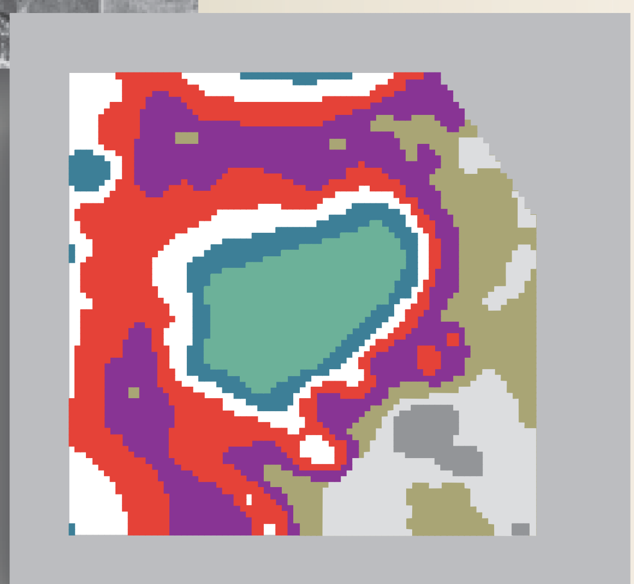
Effects of Recharge, Upper Floridan Aquifer Heads, and Time Scale on Simulated Ground-Water Exchange with Lake Starr, a Seepage Lake in Central Florida

Water-Resources Investigations Report 02-4295

Prepared in cooperation with
SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT



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By Amy Swancar *and* Terrie M. Lee

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Tallahassee, Florida
2003

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS, DATUMS, AND ABBREVIATIONS

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
foot (ft)	0.3048	meter (m)
square foot (ft^2)	0.09290	square meter (m^2)
acre	0.4047	hectare (ha)
square mile (mi^2)	2.59	square kilometer (km^2)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per day (ft^3/d)	0.028317	cubic meter per day (m^3/d)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)

ACRONYMS AND ABBREVIATIONS

RMSE	root mean squared error
K	hydraulic conductivity
K_v	vertical hydraulic conductivity
K_h	horizontal hydraulic conductivity
r^2	coefficient of determination
USGS	U.S. Geological Survey

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

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ABSTRACT

Lake Starr and other lakes in the mantled karst terrain of Florida's Central Lake District are surrounded by a conductive surficial aquifer system that receives highly variable recharge from rainfall. In addition, downward leakage from these lakes varies as heads in the underlying Upper Floridan aquifer change seasonally and with pumpage. A saturated three-dimensional finite-difference ground-water flow model was used to simulate the effects of recharge, Upper Floridan aquifer heads, and model time scale on ground-water exchange with Lake Starr. The lake was simulated as an active part of the model using high hydraulic conductivity cells. Simulated ground-water flow was compared to net ground-water flow estimated from a rigorously derived water budget for the 2-year period August 1996-July 1998.

Calibrating saturated ground-water flow models with monthly stress periods to a monthly lake water budget will result in underpredicting gross inflow to, and leakage from, ridge lakes in Florida. Underprediction of ground-water inflow occurs because recharge stresses and ground-water flow responses during rainy periods are averaged over too long a time period using monthly stress periods. When inflow is underestimated during calibration, leakage also is underestimated because inflow and leakage are correlated if lake stage is maintained over the long term. Underpredicted leakage reduces the implied effect of ground-water withdrawals from the Upper Floridan aquifer on the lake.

Calibrating the weekly simulation required accounting for transient responses in the water table near the lake that generated the greater range of net ground-water flow values seen in the weekly water budget. Calibrating to the weekly lake water budget also required increasing the value of annual recharge in the nearshore region well above the initial estimate of 35 percent of the rainfall, and increasing the hydraulic conductivity of the deposits around and beneath the lake.

To simulate the total ground-water inflow to lakes, saturated-flow models of lake basins need to account for the potential effects of rapid and efficient recharge in the surficial aquifer system closest to the lake. In this part of the basin, the ability to accurately estimate recharge is crucial because the water table is shallowest and the response time between rainfall and recharge is shortest. Use of the one-dimensional LEACHM model to simulate the effects of the unsaturated zone on the timing and magnitude of recharge in the nearshore improved the simulation of peak values of ground-water inflow to Lake Starr. Results of weekly simulations suggest that weekly recharge can approach the majority of weekly rainfall on the nearshore part of the lake basin. However, even though a weekly

simulation with higher recharge in the nearshore was able to reproduce the extremes of ground-water exchange with the lake more accurately, it was not *consistently* better at predicting net ground-water flow within the water budget error than a simulation with lower recharge. The more subtle effects of rainfall and recharge on ground-water inflow to the lake were more difficult to simulate. The use of variably saturated flow modeling, with time scales that are shorter than weekly and finer spatial discretization, is probably necessary to understand these processes. The basin-wide model of Lake Starr had difficulty simulating the full spectrum of ground-water inflows observed in the water budget because of insufficient information about recharge to ground water, and because of practical limits on spatial and temporal discretization in a model at this scale.

In contrast, the saturated flow model appeared to successfully simulate the effects of heads in the Upper Floridan aquifer on water levels and ground-water exchange with the lake at both weekly and monthly stress periods. Most of the variability in lake leakage can be explained by the average vertical head difference between the lake and a representative Upper Floridan aquifer well. Simulated lake leakage was correlated ($r^2 = 0.86$) to the average head difference between the lake and a representative Upper Floridan aquifer well, suggesting that leakage was largely a linear function of this head difference.

The best estimate of weekly or monthly ground-water inflow can be derived using the water budget and simulated lake leakage. Ground-water inflow is calculated as a new residual to the water budget for Lake Starr after substituting the simulated values of lake leakage into the equation. Using this combined approach to calculate the ground-water inflow to Lake Starr gave gross inflow estimates of 15,689,000 and 20,778,000 cubic feet for the first and second years of the study, respectively (33 and 42 inches per year, respectively). Ground-water inflow was about 42 percent of the total inflow to the lake for the 2-year time period. Lake leakage was estimated to be 14,389,000 and 12,115,000 cubic feet per year for the first and second years, respectively (29 and 24 inches per year, respectively), and was 31 percent of the total outflow during the 2 years.

The linear regression between simulated lake leakage and average head difference between the lake and an index well provides a method for estimating leakage from Lake Starr beyond the modeled time period. Leakage estimates from the relation with head difference could be used along with a lake water budget to estimate ground-water inflow over any period that water budget and average head measurements in the index well are available.

INTRODUCTION

Ground-water inflow and lake leakage can be important components of lake water budgets (Stauffer, 1985; Crowe, 1989; Grubbs, 1995; LaBaugh and others, 1995; Sacks and others, 1998). Lake basins in the karst terrain of central Florida are subject to highly variable rainfall, both annually and seasonally, that affects the interaction between lakes and ground water. Ground-water withdrawals from the deeper Upper Floridan aquifer system, which also are time-variable, affect ground-water interactions with many of these lakes. Understanding the effects of changing rainfall patterns and ground-water withdrawals on lake water budgets is a fundamental requirement for water managers who must safeguard lake water levels and set limits on ground-water withdrawals from the underlying aquifers (Barcelo and others, 1990; Southwest Florida Water Management District, 1994).

Combining ground-water flow modeling of lake basins with detailed lake water budgets is a balanced approach to understanding the effects of hydrogeologic setting, climate and ground-water pumping on ground-water exchange (Lee, 1996; Lee and Swancar, 1997; Choi and Harvey, 2000; Swancar and others, 2000; Merritt, 2001). However, differences in the magnitude of ground-water exchange estimated by modeling and water budgets reveal ground-water flow processes inadequately accounted for by the models. To date, the U.S. Geological Survey (USGS) has used this combined approach to investigate five lakes in mantled karst settings in Florida (Grubbs, 1995; Lee, 1996, Lee and Swancar, 1997; Merritt, 2001). At the two seepage lake basins modeled in greatest detail, three-dimensional transient saturated ground-water flow models were used to simulate ground-water fluxes to and from the lakes. These fluxes were then compared with detailed monthly lake water budgets. The models underestimated ground-water inflow to the lakes for months with large rainfall totals when compared with the lake water budget (Grubbs, 1995; Lee, 1996).

During the driest periods, the models underestimated lake leakage. These models probably underestimated ground-water inflow in part because they failed to simulate the ground-water inflow generated by short-lived water-table mounds near the lakeshore. Rapid water table mounding has been simulated using a more detailed variably saturated ground-water flow model of a small portion of the lake basin, and daily boundary conditions (Lee, 2000). However, this process has not been evident in saturated flow models calibrated to monthly lake water budgets.

The weekly water budget of Lake Starr provides evidence that short-lived, water-table mounding affects ground-water inflow to the lake (Swancar and others, 2000). Water-table mounding was documented within 150 feet (ft) of the water's edge of Lake Starr during weeks with large ground-water inflows. The water budget of Lake Starr also suggests that ground-water pumping increased the lake leakage by lowering the potentiometric surface of the Upper Floridan aquifer for periods as short as weekly. If processes that occur within a week significantly affect lake water budgets, then calibrating flow models to weekly fluxes should clarify relevant processes for lakes in mantled karst terrain of central Florida. Improving our ability to simulate short-term ground-water exchanges with Florida lakes also should improve our estimates of annual ground-water exchanges.

Purpose and Scope

The purpose of this study is to (1) quantify ground-water inflow and lake leakage using a three-dimensional, saturated ground-water flow model of the Lake Starr basin, and (2) to investigate how representing the time-varying boundary conditions (recharge to the surficial aquifer system and the potentiometric surface of the Upper Floridan aquifer) affect simulated ground-water fluxes. Ground-water inflow to the lake and lake water leaking into the surficial aquifer system (hereafter referred to as lake leakage) were simulated over a 2-year period from August 1996 through July 1998. The two boundary conditions were represented spatially to different levels of detail, and were represented in transient simulations using both monthly and weekly averaged data.

Simulated values of net ground-water flow were compared with the more accurate net ground-water flow calculated from a rigorously derived lake water budget. The difference between the gross or total ground-water inflow and the gross lake leakage for any given time period is the net ground-water flow. The agreement between the two estimates of net ground-water flow indicated whether or not the representation of boundary conditions improved the simulation.

The model described in this report is based on a study of Lake Starr by Swancar and others (2000). The basin hydrogeology, weekly and monthly lake water budgets, and the occurrence of transient water-table mounds near the edge of the lake are described in that report. This report as well as the initial report by Swancar and others (2000) are extensions of a study by Sacks and others (1998), who used lake water budget and chemical and isotopic mass balance approaches to estimate ground-water exchange at Lake Starr and nine other central Florida lakes. All of these studies were funded cooperatively by the USGS and the Southwest Florida Water Management District.

Acknowledgments

The assistance of the property owners around Lake Starr in the monitoring efforts associated with this study was greatly appreciated. Thanks to Keith Halford for constructing a parameter estimation ground-water flow model on a hypothetical lake/ground-water system, and for helpful discussions. Thanks to Dick Yager for encouragement and assistance in using the one-dimensional unsaturated flow model to estimate recharge.

BACKGROUND

Lake Starr is representative of the many lakes in Florida's Central Lake District, an upland area of well-drained sand ridges (Brooks, 1981). It is a 135-acre lake (at a stage of 105 ft above NGVD of 1929) in a topographic basin with no natural surface drainage (fig. 1). Land and water-use in the Lake Starr basin also are representative of the region. Homes on relatively large (1- to 4-acre) lots surround the lake. Commercial citrus groves are located in higher parts of the basin. A few lakefront residents pump water directly from the lake for irrigation of landscaping or citrus trees, but this component of the lake water budget is estimated to be relatively small (less than 3 inches per year (in/yr), Swancar and others, 2000). Soils in the basin are mostly excessively drained fine-to-medium silica sands of the Candler series (Soil Conservation Service, 1990).

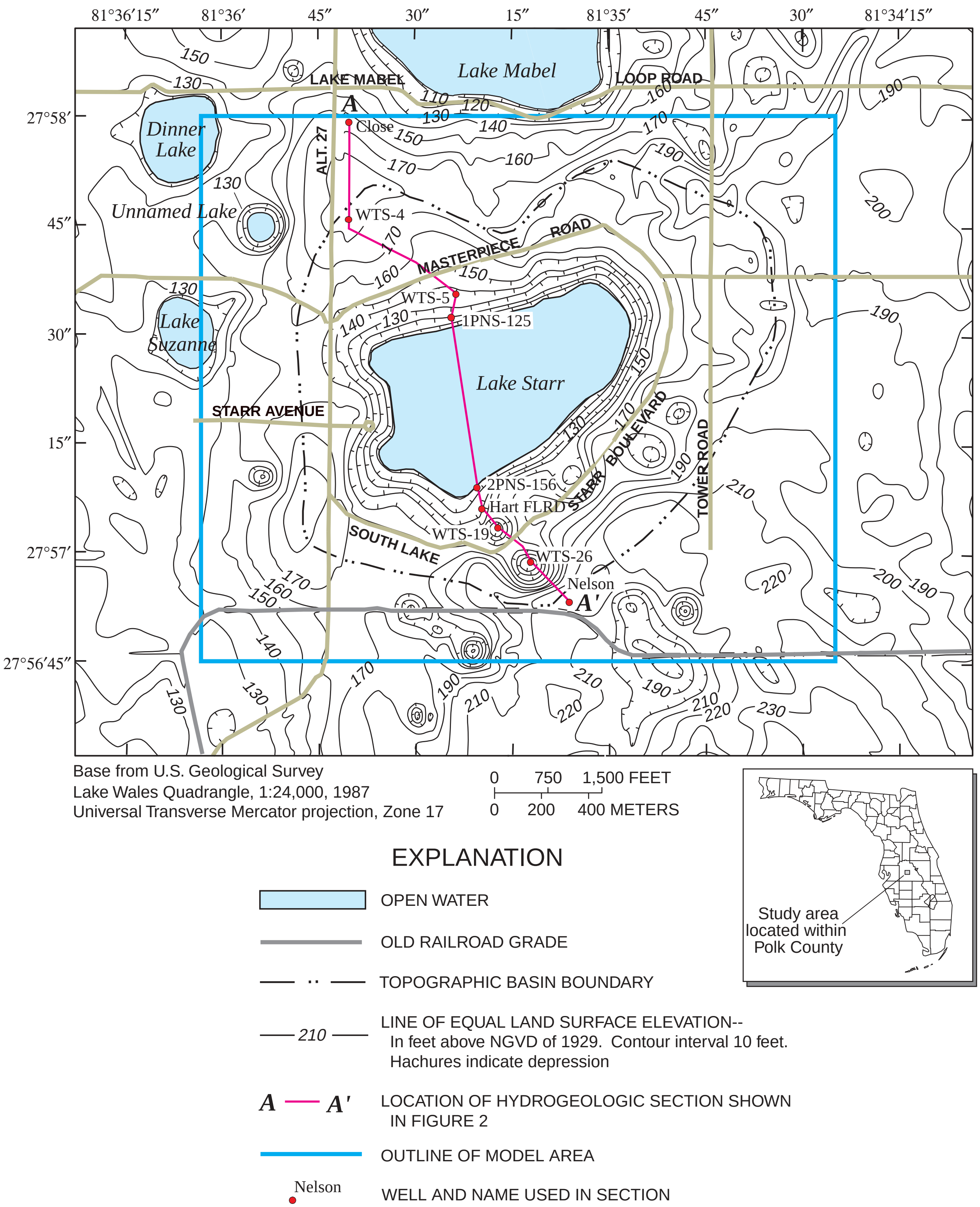


Figure 1. Topography and outline of model area of the Lake Starr basin.

Near the shoreline, the soils (Myakka series) are typically more organic and poorly drained because of shallow depths to the water table. Topography is controlled by sinkhole formation in this mantled karst terrain. Up to 200 ft of surficial sands and clays overlie a thick carbonate sequence that begins at about NGVD of 1929. The numerous lakes and sinkholes in the region result from collapse or subsidence of overlying sediments into voids formed by dissolution of the underlying limestone (Sinclair and others, 1985; Tihansky, 1999).

Hydrogeologic Setting

The two aquifers of interest in the study of the lake are the surficial aquifer system and the underlying Upper Floridan aquifer (fig. 2). The surficial aquifer system (Southeastern Geological Society, 1986) surrounds the lake and is comprised of unconsolidated sand and clay sediments. The water table in the surficial aquifer system is close to land surface near the lakeshore but is over 120 ft below land surface beneath the highest parts of the basin. A thin and discontinuous layer of clay, called the intermediate confining unit, underlies the surficial aquifer system and the lake. This unit separates the surficial aquifer system from the confined carbonate Upper Floridan aquifer, and ranges in thickness from 20 to 40 ft. Although breaches in the intermediate confining unit occur throughout the basin, they are most common on the southeast side of the lake. Breaches in the intermediate confining unit are formed by sinkholes that allow clays of the intermediate confining unit and sandy surficial deposits to be transported downward along columns or “pipes” into solution cavities in the underlying limestone aquifer. Two breaches exist under the deeper parts of the lake (Swancar and others, 2000).

The Central Lake District is a recharge area for the Upper Floridan aquifer, and water in the Lake Starr basin flows downward from the lake and the surficial aquifer system to the underlying Upper Floridan aquifer (Swancar and others, 2000). Recharge to the Upper Floridan aquifer is enhanced by breaches in the intermediate confining unit. The top of the Upper Floridan aquifer is about 30 ft above NGVD of 1929 on the west side of the basin and slopes downward to about 20 ft below NGVD of 1929 on the east side. Superimposed on this sloping limestone surface are depressions due to irregular dissolution and collapse.

Lake Starr is a flow-through lake with respect to the surficial aquifer system. Ground water flows into the lake on the northwest side, whereas water flows out of the lake into the surficial aquifer system on the southeast side of the lake (fig. 3A). In some lakes, the proportion of the lake’s perimeter that receives lateral ground-water inflow from its basin varies seasonally (Sacks and others, 1998; Metz and Sacks, 2002). At Lake Starr, however, the lakeshore areas experiencing ground-water inflow and outflow did not vary substantially during 3 years of data collection, except during periods during and immediately after large rain events. Contrary to the topography, ground water flows toward the highest hillside in the basin on the southeast side of the lake, which is also the direction of several conspicuous sinkholes (figs. 1 and 2).

Short-lived water-table mounding was observed in continuously monitored wells near the inflow and outflow sides of Lake Starr following rainstorms (Swancar and others, 2000). Mounds on the outflow side of the lake briefly reversed the flow direction, temporarily reducing lateral leakage and generating ground-water inflow. For example, during a particularly wet week (July 27-August 2, 1997), ground-water inflow to the lake from transient mounding could have generated one-half the volume of positive net ground-water flow calculated from the lake water budget for that week (Swancar and others, 2000). Flow reversals typically lasted less than a day. The duration and size of transient water-table mounds are related to the volume of rain, depth to water, topography, and soil properties and their degree of saturation.

The potentiometric surface of the Upper Floridan aquifer (a surface analogous to the water table, but for a confined aquifer) slopes downward from northwest to southeast across the lake basin, making the ground-water flow direction in this aquifer similar to that in the surficial aquifer system (fig. 3b). Heads in the Upper Floridan aquifer rose and declined more steeply than heads in the surficial aquifer system, and were strongly affected by local and regional irrigation pumping for citrus cultivation (fig. 4). The potentiometric surface of the Upper Floridan aquifer was highest in March 1998, following an unusually wet winter. On the west and northwest sides of the lake basin, heads in the Upper Floridan aquifer were very close to or higher than lake stage from December 1997 through March 1998. As a result, the potential was low for downward flow of water on the northwest side of the basin during this period. On the southeast side of the lake, heads in the

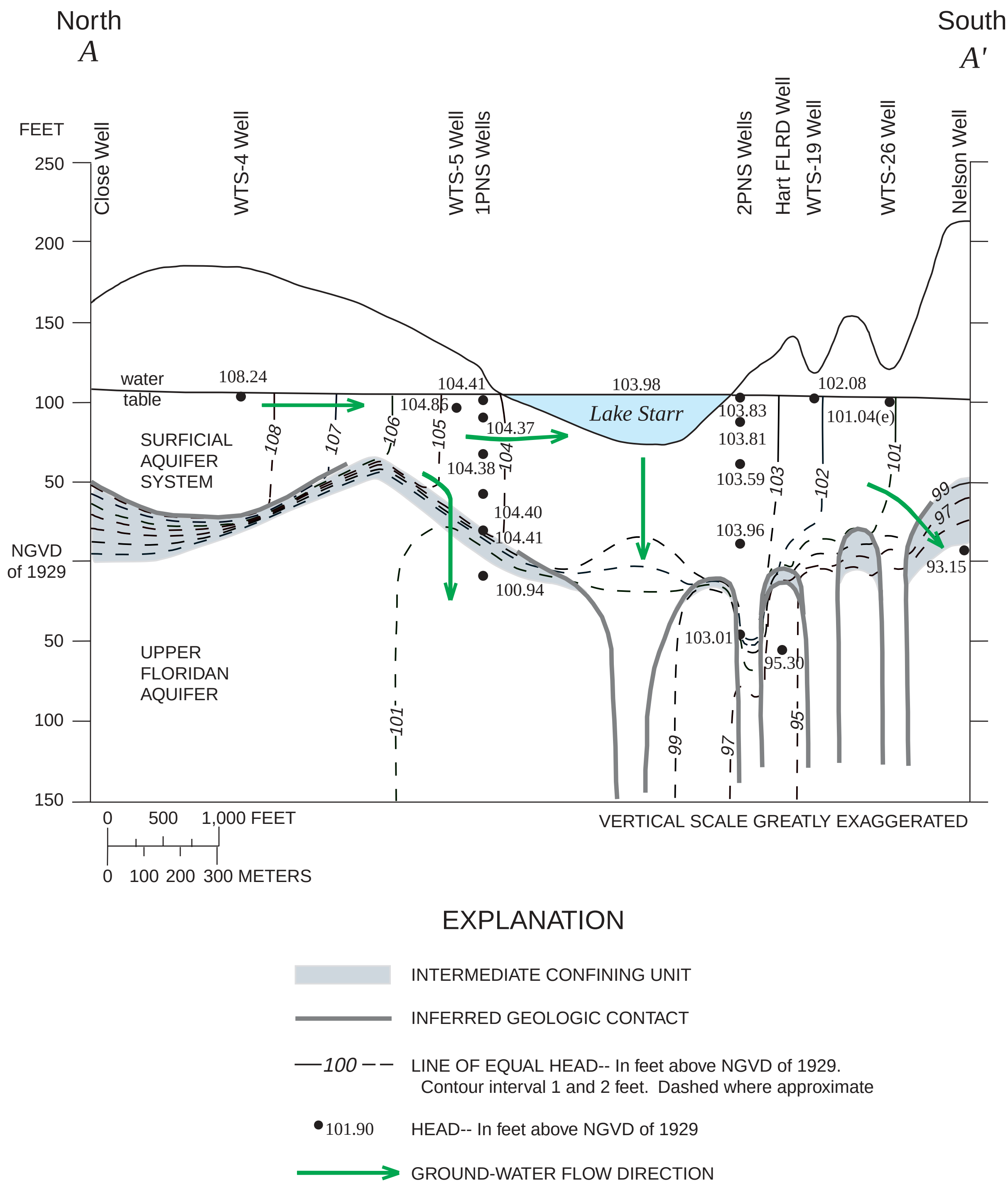
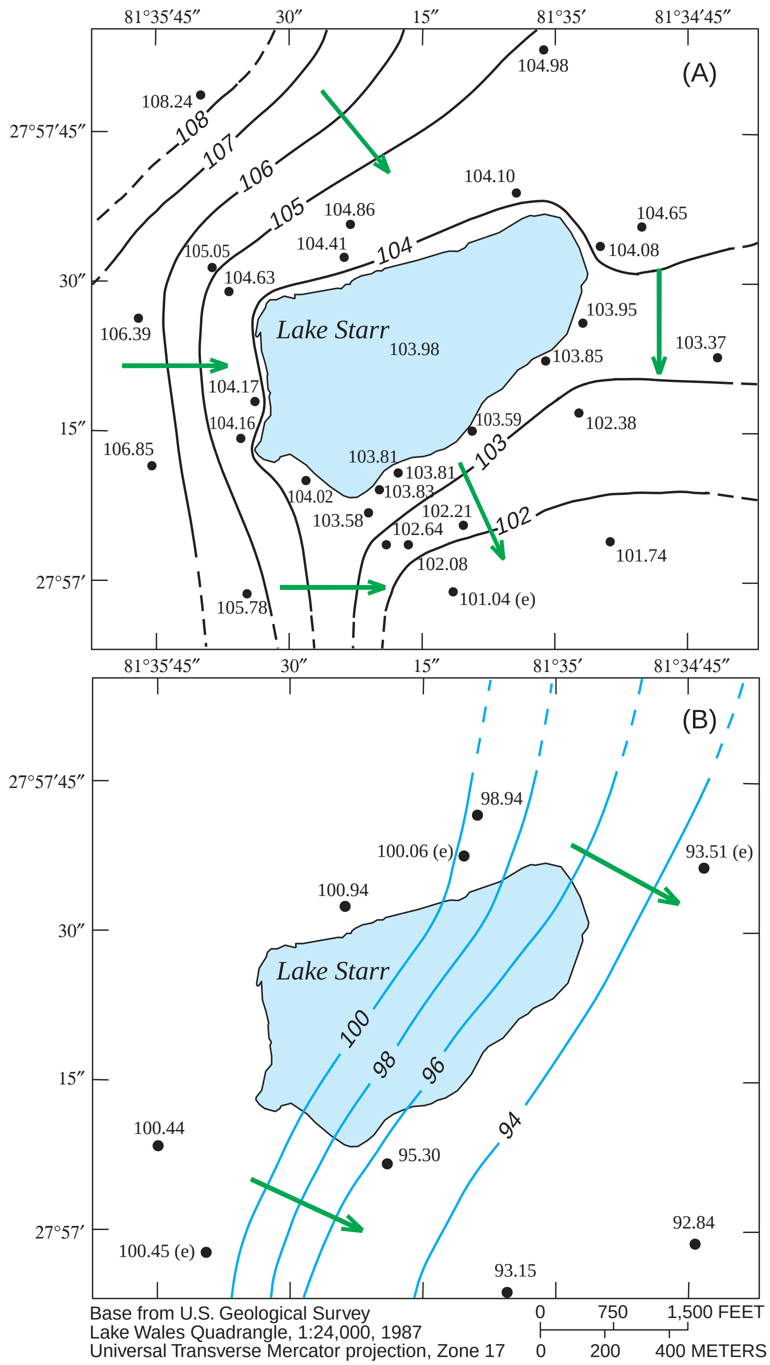


Figure 2. Vertical head distribution along section *A-A′* for representative low water-level condition, May 29, 1997, (line of section shown in figure 1).



EXPLANATION

– –108 —— LINE OF EQUAL WATER-TABLE ALTITUDE-- In feet above NGVD of 1929. Contour interval 1 foot. Dashed where approximate

—100– – POTENTIOMETRIC CONTOUR-- Showing altitude at which water would have stood in tightly cased wells. Contour interval 2 feet. Dashed where approximate. Datum is NGVD of 1929

100.45 ● OBSERVATION WELL-- Number is altitude of water level in well in feet above NGVD of 1929, (e) estimated value

→ GROUND-WATER FLOW DIRECTION

Figure 3. Maps showing (A) water table configuration and (B) potentiometric surface of the Upper Floridan aquifer in the Lake Starr basin for representative low water-level condition, May 29, 1997.

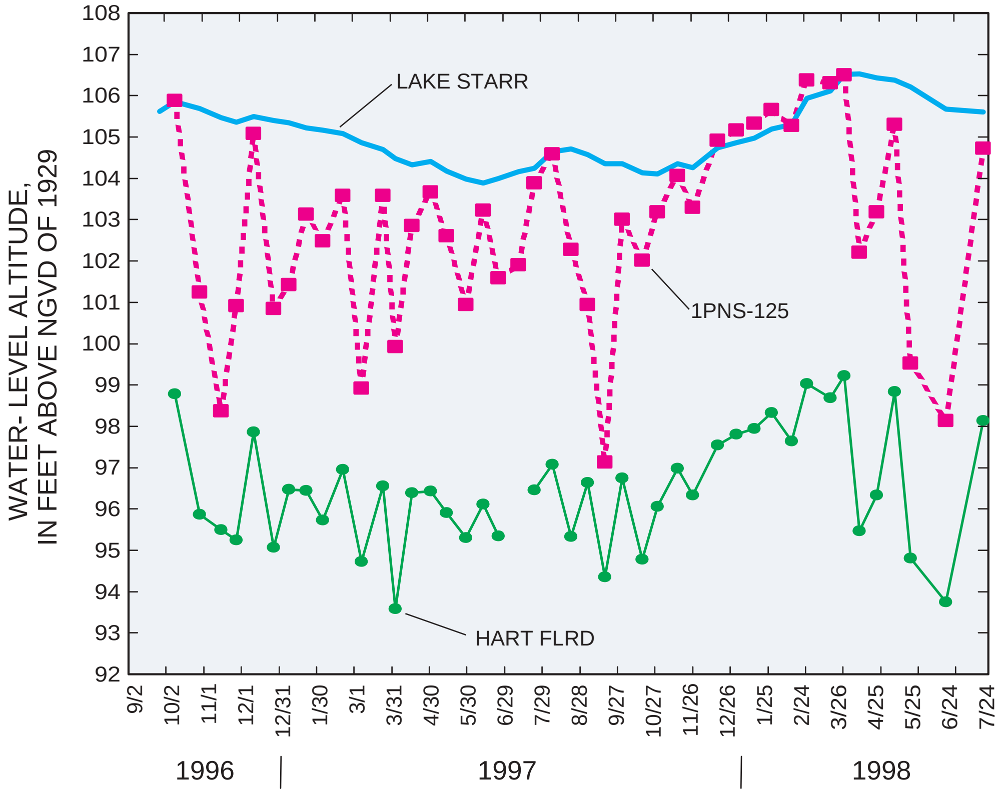


Figure 4. Hydrographs of selected Upper Floridan aquifer wells and Lake Starr stage (well locations shown on figure 1).

Upper Floridan aquifer were always at least 5 ft lower than the lake stage. The potentiometric surface of the Upper Floridan aquifer was lowest in the spring and early summer months (April, May, and June) of 1997 and 1998, when it was from 3 to 10 ft lower than the lake stage from the west to the east side of the basin, respectively.

Heads in the Upper Floridan aquifer responded differently to ground-water pumpage in different parts of the basin (fig. 4). Heads measured in wells on the northwest side of the lake showed steep rises and drops in response to pumping, whereas heads measured in wells on the southeast side of the basin showed a more moderated response. Measured heads in the Upper Floridan aquifer well 1PNS-125 on the northwest side of the basin ranged from 97.13 to 106.50 ft above NGVD of 1929, whereas heads in the Hart FLRD well on the southeast side ranged from 93.58 to 99.22 ft above NGVD of 1929. The difference in response is partly due to the 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 (figs. 1 and 2), indicate breaches in the intermediate confining unit that reduce confinement (Swancar and others, 2000).

On the south side of the lake, a nest of wells was drilled in an area where collapse of overlying units into the Upper Floridan aquifer had occurred. This nest of wells provided a unique opportunity to study the hydrologic character of a collapse feature. The deepest well at the 2PNS site (2PNS-156 for 156 ft below land surface), found sand at a depth of 46 ft below NGVD of 1929, or tens of feet below the top of the Upper Floridan aquifer in other areas of the basin (fig. 2). Sand instead of the limestone of the Upper Floridan aquifer at this altitude indicated collapse. The downward head difference between the lake and this well was statistically correlated to the head in a nearby Upper Floridan aquifer well (Hart FLRD well, see figs. 1 and 2) (r^2 (coefficient of determination) = 0.80, standard error = 0.073 ft), indicating a connection between the sinkhole and the aquifer. The downward head difference increased by about 0.1 ft for every 1 ft decrease in the

Upper Floridan aquifer head. Heads in well 2PNS-156 were consistently about 6 ft higher than heads in the Hart FLRD well, which is about 300 ft to the south of the 2PNS well nest. This substantial head difference indicates that even though a connection exists between the sinkhole and the aquifer, some degree of confinement is still in place between these two points.

Nearly all water for residential and agricultural use in the basin comes from wells drilled into the Upper Floridan aquifer. Irrigation of citrus groves is the largest water use. In the 6 square miles (mi^2) surrounding Lake Starr, 14 large-capacity, deep wells were permitted to pump ground water from the Upper Floridan aquifer at average rates from 100,000 to 284,600 gallons per day (gal/d) per well (J. Whalen, Southwest Florida Water Management District, written commun., 1999). Thirty-six permits for ground-water withdrawals averaging less than 100,000 gal/d also existed in this area in 1999. Pumping causes head declines of up to 15 ft in the Upper Floridan aquifer in the lake basin for short periods, and the region has been designated a Water-Use Caution Area by the Southwest Florida Water Management District because of concerns about the effects of ground water-use on both surface- and ground-water levels (Yobbi, 1996).

Water Budget Approach

Ground-water exchanges with Lake Starr computed using the lake water budget provide the basis for evaluating the accuracy of simulated ground-water flow to and from the lake. When a water budget approach is applied in detail, the errors in estimating net ground-water flow to the lake can be substantially less than those inherent in modeling approaches (Lee and Swancar, 1997). A detailed water budget was computed for Lake Starr for a 2-year period (July 20, 1996-August 1, 1998). Results are presented in Swancar and others (2000), and a brief summary of the water budget approach is presented below.

For a seepage lake with no surface-water inflows or outflows, net ground-water flow (the difference between ground-water inflow and outflow) can be calculated as a residual to the lake water budget using the equation:

$$\text{Net GW} = G_i - G_o = \Delta S - P + E + Q \pm e_{\Delta S} \pm e_P \pm e_E \pm e_Q \qquad (1)$$

where Net GW is the net ground-water flow to the lake during a given time period, ΔS is the change in lake volume for that time period, P is precipitation, E is evaporation, G_i is ground-water inflow, G_o is ground-water outflow or lake leakage, Q is irrigation withdrawal directly from the lake, and other terms are errors associated with each component. All of the terms are expressed in units of volume or as depths over the average lake surface area for the given period. Irrigation directly from the lake (Q) is a small loss term in the lake water budget for Lake Starr that can be of minor importance in its seasonal or annual water budgets. This term is not relevant for some lakes.

The net ground-water flow term is positive for periods when ground-water inflow exceeds outflow, and negative when outflow exceeds inflow. Positive values of net ground-water flow are sometimes referred to as net ground-water *in*flow, and negative values as net ground-water *out*flow. In this study, the net ground-water flow term derived from the water budget was used to track changes in the gross ground-water fluxes to the lake. For example, if net ground-water flow was negative in one week, and large and positive in the following week, the implication was that the lake received a large amount of ground-water inflow during the second week. Lake leakage also may have been reduced, but generally this change is due to a large increase in ground-water inflow associated with a recharge event.

As shown in equation 1, the Net GW term includes the errors in the other water budget components. For some time periods, this error can approach the size of the net ground-water term, making the interpretation difficult. In general, errors expressed as a percentage increase for shorter time periods and decrease for longer periods. Errors in monthly water budget terms were assumed to be 5 percent for rainfall, 15 percent for evaporation, 5 percent for change in stage, and 100 percent for direct pumping from the lake. For weekly water budgets, rainfall error was assumed to be 10 percent, and for annual water budgets, evaporation error was assumed to be 10 percent (Swancar and others, 2000). The overall error is the square root of the sum of the individual errors squared (Winter, 1981):

$$e_{\text{net GW}} = [(e_{\Delta S})^2 + (e_P)^2 + (e_E)^2 + (e_Q)^2]^{1/2} \qquad (2)$$

Runoff to the lake was assumed to be negligible in the water budget. During a few intense storms, hourly increases in stage were sometimes slightly greater than the measured rainfall, which could be interpreted as either runoff or transient ground-water inflow. These discrepancies also could be due to errors in the rainfall and stage measurements. The assumption that runoff is negligible is reasonable because basin soils are excessively drained and most of the basin is unpaved. Even if runoff does occur rarely, it is unlikely that the volume of runoff from the basin exceeds the 10 percent error assumed for the measurement of rain falling directly on the lake.

Monthly water budget terms for Lake Starr for the 2-year period August 1996 through July 1998 are shown in figure 5. 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. Overall, the lake lost water the first year (-4.9 inches) and gained water the second year (+12.7 inches).

The annual net ground-water flow was positive in both years of the study (3.9 inches the first year and 17.5 inches the second year), indicating that ground-water inflow was greater than lake leakage. Positive net ground-water flow occurred mainly in months with positive net precipitation (rainfall minus evaporation), but also occurred in drier months that followed periods of high rainfall (fig. 5). For example, despite low rainfall in April and May 1998, net ground-water flow continued to be positive in response to above average rainfall from November 1997 through March 1998. Negative net ground-water flow typically occurred in drier months when net precipitation was negative. 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. Ground-water inflow was higher during the second year because half of the rainfall occurred in the winter when evapotranspiration losses were smaller, resulting in greater recharge to the ground-water basin. Lake leakage was probably reduced during the second year because the head in the Upper Floridan aquifer was higher (Swancar and others, 2000).

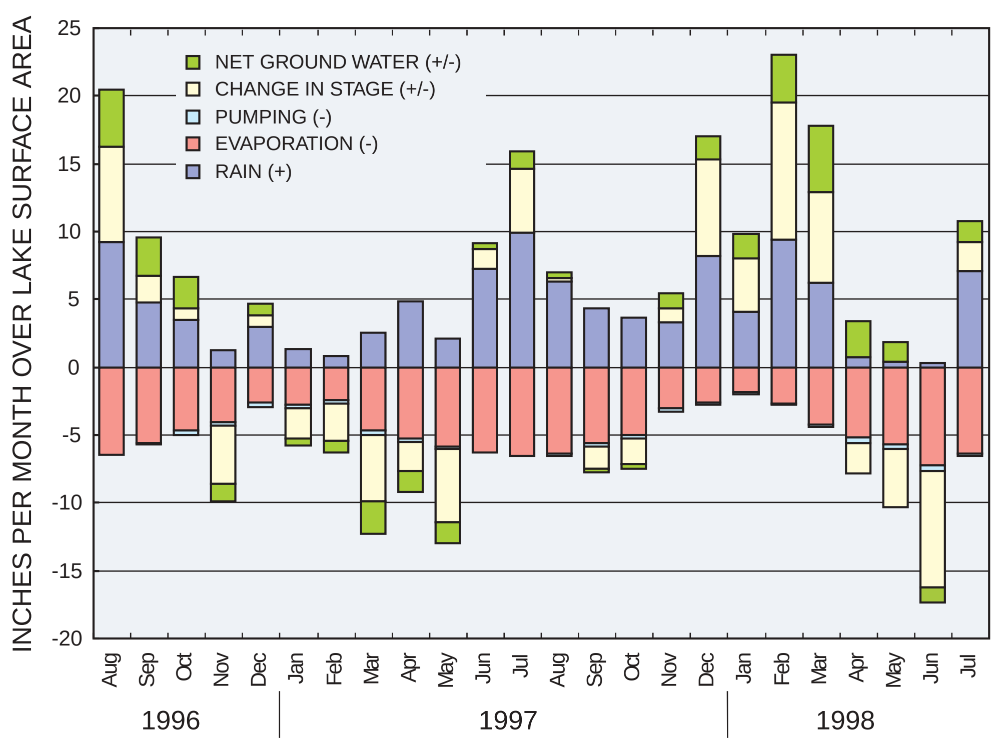


Figure 5. Monthly water-budget terms for Lake Starr, August 1996 through July 1998.

The water budget indicated that ground-water exchange with Lake Starr was responsive to the short-term fluctuations in Upper Floridan aquifer heads. Weekly and monthly net ground-water flow was correlated to the head in the Upper Floridan aquifer. Swancar and others (2000) found that changes in weekly average head in the Upper Floridan aquifer could account for 59 percent of the variability of weekly net ground-water flow to Lake Starr. Sacks and others (1998) also inferred the potential for increased leakage from some lakes in response to changes in Upper Floridan aquifer heads on a weekly or shorter time scale. The daily drop in lake stage at several lakes in the Central Lakes District (for days without rainfall) was found to be greatest for days with air temperatures below freezing. These were the same days when heavy ground-water pumpage, and steep declines in Upper Floridan aquifer heads, were most likely to occur as a result of irrigating the local citrus crop for freeze protection.

The water budget analysis also indicated that ground-water inflow to Lake Starr was highly variable from week to week. Months with large, positive net ground-water flow typically resulted from only 1 or 2 weeks with large amounts of net ground-water inflow. Weeks with large net ground-water inflows typically had one or two large daily rainfall events and showed transient water-table mounding and flow-reversals near the shoreline. Because *daily* rainfall and recharge processes had an important effect on ground-water inflow, the weekly and monthly net ground-water flows were not well correlated to the weekly or monthly total rainfall or net precipitation (Swancar and others, 2000).

DESCRIPTION OF THE GROUND-WATER MODEL

A three-dimensional finite-difference numerical ground-water flow model of the Lake Starr basin was constructed using the USGS model code MODFLOW (McDonald and Harbaugh, 1988). The model simulated ground-water flow in the surficial aquifer system and the intermediate confining unit within a 3-mi^2 area surrounding Lake Starr (fig. 1). The model also simulated Upper Floridan aquifer heads in cells where the head was not specified. The model consisted of 98 rows and 105 columns of cells that were 100 by 100 ft (fig. 6). The active part of the model was 78 rows by 79 columns. The outer 10 rows (on the north and south sides) and 10 and 16 columns (on the west and east sides, respectively) were used to test boundary conditions, and were inactive in most simulations. In addition, the northeast corner of the model (approximately 192,000 ft^2) also was inactive in most simulations (fig. 6). The steady-state model consisted of 22 layers that varied in thickness from 1 to 91 ft (fig. 7). On the southeast side of the lake, the bottom of model layer 1 was lowered so that the simulated water table stayed within layer 1 during transient simulations. The steady-state model contained more layers than the transient model. To reduce the running time, the number of layers was reduced to 16 for transient simulations. For transient simulations, layers 12-14 and 15-17, which represented the deep surficial aquifer system and the intermediate confining unit, respectively, were combined into two layers. Layers 18-20, which represented the shallow Upper Floridan aquifer, also were combined into one layer. Porosity of hydrogeologic units throughout the model was 0.3, specific storage was 5 x 10^{-5}, and specific yield of the surficial aquifer system was 0.2 per ft.

Hydrogeologic Units in the Model

The representation of hydrogeologic units in the model was based on geologic and geophysical logs of wells in the basin, and sublake geology interpreted from a seismic reflection survey of the lake (Swancar and others, 2000). Initial estimates of hydraulic properties of different hydrogeologic units were from field measurements or other references (Lee, 1996; Yobbi, 1996; Lee and Swancar, 1997). Values of hydraulic parameters were adjusted within realistic ranges during model calibration to improve the simulation of heads in the basin and ground-water exchanges with the lake. Calibrated values for parameters used in the steady-state simulation are listed in table 1.

Surficial Aquifer System

The uppermost 14 layers of the steady-state model (12 for transient) represented the surficial aquifer system. The horizontal hydraulic conductivity (K_h) values for the surficial aquifer system were estimated from slug tests made in wells in the basin and ranged from 1 to 60 ft per day (ft/d). Slug tests indicated that deeper wells had lower K_h (1-10 ft/d) compared to shallow wells (20-60 ft/d). Hydraulic conductivity (K) of the surficial aquifer system was assumed to decrease with depth below land surface. Modeled K_h values were reduced throughout the surficial aquifer system in

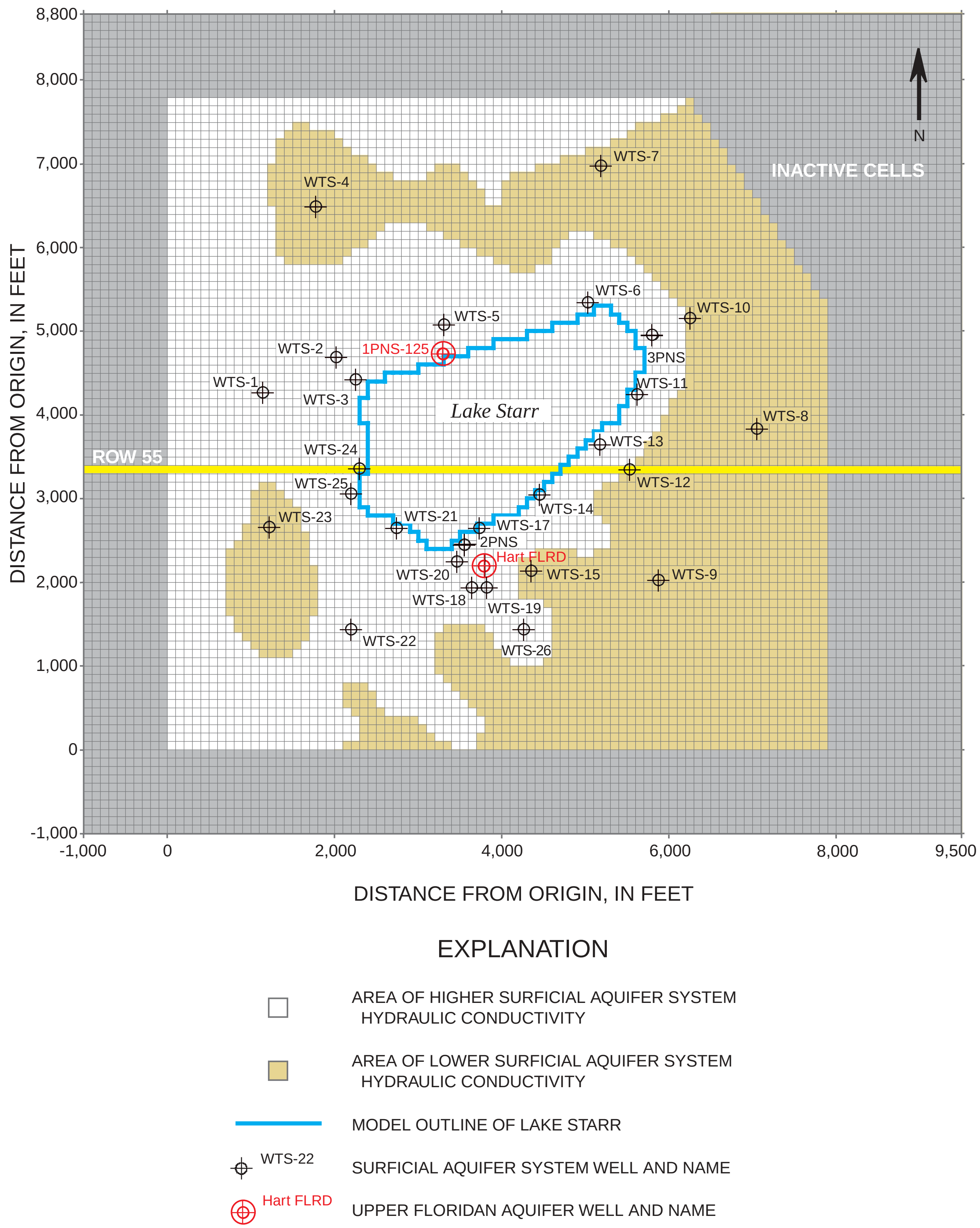


Figure 6. Model grid and location of monitor wells.

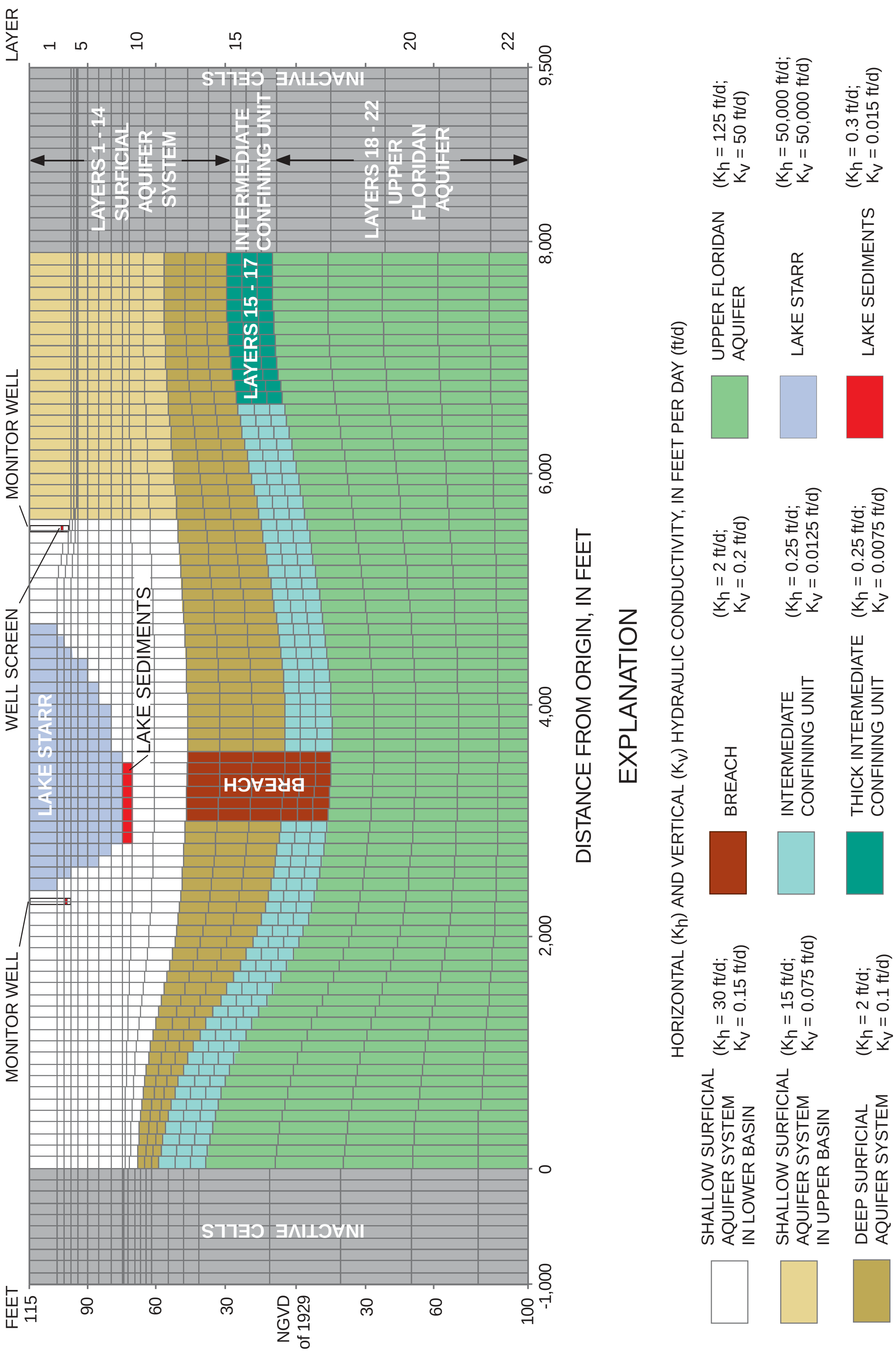


Figure 7. Vertical discretization and calibrated values of hydraulic conductivity for steady-state simulation along row 55.

Table 1. Calibrated values of hydraulic parameters used in the steady-state model

[K_h, horizontal hydraulic conductivity; K_v, vertical hydraulic conductivity]

Parameter	Value	
Recharge (inches per year)		
Basin recharge	18	
Lake recharge	-4	
Hydraulic Conductivities (feet per day)	K_h	K_v
Lake	50,000	50,000
Lower basin surficial aquifer system	30	1.5
Upper basin surficial aquifer system	15	0.75
Deep surficial aquifer system	2	0.1
Upper Floridan aquifer	125	50
Intermediate confining unit	0.25	0.0125
Thicker confining unit	0.25	0.0075
Breaches in confining unit	2	0.2
2PNS "wall" [1]	0.02	0.001
Lake sediments	0.3	0.015
Anisotropy (ratio of horizontal to vertical K)		
Breaches	10:1	
Lake	1:1	
Upper Floridan aquifer	5:2	
Rest of model	20:1	

[1] The 2PNS "wall" simulates confining conditions on the sides of a collapse feature.

the upper basin because of the increased depth to water and in the deepest surficial aquifer system (layers 12-14) to reflect this relation (fig. 7). Anisotropy (the ratio of horizontal to vertical hydraulic conductivity) was specified as 20:1 for most of the model. However, anisotropy was decreased to 10:1 in model cells representing breaches in the confining unit to reflect increased vertical hydraulic conductivity (K_v) caused by disruption of sediment layering.

Intermediate Confining Unit

Layers 15-17 in the steady-state model (layer 13 in transient models) represented the intermediate confining unit where this unit was present in the subsurface, and breaches in the intermediate confining unit where confinement was locally absent. Reducing the intermediate confining unit from three layers to one for transient simulations did not affect the head difference across the unit. Whether one or three layers were simulated, this unit had a uniform thickness of 20 ft in the model; for steady-state simulations, the K values are specified in table 1. Where the intermediate confining unit was represented in the model, K_h was 0.25 ft/d and K_v was 0.0125 ft/d; where breaches were represented, K_h was 2 ft/d and K_v was 0.2 ft/d (fig. 8). In areas of the basin where the intermediate confining unit was thicker than 20 ft (primarily the east side of the basin, see fig. 8), a lower K_v (0.0075 ft/d) was specified for the cells in this layer. Hydraulic properties for the intermediate confining unit and the Upper Floridan aquifer used in the model were similar to those used in other flow models of these units (Lee, 1996; Yobbi, 1996; Lee and Swancar, 1997). The altitude of the bottom of the intermediate confining unit conformed to the top of the Upper Floridan aquifer.

Upper Floridan Aquifer

Layers 18 through 22 represented the Upper Floridan aquifer throughout most of the steady-state model (layers 18-20 for transient). Because the Upper Floridan aquifer was treated as a specified-head boundary, it could have been modeled as a single layer except for the need to simulate a breach that extended downward into the aquifer in a small area near the lake on the south side, surrounding the 2PNS well nest (fig. 1). The specified-head boundary acted as a discharge zone (sink) for the model because all of the water that enters the basin as recharge was either lost to lake evaporation or flow to the Upper Floridan aquifer. The K_h and K_v values of the Upper Floridan aquifer were 125 and 50 ft/d, respectively (table 1 and fig. 7).

Breaches in the Intermediate Confining Unit

Breaches in the intermediate confining unit were represented in parts of the basin where sinkholes were indicated by well logs or seismic data (fig. 8). Sinkholes were also assumed to underlie closed topographic lows in the land surface, including other lakes within the modeled area. Breaches in the intermediate confining unit were represented by areas that had hydraulic properties similar to the overlying surficial aquifer system. The thickness of the unit, the size of the breaches, and the hydraulic properties of the confining unit and breaches control ground-water flow across these layers. It is possible that a number of slightly different representations of sinkholes in the model could produce the same leakage rate across the confining unit to the Upper Floridan aquifer. For example, making sinkholes either larger or leakier can increase leakage across the layer(s) that represent the intermediate confining unit.

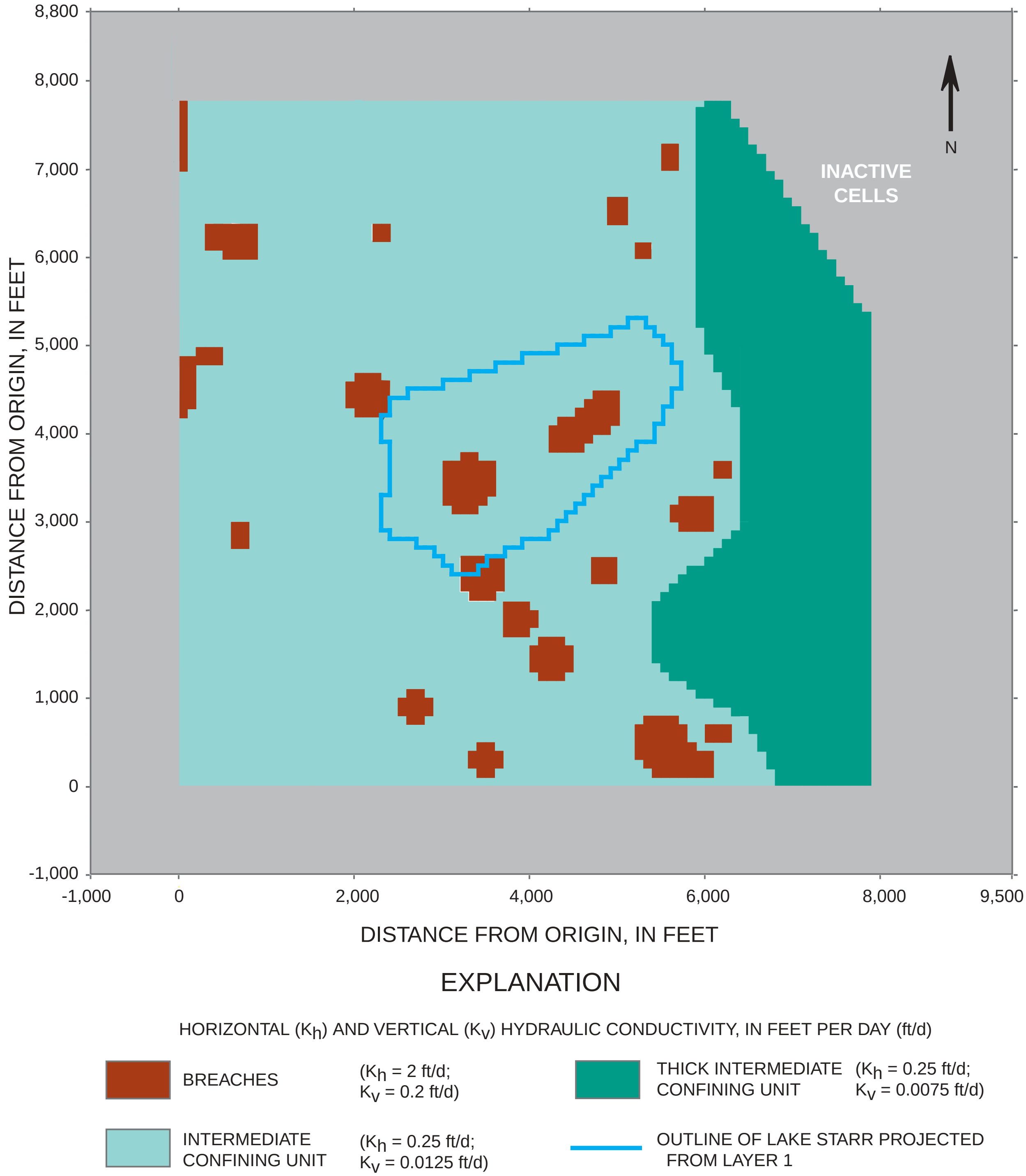


Figure 8. Spatial distribution of hydraulic conductivity of the intermediate confining unit for the steady-state model.

A collapse feature (sinkhole) that encompasses well nest 2PNS was represented in the model by a vertical shaft into the Upper Floridan aquifer that was infilled with surficial aquifer system materials (fig. 9). To simulate the observed head difference between 2PNS-156 and the Hart FLRD well, low-conductivity cells that retarded flow into the surrounding Upper Floridan aquifer cells were placed around this column of sandy material (2PNS “wall,” fig. 9).

Method Used to Simulate Lake Starr

Lake Starr was represented as an area of active cells in model layers 1 to 8 (fig. 6 and 7). In steady-state simulations, lake cells had a uniform K value of 50,000 ft/d, whereas in transient simulations the value was 10,000 ft/d. Values higher than these caused problems with numeric convergence. For the lake cells, a storage coefficient of 0.999 was specified because the model preprocessor (Visual MODFLOW; Guiguer and Franz, 1997) would not allow a storage coefficient of 1. The large K of lake cells resulted in a low head gradient across the lake. The simulated head gradient across the lake surface was typically less than or equal to 0.05 ft in a 1,000 ft distance, or 5×10^{-5}.

In transient simulations, the lake stage and volume fluctuated in the top model layer (layer 1) in response to changes in net recharge to the lake and to flows to and from other parts of the model (ground-water exchanges). The lake volume in underlying model layers was constant. Stage-volume-area relations for the lake are given in Swancar and others (2000). A thin layer of lake sediments was simulated beneath the deeper parts of the lake in layer 9 of the model. Sediments at Lake Starr are relatively thin (maximum thickness 5 ft), and cover only about a quarter of the lake bottom (Swancar and others, 2000).

The lake area in the top layer was fixed at 5,900,000 square ft (ft^2), an area that corresponds to an altitude of 105.00 ft above NGVD of 1929. The error associated with using a fixed area for the top layer of the lake was always less than 0.05 ft of lake stage, or 0.3 percent of the average lake volume during the study period. This calculation is based on the difference between the simulated volume at the stage farthest from 105.00 ft that occurred during the study (106.56 ft), and the measured volume at that altitude. Because the stage never changed this much within a model stress period, the error in individual time periods would always be less. The error associated with using a constant surface area could be unacceptable in some applications, especially if the surface area changed rapidly as stage changed. These effects could be minimized by using methods described in Cheng and Anderson (1993) or Merritt and Konikow (2000).

Boundary Conditions for Steady-State Simulations

Three boundary conditions were used to characterize the ground-water flow system in the Lake Starr basin: (1) a lateral no-flow boundary, (2) an upper specified-flow (recharge) boundary, and (3) a lower specified-head (Upper Floridan aquifer) boundary.

Lateral Boundaries

Lateral model boundaries were specified as no-flow boundaries in all steady-state and transient simulations. The northern, southern, and eastern boundaries of the model coincided with lateral ground-water flow paths, where ground water flowed along the boundary rather than across it. In addition, the predominance of vertical ground-water flow in the Lake Starr basin meant that lateral boundaries could be treated as no-flow boundaries if they were sufficiently far from the lake so that horizontal ground-water flow components at the boundary were minimal. The western model boundary was not along a horizontal flow path based on water-table configuration, but was in an area where flow was predominantly vertical. Despite deviating from the ideal conditions for a no-flow boundary on the west side of the model, all of the lateral model boundaries were sufficiently far enough away from the lake so that the effect of the boundary condition on ground-water flow to and from the lake was minimal. Extending the boundaries farther out on all sides by 1,000 ft for both steady-state and transient simulations increased net ground-water flow to the lake by less than 5 percent. Nearly all of the water that entered the model as recharge in the area beyond the original model boundary flowed downward to the Upper Floridan aquifer rather than to the lake.

Previous studies of lake basins have simulated lateral boundaries using specified heads to represent nearby lakes (Lee, 1996; Merritt, 2001). Representing lakes that surround the Lake Starr topographic basin (Dinner, Suzanne, and Mabel, see fig. 1) with specified-head boundaries in steady-state simulations did not affect the shape of the simulated water table or ground-water exchange with the lake. The model

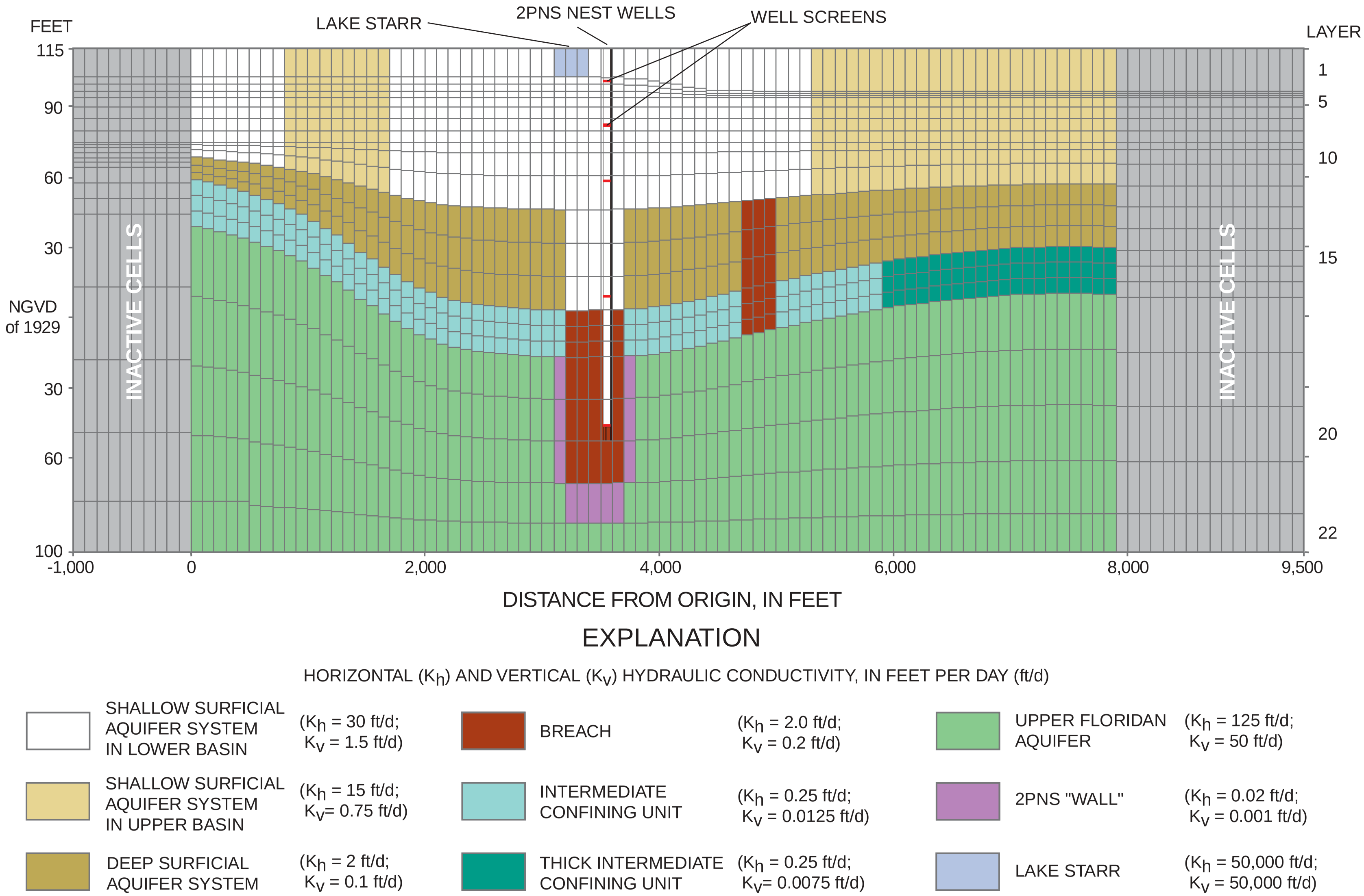


Figure 9. Model row 64 through 2PNS piezometer nest wells showing hydraulic conductivity zones used in steady-state simulation.

produced water-table altitudes in these parts of the model that were similar to the observed stages of the surrounding lakes without the use of specified heads.

Recharge

The upper boundary of the ground-water and lake flow system was defined by the water-table and lake surface. Recharge to the surficial aquifer system and the lake was represented as a specified flux to the upper boundary of the model. The location of the upper boundary is partially determined by the flux of water (recharge) applied to the uppermost active cell. Recharge to the lake was net precipitation, computed as the difference between rainfall and evaporation for a given time period. Rainfall and evaporation were measured at Lake Starr using a tipping-bucket rain gage at the edge of the lake and the energy-budget method, respectively (Swancar and others, 2000). For steady-state simulations, recharge to the lake was -4 in/yr, indicating that on average, evaporation exceeded precipitation over the lake during the study period. The contribution of runoff from the basin to lake recharge was assumed to be negligible.

Steady-state simulations were calibrated to average conditions during the 2-year study, which were assumed to be similar to long-term climatic conditions. Annual rainfall during the study (50.68 and 54.09 inches per year for August 1996 through July 1997 and August 1997 through July 1998, respectively) was close to the long-term average of 51.99 inches per year.

Initial estimates of the recharge rate to the surficial aquifer system in the steady-state simulation were based on a chloride mass-balance between rainfall and shallow ground water. Assuming the chloride mass is conservative, the chloride concentrations in rain and ground water (measured where land-use effects on chloride concentrations are expected to be negligible) can be used to estimate the percentage of rain that reaches the ground-water system. Using this method, recharge to the surficial aquifer system was estimated to range between 28 and 37 percent of average annual rainfall (L.A. Sacks, U.S. Geological Survey, written commun., 1998), or between 15 and 19 in/yr. In similar upland settings in other parts of the State, Lee (1996) estimated recharge to be 26 percent of the annual rainfall during a drought year based on a calibrated model, whereas Sumner (1996) found that rainfall minus evapotranspiration was between 43 and 53 percent of rainfall during a year with average rainfall. In steady-state simulations, average recharge to the surficial aquifer system was assumed to be 35 percent of rainfall, or 18 in/yr, and recharge rates ranging from $\pm$25 to $\pm$50 percent were considered in the sensitivity analysis.

Upper Floridan Aquifer

The lower boundary of the ground-water flow system, which represents the Upper Floridan aquifer, was defined by a specified-head boundary. In steady-state simulations, head was specified in all of layer 22 and in the parts of layers 18 and 21 that represented the Upper Floridan aquifer. The steady-state specified-head boundary was defined by a potentiometric surface contoured to median heads observed in 10 Upper Floridan aquifer wells in the basin (fig. 10). Heads in these wells were measured or estimated biweekly (Coffin and Fletcher, 1998, 1999; Swancar and others, 2000). The highest head in the steady-state potentiometric surface occurred at the western boundary (106.50 ft), and the lowest head was at the southeastern corner (92.24 ft).

Boundary Conditions for Transient Simulations

During transient simulations, recharge and Upper Floridan aquifer specified heads were redefined for different blocks of time. The convention of McDonald and Harbaugh (1988) and Anderson and Woessner (1992, p. 206) was followed; these blocks of time are referred to as “stress periods.” Other external stresses on the flow system, such as pumping from wells, were absent from the simulations. The effects of ground-water pumpage were incorporated into the model through the Upper Floridan aquifer boundary. Because only boundary conditions changed with time, a stress period in this report is synonymous with the term “boundary stress period” used in the MODFLOW documentation (McDonald and Harbaugh, 1988).

Transient simulations represented variations in recharge and head in the Upper Floridan aquifer over a 27-month period from May 1996 through July 1998. Transient simulations were prepared using monthly and weekly stress periods to assess the sensitivity of results to the length of the stress period. Transient simulations were begun 3 months before the study period (August 1996-July 1998) to minimize the effect of initial conditions on the transient results. Initial head conditions for transient simulations came from a steady-state simulation that was calibrated to ground-water levels

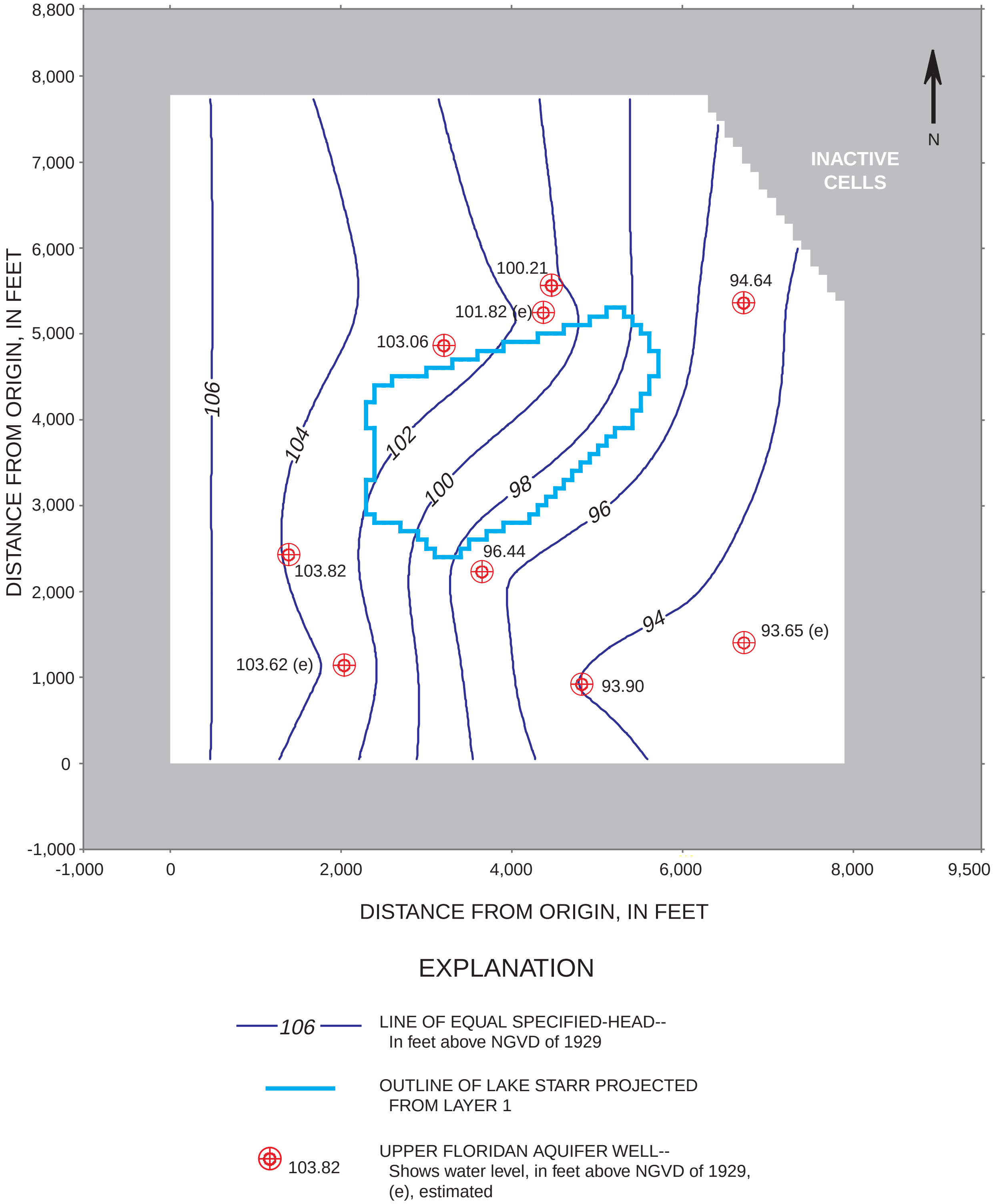


Figure 10. Upper Floridan aquifer heads specified in steady-state simulation.

observed in early May 1996. Weekly stress periods corresponded to periods over which water budgets already had been calculated (Swancar and others, 2000). These “weekly” periods were nearly all 7 days in length, but ranged from 5 to 13 days because of a few periods of missing record that affected the evaporation calculation.

Comparison of the weekly and monthly simulations reveals how stress-period length affects interpretation of the flow system. Shortening the stress period from monthly to weekly greatly increases the variability in recharge because, typically, most of the rain that falls within a month actually occurs within a few days. This variability changes some of the underlying presumptions in the model. Namely, the increased variability of recharge requires that the ground-water flow system respond more quickly to the imposed stress. Thus, the weekly model is expected to be fundamentally different from the monthly model because it presumes a system that responds more rapidly to stresses.

Recharge

In transient as well as steady-state simulations, recharge to the water table was calculated as a function of rainfall. But for transient simulations, the timing of recharge was lagged behind rainfall events to reflect the traveltime through the unsaturated zone (table 2). The basin was divided into seven zones based on the thickness of the unsaturated zone (fig. 11). The time delay in each zone was determined by computing the time delay between peak lake stage and peak ground-water levels at 26 water-table wells in the basin (see fig. 6 for well locations). An average time delay was computed for each well, and these delays were applied to areas of the model where the land-surface altitude was within the same altitude range as the well (table 2). Land-surface altitude was a fairly accurate indicator of the unsaturated zone thickness because the water table was relatively flat compared to the land surface.

Three methods were used to compute recharge to the surficial aquifer system during transient simulations. To compare the results, each method was adjusted to deliver the same total amount of recharge over the 2-year water budget period. This amount of recharge was initially specified as 35 percent of the total rainfall for the 2 years of the study. In later transient simulations, total recharge in some parts of the

Table 2. Depth to water, land-surface altitude, and assumed time delay for recharge to reach the water table

[<, less than; >, greater than; altitudes relative to National Vertical Geodetic Datum of 1929]

Depth to water (feet)	Land-surface altitude (feet)	Time delay (days)
0-20	<125	0
21-40	126-145	10
41-60	146-165	25
61-80	166-185	35
81-100	186-205	45
101-120	206-220	55
121-140	>220	65

model was revised to as high as 86 percent of the 2-year rainfall. The three methods distributed this total recharge differently within the 2-year timeframe.

The first method simply assumed that recharge over the stress period was equal to a fixed percentage (35 percent initially) of the rainfall within the stress period. The second method accounted for evaporation losses and intensity of rainfall by weighting larger rain events more heavily than smaller events, so that larger events generated more recharge. Rainfall events beneath a certain threshold contributed no recharge, and when daily rainfall was less than daily evaporation, recharge was assumed to be zero. This method was based on that of Lee (1996), and is referred to as the “threshold” method in this report.

Daily threshold recharge was estimated using the equation:

$$\text{Recharge} = (\text{Total daily rainfall} - \text{monthly average evaporation}) * WF \qquad (3)$$

where WF is the weighting factor and all units are in inches per day (in/d) except for the weighting factor, which is dimensionless. The weighting factor was defined as follows for threshold recharge summing to 35 percent of the 2-year rainfall:

Daily net precipitation (Inches)	Weighting factor (unitless)
<0.50	0.10
0.50-0.74	0.25
0.75-0.99	0.35
1.00-1.24	0.50
1.25-1.39	0.60
1.40-1.99	0.70
2.00-2.99	0.80
<3.00	0.95

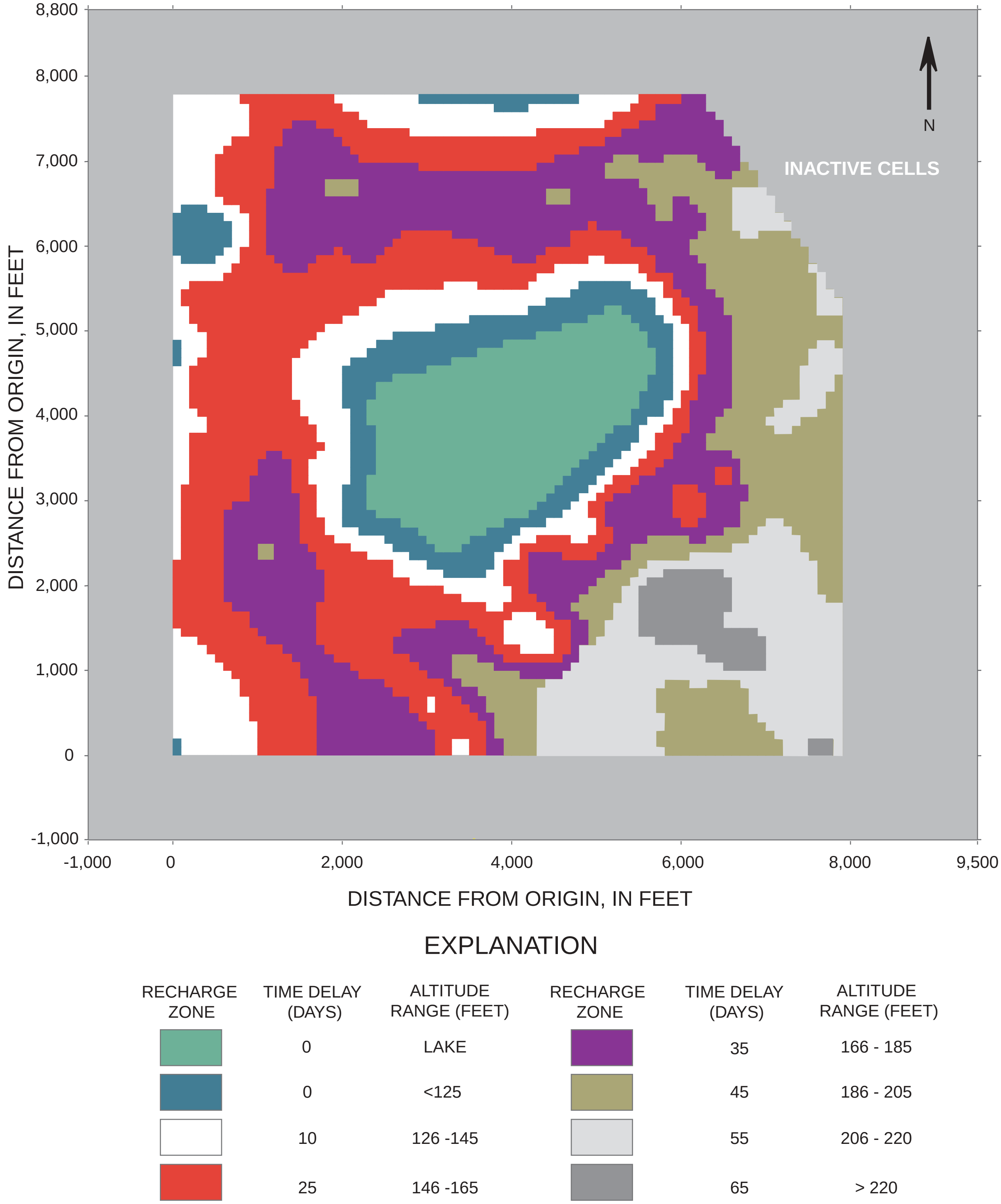


Figure 11. Simulated recharge zones depicting estimated time delay between rainfall and recharge at the water table.

The third method for estimating recharge used the one-dimensional unsaturated flow model LEACHM (Hutson and Wagenet, 1992). Daily recharge calculated by LEACHM is based upon daily rainfall, the physical character and moisture status of the soils above the water table, and losses attributed to evapotranspiration. This method performed a daily accounting of water stored in the unsaturated zone. Using this method, a storm occurring during a wet period generated more recharge than a similar storm during a drier period because available storage in the unsaturated zone was already used up. LEACHM can simulate both water and chemical transport, but only the water transport part of the model was used to estimate recharge. Soil moisture accounting was computed using the capacity or “tipping bucket” approach of Addiscott (1977). Representative soils (fine sand, less than 3 percent silt, no clay) and shallow-rooted vegetation (grass) were used in the initial LEACHM model to achieve the 35 percent of total 2-year rainfall criterion. In a later test of the ground-water flow model, recharge was increased from 35 to 86 percent of 2-year rainfall by reducing the silt content of the soil to 1 percent and eliminating the shallow-rooted vegetation in the LEACHM model.

The one-dimensional LEACHM model consisted of 20 vertical segments of 10 centimeters (3.94 inches) each, for a total profile thickness of 2 meters (6.56 ft). The LEACHM model was designed for use in areas where the water table is shallow; however, it was adapted for use with the deeper water table found in the Lake Starr basin by applying the time delay. Weekly potential evapotranspiration was estimated as a function of the open-water evaporation calculated for Lake Starr, adjusted to fit the time scale required for the LEACHM model (R.M. Yager, U.S. Geological Survey, written commun., 2000). Evaporation estimates for periods before August 1996 were assumed to be equal to the evaporation estimates for the same week in 1997.

Daily recharge rates calculated from the threshold and LEACHM methods were averaged over either monthly or weekly periods for transient simulations. The recharge flux to the model had the least variable distribution with time when recharge was calculated as a fixed percentage of rainfall during the stress period. The LEACHM method generated the most variable flux with time, and the threshold method generated a flux distribution that fell between the other two methods (fig. 12).

Upper Floridan Aquifer

To represent the potentiometric surface of the Upper Floridan aquifer in transient simulations, heads were specified at cells located along equipotential contour lines in the lowest Upper Floridan aquifer layer (layer 16) (fig. 13). The head values specified for these cells changed at each stress period. Heads were simulated in the remaining cells of layer 16 and in the parts of layers 14 and 15 that represented the Upper Floridan aquifer. Model cells between specified-head cells were active, and due to the high K_h in this layer (125 ft/d), simulated heads between contours were a linear interpolation of the contoured specified heads. The results of simulating the Upper Floridan aquifer boundary condition in this manner were virtually identical to results when heads in all of the cells in layer 16 were specified. The boundary was much simpler to construct in this way given the number of transient stress periods.

The potentiometric surface of the Upper Floridan aquifer beneath Lake Starr was strongly affected by pumping and was highly variable in time. To estimate the average head condition for each stress period, biweekly measurements of representative wells on the northwest and southeast sides of the lake (1PNS-125 and Hart FLRD, respectively) were first linearly correlated to hourly readings at nearby wells that had continuous water-level recorders. Biweekly measurements at well 1PNS-125 on the northwest side of the Lake Starr were correlated to hourly water levels in well ROMP 58, located about 2.5 miles southwest of the lake, and biweekly heads in the Hart FLRD well on the southeast side of the lake were correlated to hourly water levels in well ROMP 57A, located about 4.5 miles southeast of the lake (Coffin and Fletcher, 1998, 1999). Then, a synthetic hourly record was generated for the two wells within the lake topographic basin, and an average head condition for the stress period was derived from the synthetic data. The difference between the average synthetic head over a stress period and the 2-year average measured head at each of these two wells was calculated. These deviations from the average head were used to define the rise and fall of each of the contour lines that determined the lower specified-head boundary to the model (fig. 14).

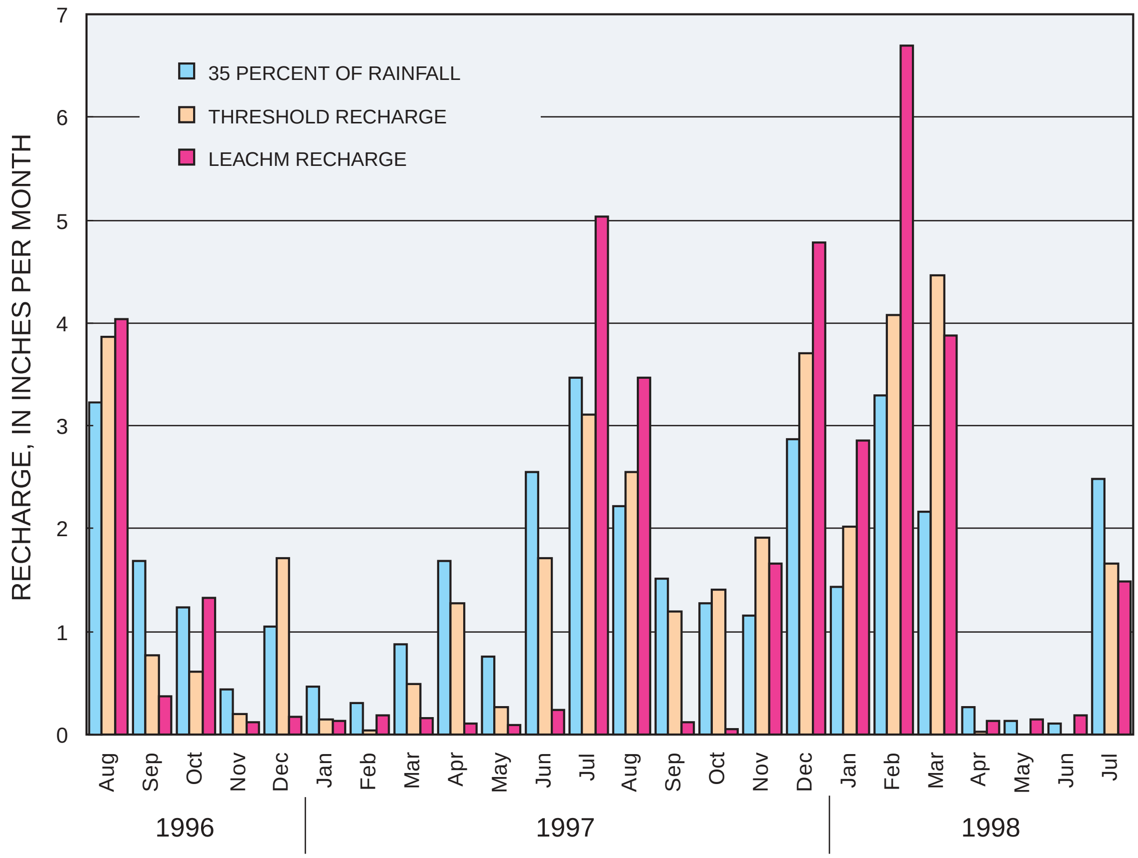


Figure 12. Monthly recharge rates using three recharge methods, August 1996 through July 1998.

RESULTS OF STEADY-STATE SIMULATIONS

Steady-state conditions in the Lake Starr basin were simulated to (1) describe the long-term average heads and fluxes in the basin, (2) to test the sensitivity of the model to changes in input parameters, (3) to determine areas of the basin that contributed ground-water to the lake, and (4) to establish initial conditions for transient simulations. Two steady-state models were constructed. One was calibrated to long-term heads and fluxes, and the other was calibrated to May 1996 head conditions. The May 1996 steady-state simulation was used to define initial head conditions for transient simulations.

For the long-term steady-state simulation, simulated heads were calibrated to median water levels measured in 26 water-table wells and 13 piezometers over an 18-month period (see fig. 6 for well locations, or Swancar and others (2000) fig. 5 and table 2 for more detail on monitor wells). Simulated steady-state ground-water inflow to the lake also was calibrated to an estimate of the annual average ground-water inflow to Lake Starr calculated using an isotope mass-balance approach along with water budget data to derive gross ground-water inflow from the net ground-water term (31,000 cubic ft per day (ft^3/d) ± 50 percent, or about 23 in/yr ± 11.5 inches; Sacks and others, 1998). The focus of the steady-state calibration was on heads, however, as many different steady-state simulations produced ground-water inflow that was within the error of this estimate.

The steady-state simulation provided a good fit to the median water-table configuration (fig. 15) and median vertical head distribution in the aquifer beneath Lake Starr. The overall root-mean-squared error (RMSE)

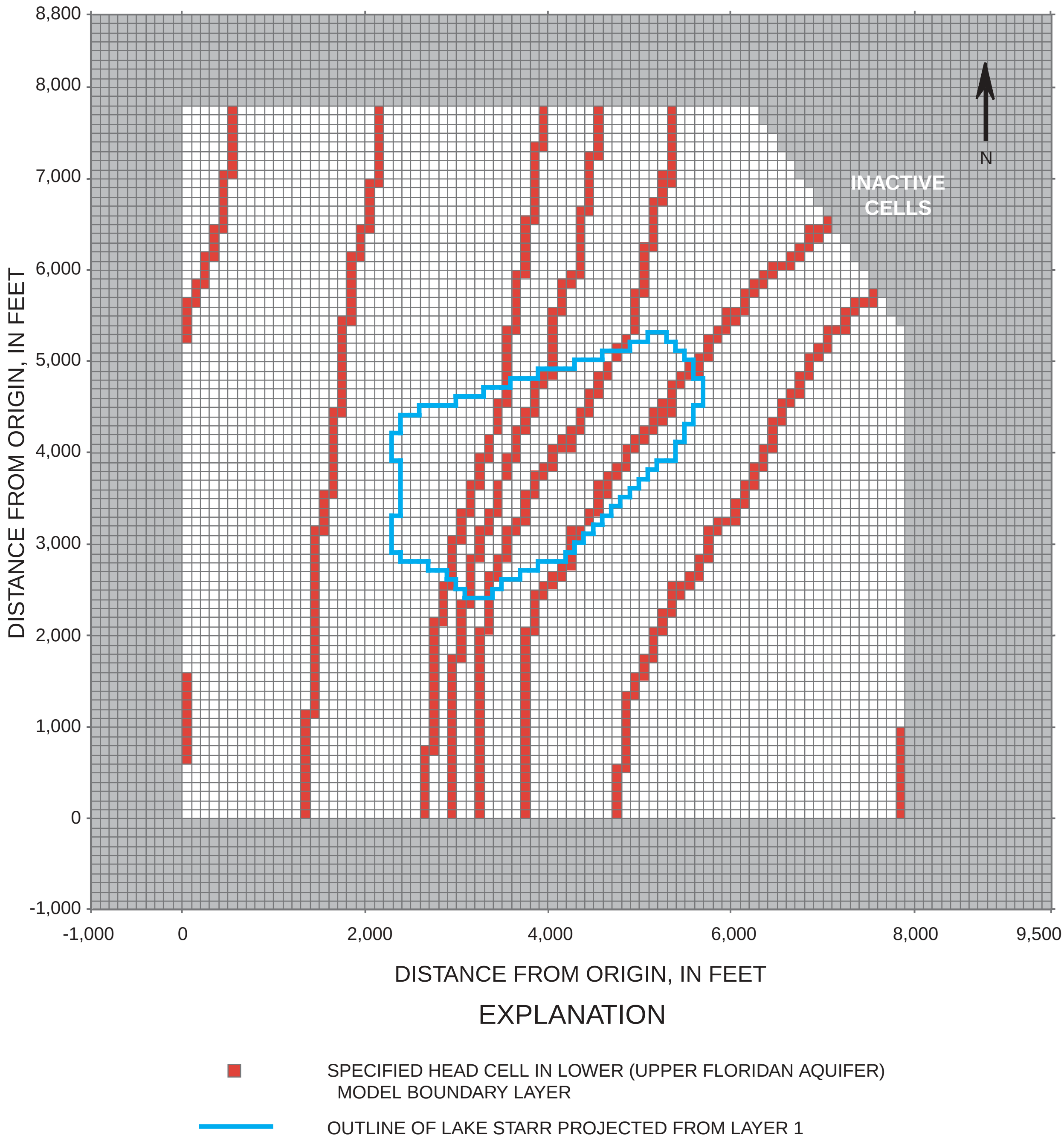


Figure 13. Specified head cells for transient simulations in layer 16 of the Lake Starr basin model.

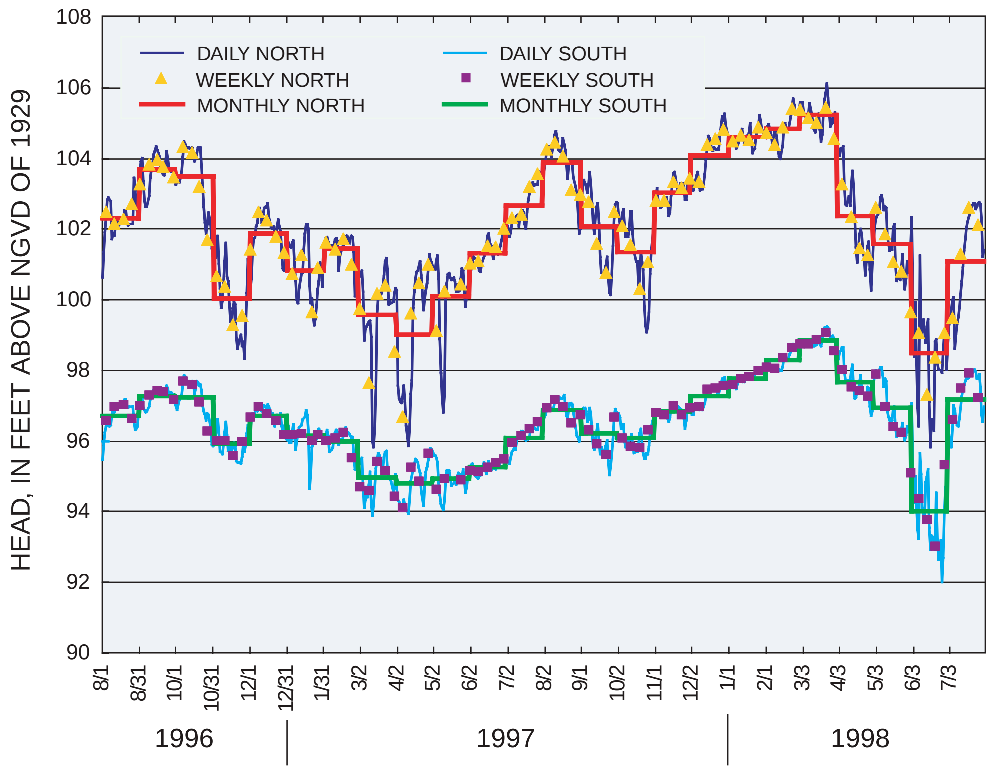


Figure 14. Estimated daily heads in the Upper Floridan aquifer on the north and south sides of Lake Starr and weekly and monthly variation in specified head used in the ground-water flow model, August 1996 through July 1998.

between simulated and median observed water levels was less than 0.5 ft (fig. 16). The RMSE is the square root of the sum of squares of differences between calculated and observed heads divided by the number of observation wells. The RMSE is an approximation of the standard deviation, which means that two-thirds of the errors between simulated and median observed water levels were less than 0.5 ft. The steady-state simulated lake stage was 104.17 ft above NGVD of 1929, 0.53 ft less than the 18-month median value of 104.70 ft. Simulated ground-water inflow and lake leakage were calculated using the zone budget program of Harbaugh (1990); these flows were then summed to derive net ground-water flow to the lake.

On a steady-state basis, 98 percent of the total recharge within the model area ultimately flows to the Upper Floridan aquifer specified-head cells (table 3). Of the total recharge to the land surface of 220,400 ft^3/d (18 inches per year), 215,000 ft^3/d ultimately flows to the specified-head cells. Steady-state ground-water inflow to the lake was within the error of the inflow estimate from the isotope mass-balance approach. Net ground-water flow to the lake was equal to the net precipitation (rainfall minus evaporation) (table 3).

Table 3. Steady-state fluxes in the Lake Starr model

[Fluxes to and from lake, in inches, are relative to lake surface area at 105 feet above NGVD of 1929; other fluxes, in inches, are relative to applicable basin areas]

Flux	Volume (cubic feet)	Flux over surface area (inches/year)
Recharge to basin	220,400	18.0
Recharge to lake	-5,400	-4.0
Ground-water inflow to lake	26,300	19.5
Lake leakage	20,900	15.5
Net ground-water flow to lake	5,400	4.0
Flow to specified head cells	215,000	6.1

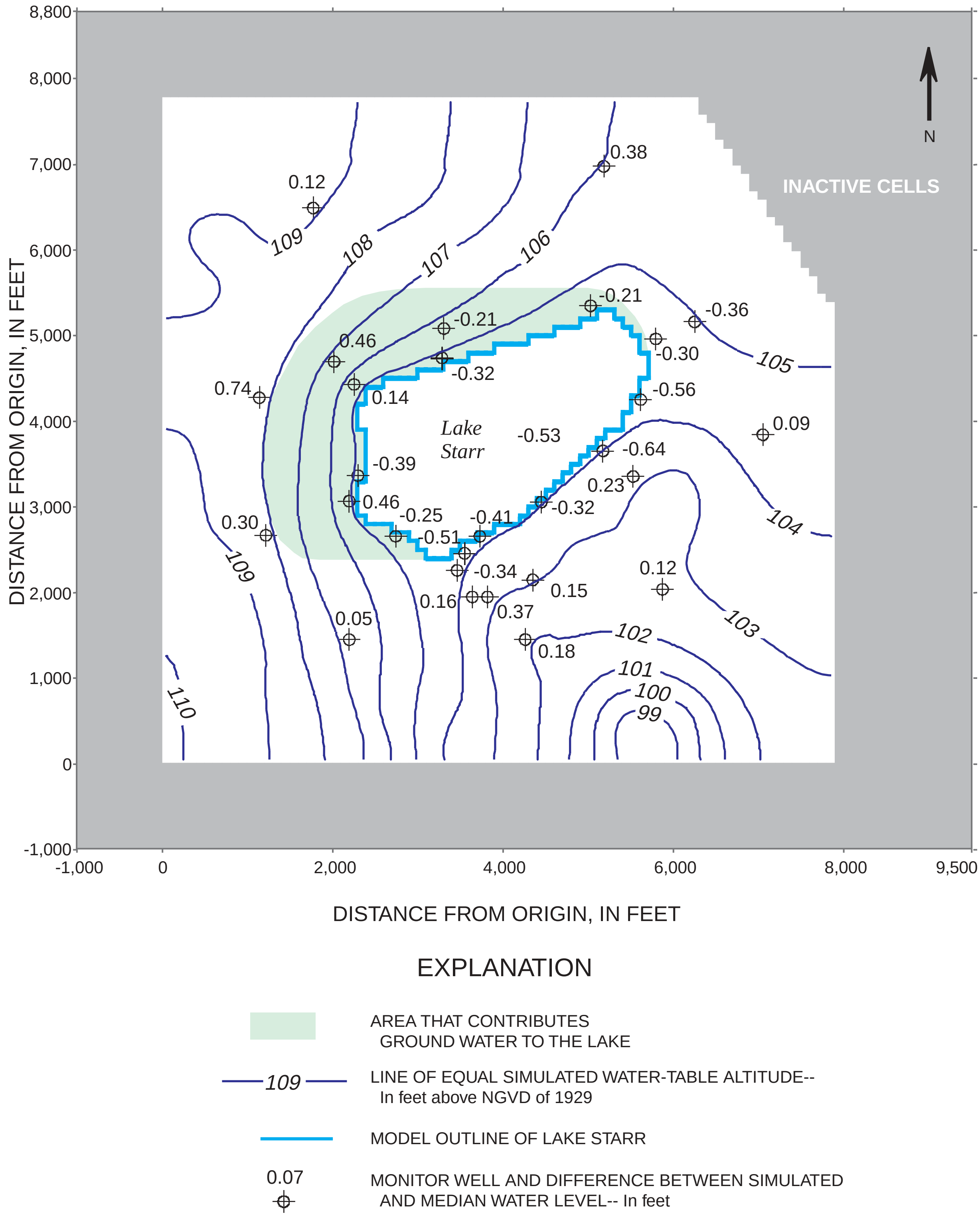


Figure 15. Steady-state simulated water-table altitudes, water-table and water-level residuals, and area that contributes ground water to the lake, median September 1996-February 1998 conditions.

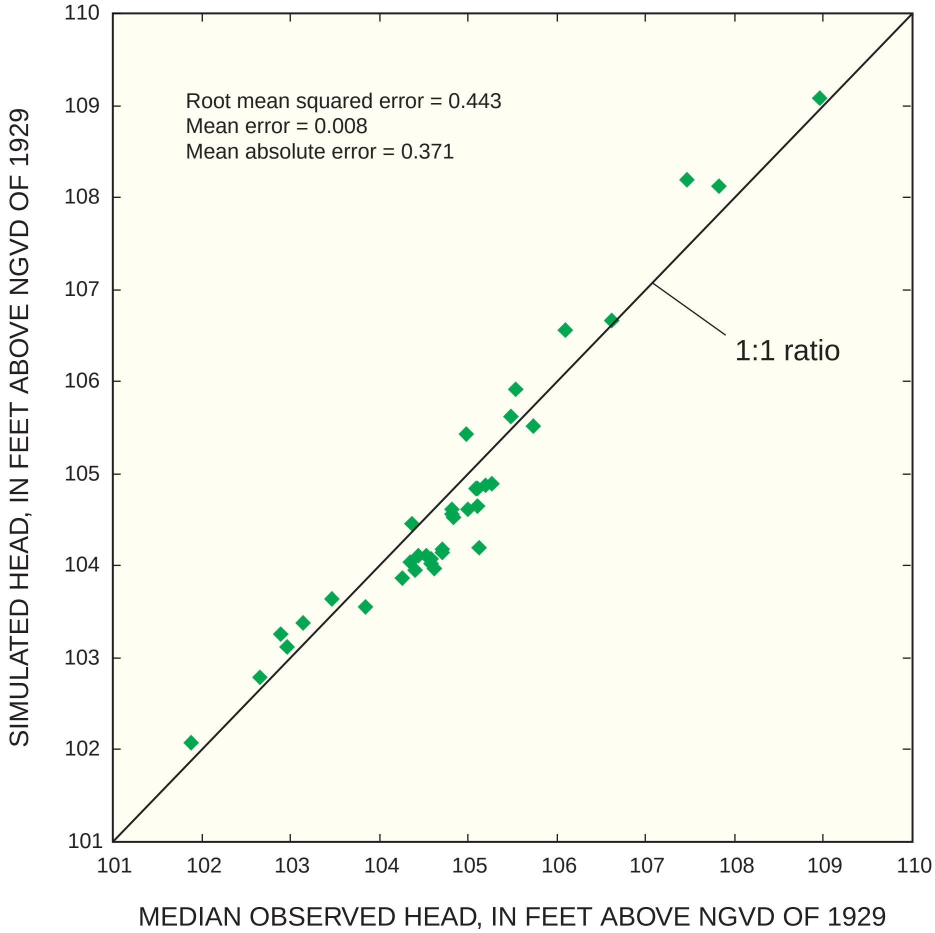


Figure 16. Comparison of simulated heads to median observed heads in the Lake Starr basin for the calibrated steady-state model, median September 1996-February 1998.

Simulated heads and fluxes were most sensitive to recharge and K values in the intermediate confining unit (including breaches) and the surficial aquifer system (table 4). Heads were less sensitive to hydraulic conductivity in the surficial aquifer system, with fluxes to and from the lake directly related to changes in this value. Lower ranks of sensitivities (1-3) meant that the model results (RMSE in head, lake stage, and ground-water inflow) changed more in response to changes in the value of these parameters. Certain model results are more sensitive to some parameters than others. For example, intermediate confining unit K has a strong effect on heads throughout the basin, but has less effect on ground-water inflow to the lake, whereas the K of the surficial aquifer system has a strong effect on ground-water inflow but a lesser effect on heads. It is most critical to accurately define parameters such as recharge that have low rankings for more than one model result when the goal is a realistic simulation of the lake/ground-water system. The presence of organic lake sediments in the model had little effect on simulated ground-water exchange with the lake. Because organic sediments covered a relatively small area of the bottom of Lake Starr, their presence or absence in the model did not appear to inhibit ground-water exchange, which could still occur across most of the lake bottom.

In steady-state simulations, there is no change in aquifer storage, and conservation of mass requires that all of the water that comes into the model as recharge either flows to the Upper Floridan aquifer or is lost as lake evaporation. Most of the water that enters the Lake Starr model as recharge flows to the Upper Floridan

Table 4. Sensitivity of steady-state model results to changes in recharge and hydraulic conductivity parameters

[RMSE, root mean squared error of simulated heads; %, percent; ft, feet above NGVD of 1929; ft^3/d, cubic feet per day; K, hydraulic conductivity; SAS, surficial aquifer system; ICU, intermediate confining unit; 2PNS, 2PNS well nest; values with asterisks (*) are the 3 most sensitive parameters for each result]

Parameter	Change in result for given change in parameter								
	RMSE (ft) [calibrated model result, 0.39]		Rank	Lake stage (ft) [calibrated model result, 104.17]		Rank	Ground-water inflow (ft^3/d) [calibrated model result, 26,320]		Rank
	-50%	+50%		-50%	+50%		-50%	+50%	
Basin recharge	2.78	2.55	*1	101.66	106.61	*1	19,730	32,920	*1
Lake recharge	0.47	0.34	7	104.01	104.34	7	27,550	25,000	5
Lower basin SAS K	0.73	0.34	5	103.64	104.45	5	21,010	29,440	*2
Upper basin SAS K	0.44	0.39	8	104.18	104.18	8.5	25,530	26,330	6
Deep SAS K	0.63	0.52	6	104.82	103.92	4	26,180	26,490	8
ICU K	1.75	1.09	*2	106.04	103.26	*2	28,750	25,510	4
Thick ICU K (east side)	0.74	0.65	4	104.61	103.91	6	26,640	26,560	7
Breach K	0.85	0.80	*3	105.05	103.59	*3	23,360	28,280	*3
2PNS "wall" K	0.39	0.40	9	104.18	104.16	8.5	26,410	26,350	9.5
Lake sediment K	0.39	0.39	10	104.17	104.17	10	26,220	26,340	9.5

aquifer specified-head boundary. For a given recharge rate, the rate of flow across the intermediate confining unit largely determines head conditions throughout the surficial aquifer system. A simple parameter estimation model of a similar hypothetical lake/ground-water system using the MODOPTIM program by Halford (1992) indicated that recharge and intermediate confining unit K_v were significantly correlated. Because of this correlation, it is prudent to decide which of these parameters is best known. Then, a value for that parameter is set, and calibration is used to determine the lesser-known parameter. For this model, as in Lee (1996), recharge was assumed to be known more accurately than confining unit properties, and confining unit properties were varied in the calibration process using a trial-and-error approach (Anderson and Woessner, 1992).

Simulation of water levels in the 2PNS well nest was successful after the model was modified to reflect the increased hydraulic connection between the surficial aquifer system and the breach in which the wells were located, and after adding a vertical “barrier” between the deeper parts of the breach and the surrounding Upper Floridan aquifer cells. Without the barrier, water flowed from the breach to the specified-head cells too rapidly to maintain the observed head difference (about 6 ft) between the nested wells and the nearest Upper Floridan aquifer well. Simulation of the downward vertical gradient observed at this nest was improved by using three layers for the intermediate confining unit/breach cells because the model was better able to represent the vertical head differences seen in the nest when more layers were present. Simulated heads in the 2PNS nest were lower than observed heads by about the same amount (0.29-0.56 ft) as the simulated lake level was below its observed water level (0.53 ft). The simulated downward head difference was 0.52 ft compared to the observed difference of 0.75 ft.

Accurately representing the potentiometric surface of the Upper Floridan aquifer was essential to successfully simulating the water-table configuration in the steady-state model. The slope of the potentiometric surface across the basin has a strong effect on the water-table shape and imposes the same flow direction in the surficial aquifer system, causing lake water to flow out along the southeast shore despite the higher topography on this side of the basin. Variations in the intermediate confining unit thickness and breaches in this unit superimpose an additional effect on the water-table shape, lowering the water table in the southern part of the basin where the confining unit is more dissected, and raising the water table where the confining unit is thicker. For example, to calibrate the steady-state model to water levels in the area around wells WTS-19 and WTS-26, located in sinkholes on the south side of the lake (see fig. 1), breaches in the intermediate confining unit were added. Otherwise, simulated heads in these wells were higher than observed.

Ground-water flow paths were delineated using the particle-tracking method of Pollock (1994) to determine areas of the basin that contributed ground-water inflow to the lake (figs. 15 and 17). The area contributing ground water to the lake, called the ground-water catchment, was west and north of the lake and extended about 1,200 ft from the lake on the west side. The steady-state ground-water catchment covered about 16 percent of the topographic basin (116 of 736 acres). Rainfall recharging the surficial aquifer system outside the ground-water catchment flowed downward to the Upper Floridan aquifer rather than to the lake. Most of the ground water flowing into the lake entered at shallow depths along the lake bottom and came from the parts of the basin closest to the lake. Ground-water flow paths entered the lake at depths up to about 15 ft below the lake surface on the west side of the lake in the steady-state simulation. Seventy-three percent of the ground water entering the lake from a row on the west side (row 55, see figs. 6 and 17) originated as recharge within 900 ft of the lakeshore. The maximum simulated traveltime for recharge to reach the lake was about 25 years, and the minimum was less than 20 days for a particle starting about 30 ft from the simulated lake shore. Most flow paths to the lake had traveltimes that were less than 10 years. Minimum traveltimes to reach the Upper Floridan aquifer were about 5 years. The computed traveltime is directly related to the assumed porosity of 0.3; smaller porosity values would yield proportionally shorter traveltimes.

Two additional long-term steady-state simulations were conducted to assess the possible effect of changing heads in the Upper Floridan aquifer on ground-water catchment size. The highest observed Upper Floridan aquifer heads were about 3 ft higher than the median levels, and occurred during about 10 percent of the 2-year study period. These levels are comparable to a predevelopment condition. When the steady-state Upper Floridan aquifer heads were raised by 3 ft, the ground-water catchment area increased from 16 to 20 percent of the topographic basin, ground-water inflow to the lake was 20 percent greater, and the lake stage was 2.7 ft higher compared to the original steady-state model. In contrast, the lowest observed Upper Floridan aquifer heads were about 1 ft lower than the median levels, and occurred during about 25 percent of the 2-year study period. This condition as well as the median condition reflects the lower aquifer heads induced by ground-water pumping for irrigation to meet the needs of the citrus crop whenever rainfall is insufficient for that purpose. When the steady-state Upper Floridan aquifer heads were lowered by 1 ft, the catchment area was reduced to 13 percent of the topographic basin, ground-water inflow was reduced by 15 percent, and lake stage was 0.51 ft lower compared to the original steady-state model.

Short-term or seasonal variations in recharge and Upper Floridan aquifer heads probably do not affect the size of the contributing area as much as the long-term average boundary conditions. Traveltimes along ground-water flow paths to Lake Starr range from 20 days to 25 years, but flow from farther parts of the catchment takes more than 10 years to reach the lake, whereas short-term changes in boundary conditions occur over periods of hours. According to Reilly and Pollock (1995), changes in boundary conditions begin to affect contributing areas when the time scale of the change approaches the traveltime of ground-water flow paths. However, variations in the recharge and Upper Floridan aquifer boundary conditions over shorter periods of days to weeks can have a strong effect on the *volume* of ground water that reaches the lake, which will be discussed in the following section.

To establish initial head conditions for transient simulations, an additional steady-state simulation was calibrated to heads measured in the Lake Starr basin during May 1996. The RMSE between simulated and observed heads for this simulation was 0.476 ft, and simulated lake stage was 104.49 ft, which was 0.09 ft less than observed. Simulated net ground-water inflow was 17,500 ft^3/d. Steady-state calibration was achieved by setting recharge equal to 20 in/yr, lake recharge to 4 in/yr, and by specifying Upper Floridan aquifer heads equal to levels similar to those observed during that month.

RESULTS OF TRANSIENT SIMULATIONS

The objectives of transient simulations were to quantify ground-water inflow and lake leakage and to improve the understanding of the ground-water flow system around central Florida seepage lakes and the factors affecting lake/ground-water interactions. A range of recharge rates to the surficial aquifer system and head conditions in the Upper Floridan aquifer were used in transient simulations over both monthly and weekly stress periods. Hydraulic parameters specified in the transient simulations were initially the same as steady-state simulations. Some parameters

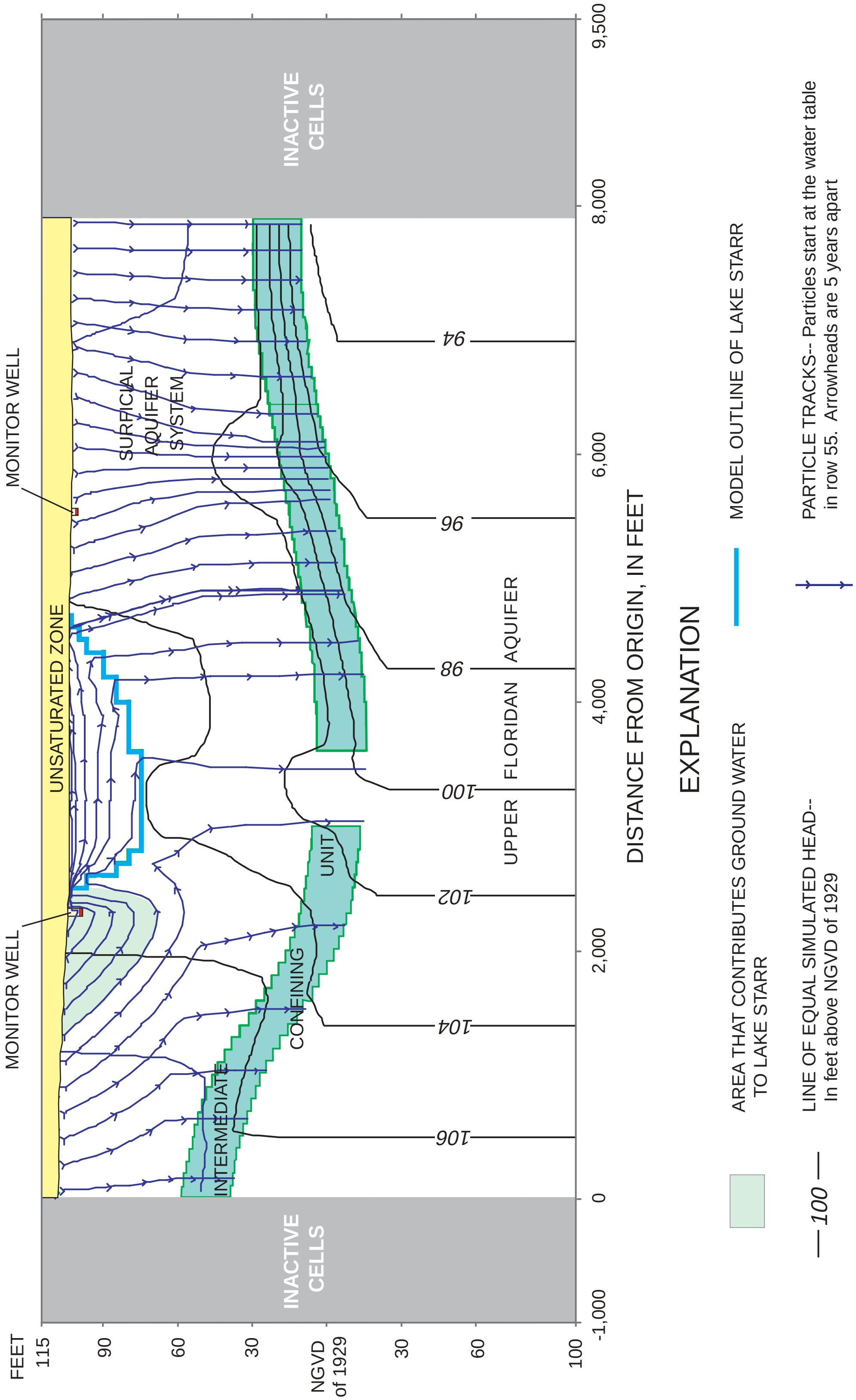


Figure 17. Particle pathlines showing direction, rates of movement, and vertical area that contributes ground water to the lake along model row 55.

(recharge and surficial aquifer K) were adjusted during calibration of the transient model to improve simulation of ground-water exchange with the lake. In general, errors in simulated heads were less than errors in simulated net ground-water flows to the lake. Results of transient simulations were sensitive to the same parameters as steady-state simulations, as well as to the specific yield of the surficial aquifer system. For transient simulations, net ground-water flow to the lake was computed as the sum of ground-water inflow and lake leakage for each stress period, assuming that average net ground-water flow over the stress period was equal to the net ground-water flow at the end of the stress period.

Monthly Simulations

Three recharge conditions (35 percent of rainfall, threshold, and LEACHM) were used to simulate monthly heads in the basin and ground-water exchange with the lake. For each recharge condition, the Upper Floridan aquifer lower boundary was represented by a monthly average potentiometric surface. All of the three recharge conditions did reasonably well simulating heads in the basin over the 2-year study period, although some recharge conditions did better than others in certain parts of the basin. In general, recharge estimated as a fixed percentage of rainfall over each stress period generated head changes that were smaller than observed, whereas the LEACHM method generated head changes that were larger than observed (fig. 18). The threshold method did the best of the three methods overall in simulating transient heads throughout the basin, but LEACHM recharge did nearly as well. The LEACHM method is not as appropriate for the upper basin, even though it was modified by applying a time delay, because it was designed for a shallow water table (Hutson and Wagenet, 1992). However, including LEACHM recharge in the model improved the simulation of ground-water flow to and from the lake compared to the other two recharge conditions (fig 19). For these reasons, a combination of threshold and LEACHM recharge methods was used in subsequent transient simulations. The threshold

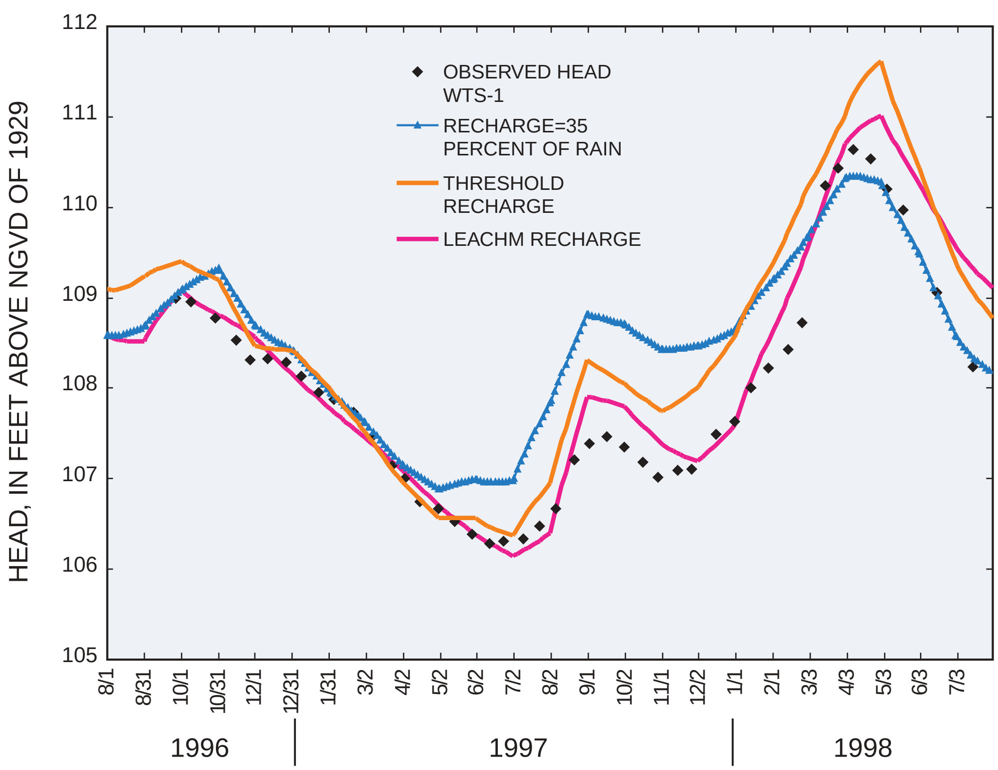


Figure 18. Effect of three different recharge boundaries on simulated head in well WTS-1 (location of well shown in figure 6).

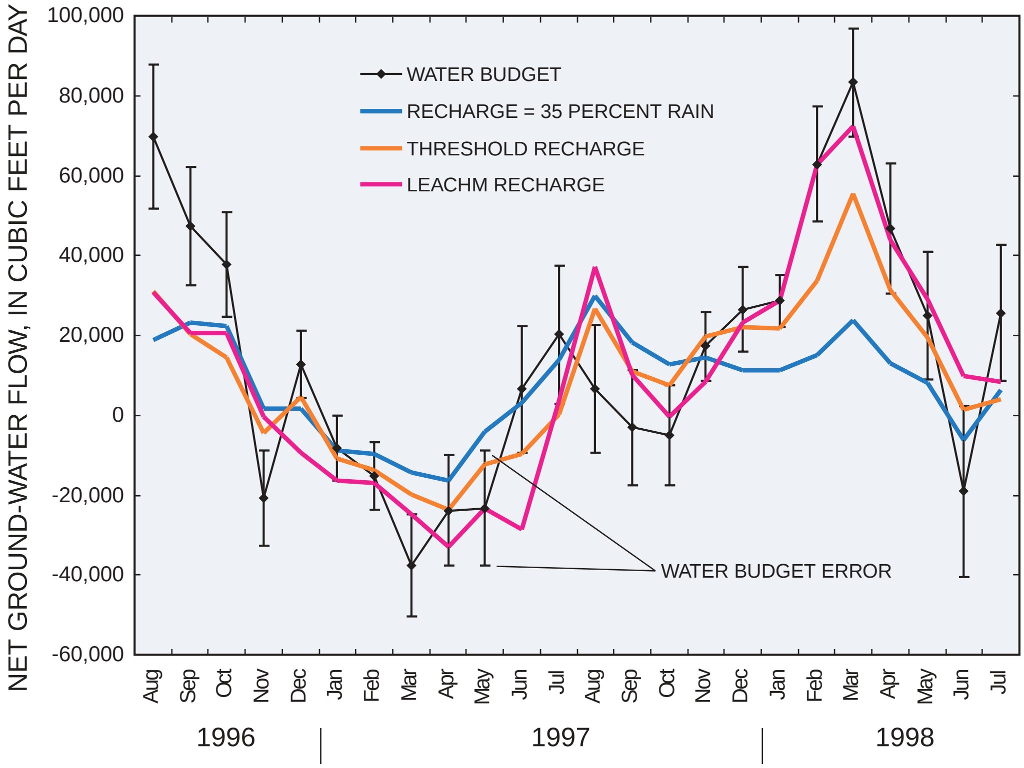


Figure 19. Effect of three different recharge boundaries on simulated monthly net ground-water flow to Lake Starr, and net ground-water flow from the water budget.

method was used to estimate recharge in the upper and middle parts of the basin where the water table was greater than 20 ft deep and the LEACHM recharge method was used near the lake where the water table was less than 20 ft deep.

Heads simulated using threshold recharge in the upper basin and LEACHM recharge near the lake were generally within 1 ft of the observed values (fig. 20A-D). Simulated heads agreed best with observed heads on the west side of the basin in the area that contributed ground-water inflow to the lake (for example see well WTS-23, fig. 20A). Agreement was not as close on the southeast side of the basin where topography was highest (well WTS-8, fig 20D). Uncertainty regarding the timing of recharge in the highest regions of the basin probably explains this lack of agreement.

Even with the combination of threshold and LEACHM recharge methods, the model failed to simulate the highest lake levels and to predict peaks and lows in net ground-water flow to the lake (figs. 21 and 22, respectively). Simulated lake stage was consistently lower than observed for the last half of 1996 and the spring of 1997. Later in 1997, simulated stage was below the peak stage that occurred in August. The large rise and fall in stage between December 1997 and July 1998 was more accurately simulated, although the peak lake stage in April 1998 was not achieved.

Simulated net ground-water flow to the lake agreed within the error bars of budget-derived estimates for only 14 of the 24 months (fig. 22). During wet periods, the monthly simulation underpredicted net ground-water inflow. For example, in March 1998, net ground-water flow to the lake calculated from the water budget was 83,300 (±13,700) ft^3/d, but the simulated net flow was only 52,500 ft^3/d. Accounting for water budget errors, the simulated net ground-water flow in March 1998 was between 54 and 75 percent of net ground-water flow estimated from the water budget. Simulated net ground-water flow fit the water budget best when net ground-water flow was near zero; periods when ground-water inflows and outflows were balanced.

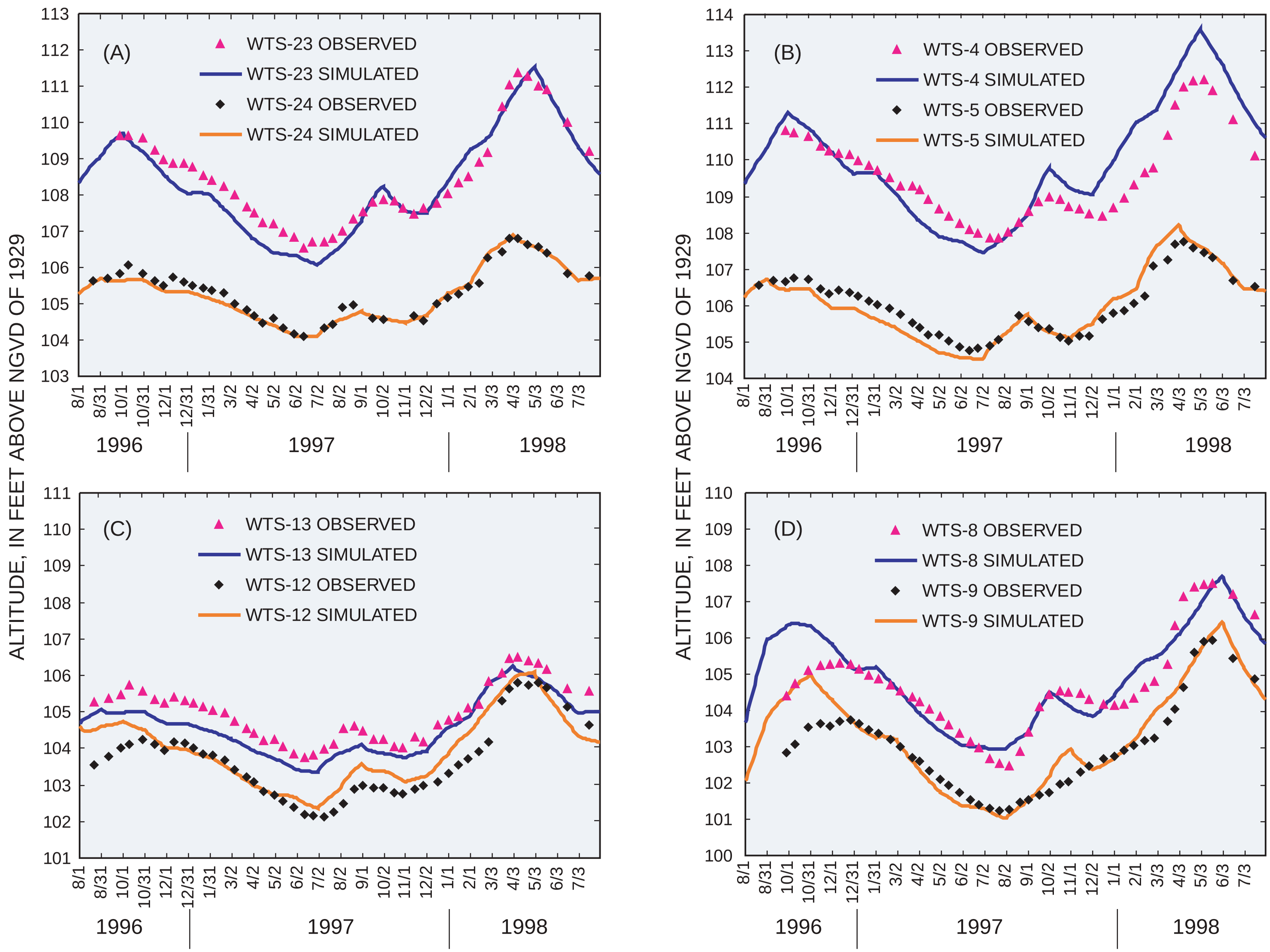


Figure 20. Observed and monthly simulated water levels in wells (A) WTS-23 and WTS-24, (B) WTS-4 and WTS-5, (C) WTS-13 and WTS-12, and (D) WTS-8 and WTS-9 (locations of wells shown in figure 6).

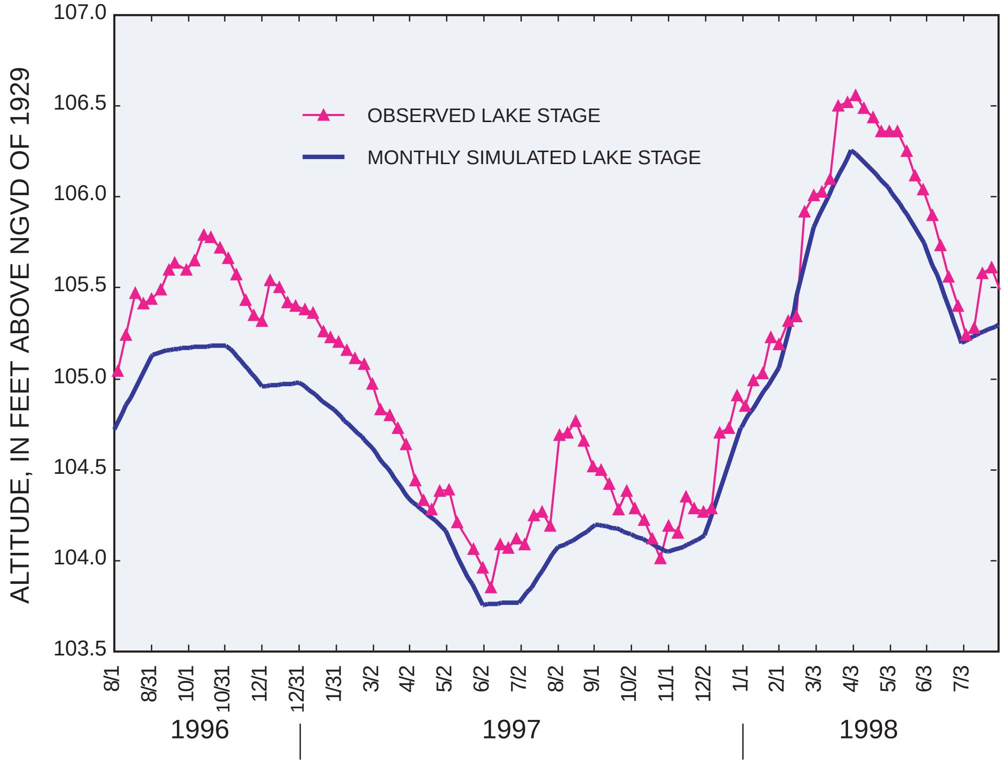


Figure 21. Measured and monthly simulated stage for Lake Starr, August 1996 through July 1998.

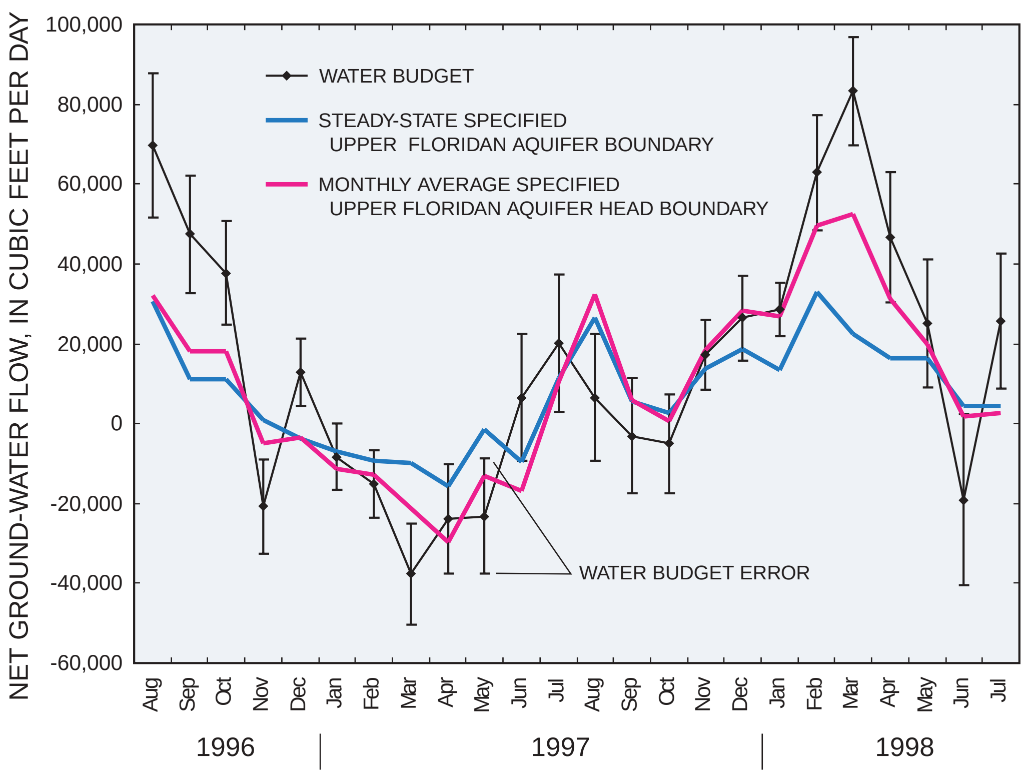


Figure 22. Effect of different Upper Floridan aquifer specified-head boundary conditions on simulated monthly net ground-water flow to Lake Starr, and net ground-water flow from the water budget.

For any given recharge condition, representing the Upper Floridan aquifer specified-head boundary with monthly averages instead of a steady-state potentiometric level improved the simulation of monthly ground-water exchange and basin water levels. To evaluate this effect, the model using the combined threshold/LEACHM recharge condition was simulated with the Upper Floridan aquifer lower specified-head boundary as a steady-state condition. The results of this model were then compared to the simulation that used monthly average specified heads to represent the Upper Floridan aquifer. Changes in water-table altitude were less than observed (hydrographs were “flatter”) in the simulation using a specified steady-state Upper Floridan aquifer lower boundary, and simulated net ground-water flow deviated more from the results of the lake water budget (fig. 22). The amplitude of simulated net ground-water flow was reduced when using specified steady-state Upper Floridan aquifer heads, and net ground-water flow was within the water budget error in only 10 of 24 months, compared with 14 of 24 from the simulation with monthly specified heads. When the potentiometric surface was highest (March 1998), ground-water inflow simulated using specified monthly Upper Floridan aquifer heads was 52 percent (21,300 ft^3/d) greater than inflow simulated with a steady-state boundary, and outflow was 47 percent (8,700 ft^3/d) less. As a result, *net* ground-water flow to the lake was 133 percent (30,000 ft^3/d) greater when the monthly average Upper Floridan aquifer head boundary was used. When the potentiometric surface was lowest (June 1998), ground-water inflow simulated using specified monthly Upper Floridan aquifer heads was 4 percent (1,200 ft^3/d) less than inflow simulated using specified steady-state Upper Floridan aquifer heads, outflow was 15 percent (3,600 ft^3/d) greater, and *net* ground-water flow to the lake was 56 percent (2,400 ft^3/d) less. Substantial errors are introduced into simulated monthly net ground-water flow if the lower boundary is specified as steady state.

Weekly Simulations

Ground-water levels in the upper basin, where the unsaturated zone was greater than about 40 ft thick, did not respond to weekly changes in rainfall. Instead, water levels in the upper basin rose and fell more gradually because of the time delay between rainfall and recharge to the water table caused by greater thickness of the unsaturated zone. Longer traveltimes and drainage of water stored in the unsaturated zone tended to smooth out the effects of individual rain events on the water table. Applying any of the recharge conditions on a weekly basis worsened the simulation of transient ground-water levels in the upper basin. For this reason, recharge rates in the upper basin for weekly transient simulations were averaged over a 4-week period, and simulated heads in upper basin wells were consequently similar to those from monthly simulations. Results of weekly simulations are therefore more reflective of changes in recharge conditions in the basin *near* the lake.

Weekly stress periods simulated lake stage more accurately than monthly stress periods, primarily because differences in rainfall and lake evaporation were accounted for on a shorter time scale (figs. 23 and 21, respectively). The simulated rise in lake stage during the winter of 1996-97 was less than observed, similar to monthly simulations. But after March 1997, the simulated changes in weekly lake stage followed observed changes more closely than monthly simulations.

Unlike monthly simulations, weekly recharge conditions simulated the occurrence of transient water-table mounds that were observed near the shoreline of Lake Starr. For example, in the weekly simulation, heads in the nearshore area occasionally rose above the lake level because of large rain events (fig. 23). These peaks in nearshore water levels reversed the ground-water flow direction on the outflow (southeast) side of the lake (for example, near well WTS-13). Flow reversals were simulated at the same times that flow reversals were observed in continuous water-level recorders. For example, after a series of large rainfall events the week of July 27-August 2, 1997, the simulated head at the end of the stress period for a cell on the southeast side of the lake near the 2PNS well nest was 0.25 ft higher than the lake. Observed flow reversals were higher but more short-lived than simulated reversals; the observed head in a nearshore well rose to 0.5 ft above lake stage on August 2, 1997, but the flow reversal lasted only about 6 hours (Swancar and others, 2000).

Weekly stress periods simulated a larger variability in net ground-water flow to the lake compared to monthly stress periods (fig. 24). Simulated weekly net ground-water flow rates ranged from –29,400 to

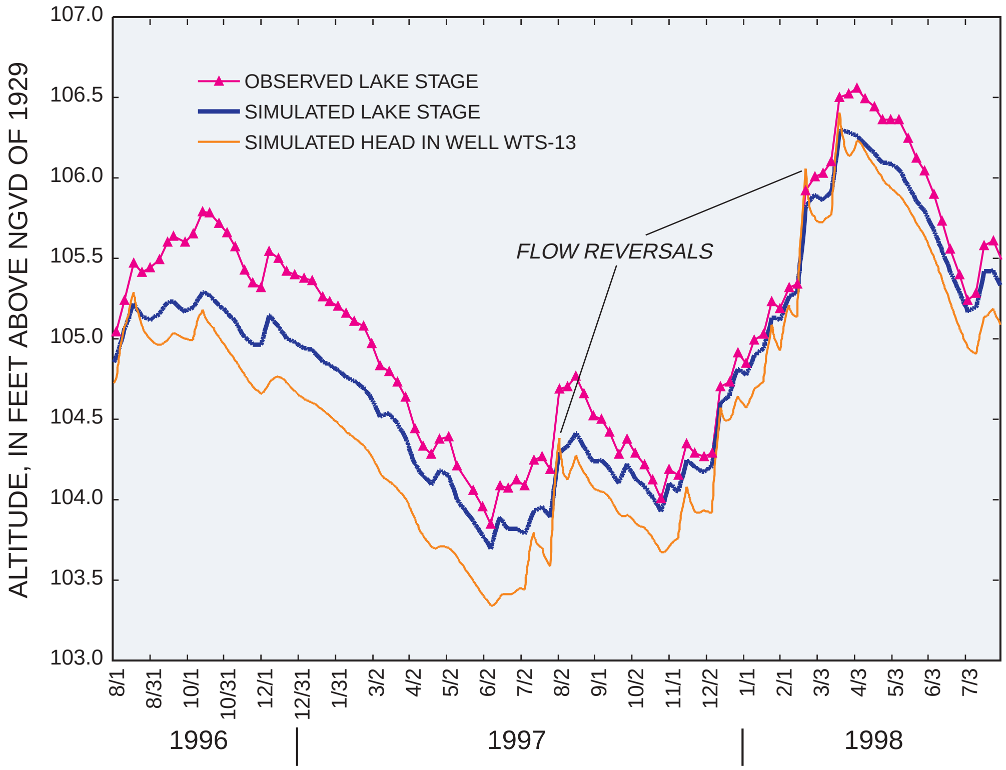


Figure 23. Weekly observed and simulated Lake Starr stage and simulated head in well WTS-13 showing flow reversals, August 1996 through July 1998 (location of well shown on figure 6).

77,400 ft^3/d, whereas monthly rates ranged from –29,800 to 52,500 ft^3/d. Weekly simulated net ground-water flow was within the error of budget-derived estimates in 46 of 105 weeks. Weekly simulation increased the peak net ground-water inflow rates compared to monthly, but peak net ground-water outflows were similar to monthly rates. However, the simulated weekly net ground-water flow rates were still well below the minimum and maximum rates derived from a weekly water budget (–59,700 and 117,500 ft^3/d, respectively).

Simulated net ground-water flow did not alternate from large net ground-water inflow to large net leakage as quickly as indicated by the weekly water budget. For example, during the fall of 1996, budget-derived net ground-water flow to the lake dropped rapidly from 64,600 to –30,000 ft^3/d, a decrease of 94,600 ft^3/d, over the 5-week period October 6 through November 10 (fig. 24A, see inset). The weekly simulated net ground-water flow fell from 30,100 to 4,900 ft^3/d, a decrease of only 25,200 ft^3/d, during the same 5-week period. The weekly water budget indicated that ground-water inflow rates were larger than simulated rates and that net ground-water flow rates changed more rapidly than simulated rates.

Like monthly simulations, weekly simulations underestimated net ground-water inflow derived from the water budget. Problems simulating ground-water inflow rather than outflow were the primary cause of underestimated net ground-water flow. Gross ground-water inflow should always exceed positive *net* ground-water flow, yet simulated gross ground-water inflow was commonly lower than the net flow derived from the water budget, even when errors in the water budget were considered. For example, simulated gross ground-water inflow was less than budget-derived net ground-water flow in 16 of the 31 weeks when net ground-water flow was both positive and larger than the water budget error. The discrepancy between the simulated and budget-derived weekly net inflows was greatest during weeks with large rainfall events and large ground-water inflows to the lake (weeks of

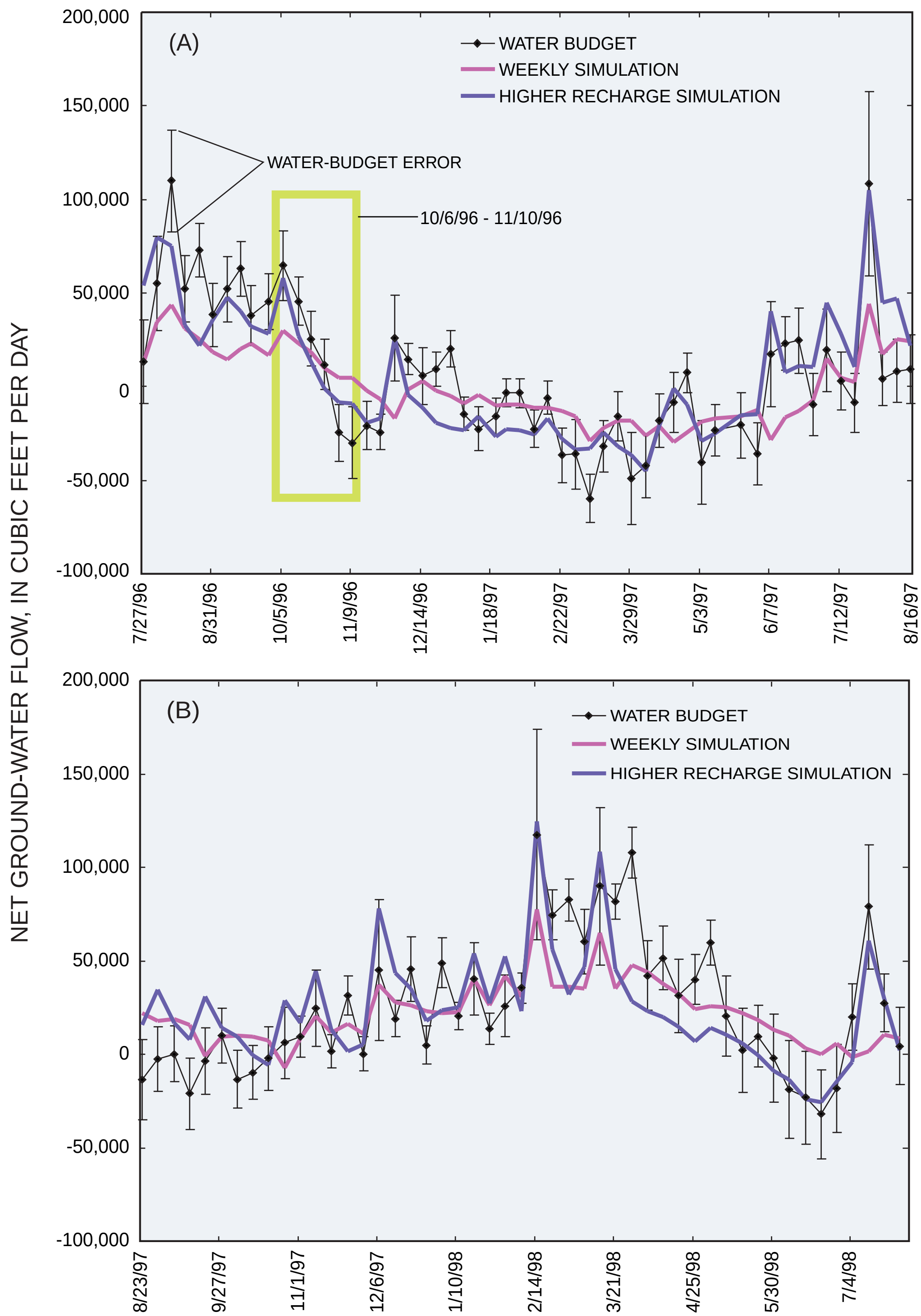


Figure 24. Weekly simulated net ground-water flow to Lake Starr, net ground-water flow from the higher recharge simulation, and net ground-water flow from the water budget from (A) July 28, 1996, to August 17, 1997, and (B) August 24, 1997, to July 26, 1998 (values plotted on the first day of the period).

August 17, 1996, July 27, 1997, and July 12, 1998, in fig. 24). This discrepancy may reflect the inability of the numerical model to adequately simulate the influence of transient mounding on ground-water inflow. Transient water-table mounding in nearshore wells could have generated half of the net ground-water flow to the lake during the week of July 27, 1997 (Swancar and others, 2000).

The representation of specified weekly Upper Floridan aquifer heads in the transient model had a smaller effect on the magnitude of simulated net ground-water flow than the representation of weekly recharge, but the effect was still noticeable. For example, during a 2-week period with low recharge (March 2-16, 1997), a decline in the average head in the Upper Floridan aquifer on the north side of the lake of 2.12 ft (see fig. 14) in the second week increased the lake leakage 22 percent, from 31,300 to 38,300 ft^3/d. This was the largest week-to-week decline in the average Upper Floridan aquifer head on this side of the lake during the study. Ground-water inflow during the second week also was affected by the change in the Upper Floridan aquifer boundary condition, dropping 41 percent from 15,400 to 9,100 ft^3/d. Net ground-water flow from the lake in the second week was 85 percent (13,400 ft^3/d) lower than the previous week, falling from -15,800 to –29,200 ft^3/d.

Higher Recharge Weekly Simulation

Both monthly and weekly simulations underestimated net ground-water inflows to Lake Starr during wet periods, and underestimated peak net ground-water outflows during dry periods. Underestimating ground-water inflow is likely due to an underestimation of recharge during wet periods. In addition, the weekly water budget indicated that the week-to-week *changes* in ground-water inflow and lake leakage could be considerably larger than simulated, suggesting faster exchange of water between the lake and the surrounding aquifer.

To test these hypotheses, a weekly simulation was run using higher recharge rates, greater K_h in the surficial aquifer system adjacent to the lake, and greater K in the sublake breaches. Simulations using higher recharge rates basin-wide raised the water table unrealistically high in the upper basin. Higher heads in the upper basin did not substantially increase ground-water inflow to the lake because most of the ground-water inflow results from recharge occurring closer to the lake. Therefore, recharge in the upper basin was not increased, as heads in this area were being accurately simulated. Instead, the higher recharge simulation tested the effect of increasing recharge only in the area closest to the lake. This higher recharge simulation was evaluated for its ability to reproduce the weekly net ground-water flow derived from the water budget.

In the higher recharge simulation, recharge in the zone closest to the lake was increased to 86 percent of the 2-year rainfall total, recharge in the second recharge zone was increased to 50 percent of rainfall, and recharge in the upper basin was kept at 35 percent of the 2-year rainfall total. Recharge for both of the nearshore zones was calculated using the unsaturated flow model LEACHM.

There is no precedent for applying recharge at greater than 50 percent of rainfall over longer time periods; however, this assumption allows us to test the effect of very high recharge rates in some weeks on ground-water flow to the lake. Recharge rates in sandy ridge soils and their annual variability are not well known, and may exceed the initial estimate of 35 percent of rainfall. For example, Sumner (1995) reported that between 43 and 53 percent of the rainfall recharged the ground-water system in a Florida ridge setting where the depth to water was less than 10 ft and the annual rainfall amount was near average. The higher recharge rates used in the nearshore for this study are consistent with results of Lee (2000), who found that daily recharge greater than 90 percent of rainfall is needed to generate the short-term water-table rise in nearshore wells during individual storm events.

In addition to increasing the nearshore recharge, two other changes were made in the higher recharge simulation to more closely match the variable timing and magnitude of weekly net ground-water flow seen in the water budget. The K_h of the surficial aquifer system in the lower basin was increased from 40 ft/d to 60 or 80 ft/d, and larger and more conductive breaches were placed in the intermediate confining unit beneath the lake. The size of sublake breaches was increased from about 10 to 18 acres, and the K of breaches was doubled. Larger breaches below the lake are plausible, as these features were estimated to total at least 16 acres in size from a seismic reflection survey of the lake (Swancar and others, 2000). The higher K_h values in the surficial aquifer in the high recharge simulation are not far outside the range of measured values; 80 ft/d is about 25 percent greater than the highest measured K (64 ft/d).

The higher recharge simulation approximated the peak weekly values of net ground-water flow from the water budget more closely than the original weekly simulation (fig. 24). Simulated net ground-water flow was within the water-budget errors for 51 of 105 weeks. The higher recharge simulation also was better at producing the relatively rapid transitions from net ground-water inflow to net ground-water outflow, as well as the steep increases in net ground-water outflow. The improved ability to simulate budget-derived drops in net ground-water flow suggests that lake leakage and the K of the sublake region were better represented in the high recharge simulation than the original model. For example, in the high recharge simulation, weekly average net ground-water flow drops from 58,000 to –9,300 ft^3/d during the 5-week period between October 6 and November 10, 1996. The total simulated decline in net ground-water flow of 67,300 ft^3/d from the high recharge simulation compares more closely to the budget-derived decline of 94,600 ft^3/d than the initial weekly simulation (25,200 ft^3/d)(fig. 24A inset). The steeper decline in simulated net ground-water flow is governed by both the greater amount of ground-water inflow and by the more conductive sublake geology.

In addition to improving the representation of the large week-to-week variations in the net ground-water flow to Lake Starr, the higher recharge simulation was the only transient model that approximated the cumulative net ground-water exchange calculated by the 2-year water budget. To quantify the error in simulated ground-water exchange with Lake Starr, the absolute value of the difference between the budget-derived and simulated net ground-water flow was calculated for each stress period, and these differences were accumulated for the 2-year study period. For comparison, the water budget error was accumulated for the same period. Comparing the cumulative absolute errors of the different simulations is more telling than comparing the total net ground-water exchanges with the lake because a simulation can generate the same annual net ground-water exchange as the water budget without simulating the extremes of ground-water exchange with the lake. The cumulative absolute error was substantially less for the higher recharge simulation than for the lower recharge simulation (fig. 25). For the 2-year period, the cumulative absolute error was 17,057 ft^3/d (12,451,400 ft^3 total) for the higher recharge simulation, which was about the same as the weekly average error

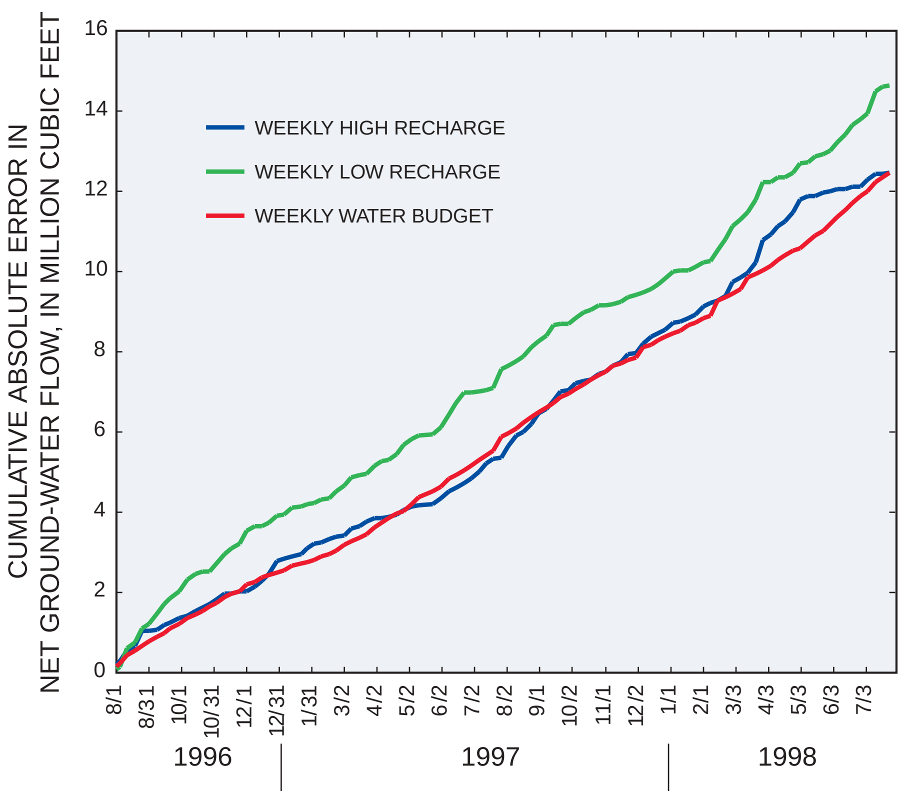


Figure 25. Cumulative absolute error in net ground-water flow for two simulations and the weekly lake water budget.

in the water budget of 17,072 ft^3/d, and well below the low recharge simulation error of 20,057 ft^3/d (14,641,700 ft^3 total). When applied over monthly stress periods, the higher recharge simulation also had a substantially lower cumulative absolute error than the lower recharge simulation and also was about the same as the monthly water budget error.

The higher recharge simulation did an excellent job predicting lake stage during the first year of the study, but simulated lake stage was higher than observed during most of the second year (fig. 26A). After the minor peak in lake stage in August 1997, the simulated stage did not drop as quickly as observed during the fall of 1997. The simulated stage remained about 0.5 ft higher than observed for the remainder of the period, although rises and falls were equivalent to observed changes. An adjusted stage (simulated stage minus 0.5 ft) also is plotted on figure 26 for comparison. An explanation for the better fit of the adjusted stage to the lake hydrograph is that the model did well simulating lake/ground-water interactions during most of the study period, but generated too much ground-water inflow during the summer of 1997 (this additional simulated ground-water inflow also is evident in figure 24). Simulated heads in nearshore wells showed more transient peaks in the higher recharge simulation because of the large recharge inputs to the water table in this part of the model, and also were higher than observed values in the second year, similar to lake stage (fig. 26B). Peaks that were of the same magnitude as those simulated (0.5-1.0 ft) were observed in continuous measurements of water levels in wells near Lake Starr during this period (Swancar and others, 2000). Water-level rises up to 3 ft have been observed in nearshore wells around lakes about 60 miles west of Lake Starr (Metz and Sacks, 2002).

The high recharge condition had little effect on the catchment contributing ground-water inflow to the lake. A steady-state simulation using the higher recharge model K distribution and recharge estimates produced a contributing area that was the same size as the original long-term steady-state simulation. If higher recharge and increased K were applied basin-wide, the size of the contributing area would be expected to increase (Lee, 2002). In the higher recharge simulation, however, changes in both recharge and hydraulic parameters were made primarily close to and beneath the lake, and therefore would not affect the contributing area as much. Offsetting the potential effects of increased K and recharge on the catchment size is an increase in flow that bypasses the lake through the more conductive surficial aquifer system and sublake breaches.

A much greater volume of ground water flows through the lake under the higher recharge condition. The gross ground-water inflow predicted by the higher recharge simulation for the 2-year period was 36,501,600 ft^3 (74.2 inches), 59 percent greater than the gross inflow predicted by the lower recharge simulation for this same period of 22,965,100 ft^3 (46.7 inches). Lake leakage from the higher recharge simulation was 26,503,100 ft^3 (53.9 inches) over the 2-year period, 72 percent greater than leakage from the lower recharge simulation of 15,408,400 ft^3 (31.3 inches). Lake leakage was 14,388,500 and 12,114,600 ft^3 per year for the first and second years, respectively (29.3 and 24.6 in/yr, respectively).

In summary, the higher recharge weekly simulation provided the best agreement with the water budget-derived estimates of ground-water exchange with Lake Starr over the 2-year budget period. The higher recharge simulation also was able to accurately reproduce both peak net ground-water inflow and outflow, and the transition between net inflow and net outflow. However, the higher recharge simulation generated too much inflow during the summer of 1997, so that simulated lake stage after this point was about 0.5 ft higher than observed.

Combined Approach for Estimating Ground-Water Inflow

The results of the higher recharge weekly simulation were coupled with water budget information from Lake Starr in a combined approach for estimating the ground-water inflow to Lake Starr. In the higher recharge weekly simulation, as in all of the simulations, lake leakage was a saturated flow process where leakage was directly proportional to the hydraulic conductivity of the material around the lake and the vertical head difference between the lake and the Upper Floridan aquifer beneath the lake. The saturated ground-water flow model can represent leakage effectively. Ground-water inflow, in contrast to lake leakage, was a nonlinear process affected by the highly variable recharge boundary. This process was more difficult to simulate. In the combined approach, simulated lake

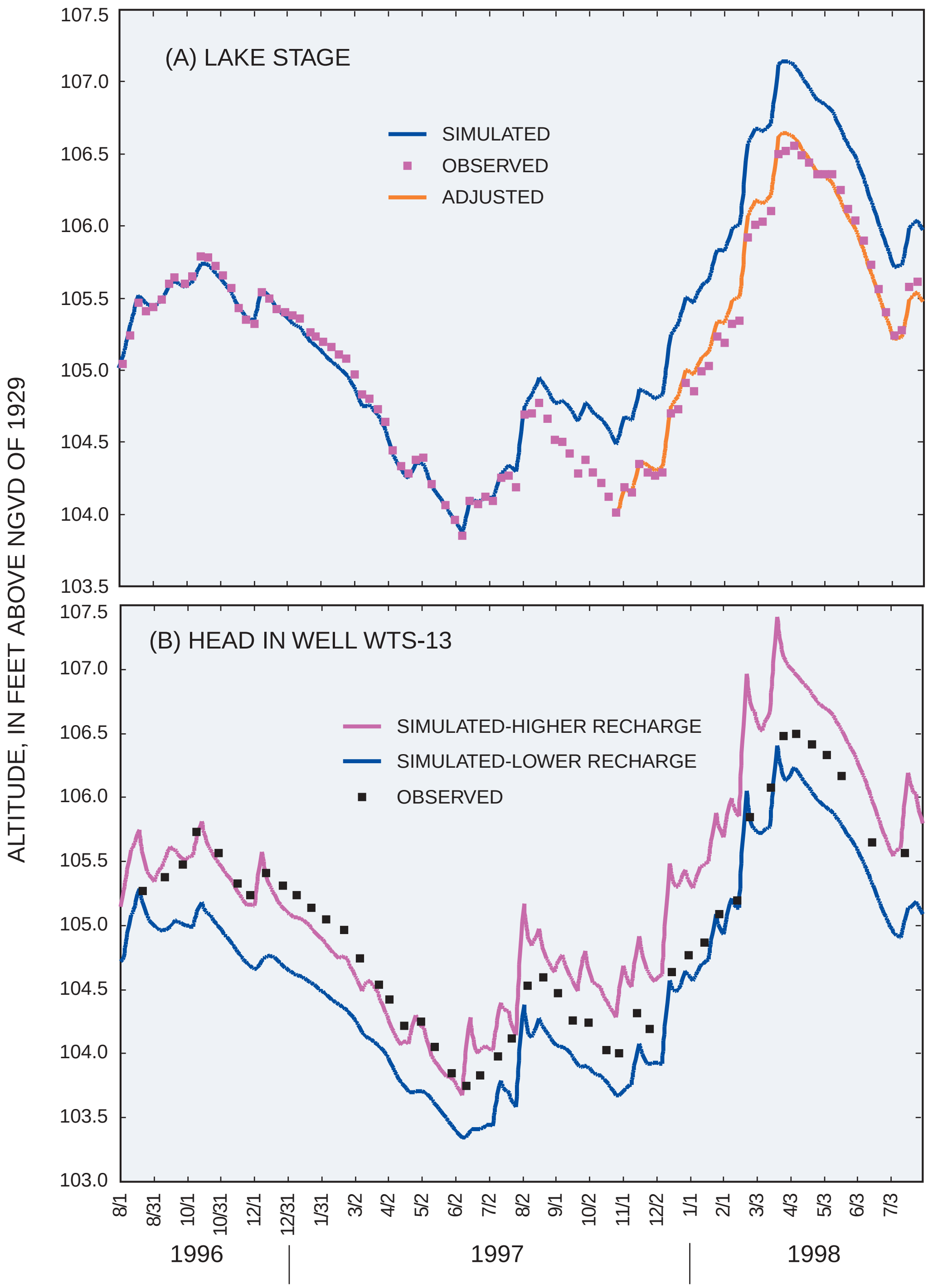


Figure 26. (A) Weekly simulated, observed, and adjusted stage of Lake Starr, and (B) weekly simulated and observed head in well WTS-13 (adjusted lake stage is 0.5 foot less than simulated).

leakage was substituted into the water budget equation and ground-water inflow is calculated as the new residual term as follows:

$$G_i = \Delta S - P + E + Q + G_o \pm e_{\Delta S} \pm e_P \pm e_E \pm e_Q \quad (4)$$

This method eliminates some of the problems estimating recharge inputs, but maintains the increased "leakiness" of the sublake ground-water flow system that was needed to simulate the transition from net ground-water inflows to outflows. When expressed as linear units over the lake surface area, simulated leakage is divided by a fixed lake area, as are other simulated fluxes to and from the lake. Inflow calculated using the combined approach is relative to a variable surface area similar to other water budget terms. By definition, net ground-water flow is the same as the water budget.

Weekly ground-water inflows calculated using the combined approach varied over a larger range of values than simulated lake leakage (outflows) (fig. 27 and table 5). Weekly ground-water inflow was generally inversely related to outflow. Weeks with increased ground-water inflow were usually accompanied by reduced outflow, with two factors contributing to this effect. First, flow reversals associated with increased ground-water inflow can temporarily reduce the percentage of the perimeter experiencing lake leakage (Lee, 2000). Secondly, and probably more importantly, vertical lake leakage can be reduced because pumping from the Upper Floridan aquifer for irrigation is reduced during wet weeks, raising heads in the Upper Floridan aquifer. During the wet season, these effects continue for many weeks at a time. Using the combined approach, the annual ground-water inflow was 16,327,200 and 21,033,900 ft^3 for the first and second years of the study, respectively (33.0 and 41.7 in/yr, respectively). Ground-water inflow was larger and lake leakage was smaller in the second year compared to the first. As a result, net ground-water flow was 13.7 inches greater the second year (3.7 and 17.4 in/yr for the first and second years, respectively). Note, net ground-water values are slightly different from those presented in Swancar and others (2000) because of differences in the way volumes are converted to linear units over the lake surface area.

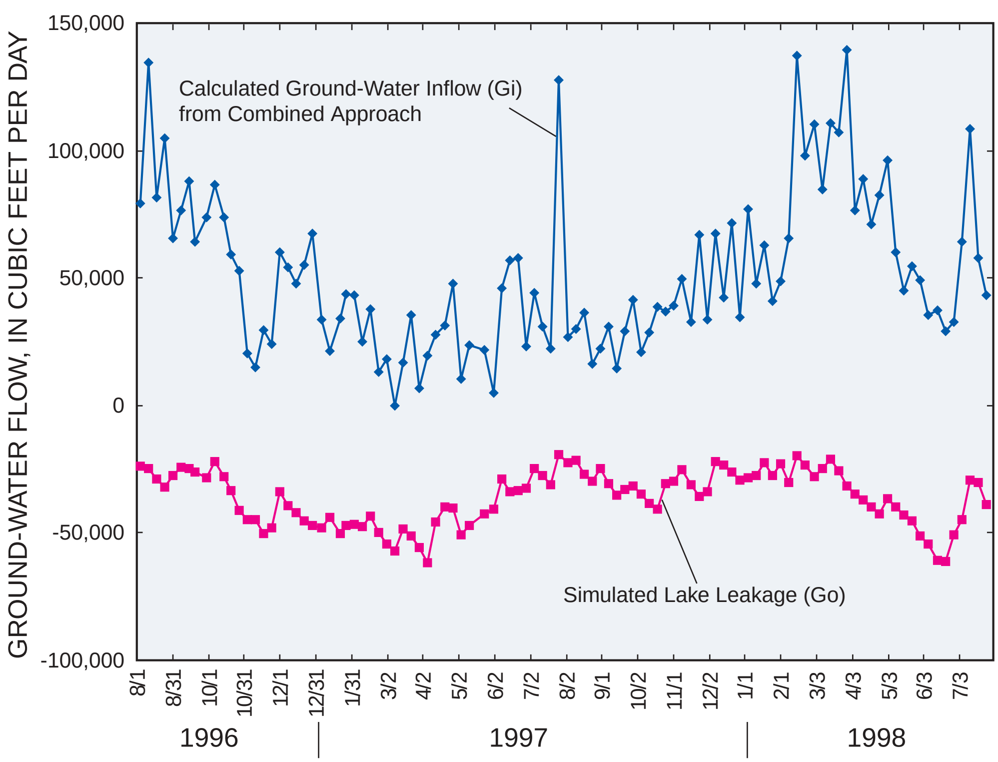


Figure 27. Weekly calculated ground-water inflow to and simulated leakage from Lake Starr during the 2-year study period.

Table 5. Weekly inflows to and outflows from Lake Starr, with ground-water inflows calculated using a combined approach, July 20, 1996, through August 1, 1998

[All units cubic feet per day unless otherwise noted; GW, ground water; %, percent; most weeks are 7 days in length, but periods vary from 5 to 13 days; calculated inflow set to zero if negative]

Week begin date	INFLOWS			OUTFLOWS			
	Rain	Calculated GW Inflow	GW inflow as % of total	Evaporation	Lake pumping	Simulated GW outflow	GW outflow as % of total
07/20/96	1,423	38,470	96	119,072	3,153	30,375	20
07/28/96	189,606	42,436	18	121,042	4,787	29,073	19
08/04/96	217,090	79,158	27	99,346	0	23,917	19
08/11/96	195,302	134,681	41	103,533	0	24,825	19
08/18/96	8,263	81,343	91	112,445	1,224	28,816	20
08/25/96	46,345	104,950	69	91,825	1,224	31,832	25
09/01/96	109,278	65,761	38	102,203	1,225	27,477	21
09/08/96	130,618	76,429	37	85,157	0	24,310	22
09/15/96	74,831	88,005	54	88,015	0	24,910	22
09/20/96	39,039	64,142	62	103,749	961	26,199	20
09/29/96	84,345	73,990	47	79,044	6,174	28,540	25
10/06/96	136,180	86,487	39	90,944	0	21,859	19
10/14/96	19,655	73,610	79	68,579	7,274	27,918	27
10/20/96	0	59,169	100	70,840	8,710	33,530	30
10/27/96	2,510	52,938	95	59,374	8,683	41,102	38
11/03/96	30,057	20,379	40	83,265	2,473	44,886	34
11/10/96	0	14,754	100	87,687	6,138	44,774	32
11/17/96	0	29,360	100	40,984	8,560	50,100	50
11/24/96	56,883	23,990	30	56,532	2,439	48,168	45
12/01/96	211,048	59,976	22	43,309	0	33,950	44
12/08/96	0	54,111	100	48,818	1,229	39,492	44
12/15/96	2,485	47,808	95	70,158	8,591	42,136	35
12/22/96	0	54,906	100	18,473	8,564	45,462	63
12/29/96	0	67,589	100	29,348	8,559	47,253	55
01/05/97	47,034	33,572	42	45,092	4,886	48,177	49
01/12/97	17,307	21,320	55	62,806	0	43,811	41
01/21/97	6,887	34,252	83	18,938	8,499	50,268	65
01/26/97	19,664	43,910	69	39,046	3,639	46,959	52
02/02/97	4,907	43,229	90	31,253	4,843	46,724	56
02/09/97	21,206	25,112	54	34,725	7,249	47,576	53
02/16/97	34,269	37,700	52	54,309	0	43,535	44
02/23/97	813	12,971	94	50,144	8,422	49,679	46
03/02/97	0	18,162	100	74,811	8,380	54,258	39
03/09/97	106,960	0	0	67,926	4,764	57,048	44
03/16/97	54,780	16,696	23	82,120	0	48,498	37
03/23/97	12,821	35,604	74	69,134	3,557	51,395	41
03/30/97	0	6,623	100	109,363	8,257	55,621	32
04/06/97	42,276	19,346	31	83,756	7,034	61,588	40
04/13/97	64,899	27,702	30	87,770	0	45,879	34
04/20/97	165,221	31,446	16	72,121	2,333	39,991	35
04/27/97	67,964	47,680	41	67,195	0	40,198	37
05/04/97	0	10,372	100	100,229	7,011	50,856	32
05/11/97	37,856	23,570	38	77,574	2,503	46,954	37
05/24/97	55,476	21,800	28	104,345	1,012	42,439	29
06/01/97	41,642	4,906	11	93,927	0	40,695	30
06/08/97	275,973	46,086	14	100,500	0	28,614	22
06/15/97	52,767	57,092	52	92,145	0	33,903	27
06/22/97	121,288	57,895	32	105,364	0	33,306	24
06/29/97	89,491	22,962	20	104,240	0	32,535	24
07/06/97	208,152	44,358	18	97,390	0	24,872	20

Table 5. Weekly inflows to and outflows from Lake Starr, with ground-water inflows calculated using a combined approach, July 20, 1996, through August 1, 1998 (Continued)

[All units cubic feet per day unless otherwise noted; GW, ground water; %, percent; most weeks are 7 days in length, but periods vary from 5 to 13 days; calculated inflow set to zero if negative]

Week begin date	INFLOWS			OUTFLOWS			
	Rain	Calculated GW Inflow	GW inflow as % of total	Evaporation	Lake pumping	Simulated GW outflow	GW outflow as % of total
07/13/97	108,983	30,715	22	95,827	0	27,499	22
07/20/97	38,519	22,454	37	95,293	0	31,049	25
07/27/97	416,592	127,686	23	111,144	0	19,169	15
08/03/97	94,563	26,629	22	90,124	0	22,656	20
08/10/97	142,956	30,233	17	92,414	0	21,744	19
08/17/97	3,694	36,384	91	103,200	2,372	27,154	20
08/24/97	11,060	16,283	60	106,094	8,274	29,972	21
08/31/97	98,407	22,300	18	111,223	1,178	24,937	18
09/07/97	22,707	30,964	58	85,735	3,528	30,723	26
09/14/97	0	14,440	100	86,063	8,200	35,432	27
09/21/97	174,329	29,240	14	85,027	3,501	32,819	27
09/28/97	730	41,515	98	83,441	1,169	31,658	27
10/05/97	50,927	21,059	29	94,689	0	34,584	27
10/12/97	5,788	28,578	83	72,757	4,649	38,365	33
10/19/97	723	38,566	98	79,394	8,112	40,743	32
10/26/97	191,533	36,693	16	50,547	1,157	30,633	37
11/02/97	28,294	39,122	58	70,275	0	29,703	30
11/09/97	187,442	49,744	21	43,837	4,647	25,076	34
11/16/97	0	32,866	100	48,547	2,337	31,285	38
11/23/97	727	67,150	99	40,309	8,175	35,787	42
11/30/97	67,676	33,851	33	46,697	4,670	33,767	40
12/07/97	319,721	67,243	17	24,175	0	22,173	48
12/14/97	65,148	42,283	39	58,891	0	23,273	28
12/21/97	115,231	71,418	38	2,197	5,947	25,901	76
12/28/97	4,469	34,416	89	59,292	1,194	29,457	33
01/04/98	75,408	77,133	51	0	4,781	28,325	86
01/11/98	53,173	47,682	47	39,122	0	27,416	41
01/18/98	156,539	62,893	29	22,937	1,203	22,415	48
01/25/98	2,267	40,935	95	48,198	2,424	27,329	35
02/01/98	149,233	48,763	25	60,627	1,212	22,906	27
02/08/98	27,021	65,551	71	40,042	4,873	30,152	40
02/15/98	428,354	137,341	24	28,532	0	19,880	41
02/22/98	72,878	97,913	57	65,396	0	23,433	26
03/01/98	9,435	110,303	92	72,377	1,263	27,821	27
03/08/98	106,561	84,774	44	101,219	1,264	24,704	19
03/15/98	346,235	110,990	24	60,235	3,807	21,191	25
03/22/98	0	107,198	100	60,256	2,600	25,497	29
03/29/98	3,246	139,412	98	64,292	9,119	31,486	30
04/05/98	0	76,659	100	98,899	9,110	34,668	24
04/12/98	0	88,696	100	89,407	9,070	37,199	27
04/19/98	6,445	70,947	92	103,488	9,041	39,726	26
04/26/98	46,353	82,586	64	81,219	5,145	42,575	33
05/03/98	20,850	96,278	82	80,409	0	36,719	31
05/10/98	0	60,294	100	115,046	7,702	39,873	25
05/17/98	0	45,135	100	113,327	8,922	42,915	26
05/24/98	5,512	54,860	91	79,634	8,864	45,256	34
05/31/98	787	49,096	98	117,385	8,817	51,217	29
06/07/98	2,342	35,415	94	128,051	8,741	54,339	28
06/14/98	0	37,464	100	119,831	8,666	60,719	32
06/21/98	13,729	28,962	68	114,359	8,594	61,098	33

Table 5. Weekly inflows to and outflows from Lake Starr, with ground-water inflows calculated using a combined approach, July 20, 1996, through August 1, 1998 (Continued)

[All units cubic feet per day unless otherwise noted; GW, ground water; %, percent; most weeks are 7 days in length, but periods vary from 5 to 13 days; calculated inflow set to zero if negative]

Week begin date	INFLOWS			OUTFLOWS			
	Rain	Calculated GW Inflow	GW inflow as % of total	Evaporation	Lake pumping	Simulated GW outflow	GW outflow as % of total
06/28/98	5,320	32,565	86	122,047	4,875	50,916	29
07/05/98	123,979	64,297	34	103,974	4,853	44,591	29
07/12/98	281,519	108,360	28	96,297	0	29,356	23
07/19/98	96,220	57,665	37	96,993	0	30,196	24
07/26/98	5,372	43,416	89	108,895	7,391	38,987	25
Total: August 1996-July 1998, in cubic feet	51,482,377	37,361,090	42	55,932,446	2,624,855	26,503,093	31

Over the 2-year study, ground-water inflow calculated using the combined approach was about 37,361,100 ft^3 and accounted for 42 percent of the total input of water to the lake, while 58 percent of inflow was from rainfall (table 5). During the relatively dry months of May and June 1998, ground-water inflow provided over 90 percent of the total inflow to the lake. During the study period, simulated lake leakage was about 26,503,100 ft^3 and accounted for 31 percent of the total losses of water from the lake, while evaporation was 66 percent and direct pumping was 3 percent. Calculated ground-water inflow and simulated lake leakage at Lake Starr were on the high end of the range of possible values calculated by Sacks and others (1998) using an isotopic mass balance, and were more than double the estimates of minimum inflow and outflow from Swancar and others (2000).

An adaptation of this combined approach can be used to calculate ground-water exchange with Lake Starr beyond the model period. Simulated leakage values are not required; instead, a statistical regression can be used to estimate lake leakage. This adaptation requires that a lake water budget and continuous head measurements in the Upper Floridan aquifer are available for the time period of interest. Simulated lake leakage was highly correlated to the average head difference between the lake and a continuously recording Upper Floridan aquifer well outside the basin (ROMP 57, fig. 28). This relation allows the monthly lake leakage to be estimated from the vertical head difference. The predictive equation explained 86 percent of the variance in the simulated leakage, and had a standard error of 0.23 inches, or about 11 percent of the average monthly value of lake leakage. The remaining variability in simulated leakage that could not be explained by the regression is probably related to the use of a single average water level to represent the Upper Floridan aquifer potentiometric surface beneath the lake. In contrast to the good relation for lake leakage, calculated ground-water inflow showed poor predictive relations with rainfall or net precipitation (r^2 = 0.12 and 0.11, respectively).

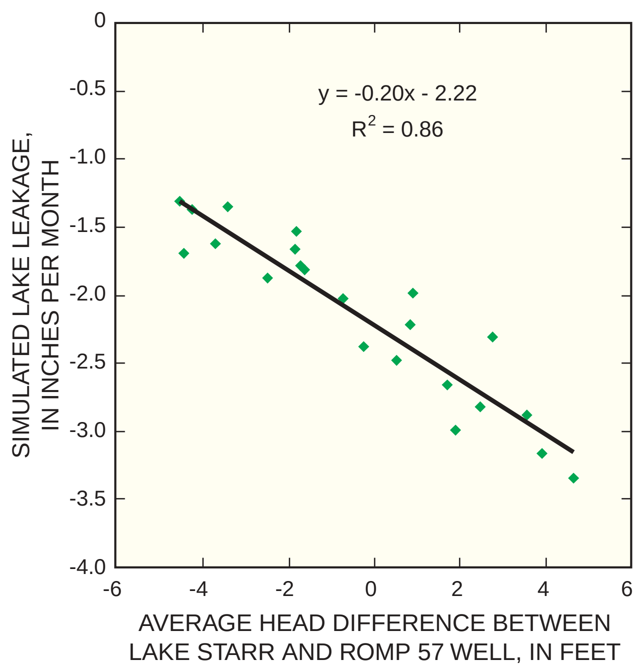


Figure 28. Relation between simulated leakage from Lake Starr and monthly average head difference between Lake Starr and ROMP 57 Upper Floridan aquifer well, August 1996 through July 1998.

Because of the correlation of leakage to the head difference between the lake and the Upper Floridan aquifer, lake leakage estimated by the regression can be substituted into the water budget, and ground-water inflow can be calculated as the new residual term to the water budget equation. This approach was used to estimate the ground-water inflow to Lake Starr beyond the model period in a study using isotopic tracers to understand lake/ground-water interactions (Sacks, 2002).

EFFECTS OF BOUNDARY CONDITIONS AND TIME SCALE ON GROUND-WATER EXCHANGE

Improving the simulation of transient boundary conditions in ground-water flow models can improve the simulation of ground-water exchange with lakes. Understanding how the recharge boundary affects simulated ground-water exchange is important because lack of information on recharge is a common model limitation. Understanding how ground-water exchange with Lake Starr is controlled by the lower specified-head boundary is important because regulated ground-water pumping largely determines the specified head. Investigating how differences in model time scale affect ground-water exchange with lakes makes it possible to determine the time scale of processes that affect lake/ground-water interactions.

Recharge Boundary

Representing unsaturated zone processes in the recharge boundary of the saturated flow model improved the simulation of ground-water levels and ground-water exchange with Lake Starr. The use of LEACHM in the nearshore region of the basin, where the water table was relatively shallow, provided more realistic timing of recharge, and magnified the recharge contribution of intense rainfall periods.

Using the lower of two recharge estimates, neither monthly nor weekly simulations came close to estimating the budget-derived estimates of net ground-water flow to Lake Starr. This result was true regardless of the temporal variability of the Upper Floridan aquifer boundary condition. However, the weekly model, like the weekly water budget, did reveal rapid changes in magnitude and direction (net gain or loss) of net ground-water flow on a week-to-week basis. The weekly simulation also was capable of generating periodic flow reversals along the outflow side of the lake.

Calibrating the weekly simulation to the net ground-water flow seen in the weekly water budget provided insight into recharge processes and the hydrogeology of Lake Starr that were lacking in the monthly simulation. The simulated and budget-derived estimates of annual net ground-water flow to Lake Starr began to converge only when the weekly recharge estimates and the aquifer hydraulic conductivity around the lake were substantially increased. With these changes, the model was able to accurately simulate the larger and more rapid changes in net ground-water flow on a week-to-week basis.

Despite the improved simulation of periods of *peak* ground-water inflows and outflows, the higher recharge simulation still had difficulty consistently predicting the smaller variations in weekly net ground-water flow. The model may have been unable to consistently simulate the weekly inflows because it could not simulate the recharge and water-table response on a daily or shorter time scale. Averaging the daily recharge rates calculated by LEACHM over a week-long stress period greatly decreased the maximum daily recharge rate applied for the week (table 6).

Table 6. Maximum daily, weekly, and monthly average recharge rates simulated by the LEACHM model

[Maximum rates are in inches per day; 35% P, soil characteristics adjusted so that LEACHM model delivers total 2-year recharge equal to 35 percent of rainfall; 86% P, total 2-year recharge is equal to 86 percent of rainfall; most weeks are 7 days in length, but periods vary from 5 to 13 days]

Month	Maximum daily rate		Maximum weekly rate		Maximum monthly rate	
	35% P	86% P	35% P	86% P	35% P	86% P
June 1996	1.30	2.58	0.46	0.82	0.17	0.36
July 1997	1.39	2.09	0.60	0.83	0.16	0.29
February 1998	1.96	2.00	0.71	0.83	0.24	0.32

Yet, variably saturated flow modeling of nearshore mound formation in a similar setting and with daily stress periods indicated that 80-90 percent of large *daily* rainfall events had to recharge the shallow water table to produce the observed water-table rise. These large daily events also were responsible for generating substantial fluxes of net ground-water inflow (Lee, 2000). Averaging daily recharge over a monthly stress period reduced the maximum recharge rates further, effectively masking the impact of these transient processes.

For a shallow water table (for example less than 6 ft), recharge from a given rainfall event could approach the majority of the net precipitation (rainfall minus daily evapotranspiration; Wu and others, 1996; Lee, 2000). However, it is unlikely that the long-term or annual average recharge is as high as 86 percent of rainfall in the closest nearshore zone defined for the lake basin. The fact that this amount of weekly recharge was required to calibrate the weekly simulation to the budget-derived net ground-water flow suggests that processes influencing ground-water inflow on a weekly basis remain only partially represented in the model.

To simulate the processes that generate highly transient ground-water inflows, the model would require even shorter stress periods and smaller grid sizes, which should represent nearshore water-table mounds more accurately. Simulation of transient water-table mounding near lakeshores requires relatively fine spatial discretization and short time scales. For example, Lee (2000) simulated transient mounding using daily stress periods and spatial discretization on the order of tens of centimeters in a two-dimensional, variably saturated finite-element model of two lake hillsides. Nearshore cells in the current model are four orders of magnitude larger, and this scale difference limits the ability of the model to accurately simulated nearshore processes. Finer temporal and spatial discretization in the nearshore could allow the model to generate the ground-water inflow to the lake seen in the water budget without having to use such a high long-term recharge rate.

One possible reason for the high nearshore recharge needed to calibrate the weekly simulation is that runoff from the basin to the lake is assumed to be negligible when this may not be true. Runoff could be occurring from saturated soils near the shoreline during intense rainfall events, but this process is probably relatively unimportant in this basin compared to transient ground-water inflow. Runoff and the earliest ground-water inflow both cause short-term rises in lake stage in excess of the amount of rainfall, so the potential effect of runoff on lake stage can be difficult to isolate. Short-term (hourly) rises in stage that were substantially in excess of rainfall occurred only a few times during the 2-year study during the most intense storms (rainfall rates greater than 1 inch per hour). Even if runoff is occurring in these few instances, its effect on lake stage is expected to be well within the 10 percent error assumed for weekly rainfall. Washouts or gullies that would be evidence of runoff to the lake were not observed at the lakeshore; however, runoff to ditches and storm drains from roads in the basin does route water from upper parts of the basin to areas closer to the lake, which could affect the distribution of recharge within the basin.

In contrast to the lack of evidence of the influence of runoff on lake stage, the influence of transient ground-water inflow was evident during the days after rain events. Lake stage rose or remained stable for several days after the largest rainfall events had ended. For example, lake stage rose 0.37 ft from March 19 to 21, 1998, in response to 4.41 inches (0.368 ft) of rain, and continued to rise another 0.04 ft by April 1, 1998, even though no more rain fell during that period. This rise could only be due to increased net ground-water flow to the lake.

To determine whether increasingly shorter stress periods could improve the prediction of ground-water flow to the lake, the higher recharge simulation was rerun using daily stress periods for the 10 weeks with the highest LEACHM recharge. In this scenario, the simulated peak ground-water inflows exceeded those from the weekly model (245,000 compared to 144,000 ft^3/d), but the total inflow generated during the 10 weeks was actually less than the weekly simulation by a significant amount (27 percent). This difference may be an artifact of the way flows to and from the lake were calculated. In calculating flows to and from the lake, flow rates at the end of the stress period were assumed to be equal to the average flow rate during the stress period. However, the magnitude of flow to or from the lake increases with each time step within the stress period, while the rate of change declines. As the stress period length increases, the flow rate at the end of the stress period is more likely to approach a stable value that is representative of the average flow rate over the stress period. For shorter stress periods (days or weeks), the flow rate at the end of the stress period is less likely to have stabilized. Using this method to calculate fluxes appears to have overestimated the magnitude of the average flow rate during the 10 weeks with the highest LEACHM recharge compared to a simulation with daily stress periods. When average flow rates for weekly stress periods were assumed to be the average of the beginning and end fluxes (similar to a running average), the daily simulation had 15 percent higher inflow compared to the weekly simulation for the same 10-week period. However, using this method for the entire 2-year study period led to lower estimates of peak net ground-water flow to the lake than previously calculated, and a poorer fit to the budget-derived net ground-water flow.

In attempting to simulate ground-water interactions with lakes in mantled karst terrain, models need to account for the effect of nearshore recharge processes. There continues to be a need for a better understanding of annual and shorter-term recharge processes for all types of hydrologic models. Future efforts on quantifying recharge rates should consider combining results of variably saturated flow models with field observations similar to Lee (2000), using geochemical tracer methods (Plummer and Friedman, 1999), and calculating recharge by subtracting evapotranspiration from rainfall (Sumner, 1996).

Upper Floridan Aquifer Boundary

Modeling results confirm that accurately representing the Upper Floridan aquifer heads spatially and temporally is important to successfully simulating the ground-water flow patterns in the basin around Lake Starr. Heads in the basin and ground-water exchange with the lake are strongly affected by heads in the Upper Floridan aquifer. The shape of the potentiometric surface of the Upper Floridan aquifer in the basin is the primary control on the flow-through pattern of the lake with respect to the surficial aquifer system, and which areas of the basin contribute ground water to the lake. Recharge superimposes temporary fluctuations on the water-table shape, but Upper Floridan aquifer heads also control the general shape of the water table. To thoroughly understand the variability of the potentiometric surface in space and time, head measurements in the Upper Floridan aquifer should be recorded continuously at several locations in the lake basin.

Heads in the Upper Floridan aquifer largely control the amount of water that leaks from the lake to the ground-water flow system. Simulated lake leakage was related to head in the Upper Floridan aquifer and the downward head difference between the lake and the Upper Floridan aquifer. Most of the response of the lake stage to pumping stresses can be represented by monthly average Upper Floridan aquifer heads, but lake stage also responds to stresses on a weekly time scale. Even pumping that lowers heads for several days is capable of affecting lake stage within the same week that the drawdown occurs. For example, pumpage principally for freeze protection of citrus crops caused the weekly average level of the Upper Floridan aquifer to drop 7 ft from the week of December 24-30, 2000, to the week of December 31-January 6, 2001 (data on file in Tampa USGS database for ROMP 57 recorder well). On a daily basis, heads ranged from 5-10 ft lower than the average of the previous week. Using the regression relation between simulated lake leakage and the head difference between the lake and the Upper Floridan aquifer, this weekly average head difference was capable of increasing outflows from Lake Starr by 53 percent, from 38,000 to 59,500 ft^3/d. This is equivalent to an additional decrease in stage of about 0.02 ft over the week.

Time Scale

As in previous modeling studies, the use of monthly stress periods at Lake Starr adequately simulated the observed head conditions in the surrounding aquifers. The monthly simulation could not, however, predict the extremes in the monthly net ground-water exchange, even when the recharge and Upper Floridan aquifer boundaries were represented in greater spatial and temporal detail than in previous studies. During the wettest months of the 2-year study period, the lake received more ground-water inflow than the model predicted. During the driest months, the lake leaked more than the model predicted.

Lake Starr is the first lake in Florida with a detailed lake water budget on a weekly timeframe for a 2-year period. The weekly water budget provided the basis for calibrating a numerical model of weekly ground-water exchange with Lake Starr. Simulating the net ground-water exchange on a weekly basis, however, required constructing a substantially different model than the monthly model. Compared to the monthly model, the weekly model required calibrating to four times as many values of net ground-water flow.

In addition, peak weekly net ground-water flow was 41 to 128 percent higher than peak monthly flow. The weekly water budget reveals that much of the ground-water inflow during a month can occur in a single week. Further, the rapid rate of decline in net ground-water inflow following a peak is not apparent at a monthly time scale. Weekly simulations required that lake interaction with the surrounding ground-water flow system be much more dynamic than implied by the monthly simulation. To agree with the budget-derived net ground-water flow, recharge and gross ground-water flow rates had to be higher, and the sublake geology and confining unit more leaky, than initial simulations.

Model stress periods and water budget time periods are inextricably linked, as accurate lake water budgets still provide the standard against which simulations are interpreted. Some inflows probably occur on time scales less than weekly, for example, those resulting from transient recharge events. The weekly water budget of Lake Starr substantiates their importance (Swancar and others, 2000). Currently, it is difficult to get interpretable lake water budgets on a shorter timeframe than weekly, because the error in daily water budget components becomes too large. At the same time, simulating ground-water exchanges that are evident from weekly lake water budgets is a sufficient challenge for the near future.

One consequence of using monthly or longer time scales in lake basin models is the underestimation of ground-water inflow to the lake, and underestimating inflow leads to underestimating lake leakage. At Lake Starr, leakage was underestimated because the K below the lake was underestimated. The higher K values needed to calibrate to weekly net ground-water fluxes lead to a revised understanding of the effects of pumpage on the lake and the surrounding water table. If management decisions are based on models that underestimate these effects because of the model time scale, lakes may not be sufficiently safeguarded from the effects of short-term drawdown in the Upper Floridan aquifer. Unintended declines in surface-water levels are the result. Effects of ground-water pumpage on the lake would also be underestimated through the use of generalized or averaged annual specified heads to represent the Upper Floridan aquifer.

SUMMARY AND CONCLUSIONS

Numerical modeling can be used as a tool to understand the effects of hydrogeologic setting, climate and ground-water pumping on ground-water exchange with lakes. A useful approach is to combine ground-water flow modeling of lake basins with detailed lake water budgets. Differences in the magnitude of ground-water exchange estimated by modeling and water budgets can reveal ground-water flow processes unaccounted for by the models. The purpose of this study was to quantify ground-water inflow and lake leakage using a three-dimensional, numerical model of the Lake Starr basin, and to investigate how representing the time-varying boundary conditions (recharge to the surficial aquifer system and the potentiometric surface of the Upper Floridan aquifer) by monthly and weekly averages affected the simulated ground-water fluxes. Ground-water inflow to the lake and lake leakage were simulated over a 2-year period from August 1996 through July 1998.

Simulated values of net ground-water flow were compared with the more accurate net ground-water flow calculated from a rigorously derived lake water budget. Net ground-water flow is the difference between the gross or total ground-water inflow and lake leakage for any given time period. In addition to calibration to measured water levels in wells, the agreement between the two estimates of net ground-water flow indicated whether or not the representation of boundary conditions improved the simulation. A finite-difference ground-water flow model of the Lake Starr basin was constructed using the USGS model code MODFLOW. The model simulated ground-water flow in the surficial aquifer system and the intermediate confining unit within a 3-mi^2 area surrounding Lake Starr. The lake was represented as an area of active cells with a very high hydraulic conductivity (K) of 10,000-50,000 ft/d.

The steady-state simulation provided a good fit to the median water-table configuration and median vertical head distribution in the aquifer beneath Lake Starr, with the root mean squared error between simulated and median observed water levels of less than 0.5 ft. Simulated heads and fluxes were most sensitive to recharge, specified heads in the Upper Floridan aquifer lower boundary, and K values in the intermediate confining unit. Heads were less sensitive to K in the surficial aquifer system, but fluxes to and from the lake were directly related to changes in this value. The head distribution of the lower boundary had a strong effect on the water-table shape, imposing a northwest to southeast flow direction on the surficial aquifer system, which caused lake water to flow into the surficial aquifer system along the southeast shore despite the higher topography on this side of the basin. The steady-state area contributing ground water to the lake, called the ground-water catchment, was west and north of the lake and extended about 1,200 ft from the lake on the west side. The ground-water catchment covered about 16 percent of the topographic basin.

In transient simulations, a combination of two methods for estimating recharge (threshold and LEACHM) produced the best agreement to both heads and fluxes. Heads were generally within 1 ft of the observed values. However, monthly simulations with total recharge set to 35 percent of 2-year rainfall failed to simulate the highest lake levels and to predict peaks and lows in net ground-water flow to the lake. Monthly simulated net ground-water flow to the lake agreed within the error bars of budget-derived estimates for only 14 of 24 months. During wet periods, the monthly simulations tended to greatly underpredict net ground-water inflow. Representing the Upper Floridan aquifer specified-head boundary with monthly averages instead of a steady-state potentiometric surface improved the simulation of monthly ground-water exchange and basin water levels. Use of a steady-state boundary to represent the Upper Floridan aquifer reduced the agreement with budget-derived fluxes to only 10 of 24 months and added substantial errors to monthly estimates of net ground-water exchange.

Weekly stress periods simulated lake stage more accurately and showed a larger variability in net ground-water flow to the lake compared to monthly stress periods. Unlike monthly stress periods, the transient water-table mounds that were observed near Lake Starr were simulated when recharge conditions were applied weekly. Weekly simulation increased the peak net ground-water inflow rates compared to monthly simulation, but peak net ground-water outflows were similar to monthly rates. The minimum and maximum simulated weekly net ground-water flow rates, however, were still well below the rates derived from the weekly water budget. Simulated net ground-water flow did not alternate from large net ground-water inflow to large net leakage as quickly as indicated by the weekly water budget. The representation of specified weekly Upper Floridan aquifer heads in the transient model had a smaller effect on the magnitude of simulated net ground-water flow than the representation of weekly recharge, but the effect was noticeable.

A weekly simulation also was run using higher recharge rates, greater K_h in the surficial aquifer system adjacent to the lake, and greater K in the sublake region. The higher recharge simulation matched the peak weekly values of net ground-water flow from the water budget more closely than the original weekly simulation. The higher recharge simulation was better at producing the relatively rapid transitions from net ground-water inflow to net ground-water outflow, as well as the steep declines in net ground-water flow that were seen in the water budget. The improved simulation of net ground-water flow suggests that lake leakage and the K of the sublake region were better represented in the high recharge simulation than in the original model. A much greater volume of ground water flowed through the lake under the higher recharge condition. The gross ground-water inflow predicted by the higher recharge simulation for the 2-year period was 59 percent greater and lake leakage was 72 percent greater than predicted by the lower recharge simulation.

Even though the higher recharge simulation was an improvement over previous simulations, particularly with respect to its ability to reproduce the extremes of net ground-water flow, this simulation did not predict net ground-water flow within the water budget error for a greater number of weeks than the low recharge simulation. This was because of insufficient information about the more subtle effects of rainfall and recharge on ground-water inflow, and practical limits on spatial and temporal discretization in a model at this scale. In contrast, the saturated flow model appeared to successfully simulate the effects of heads in the Upper Floridan aquifer on water levels and ground-water exchange with the lake at both weekly and monthly stress periods. The majority of the variability in lake leakage can be explained by the average vertical head difference between the lake and a representative Upper Floridan aquifer well. Simulated lake leakage was highly correlated to the average head difference between the lake and an Upper Floridan aquifer well, suggesting that leakage was largely a linear function of this head difference.

The results of the higher recharge weekly simulation were coupled with water budget information from Lake Starr in a combined approach for estimating the ground-water inflow to Lake Starr. In the combined approach, simulated lake leakage was substituted into the water budget equation and ground-water inflow was calculated as the new residual term. This method eliminates some of the problems estimating recharge inputs, but maintains the increased “leakiness” of the sublake ground-water flow system that was needed to simulate the transition from peak net ground-water inflows to outflows. Using this approach, ground-water inflow accounted for 42 percent of the total input of water to the lake over the 2-year study, and rainfall accounted for 58 percent of water inputs. Simulated lake leakage for the 2 years accounted for 31 percent of total water losses, while evaporation was 66 percent and direct pumping was 3 percent. An adaptation of the combined approach can be used to calculate ground-water exchange with Lake Starr beyond the model period using a regression to predict lake leakage. This adaptation requires that a lake water budget and head measurements in the Upper Floridan aquifer are available for the time period of interest.

This study illustrates how calibrating saturated ground-water flow models with monthly stress periods to a monthly lake water budget results in underpredicting gross inflow to, and leakage from, ridge lakes in Florida. Recharge stresses and ground-water flow responses during rainy periods are averaged over too long a time period using monthly stress periods. Calibrating the weekly simulation required accounting for transient responses in the water table near the lake that generated the greater range of net ground-water flow values seen in the weekly lake water budget.

To simulate the total ground-water inflow to lakes, saturated-flow models of lake basins need to account for the potential effects of rapid and efficient recharge in the surficial aquifer system closest to the lake. In this part of the basin, the ability to accurately estimate recharge is crucial because the water table is shallowest, the response time between rainfall and recharge is shortest, and daily recharge may approach the daily rainfall amount. Use of the one-dimensional unsaturated model LEACHM to simulate the effects of the unsaturated zone on the timing and magnitude of the recharge in the nearshore region of the model improved the simulation of peak values of ground-water inflow to Lake Starr. The use of variably saturated flow modeling, with time scales that are shorter than weekly and finer spatial discretization, is probably necessary to understand the subtle effects of rainfall and recharge on ground-water inflow processes. Underprediction of ground-water inflow to lakes due to inaccurate simulation of nearshore processes can reduce the implied effect of ground-water withdrawals from the Upper Floridan aquifer on the lake level.

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