0.46	1.26
9/21/97	9/27/97	61	338	19	861	951	24	-73	0.19	580	29.7	0.45	1.25
9/28/97	10/4/97	62	449	22	812	936	0	-7	0.16	580	28.9	0.44	1.22
10/5/97	10/11/97	63	413	26	803	930	7	-93	0.18	581	28.0	0.50	1.39
10/12/97	10/18/97	64	370	21	795	918	1	-53	0.19	581	27.2	0.39	1.07
10/19/97	10/25/97	65	405	23	725	887	0	-94	0.22	582	25.7	0.43	1.17
10/26/97	11/1/97	66	234	13	787	891	23	-65	0.25	582	24.8	0.27	0.75
11/2/97	11/8/97	67	335	22	698	859	3	-129	0.26	583	23.6	0.38	1.03
11/9/97	11/15/97	68	273	16	758	859	23	2	0.24	584	22.3	0.23	0.65
11/16/97	11/22/97	69	307	20	719	855	0	-46	0.25	584	21.9	0.26	0.71
11/23/97	11/29/97	70	250	18	743	855	0	-36	0.20	584	21.6	0.21	0.59
11/30/97	12/6/97	71	259	20	703	840	8	-82	0.26	584	21.1	0.25	0.69
12/7/97	12/13/97	72	183	13	768	845	34	29	0.19	585	20.1	0.13	0.35
12/14/97	12/20/97	73	260	20	662	801	5	-146	0.36	586	18.7	0.31	0.85

Table A1. Summary of weekly energy-budget components and evaporation calculations (Continued)

[All weeks are not 7 days in length; all periods start at 0000 hours and end at 2400 hours on days given; all units are averages in calories per square centimeter per day unless noted; Qs, incident solar radiation; Qr, reflected solar radiation; Qa, incident longwave radiation; Qar, reflected longwave radiation; Qbs, emitted longwave radiation; Qv, advected energy; Qx, change in stored energy; BR, Bowen ratio; L, latent heat of vaporization; To, water surface temperature; °C, degrees celsius; EEB, energy-budget evaporation]

Start date	End date	Thermal survey period	Qs	Qr	Qa	Qar + Qbs	Qv	Qx	BR (unitless)	L (cal/gm)	To (°C)	EEB (cm/day)	EEB (total inches)
12/21/97	12/27/97	74	145	8	818	855	12	91	2.57	585	20.1	0.01	0.03
12/28/97	1/3/98	75	284	21	630	792	0	-151	0.35	586	17.8	0.31	0.85
1/4/98	1/10/98	76	233	16	776	846	9	154	-0.33	585	19.7	0.00	0.00
1/11/98	1/17/98	77	261	18	695	826	5	-36	0.25	585	19.6	0.20	0.56
1/18/98	1/24/98	78	187	12	728	826	16	1	0.27	586	19.0	0.12	0.33
1/25/98	1/31/98	79	291	18	644	799	0	-76	0.30	586	18.1	0.25	0.68
2/1/98	2/7/98	80	254	17	686	802	15	-104	0.27	586	17.5	0.31	0.85
2/8/98	2/14/98	81	363	21	661	791	2	59	0.26	587	16.8	0.20	0.56
2/15/98	2/21/98	82	326	16	751	831	42	189	-0.04	586	18.9	0.14	0.40
2/22/98	2/28/98	83	354	19	719	839	7	15	0.06	585	19.9	0.32	0.89
3/1/98	3/7/98	84	454	22	670	831	1	20	0.16	585	20.0	0.36	0.98
3/8/98	3/14/98	85	505	25	630	820	10	-90	0.28	585	19.9	0.50	1.37
3/15/98	3/21/98	86	330	17	742	839	30	49	0.11	585	19.6	0.29	0.81
3/22/98	3/28/98	87	489	23	687	837	0	109	0.19	585	20.3	0.29	0.80
3/29/98	4/4/98	88	438	20	806	895	0	138	0.03	583	23.9	0.31	0.85
4/5/98	4/11/98	89	498	23	723	881	0	-23	0.18	583	24.1	0.47	1.30
4/12/98	4/18/98	90	569	25	729	879	0	100	0.13	583	23.6	0.43	1.18
4/19/98	4/25/98	91	483	20	740	885	1	-39	0.18	582	24.7	0.50	1.37
4/26/98	5/2/98	92	434	18	791	893	5	50	0.13	582	24.6	0.39	1.08
5/3/98	5/9/98	93	488	18	794	906	2	100	0.11	582	25.6	0.39	1.07
5/10/98	5/16/98	94	617	22	786	926	0	81	0.11	581	27.4	0.56	1.54
5/17/98	5/23/98	95	599	20	801	937	0	73	0.10	580	28.5	0.55	1.52
5/24/98	5/30/98	96	368	13	865	955	1	-3	0.14	580	29.5	0.39	1.08
5/31/98	6/6/98	97	603	19	860	959	0	102	0.09	579	30.1	0.58	1.60
6/7/98	6/13/98	98	558	19	862	964	0	9	0.11	579	30.6	0.64	1.76
6/14/98	6/20/98	99	563	19	870	973	0	45	0.08	579	31.3	0.60	1.66
6/21/98	6/27/98	100	499	17	873	974	2	-10	0.12	579	31.7	0.58	1.60
6/28/98	7/4/98	101	568	20	877	976	1	38	0.09	579	31.6	0.62	1.72
7/5/98	7/11/98	102	424	18	882	970	17	-46	0.18	579	31.2	0.53	1.47
7/12/98	7/18/98	103	427	16	886	961	37	22	0.19	579	30.5	0.49	1.34
7/19/98	7/25/98	104	516	19	864	973	13	60	0.15	579	31.5	0.49	1.34
7/26/98	8/1/98	105	519	18	873	983	1	15	0.13	578	32.6	0.55	1.51

Table A2. Summary of monthly energy-budget components and evaporation calculations

[All periods start at 0000 hours and end at 2400 hours for given month; all units are averages in calories per square centimeter per day unless noted; Qs, incident solar radiation; Qr, reflected solar radiation; Qa, incident longwave radiation; Qar, reflected longwave radiation; Qbs emitted longwave radiation; Qv, advected energy; Qx, change in stored energy; BR, Bowen ratio; L, latent heat of vaporization; To, water surface temperature; °C, degrees celsius; EEB, energy-budget evaporation]

Month-year	Qs	Qr	Qa	Qar + Qbs	Qv	Qx	BR (unitless)	L (cal/gm)	To (°C)	EEB (cm/day)	EEB (total inches)
Aug-96	481	19	855	962	20	0	0.17	579	30.7	0.53	6.46
Sep-96	428	19	843	954	11	-26	0.16	580	30.0	0.47	5.59
Oct-96	351	19	799	910	7	-43	0.19	582	26.3	0.38	4.61
Nov-96	310	21	724	859	2	-91	0.21	584	22.6	0.34	4.02
Dec-96	260	17	701	817	5	-27	0.24	585	19.2	0.21	2.61
Jan-97	296	19	696	818	2	-14	0.27	585	19.1	0.22	2.74
Feb-97	340	19	749	847	1	74	0.13	585	20.6	0.22	2.43
Mar-97	430	21	771	886	4	33	0.15	583	24.3	0.38	4.69
Apr-97	437	21	763	880	9	-5	0.17	583	23.7	0.45	5.28
May-97	516	21	806	923	4	48	0.15	581	27.4	0.48	5.84
Jun-97	520	20	848	947	16	43	0.16	580	29.5	0.53	6.27
Jul-97	496	20	867	966	21	18	0.17	579	31.1	0.54	6.54
Aug-97	472	20	865	969	13	-6	0.16	579	31.4	0.52	6.36
Sep-97	422	21	847	952	9	-30	0.17	580	29.8	0.47	5.60
Oct-97	371	21	779	911	7	-76	0.21	581	26.8	0.41	5.04
Nov-97	285	18	736	859	6	-46	0.25	584	22.4	0.26	3.07
Dec-97	224	16	719	828	13	-57	0.31	585	19.7	0.21	2.62
Jan-98	248	17	705	821	7	8	0.25	586	18.9	0.15	1.85
Feb-98	324	18	704	815	16	39	0.17	586	18.3	0.24	2.68
Mar-98	448	22	693	837	9	39	0.20	585	20.2	0.35	4.25
Apr-98	485	21	754	887	1	29	0.16	583	24.3	0.43	5.13
May-98	514	18	811	929	1	63	0.12	581	27.6	0.47	5.70
Jun-98	561	19	866	969	1	34	0.10	579	31.1	0.61	7.20
Jul-98	482	18	878	972	15	20	0.15	579	31.4	0.52	6.40

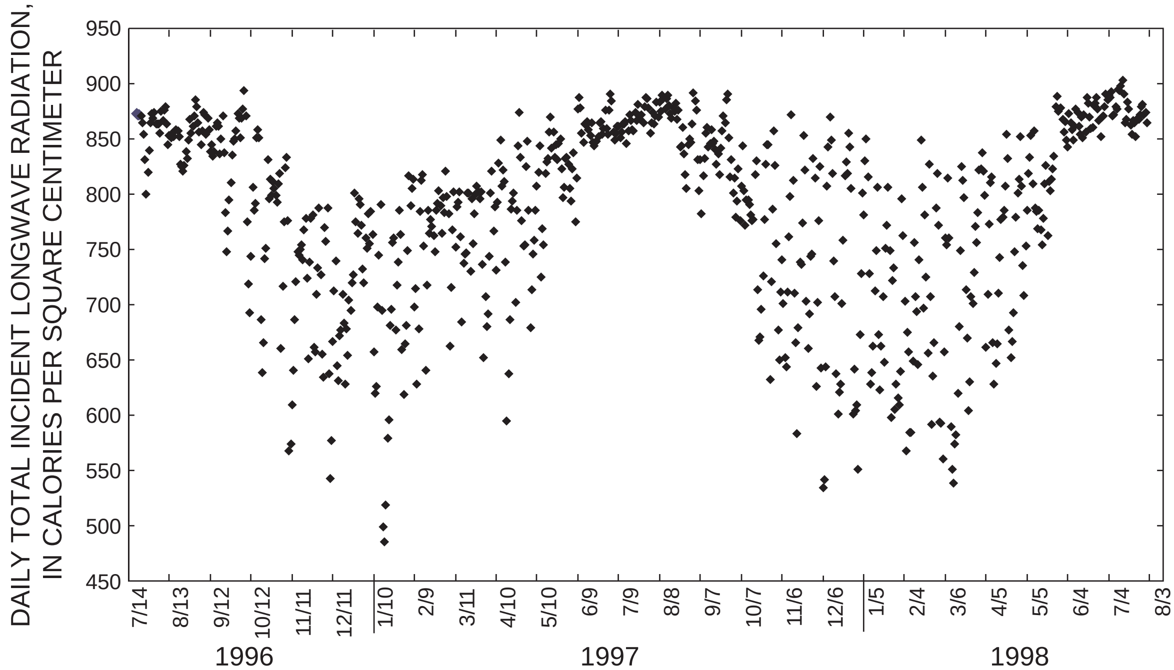

Figure A1a. Daily total incident longwave radiation.

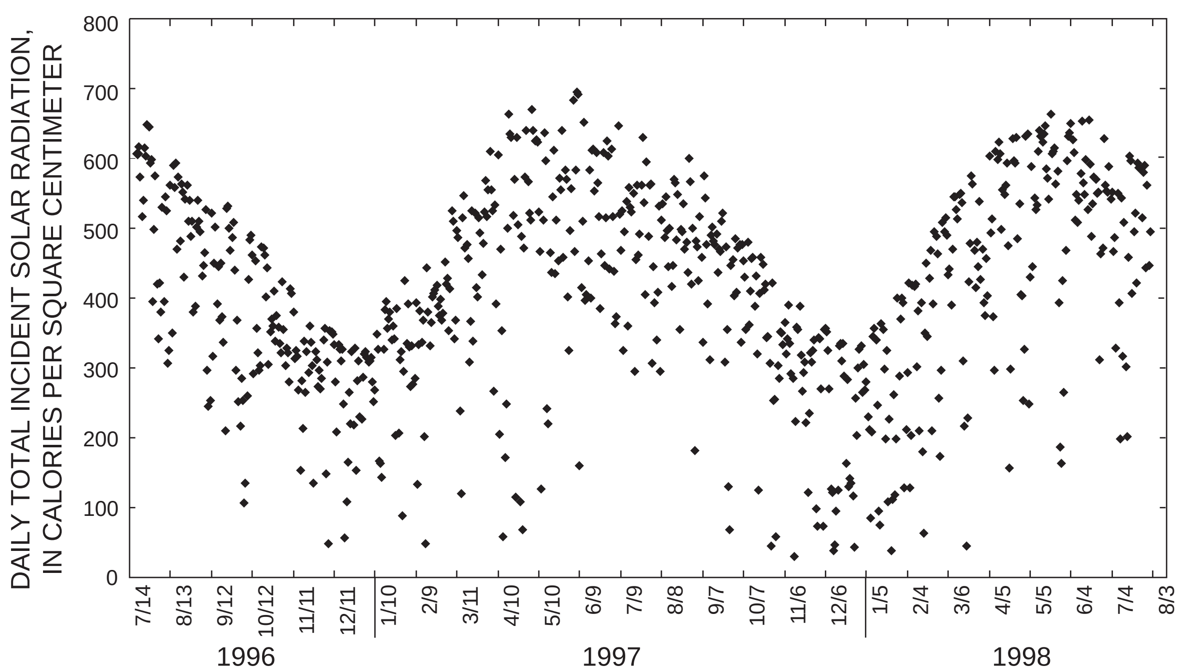

Figure A1b. Daily total incident solar radiation.

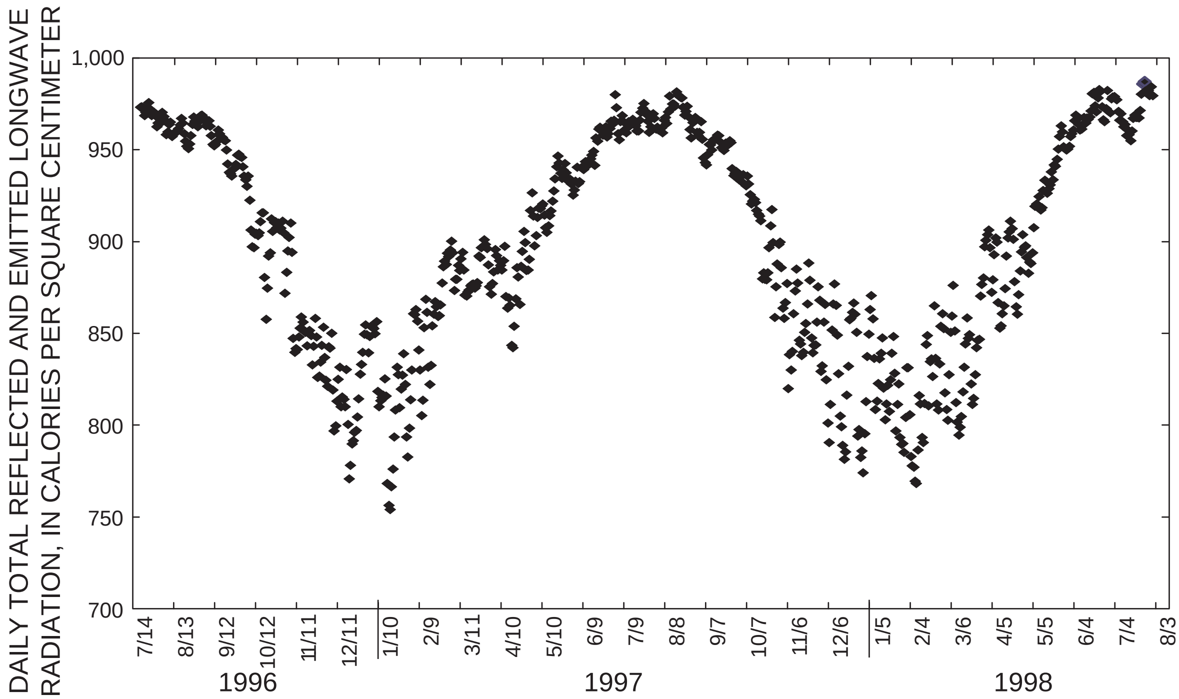

Figure A1c. Daily total reflected and emitted longwave radiation.

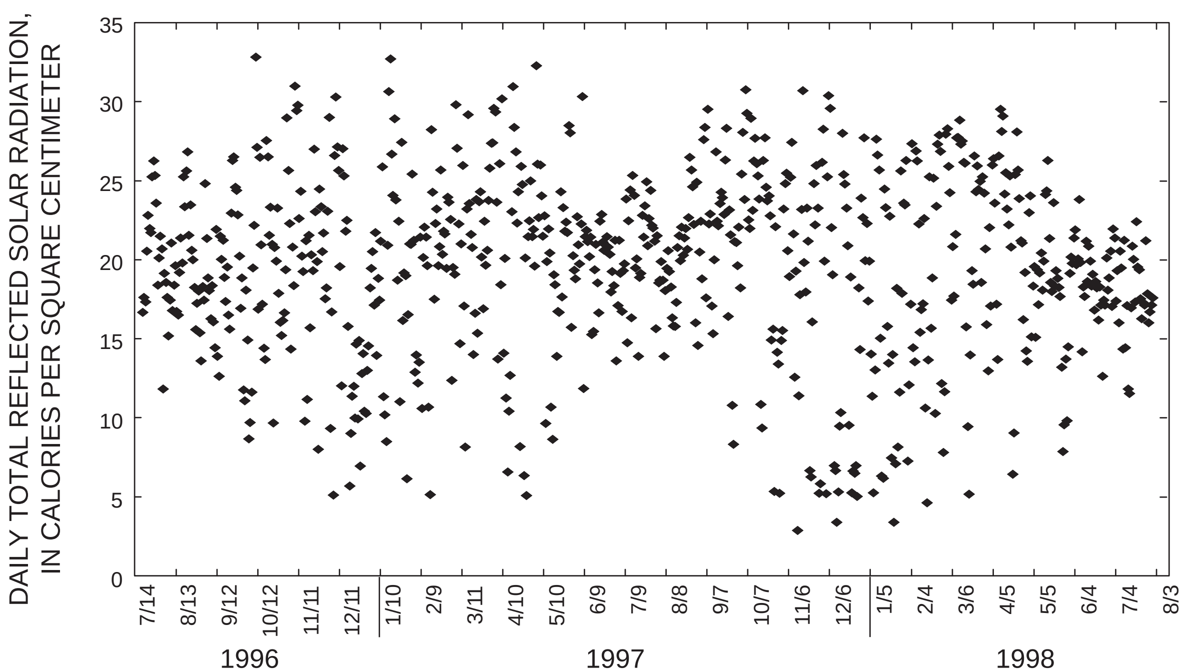

Figure A1d. Daily total reflected solar radiation.

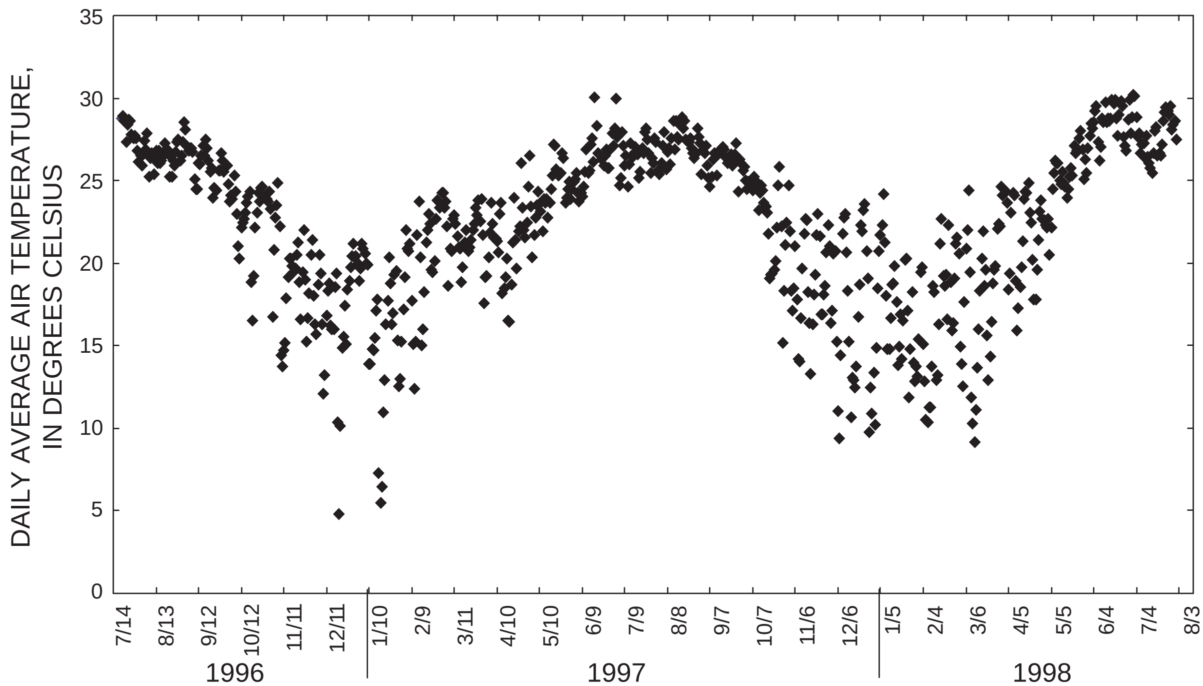

Figure A2a. Daily average air temperature.

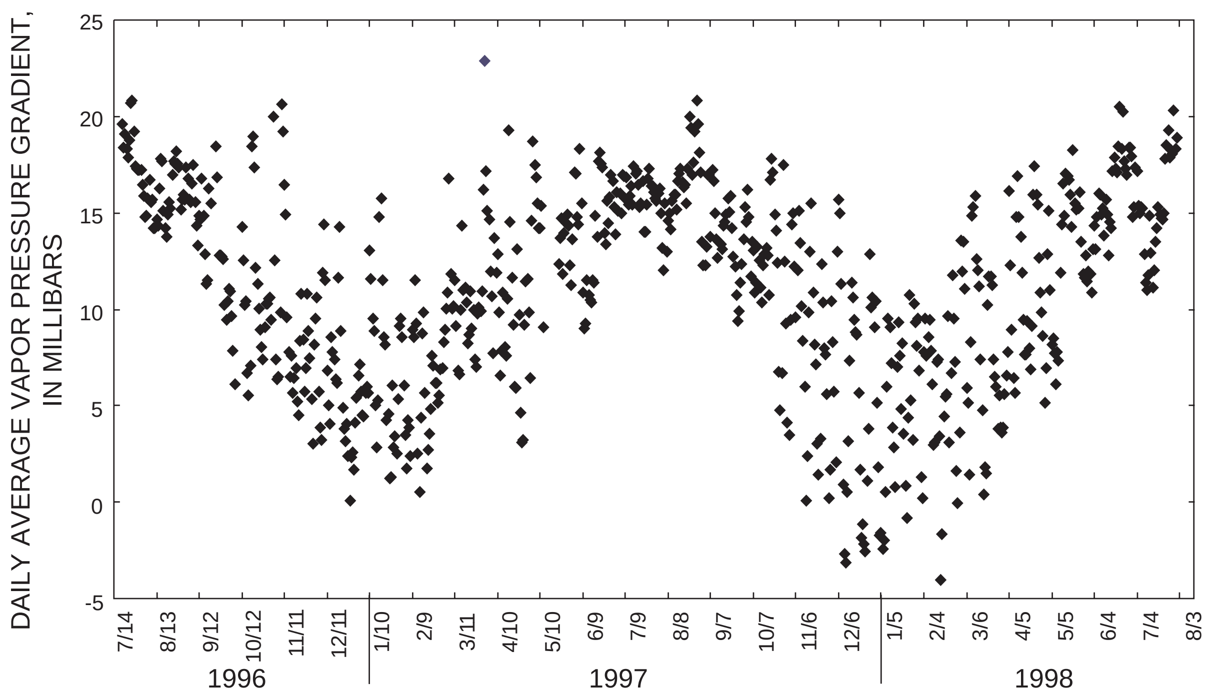

Figure A2b. Daily average vapor pressure gradient.

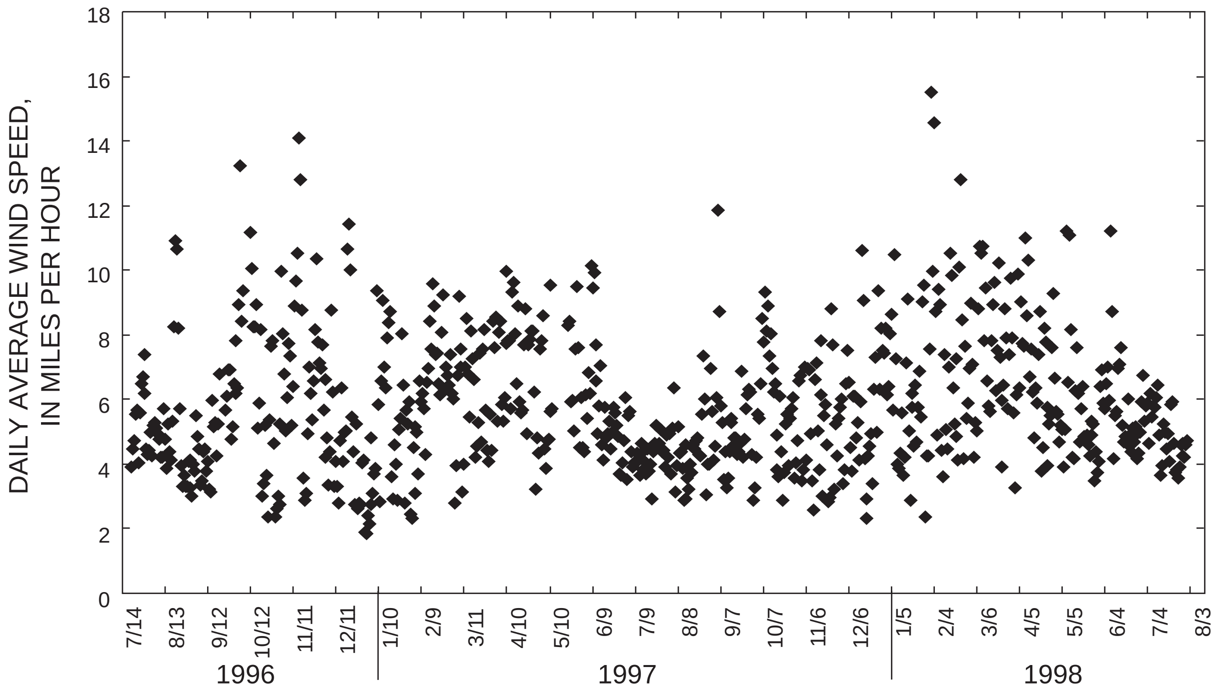

Figure A2c. Daily average wind speed at 2 meters above Lake Starr.

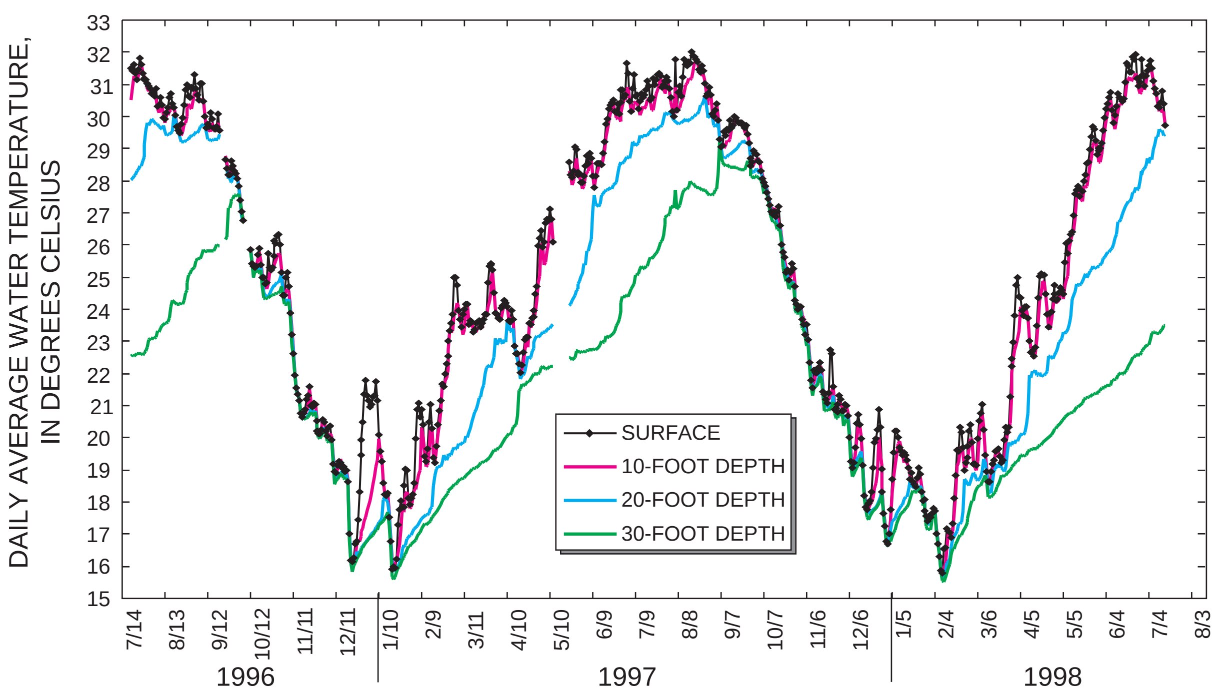

Figure A2d. Daily average water temperature at four depths in Lake Starr.