# Simulation of the Interaction of Karstic Lakes Magnolia and Brooklyn with the Upper Floridan Aquifer, Southwestern Clay County, Florida

Water-Resources Investigations Report 00-4204

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY


Prepared in cooperation with:

St. Johns River
Water Management District

Southwest Florida
Water Management District

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By Michael L. Merritt

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U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
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Box 25286
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# CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATIONS AND ACRONYMS

| Multiply | By | To obtain |
|---|---|---|
| | ***Length*** | |
| foot (ft) | 0.3048 | meter |
| | ***Area*** | |
| square foot ($ft^2$) | 0.0929 | square meter |
| | ***Volume*** | |
| cubic foot ($ft^3$) | 0.028317 | cubic meter |
| | ***Flow*** | |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second |
| cubic foot per second ($ft^3/s$) | 0.6463 | million gallons per day |
| inch per day (in/d) | 2.54 | centimeter per day |
| | ***Hydraulic Conductivity*** | |
| foot per day (ft/d) | 0.3048 | meter per day |
| | ****Transmissivity*** | |
| foot squared per day ($ft^2/d$) | 0.09290 | meter squared per day |

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows: °C=(°F-32)/1.8.

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

***Transmissivity:** The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/d)/ft^2]ft$. In this report, the mathematically reduced form, foot squared per day ($ft^2/d$), is used for convenience.

Acronyms and additional abbreviations used in report:

| | |
|---|---|
| BCF | Block-Centered Flow |
| CHD | Time-Variant Specified-Head |
| $d^{-1}$ | Per day (feet per day per foot of thickness) |
| ET | Evapotranspiration |
| ft/ft | Feet per foot |
| FHB | Flow and Head Boundary |
| GHB | General Head Boundary |
| GIS | Geographical Information System |
| MOC3D | Three-Dimensional Method-of-Characteristics Solute-Transport Model |
| MODFLOW | U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model |
| NOAA | National Oceanographic and Atmospheric Administration |
| Rmf | Rainfall memory factor |
| SJRWMD | St. Johns River Water Management District |
| SWFWMD | Southwest Florida Water Management District |
| SIP | Strongly-Implicit Procedure |
| USGS | U.S. Geological Survey |
| UF | University of Florida |

# Simulation of the Interaction of Karstic Lakes Magnolia and Brooklyn with the Upper Floridan Aquifer, Southwestern Clay County, Florida

*By* Michael L. Merritt

## Abstract

The stage of Lake Brooklyn, in southwestern Clay County, Florida, has varied over a range of 27 feet since measurements by the U.S. Geological Survey began in July 1957. The large stage changes have been attributed to the relation between highly transient surface-water inflow to the lake and subsurface conduits of karstic origin that permit a high rate of leakage from the lake to the Upper Floridan aquifer. After the most recent and severe stage decline (1990-1994), the U.S. Geological Survey began a study that entailed the use of numerical ground-water flow models to simulate the interaction of the lake with the Upper Floridan aquifer and the large fluctuations of stage that were a part of that process. A package (set of computer programs) designed to represent lake/aquifer interaction in the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model (MODFLOW-96) and the Three-Dimensional Method-of-Characteristics Solute-Transport Model (MOC3D) simulators was prepared as part of this study, and a demonstration of its capability was a primary objective of the study. (Although the official names are Brooklyn Lake and Magnolia Lake (Florida Geographic Names), in this report the local names, Lake Brooklyn and Lake Magnolia, are used.)

In the simulator of lake/aquifer interaction used in this investigation, the stage of each lake in a simulation is updated in successive time steps by a budget process that takes into account ground-water seepage, precipitation upon and evaporation from the lake surface, stream inflows and outflows, overland runoff inflows, and augmentation or depletion by artificial means. The simulator was given the capability to simulate both the division of a lake into separate pools as lake stage falls and the coalescence of several pools into a single lake as the stage rises. This representational capability was required to simulate Lake Brooklyn, which can divide into as many as 10 separate pools at sufficiently low stage.

In the first of two calibrated models, recharge to the water table, specified as a monthly rate, was set equal to 40 percent of the monthly rainfall rate. The specified rate of inflow to the uppermost stream segment was set equal to outflows from Lake Lowry estimated from lake stage and the 1994-97 rating table. Leakage to the intermediate and Upper Floridan aquifers was assumed to occur from the surficial aquifer system through the confining layers directly beneath deeper parts of the lake bottom. A leakance coefficient value of 0.001 feet per day per foot of thickness was used beneath Lake Magnolia, and a value of 0.005 feet per day per foot of thickness was used beneath most of Lake Brooklyn. With these values, the conductance through the confining layers beneath Lake Brooklyn was about 19 times that beneath Lake Magnolia.

The simulated stages of Lake Brooklyn matched the measured stages reasonably well in the early (1957-72) and later (1990-98) parts of the simulation time period, but the match was

unsatisfactory in an intermediate time period (1973-89). To resolve this discrepancy, the hypothesis was proposed that undocumented losses of water from Alligator Creek upstream from Lake Brooklyn or from the lake itself occurred between 1973 and 1989 when there was sufficient streamflow. The resulting simulation of lake stages matched the measured lake stages accurately during the entire simulation time period. The model was then revised to incorporate the assumption that only 20 percent of precipitation recharged the water table (the second calibrated model). Recalibration of the model required that leakance values for the confining units under deeper parts of the lakes also be reduced by nearly 50 percent. The stages simulated with the new parameter assumptions, but retaining the assumption of surface-water losses, were an excellent match of the measured values. The stage of Lake Magnolia was also simulated accurately. The results of sensitivity analyses show that simulated streamflow between Lakes Magnolia and Brooklyn tends to be water-budget controlled, and is not appreciably affected by the specified outflow altitude or channel characteristics of the receiving stream.

To match heads measured in observation wells of the surficial aquifer network, the assigned hydraulic conductivity values were zoned, and ranged from a minimum of 4 feet per day to a maximum of 400 feet per day in the first calibrated model. These values were reduced by about 50 percent in the second calibrated model. Differences between observation wells were noted in the abruptness of changes of measured head values, and in the relation of the timing of peak measured heads and simulated peak heads. These differences seemed to be correlated with the depth of the water table below land surface. Spatially uniform values of transmissivity were specified for the intermediate (10,000 feet squared per day) and Upper Floridan (100,000 feet squared per day) aquifers. Simulated heads in the Upper Floridan aquifer layer follow the trend of the heads measured in a long-term observation well with data beginning in 1960. This result suggests that the observed head decline could be explained entirely in terms of the stage decline in Lake Brooklyn and may not indicate a regional trend.

## INTRODUCTION

Some karstic lakes in north central Florida interact with the underlying Floridan aquifer system (Clark and others, 1963). The upper part, the Upper Floridan aquifer, is characterized by a high degree of solution porosity and high permeability. Karstic lakes in the region form as sinkholes when clastic materials of the surficial aquifer system and its underlying confining layer settle into solution cavities of the Upper Floridan aquifer (Schiffer, 1998). Depending on the thickness or type of material infilling or covering the solution cavities, the resulting lakes may or may not be hydraulically isolated from the Upper Floridan aquifer by the collapsed sediments. Lakes that are not hydraulically isolated may exhibit large stage fluctuations as water drains to the aquifer during dry periods, and is replenished in excess of the drainage rate during wet periods. These lakes are termed “unstable” lakes (Motz and others, 1991). Lakes that are relatively isolated hydraulically from the Upper Floridan aquifer exchange water mainly by ground-water seepage with the surficial aquifer system. Because the surficial aquifer has relatively low permeability, the stages of these lakes fluctuate only slightly. These lakes are termed “stable” lakes.

Lakes in the Upper Etonia Creek Basin (fig. 1) exhibit a wide range of stability (lake-level fluctuation). Lakes Magnolia and Lowry are stable, with stages that rarely vary more than 2-3 feet (ft) (fig. 2). Lake Brooklyn, in contrast, is unstable; its stage has varied as much as 27 ft since July 1957 when the U.S. Geological Survey began taking measurements. The most stable lake in Florida, Blue Pond, and the most unstable, Pebble Lake (Motz and others, 1991, app. A2), also are located in the study area (fig. 1).

Although the official names are Brooklyn Lake and Magnolia Lake (Florida Geographic Names), in this report the local names, Lake Brooklyn and Lake Magnolia, are used.

The instability of some Florida lakes is a phenomenon that requires the attention and response of public agencies. In central and north Florida, the most desirable locations for homes, particularly those used for recreation and retirement, are on land surrounding lakes. When an unstable lake adjacent to a home quickly becomes dry or floods to an unanticipated extent, the concerns of homeowners are made known to water management agencies, who must act to deal with the homeowners’ concerns. As a result, certain unstable lakes, such as Lake Brooklyn, have been extensively studied by hydrologists.

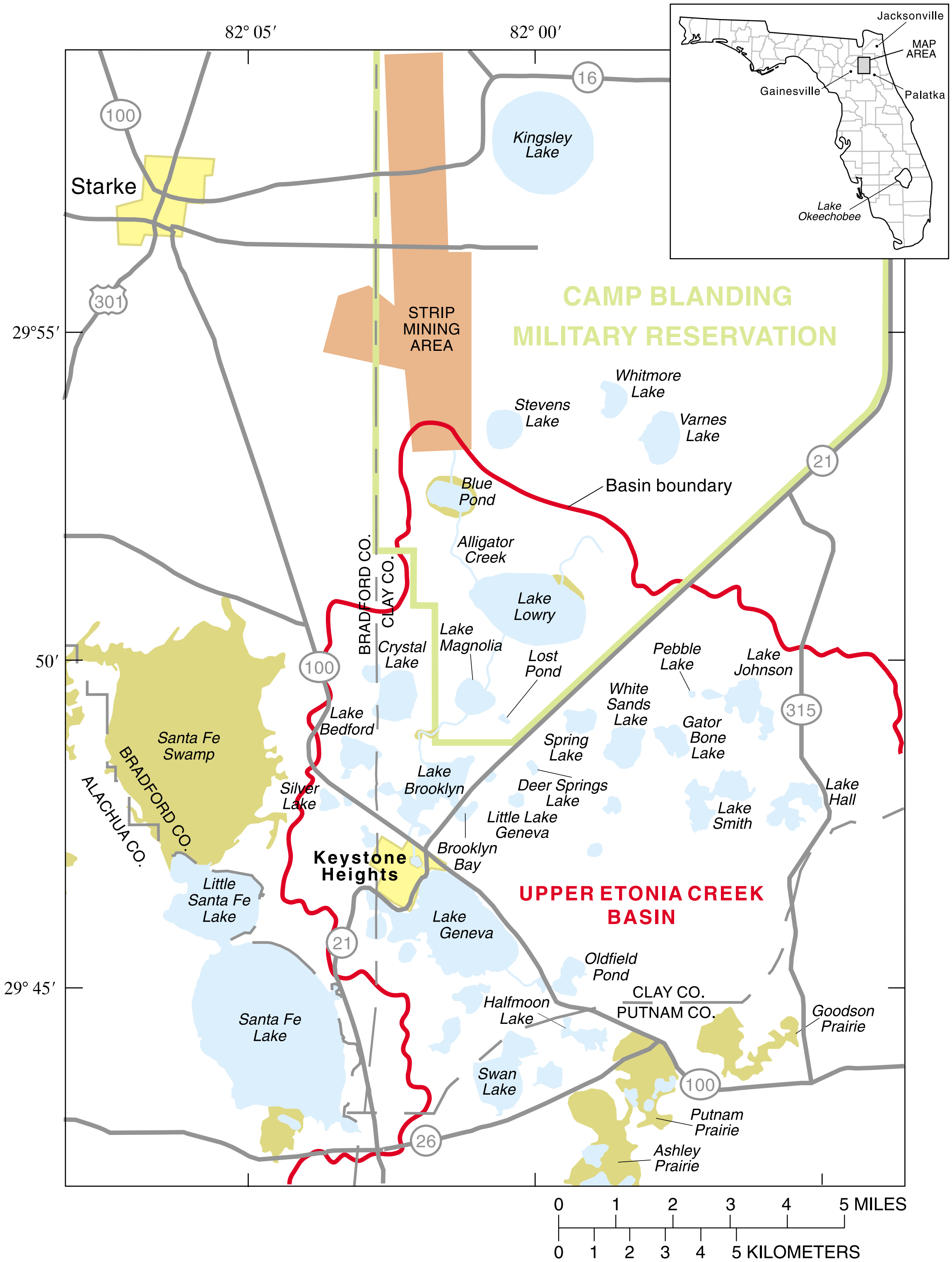



**Figure 1.** Location of the study area.

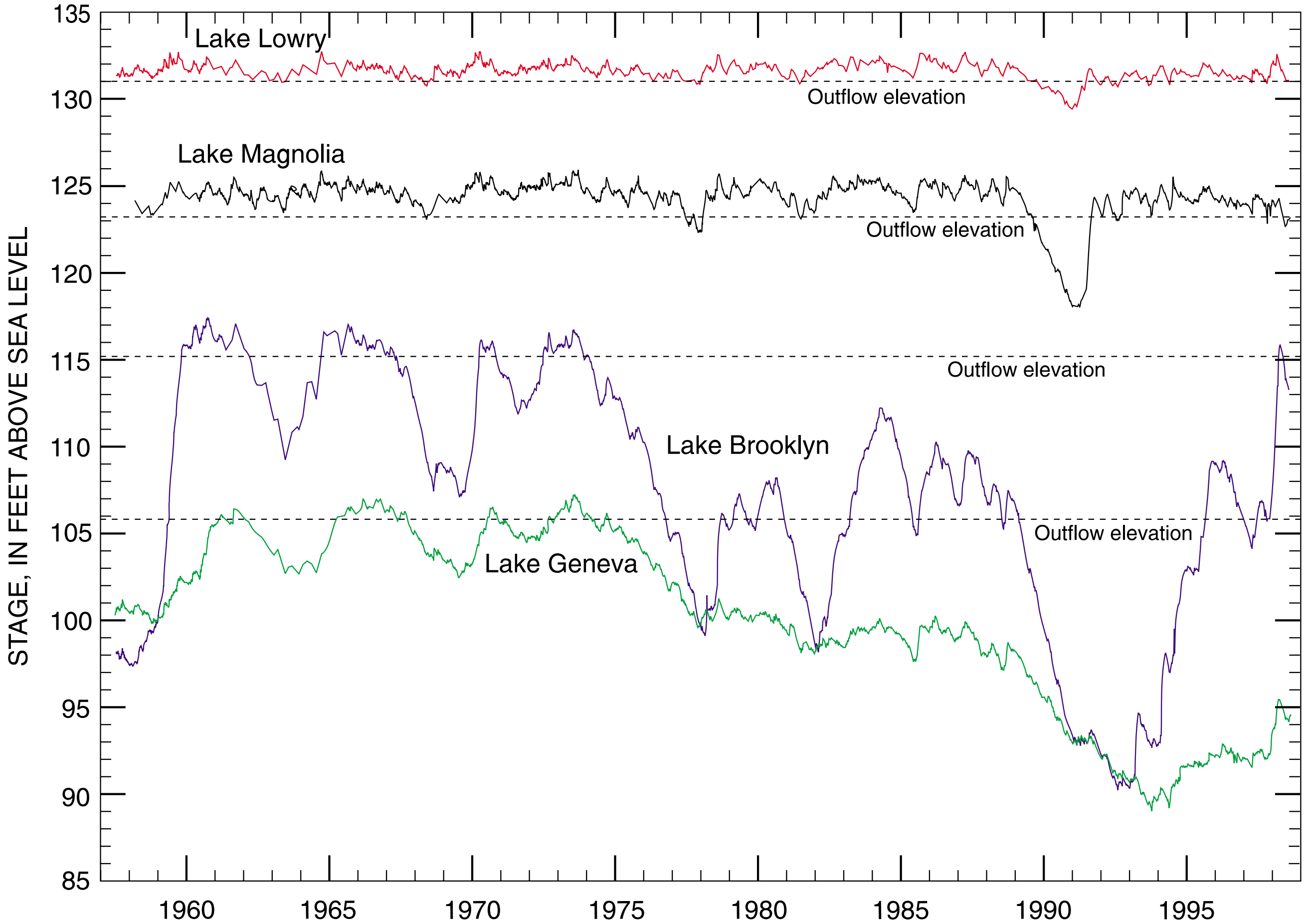



**Figure 2.** Stages of four interconnected lakes in the Upper Etonia Creek Basin, 1957-98.

Lake Brooklyn has undergone stage declines of over 15 ft in 1957-58, 1976-78, 1981-82, and 1989-95 (fig. 2), with the last decline being the most severe. Less severe stage declines occurred in 1962-64 and 1968-69. After the most recent and severe stage decline, the U.S. Geological Survey (USGS) began a study in 1994 with the St. Johns River Water Management District (SJRWMD) to study the stage declines. The objective of the study was the application of numerical ground-water flow models to simulate the interaction of Lake Brooklyn with the Upper Floridan aquifer and the resultant stage fluctuations in the lake. The techniques developed to perform this analysis could prove useful in analyzing other problems involving lake-aquifer interaction in Florida and elsewhere.

The primary goal of the study was to develop simulation methods that would represent the interaction between the lake and aquifer and could be incorporated into a model of ground-water flow. A package of computer subroutines to represent this interaction in the USGS MODFLOW-96 and MOC3D simulators was prepared as part of this study, and a demonstration of the model's capability was a primary objective of this investigation. Additional cooperative support for the preparation of the Lake Package, which is documented separately (Merritt and Konikow, 2000), was received from the Southwest Florida Water Management District (SWFWMD).

## Purpose and Scope

The principal purpose of this report is to document the application of MODFLOW-96 and the USGS Lake Package (Merritt and Konikow, 2000) to the problem of simulating the interaction of Lake Brooklyn with the Upper Floridan aquifer. The hydrology of the system of lakes in the Upper Etonia Creek Basin and the hydrogeology of the surficial aquifer system, the intermediate aquifer system or intermediate confining unit, and the Upper Floridan aquifer are described briefly, based on previous descriptions and USGS data collected for this project between 1994 and 1997. The discussion of the numerical simulation includes the design of the simulator, the choice of parameters quantitatively characterizing the various hydrologic processes taking place, sensitivity analyses showing the significance of various hydrologic processes, and conclusions derived from the simulation. Special attention is given to the processes represented by the Lake Package and the interaction of the lake with the surficial and Upper Floridan aquifers.

A representation of Lake Magnolia, a stable lake, is incorporated into the simulation for comparison with unstable Lake Brooklyn. Streams entering Lake Magnolia, connecting the two lakes, and leaving Lake Brooklyn are also represented. Smaller lakes in the vicinity are not represented.

## Previous Studies

In response to the second most severe stage decline of Lake Brooklyn, which occurred between 1954 and 1958, the USGS performed a comprehensive hydrologic investigation of the area. Results of the investigation were reported by Clark and others (1963) and included a description of local hydrogeology, chemical analyses of water in Lakes Sand Hill (now Lowry), Magnolia, and Brooklyn, and a description of the movement of water between the water-table aquifer and Lake Brooklyn. Clark and others (1964) reported on the hydrology of a larger area comprising Alachua, Bradford, Clay, and Union Counties.

Following a 2-month period of flooding (August and September 1973) in the lower part of the Upper Etonia Creek Basin (Oldfield Pond, Halfmoon Lake, and Putnam Prairie, fig. 1), the U.S. Army Corps of Engineers (1975) published the results of a flood-plain study of the area. A study of the surface-water and ground-water resources of the area, which included additional data collection and analysis, was conducted by the SJRWMD (Yobbi and Chappell, 1979). After the stage of Lake Brooklyn had reached a historical low in 1991, the SJRWMD conducted a study (Robison, 1992) in which a rainfall, runoff, and routing model was used to simulate the surface flow system that included Blue Pond, Lakes Lowry, Magnolia, and Brooklyn, their surrounding basins, and the stream channel, Alligator Creek, which linked them sequentially. The model also accounted for losses and gains to the surrounding water-table aquifer. Leakage losses to the Upper Floridan aquifer were also represented. The model was used to assess the possible ameliorative effects of making changes to the channels linking the lakes. The report also included surveys conducted by SJRWMD personnel of stream channel bottom altitudes between Blue Pond and Lake Brooklyn.

In 1990, a study of the lakes of the Upper Etonia Creek Basin and the local ground-water system was begun by the University of Florida (UF). Motz and others (1991) prepared an updated summary of data describing lakes in the basin and characteristics of the surficial aquifer system, the intermediate aquifer system or confining unit, and the Floridan aquifer system. They also discussed long-term trends in rainfall, lake levels, and heads in the aquifers, and identified below-average rainfall as the “the primary cause of the lake-level declines” in the basin. In the second phase of the study, Motz and others (1994) compiled and interpreted additional data and constructed a hydrogeologic section that was used as a basis for a cross-sectional flow model. Short-term water budgets for periods when interconnecting streams were not flowing were used to determine leakage rates to the Upper Floridan aquifer. Then the leakage rates were used in long-term water-budget computations to simulate the stages of Lakes Sand Hill (Lowry), Magnolia, Brooklyn, and Geneva. Variations of the calibrated water budgets were used to assess certain hypothetical conditions in the Upper Floridan aquifer.

The water-budget equations of Motz and others (1994) assumed that the lakes exchanged no water with the surrounding surficial aquifer system. This assumption was made because no data were available upon which to base an estimate of such exchanges. A further study was conducted by the UF (Annable and others, 1996) that entailed the construction and monitoring of a network of 33 surficial aquifer system wells in the vicinity of Lakes Lowry, Magnolia, Brooklyn, and Geneva. Slug tests were performed on most wells, and a group of wells was installed in the vicinity of Halfmoon Lake for an aquifer test. Based on the resulting water-level and transmissivity data, a flow net analysis was performed for estimates of water exchanges between Lakes Lowry, Magnolia, Brooklyn, and Geneva and the surrounding surficial aquifer system. These leakage amounts were then used to refine the short-term and long-term water budgets of Motz and others (1994). In none of the revised water budgets were the estimated exchanges with the surficial aquifer system a major part of the lake water budgets.

The previous studies indicated the importance of the altitude of the potentiometric surface of the Upper Floridan aquifer in the Upper Etonia Creek Basin in controlling the stage of Lake Brooklyn. The UF conducted a further study (Motz and others, 1995) to make a quantitative estimate of the decline of the potentiometric surface in northeastern Florida during a 25-year period. A multi-variate regression analysis was used to assess the relation of the altitude of the potentiometric surface to rainfall, evaporation, and ground-water pumpage. A quasi-three dimensional model of ground-water flow was developed for a region of northeastern Florida centered around Keystone Heights (fig. 1). The model was used to predict that, in 2010, the additional drawdown in the Keystone Heights area caused by regional pumping near Jacksonville, Gainesville, and Palatka would be small and would have negligible effect on the stage of Lake Brooklyn.

Additional studies conducted in the Upper Etonia Creek Basin include two field investigations using high resolution seismic profiling techniques. A consultant working for the SJRWMD (Subsurface Detection Investigations, Inc., 1992) performed a seismic reflection survey of Lakes Brooklyn and Geneva. At the time the survey was performed, the stage of Lake Brooklyn was low and the lake had subdivided into separate pools. Four such pools were selected for seismic reflection transects. The profiling revealed numerous collapse features in the formations overlying the Upper Floridan aquifer. The USGS (Kindinger and others, 1994) performed seismic-reflection surveys of Lakes Kingsley, Lowry, and Magnolia. Lake Lowry data were interpreted as indicating the presence of two overlapping subsidence features. Lake Magnolia data were interpreted as showing a single large subsidence feature, probably covered with organic sediment and sand.


## Acknowledgements

The author is indebted to the past and present presidents of the Lake Brooklyn Civic Association, Mr. Philip Baumgardner and Mr. James Hayhurst, for providing background information about the hydrology of the lake system that includes Blue Pond, Lakes Lowry, Magnolia, and Brooklyn, and for describing their efforts since 1994 to restore the historical drainage area for the upper lakes, thus improving the flow conditions of Alligator Creek. Mr. Hayhurst provided the author with a guided tour of Alligator Creek between Lakes Magnolia and Brooklyn.

The author is also grateful to Dr. Louis Motz of the University of Florida for two guided tours of the lake system from the wilderness shore of Blue Pond to the relict culverts that once received outflow on the southern side of Lake Geneva.


## HYDROLOGY OF THE STUDY AREA

The study area (fig. 1) includes part of the Upper Etonia Creek Basin. Santa Fe Lake forms the headwaters of the Santa Fe River Basin and was not a subject of investigation in this study. This section describes the subsurface geology and hydrogeology, rainfall and evapotranspiration in or near the study area, the hydrology of the lake and stream systems, and long-term trends in lake-stage and rainfall/lake-stage relations.

| GEOLOGIC AGE | LITHOSTRATIGRAPHIC UNITS | HYDROGEOLOGIC UNITS | |
|---|---|---|---|
| PLEISTOCENE AND RECENT | POST-HAWTHORN UNDIFFERENTIATED | SURFICIAL AQUIFER SYSTEM | |
| PLIOCENE | | | |
| MIOCENE | HAWTHORN GROUP | INTERMEDIATE AQUIFER SYSTEM OR INTERMEDIATE CONFINING UNIT | |
| | UNCONFORMITY | | |
| LATE EOCENE | OCALA LIMESTONE | UPPER FLORIDAN AQUIFER | FLORIDAN AQUIFER SYSTEM |
| MIDDLE EOCENE | AVON PARK FORMATION | MIDDLE SEMICONFINING UNIT | |
| EARLY EOCENE | OLDSMAR FORMATION | LOWER FLORIDAN AQUIFER | |
| PALEOCENE | CEDAR KEYS FORMATION | SUB-FLORIDAN CONFINING UNIT | |

**Figure 3.** Lithostratigraphy and hydrostratigraphy within the area of study.

## Aquifers and Confining Units

The description of area hydrogeology includes discussions of the surficial aquifer system, the intermediate aquifer system and its confining beds where present, and the Floridan aquifer system (fig. 3). The depths and approximate thicknesses (where known) and hydraulic properties that are presented are based on descriptions available from published sources.

### Surficial Aquifer System

The surficial aquifer system is identified by Clark and others (1963, p. 110) as unnamed deposits of sand and clayey sand of Miocene to Recent age that occur from land surface to a depth of 50 to 85 ft. “The water table is generally a subdued reflection of the topography . . . but can be several tens of feet below land surface” (Tibbals, 1990, p. 11) because of the relatively low permeability of the surficial aquifer system and the variability of land surface altitude in the study area. The surficial aquifer system is rarely used as a source of supply because of low yield to wells, but the aquifer is highly important as a source of recharge to the Upper Floridan aquifer in the area of study. Clark and others found no evidence that downward percolation of water was impeded by the clayey sand, which occurs as lenses.

Motz and others (1994) cite estimates of 950 to 7,000 feet squared per day ($ft^2/d$) for the transmissivity of the surficial aquifer system in north-central Florida, but because of the variability of the lithology and aquifer thickness and the distant location of each of the estimates from the area of study, these estimates cannot be considered reliably descriptive of conditions there. The UF drilled 33 wells into the surficial aquifer system in the study area (Annable and others, 1996). Wells in the Camp Blanding Military Reservation were completed with 6-inch-diameter casing by U.S. Army personnel, and the remaining wells were drilled with 2-inch-diameter casing under a contract with the SJRWMD. Together with two previously-drilled wells (C-0444 and C-0452), this network of 35 wells (fig. 4) was used to measure water-table altitudes in the basin. After a period of water-level measurements by the UF, which began in May 1994, the USGS measured water levels in these wells from February 1996 to September 1997. USGS identification numbers for the wells and various data prepared by graduate students of the UF (Annable and others, 1996, app. B) are presented in table 1. USGS water-level measurements ended in September 1997, and the UF resumed water-level measurements in these wells under terms of a contract with the SJRWMD.

**Table 1.** Descriptive data for wells of the surficial aquifer system network

[MP, measuring point]

| Local number | Site identification number | Well diameter (inches) | MP altitude, feet above sea level | Well depth below top of casing (feet) | Length of casing (feet) |
|---|---|---|---|---|---|
| C-0444 | none | 2 | 161.65 | 87 | 67 |
| C-0452 | 294807082020902 | 2 | 146.23 | 67 | 66 |
| C-0512 | 295124082010101 | 6 | 185.61 | 79 | 60 |
| C-0513 | 295123082002101 | 6 | 185.90 | 48 | 30 |
| C-0514 | 295107081590001 | 6 | 186.84 | 75 | 60 |
| C-0515 | 295026081585201 | 6 | 173.27 | 78 | 60 |
| C-0516 | 294949081592101 | 6 | 180.47 | 70 | 50 |
| C-0517 | 295004082002001 | 6 | 179.38 | 71 | 55 |
| C-0518 | 294921082003801 | 6 | 147.65 | 48 | 30 |
| C-0519 | 294903082005201 | 6 | 144.71 | 46 | 30 |
| C-0520 | 294930082013601 | 6 | 165.60 | 59 | 40 |
| C-0521 | 294948082011501 | 6 | 174.36 | 49 | 30 |
| C-0522 | 295018082004801 | 6 | 166.17 | 79 | 60 |
| C-0523 | 295018082004802 | 6 | 165.88 | 74 | 60 |
| C-0524 | 295058082013601 | 6 | 181.34 | 79 | 60 |
| B-0098 | 294513082024801 | 2 | 151.52 | 44 | 28 |
| B-0099 | 294609082030801 | 2 | 143.60 | 64 | 38 |
| C-0500 | 294636082024101 | 2 | 134.69 | 76 | 38 |
| C-0501 | 294528082001001 | 2 | 120.48 | 60 | 25 |
| C-0502 | 294457082013101 | 2 | 127.54 | 47 | 25 |
| C-0503 | 294834082013001 | 2 | 145.03 | 64 | 38 |
| B-0100 | 294543082033301 | 2 | 148.66 | 45 | 26 |
| B-0101 | 294538082041101 | 2 | 155.02 | 50 | 16 |
| B-0102 | 294542082035401 | 2 | 150.31 | 49 | 26 |
| C-0505 | 294511082015901 | 2 | 139.99 | 53 | 35 |
| B-0103 | 294509082032301 | 2 | 152.42 | 51 | 19 |
| C-0506 | 294710082014101 | 2 | 148.83 | 78 | 48 |
| C-0507 | 294619082003601 | 2 | 136.74 | 53 | 33 |
| C-0508 | 294502082003201 | 2 | 141.83 | 66 | 46 |
| C-0510 | 294809082024401 | 2 | 164.95 | 84 | 54 |
| C-0511 | 294658082005901 | 2 | 147.33 | 50 | 30 |
| B-0104 | 294659082031601 | 2 | 164.17 | 56 | 43 |
| B-0105 | 294644082033301 | 2 | 167.43 | 59 | 35 |
| B-0106 | 294728082034901 | 2 | 156.77 | 56 | 37 |
| B-0107 | 294521082034401 | 2 | 156.55 | 54 | 25 |

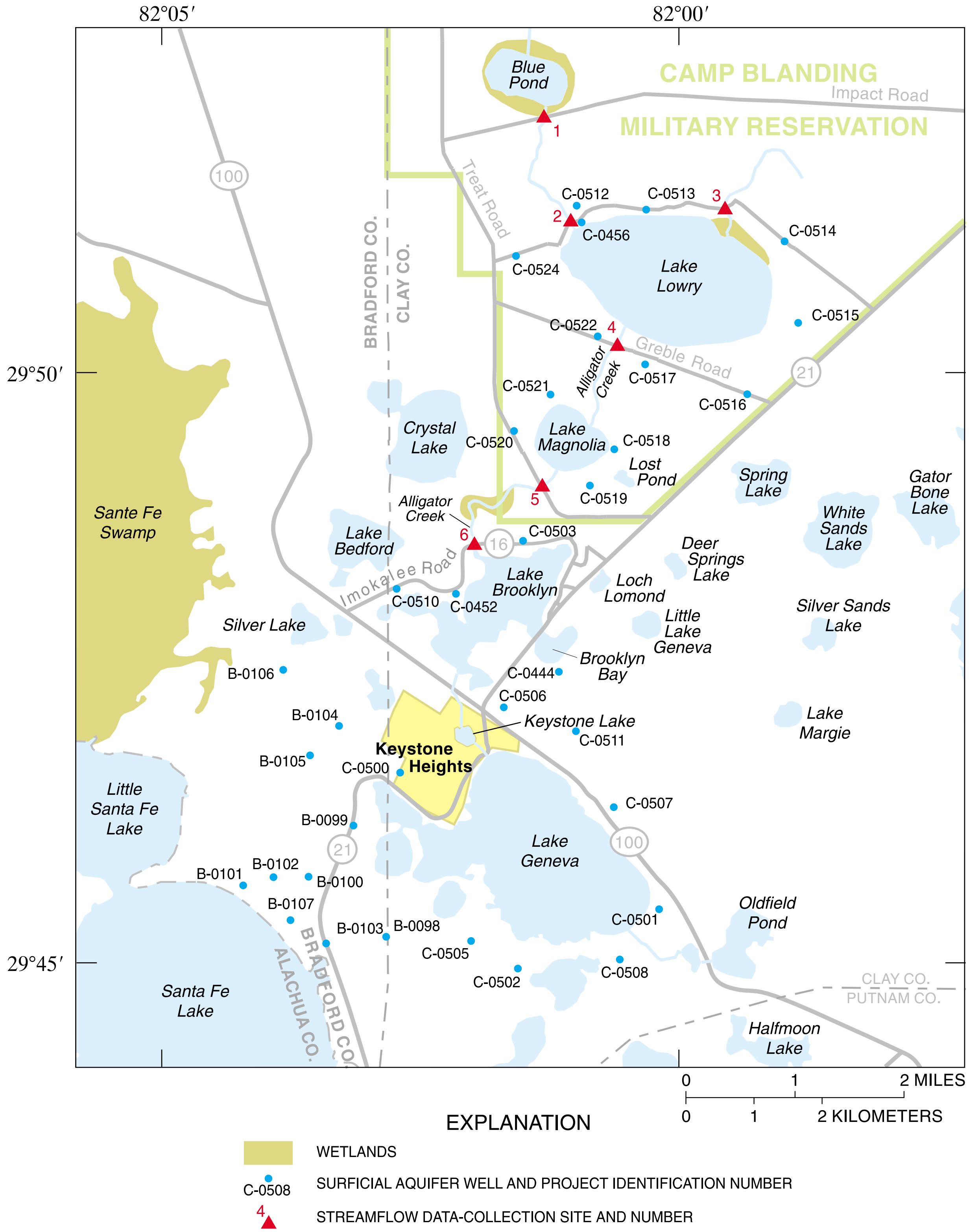



**Figure 4.** Locations of surficial aquifer system wells and streamflow data-collection sites providing data for the study.

The UF performed slug tests in October 1993 at a cluster of four surficial wells near Halfmoon Lake (fig. 1) that were not included in the monitoring network shown in fig. 4. Resulting estimates of hydraulic conductivity were 1.0 to 7.3 feet per day (ft/d) (Annable and others, 1996). The UF performed aquifer tests in December 1993, and reported transmissivity estimates ranging from 600 to 1,230 $ft^2$/d (Annable and others, 1996), or hydraulic conductivity estimates ranging from 30 to 62 ft/d. The UF performed slug tests at 13 more surficial wells in January and February 1994, providing hydraulic conductivity estimates of 1.5 to 17.6 ft/d. A two-well aquifer test conducted at an unspecified time at Camp Blanding by the UF yielded a transmissivity estimate of 560 $ft^2$/d and a hydraulic conductivity estimate of 10 ft/d.

Given the cited estimates of horizontal hydraulic conductivity, and assuming that vertical hydraulic conductivities are not significantly lower, it is unlikely that appreciable vertical hydraulic gradients could exist in the surficial aquifer system at depths greater than the depths of the surficial aquifer system network wells. Thus, the water levels in these wells are considered to be accurate measurements of the water-table altitude. However, the values of hydraulic conductivity are sufficiently low that water-table altitudes are primarily determined by local rather than regional processes of recharge and drainage. Thus, the water-table altitude can vary appreciably over short distances and can be "a subdued reflection of land surface" (Tibbals,1990). Heads computed by a numerical model of the surficial aquifer system will be relatively insensitive to boundary conditions specified around the perimeter of an area of regional scale.

### Intermediate Aquifer System and Confining Unit

The confining unit that lies between the surficial aquifer system and the Floridan aquifer system generally corresponds to the Hawthorn Group of early to late Miocene age. Miller (1986, p. 37) describes the lithology of the Hawthorn as "a complexly interbedded, highly variable sequence that consists mostly of clay, silt and sand beds, all of which contain scarce to abundant phosphate." Miller (1986) also refers to "the dolomite and limestone beds of the Hawthorn." Miller (1986) considered the less permeable parts of the Hawthorn to be the upper confining unit of the Floridan aquifer system. The top of the Hawthorn Group away from the immediate vicinity of lakes is typically 50 to 100 ft above sea level, or about 50 to 80 ft below land surface (Clark and others, 1963).

Clark and others (1963) noted that "the confining bed locally includes secondary artesian aquifers." Motz and others (1994) referred to an "intermediate aquifer system," considered to be permeable strata within the solution-riddled limestone, dolomite, sand, and shell beds of the Hawthorn. On the basis of limited data, Motz and others (1994) hypothesized that this aquifer can occur locally near the top or the bottom of the Hawthorn beds, particularly where the deposits have been disturbed by the formation of karst features on the underlying Ocala Limestone. No author has ventured to identify the "intermediate aquifer system" with specific formations within the Hawthorn Group or to define it on an areal basis. Clark and others (1964, p. 115) hypothesized that "although the limestone layers in the Hawthorn Formation are limited in area, they are probably connected with other permeable zones of material such as sand layers." Despite the ambiguity of the definition, the intermediate aquifer system is of considerable significance locally to well drillers and homeowners as one of the principal local sources for domestic self-supply wells (Clark and others, 1964, p. 118). The head in the intermediate aquifer system is between that in the surficial aquifer system and that in the Upper Floridan aquifer (fig. 5). No measurements of transmissivity are known to exist.

### Floridan Aquifer System

The most productive source of water in north-central Florida is the Floridan aquifer system, which is overlain by the confining unit and the surficial aquifer system of relatively low permeability. Miller (1986) identifies the Floridan aquifer system in the study area as rocks of the following formations, in reverse order of age: (1) the upper part of the Cedar Keys Formation of Paleocene age (where it contains permeable carbonates); (2) the Oldsmar Formation of early Eocene age; (3) the Avon Park Formation of middle Eocene age; and (4) the Ocala Limestone of late Eocene age (fig. 3). The rocks are massive to solution-riddled limestone and dolomite. Consolidated limestone having solution porosity in the lower part of the Suwannee Limestone (of Oligocene age) is also considered part of the Floridan aquifer system elsewhere, but the Suwannee Limestone is absent in the study area.

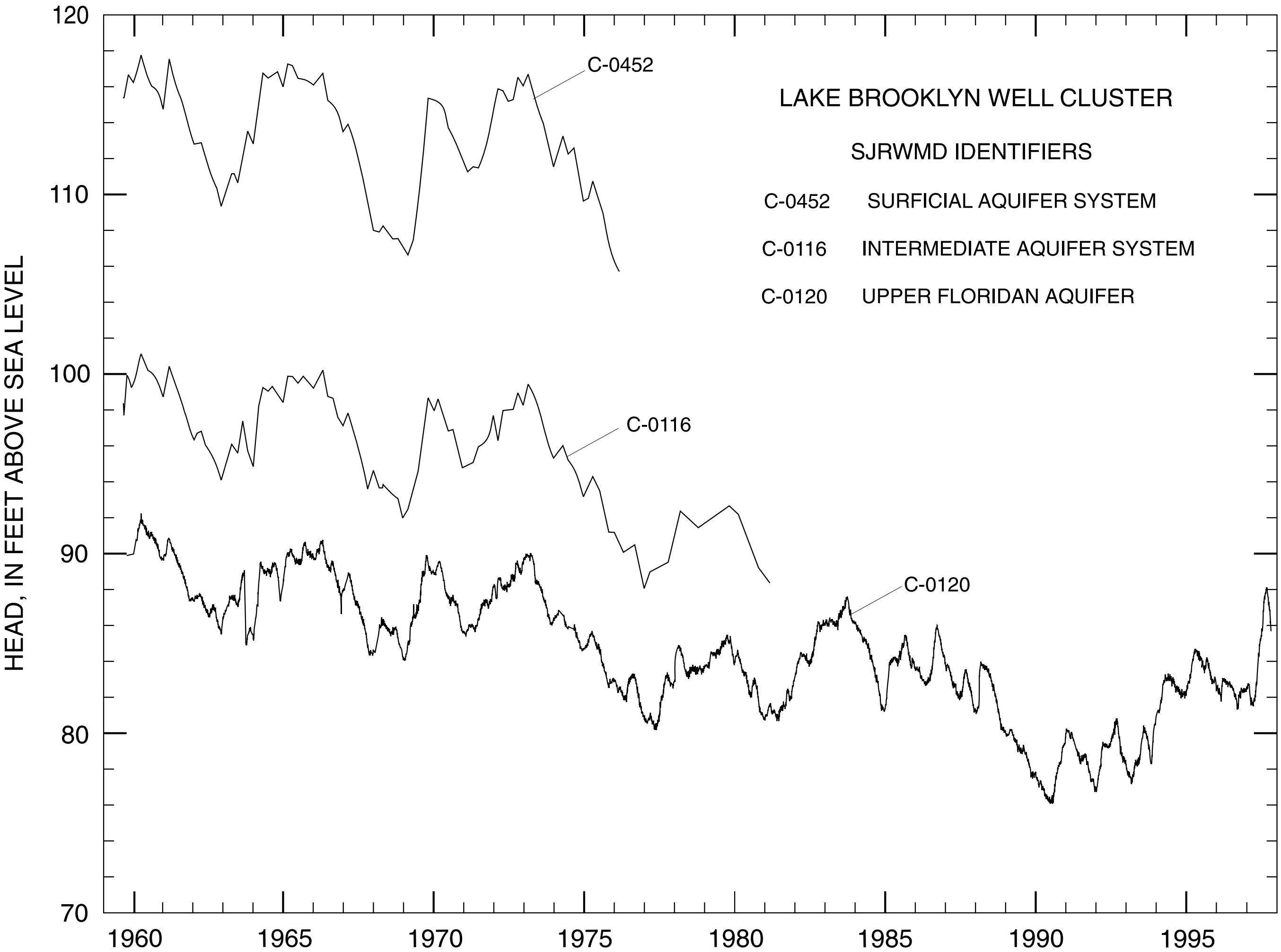



**Figure 5.** Heads in the surficial, intermediate, and Upper Floridan aquifers near the western shore of Lake Brooklyn.

The unconformity at the top of the Ocala Limestone (fig. 3) is described by Miller (1986, p. 30) as "locally very irregular as a result of the dissolution of the limestone and the development of karst topography." The Ocala Limestone is described as "one of the most permeable rock units in the Floridan aquifer system" and the upper, most permeable rocks are considered to be part of the hydraulic unit referred to as the Upper Floridan aquifer. According to Miller (1986, p. 45), "the presence of a middle confining unit . . . has led to a conceptual model for the Floridan aquifer system that consists of two active permeable zones (the Upper and Lower Floridan aquifers) separated by a zone of low permeability (a middle confining unit). Because of this simplified layering scheme, it is necessary to greatly generalize the highly complex sequence of high- and low-permeability rocks that comprise the aquifer system."

In four wells drilled by the SJRWMD in 1991, the top of the Ocala Limestone was penetrated between 180 and 220 ft below land surface, or from 50 to 110 ft below sea level (Motz and others, 1994). Nine of the wells drilled in the Lake Brooklyn area by Clark and others (1963) penetrated the Floridan aquifer. One well was drilled to 319 ft below sea level in a filled sink, illustrating the uneven, karstic nature of the top of the Ocala Limestone. A regional map showing the altitude of the top of the "Ocala Group" (old name) (Clark and others, 1964, p. 12-13) shows that the top of the Ocala Limestone rises southwesterly in the study area, from about 80 ft below sea level just northeast of Lake Lowry to 40 ft below sea level in the vicinity of Lake Geneva.

Transmissivity estimates for the Upper Floridan aquifer based on analysis of pumping tests in the study area range from 50,000 to 500,000 $ft^2/d$ (Motz and others, 1995). In calibrating a regional model of flow in the Floridan aquifer system, Motz and others (1995) used a value of 100,000 $ft^2/d$ for the Upper Etonia Creek Basin. When transmissivities are high, as in the Upper Floridan aquifer, the potentiometric surface tends to be relatively flat over large areas regardless of local recharge or pumping. Heads computed in numerical models of the Upper Floridan aquifer can be highly sensitive to the values specified for boundary conditions on the perimeter of the modeled region.

Heads in the Upper Floridan aquifer are about 25 ft below those in the surficial aquifer system near Lake Brooklyn (fig. 5), and probably are substantially below those in the surficial aquifer system everywhere in the study area, which is, therefore, part of an area of recharge for the Upper Floridan aquifer. Support for this conclusion is provided by a consideration of Floridan aquifer heads measured in a four-county area including the study area (fig. 6) in September 1998 for use in preparing a potentiometric-surface map for the Floridan aquifer in north-central Florida (Bradner, 1999). The region of lakes that is the subject of this study lies within the 80-ft contour that demarcates the center of a regional high in the potentiometric surface. Because the transmissivity of the Upper Floridan aquifer probably is as high in this area as elsewhere, the potentiometric high indicates an area of relatively high recharge for the Upper Floridan aquifer.

In the Keystone Heights area, heads in the Upper Floridan aquifer declined until about 1990, when they began a substantial recovery (fig. 5), based on head values measured in the “Keystone well” (SJRWMD identifier C-0120) by the USGS until October 1993 and by the SJRWMD thereafter. Well C-0120 is at the map location of surficial aquifer system well C-0452 (fig. 4). Long-term averages of the head values are listed in the following table. The later 1995-98 average reflects a substantial increase from the long-term lows of 1990-94.

| Years | Head values |
|---|---|
| 1960-69 | 87.74 feet |
| 1970-79 | 85.11 feet |
| 1980-89 | 83.10 feet |
| 1990-94 | 78.42 feet |
| 1995-98 (March) | 82.84 feet |

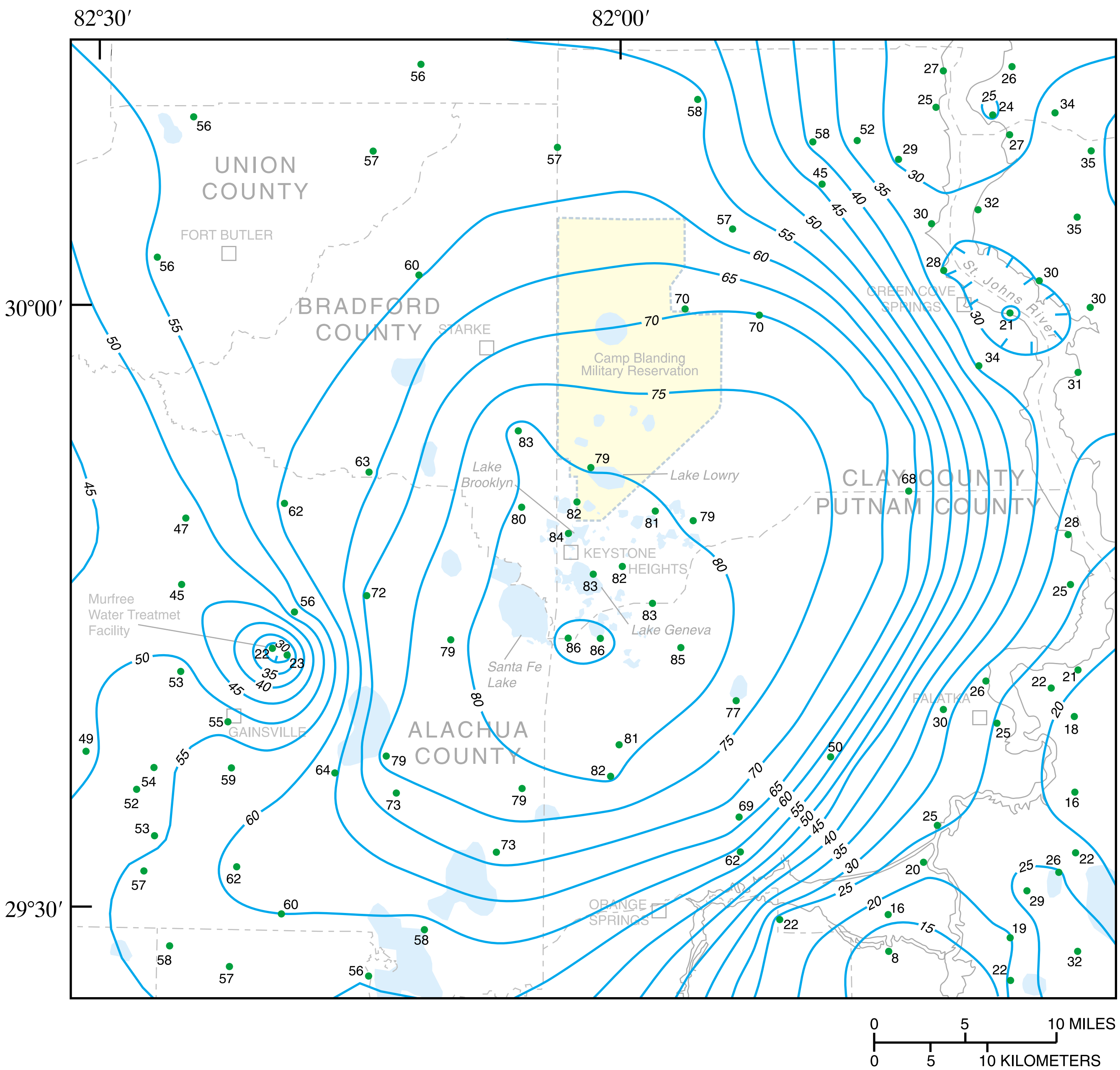
The explanation for the long-term head decline is not clear, and this subject will receive further discussion later in this report based on results from the model analysis. Large-scale pumping for public supply (Motz and others, 1991) occurs near the cities of Jacksonville (fig. 1), Gainesville (fig. 6), and Palatka (fig. 6), but their distance from the study area and the rates of pumping suggest that heads in the Upper Floridan aquifer in the study area should not be appreciably affected by the pumping. The effects of pumping from the well field near Gainesville are evident in the drawdown northeast of the city (fig. 6), but do not appear to extend to the study area.

Local pumping of the Upper Floridan aquifer for sand-mining operations occurs in the strip-mining area east of Starke (fig. 1), north of White Sands and Gator Bone Lakes (fig. 4), and in northeastern Putnam County east of Putnam Prairie and south of Hwy. 100 (fig. 1). However, an evaluation by Motz and others (1995) indicates that the rates of withdrawal are insufficient to cause a local lowering of the potentiometric surface, given the high transmissivity of the Upper Floridan aquifer. Municipal supply in the Keystone Heights area is also obtained from the Upper Floridan aquifer, but the quantities pumped are substantially less than those pumped for sand-mining activities (Motz and others, 1991).

A detailed description of the base of the Upper Floridan aquifer, confining units underlying the Upper Floridan aquifer, or the Lower Floridan aquifer in the study area was not known to be available at the time this report was prepared (2000). The regional maps prepared by Miller (1986, pls. 28 and 32) suggest 200-300 ft and 1,100 ft to be the respective thicknesses of the Upper and Lower Floridan aquifers in the study area. Miller (1986) also indicates that the middle semi-confining unit between the Upper and Lower Floridan aquifers is absent to the west of the study area in the sense that deposits contemporaneous with the confining layer to the east of the study area do not have confining characteristics.

## Rainfall and Evapotranspiration

The average annual rainfall recorded in Gainesville, Fla., 21 miles southwest of Keystone Heights, in the years 1931-98, was 52.3 inches (fig. 7). “On the average, the area (Keystone Heights) receives over half of its annual rainfall during the 4-month period June through September” (Clark and others, 1964, p. 60). These authors also state that “the area’s rainfall occurs as two general types: (1) summer rainfall that is mostly shower and thunderstorm activity; and (2) winter and early spring rainfall that is more the widespread general type associated with frontal activity.” Annual rainfall totals during the 1931-98 period varied from the average by nearly 25 inches above in 1964 to nearly 19 inches below in 1977 (fig. 7). The yearly annual-rainfall departures from the average exhibit long-term trends: (1) generally below average through 1943; (2) generally above average from 1944 through 1972; and (3) generally below average after 1972. These trends are clearly indicated on the cumulative-departure graph prepared by Motz and others (1994, p. 15, fig. 2.5). Long-term rainfall trends and pronounced short-term rainfall trends generally are correlated with stage variations measured in various lakes of the region (fig. 2).




## EXPLANATION

20 POTENTIOMETRIC CONTOUR -- Shows altitude at which water level would have stood in tightly cased wells. Hachures indicate depression. Contour interval 5 feet. Datum is sea level

57 WELL -- Number is altitude of water level in well in feet above sea level

**Figure 6.** Potentiometric surface of the Upper Floridan aquifer in north-central Florida, including the Upper Etonia Creek Basin, September 1998 (from Bradner, 1999).

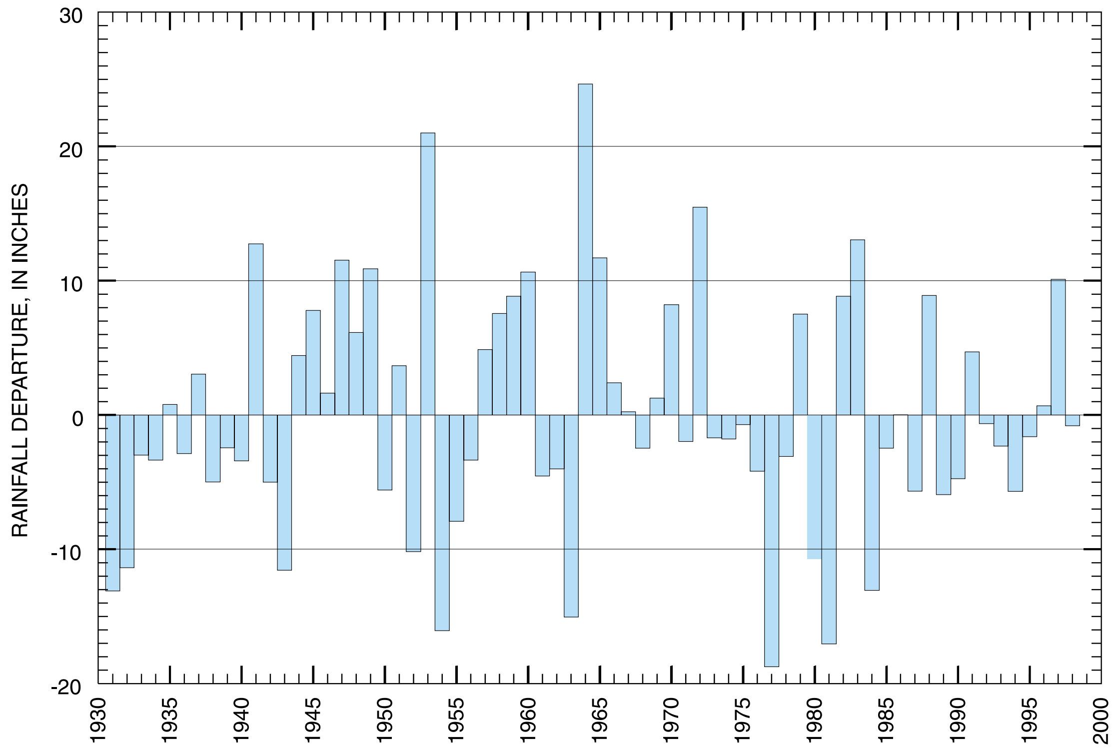



**Figure 7.** Yearly departure from 1931-98 average yearly rainfall (52.3 inches) at Gainesville, Fla.

In recent years, the SJRWMD has acquired daily rainfall data from tipping bucket instruments at Lakes Lowry, Brooklyn, Geneva, and Bedford; monthly totals from February 1992 through July 1996 are reported by Souza (1997). A tipping bucket device was installed on a raft on Lake Magnolia as part of this study and daily rainfall data were obtained from May 1995 through September 1997. This record of rainfall lacks values between October 19 and November 6, 1996. One researcher (T.C. Winter, USGS, written commun., 1999) notes "that tipping bucket gages significantly undercount intense rainfalls and undercount somewhat even at moderate intensities."

The rate of evapotranspiration from land surface and evaporation from surface-water bodies has a substantial seasonal variation, and is positively correlated to air temperature and the amount of solar radiation. Average monthly pan evaporation rates measured by the U.S. Weather Service of the National Oceanographic and Atmospheric Administration (NOAA) from 1953 to 1988 in Gainesville ranged from 0.092 inches per day (in/d) for January to 0.251 in/d for May. Lake evaporation rates are less than pan evaporation rates, and Kohler (1954) determined monthly pan-to-lake coefficients to convert pan evaporation rates to evaporation rates for Lake Okeechobee in southern Florida. Gainesville pan evaporation rate values and the pan-to-lake coefficients of Kohler (1954) were provided to the author by E.R. German (USGS, written commun., 1998), who used these values in an earlier study (German, 1997). The following table lists the average monthly rainfall and pan evaporation rates in inches per day for Gainesville and Kohler's (1954) pan-to-lake coefficients.

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rainfall | 0.111 | 0.151 | 0.119 | 0.092 | 0.122 | 0.214 | 0.210 | 0.248 | 0.191 | 0.056 | 0.079 | 0.103 |
| Pan evaporation | .092 | .124 | .175 | .233 | .251 | .241 | .226 | .204 | .187 | .157 | .115 | .087 |
| Pan coefficient | .77 | .69 | .77 | .84 | .82 | .85 | .91 | .91 | .87 | .76 | .71 | .83 |

## Watersheds and Surface-Water Bodies

The northern part of the study area is at the southern end of a landform known as the Trail Ridge, characterized by sand hills and scattered karst features. In the southern part of the study area, the sand hills grade into flatter lowlands and marshes, which are also marked by numerous karst features originating from dissolution of subsurface limestone formations (Clark and others, 1964). Many of the karst features are lakes, some of which are linked in downstream succession by streams. The irregular topography (fig. 8) is characteristic of an area of low rolling sandhills altered by the development of karst features and streams, as well as by anthropogenic modifications. Land-surface altitudes range above 200 ft in the northern and northeastern part of the area, whereas land-surface altitudes are as low as 100 ft in the southeastern part of the area. To show the relation of lakes to the topography, lake stages for September 1998 are also shown on fig. 8. The value in figure 8 for Santa Fe Lake is for late October.

The lakes in the study area are karstic in origin and rainfall is the source of water, which can be acquired by direct capture of precipitation, by overland runoff after precipitation, by ground-water seepage from surficial aquifer systems recharged by percolation of rainfall, or by inflow from streams fed, in turn, by seepage from ground water or flow from other lakes. Ground-water seepage in the study area is considered a substantially more important source of water for the lakes than direct runoff. Most of the lakes in the study area are considered seepage lakes, in that they release water only by seepage through the lakebed or by evaporation (Schiffer, 1998). However, Blue Pond and Lakes Lowry, Magnolia, Brooklyn, and Geneva (fig. 4), the lakes important to this study, are interconnected by streams, so water is also released to outflowing streams. This process tends to limit the maximum altitude that lake stages can reach. Because the lakes are also recharged by inflowing streams, the basin areas contributing rainfall to lake storage is enlarged beyond the basin that contributes seepage or runoff to the lakes.

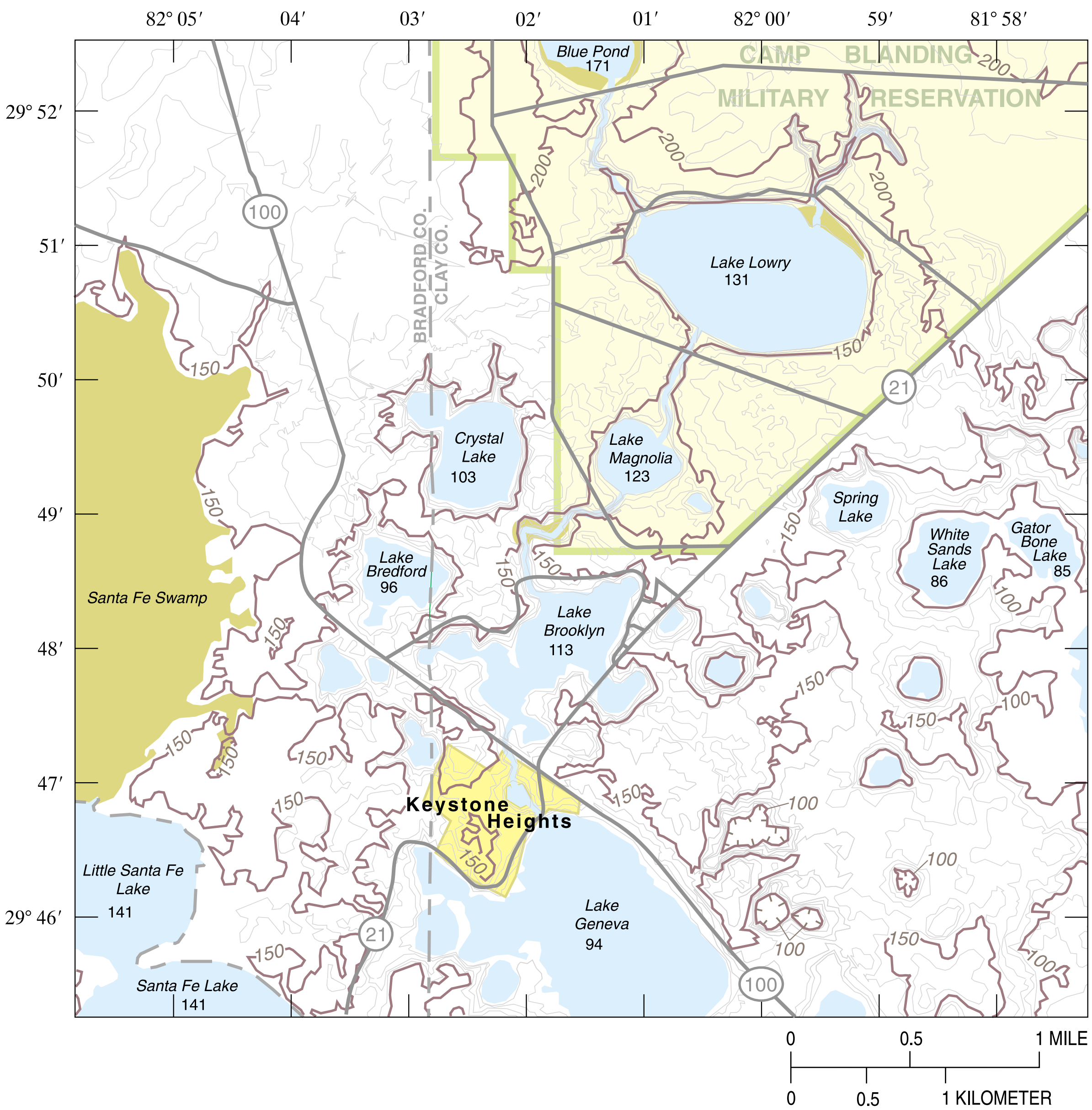
Blue Pond, Lake Lowry, and Lake Magnolia lie within the confines of Camp Blanding (fig. 4), a military reservation used jointly by the U.S. Army and the Florida National Guard. Although the lakes and land areas surrounding the lakes and military reservation are used occasionally for military exercises and commonly opened to the public for hunting, fishing, and other recreational uses, the lakes remain in a relatively pristine state. Lakes Brooklyn and Geneva are part of the greater Keystone Heights residential area, a community largely composed of retirees and vacation-home owners and within commuting distance of Gainesville, Palatka, and Jacksonville, Fla. These lakes are surrounded by homes, private campgrounds, and public recreation areas.

The following table lists the surface areas and outlet altitudes of the five lakes. The surface area values were extracted from a Geographical Information System (GIS) polygon coverage of regional hydraulic features constructed by digitizing USGS 1:100,000 scale metric maps of 1978-81. The metric maps were compiled from earlier USGS 7.5-minute 1:24,000 scale topographic maps that represent the lake stages when the maps were drawn in the mid-1970's. The outlet altitude values in the table are from Motz and others (1994). The outlet altitude for Lake Magnolia has changed as a result of channel modifications completed in 1997.

| Lake | Surface area (square feet) | Outlet altitude (feet) |
|---|---|---|
| Blue Pond | 8,608,000 | 171.0 |
| Lowry | 54,457,000 | 131.0 |
| Magnolia | 9,077,000 | 123.2 |
| Brooklyn | 28,315,000 | 115.2 |
| Geneva | 75,539,000 | 105.8 |

To provide perspective into the storage characteristics of the lakes in relation to the surface-water system in the basin, a calculation was made of the approximate amount of time required for the lakes to fill if they are recharged from a stream at an inflow rate of 25 cubic feet per second ($ft^3/s$), a relatively high but not unusual rate for inflows to Lakes Magnolia and Brooklyn, assuming there are no other fluid losses and gains. These data are given in the table below. Lake volumes for stages equal to the outlet altitudes of Blue Pond and Lakes Lowry, Magnolia and Brooklyn, and at a stage of 102.5 ft in Lake Geneva, were obtained from the quadratic-curve approximations of the stage/volume relations developed by Motz and others (1994, p. 95-96, fig. 7.2). Times given in the table are for the lakes to fill to these stages from a completely void volume, and to rise 1 ft above these stages.

| Lake | Volume ($ft^3 \times 10^6$) | Days to fill from void volume | Days to rise 1 foot |
|---|---|---|---|
| Blue Pond | 160.35 | 74 | 4 |
| Lowry | 818.22 | 378 | 25 |
| Magnolia | 221.20 | 102 | 4 |
| Brooklyn | 433.33 | 201 | 13 |
| Geneva | 1,049.07 | 486 | 35 |




EXPLANATION

LAKES AND STAGES IN FEET ABOVE SEA LEVEL, SEPETEMBER 1998

WETLANDS

150 TOPOGRAPHIC CONTOUR -- Shows altitude of land surface, in feet. Hachures indicate depression. Contour interval 10 feet. Datum is sea level

**Figure 8.** Generalized topography of the study area.

The five lakes are linked in succession by streams that share the collective name Alligator Creek. As part of this study, three gaging stations equipped with continuous recorders were established on sections of Alligator Creek, augmenting earlier streamflow measurements made by SJRWMD at eight locations in the basin. The locations of streamflow measurement stations important to this study are shown in figure 4 and descriptions are listed in table 2. Miscellaneous measurements were also made by the USGS between 1956 and 1960 at stations 1, 4, and 5.

### Blue Pond Basin to Lake Lowry

The uppermost lake of the chain, Blue Pond, was once fed by runoff and groundwater seepage from a wetland that extended several miles to the north and west. A half-mile long stream in a ravine to the north of Blue Pond (fig. 4) was fed by ground-water seepage from surrounding land of higher altitude. Much of the surficial drainage to Blue Pond from the north was altered by the construction of berms, roads, canals, and borrow pits dating to the early 1950's. In 1992, the concerns of local citizens led to a study of the hydrology of the basin that resulted in a series of modifications to restore historical flows (James Hayhurst, Lake Brooklyn Civic Association, oral commun., 1998). The maximum depth of Blue Pond is about 40 ft (Clark and others, 1964, fig. 37. p. 65).

The 1.25-mile distance between Blue Pond and Lake Lowry, formerly called Lake Sand Hill, is transected by a segment of Alligator Creek in a winding ravine with sides 20 to 40 ft deep. The streambed slopes from 171 ft near the outlet from Blue Pond to 127 ft at the confluence with Lake Lowry (Robison, 1992). The St. Johns River Water Management District made 27 streamflow measurements about 500 ft upstream from Lake Lowry (site 2, fig. 4) between May 1993 and July 1995. During this time period, the measured streamflow ranged from 0.5 $ft^3/s$ to 21.2 $ft^3/s$, with a mean of 5.3 $ft^3/s$. Five flow measurements made at Impact Road just downstream from Blue Pond (site 1, fig. 4) at times concurrent with other measurements ranged from 0 to 1.9 $ft^3/s$ less than the other measurements. Lake Lowry is also recharged from the northeast by a stream with three tributaries extending as far as 1.3 miles to the north in ravines 30 to 40 ft below surrounding land surface. The source of the water is seepage from the surficial aquifer system. The St. Johns River Water Management District made 12 flow measurements just upstream from the point of inflow to Lake Lowry (site 3, fig. 4) during the same time period as the other measurements. Values ranged from 3.5 to 5.7 $ft^3/s$, and the mean was 4.4 $ft^3/s$.

### Lake Lowry Outlet to Lake Magnolia

Lake Lowry is a stable lake; between 1957 and 1998, the lake stage varied from 129.4 ft to 132.7 ft (fig. 2). The maximum depth of Lake Lowry is about 30 ft (Clark and others, 1964, fig. 38, p. 66). According to Kindinger and others (1994), Lake Lowry appears to be formed from two large overlapping subsidence features.

Lakes Lowry and Magnolia, 0.95 mile (mi) apart, are connected by a 1.2-mi long segment of Alligator Creek in a ravine with sides about 30 ft deep. The streambed altitude decreases from 131.0 to 121.1 ft, although there are intervening sections below 120 ft (Robison, 1992). Despite the small range of variation in the stage of Lake Lowry, the variation in measured outflow to the segment of Alligator Creek below Lake Lowry varies substantially, from 1.7 to 23.6 $ft^3/s$, over

**Table 2.** Streamflow data-collection sites

[Map numbers refer to fig. 4. Agency: SJRWMD, St. Johns River Water Management District; USGS, U.S. Geological Survey]

| Map number | Site identification number | Site Name | Type of measurement: Continuous recorder | Type of measurement: Miscellaneous | Agency | Datum of gage (feet, mean sea level) |
|---|---|---|---|---|---|---|
| 1 | 02244551 | Blue Pond Outlet near Keystone Heights | no | 2/95 - 8/97 | USGS | 143.98 |
| | | | | 5/93 - 8/94 | SJRWMD | unknown |
| 2 | none | Alligator Creek above Lake Lowry | no | 5/93 - 7/95 | SJRWMD | unknown |
| 3 | none | Northeast Inflow to Lake Lowry | no | 5/93 - 7/95 | SJRWMD | unknown |
| 4 | 02244601 | Sand Hill Lake Outlet near Keystone Heights | 12/94 - 9/97 | | USGS | 106.31 |
| | | (Greble Road) | | 5/93 - 8/94 | SJRWMD | unknown |
| 5 | 02244651 | Magnolia Lake Outlet near Keystone Heights | 11/94 - 9/97 | | USGS | 108.09 |
| | | (Treat Road) | | 9/91 - 3/95 | SJRWMD | unknown |
| 6 | 02244690 | Alligator Creek near Keystone Heights | 11/94 - 9/97 | | USGS | 102.90 |
| | | (Immokalee Road) | | 3/92 - 3/95 | SJRWMD | unknown |

a stage range of only 1.3 ft. In December 1994, the USGS installed a stage recorder at Greble Road, 0.1 mi downstream of Lake Lowry (site 4, fig. 4), and began a program of regular flow measurements that made possible the development of a rating for the gage. The discharge monitoring continued through September 1997 (fig. 9). The highest discharge appearing in the rating table is 23.6 $ft^3/s$.

The rating table could not be applied directly to the lake stage values in earlier years to estimate flows, because stream stage at the recorder location is always slightly less than the lake stage. Therefore, as part of this study, stage values from the recorder on Alligator Creek at Greble Road were compared with concurrent lake altitude values to obtain an average difference that could be used as a correction value. The first step was to add the recorder datum value of 106.31 ft to the recorder stage values. In 29 pairs of values, the mean difference between lake and recorder stages was 1.57 ft, the range of differences was 1.42 to 1.69 ft, and the standard deviation of the samples (differences) was 0.07 ft. This result made it possible to estimate stages at the 1994-97 recorder location referenced to the recorder datum over the period of record of Lake Lowry stage measurements (July 1957 to 1998), by subtracting the mean difference and the recorder datum (1.57 ft + 106.31 ft = 107.88 ft) from the lake stage values. Then, flow rates at the recorder location from 1957 to 1998 were estimated by applying the 1994-97 rating table.

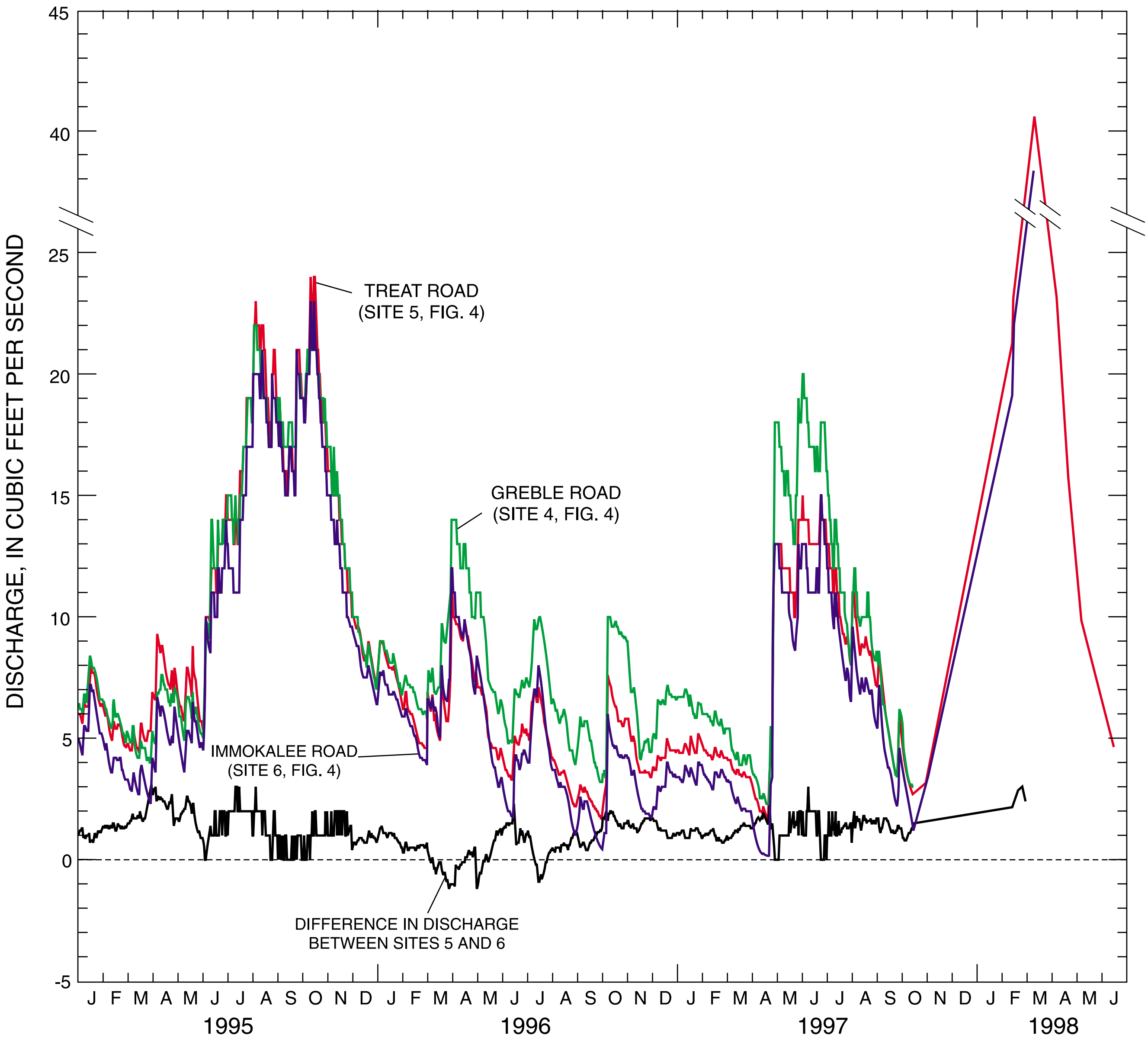



**Figure 9.** Discharge measured at three streamflow data-collection sites on Alligator Creek.

The resulting flow values ranged from zero during short periods when the lake stage decreased below the outlet altitude of 131.0 ft to a high of 35.7 $ft^3/s$ for a short period in September 1964. Values higher than 23.60 $ft^3/s$ were computed by extrapolation, based on the last two entries in the rating table, and could be underestimates of the true flow. Subject to the qualification that the outflow could have changed periodically with unrecorded changes in the configuration of the stream channel near the outlet point from the lake, the resulting estimates were later used in the construction of a mathematical simulation of lake/aquifer interaction.

Lake Magnolia is a relatively stable lake where the stage has ranged from 117.7 to 125.6 ft between 1958 and 1998 (fig. 2). Probably originating as a single subsidence feature (Kindinger and others, 1994), the maximum lake depth is about 47 ft (fig. 10). Presently, the shores of the lake are relatively pristine, except for the presence of a U. S. Army training camp on the eastern shore and a public boat launching ramp on the northwestern shore.

### Alligator Creek Between Lakes Magnolia and Brooklyn

The 1.15 mi between the point of outflow from Lake Magnolia and the point of inflow to Lake Brooklyn is traversed by a a meandering section of Alligator Creek that is confined within a ravine with 30-ft-deep sides for most of its length. About 0.65 mi from the Lake Magnolia outlet, the stream widens into a wetland for about 0.5 mi (fig. 4). Downstream from the wetland and outside the military reservation boundary, the stream is surrounded by low-density housing.

A dam had been built on this section of Alligator Creek for road access during a period of drought and no flow in the creek in the late 1950's. In March 1958, the dam was removed because standing water began to pool behind it. The exact location of the dam is

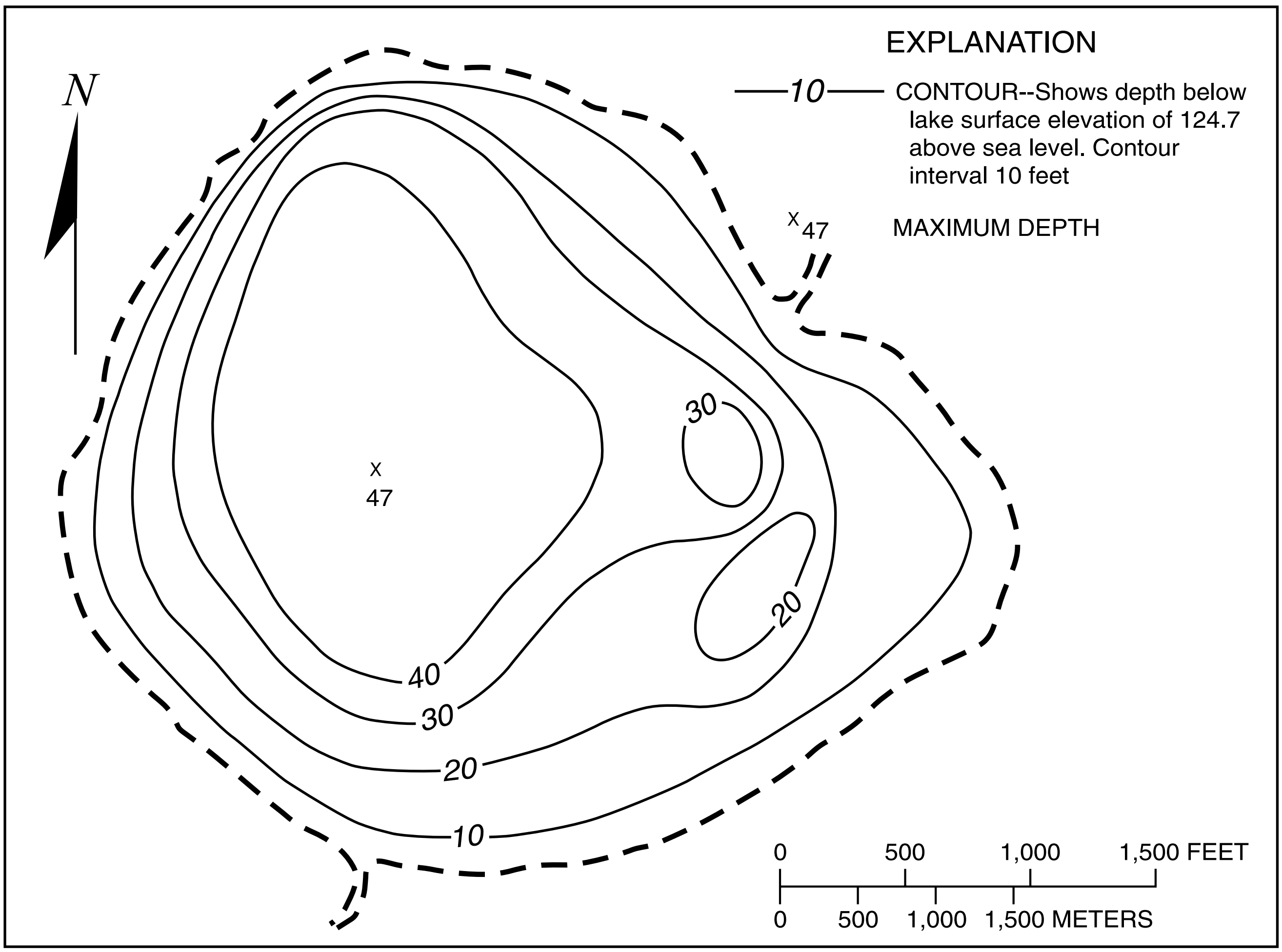



**Figure 10.** Lines of equal depth in Lake Magnolia at a lake-surface elevation of 124.7 feet, measured November 28, 1960 (modified from Clark and others, 1964, fig. 39).

unknown. Several months later, local citizens cleared the parts of the stream channel upstream and downstream of the wetland areas to facilitate flow. In September 1973, in response to flooding of Lakes Brooklyn and Geneva, Oldfield Pond, and Halfmoon Lake, a temporary dam was placed on Alligator Creek, probably near the Lake Magnolia outlet, although the exact location is unknown. The effect can be seen in the hydrograph of the stage of Lake Magnolia (fig. 2) as a short-lived stage increase of about 0.4 ft at a time when all other lakes in the region had a declining stage. Nothing is known of the fate of this dam, and the period of flooding was followed by a dry period of rapidly declining stages in all lakes in the basin.

An August 1986 report in a local newspaper claimed that sand from a National Guard borrow pit was periodically filling and blocking the Alligator Creek channel near the Lake Magnolia outlet, but a field check by SJRWMD personnel revealed no problem. Alligator Creek ceased to flow between Lake Magnolia and Lake Brooklyn during the dry period from September 1989 through August 1991. The upper section of the channel (upstream from the wetland) was cleared of plants, tree stumps, and debris in the early 1990’s after flow resumed. In November 1997, the high spots in the upper section of the channel were lowered so that the maximum bottom altitude was 121 ft. The effect of this action on the stage of Lake Magnolia was an immediate reduction of between 1 and 2 ft, based on a comparison with the stage behavior of other lakes in the area (fig. 2).

The culverts under the section of Treat Road that passes over Alligator Creek 0.25 mi downstream from Lake Magnolia have been raised and lowered several times: (1) in the early 1950’s, when new culverts were placed over old culverts after a fire; (2) in 1987, when the National Guard placed a new single culvert higher than the previous one; and (3) in July 1994, when the culvert was lowered 3 ft at the insistence of a local citizens group (James Hayhurst, Lake Brooklyn Civic Association, oral commun., 1998). The latter two actions were taken during the period of stage data collection from Lake Magnolia, but the data show no apparent effect from the culvert altitude change. The stage of Lake Magnolia rose about 2 ft in June and July 1994, and slight effects on the lake stage caused by lowering the culvert may be obscured by the magnitude of the rise.

A large nursery has been in operation on high ground east of Alligator Creek and south of the wetlands section between Lakes Magnolia and Brooklyn for several decades. The present owner of the nursery acquired the property in 1980, when the first of four 4-in-diameter irrigation-supply wells equipped with 5 horsepower pumps and tapping the Upper Floridan aquifer between 120 and 240 ft was installed (Robert Byrnes, owner of the Trail Ridge Nursery, oral commun., 1999). Most of the irrigation is by the drip method, and the owner estimates the average daily consumption at about 85,000 gallons (0.13 $ft^3/s$) and the peak daily consumption at 115,000 gallons (0.18 $ft^3/s$).

In the mid-1950’s, a previous owner of the nursery used a parcel of land across the stream from the nursery for citrus farming. There are indications that the southern part of the present nursery was also used for this purpose. According to Robert Byrnes (Trail Ridge Nursery, oral commun., 1999), as the grove was being established, a dam was placed in Alligator Creek, and an unknown volume of water was withdrawn from the creek for irrigation. The grove was said to have been destroyed by a severe freeze in the early 1980’s.

In November 1994, the USGS installed stage recorders as part of this study on Alligator Creek at Treat Road and Immokalee Road (fig. 4, sites 5 and 6), and began a program of regular flow measurements for the purpose of developing ratings for the gages. Stage and discharge monitoring continued through September 1997. The highest observed discharge value used in the rating table for the Treat Road gage was 29.30 $ft^3/s$.

Stage values from the recorder at Treat Road were compared with concurrent lake altitude values by adding the recorder datum value of 108.09 ft to the stage values. In 154 pairs of values, the mean difference was 1.12 ft, the range of differences was 0.83 to 1.31 ft, and the standard deviation of the samples (differences) was 0.09 ft. This result made possible an independent data-based estimate of flows into Alligator Creek from Lake Magnolia over the period of record of measurements (March 1958 to 1998) of stage in Lake Magnolia by subtracting 109.21 ft (= 1.12 ft + 108.09 ft) from the lake stage values and applying the rating table. This procedure assumes that the stream channel near its outlet from Lake Magnolia remained relatively unchanged over the period of the estimates. Flow values estimated from this procedure ranged from zero, during periods when the lake stage decreased below the outlet altitude of about 123.2 ft (the outlet altitude was lower after November 1997) to 49.6 $ft^3/s$ in September 1973. Discharge values exceeding the limit of the rating table (29.30 $ft^3/s$) were estimated by extrapolation based on the last two values in the table, and may underestimate the actual magnitude of flow. The discharge estimates were used for a qualitative comparison with values of flow estimated by the simulator of lake/aquifer interaction, which will be described in later sections of this report.

The presence of stream gages below Lake Lowry and on the upper and lower ends of Alligator Creek between Lakes Magnolia and Brooklyn made it possible to assess the magnitudes of losses and gains during the period of continuous recorder operation (November 1994 to September 1997). As shown by the two discharge hydrographs between Lakes Magnolia and Brooklyn (sites 5 and 6 in fig. 9), there were only slight gains and losses during this period, which included periods of both high and low flow (0.1 to 41.5 $ft^3/s$). (Measurements after September 1997 were made by students of the UF). Generally, the flow at Treat Road was higher by about 1 to 2 $ft^3/s$, indicating that the stream segment was losing water, but in certain time periods (March-May 1996, July 1996), the flow at Immokalee Road was as much as 1 $ft^3/s$ higher, showing that the stream was gaining water. Even when high flows occurred during the El Niño winter of 1997-98, the difference in discharges was no more than 3 $ft^3/s$, indicating it is likely that substantial losses of water do not occur in this stream reach as the result of naturally occurring conditions. Discharge values in this figure are only reported to two significant figures, a USGS policy that reflects the accuracy limitation of this type of measurement.

Additional perspective into the behavior of the surface-water flow system is gained by considering the three discharge hydrographs (fig. 9) together. During the period of the measurements, the magnitude of flow in Alligator Creek did not vary greatly from emergence of the stream from Lake Lowry to entrance into Lake Brooklyn. Lake Magnolia appears to have acted primarily as a temporary holding pond for the transmission of water between Lakes Lowry and Brooklyn.

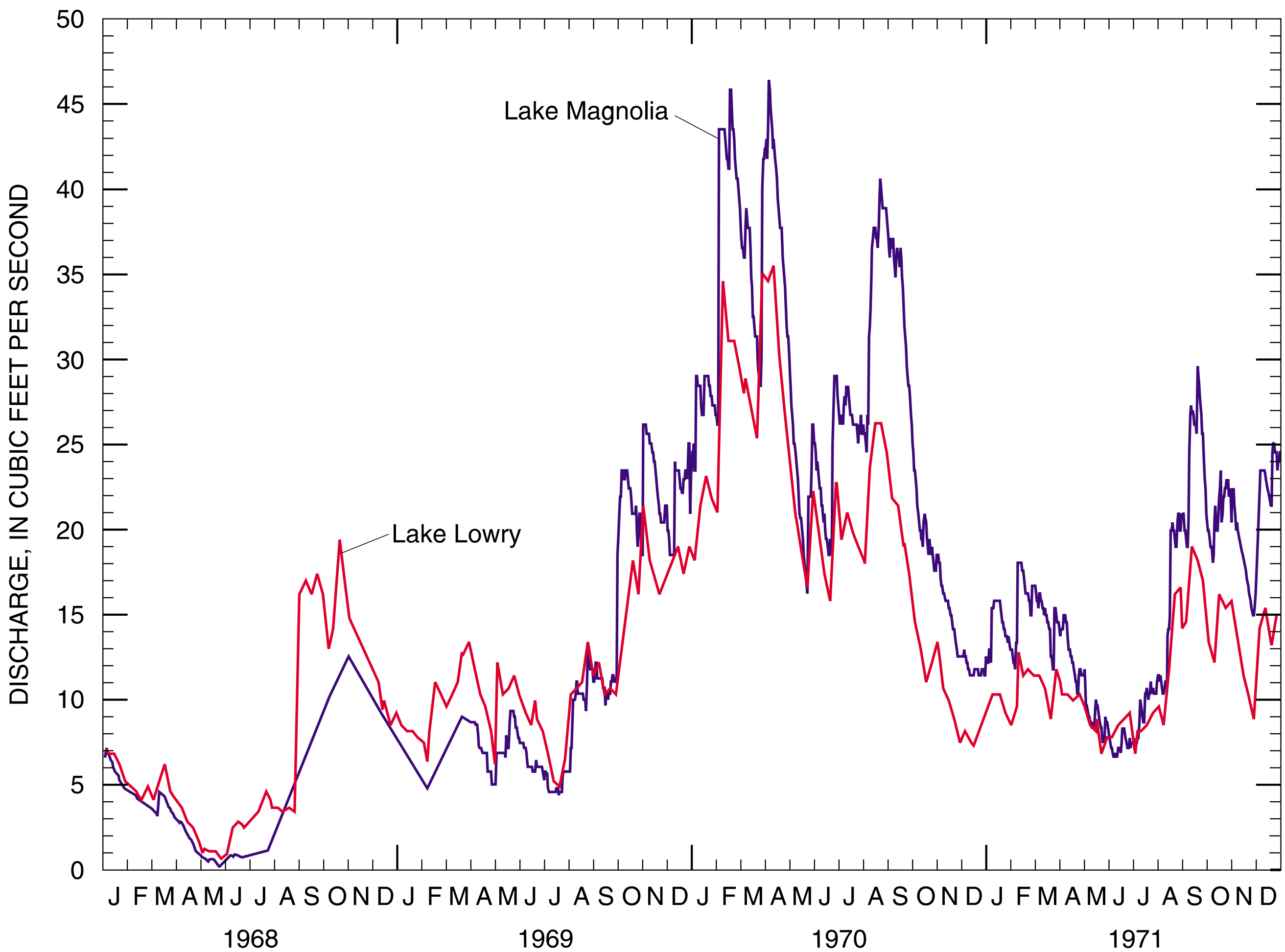



**Figure 11.** Estimated discharges from Lakes Lowry and Magnolia computed from measured lake stages and the 1994-97 USGS rating tables.

During the high-flow period of May through December 1995, there seems to have been little loss or gain of flow between Lakes Lowry and Brooklyn. In the somewhat drier period between April 1996 and April 1997, there were gradual losses of water volume, perhaps from evaporation or ground-water seepage, as the water moved from Lake Lowry to Lake Brooklyn, but the difference in discharge between the Lake Lowry and Lake Magnolia outlets did not exceed 5 $ft^3$/s.

Stream outflows from Lakes Lowry and Magnolia estimated from the lake stage data of 1957-98 occasionally show a relation somewhat different from that of the 1994-97 field measurements. Estimated discharges for 1968-71 (fig. 11) show patterns typical of the entire 1957-98 time period. In viewing these hydrographs, it is noted again that the rating table for Lake Lowry does not provide a stage-discharge relation for stages higher than 23.60 $ft^3$/s, and the rating table for Lake Magnolia does not provide a relation for discharges higher than 29.30 $ft^3$/s, so higher discharges in the hydrographs may not be accurately estimated. During the dry period that extends through 1968 until about October 1969, the estimated outflow from Lake Magnolia is less than or the same as that from Lake Lowry, a pattern similar to that of the 1994-97 discharge measurements. However, during a period of high lake stages from October 1969 to May 1971, the estimated outflow from Lake Magnolia is the higher of the two, especially during peak periods. Although there could be uncertainty associated with high discharge estimates, this relation could indicate that the surface-water flow system gained flow from the basin surrounding Lake Magnolia by runoff or by ground-water seepage during high rainfall periods. Although the hydrographs are highly correlated, the Lake Magnolia discharge exceeds that of Lake Lowry by as much as 15 $ft^3$/s during peak periods, taking into account a slight time lag between the peaks (Lake Lowry first and Lake Magnolia a few days later).

Flow measurements in Alligator Creek at Immokalee Road (site 6, fig. 4) were not made after February 1998 because the stage of the creek at this location began to show the effect of backwater from Lake Brooklyn. Backwater effects have been even more pronounced in past time periods. The 1949 USGS 7.5-minute topographic map for Keystone Heights, drawn after several years of above-average rainfall, shows backwater from the lake extending into the center of the wetlands area on the creek (fig. 4), nearly halfway to Lake Magnolia.

### Lakes Brooklyn and Geneva and the Basin Downstream

The irregular shape of highly unstable Lake Brooklyn reflects an origin as a coalescence of numerous collapse features (Subsurface Detection Investigations, Inc., 1992), which are said to “show fractures and faulting . . . that may provide some degree of hydraulic connection between the lake and the Upper Floridan aquifer.” Sinkhole development in the area is a continuous process, and as recently as December 1985, a 40-ft-deep sinkhole developed in a land area near the southwestern shore of the lake. The main part of the lake is relatively shallow, with individual pools reaching depths of 30 to 34 ft (fig. 12), but one pool on the west side of the lake is 47 ft deep. When the stage of Lake Brooklyn decreases substantially, the lake divides into as many as 10 separate pools (fig. 13). A vivid portrayal of the contrast in the appearance of the lake at high and low stages is shown by the photographic reproductions in figure 14.

Limited direct use of water from Lake Brooklyn is known to have occurred prior to the severe stage decline of 1990-94. Some lakeside residents pumped water from the lake for lawn irrigation, a practice that is now discouraged by water managers.

The shallow channel of Alligator Creek downstream from Lake Brooklyn emerges in a residential area and is routed through a series of culverts until it reaches Keystone Lake in the center of Keystone Heights. From Keystone Lake, the channel extends southeastward to a public recreational area on the shore of Lake Geneva, where the stream is routed to a structure designed to break up the flow to prevent scour of the sand beach. The last flow from Lake Brooklyn prior to this study occurred in January 1974. Heavy rains during the El Niño winter of 1997-98 again raised the stage of Lake Brooklyn above the outflow altitude, and outflow occurred between late March and early May 1998. Keystone Lake flooded because the culvert under a local road constructed during the previous quarter of a century of no flow in Alligator Creek was too high in altitude. The berm for the road was removed in May 1998 and water flowed into Lake Geneva for a brief period before a new road berm with a lower culvert was constructed.

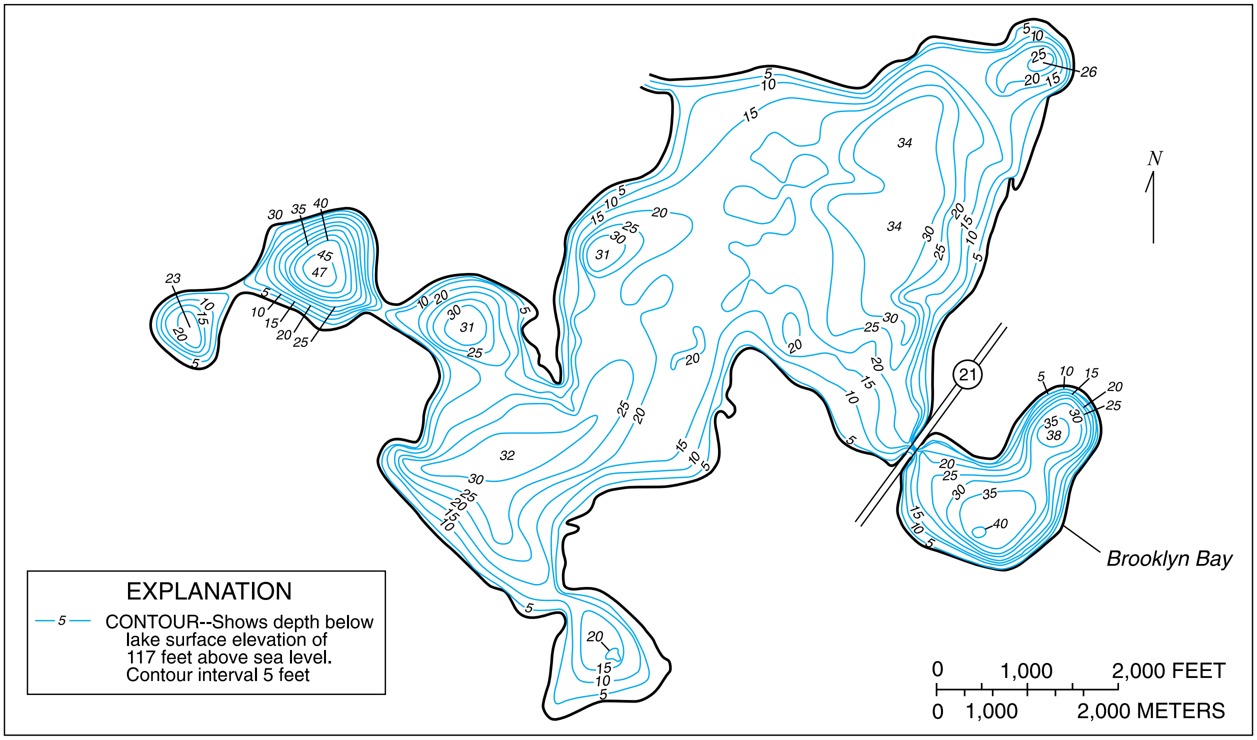



**Figure 12.** Lines of equal depth in Lake Brooklyn at a lake-surface elevation of 117 feet (modified from Clark and others, 1963, fig. 6).

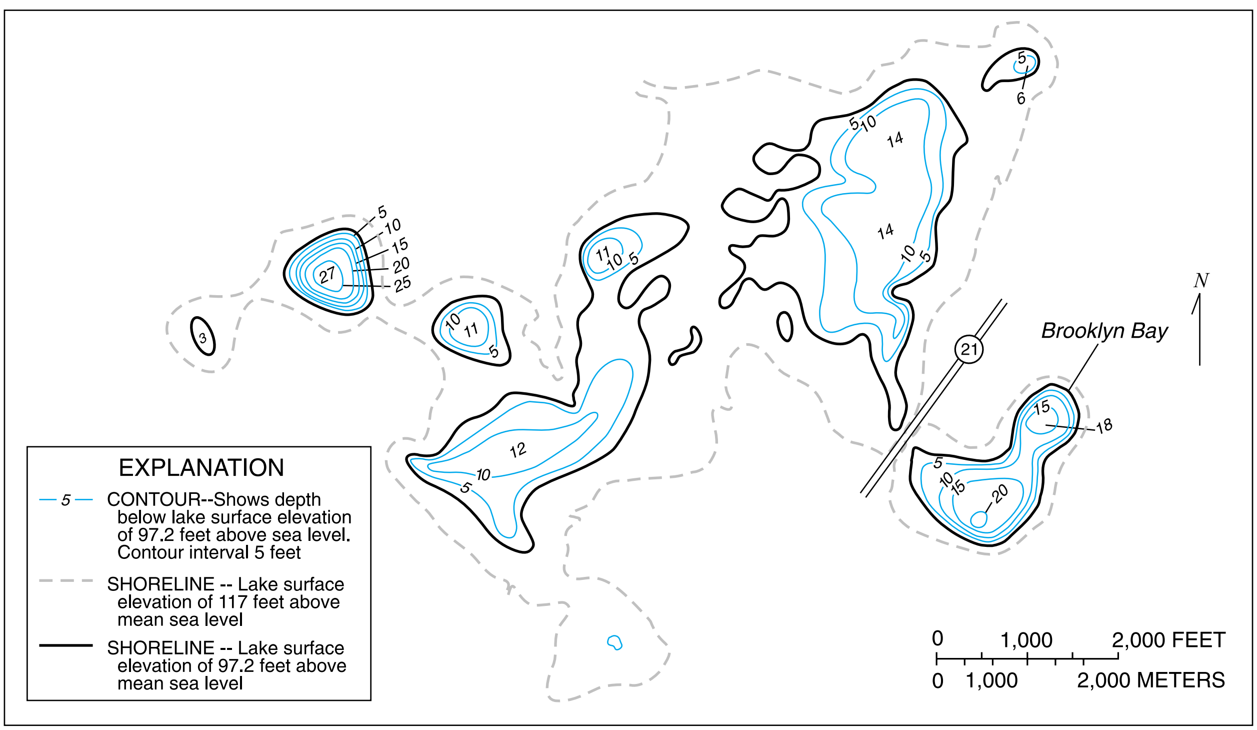



**Figure 13.** Lines of equal depth in Lake Brooklyn at a lake-surface elevation of 97.2 feet, measured in February 1958 (modified from Clark and others, 1963, fig. 7).


**Figure 14.** Lake Brooklyn at low and high stages as seen from the bridge on Highway 21.

Lake Geneva is a relatively unstable lake where the stage varied from 89.02 ft to 107.23 ft between 1957 and 1998. The maximum depth of the lake is 29 ft. The irregular outline of the lake suggests the coalescence of multiple collapse features. According to Subsurface Detection Investigations, Inc. (1992), "some regions are highly faulted and may provide direct connection to the Upper Floridan aquifer." The reasons for the stage behavior of Lake Geneva are complex because the lake's water budget depends partly on flows from Lake Brooklyn, which, apart from the minor quantities of April 1998, have not occurred since January 1974.

An outflow channel on the southeastern shore of Lake Geneva passes through a private property before going into a pair of road culverts that are overgrown by weeds and have not flowed since September 1974. When substantial flows last occurred in September 1973, the water passed through areas of low altitude into Oldfield Pond, Halfmoon Lake, and then into the wetland known as Putnam Prairie (fig. 1).

## Long-Term Trends in Lake-Stage and Lake-Stage/Rainfall Relations

As noted earlier, cumulative annual rainfall departures from the 1931-98 average measured at Gainesville (fig. 7) seemed well correlated with major changes in stage at Lake Brooklyn and with smaller stage variations in other lakes in the study area. For example, when annual rainfall was well below average in 1954-56, the stage in Lake Brooklyn declined substantially to below 97 ft. When annual rainfall was above average in the years 1957-60, the stage of Lake Brooklyn rose to a level above the outflow altitude from late 1959 to early 1962. Low rainfall in 1961-63 corresponded to a decline in the lake stage, and high rainfall in 1964-66 corresponded to a 3-year period in which the stage was above the lake outflow altitude. This relation between rainfall surplus or deficit and the stage in Lake Brooklyn is approximately quantified by the computation that will be termed a "rainfall memory factor" (*Rmf*), computed as a linearly weighted sum of previous monthly rainfall totals as follows:

$$Rmf = \sum_{i=1}^{n} R_i[1-(i-1)/n] - \overline{Rmf}, \qquad (1)$$

where

$R_i$ is the rainfall total for month $i$, and

$n$ is the number of months in system "memory."

The values are normalized by subtracting $\overline{Rmf}$, the mean of all computed *Rmf* values. An analogous relation in which rainfall was weighted with an exponential decay coefficient was also tried with some useful results, but the linear decay coefficient was chosen for the analysis as best illustrating the relation between rainfall and lake stage.

Various system memory lengths were tried, but results were mutually similar. Assuming a system memory length of 60 months (5 years) in equation 1, the resulting *Rmf* values (fig. 15) clearly show a correlation between the cumulative rainfall highs of 1960, 1966, 1970, and 1972 with high stages in Lake Brooklyn, and a correlation between cumulative rainfall lows of 1963, 1978, and 1981-82 with low stages in Lake Brooklyn. Also correlated are the low stages of 1969, 1971, and the early 1980's, when the normalized *Rmf* value was around or slightly below zero. However, the *Rmf* values do not correlate with the severe decline in lake stage that occurred in 1989-93.

A correlation between two sets of data suggests but does not prove that there is a causal relation between the two processes that they measure, and does not imply that there are not other processes that may have a causal relation with one or both of the two processes measured. The correlation shown in figure 15 for most time periods suggests that the increase or decrease of lake stage in most time periods is at least partly caused by fluctuations in antecedent rainfall. A correlation does not rule out the possibility that there may have been other important causal factors as well.

The apparent lack of correlation between *Rmf* and lake stage in the 1989-93 time period (fig. 15) suggests that lack of rainfall may not have been the primary cause of the decline in stage during this time period. The rapid stage declines in Lake Brooklyn and Lake Magnolia in 1989-90 are related to the stage decline in Lake Lowry upstream and the consequent loss of streamflow to the lower lakes in that time period. The stage decline in Lake Lowry does not appear to be related to deficient rainfall, as rainfall quantities were only slightly less than normal from 1985 to 1995. Therefore, the cause of this stage decline is unknown. Similar declines have not occurred at any other time during the period (1957-1998) that the stage of this lake has been measured, even during periods of substantial deficit of antecedent rainfall (fig. 15).

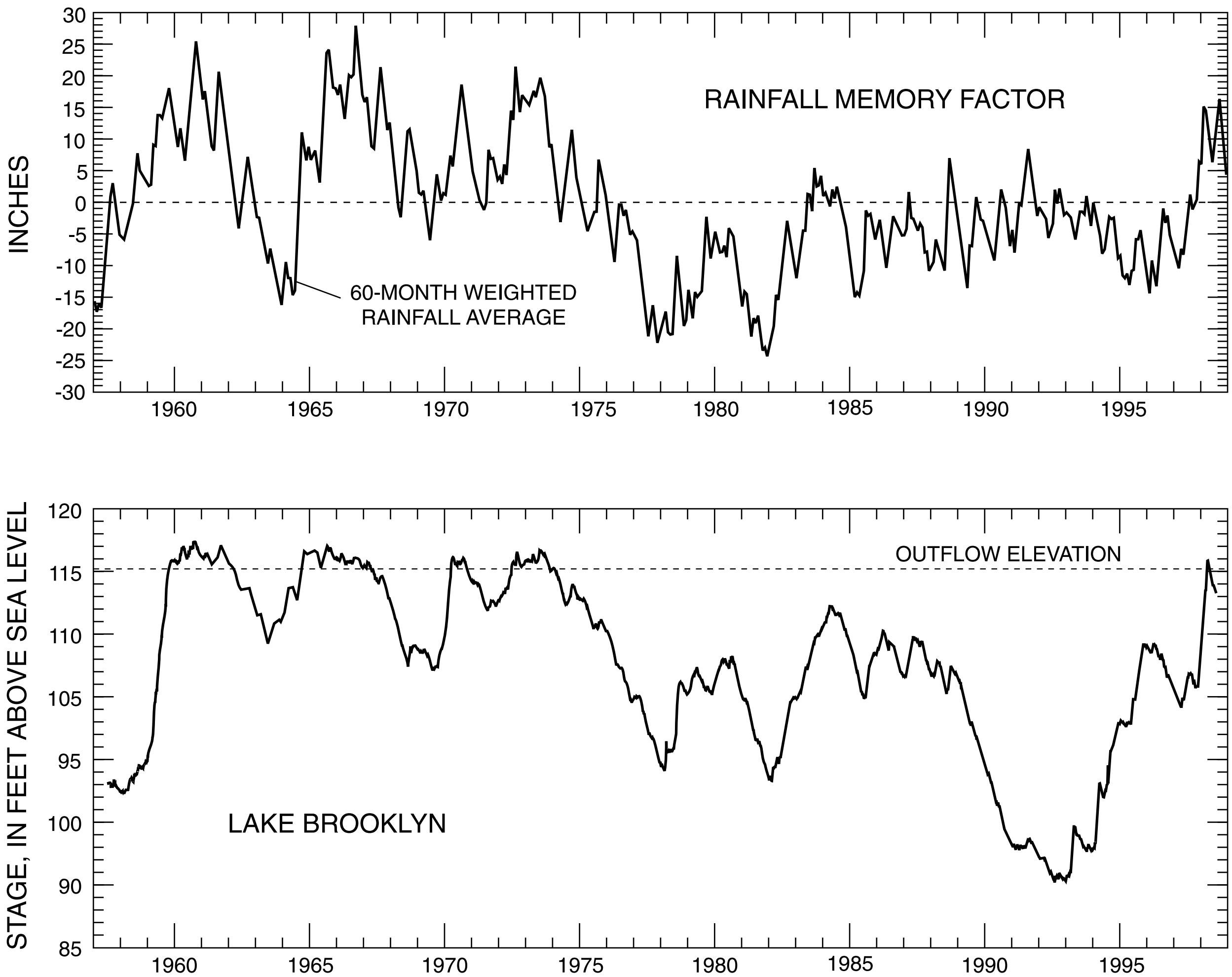



**Figure 15.** Rainfall memory factor and the stage of Lake Brooklyn, 1957-98.

Another type of long-term relation is obtained by relating the stage in Lake Brooklyn to estimated upstream outflows from Lakes Lowry and Magnolia. The lake outflow estimates are not independent of rainfall occurring in the basin, but provide another point of perspective to view the relation of lake stage to overall basin recharge. First, stages from the three lakes and estimated outflows from the two upper lakes were averaged over seven selected periods of time ranging from 8 to 44 months in duration when the stages of the two upper lakes remained high (table 3). There is a good correlation between the stages and heights above the outflow altitude of stable Lake Lowry and relatively stable Lake Magnolia. However, it is clear that there is a lack of correlation between the stages of Lake Magnolia and unstable Lake Brooklyn. The stage of Lake Magnolia and its height above the outflow altitude of 123.2 ft remained about the same in all seven time periods, but the stage of Lake Brooklyn is 8 to 10 ft lower in the last three time periods, in the late 1970's and in the 1980's, than in the four earlier time periods in the 1960's and early 1970's. This suggests that some factor or process affecting the water budget of the lower part of the lake system (Lakes Magnolia and Brooklyn) changed during the time period of the data presented in table 3.

**Table 3.** Stage of Lakes Lowry, Magnolia, and Brooklyn and estimated discharge averages from Lakes Lowry and Magnolia for selected time periods of high stage in Lake Magnolia

[$ft^3/s$, feet cubed per second]

| Time period | Lake Lowry | | Lake Magnolia | | Lake Brooklyn | | Exceeds outflow elevation by (feet) | | Estimated average outflow discharge ($ft^3/s$) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Average stage (feet) | Number of measure-ments | Average stage (feet) | Number of measure-ments | Average stage (feet) | Number of measure-ments | Lake Lowry [a](131.0) | Lake Magnolia [a](123.2) | Lake Lowry | Lake Magnolia |
| Oct 1959-Feb 1962 | 131.83 | 64 | 124.64 | 684 | 116.28 | 204 | 0.83 | 1.44 | 16.56 | 15.73 |
| Sep 1964-Apr 1967 | 131.82 | 98 | 124.93 | 839 | 115.96 | 105 | .82 | 1.73 | 16.18 | 22.17 |
| Mar 1970-Oct 1970 | 132.05 | 34 | 125.19 | 211 | 115.72 | 33 | 1.05 | 1.99 | 20.97 | 28.94 |
| June 1972-Nov 1973 | 131.97 | 71 | 125.23 | 511 | ‘ 115.91 | 84 | .97 | 2.03 | 19.36 | 29.98 |
| Mar 1978-Oct 1980 | 131.88 | 47 | 124.58 | 237 | 105.59 | 147 | .88 | 1.38 | 17.41 | 14.42 |
| Apr 1982-Jan 1985 | 132.05 | 43 | 124.98 | 160 | 107.65 | 161 | 1.05 | 1.78 | 20.99 | 23.71 |
| Aug 1985-Mar 1989 | 131.95 | 65 | 124.84 | 211 | 107.88 | 213 | .95 | 1.64 | 19.09 | 20.34 |

[a]Outflow elevation.

## NUMERICAL SIMULATION OF LAKE/ AQUIFER INTERACTION

Although the general hydrology of the study area and of Lake Brooklyn has been investigated in this and numerous previous studies, and water-budget models have been developed to describe exchanges of water between Lake Brooklyn and the atmosphere, inflowing and outflowing streams, and the ground-water system, no investigator has previously attempted to use a deterministic model to simulate the hydrologic system that includes the lake and the aquifer system. Application of a deterministic model would be valuable because it could quantitatively test hypotheses advanced by previous investigators to explain the unstable nature of Lake Brooklyn. For such a test to produce worthwhile results, it is not necessary to fully validate a unique set of parametric coefficients to calibrate the model. Given the complexity of the hydrologic system being modeled, such an objective may not even be achievable. Rather, the ability to replicate observed data with one or more reasonable and defensible sets of parameter choices would serve the desired purpose of supporting the conceptual model of previous investigators.

The principal obstacle to the use of a deterministic model has been the lack of a simulator with the capability of representing a dynamically changing lake and the dynamic interaction of the lake with the aquifer system. For the purpose of this study, simulation methods were developed to make this type of analysis possible. The following sections describe the simulator used for the analysis, the lake representational methods developed, the design and application of the simulator, and conclusions derived from the model's use.

### Simulation Code

The code selected for the simulation analysis was MODFLOW-96, a modular, three-dimensional, finite-difference simulator of saturated-zone ground-water flow in confined or unconfined aquifers developed by the USGS (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996a; and Harbaugh and McDonald, 1996b). The model solves the following equation for ground-water flow:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W = S_s\frac{\partial h}{\partial t} \quad (2)$$

where

$K_{xx}$, $K_{yy}$, and $K_{zz}$ are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity ($Lt^{-1}$);

$h$ is the potentiometric head (L);

$W$ is a volumetric flux per unit volume and represents sources and/or sinks of water ($t^{-1}$);

$S_s$ is the specific storage of the porous material ($L^{-1}$); and

$t$ is time (t).

The modular structure of the program permits the representation of a variety of sources and sinks of fluid, such as rainfall recharge, evapotranspiration (ET), fluxes to and from streams, reservoirs, lakes, drains, and wells, the specification of a variety of boundary condition types and solution methods, and the application of solutions to special types of flow problems. A Lake Package developed for this study to simulate the interaction of a lake with an underlying aquifer has been documented in a report by Merritt and Konikow (2000). The Lake Package is designed to operate with MODFLOW and also with the USGS solute-transport model MOC3D (Konikow and others, 1996). The present study was conducted without the aid of a graphical user interface.

## Representing Lakes in the Simulator

The Lake Package represents an improvement of previous methods of representing lakes, such as those implemented in the River Package of MODFLOW or the Reservoir Package of MODFLOW (Fenske and others, 1996), in that the lake stage can vary interactively with ground-water levels. The USGS Lake Package is a substantially revised version of an earlier package developed by Cheng and Anderson (1993) to which various new features have been added. The approach used in both packages is to identify cells within the model grid as parts of one or more lakes. The cells are then made inactive in the simulation and interfaces between the lake cells and the surrounding aquifer are identified and assigned conductance values based on: (1) aquifer hydraulic conductivity and (2) a set of leakance values assigned to represent the retarding effect of the lakebed on the transmission of water. Therefore, the accuracy with which the lake can be represented depends on the model grid dimensions. The sum of the vertical thicknesses of lake cells in a vertical column of the grid should approximately represent the depth of the lake in that sector of the simulated lake, so that the stage/volume relation of the lake will be adequately represented in the model.

In each iteration for a solution for aquifer heads in a MODFLOW time step, Darcy's Law is applied to compute exchanges of fluid between the aquifer and lake at each lake/aquifer interface. The cumulative lake/aquifer flux for each aquifer grid cell then becomes part of the source/sink term in the finite-difference approximation of the ground-water flow equation for that grid cell. The stage of each lake varies dynamically from one MODFLOW time step to the next by means of a budget process that takes into account ground-water seepage, precipitation upon and evaporation from the lake surface, stream inflows and outflows, overland runoff inflows, and augmentation or depletion by artificial means. The Stream Package (David E. Prudic and Leonard F. Konikow, USGS, written commun., 2000) specifies the linkages for interchanges of water between streams and lakes.

The Lake Package has the capability to simulate the occurrence of drying and rewetting in parts of lakes or of entire lakes. Evapotranspiration and rainfall recharge on the land surface and evaporation and rainfall recharge on the lake surface (separately specified in the input data set) are always applied to the correct grid-cell columns as partial lake drying and rewetting occur. Another capability provided by the package is to simulate the division of a lake into separate lakes with drying or the coalescence of several lakes separated by areas of low land-surface altitude into a single lake with rising stage. Both of these capabilities were needed in addressing the problem of simulating the large stage variations in Lake Brooklyn, and may be useful for simulating lake-stage fluctuations in other lakes in other parts of the United States. The package also has the capability to simulate lake/aquifer interaction in a steady-state MODFLOW solution, and to compute lake stage semi-implicitly or fully implicitly in cases where solution stability problems can be ameliorated with such an approach. Neither of the latter capabilities were needed in this study.

## Conceptual Model of the Hydrologic System and Simulator Implementation

The Lake Package was used to simulate the interaction of two lakes, stable Lake Magnolia and unstable Lake Brooklyn, with the surficial aquifer system and with the intermediate and Upper Floridan aquifers. A conceptualization of the relative importance and interrelation of hydrologic processes affecting the volumes of water contained in the lakes and interchanges of water between surface-water bodies and the various aquifers in the study area is presented in the following sections. This conceptualization (fig. 16) benefits from the hindsight available from the completed study.

Lake Magnolia illustrates the simpler conceptual model of lake/aquifer interaction of the two lakes. Lake Magnolia exchanges water with the surrounding surficial aquifer system composed of clastic materials of relatively low permeability. The permeability, however, is sufficient that most rainfall infiltrates the soil and does not become overland runoff. The lake also gains or loses water from the atmosphere depending on whether the net recharge (precipitation minus evaporation) is positive or negative. Another important mechanism for the gain or loss of water is stream inflow and outflow. The magnitudes of all of these fluxes are mutually related through the operation of the hydrologic system, although they are conceptually separable as mechanisms for modeling purposes. Artificial depletion or augmentation of the lake volume most likely has never occurred in Lake Magnolia.

Although there is the potential for large exchanges of water between the lake and the surrounding surficial aquifer system, the lake stage and the head in the aquifer normally remain nearly the same, so that only minor amounts of water are exchanged to maintain this approximate equilibrium as lake stage and aquifer heads change in response to other stresses. Without field data describing seepage through the lakebed or the use of a simulator, it is difficult to estimate an approximate range for the quantity of water exchanged. Estimating the small amount of leakage from the lake and surrounding aquifer to the Floridan aquifer also would require a simulator.

The maximum monthly rainfall recorded in Gainesville since 1931 is 15.15 inches, which was recorded in August 1945. This amount is equivalent to a flux of 4.3 $ft^3/s$ on the surface of Lake Magnolia. The maximum monthly average evaporation, based on Kohler's (1954) pan-to-lake coefficients, is 0.21 in/d, equivalent to a flux of 1.8 $ft^3/s$ from the surface of Lake Magnolia. Therefore, these two values probably bracket the total flux of water exchanged directly between the lake and the atmosphere. In contrast, inflows to the lake from Alligator Creek and outflows from the lake to Alligator Creek can range as high as the estimated outflow of 49.7 $ft^3/s$ in September 1973, although the maximum monthly average is less than this value. As noted previously, however, Lake Magnolia is at the center of a flow-through system, and inflows and outflows normally are either both high or both low, and balanced to some extent (figs. 9 and 11). It seems likely that net streamflow is the dominant term in the water budget of Lake Magnolia when high streamflows occur; atmospheric fluxes and ground-water seepage also are important terms that become dominant when streamflow fluxes are low or non-existent.

In Lake Brooklyn, ground-water seepage fluxes and atmospheric fluxes are greater than those of Lake Magnolia by virtue of the larger bottom and surface areas of the lake. Based on a comparison of surface areas of the two lakes, ET could range as high as 5.6 $ft^3/s$ and rainfall recharge could be as high as 13.4 $ft^3/s$. Maximum stream inflow is about the same as the outflow from Lake Magnolia, but the outflow from Lake Brooklyn is usually zero as the stage is usually below the outlet altitude (fig. 2). In addition, there is a substantial loss of water from the lake and surrounding surficial aquifer system to the Floridan aquifer system (Clark and others, 1963). Therefore, it seems likely that net streamflow and leakage to the Floridan aquifer are the dominant terms in the water budget (as indicated in figure 16), with atmospheric fluxes and seepage to the surficial aquifer system less important terms when large streamflows occur, however, these latter terms become more important when the rate of stream inflow to the lake is low or zero. Because the two dominant fluxes probably would not be strongly correlated, it is also apparent that the water budget of Lake Brooklyn would tend to be more volatile than that of Lake Magnolia, making the lake more unstable.

Because of the downward hydraulic gradient in the study area, water moves downward from the surficial aquifer system through the intermediate aquifer system and confining unit to the Upper Floridan aquifer, where the water moves laterally downgradient at a relatively rapid rate, given the high transmissivity of the Upper Floridan; Motz and others (1995) estimated the transmissivity of the Upper Floridan to be about 100,000 $ft^2/d$ in the study area. Because the Keystone Heights area is near and somewhat north of the center of a regional potentiometric high, water leaking into the Upper Floridan aquifer will move westward, northward, and eastward.

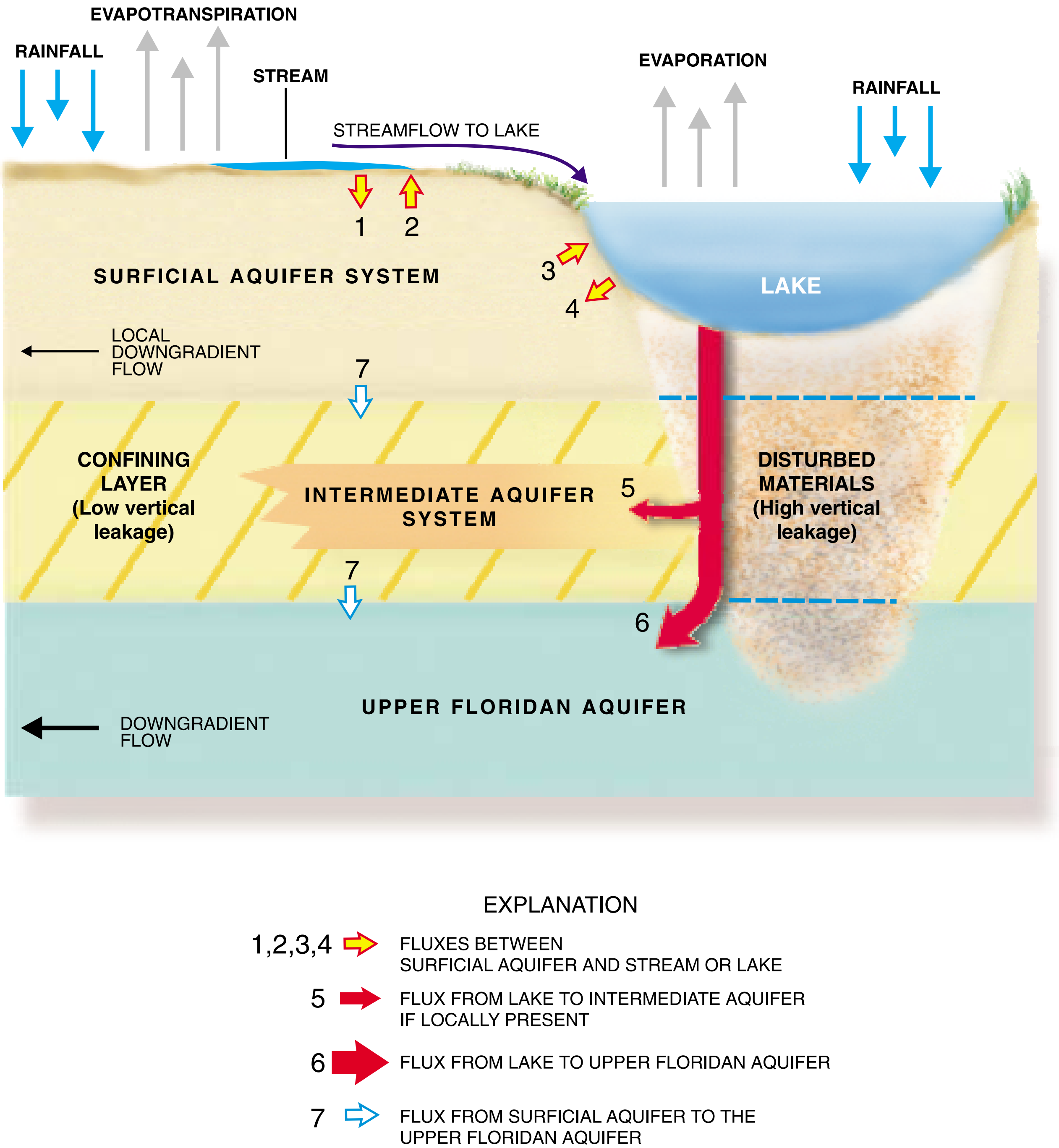



**Figure 16.** Pattern of water fluxes among stream, lake, and various aquifers.

The process of downward leakage to the Upper Floridan aquifer also needs a conceptual description. As discussed earlier, the top of the Ocala Limestone, which coincides with the top of the Upper Floridan aquifer, averages about 200 ft below land surface. The top of the Hawthorn Formation (intermediate confining unit) is about 50-80 ft below land surface. As a result of the relatively low permeability of the surficial aquifer system, which is only 50-80 ft thick, and the still lower permeability of the confining unit, lateral movement of water in the surficial aquifer and confining unit is relatively slow in the study area. Because of the short vertical distance to the highly transmissive Upper Floridan aquifer, most water leaking downward from the surface probably moves almost vertically to the Upper Floridan aquifer near the water's point of entry at the surface.

Beneath the lakebeds, the movement of water is harder to characterize because original subsurface deposits have been disturbed or displaced by the karstic processes that formed the lakes. In these locations, the downward movement of water seeping through the lakebeds might occur through a few large conduits intersecting the lakebeds, or the downward movement of water may be more diffuse, occurring through an aggregate of disturbed materials. In the first case, the rate of downward leakage from the lake would be appreciably reduced if areas of the lakebeds intersected by conduits became dry. In the second case, drying parts of the lake would affect the rate of downward leakage only in proportion to the amount of lakebed exposed. None of the lakes in the study area are deep enough to penetrate the limestone beds of the Upper Floridan aquifer, although limestone beds of the Hawthorn Formation could be exposed on the bottoms of the deeper lakes.

Because detailed information is lacking on the nature of the subsurface beneath the lakes considered in this study, a scenario of distributed downward leakage was adopted as the most intuitively reasonable assumption, consistent with the view that the lake is underlain by an aggregate of disturbed materials with spatially-uniform hydraulic properties. Assuming that the disturbed materials are also of relatively low hydraulic conductivity, the downward movement of water seeping through the lakebed will still be nearly vertical and will reach the Upper Floridan aquifer near the point of origin beneath the lakebed.

Because the confining layers separating the surficial aquifer system and the Upper Floridan aquifer under the lakes are assumed to have been replaced by more permeable materials by the karstic processes that formed the lakes, they were parameterized (as will be described later) to permit downward leakage everywhere directly beneath the lakes at a much higher rate than elsewhere. This conceptualization is adequate to support the analysis of the Lake Brooklyn water budget that is the purpose of this study. Data are not available to quantify the separation of leakage volumes between point sources and areally distributed downward leakage away from conduits formed by karstic processes in the study area.

The 10-40 ft of replaced materials directly underlying the lakes and in the depth interval equivalent to the surficial aquifer system were assumed to have the same relatively low horizontal and vertical permeability as the laterally adjacent surficial aquifer system in areas not overlain by lakes. Because the movement of water in the disturbed materials beneath the lakes is assumed to be primarily in the vertical direction, the selected approach makes it feasible to independently control the amount of leakage from isolated pools of Lake Brooklyn when the stage is low.

Because permeable limestone beds tapped by domestic self-supply wells (the intermediate aquifer system of Motz and others, 1994) are present within the confining unit, they should also be included in the model as a confined aquifer. Therefore, in the conceptual model of the hydrogeologic system, the surficial aquifer system and the Upper Floridan aquifer are considered to be separated by two confining units separated by an areally extensive confined aquifer having a transmissivity substantially less than that of the Upper Floridan aquifer and an average hydraulic head intermediate between that of the surficial aquifer and that of the Upper Floridan aquifer. Some of the water leaking downward from the lakebeds and through the upper of the two confining units will be intercepted by this secondary aquifer, but a greater amount of water will circulate further downward to the highly transmissive Upper Floridan aquifer.

To apply MODFLOW, various modular packages were needed to represent lakes and streams, their interconnection, and their interaction with the surficial aquifer system. The Lake Package (Merritt and Konikow, 2000) and an older version of the Stream Package (Prudic, 1989) modified for this study were used. Simulation of the water table in the surficial aquifer system in the vicinity of the lakes required use of the Recharge and Evapotranspiration Packages (McDonald and Harbaugh, 1988). Because of the low permeability of the surficial aquifer system, it was possible to use specified-head boundary conditions around the perimeter of a small area surrounding the lakes. Because the Flow and Head Boundary (FHB1) Package (Leake and Lilly, 1997) was not available at the outset of the study (1995), the Time-Variant Specified Head Package (CHD) (Leake and Prudic, 1991) was used for this purpose.

Representation of leakage to the Upper Floridan aquifer only required that the Upper Floridan be represented as a sink or a drain. Explicit representation of flow patterns within the Upper Floridan was unnecessary. It was considered advantageous, however, to simulate to some extent the influence of the leakage on heads in the Upper Floridan aquifer. This was done by entering a layer in the model grid for the Upper Floridan aquifer and specifying boundary conditions at a distance from the modeled area using the General Head Boundary (GHB) Package (McDonald and Harbaugh, 1988). A model layer was added above the Upper Floridan aquifer layer to represent the intermediate aquifer system, and boundary conditions also were specified at a distance using the GHB Package.

The selection of packages used to simulate the hydrogeologic system as conceptualized was completed with the selection of the Block-Centered Flow Package (BCF) and the Strongly-Implicit Procedure Package (SIP) (McDonald and Harbaugh, 1988). The BCF package implements standard block-centered finite-difference mathematics for approximating the ground-water flow equation for heads in the aquifer. The SIP package implements the SIP iterative solver for solution of the ground-water flow equation.

## Grid Design and Boundary Conditions

The most convenient choice of an area for the model was one that encompassed Lakes Magnolia and Brooklyn but excluded other large lakes. The model grid (fig. 17) was 24 cells wide, 31 cells long, and encompassed a 12,464 ft by 27,395 ft area, and was rotated 39 degrees from the north-south axis. Edges of the grid transected edges of several large lakes of known stage, which facilitated the selection of surficial aquifer system boundary-head values. Surficial aquifer system wells located near the boundary were also used to estimate specified boundary-head values. The irregular grid spacing was designed to best fit the irregular shape and bathymetry of the space occupied by Lakes Magnolia and Brooklyn within the model. In particular, long, narrow grid nodes were needed to represent narrow necks connecting larger pools.

The vertical discretization of the model (fig. 18) consisted of an upper five layers representing the surficial aquifer system, and two lower layers, each separated from the next higher layer by a confining layer, representing the intermediate and Upper Floridan aquifers. Although surficial aquifer system layers 2 through 5 are depicted as each being 10-ft thick, the top layer is not given a dimension in MODFLOW; it is assumed that any head value computed in the upper layer represents a water table below land surface. As an example, heads greater than 145 ft above sea level were computed at the model location of one of the observation wells in the surficial aquifer system. Bottom elevations specified for the five layers were 107, 97, 87, 77, and 67 ft above sea level. This specification was required because the space of one or more lakes occupied parts of all five layers, and the logic of the Lake Package requires that all such layers be represented as either unconfined or convertible (LAYCON = 1 or 3), which requires a specification of bottom altitude for those layers.

The approximate depths of the lakes in vertical columns of grid cells were estimated by overlaying the model grid (fig. 17) on enlarged views of the bathymetry (figs. 10 and 12). The rows and columns of the grid occupied by the lakes are indicated in figure 19 by non-shaded cells containing numbers that indicate the number of layers occupied by the lake in each row and column position. The number, divided by 10, is the number of layers occupied by the lake, and indicates the depth of the lake in that vertical column of the grid. For instance, the number 40 in a non-shaded grid cell indicates that four layers are occupied by a section of a lake in the column of grid cells in that row and column position, and that the bottom of the lake is specified to be at an elevation of 77 ft above sea level in that vertical column.

With Lakes Brooklyn and Magnolia defined spatially within the model grid, it was possible to define the relation of stage and volume for each lake implicit in their spatial representation (figs. 20 and 21, respectively). Strong inflections of the Lake Brooklyn graph, and weaker inflections of the Lake Magnolia graph, occur at 87 and 97 ft, the bottoms of layers 2 and 3, respectively. Slight inflections at 77 ft (the bottom of layer 4) and 107 ft (the bottom of layer 1) are barely discernible. The true stage/volume relation should be a smooth curve passing through the same stage/volume range.

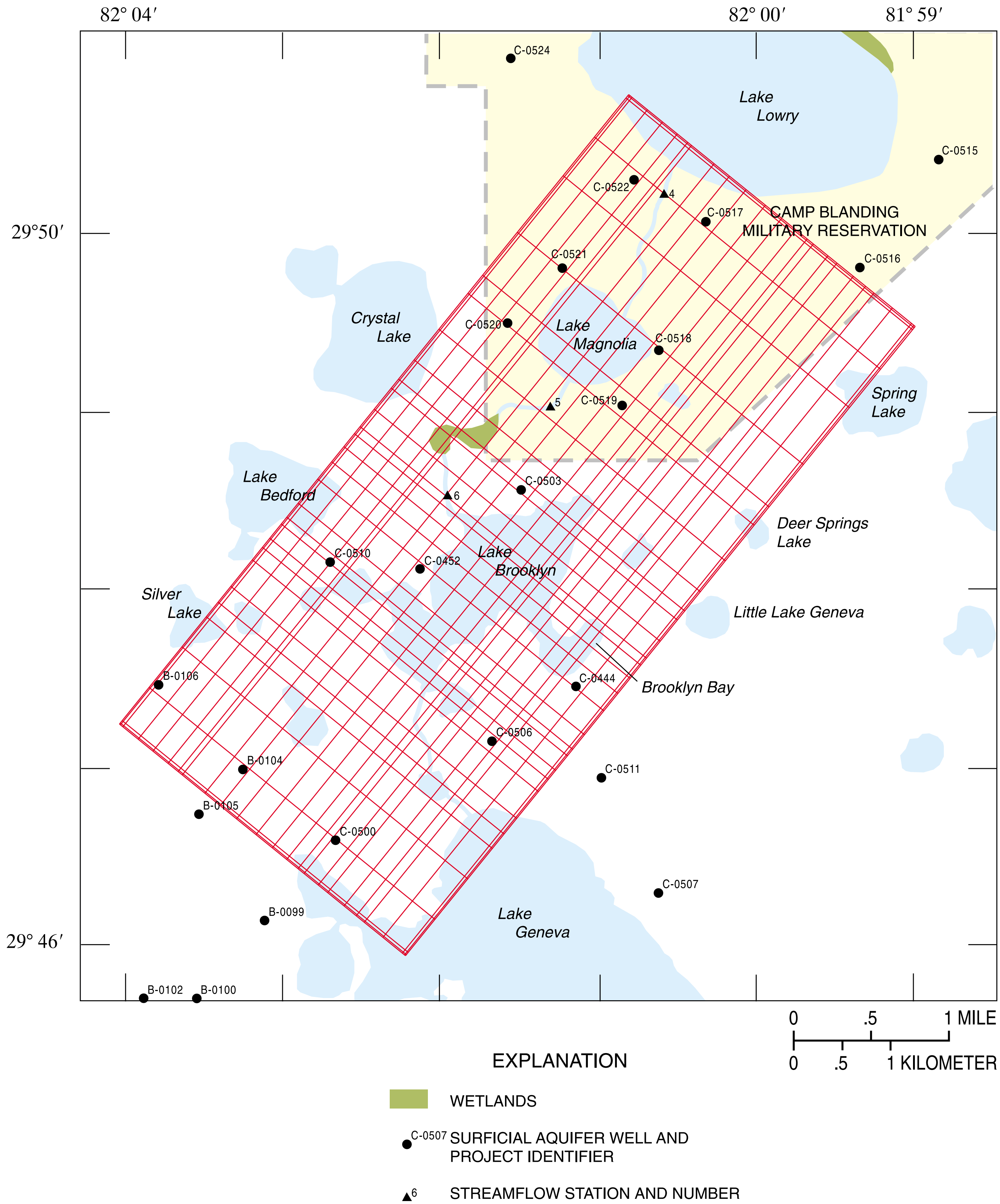



**Figure 17.** Horizontal discretization of the lakes model.

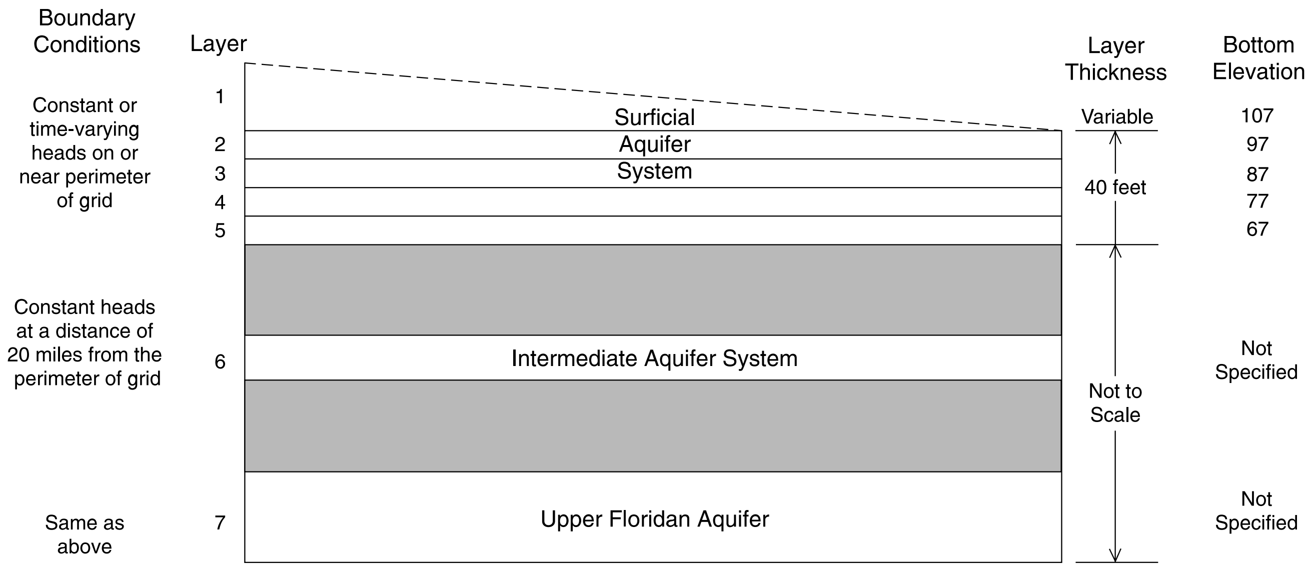


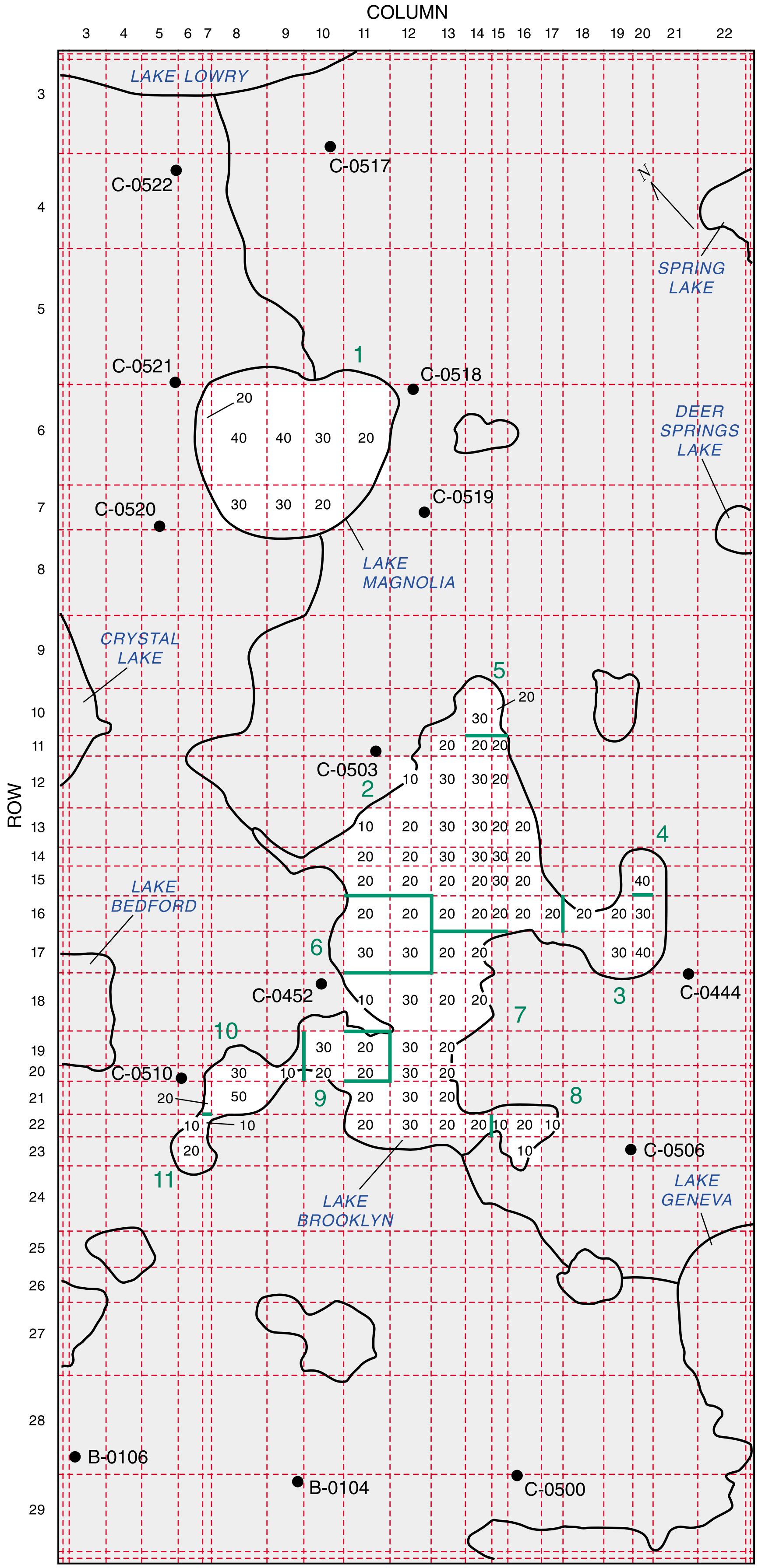

**Figure 18.** Vertical discretization of the lakes model.

The stage/volume relations were compared with those presented in the form of quadratic curves by Motz and others (1994, p. 95-96); simulated volumes at the outlet elevations for Lakes Magnolia and Brooklyn exceeded those estimated by Motz (1994) by 38 and 21 percent, respectively. The cause of the discrepancy is not known, but a sensitivity analysis (to be described later) was performed to assess the effect of errors in estimating the lake depth in various parts of the grid.

Because of the irregular bathymetry of Lake Brooklyn, the model must simulate the separation of the lake into distinct pools as lake stage drops and the coalescence of the pools into a single lake as the stage rises (figs. 12 and 13). Therefore, the logic of lake coalescence/separation incorporated into the Lake Package requires that each pool be identified as a separate lake ("sublake") in the input specifications. This division is shown in figure 19. The pattern of lake joining and the "sill altitude" at which the sublakes connect was determined from a study of lake bathymetry and is specified in the input to the Lake Package. The main upper part of Lake Brooklyn that receives inflows from Alligator Creek (sublake 2) is connected to sublake 5 at 105 ft, to sublake 3 at 99 ft, and to sublake 7 at 100 ft. Sublake 7, in turn, is connected to sublake 6 at 95 ft, to sublake 8 at 104 ft, and to sublake 9 at 102 ft. Defining the connection of sublake 2 to 7 and the connection of sublake 7 to 6 (rather than 2 to both 6 and 7) was based on the fact that the sandbar that divides sublake 2 from 7 and sublake 2 from 6 lies at an altitude of 100 ft, whereas the sandbar that divides sublake 7 from 6 lies at a lower altitude of 95 ft. This procedure allows sublakes 6 and 7 to be connected when they are both still separated from sublake 2.

In the final calibration, the lake separation was simplified by assuming that sublakes 2, 6, 7, and 9 were all connected at an altitude of 90 ft. This procedure was adopted because the stage of sublake 2 responded to changes in stream inflow at very low stages as if it had a stage/volume relation similar to the four combined sublakes. Possibly, shallow sandbars separating the four sublakes were not effective in hydraulically separating the bodies of water, or shallow channels dug by local residents diverted water from larger pools that may have temporarily had a higher stage.

The lake connection specifications are completed by setting a sill altitude of 114 ft between sublakes 9 and 10, and a sill altitude of 115 ft between sublakes 10 and 11. Because Lake Magnolia is a simple, bowl-shaped lake with no sandbars and does not undergo substantial stage fluctuations, it was specified as sublake 1 (or lake 1) with no possible connections to other sublakes.



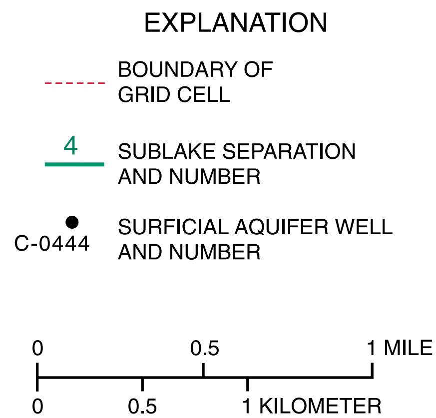




**Figure 19.** Horizontal placement of lakes in model grid, specified depths, and sublake boundaries.

In the upper five layers representing the surficial aquifer system, time-invariant heads were specified as boundary conditions around the perimeter of the model grid (fig. 17), with exceptions to be described presently. Stages at most of the lakes (Lowry, Crystal, Bedford, and Spring Lakes) on or near the model boundary and water levels measured in the water-table wells (fig. 4) located at some distance from Lake Brooklyn varied in the 1994-97 measurement period by only 3 to 6 ft. Earlier (1960) data from Loch Lomond indicate that somewhat higher stages may have occurred in periods of high water before the 1994-97 period. More recent data collected by the UF during the wet El Niño winter of 1997-98 also show water levels as much as 5 ft higher than the 1994-97 USGS data-collection-period averages.

Despite the indication that larger variations occurred in historical high-water periods, median values of well water levels from the 1994-97 period were chosen as representative and used to specify boundary heads constant in time for the entire simulation period (1957-98). Where the boundary transected lakes, a median value for lake stage was used (132 ft for Lake Lowry, 104 ft for Crystal Lake, 95 ft for Lake Bedford, and 90 ft for Spring Lake). A value of 90 ft was assumed for Deer Springs Lake (fig. 1). Based on the higher values of water level measured at wells located at a distance from lakes (the median water level measured in C-0517 was about 150 ft), boundary-head values interpolated between lakes lying on the boundary were specified as being higher than the lake stages.

The exception to this procedure of boundary-condition specification in the layers representing the surficial aquifer system was to omit entirely the boundary specification for the upper two layers where the grid boundary transected Lake Geneva, where the head varied from 89 to 107 ft over the period of record. The boundary cells affected were rows 25-31 on the eastern boundary (fig. 19) and columns 14-24 on the southern boundary. At these grid locations, in layers 3-5 of the surficial aquifer system, boundary heads were specified to be time-varying and given monthly values equal to the monthly average stages of Lake Geneva. Omitting

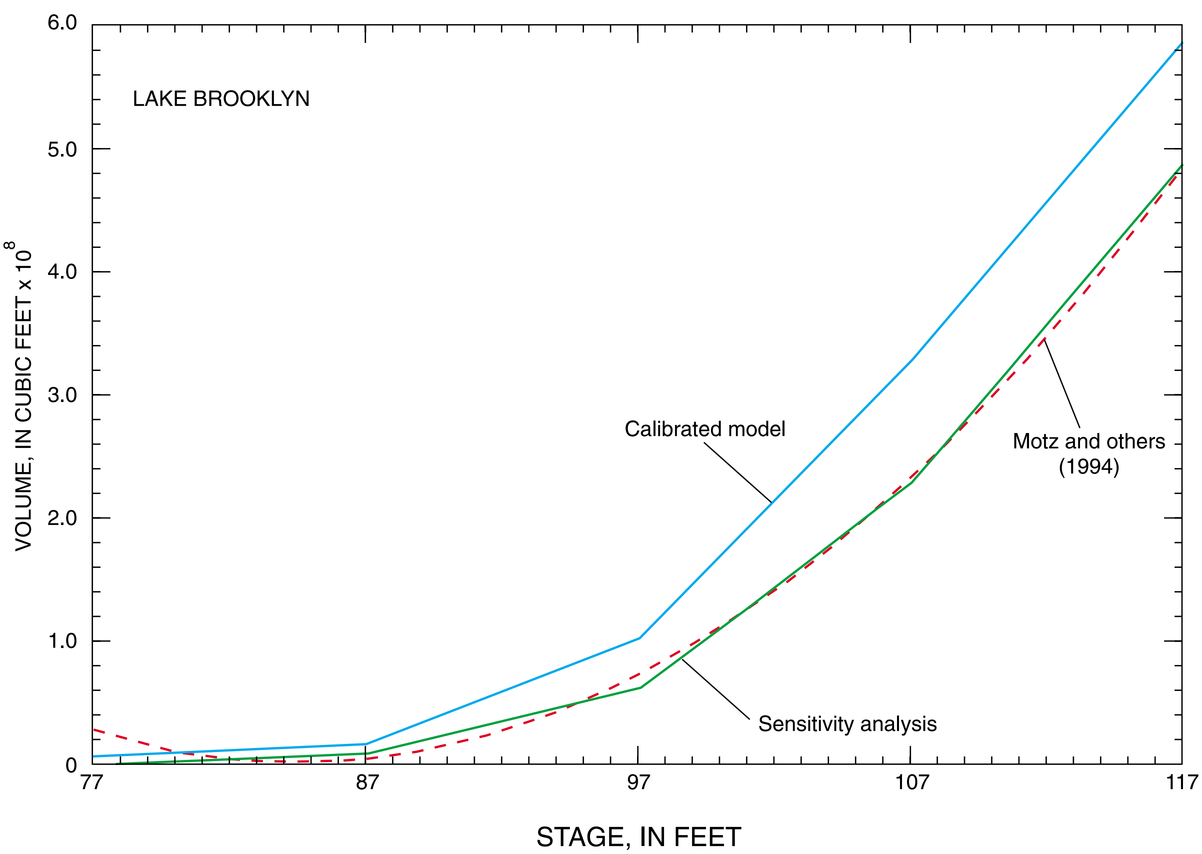



**Figure 20.** Various stage/volume relations for Lake Brooklyn.

the boundary specifications from the upper two layers at these locations avoided a MODFLOW error termination when the Lake Geneva stage, used as the boundary value, fell below the bottom elevation of one or both of these layers.

During calibration of the model, head values close to the boundary (columns 3-4, 21-22, rows 3-4, 28-29) often were substantially different from the values at the boundary. Because the hydraulic conductivity values used to calibrate the model were relatively low, heads within the modeled area were expected to be relatively insensitive to the specified boundary values. To demonstrate this fact, two sensitivity tests were performed: (1) all specified boundary heads except the time-varying ones bordering Lake Geneva were raised 5 ft, and (2) these same boundary values were decreased 5 ft. The result was virtually no difference in stages computed for Lakes Brooklyn and Magnolia, and virtually no difference in heads computed at observation-well locations in the surficial and Upper Floridan aquifers, based on a comparison of computed 1957-98 hydrographs. This result verifies that model computations for lake stages and surficial aquifer system heads were insensitive to the choice of constant boundary-head values, so uncertainties associated with the choice of boundary-head values should not be a matter of concern.

The choice of boundary-head values based on the stage of Lake Geneva did have an observable effect on heads computed at the locations of nearby observation wells. Because there is a firm basis for the choice of these boundary-head values, they were not considered a possible source of error.

A rigorous simulation of the Upper Floridan aquifer was not attempted; therefore, only a generalized representation of boundary conditions for that layer was necessary. Based on a consideration of regional potentiometric gradients surrounding the study area (fig. 6), it was inferred that water leaking to the Upper Floridan moves to the west, north, and east, where a 60-ft potentiometric-surface contour is located about 20 mi from the study area. Using the GHB package, a

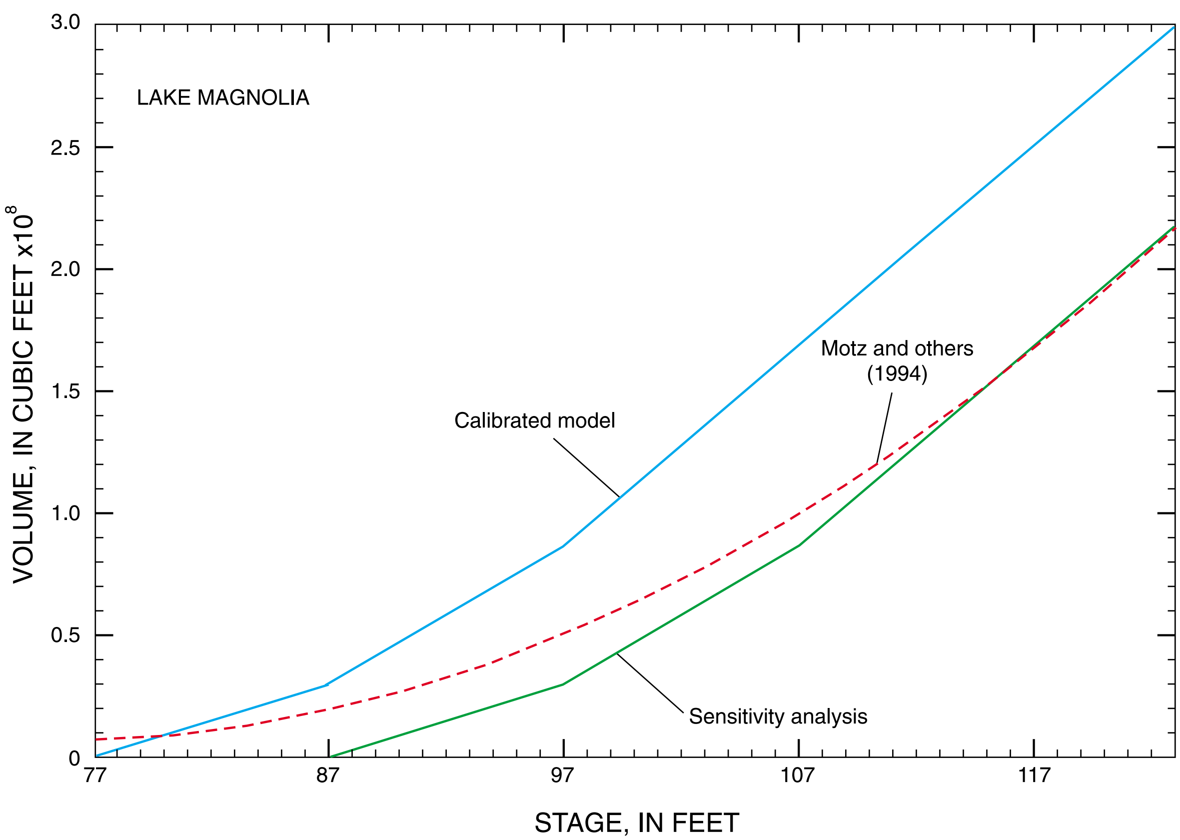



**Figure 21.** Various stage/volume relations for Lake Magnolia.

boundary value of 60 ft was assigned to each boundary cell in the Upper Floridan aquifer layer (layer 7), together with a specified conductance that represented both the transmissivity of the Upper Floridan aquifer and the 20-mi distance to the location where the head value was assumed to apply. This procedure allowed simulated heads in the Upper Floridan aquifer layer in the study area to rise under the influence of leakage from Lakes Brooklyn and Magnolia in a representative manner. Boundary-head values were assigned to the intermediate aquifer system layer (layer 6) in a similar fashion, but were assumed to be 10 ft higher than boundary-head values in the Upper Floridan aquifer, based on the record from wells located near the west shore of Lake Brooklyn (fig. 4). As transmissivity values were adjusted during calibration, the specified conductance values were recomputed.

## Aquifer Hydraulic Property Specifications

The general methods of assigning hydraulic properties to the model will be described in this section, and values used in the calibrated model will be presented. Discussion of the hydrologic significance of the value choices and the results of various sensitivity analyses will be presented in later sections.

Because layers 1-5 were surficial or convertible, parameter values needed to be specified to represent the hydraulic conductivity of the material forming the surficial aquifer system. To match heads measured in the surficial aquifer wells, the assigned hydraulic conductivity values were zoned (fig. 22); initially assigned values ranged from a minimum of 4 ft/d to a maximum of 400 ft/d. The lower part of this range of values is in general agreement with results of slug tests reported by Annable and others (1996). In the absence of any evidence of spatially extensive hydraulic layering in the surficial aquifer system, specified values were made vertically uniform in the five layers representing the surficial aquifer system in the study area. Hydraulic conductivity was considered to be horizontally isotropic everywhere (parameter TRPY = 1.0 in all grid cells).

A vertical hydraulic conductivity of 3 ft/d was assumed to be representative of the surficial aquifer system in the area. Although no data were known to be available as a basis for this assumption, the value was a conservative choice in that it was large enough to ensure that computed heads would be vertically uniform in the five layers representing the surficial aquifer system, and water leaking through the lakebed could move readily downward to the confining layer. (When a vertical hydraulic conductivity of 30 ft/d was used in a sensitivity analysis, simulated lake stages and heads in the surficial aquifer were unchanged.) Because the model code required the specification of a leakance value between layers instead of a vertical hydraulic conductivity value, the leakance between layers 2 and 3, 3 and 4, and 4 and 5 was specified to be 0.3 feet per day per foot of thickness ($d^{-1}$) (the vertical hydraulic conductivity divided by the 10-ft vertical difference between grid cell centers).

Initially, the same value was used for the leakance between layers 1 and 2, but these values were revised and distributed to represent the approximate and spatially varying difference between the center of the saturated thickness of layer 1 and the center of layer 2. This was accomplished by a cell-wise multiplication of the vertical leakance values by the assumed vertical internodal distance of 10 ft, and division by the actual internodal distances based on a previous calculation of water-table altitudes. This would need to be done iteratively if the resulting water-table altitudes changed appreciably. However, this procedure had a negligible effect on the computational results, probably because the vertical hydraulic conductivity was sufficiently high that heads were vertically uniform in layers representing the surficial aquifer system.

The leakance value assigned to all horizontal and vertical cell interfaces between the lakes and the surficial aquifer system, representing the degree of lakebed impedence, was 2.5 $d^{-1}$. This value is equivalent to a hydraulic conductivity of 2.5 ft/d over a bed thickness of 1 ft, or a hydraulic conductivity of 0.25 ft/d over a lakebed thickness of 0.1 ft. No data were available to validate this specification. The value chosen, however, was conservative in that it was large enough so that there was virtually no head separation between the lake and the aquifer, and represented the assumption that the lakebed did not provide any effective confinement affecting exchanges of water between the lake and the aquifer.

Because layer 1 was specified as unconfined (LAYCON = 1), the specification of a value for specific yield was required. Varied as a calibration parameter to match measured heads in the surficial aquifer system wells (fig. 4), the value chosen was 0.09. Such a value would be low for rocks with secondary porosity, such as solution-riddled limestone, but was accepted for purposes of this study as representative of the silty sands forming the surficial aquifer system in the study area. Surficial aquifer system layers 2-5 were specified as

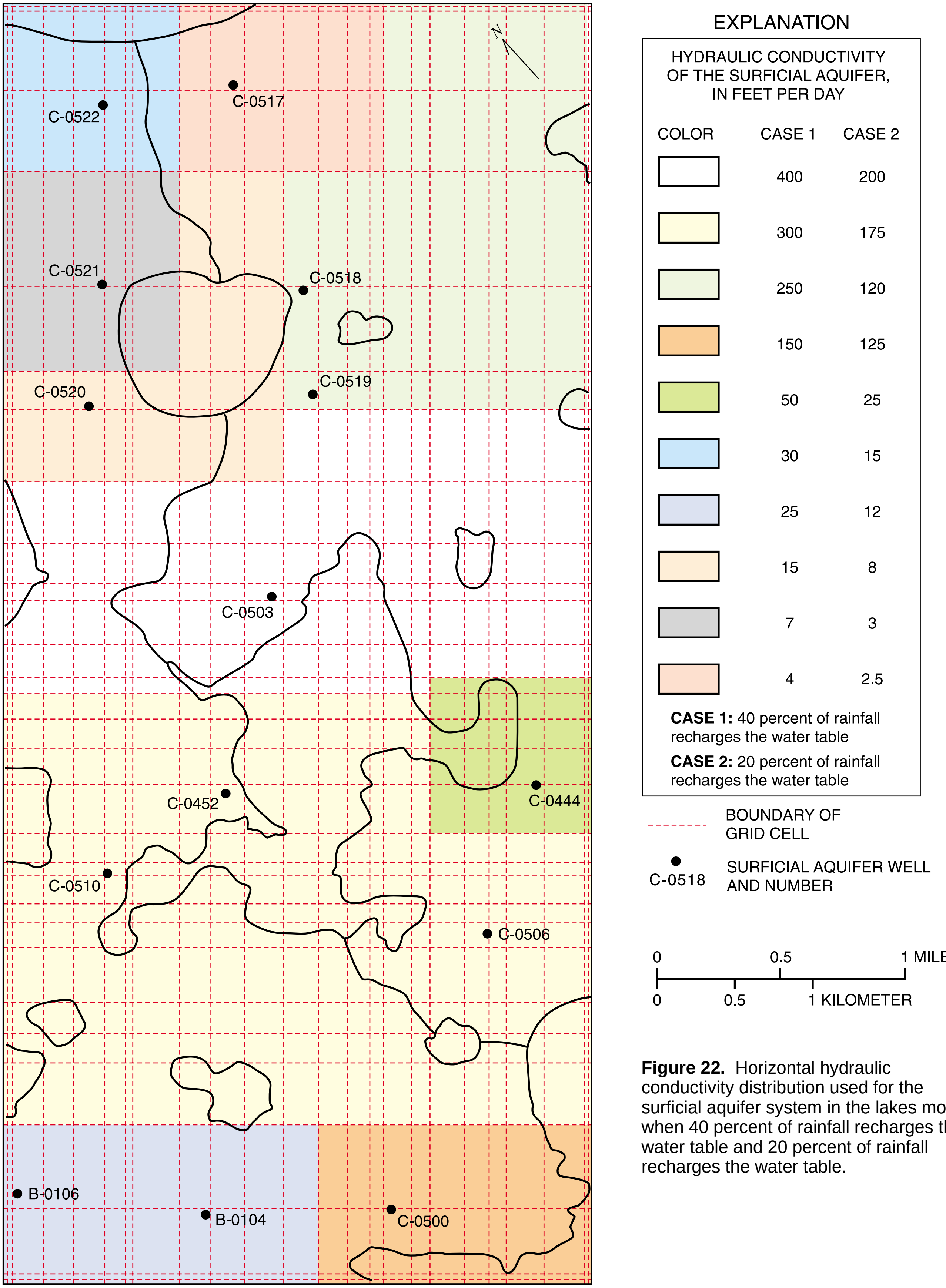



**Figure 22.** Horizontal hydraulic conductivity distribution used for the surficial aquifer system in the lakes model when 40 percent of rainfall recharges the water table and 20 percent of rainfall recharges the water table.

convertible (LAYCON = 3), so that it was necessary to specify primary and secondary storage coefficients, with the first being a confined storage coefficient (0.0003) for use when the layer is fully saturated and overlain by a partially saturated aquifer layer. The secondary coefficient (0.09) was a specific yield value for use when the layer converted to unconfined because the overlying layer was dry. Aquifer layers 6 and 7, representing the intermediate and Upper Floridan aquifers, were specified as confined (LAYCON = 0) and required the specification of a confined storage coefficient (0.0003).

Spatially uniform values of transmissivity were specified for the confined intermediate (10,000 $ft^2/d$) and Upper Floridan (100,000 $ft^2/d$) aquifers. These values of transmissivity were used in generating conductance values for use with the general head boundaries. Transmissivity was considered to be horizontally isotropic (TRPY = 1.0 in all grid cells).

Leakance through the confining layers separating the surficial and intermediate aquifers (between layers 5 and 6) and between the intermediate and Upper Floridan aquifers (layers 6 and 7) was considered to be very small except beneath the lakes by the specification of a uniformly low coefficient value ($1x10^{-6}$ $d^{-1}$) for each confining layer. Although the cited leakance value was the low end of the range of values used in the regional model developed by Tibbals (1990), a substantially higher value was used by Tibbals in the study area, reflecting the leakage that also occurs through karstic lakes in this part of the region.

To resolve questions regarding the possible effects of a higher degree of regional leakance, a sensitivity analysis, to be described later, was performed in which the areal leakance value was increased. Additional leakage may occur elsewhere besides underneath the lakes, but the problem of distributing leakage to the confined layers between lake and land areas was considered beyond the scope of this study. For purposes of this study, it was only necessary to provide a mechanism for drainage of lake water to the Upper Floridan aquifer, and the cited parameterization accomplished this purpose.

Leakance coefficients for the confining units beneath the lakes were determined by model calibration. A leakance coefficient value of 0.001 $d^{-1}$ was used beneath Lake Magnolia and a value of 0.005 $d^{-1}$ was used beneath most of the part of Lake Brooklyn specified to be at least two model layers deep (bottom altitude 97 ft or lower). Exceptions were Brooklyn Bay (sublakes 3 and 4, fig. 19) where the value used in cells where the bay was specified to be at least 3 layers deep (bottom altitude 87 ft or lower) was 0.02 $d^{-1}$, and the deepest pool (sublake 10, fig. 19), where the value used was 0.03 $d^{-1}$. Higher leakance values were used beneath Brooklyn Bay because the stage decreased even lower than the main part of Lake Brooklyn during the stage decline of 1990-94. Water levels in well C-0510 in the surficial aquifer system and near the shore of sublake 10 were also very low during this period, indicating that the unmeasured stage in sublake 10 also must have declined very low. Therefore, high leakance values beneath sublake 10 were specified in an attempt to simulate such a decline.

Without higher leakance values, the smaller pools tended to have higher stages than the large pools because of the higher perimeter-area to volume ratios. If hydraulic gradients near the lake perimeters are similar, recharge to the various lakes is proportional to their perimeter areas, and smaller lakes will, therefore, have a higher ground-water recharge to volume ratio, and will tend to increase in stage more quickly than larger lakes.

The conductance between the surficial aquifer system beneath Lake Brooklyn and the intermediate aquifer system can be calculated as the sum of leakance through the confining layer times the bottom area for all of the pools that compose Lake Brooklyn. With the cited distribution of leakance values, this conductance was 15.67 x $10^4$ $ft^2/d$. Similarly, the conductance between the surficial aquifer system beneath Lake Magnolia and the intermediate aquifer system was 0.815 x $10^4$ $ft^2/d$, so that the conductance beneath Lake Brooklyn was about 19 times greater than that beneath Lake Magnolia. In the remainder of the area within the model boundaries, where the specified leakance was 1 x $10^{-6}$ $d^{-1}$, the total conductance was 0.031 x $10^4$ $ft^2/d$. The leakances, and corresponding conductances, specified for the confining layer between the intermediate and Upper Floridan aquifers were the same as for the confining layer between the surficial and intermediate aquifers, so that the conductance between the surficial and Upper Floridan aquifers was one-half the cited values, assuming a harmonic mean relation in combining the conductances for the two confining units.

The WETDRY parameter used for rewetting grid cells in the surficial and convertible layers (layers 1-5) that become dry during a transient simulation (McDonald and others, 1991) was set equal to -0.2 ft, the absolute value of which is a threshhold for initiating the rewetting of a node. WETDRY was set equal to 0 in lake cells. The specification of a negative value indicates that “only the cell below a dry cell can cause the cell to become wet” (McDonald and others, 1991, p. 23). The scaling factor WETFCT was set equal to 1.0. Using a larger value in early model runs led to uncontrolled oscillatory behavior during drying and rewetting.

## Rainfall and Evapotranspiration Specifications

The interrelation of recharge and ET in the sandy materials composing the surficial aquifer system in the study area is complex, owing to the variable depth of the water table below land surface, the manner in which water percolates through the unsaturated zone, and the variability of atmospheric conditions. Therefore, a straightforward application of the MODFLOW Recharge and ET Packages was not appropriate for this study. The author was unable to find previously documented applications of transient ground-water models to the simulation of flow in the surficial aquifer system of east-central Florida.

Tibbals (1990, p. 10) postulated a model of ET in which the average annual ET decreased non-linearly from a maximum of about 48 in/yr in areas where the water table was near land surface to a minimum of 30 in/yr in areas where the water table was more than 15 ft below land surface. Using water-table altitude as an index is meaningful in east-central Florida because, in areas of substantial relief, the areal variation of water-table altitude is much greater than the variation at a given location during an average year, owing to the relatively low permeability of the materials composing the aquifer and the consequent poor drainage. Therefore, locations less than a mile apart can be characterized by a typical water-table altitude. Tibbals’ estimates (1990, p. 7) were based on an assumed total annual rainfall average of 52 in/yr in east-central Florida (about the same as measured in Gainesville from 1931 to 1998).

Recharge to the water table, specified as a monthly rate, was set equal to 40 percent of the monthly rainfall rate recorded at Gainesville, approximately the same as postulated by Tibbals (1990). Quantities of rainfall recorded by the SJRWMD at Lake Brooklyn were used beginning with February 1992. To account for the increased ET in areas where the water table was near land surface, maximum ET rates equal to long-term monthly average pan evaporation rates measured at Gainesville were specified. The ET Package assumes a linear decrease to a specified extinction depth, which was set at 15 ft below a specified “ET surface.” In this application, the ET surface was assumed to be the same as land-surface altitude, and values for each horizontal grid-cell location were estimated by overlaying the model grid (fig. 17) on a map of land-surface altitude contours (fig. 8).

Recharge to the surface areas of lakes was separately specified in the Lake Package to be the full amount of recorded monthly rainfall. Lake evaporation was specified as average monthly pan evaporation at Gainesville and modified by the previously cited monthly pan-to-lake coefficients of Kohler (1954).

## Representation of Alligator Creek

Because stream inflow and outflow are principal components of the water budgets of the various lakes during periods of moderate to high flow, it is important to represent the streams linking the lakes in the model and to simulate the quantities of water exchanged by the lakes and streams. Alligator Creek between Lakes Lowry and Magnolia was represented by use of the Stream Package (Prudic, 1989) as occurring in five grid cells (five reaches) in layer one, from row 3, column 8 (fig. 19) to row 5, column 10. Because this stream segment is the furthest upstream of those in the modeled area, and Lake Lowry is not explicitly represented in the model, a direct specification of inflow to this segment was necessary. The amounts specified were the flows from Lake Lowry estimated from historical stage data using the 1994-97 rating table. The altitude of the top of the streambed was assumed to decrease from 131 ft to 125 ft in the downstream direction. The volume of flow at the lower end of the stream segment became the stream inflow volume added to Lake Magnolia.

Alligator Creek between Lakes Magnolia and Brooklyn, the second stream segment, was represented as occurring in nine grid cells (nine reaches), starting from row 8, column 10, and ending in row 14, column 10. The segment was assumed not to extend into columns 6 or 7. The volume of inflow to the reach was calculated by modifications to the Stream Package that applied Manning’s equation (Chow, 1959) to the difference in altitude between lake stage and the top of the streambed. The altitude of the top of the streambed was assumed to decrease from 123 to 109 ft in the downstream direction. The outlet altitude of flows from Lake Magnolia was changed to 123.5 ft after the no-flow period of 1990-91. It was changed back to 123 ft after a computation time corresponding to the channel-clearing operation that took place in June 1994. The streamflow volume at the lower end of the reach became the inflow volume to Lake Brooklyn.

Alligator Creek below Lake Brooklyn, the third stream segment, was represented as occurring in ten grid cells (ten reaches), starting from row 23, column 13, and ending in row 26, column 22, close to the model boundary. The inflow to this segment was calculated by Manning's equation. The altitude of the top of the streambed was assumed to decrease from 115 to 110.5 ft in the downstream direction.

The first, second, and third stream segments were assigned uniform widths of 5, 9, and 25 ft, respectively. In each reach, the streambeds were assumed to be 0.5 ft thick and to have a conductance of 6,000 $ft^2/d$. Given a specified stream width of 5 ft, this conductance value is equivalent to assuming a hydraulic conductivity of the streambed of 0.4 ft/d if the reach length in a cell is 1,500 ft and of 0.8 ft/d if the reach length in a cell is 750 ft. These hydraulic conductivity values would be halved if the stream width were 10 ft. These conductance assignments had the effect of allowing the simulated stream segments to gain or lose a small percentage of their flow during transit from the upper to lower ends, as has been observed from field data.

Stream stage in each reach was calculated by the Stream Package. The first and third segments were assigned a slope of 0.001 foot per foot (ft/ft), and the second segment was assigned a slope of 0.002 ft/ft. Manning's coefficient was specified to be 0.05. These generalized specifications are based on field observations of the stream segments, where it was noted that flow in the meandering channel was obstructed by the uneven bottom, rocks, tree stumps, and vegetation, on previously cited surveys of the stream (Robison, 1992), and on the results of model calibration. It will be shown later in this report that streamflow was largely controlled by the amount of water in the originating lake and was not dependent on the specified channel characteristics.

## Calibration of the Model

The principal parameters used for curve matching in the initial calibration steps were the hydraulic conductivity and specific yield of the surficial aquifer system (primarily affecting the heads simulated in the surficial aquifer system) and the values of leakance through the confining layers between the surficial aquifer system beneath the lakes and the intermediate and Upper Floridan aquifers (primarily affecting the lake stages). The values of these parameters cited in the previous sections were determined by a series of calibration runs. Other parameter values, for river characteristics, atmospheric fluxes, and for properties of the confined aquifers, were either satisfactory or needed only slight adjustments in the initial stages of calibration.

A spatially uniform initial head distribution was specified for each layer of the model. Values used were 124 ft for layers 1-5 (surficial aquifer system), 65 ft in layer 6 (intermediate aquifer system), and 55 ft (Upper Floridan aquifer). Initial lake stages were 124 ft in Lake Magnolia and 98 ft in all the sublakes of Lake Brooklyn. The latter values were based on stage records for Lake Brooklyn in July 1957. The 1957-98 simulation time period was divided into monthly stress periods of 10 time steps each. (Each month was considered to be 30.4375 days.) Specifications for rainfall recharge, ET, and flow at the head of the first stream reach were monthly average values. Overland runoff was assumed to be zero in all months.

The simulated stages of Lake Brooklyn (fig. 23, 40 percent rainfall recharge) matched the measured stages poorly in 1957-58, reasonably well in early and

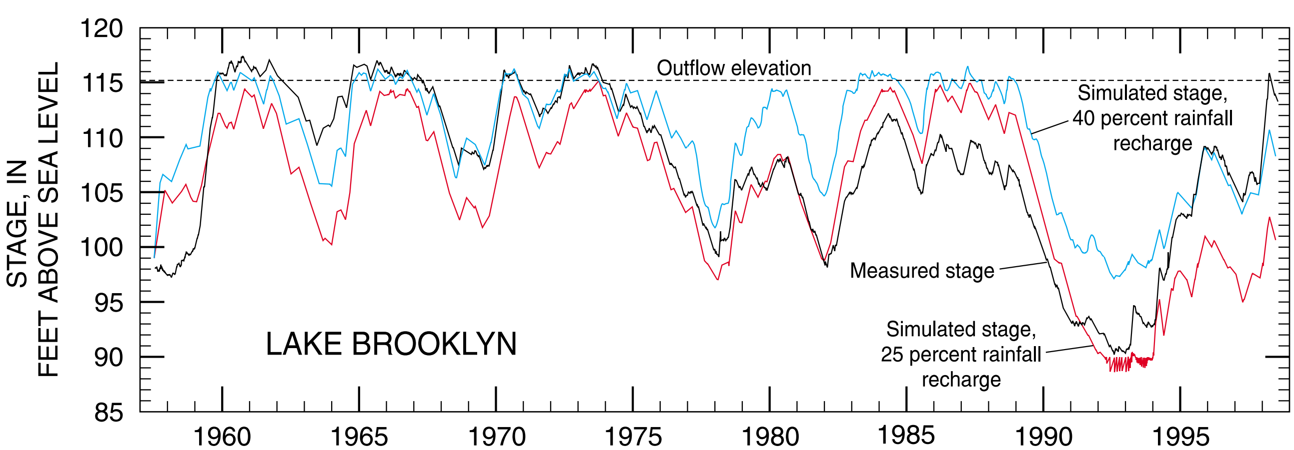



**Figure 23.** Results of pre-calibration simulations assuming 40 percent of rainfall recharges the water table and 25 percent of rainfall recharges the water table.

late time periods (1959-74 and 1994-1997), but was a clearly unsatisfactory match in the intermediate time period (1975-93). The poor match in 1957-58 was the result of using the value of 124 ft for initial head in the aquifer. Because of the lack of agreement in the 1975-93 time period, additional work was needed to obtain an acceptable simulation of the lake/aquifer system.

### Analyses of the Sensitivity of Lake Brooklyn Stage to Various Parameters

To gain an understanding of the relative importance of the various hydrologic mechanisms as components of the hydrologic system and as factors affecting the calibration of the model, and to resolve the calibration problem, sensitivity analyses were performed for various parameters, both those that were adjusted for calibration and those that were based on measurements or on the work of previous investigators. In particular, a means was needed to reduce the simulated stages for Lake Brooklyn between 1975 and 1993. The initial simulation showed lake stage to be above the outflow altitude of Lake Brooklyn during periods of high simulated inflow from Lake Magnolia between 1983 and 1988. In actuality, the lake stage remained well below the outflow altitude despite high inflows from Lake Magnolia (as noted in a previous section).

In one such sensitivity analysis (fig. 23), the amount of rainfall estimated to recharge the water table was decreased from 40 to 25 percent. Results were quite unsatisfactory, as simulated Lake Brooklyn stages remained substantially higher than measured between 1982 and 1988, while simulated stages between 1959 and 1978 were substantially lower than measured and reached the outflow altitude only once, at a simulation time corresponding to late summer 1973. The results of the analysis also demonstrated the importance of aquifer recharge, which influences lake stage by contributing to lake recharge by direct ground-water seepage and also by contributing to Alligator Creek inflow, which represents upstream basin capture of rainfall and subsequent ground-water seepage to upstream lakes with outflowing streams. In both the preliminary simulation and the sensitivity analysis, the amount of rainfall directly on the lake was specified to be 100 percent of the measured rate.

Another sensitivity analysis addressed the possibility that the monthly average land ET rates (based on Gainesville pan evaporation data) and lake evaporation rates (based on Gainesville pan evaporation data and Kohler's (1954) pan-to-lake coefficients) may not be correct. The estimated rates for both land and lake were uniformly increased and decreased by 25 percent. Results (fig. 24) showed that the specified rates were important only when the Lake Brooklyn stage was below the outlet altitude. Differences between the simulated stages in the various runs became greater as the simulated stage decreased from a previous stage that was above the outlet altitude. The result offered little help in resolving the calibration problem, as simulated 1983-88 stages remained mostly above the outlet altitude.

Additional sensitivity analyses were run to evaluate the importance of the hydraulic conductivity and specific yield of the surficial aquifer system in determining the stage of Lake Brooklyn. In one analysis, hydraulic conductivity estimates (fig. 22) were increased and decreased by 50 percent. In another analysis, the specific yield estimate of 9 percent was increased to 13.5 percent and decreased to 6 percent. In the two analyses (results not illustrated), Lake Brooklyn stages were affected only when the stages

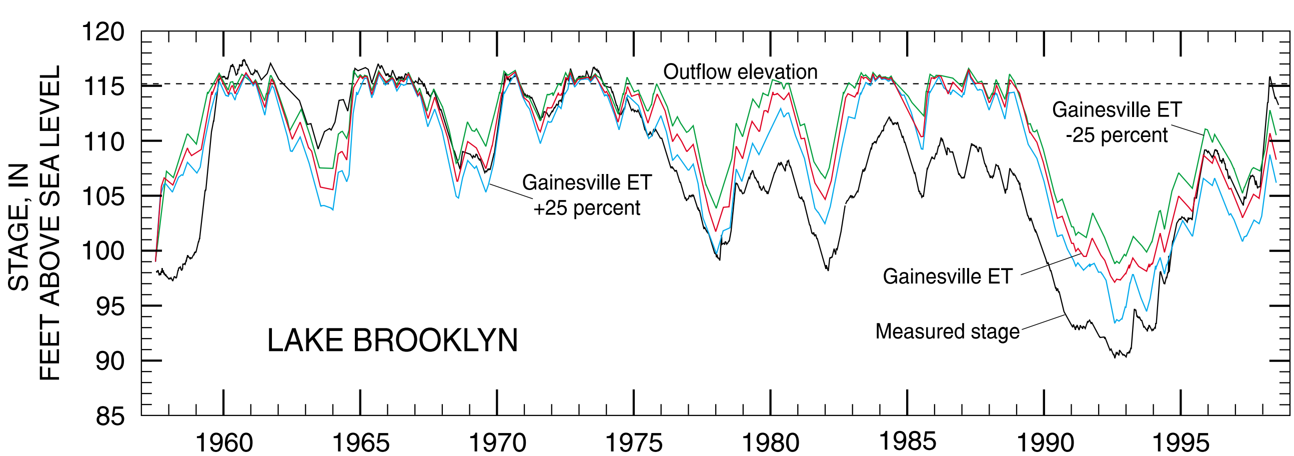



**Figure 24.** Results of pre-calibration simulations in which land evapotranspiration (ET) and lake evaporation are increased and decreased by 25 percent.

were low. The simulated stages for late 1992 varied by as much as 2 or 3 ft, whereas stages at about 110 ft varied by less than 1 ft. Stages at about the outflow altitude varied little. Results indicated that the simulated variations in the two parameters can have an appreciable cumulative effect after a long period of decreasing stage, but otherwise did not appreciably affect the stage of Lake Brooklyn, even though the rate of ground-water seepage to and from the lake is determined by the hydraulic conductivity of the material of the surrounding surficial aquifer system.

The result of these analyses is probably explained by the tendency of lake stage and aquifer heads to maintain an approximate equilibrium balance that is disturbed only when one or the other changes rapidly in response to imposed stress. This principal is illustrated by the simulated 1957-66 hydrographs for Lake Brooklyn and surficial-aquifer well C-0452 (fig. 25). In this test run, the uniform initial head in the aquifer was 124 ft and the initial stage of Lake Brooklyn was 98 ft. During the initial 6 months of the simulation, the head at the location of well C-0452, close to Lake Brooklyn (fig. 4), dropped rapidly as the lake stage increased rapidly. For the subsequent 9.5 years, the simulated head difference did not exceed 4 ft. The simulated head at the well always equaled or exceeded the lake stage, indicating that seepage from the aquifer to the lake was the usual situation during this period. The head difference, and consequent rate of seepage, tended to increase during periods when the lake stage was low and when the water table increased rapidly in response to high rates of rainfall.

Hydraulic conductivity variations of much greater magnitude than those specified in the sensitivity analyses would probably have had a more substantial effect on lake stages in the lower ranges. Results of the analyses also showed that varying these parameters would not resolve the calibration problem. The sensitivity of simulated heads in the surficial aquifer system to these parameter specifications are described later.

In another sensitivity analysis, leakance values for the confining layers between the surficial and the intermediate aquifer systems and between the intermediate and Upper Floridan aquifers were increased and decreased by 25 percent from the previously cited values, and also quadrupled (fig. 26). As in the previously described analyses, when 25 percent variations are specified, variations in lake stage are appreciable (as much as 3 ft) in the lower ranges of lake stage, but negligibly small when the lake is at or above the outflow altitude. When the Lake Brooklyn leakance of 0.005 $d^{-1}$ is quadrupled, however, the entire simulated record of lake stage is substantially affected. The resulting hydrograph of simulated lake stage matches the lake stage measured between 1982 and 1989; however, measured and simulated stages do not match in any other time period. The simulated stage remains at least 3 ft below the outflow altitude throughout the entire simulation period, and the low lake stages of 1990-94 are substantially underestimated. As with previously described analyses, results do not resolve the simulation problem.

Additional sensitivity analyses were performed to assess the response of lake stage to possible errors in the specification of the head in the Upper Floridan aquifer at a 20-mi distance or in the specification of the transmissivity of the Upper Floridan aquifer. In the first set of analyses (fig. 27), the boundary-head value was increased to 75 ft and decreased to 45 ft. Although substantial differences in the stage of Lake Brooklyn are

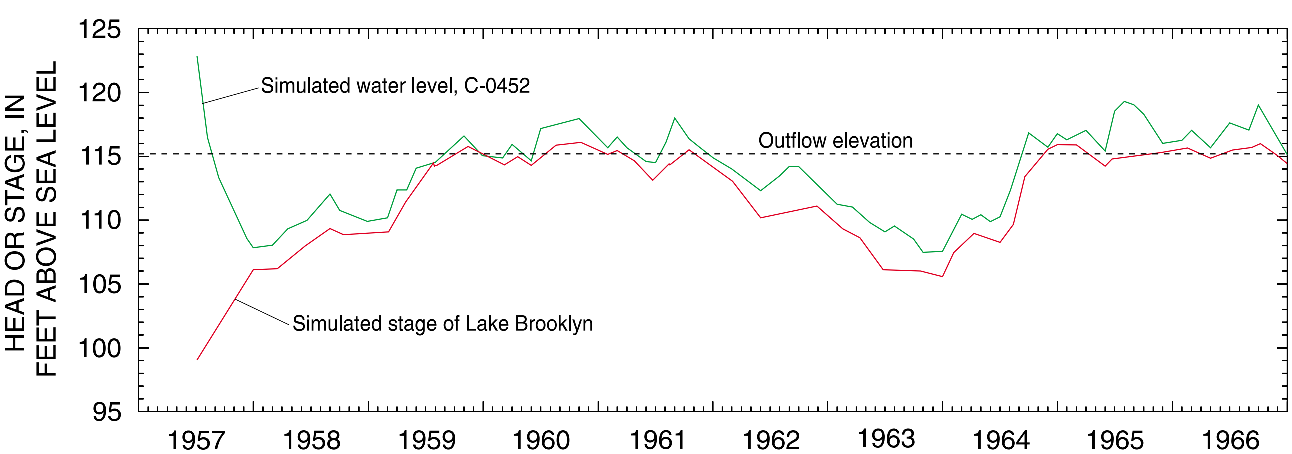



**Figure 25.** Simulated stage in Lake Brooklyn and simulated water-table altitude at the location of surficial aquifer well C-0452.

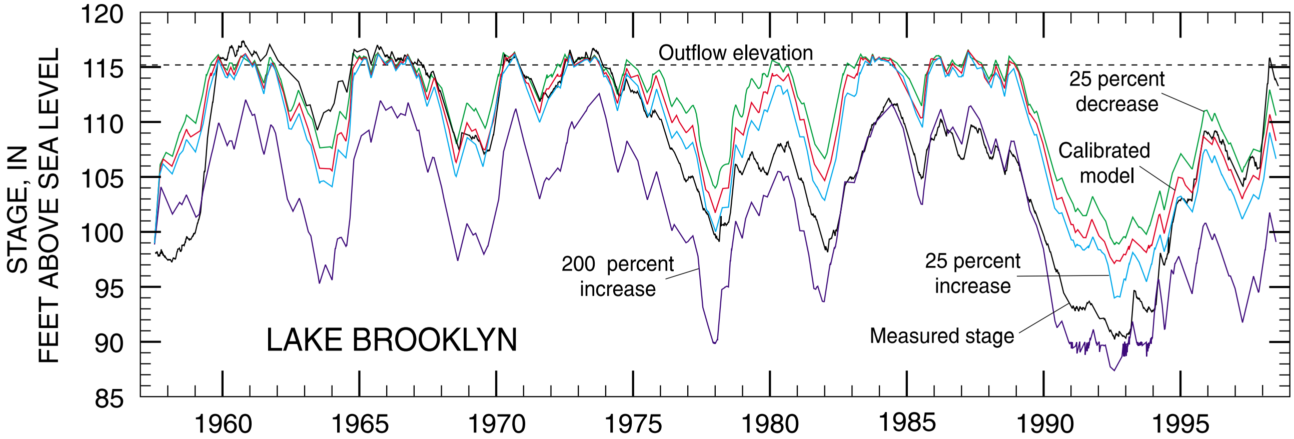



**Figure 26.** Results of pre-calibration simulations in which leakance through the confining layers is increased by 25 percent, decreased by 25 percent, and quadrupled.

computed, the calibration problem is not resolved; when simulated stage in the 1983-89 time period is lowered almost enough to match measured stage, the simulated stage is too low in other time periods. In the second set of analyses, the transmissivity of the Upper Floridan aquifer was increased to 125,000 $ft^2$/d and decreased to 75,000 $ft^2$/d. The conductance factors for the general head boundaries at the 20-mi distance were also modified. Results and their interpretation are qualitatively similar to those of the leakance analysis, and therefore, are not illustrated. Sensitivity analyses for leakance, the value of boundary head in the Upper Floridan aquifer, and the transmissivity of the Upper Floridan aquifer should have the same qualitative result and interpretation, because these parameters all govern the same process, the rate of leakage of water from the lake to, and dispersal within, the Upper Floridan aquifer.

Sensitivity analyses were also performed for parameters affecting flow in the simulated stream segments representing Alligator Creek. Although some results were of interest, there was virtually no effect on the simulated stage of Lake Brooklyn, and discussion of these results is deferred to a later section.

### Water-Budget Considerations

To gain a better understanding of the problem in calibrating the model during the 1983-89 time period, simulated Lake Brooklyn water-budget data for the same time period were examined. An example is the water-budget data, expressed as volumes, for the last time step of the monthly stress period corresponding to the month of November 1985 (fig. 28). At that time, the measured stage of Lake Brooklyn was about 108.5 ft, but the corresponding simulated stage was 0.8 ft above the outlet altitude of 115 ft specified in the model. All

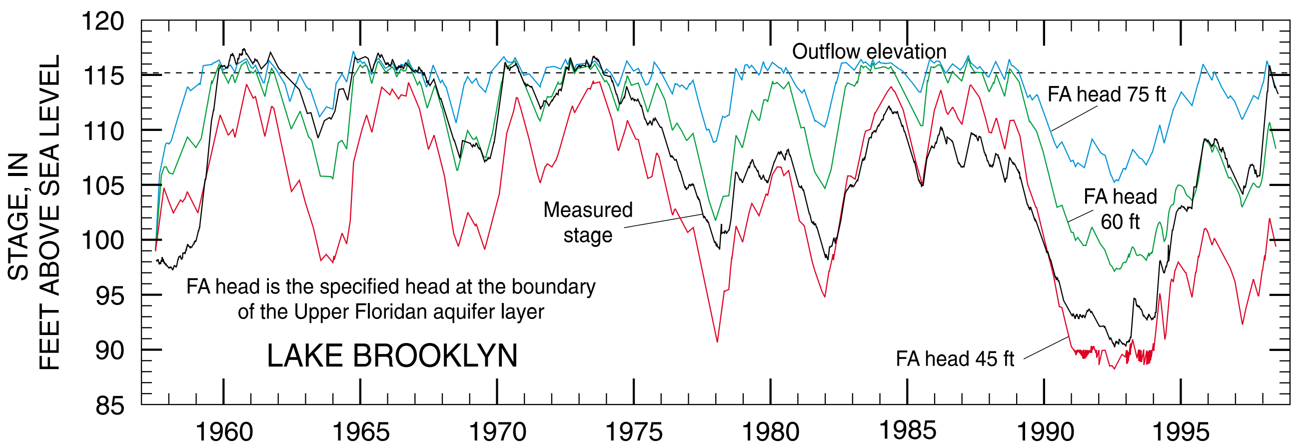
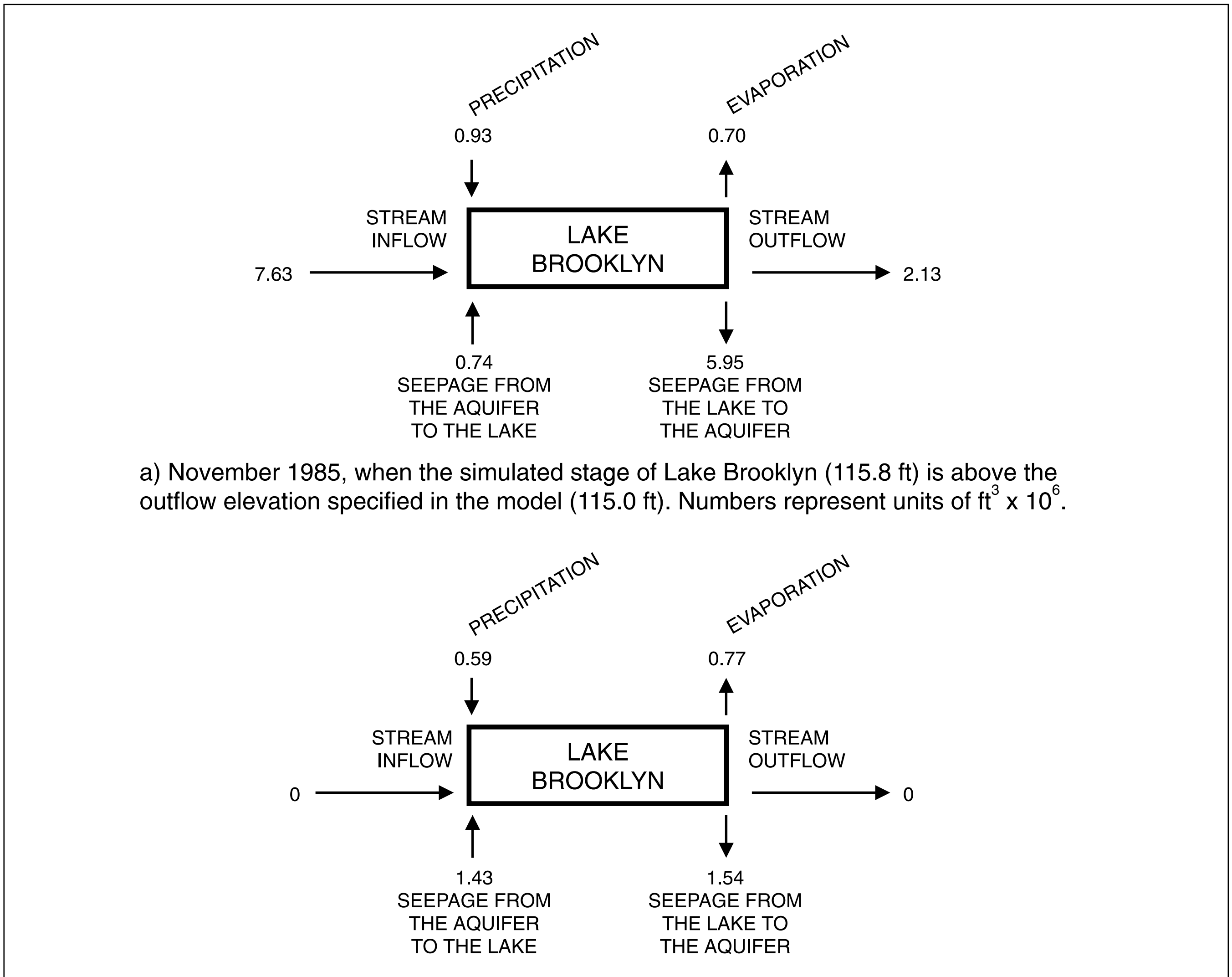



**Figure 27.** Results of pre-calibration simulations in which the specified boundary head at a 20-mile distance in the Upper Floridan aquifer was increased to 75 feet and decreased to 45 feet.




a) November 1985, when the simulated stage of Lake Brooklyn (115.8 ft) is above the outflow elevation specified in the model (115.0 ft). Numbers represent units of $ft^3 \times 10^6$.

b) October 1992, when the simulated stage of Lake Brooklyn (97.3 ft) is below the outflow elevation specified in the model (115.0 ft). Numbers represent units of $ft^3 \times 10^6$.

**Figure 28.** Simulated hydrologic budgets for Lake Brooklyn for times when the simulated stage is above and below the specified outflow elevation (115 ft).

sublakes of Lake Brooklyn are connected at this simulated altitude. The total precipitation and evaporation volumes for Lake Brooklyn simulated by the model for this time step were $0.93 \times 10^6$ and $0.70 \times 10^6$ $ft^3$, respectively, for a net positive recharge of $0.23 \times 10^6$ $ft^3$, and zero runoff was assumed. Seepage from the aquifer to the lake and seepage from the lake to the aquifer were computed to be $0.74 \times 10^6$ and $5.95 \times 10^6$ $ft^3$, respectively, for a net seepage of $5.21 \times 10^6$ $ft^3$ from the lake into the aquifer. Surface-water inflow and outflow were $7.63 \times 10^6$ and $2.13 \times 10^6$ $ft^3$, respectively, for a net simulated surface-water inflow of $5.50 \times 10^6$ $ft^3$. The difference between all inflows and all outflows, about $0.52 \times 10^6$ $ft^3$, was manifest in a stage increase of about 0.018 ft for the time step. The simulated streamflow rate into Lake Brooklyn was 28.7 $ft^3$/s and the simulated stream outflow rate was 8.11 $ft^3$/s.

Evidently, the dominant terms in the water budget are surface-water inflow (largest), ground-water outflow (second largest), and surface-water outflow (third largest). Compared to these quantities, the precipitation and evaporation volumes are of secondary importance. The conceptual scenario is that Lake Brooklyn is recharged by a high rate of inflow from Alligator Creek. Most of this inflow is going to ground-water recharge (of which, the dominant part is leakage to the confined aquifers) and most of the remainder leaves Lake Brooklyn as outflow to the segment of Alligator Creek below Lake Brooklyn. A relatively small quantity remains in the lake as an increase in storage, increasing the stage.

In October 1992, Lake Brooklyn consisted of four connected pools (sublakes 2, 6, 7, and 9). Other outlying pools were unconnected to the four main pools. By contrast with the lake water budget for November 1985, the lake water budget in October 1992 (fig. 28), when the simulated stage was about 97.3 ft, was determined by only four of the previous terms, because stream inflow and outflow had ceased. The combined precipitation and evaporation volumes computed for the four main pools were $0.59 \times 10^6$ and $0.77 \times 10^6$ $ft^3$, respectively, for a net loss of $0.18 \times 10^6$ $ft^3$. Seepage from the aquifer to the lake and seepage from the lake to the aquifer were computed to be $1.43 \times 10^6$ and $1.54 \times 10^6$ $ft^3$, respectively, for a net seepage of $0.11 \times 10^6$ $ft^3$ into the aquifer. The difference between inflows and outflows, about $0.29 \times 10^6$ $ft^3$, was manifest in a stage decrease of about 0.016 ft for the four connected pools during the time step.

In this time period, the four terms in the lake water budget for the four pools are approximately of the same order of magnitude, so appreciable changes in any one of them will have an appreciable effect on the stage. This explains why the sensitivity analyses for rainfall and evaporation rates showed a substantial effect on lake stage when the latter was low.

Calibration of the model in the 1975-93 time period cannot be accomplished by manipulating the relatively small values of precipitation and evaporation from the lake, which are not an important part of the water budget when stream inflows are high, as in November 1985. If the possibility of a natural or anthropogenic loss or withdrawal from the stream or lake is excluded, then one of three volume fluxes would require modification: stream inflow, leakage to the confined aquifers, or stream outflow. The latter is unavailable as a calibration parameter, however, because no actual stream outflow occurred during the 1983-89 time period.

Of the remaining possibilities, the first that will be considered is that of possible changes in the specified leakage rates. In one of the sensitivity analyses, the leakage rate was increased until the lake stage matched the recorded measurements for the time period (fig. 26), but this result was accompanied by an unacceptable lowering of the stage of Lake Brooklyn during other time periods. Robison (1992, p. 12, fig. 6) resolved a similar calibration problem with another water-budget model by assuming that the leakage rate from Lake Brooklyn increased by a factor of 3 when the stage increased from 101 to 102 ft. The leakage rate was assumed to have a gradual, linear rate of increase with lake stage in other stage ranges. This scenario, however, is reasonable only if discrete entry points to conduits penetrating the confining layers are underwater at 102 ft but exposed to air at 101 ft. This scenario is contrary to the conceptual description of the leakage process described earlier in this report, and no data is known to support this scenario.

One hypothesis that could resolve the calibration problem is that a temporary increase in the rate of leakage to the confined aquifers occurred as a result of naturally occurring subsurface geologic or geochemical processes. It was previously noted that a sinkhole developed near the southwestern shore of the Lake Brooklyn in December 1985. Possibly, additional conduits for the movement of water from the lake to the confined aquifers formed on or before this date, but gradually became blocked during the two succeeding decades, effectively restoring the overall rate of leakage from Lake Brooklyn to its previous rate. Given presently available data, it is not possible to confirm or refute this hypothesis.

Another hypothesis deserving consideration is that a temporary increase in the rate of leakage occurred as a result of heavy pumpage of the Upper Floridan aquifer and the consequent drawdown of the aquifer in the vicinity of Lake Brooklyn. Pumping from the Upper Floridan aquifer is known to have occurred at the previously cited sand mines located north, east, and southeast of Lake Brooklyn. The magnitude of pumping, however, was relatively small, and an analysis by Motz and others (1995) apparently disposed of the possibility that sand-mining pumping had any appreciable effect on the potentiometric surface of the Upper Floridan aquifer. Other undocumented pumping on a small scale likely occurred (the wells used by the nursery on Alligator Creek are an example), because small-diameter wells tapping the Upper Floridan aquifer did not require a permit from state agencies. The lack of a large population or any substantial industrial presence in the area other than the sand mines indicates that local pumping was not a cause of the gradual decline in the potentiometric surface of the Upper Floridan aquifer. (Most domestic self-supply wells used by residences in the area tapped the intermediate aquifer system.) Causes of this decline are discussed in a later section of this report.

A third hypothesis that could explain the low lake stages of 1975-93 compared to the higher simulated stages assumes that estimated values of streamflow to Lake Brooklyn are too high. Unrealistically high outflow rates from Lake Lowry may have been computed using the 1994-97 rating curve if the outflow altitude had been higher during the earlier time period. Computed outflow rates from Lake Magnolia would also be too high. The long-term stage data from Lakes Lowry and Magnolia (fig. 2), however, do not appear to show abrupt discontinuities or changes in long-term trends in stage that would support this possibility. This hypothesis would require that lower outflow rates from Lake Lowry coincide with simultaneous, undocumented changes in outflow elevations of both Lake Lowry and Lake Magnolia at two separate times, near the beginning and end of the 1975-93 time period. This hypothesis of inaccurate streamflow estimates is also refuted by other results of the model calibration, which are discussed later.

The possibility of model error must also be acknowledged, although appropriate care was used in developing the model, and some possible sources of error were analyzed by the application of sensitivity-analysis techniques. Other possible sources of error include limited data describing lake bathymetry and the related stage/volume relation, a lack of data describing the possible variation of lake evaporation with lake stage, and a lack of data describing the distribution of confining-layer leakage beneath the lakes and beneath land areas away from the lakes.

### Undocumented Losses of Surface Water

Another hypothesis that could explain the low lake stages of 1975-93 assumes that undocumented losses of water occurred either from Alligator Creek upstream from Lake Brooklyn or from the lake itself. For simulation purposes, it was assumed that losses of water from Alligator Creek upstream from Lake Brooklyn or from the lake occurred between 1973 and 1989 at times when there was sufficient streamflow. The hypothetical losses were specified in the Lake Package input, without loss of generality, as artificial withdrawals from the lake. After a series of runs in which the amounts were adjusted, the time-varying schedule of specified withdrawals shown in figure 29 was postulated. The withdrawals were large and generally increased with time, ranging from 2.5 $ft^3/s$ from 1973 through 1978 to a high of 12.5 $ft^3/s$ in 1985-86. The calibrated withdrawal rate varied from 7.5 to 10 $ft^3/s$ between 1975 and 1984 and between 1986 and 1989, after which no more withdrawals were specified. The withdrawals were not allowed to exceed the amount of streamflow, and were of zero magnitude when streamflow ceased during dry periods. The highest hypothetical withdrawal rates used to calibrate the model occurred just after dry periods of low flow and no simulated withdrawals.

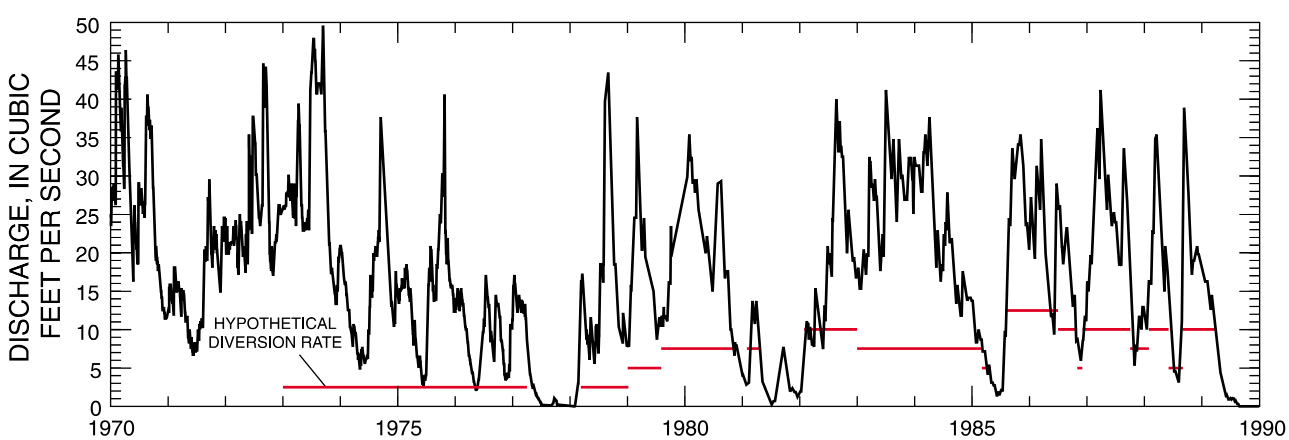



**Figure 29.** Estimated discharge from Lake Magnolia and the hypothetical diversion rates assumed for model calibration.

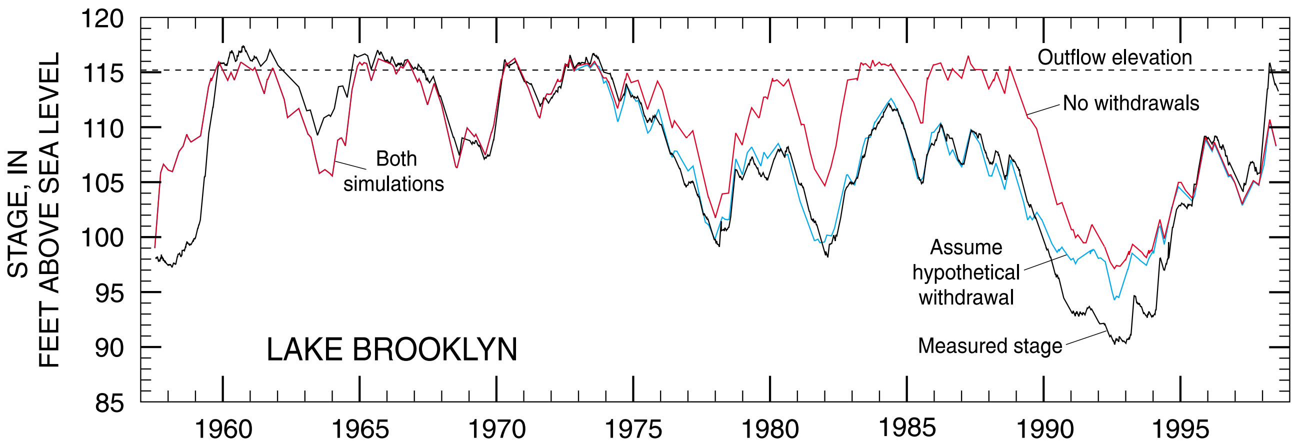



**Figure 30.** Measured stage in Lake Brooklyn and stages simulated by model when it is assumed that there are no withdrawals and withdrawals of time-varying magnitude occurring when sufficient streamflow was available from Alligator Creek between Lakes Magnolia and Brooklyn.

The resulting simulation of lake stages (fig. 30) matches the measured lake stages quite accurately, except for the 1957-58 period and the dry period from 1990 to 1994, during which the simulated lake stage exceeded the measured stage by about 5 ft. The rapid rise of the stage of Lake Brooklyn during the wet El Niño winter of 1997-98 is also not simulated, possibly because of unrepresentative rainfall data. The measured rainfall amounts at Lake Brooklyn for December 1997 and February 1998 (6.70 and 10.42 in., respectively) were well below amounts measured at Gainesville (10.20 and 13.48 in., respectively) and at other sites in the northern and central parts of the state, and may not have been representative of true rainfall amounts. The possibility also exists that appreciable quantities of overland runoff, assumed to be negligible, occurred during this high rainfall period and during an earlier high rainfall period in late summer 1995.

There are several possible explanations that would account for a substantial loss of water from either the river or the lake, none of which is supported by documentary evidence. Possible explanations, both naturally occurring phenomena, as well as human activities include: (1) leakage to the confined aquifers may have increased temporarily as a result of naturally occurring geologic or geochemical processes (discussed previously); (2) water may have been diverted intentionally by local homeowners or businesses or other local entities; or (3) a temporary impoundment may have greatly increased the rate of evaporation or leakage through the streambed.

Motz and others (1994, p. 142) calibrated a water-budget model for each of the lakes in the chain for the 1965-91 time period by adjusting “the percentage of surface-water inflow that reached each lake as discharge from the upstream lake.” Losses were attributed to leakage to the surficial aquifer system and to evaporation from the stream channel. The loss between Lakes Lowry and Magnolia was estimated to be 8 percent, and the loss between Lakes Magnolia and Brooklyn was estimated to be 35 percent. Assuming a loss of the latter magnitude in flow between Lakes Magnolia and Brooklyn is not feasible, however, in the context of the present analysis because: (1) the apparent loss is not consistent over the entire period of record, but appears to occur only between 1973 and 1989; and (2) streamflow data now available for the upper and lower ends of the stream segment joining the two lakes (fig. 9) shows that, given the conditions that existed between 1994 and 1997, the loss of streamflow rarely exceeded 2 $ft^3/s$, even when streamflows were as high as 40 $ft^3/s$.

Human utilization of the water resources of Alligator Creek or Lakes Magnolia and Brooklyn has not been restricted, regulated, or reported until relatively recently. One previously cited anthropogenic diversion described by local residents is reported to have occurred in the mid and late 1950’s, and possibly later, when water from Alligator Creek was used to irrigate a citrus grove while the trees were young and becoming established. Although previous owners of the nursery on Alligator Creek may have used overhead irrigation with water obtained from the creek, it seems unlikely that consumption was as great as the 2.5-12.5 $ft^3/s$ needed to calibrate the model.

In the past, some Lake Brooklyn homeowners pumped water directly from the lake for lawn irrigation (P. Baumgardner, former President of the Lake Brooklyn Civic Association, oral commun., 1998), a practice now discouraged by water managers. The number of homeowners consuming lake water for this purpose, and the volume of water consumed, are unknown, but would have increased during the 1970's and later as the lakefront population increased. L. C. Murray (USGS, written commun., 1999) estimates that a single household irrigating 2 acres at a rate of 30 inches per year (in/yr) would use water at a constant average rate of 0.0069 $ft^3/s$. At this rate, 362 households would use a total of 2.5 $ft^3/s$. James Hayhurst (President of the Lake Brooklyn Civic Association, oral commun., 1998) believes that, at present (1999), there may be as many as 500 homes surrounding Lake Brooklyn. Assuming an average domestic supply use of 450 gallons per day per household (L. C. Murray, USGS, written commun., 1999), the number of households using a cumulative average of 2.5 $ft^3/s$ would be nearly 10 times the number cited above. Though not impossible, it seems unlikely that the water losses could be explained by local irrigation withdrawals or by domestic self-supply by homeowners.

The assumption that water losses of the cited magnitude occurred allows the water budget inherent in the simulation to be balanced. However, as previously noted, documented evidence pointing to a specific cause, whether natural or anthropogenic, is lacking, and, if water losses did occur as hypothesized, this study could not identify the cause. The comparison between stages simulated when no withdrawals are specified and the measured stage (fig. 30) suggests that, if surface-water losses did not occur as postulated, the low stages in Lake Brooklyn from 1978 through 1988 would not have occurred, the lake would likely have maintained a stage above its outlet altitude for much of this period, and flow to Lake Geneva would have continued through 1988. The low stages of 1989-94 would still have occurred, but would have been less severe in the initial part of this period.

### Uncertainties in Rainfall Recharge Rate

The depth to the water table in the study area (fig. 8) may be as much as 70 ft below land surface. There have been few, if any, previous transient models of water-table altitude in the surficial aquifer system of central and northern Florida, and little is known about the mechanisms or quantities of recharge to deep water tables in the low-permeability materials of the surficial aquifer system. Therefore, model parameter specifications based on the estimates of minimum annual ET from deep water tables (30 inches) cited by Tibbals (1990, p. 10) should be regarded as tentative.

The previously described calibrated model, incorporating the assumption that 40 percent of precipitation recharged the water table (fig. 30), was revised to incorporate a new assumption that only 20 percent of precipitation recharged the water table. Recalibration of the model required that estimated hydraulic conductivities in the surficial aquifer system be reduced by approximately 50 percent (fig. 22), and that leakance values for the confining units under the deeper parts of the lakes also be reduced by nearly 50 percent. Leakances specified beneath Lake Brooklyn were 0.0026 $d^{-1}$ for the main part of the lake, 0.005 $d^{-1}$ for Brooklyn Bay, and 0.02 $d^{-1}$ for sublake 10. The leakance specified beneath Lake Magnolia was 0.00054 $d^{-1}$. The leakance used in other parts of the modeled area away from the lakes was unchanged ($1.0 \times 10^{-6}$ $d^{-1}$). With the revised leakance values, the conductance of the confining layer beneath Lake Brooklyn became $7.88 \times 10^4$ $ft^2/d$, and the conductance of the confining layer beneath Lake Magnolia became $0.44 \times 10^4$ $ft^2/d$. The specific yield of the surficial aquifer system was also revised downward to 7 percent. Assumed 1973-89 water-loss quantities (fig. 29) remained the same.

The stages simulated with the new parameter assumptions (fig. 31) are an excellent match of the measured values, and can be considered a second calibrated model. The steep stage decline during 1990-94 is closely matched by the simulated stages. As before, the 1957-58 data still are not matched, and the rapid rises in lake stage in 1995 and 1997-98 are not quite matched. Nevertheless, the simulation is the most satisfactorily achieved during this study, and tends to lend credence to the lower value used as an estimate of the amount of rainfall that recharges the water table in the study area.

### Sublake Connection in Lake Brooklyn

Initially, the four main pools of Lake Brooklyn (sublakes 2, 6, 7, and 9) were assigned separate sill altitudes with one another based on bathymetry, as described earlier in this report. However, this procedure led to exaggerated oscillations in the stage of sublake 2, which receives inflows from Lake Magnolia, as it fills up before overflowing into the other sublakes at various stages. The stages measured in sublake 2, however, varied less with time than the simulated stage, and seemed to represent a common stage of at least the four main pools. Therefore, it was hypothesized that these four pools may not have been hydraulically isolated by the intervening sandbars or that shallow ditches dug by local homeowners could have kept the pools connected. Therefore, a common sill altitude of 90 ft was assigned to the three sublakes (sublakes 6, 7, and 9) of the center lake (sublake 2).

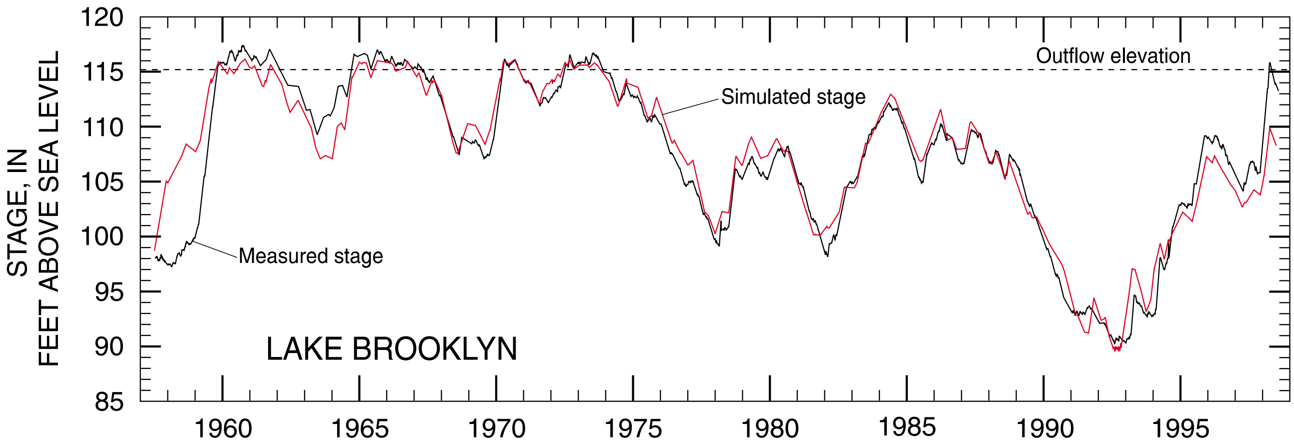



**Figure 31.** Measured and simulated stages in Lake Brooklyn when it is assumed that 20 percent of rainfall recharges the water table and a diversion rate is specified that does not exceed the rate of flow in Alligator Creek.

Simulated stages for Brooklyn Bay (sublakes 3 and 4) were lower than those of the main pools (sublakes 2, 6, 7, and 9) during the latter part of the stage decline of 1990-94, as was true of measured stages for the lake and the bay (fig. 32). To represent the continued stage decline of Brooklyn Bay as the main part of Lake Brooklyn filled, a large leakance (0.005 $d^{-1}$) under Brooklyn Bay was specified, as was a relatively low value (25 ft/d) for the hydraulic conductivity of the surficial aquifer system (to reduce ground-water seepage into the bay). With these values, the simulated stage of Brooklyn Bay (fig. 32) began to approximate the measured stage. The simulated stage, however, is lower than the measured stage from May 1991 through July 1993 and higher than the measured stage during the early part of 1994. Both simulated and measured stages abruptly become equal to the stage of the main part of Lake Brooklyn at the specified sill altitude of 100 ft. In reality, at the end of July 1994, the rapidly rising waters of Lake Brooklyn broke through the sandbar beneath the Highway 21 bridge separating the main part of the lake from Brooklyn Bay, filling the bay to the stage of the lake in less than a day, and lowering the stage of the main part of the lake by more than a foot. The process also permanently eroded the sandbar and lowered the bathymetric sill altitude above which the lake and the bay coalesce into one pool.

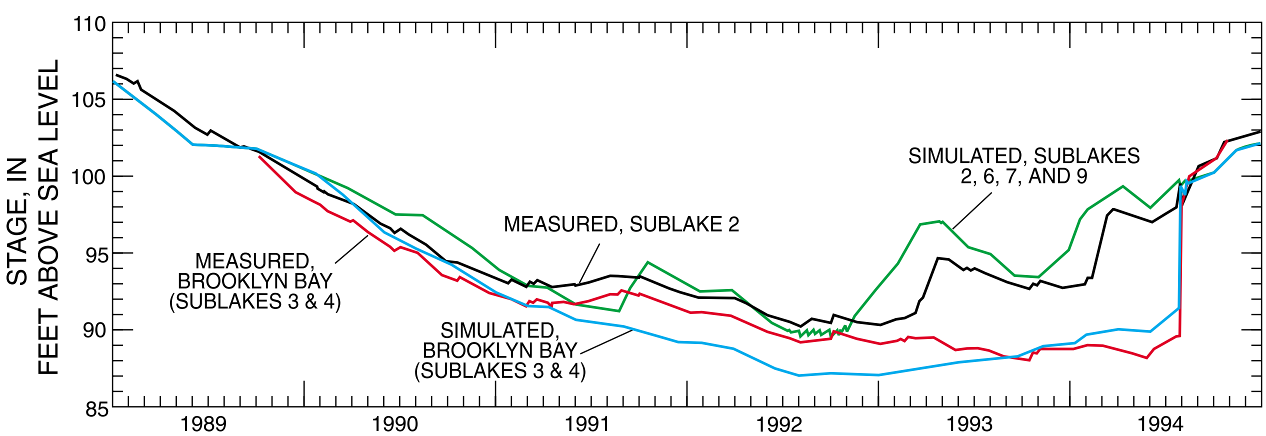



**Figure 32.** Measured and simulated stages of the main part of Lake Brooklyn (sublakes 2, 6, 7, and 9) and in Brooklyn Bay (sublakes 3 and 4) during the severe stage decline of 1990-94.

### Simulating the Stage of Lake Magnolia

The stage of Lake Magnolia was simulated quite accurately (fig. 33), assuming an outflow altitude of 123 ft, a leakance through the confining layers under the lake of 0.00054 $d^{-1}$, and values for stream channel parameters that have been previously cited. Surface-water loss rates (fig. 29) were specified, and the percent of rainfall recharge reaching the water table was 20 percent. The outflow altitude was specified to be 123.5 ft from June 1991 to June 1994. This is based on obtaining a more precise fit of the stage of Lake Magnolia after the period of no flow in the stream in 1990-91. It is hypothesized that unknown changes occurring in the channel during the dry period might have caused an increase in the effective outflow elevation. The part of the channel above Treat Road was cleaned and cleared in June-July 1994.

Without the leakance specification cited above, the 7-ft stage decline measured in early 1991 could not have been simulated. When the areal leakance value of $10^{-6}$ $d^{-1}$ was specified under Lake Magnolia, the minimum stage was 122.8 ft, only slightly below the outlet altitude. The simulated discharge from Lake Magnolia (fig. 34) was usually similar in magnitude to the estimated flow from Lake Lowry, although the simulated flow rate was commonly 1 to 5 $ft^3/s$ less than Lake Lowry outflow at peaks and lows of the estimated and simulated flow rates. The function of Lake Magnolia as a flow-through lake, or as a reservoir for temporary storage in the stream system, is highlighted by this result. The specified leakance of the streambed was

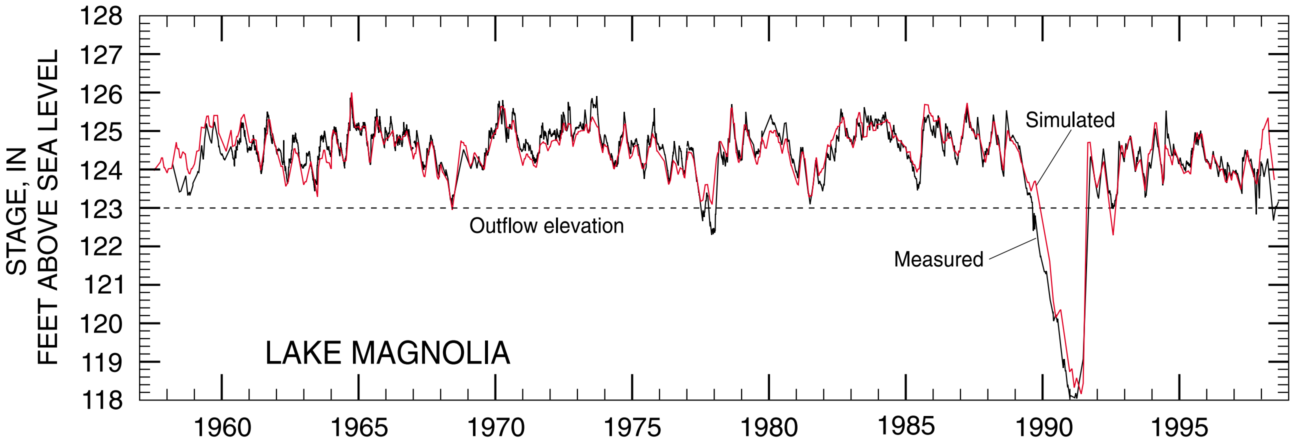



**Figure 33.** Measured stage of Lake Magnolia and the stage simulated when it is assumed that 20 percent of rainfall recharges the water table.

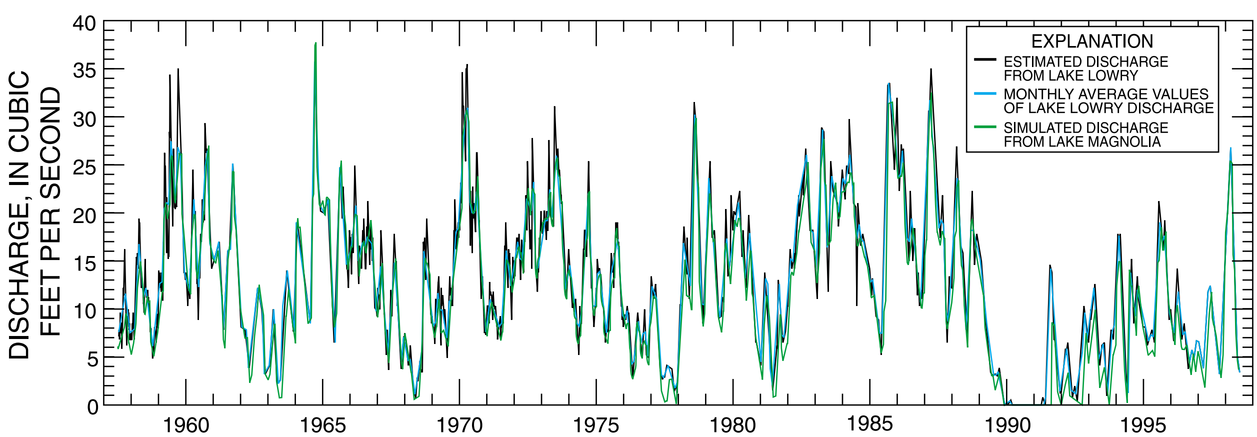



**Figure 34.** Discharge from Lake Lowry estimated from lake stage and the 1994-97 rating table, monthly discharge estimates used in the model, and simulated discharges from Lake Magnolia.

sufficient to allow small losses or gains of flow in the stream segments upstream and downstream from Lake Magnolia. Typically, the stream segment between Lakes Lowry and Magnolia was simulated as gaining from 0.8 to 1.1 $ft^3/s$, while the stream segment between Lakes Magnolia and Brooklyn was simulated as losing from 0.5 to 0.8 $ft^3/s$.

The simulation of the stage of Lake Magnolia breaks down after November 1997. At this time, the upper part of the stream channel below Lake Magnolia was improved, lowering the outlet altitude a foot or more, which is clearly indicated by the computation of a lake stage higher than measured after this date. No attempt was made to compensate for the change in the model calibration.

The relation of lake stage to the specification of outlet altitude and to other parameters describing characteristics of the downstream channel was considered in three sensitivity analyses. Lake Magnolia was a better choice than Lake Brooklyn for these analyses because Lake Brooklyn did not have outflow during much of the simulation period. Sensitivity tests were designed in which: (1) the outlet altitude was increased by 1 ft for the entire 1957-98 simulation time period; (2) the roughness coefficient of all three stream segments was reduced from 0.05 (rough, high impedance channel) to 0.01 (a clear channel with little impedance to flow); and (3) the stream width was halved (2 ft upstream from Lake Brooklyn and 4 ft downstream from Lake Brooklyn). An earlier, preliminary simulation of lake stages was used for these analyses. In these earlier analyses, it was assumed that 40 percent of rainfall recharged the water table and there were no surface-water losses. Results of the three analyses (figs. 35-37) show a substantial effect on the stage of Lake Magnolia. The changes in simulated streamflow rates between Lakes Magnolia and Brooklyn were negligible.

When the outlet altitude was increased 1 ft, the result was a rise in the simulated stage of Lake Magnolia of about 1 ft. When the roughness coefficient was decreased, the simulated stage was lowered between 1 and 2 ft. When the channel width was halved, the result was a substantial increase in lake stage at high stages and streamflow rates, and a negligible to moderate increase in lake stage when the stage and streamflow rate were low. In each of the sensitivity analyses, when a specified characteristic of the downstream channel segment or the outflow altitude was modified, the simulated stage of the originating lake (Lake Magnolia) changed to compensate for the specified channel modification, maintaining the streamflow rate virtually the same as in the calibrated simulation. The results show that streamflow tends to be controlled by the amount of water available in the originating lake, and is not appreciably affected by outflow elevation or by the channel characteristics of the receiving stream.

This result has significance for efforts to augment the volume of water contained in Lake Brooklyn (thereby increasing its stage). Efforts to improve the flow characteristics of Alligator Creek likely have had only a temporary effect on the amount of water reaching Lake Brooklyn by streamflow.

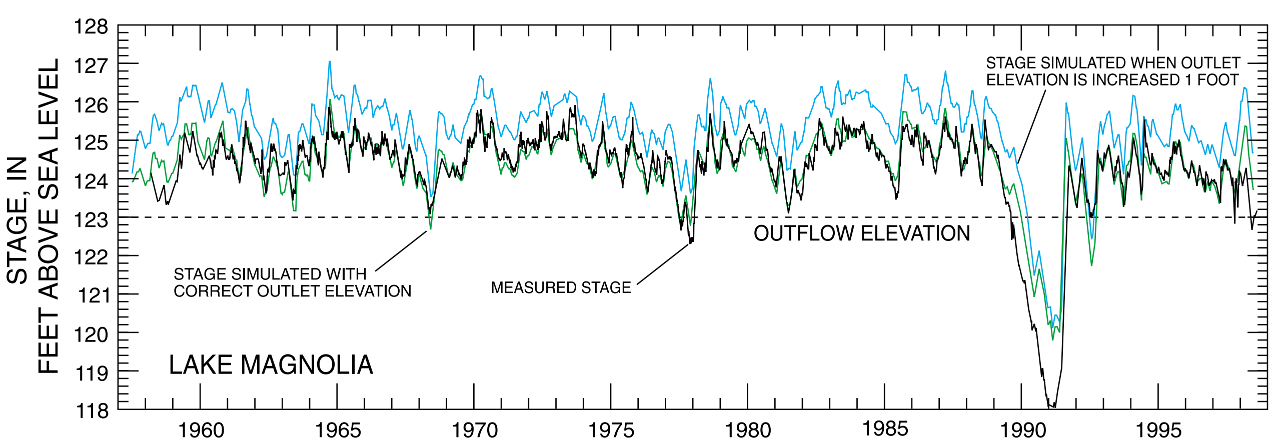



**Figure 35.** Results of sensitivity analysis in which the outlet elevation of Lake Magnolia is increased by 1 foot.

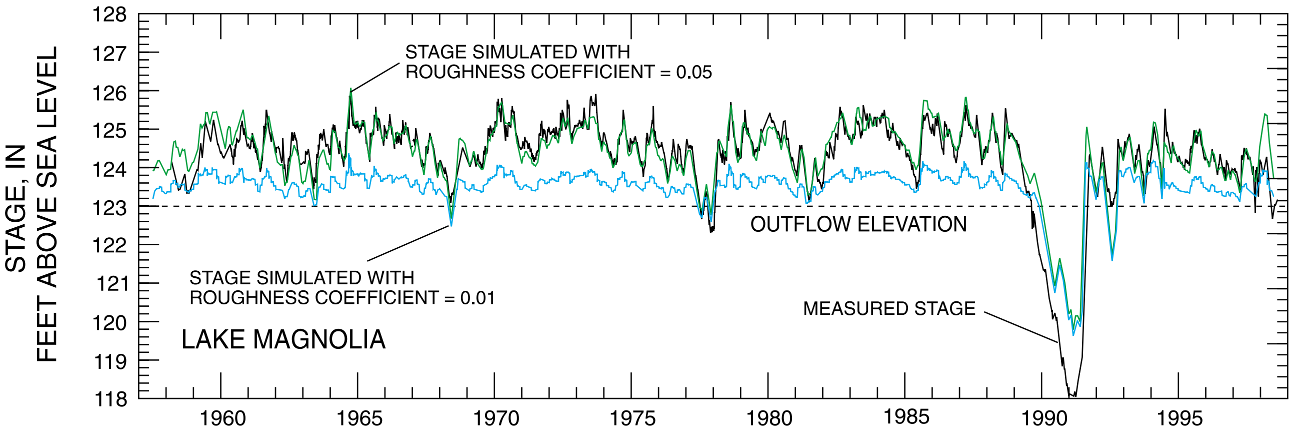



**Figure 36.** Results of sensitivity analysis in which the stream roughness coefficient has been reduced from 0.05 to 0.01.

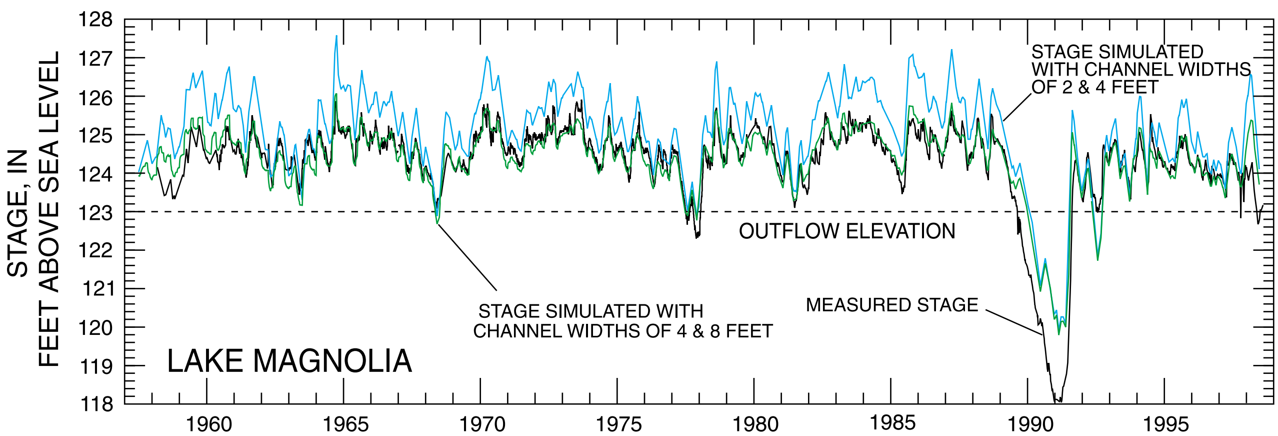



**Figure 37.** Results of sensitivity analysis in which the stream widths have been halved.

### Simulating the Altitude of the Water Table

The transient simulation of water-table altitudes in the surficial aquifer system was the first known to have been attempted in the hydrologic environment of north-central Florida, and therefore, no standard techniques were available for guidance. Water levels measured in selected wells of the surficial aquifer system network (fig. 4) were approximately matched (fig. 38) by specifying the hydraulic conductivity distributions shown in figure 22 for the two simulations assuming that: (1) 40 percent of rainfall recharged the water table, and (2) 20 percent of rainfall recharged the water table. The hydraulic conductivity values that correspond to the assumption of 40-percent rainfall recharge were approximately twice those corresponding to the assumption of 20-percent rainfall recharge. Although the hydraulic conductivity values used were in general agreement with the results of slug tests, the distribution of the hydraulic conductivity values is strictly the result of curve-matching, and no hydrologic rationale is offered to justify it. It is noted, however, that the lower values, ranging to two orders of magnitude less than the higher values, seem to correspond to areas of higher land-surface altitude. Slight differences between the simulated and measured water-table altitudes could have been resolved by additional adjustments of the selected hydraulic conductivity values, but the additional effort did not seem to be justified.

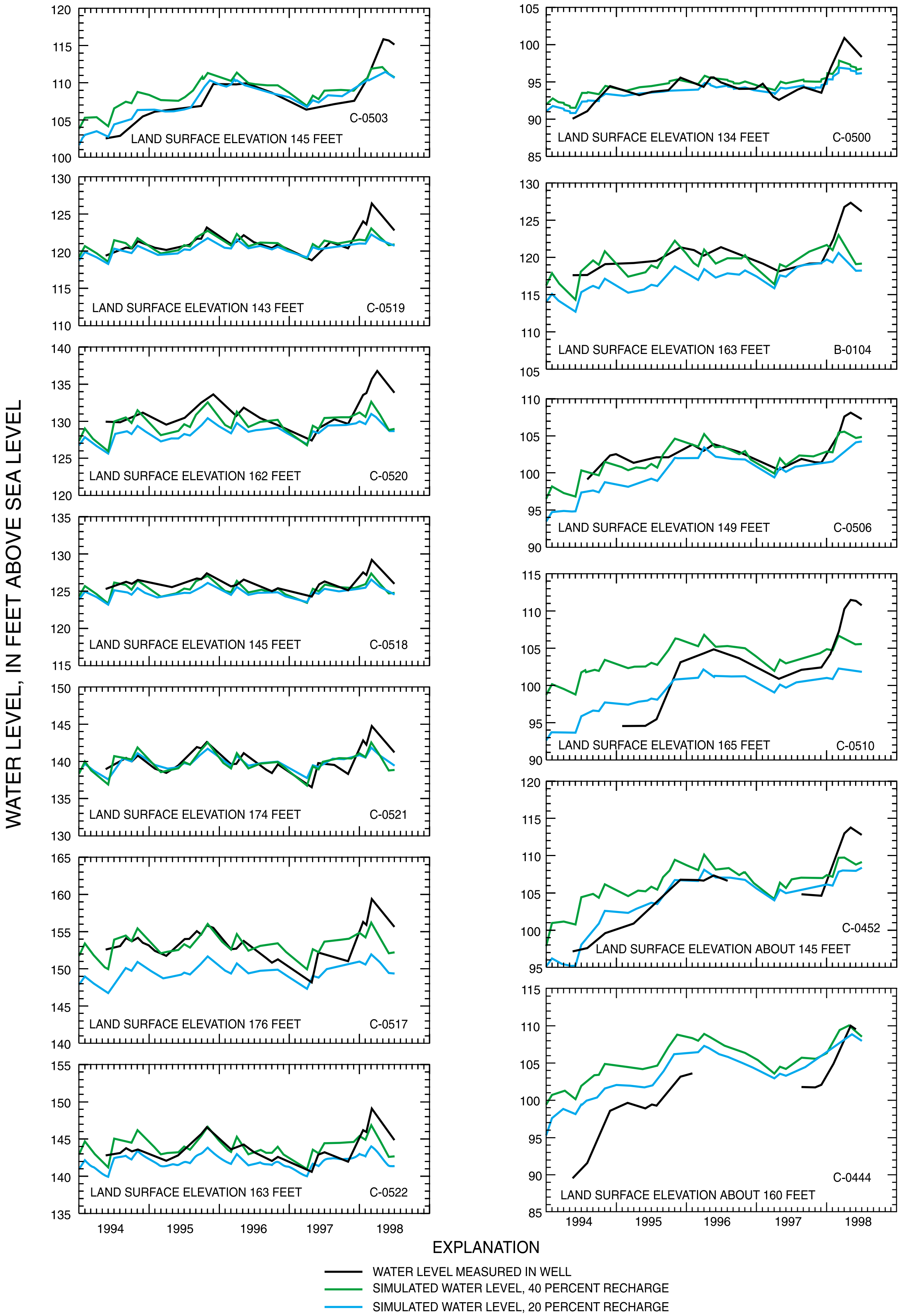



**Figure 38.** Measured heads at observation wells in the surficial aquifer and simulated heads at corresponding locations in the model grid when it is assumed that 40 percent of rainfall recharges the water table and 20 percent of rainfall recharges the water table.

The lack of agreement between simulated and measured water-table altitudes for the wet El Niño winter of 1997-98 probably arises from the use of rainfall data that underestimated the true amount of rainfall in this period, as cited in the earlier discussion of the simulation of the stage in Lake Brooklyn. The lack of agreement at C-0510 in early 1995 suggests that the use of even higher leakance values beneath nearby sublake 10 may have been appropriate. The hydraulic conductivity values used in the area of Brooklyn Bay, appreciably lower than hydraulic conductivity values used in adjacent regions, were selected to allow the model to simulate the prolonged stage decline in the bay near the end of the 1990-94 low-stage regime in Lake Brooklyn. The lack of agreement at C-0444 in 1994-95, however, suggests that the hydraulic connection between C-0444 and Brooklyn Bay may have been better than assumed, and also suggests that the hydraulic conductivity of the surficial aquifer system in this region may have been higher than estimated. If so, appreciably higher values of leakance through the confining layers would have been appropriate beneath Brooklyn Bay.

Differences are noted in the abruptness of changes of measured head values and in the relation of the timing of peak measured heads and simulated peak heads. These differences seem correlated to the depth of the water table below land surface. In one example (C-0519), measured water levels change abruptly in response to rainfall events, and measured and simulated peaks, particularly those for early November 1994, early November 1995, and early March 1998, approximately coincide. At C-0519, the water table averages 22-23 ft below land surface during the period illustrated. C-0519 is located in the region with the highest specified hydraulic conductivity value. In another example, the water level measured in C-0506 varies smoothly with few sharp peaks, and lags the sharp simulated peaks by about 2 months. At C-0506, the water table averages 45-50 ft below land surface during the period illustrated. C-0506 is located in the region with the second-highest specified hydraulic conductivity value.

A sensitivity analysis was performed to assess the dependence of heads simulated for the surficial aquifer system to the specification of hydraulic conductivity values. The simulation assuming that 20 percent of rainfall recharged the water table was used as a control, and hydraulic conductivity values were increased and decreased uniformly by 25 percent. Generally, the simulated well locations showing the greater sensitivities were in regions of lower specified hydraulic conductivity values (fig. 39). Exceptions to this rule seem related to the nearness of the simulated well to boundaries or to simulated lakes.

The successful replication of water levels in the surficial aquifer well network may not validate the assumption of the specified distribution of hydraulic conductivity values. This distribution could mask another relation, perhaps a distribution of the amount of water recharging the water table. The latter process could vary spatially in relation to the average depth of the water table below land surface or to spatially varying geologic controls governing the amount of percolation to the water table. Such considerations highlight the need for further research into the nature and quantitative aspects of processes that occur in the subsurface after rainwater percolates into the sandy soils of north-central Florida.

### Simulating the Head in a Well in the Upper Floridan Aquifer

The use of a specified-head boundary condition at a 20-mi distance from lateral model boundaries gave the simulator the capability to simulate an increase in head within the model boundaries in the model layers representing the confined aquifers, although the model was not constructed to be a precise simulator of the head distribution in those layers. In the highly generalized layers representing the intermediate and Upper Floridan aquifers, simulated head increases were greatest beneath the lakes where the highest leakance rates through the confining layers were specified. For a quantitative comparison with field data, heads measured in Floridan aquifer well C-0120 from 1960 to 1998 were used. Well C-0120 (SJRWMD designation) is located at the map coordinates of surficial aquifer system well C-0452 (fig. 4) on the western shore of Lake Brooklyn, and should, therefore, show the effect of leakage from the lake through the surficial aquifer system and underlying confining layers. Heads in well C-0120 were measured by the USGS through late October 1993 and have been measured by the SJRWMD since that time.

Measured and simulated heads in the Upper Floridan aquifer are compared to one another and to the stage of Lake Brooklyn (fig. 40). Simulated heads follow the trend of the measured heads quite well, although the simulated heads do not quite match the downward trend of the field data in the late 1980's. The strong rise in measured head of the wet El Niño winter of 1997-98 is not matched because the stage of Lake Brooklyn was not matched, probably as a result of underspecifying rainfall amounts for this period of time. Measured heads also seem to be a subdued reflection of the stage of Lake Brooklyn.

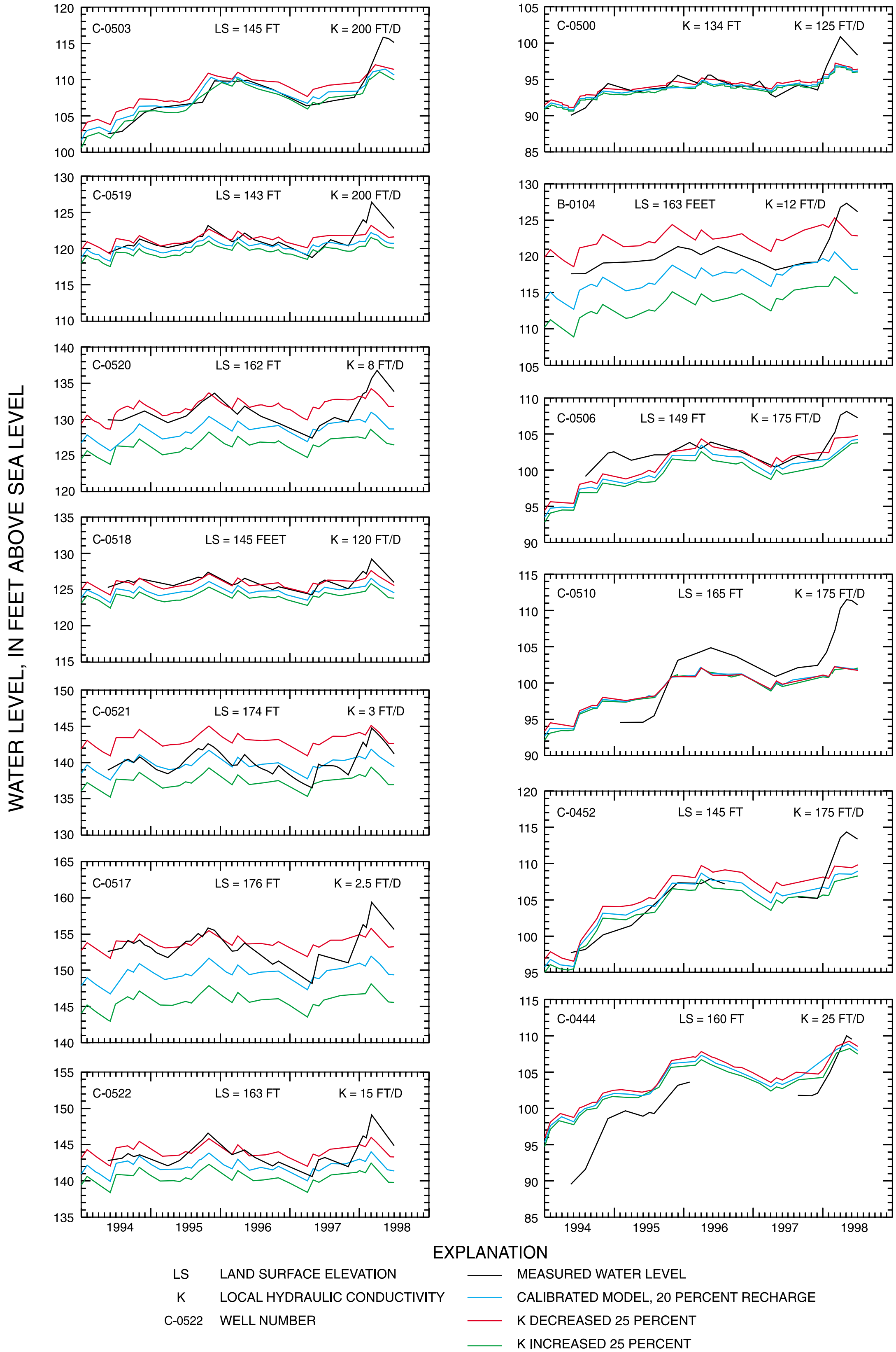



**Figure 39.** Results of sensitivity analyses in which the hydraulic conductivity values for the surficial aquifer were uniformly increased and decreased by 25 percent.

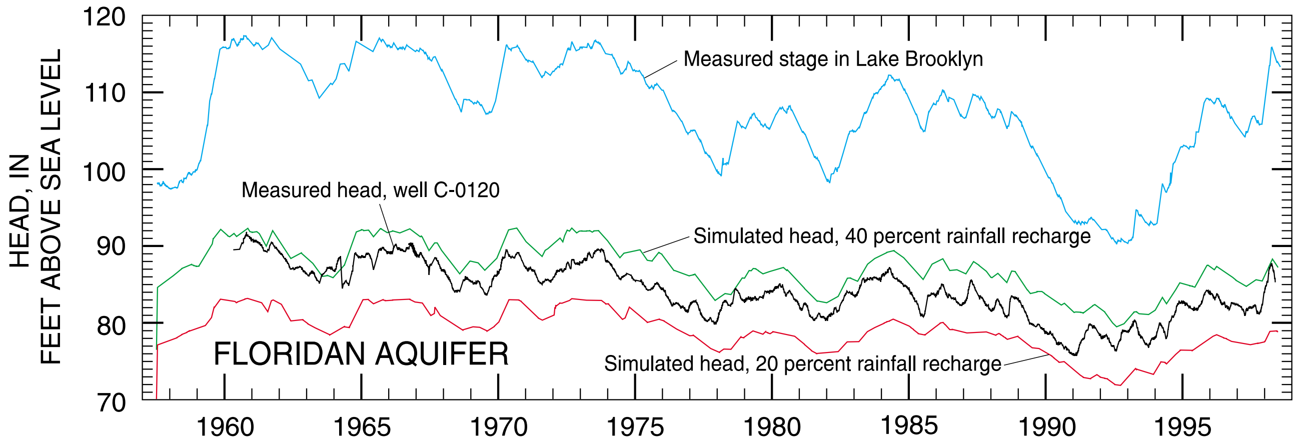



**Figure 40.** Measured and simulated heads in the Upper Floridan aquifer at the location of well C-0120 and the measured stage of Lake Brooklyn.

The simulated heads easily could have been raised and lowered a few feet for a better overall match by adjusting the transmissivity assigned to the Upper Floridan aquifer layer, which would have necessitated some recalibration of leakance and surficial aquifer system hydraulic conductivity values. However, such effort was considered unwarranted, given the highly generalized nature of the representation of the Floridan aquifer. The head measured in well C-0120 represents the effect of all leakage processes allowing water to reach the Upper Floridan aquifer in the region, many of which may not be explicitly represented in the model of the present study. In particular, higher heads have been estimated south of the study area (fig. 6), suggesting that additional leakage may occur from other lakes outside the model boundaries or through buried karstic features beneath the present-day (2000) land surface.

The simulation results (fig. 40) do not support the hypothesis that a regional or local drawdown of the Upper Floridan aquifer may have been partly responsible for the lowered stage of Lake Brooklyn. The boundary conditions for the Upper Floridan aquifer remained constant throughout the simulation period (1957-98). Yet the model depicts a realistic decline in head in the Upper Floridan aquifer layer through the early 1990's, apparently the result of rather than the cause of the decline in stage of Lake Brooklyn. This result suggests that the observed head decline in well C-0120 since 1960 could be explained completely in terms of the stage decline in Lake Brooklyn.

## Analysis of Possible Errors in Areal Leakance and Bathymetry Specifications

The assignment of confining unit leakance values of 1 x $10^{-6}$ $d^{-1}$ throughout most of the model area and from 1 x $10^{-3}$ to 3 x $10^{-2}$ $d^{-1}$ beneath the lakes was considered to approximately represent the process of recharge to the confined intermediate and Upper Floridan aquifers. Conceptually, it is assumed that most recharge is localized where karstic processes have disturbed the confining unit, as under Lake Brooklyn. The value of 1 x $10^{-6}$ $d^{-1}$ assigned to the remainder of the area within the model was at the low end of the range of values assigned to large areas of the regional model constructed by Tibbals (1990). Although Tibbals (1990) used leakance values ranging from 1 x $10^{-4}$ to 3 x $10^{-4}$ $d^{-1}$ in an area that includes Lake Brooklyn, these values represented the confined effect of distributed leakage through the confining unit and localized leakage at a higher rate where the confining unit is breached.

The determination of leakage rates throughout the modeled area (fig. 17) is beyond the scope of this study and would require additional data that are not available. Nevertheless, an assessment of the effect on the calibrated model of using the low regional leakance value was considered useful for the purpose of understanding how the calibrated model was influenced by this specification and for determining whether problems that arose in calibrating the model could be related to this specification. In a sensitivity analysis, this value was increased by an order of magnitude to 1 x $10^{-5}$ $d^{-1}$.

The results included a slight (less than 1 ft) decrease in the simulated stage of Lake Brooklyn (fig. 41) when that stage had been below the specified outlet elevation for several years or more. The low simulated stage of Lake Magnolia in 1991 decreased further, by another 6 ft (not illustrated), but the simulated stage of Lake Magnolia was unaffected in other time periods. The simulated head for the Upper Floridan aquifer increased by a slight amount in some time periods, but never by more than 0.5 ft. The most noticeable changes were decreases in water levels simulated in the surficial aquifer system at the locations of observation wells. The differences ranged from less than 0.5 ft in the part of the area assigned a hydraulic conductivity of greater than 100 ft/d to nearly 5 ft at well C-0517, where the specified hydraulic conductivity was 2.5 ft/d.

The differences in stages and heads in the revised simulation were not substantial, and the revised hydrograph of the stage of Lake Brooklyn (fig. 41) could be considered an acceptable calibration. If the regional leakance value were increased further, some model recalibration would become necessary, most likely entailing the use of lower leakance values beneath the lakes. There are no differences in the sensitivity analysis that indicate that varying the regional leakance value could obviate the necessity of specifying withdrawals to represent surface-water losses between 1973 and 1989.

The assignment of depths in the lakes in columns of the grid was done with careful attention to detail and was based on the same data (Clark and others, 1963) used by Motz and others (1994) to develop a quadratic relation between stage and volume. The lack of agreement between the stage/volume relation of the present model using these depth assignments and the quadratic equation of Motz and others (1994) suggested the need to test the calibrated model to determine how results would change if a different stage/volume relation were used. For this purpose, the calibrated model was rerun with revised depth specifications that more closely approximated the relations of Motz and others (1994) for Lakes Magnolia and Brooklyn (figs. 20 and 21). To accomplish this task, lake depths in some vertical columns of the grid (fig. 19) were reduced by 10 ft, raising the specified bottom surface of those sections of the two lakes, and thus reducing the total lake volume associated with a specific depth. The entire bottom surface of Lake Magnolia was raised 10 ft, and about half of the bottom surface of Lake Brooklyn was raised 10 ft in the model representation.

Results were similar in many respects to those of the previous sensitivity analysis in that they did not show substantial differences in simulated stages or heads (fig. 41). Stages in Lake Brooklyn were affected mainly at simulation times when they were far below the outlet elevation and decreasing, apparently because the surface area of the lake at lower stages was less than before. Simulated stages between 1977 and 1992 were usually within 1 ft of those of the calibrated model. The stage decrease of 1990 began earlier and was more rapid, and the two simulations differed by as much as 6 ft in that year. Lake Magnolia stages (not illustrated) were unaffected except during the decline of 1990-91. In this period, the sensitivity analysis indicated a low of 8 ft below that simulated by the calibrated model. Simulated heads in the Upper Floridan aquifer were as much as 1 ft lower than those of the calibrated model in some time periods. Simulated heads in the surficial aquifer were virtually unaffected.

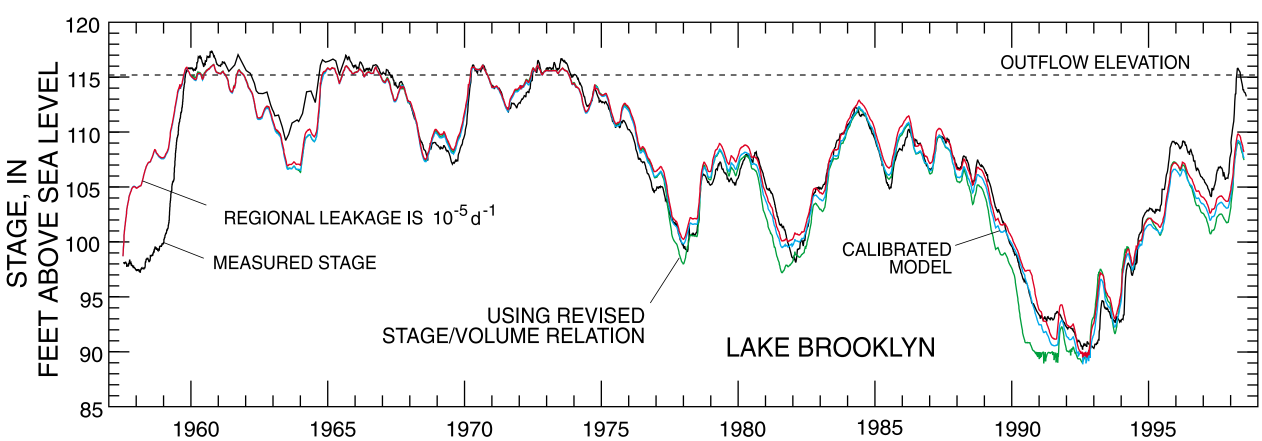



**Figure 41.** Results of sensitivity analyses in which the regional leakance through the confining layers was increased and the stage/volume relations for Lakes Magnolia and Brooklyn were changed.

As with the previous sensitivity analysis, the differences in the revised simulation were not substantial and recalibration of the model might have been achieved by using lower leakance values beneath the lakes. Another result of this analysis is that the revised simulation does not show changes that would obviate the need to specify withdrawals that represented surface-water losses between 1973 and 1989.

## SUMMARY

Some karstic lakes in north central Florida interact with the underlying Floridan aquifer system. The upper part of the Floridan aquifer system, the Upper Floridan aquifer, is characterized by a high degree of solution porosity and high permeability. Lakes that are not hydraulically isolated from the Upper Floridan aquifer may exhibit large stage fluctuations as water drains to the aquifer during dry periods and is replenished in excess of the drainage rate during wet periods. For example, the stage of Lake Brooklyn, in southwestern Clay County, has varied over a range of 27 ft since July 1957, when the U.S. Geological Survey (USGS) began taking measurements. After the most recent and severe stage reduction, the USGS proposed a study that entailed the use of numerical ground-water flow models to simulate the interaction of Lake Brooklyn with the Upper Floridan aquifer and the fluctuations of stage in the lake that were a part of that process. A package to represent lake/aquifer interaction in the USGS MODFLOW-96 and MOC3D simulators was prepared as part of this study, and a demonstration of its capability was considered to be the primary objective of this investigation.

The most productive source of water in a larger region that includes the study area is the Floridan aquifer system, which is overlain by a confining unit and a surficial aquifer system of relatively low permeability. The region of lakes that is the subject of the present study lies within the 80-ft contour that demarcates the center of a regional high in the potentiometric surface of the Upper Floridan aquifer and probably indicates an area of recharge for the Upper Floridan aquifer. The intermediate aquifer system, considered to be permeable strata within the Hawthorn Group, is of considerable importance locally to well drillers and homeowners, as it is one of the principal local sources for domestic self-supply wells. The surficial aquifer system is identified as an upper 50 to 85 ft of unnamed deposits of clay and coarse clastics of early Pleistocene age. The surficial aquifer system is rarely used as a source of supply because of its low yield to wells, but the system is highly important as a source of recharge to the Upper Floridan aquifer in the area of study.

The lakes in the study area are karstic in origin. Rainfall is the source of water to these lakes, and may be acquired by direct capture of precipitation, by overland runoff after precipitation, by ground-water seepage from surficial aquifer systems recharged by percolation of rainfall, or by inflow from streams fed by seepage from ground water or flow from other lakes. Blue Pond and Lakes Lowry, Magnolia, Brooklyn, and Geneva, which are the lakes important to this study, are interconnected by streams that share the collective name of Alligator Creek. As part of this study, three gaging stations equipped with continuous recorders were established on sections of Alligator Creek, augmenting earlier streamflow measurements made by St. Johns River Water Management District at eight locations in the basin. Based on data from the stream gages on the upper and lower ends of Alligator Creek between Lakes Magnolia and Brooklyn, there were only slight gains and losses during the period November 1994 to September 1997, which included periods of both high and low flow (0.1 to 41.5 $ft^3/s$).

In the Lake Package developed for use in this study, lake stage varies interactively with ground-water levels. The stage of each lake is updated for each MODFLOW time step by a budget process that takes into account ground-water seepage, precipitation upon and evaporation from the lake surface, stream inflows and outflows, overland runoff inflows, and augmentation or depletion by artificial means. The MODFLOW Stream Package was modified to provide a means for representing the interchanges of water between the streams and lakes. The Lake Package has the capability to simulate the occurrence of drying and rewetting in parts of lakes or of entire lakes. Another capability provided by the package is to simulate both the division of a lake into separate lakes with drying, and the coalescence of several lakes (separated by areas of low land-surface altitude) into a single lake with rising stage.

The modeled area was discretized laterally into 24 columns and 31 rows. The axis of coordinates of the model was aligned 39 degrees from north-south so that the model domain would encompass Lakes Magnolia and Brooklyn but exclude other large lakes. The vertical discretization of the model consisted of five upper layers representing the surficial aquifer system, and two lower layers, each separated from the next higher layer by a confining layer, representing the intermediate and Upper Floridan aquifers. Because Lake Brooklyn consists of 10 deep pools separated by shallow sandbars, and divides into separate pools when the stage decreases, the method used by the Lake Package to represent lake coalescence and separation requires that each pool be identified as a separate lake ("sublake") in the input specifications. Specified-head boundary conditions on the perimeter of the grid were assigned to the five upper layers representing the surficial aquifer system. Model computations for lake stages and surficial aquifer system heads were insensitive to the choice of constant boundary-head values for the surficial aquifer system layers.

In the first calibrated model, recharge to the water table, specified as a monthly rate, was set equal to 40 percent of the monthly rainfall rate recorded at Gainesville, or at Lake Brooklyn beginning with February 1992. Lake evaporation was specified as average monthly pan evaporation at Gainesville modified by literature values for monthly pan-to-lake coefficients. The streams linking the lakes were represented as three stream segments using the MODFLOW Stream Package. The specified rate of inflow to the uppermost stream segment was set equal to outflows from Lake Lowry estimated from lake stage and the 1994-97 rating table. To match heads measured in the surficial aquifer wells, the assigned hydraulic conductivity values were zoned, and ranged from a minimum of 4 ft/d to a maximum of 400 ft/d. Spatially uniform values of transmissivity were specified for the intermediate (10,000 $ft^2$/d) and Upper Floridan (100,000 $ft^2$/d) aquifers. For purposes of this study, virtually all leakage to the confined aquifers was assumed to occur from the surficial aquifer system through the confining layers directly beneath the deeper parts of the lake bottoms. A leakance coefficient value of 0.001 $d^{-1}$ was used under Lake Magnolia and a value of 0.005 $d^{-1}$ was used for most of Lake Brooklyn. With these values, the conductance beneath Lake Brooklyn was about 19 times that beneath Lake Magnolia.

The principal parameters used for calibration were the hydraulic conductivity and specific yield of the surficial aquifer system (primarily affecting the heads simulated in the surficial aquifer system), and the values of leakance through the confining layers between the surficial aquifer system beneath the lakes and the intermediate and Upper Floridan aquifers (primarily affecting the lake stages). The simulated stage hydrograph for Lake Brooklyn matched the measured stages reasonably well in early and late time periods, but was clearly an unsatisfactory match in the intermediate time period. To resolve this discrepancy, the hypothesis was proposed that losses of surface water from Alligator Creek above Lake Brooklyn or from Lake Brooklyn itself occurred between 1973 and 1989 when there was sufficient streamflow. The hypothetical water losses were large and increased with time, ranging from 2.5 $ft^3$/s in 1973-78 to a high of 12.5 $ft^3$/s in 1985-86. The water losses were not allowed to exceed the amount of streamflow, and were of zero magnitude when streamflow ceased during dry periods. The resulting simulation of lake stages matched the measured lake stages accurately in most time periods. Possible explanations for a substantial loss of water from either the creek or the lake include either naturally occurring phenomena such as karstic processes or losses caused by human activities. No documented evidence exists to support either of these explanations.

The calibrated model incorporating the assumption that 40 percent of precipitation recharged the water table was revised to incorporate a new assumption that only 20 percent of precipitation recharged the water table (the second calibrated model). Recalibration of the model required that estimated hydraulic conductivities in the surficial aquifer system be reduced by approximately 50 percent and that leakance values for the confining units under deeper parts of the lakes also be reduced by nearly 50 percent. The stages simulated with the new parameter assumptions, but including the hypothetical withdrawals, were an excellent match of the measured values.

The stage of Lake Magnolia was simulated quite accurately, but without specifying a high leakance under the lake, the 7-ft stage decline measured in early 1991 could not have been simulated. The relation of lake stage to the specification of outlet altitude and to other parameters describing characteristics of the downstream channel was considered in three sensitivity analyses to test specifications for: (1) outlet altitude; (2) roughness coefficient; and (3) stream width. Results of the three analyses show a substantial effect on the stage of Lake Magnolia. Simulated changes in streamflow rates between Lakes Magnolia and Brooklyn were negligible. The results show that streamflow tends to be controlled by the amount of water available in the originating lake, and is not appreciably affected by outflow altitude or channel characteristics of the receiving stream. This result has important implications for efforts to augment the volume of water contained in

Lake Brooklyn. Efforts to improve the characteristics of Alligator Creek likely have had only a temporary effect on the amount of water reaching Lake Brooklyn by streamflow.

Water levels measured in wells of the surficial aquifer system network were approximately matched. The distribution of hydraulic conductivity values is strictly the result of curve-matching, but it is observed that the lower values, ranging to two orders of magnitude less than the higher values, seem to correspond to areas of higher land altitude. Differences in the abruptness of measured head value changes, and in the relation of the timing of peak measured and simulated heads, seem correlated to the depth of the water table below land surface. The successful replication of water levels in the surficial-aquifer well network may not validate the specified distribution of hydraulic conductivity values. This distribution could, in fact, mask another relation, perhaps an areal variation in the amount of water recharging the water table.

Simulated heads in the Upper Floridan aquifer layer follow the trend of the measured heads, although the simulated heads do not quite match the downward trend of the field data in the late 1980's. The boundary conditions for the Upper Floridan remained constant throughout the simulation period (1957-98). Yet, the model depicts a realistic decline in head in the Upper Floridan aquifer layer through the early 1990's. This result suggests that the observed head decline in well C-0120 since 1960 could be explained entirely in terms of the stage decline in Lake Brooklyn and may not indicate a regional trend.

The primary purpose of the study was to demonstrate the application of the USGS Lake Package to a reasonably complex field problem. This objective was accomplished. Results of this study can provide guidance to local water managers and to other hydrologists in applying quantitative methods to hydrologic problems involving the interaction of lakes and aquifers.

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