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Glynn County pond site

Bulloch County pond site

Scientific Investigations Report 2004-5260

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Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). Historical data collected and stored as North American Datum 1927 have been converted to NAD 83 for this publication.

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). Historical data collected and stored as National Geodetic Vertical Datum of 1929 have been converted to NAVD 88 for this publication.

Pond-Aquifer Flow and Water Availability in the Vicinity of Two Coastal Area Seepage Ponds, Glynn and Bulloch Counties, Georgia

By John S. Clarke[1] and Malek Abu Rumman[2]

Abstract

Pond-aquifer flow and water availability at excavated seepage pond sites in Glynn County and in southern Bulloch County, Georgia, were evaluated to determine their potential as sources of water supply for irrigation. Excavated seepage ponds derive water primarily from ground water seeping into the pond, in a manner similar to a dug well completed in a surficial aquifer. The availability of water from seepage ponds is controlled by the permeability of surficial deposits, the amount of precipitation recharging the ground-water system, and the volume of water stored in the pond. The viability of seepage ponds as supplies for irrigation is limited by low seepage rates and high dependence on climatic conditions. Ponds will not refill unless there is adequate precipitation to recharge the surficial aquifer, which subsequently drains (seeps) into the pond.

Ground-water seepage was estimated using a water-budget approach that utilized on-site climatic and hydrologic measurements, computing pond-volume changes during pond pumping tests, and by digital simulation using steady-state and transient ground-water flow models. From August 1999 to May 2000, the Glynn County pond was mostly losing water (as indicated by negative net seepage); whereas from October 2000 to June 2001, the Bulloch County pond was mostly gaining water. At both sites, most ground-water seepage entered the pond following major rainfall events that provided recharge to the surficial aquifer. Net ground-water seepage, estimated using water-budget analysis and simulation, ranged from –11.5 to 15 gallons per minute (gal/min) at the Glynn County pond site and from –55 to 31 gal/min at the Bulloch County pond site.

Simulated values during pumping tests indicate that ground-water seepage to both ponds increases with decreased pond stage. At the Glynn County pond, simulated net ground-water seepage varied between 7.8 gal/min at the beginning of the test (high pond stage and low hydraulic gradient) and 103 gal/min at the end of the test (low pond stage and high hydraulic gradient). At the Bulloch County pond site, values ranged from –17.7 gal/min at the beginning of the test to 15 gal/min at the end of the test.

Results at the two pond sites indicate that the use of excavated seepage ponds as sources for irrigation supply is limited by pond-storage volume and low net ground-water seepage rates during periods of low precipitation. Pumps withdrawing 1,000 gal/min for 10 hours per day—under climatic and hydrologic conditions similar to those observed during pond pumping tests at each site—would drain the Glynn County pond within 30 days and the Bulloch County pond within 3.5 days. Because the two pond sites are considered to represent the extremes of likely conditions to be encountered in the coastal Georgia area, it is likely that other seepage ponds would have similar storage-depletion rates.

Introduction

The Upper Floridan aquifer is the principal source of water in the coastal area of Georgia. Declining water levels and localized saltwater contamination have resulted in State-restricted ("capped") withdrawals from the aquifer and have prompted interest in developing supplemental sources of ground water. In the coastal area, seepage ponds are sometimes excavated for golf courses, farms, or communities by digging through sandy surface soils until the water table is reached. Because these ponds are largely isolated from surface-water runoff, water is mostly derived from ground water seeping into the pond. Seepage ponds are often used to supply water for irrigation; however, the water-supply potential of such ponds is poorly understood. The U.S. Geological Survey (USGS)—in cooperation with the Georgia Department of Natural Resources, Environmental Protection Division (GaEPD)—conducted a study during 1999–2001 to evaluate pond-aquifer flow and water availability at two pond sites in coastal Georgia to determine their potential use as supplemental sources of water for irrigation.

[1]U.S. Geological Survey; [2]Georgia Institute of Technology

Purpose and Scope

This report describes results of investigations to evaluate the water-supply potential at seepage pond sites at Brunswick, Glynn County, and in southern Bulloch County, Georgia. Included are descriptions of the hydrogeologic setting, estimates of a hydrologic budget and ground-water seepage rates, development and calibration of steady-state and transient ground-water flow models, and an assessment of water availability based on pond pumping tests and simulation results. The report is based on data collected during a period of drought in coastal Georgia—from August 1999 to October 2000 at the Glynn County pond site and from October 2000 to July 2001 at the Bulloch County pond site. Each pond site was characterized by constructing test wells; collecting core and cuttings samples and borehole geophysical logs; conducting pond bathymetric and bottom-temperature surveys; installing continuously monitored weather stations, pond-stage, and ground-water level recorders; and measuring periodic water levels from on-site and surrounding area wells. Long-term pumping tests were conducted at each pond to estimate ground-water seepage and to evaluate effects of pumping on ground-water levels. Steady-state and transient ground-water flow models were developed for each site to assess pond-aquifer relations and to estimate ground-water seepage rates and hydraulic properties of the surficial aquifer.

Study Area

To assess the water-supply potential of seepage ponds, two sites located in areas of contrasting hydrologic, physiographic, and soil conditions were selected to evaluate pond-aquifer relations and possible ranges of water availability (fig. 1). The Glynn County pond site is located in the Coastal Lowlands physiographic division (LaForge and others, 1925), near the Atlantic Ocean, in an area characterized by low relief and high-permeability sandy soils. The Bulloch County pond site is located in the Coastal Terraces physiographic division (LaForge and others, 1925), in an area characterized by low relief and low-permeability clayey soils. During 1961–90, precipitation averaged about 49 inches per year (in/yr) at the Glynn County pond site and about 47 in/yr at the Bulloch County pond site (Sherlyn Priest, U.S. Geological Survey, written commun., 2002). The two sites are described in greater detail in subsequent sections of this report.

Previous Studies

Several publications have described ground-water flow near seepage ponds and lakes. Winter (1976, 1978) described numerical simulations of steady-state ground-water flow near lakes under various hydrologic conditions. Beck (1978) estimated water yield from shallow ponds in Coastal Plain settings by considering ponds as large-diameter wells and using hydraulic conductivity derived from grain-size analyses of surficial sands. Beck (1978) concluded that a yield of 100,000 gallons per day (gal/d), or 69.4 gallons per minute (gal/min), could be obtained from a 15-foot-deep pond having a 100-foot (ft) radius.

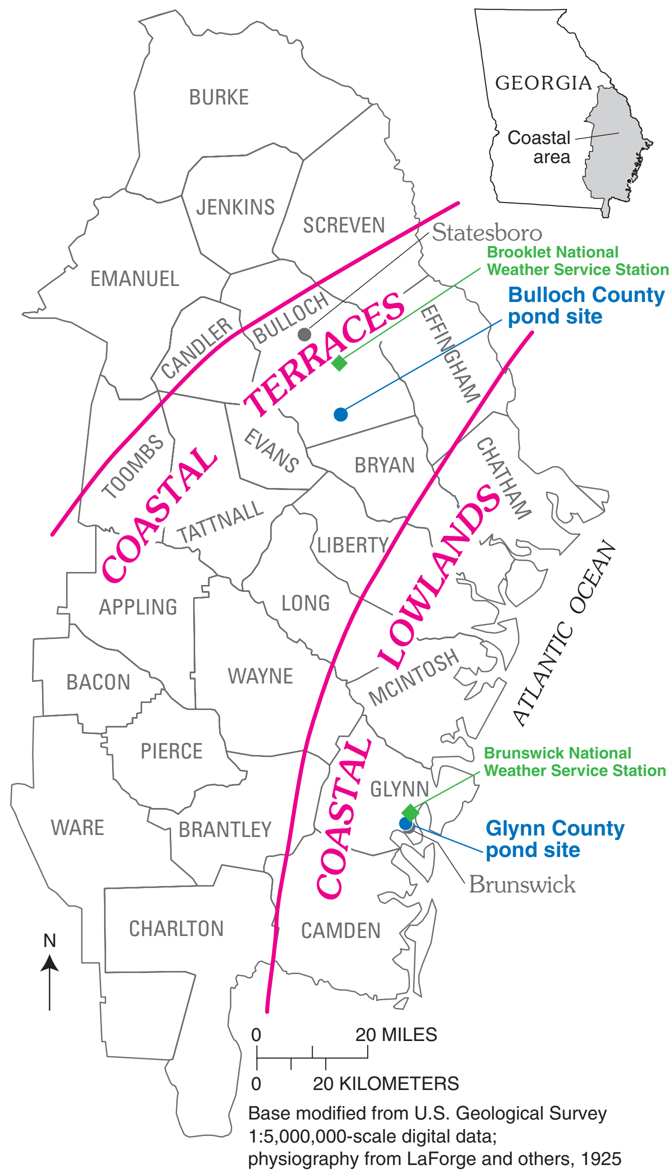


Figure 1. Coastal Georgia area and location of Glynn County and Bulloch County pond sites.

Krabbenhoft and others (1990) described three-dimensional simulation of ground-water exchange at Sparkling Lake, Wisconsin. The simulations indicated that ground-water recharge has a greater influence on inflow to the lake than outflow from the lake. Studies by Sacks and others (1992), Grubbs (1995), Lee (1996), Lee and Swancar (1997), and Metz and Sacks (2002) provided detailed descriptions of lake hydrologic budgets and lake-aquifer flow. Sacks and others (1992) described the hydrogeologic setting and a preliminary analysis of data to compute a hydrologic budget at Lake Barco, Florida. Grubbs (1995) described the development of a hydrologic budget and simulation of lake-aquifer flow at Lake Five-O, Florida, and indicated that ground-water flow to the lake was an important component of the lake hydrologic budget. Lee (1996) described hydrogeologic controls on lake-aquifer interaction at Lake Barco, Florida. Lee and Swancar (1997) described the importance of ground-water seepage and evaporation on hydrologic-budget computations for Lake Lucerne in Florida and provided a detailed error analysis of all components of the hydrologic budget. Metz and Sacks (2002) compared the hydrogeologic setting, ground-water flow patterns, water budgets, and water quality of three lakes in west-central Florida.

Methods to estimate evaporation include studies by Sacks and others (1994) and Winter and Rosenberry (1995). Sacks and others (1994) compared evaporative losses from two morphometrically different seepage lakes in Florida using estimates derived using an energy-budget method. The study determined that the thermal regime of a lake must be considered to provide more accurate estimates of seasonal evaporation rates from a deep lake. Winter and Rosenberry (1995) evaluated 11 equations used for determining evaporation at a small lake in the north-central United States.

Acknowledgments

The authors appreciate the assistance of Dr. Gene Kieferl, Coastal Georgia Community College, and Mr. Chuck Lee, landowner, for providing access to the Glynn County and Bulloch County pond sites, respectively. John Wentworth, Georgia Department of Transportation, provided access to drilling sites located along Interstate Highway 16 in Bulloch County. Wes Harris, Georgia Cooperative Extension Service, helped evaluate potential pond test sites in Bulloch County.

Dr. Aris Georgakakos, Georgia Institute of Technology, provided support and technical advice during the course of the study. Dr. Gerrit Hoogenboom, The University of Georgia, provided assistance in the installation of climatic monitoring stations at each pond site. Joe Sheridan and George Barfield, U.S. Department of Agriculture, provided assistance in the construction of test wells at the Glynn County pond site. Test wells at the Bulloch County pond site were constructed with the help of Mark Hall, Harold Baker, and John Sides of the Georgia Geologic Survey.

Michael F. Peck, Alan M. Cressler, David C. Leeth, Welby L. Stayton, Donald R. Dowling, and Christopher B. Walls, USGS, provided valuable assistance in site setup and in monitoring hydrologic conditions during pond pumping tests. DáVette Taylor-Harris, Michael T. Laitta, and Keith W. McFadden, USGS, developed the project database and applied Geographic Information System techniques to plot hydrologic data and compute estimates of pond volume. Douglas D. Nagle and Paul D. Ankcorn, USGS, conducted bathymetric surveys at the pond sites.

Estimation of Ground-Water Seepage

Ground-water seepage represents water either entering or leaving a pond as the result of hydraulic gradients between the aquifer and the pond. Net seepage is the difference between ground-water inflow minus outflow—when positive, more ground water enters than leaves the pond; when negative, more ground water leaves than enters the pond. The following relation (Darcy's Law) applies:

$$Q = K\,I\,A \tag{1}$$

where

Q is the seepage rate in cubic feet per day,

K is the hydraulic conductivity in feet per day,

I is the hydraulic gradient in feet per foot, and

A is the cross-sectional area in square feet.

Hydraulic conductivity is a temporal constant; both hydraulic gradient and cross-sectional area (area in which aquifer is in contact with pond bottom) may change as pond stage or ground-water levels change. Hydraulic gradients can be either toward the pond or away from the pond. Rates and directions of ground-water seepage vary depending on ground-water levels and pond stage and related changes in hydraulic gradient and cross-sectional area. Decreased pond stage or increased ground-water levels result in an increased hydraulic gradient toward the pond and increased rates of seepage to the pond. Increased pond stage results in a decreased or reversed hydraulic gradient, whereby seepage inflow is either decreased or reversed.

Ground-water seepage was estimated (1) using a water-budget approach that utilized on-site climatic and hydrologic measurements, (2) computing pond-volume changes during a pond pumping test, and (3) by digital simulation using steady-state and transient ground-water flow models. These estimates were used to assess the availability of water at both sites.

Water Budget

The water-budget approach used measurements of precipitation, pond evaporation, and pond-volume changes to estimate net ground-water seepage. Because surface-water inflow and outflow do not occur at either pond site and overland runoff is negligible because of permeable soils and low relief, these terms were omitted from the water budget. The method used to compute net ground-water seepage was virtually the same as that used by Pollman and others (1991), whereby the volumetric hydrologic budget for the pond is given by:

$$\Delta V - \varepsilon_{\Delta V} = (P +/- \varepsilon_P) - (E +/- \varepsilon_E) + (Gi +/- \varepsilon_{Gi}) - (Go +/- \varepsilon_{Go}) \tag{2}$$

where

ΔV is the pond volume change,

P is precipitation,

E is lake evaporation,

Gi is ground-water seepage into to the pond,

Go is ground-water seepage out from the pond, and

ε_θ is the error associated with the estimate of hydrologic variable θ.

Equation 2 can be rearranged to solve for net ground-water seepage:

$$Gnet = (Gi +/- \varepsilon_{Gi}) - (Go +/- \varepsilon_{Go})$$

$$Gnet = (\Delta V +/- \varepsilon_{\Delta V}) - (P +/- \varepsilon_P) + (E +/- \varepsilon_E) \tag{3}$$

With the exception of the error terms, all the terms on the right side of equation 3 were measured directly or indirectly. The “Area and Volume Statistics” function of the ARCVIEW3.1™ 3D-Analyst Tool was used to compute pond volume and area at each site using results of bathymetric surveys and projecting for a range of pond stages. Bathymetric surveys featured a location accuracy within a few feet, and bathymetry accuracy within 0.5 percent of indicated depth (D.D. Nagle, U.S. Geological Survey, written commun., 2004). Continuous relations between pond stage, pond volume, and pond area were developed using polynomial regression of pond stage and pond volume and pond stage and pond area. Changes in pond volume were computed by comparing volumes at different pond stages.

Precipitation and evaporation estimates were derived using data from automated weather stations installed at each site by the University of Georgia, Department of Biological and Agricultural Engineering, as part of the Georgia Automated Environmental Monitoring Network (*http://www.griffin.peachnet.edu/bae*). Sensors at each weather station measure air temperature, relative humidity, wind speed and direction, net and total solar radiation, barometric pressure, precipitation, and soil temperature at 2-, 4-, and 8-inch depths. Volumetric estimates of precipitation and evaporation were computed by multiplying total precipitation or evaporation (in volume per unit surface area units) by area.

For land areas, potential evapotranspiration was estimated by using the Priestly-Taylor method (Stewart and Rouse, 1976), as reported by the Georgia Automated Environmental Monitoring Network (*http://www.griffin.peachnet.edu/bae*). In the area of each pond, potential evapotranspiration was estimated by using the Penman method (Winter and Rosenberry, 1995):

$$PET = (s/(s + \gamma))(Q_n - Q_x) + (\gamma/(s + \gamma)) * [(15.36(0.5+0.01U_2))(e_0 - e_a)] \qquad (4)$$

where

PET is the potential evaporation (in calories per square centimeter per day),

$s/(s + \gamma)$ and $\gamma/(s + \gamma)$ are parameters derived from the slope of the saturated vapor pressure-temperature curve at the mean air temperature,

γ is the psychrometric constant equal to 0.66,

Q_n is net radiation (in calories per square centimeter per day),

Q_x is change in heat stored in the pond (in calories per square centimeter per day),

U_2 is wind speed at 2 meters above surface (in meters per second),

e_0 is saturated vapor pressure (in millibars), and

e_a is vapor pressure at air temperature and relative humidity (in millibars).

Data from the weather stations were used to compute evaporation estimates. In addition, to determine the change in heat stored in the pond (Q_x), temperature probes were installed at varying pond depths to record changes in daily temperatures. At the Glynn County pond site, temperature probes were installed at depths of 1, 2.5, 22, and 24 ft, with an average temperature difference between the uppermost and deepest probe of 5.2 degrees Celsius (^oC). At the Bulloch County pond site, temperature probes were installed at 1-ft depth increments between 0 and 5 ft, with an average temperature difference between the uppermost and lowermost probe of 0.4^oC. In each pond, the temperature data from all depths were averaged and used to calculate the term Q_x as follows:

$$Q_x = \rho * C_p * \Delta T * D, \qquad (5)$$

where

ρ is the water density (grams per cubic centimeter),

C_p is the specific heat of water at constant pressure taken as 1.007 calories/gram/degree Kelvin,

–T is the pond temperature change on a biweekly basis in degrees Kelvin, and

D is the average water depth in the pond (centimeters).

The influence of measurement errors of each water-budget component is important to the interpretation of the final water budget (Winter, 1981). Error estimates provide an indication of how well individual hydrologic fluxes are understood and measured, and are a measure of the reliability or accuracy of the hydrologic budget as a predictive tool (Lee and Swancar, 1997). Although the error, ε_{Gnet}, associated with a given net ground-water seepage estimate is unknown, the uncertainty of Gnet can be characterized by computing a confidence interval as follows:

$$Gnet \pm Z_{\alpha/2}\, \sigma_{Gnet}, \qquad (6)$$

where

$Z_{\alpha/2}$ is the standard normal deviate for an $\alpha/2$ level of significance, and

$\sigma_{\varepsilon Gnet}$ is the standard deviation of ε_{Gnet}.

This approach assumes that the error, ε_{Gnet}, associated with Gnet follows a normal distribution with mean equal to zero (Gnet is assumed to be unbiased) and has a variance equal to $\sigma^2_{\varepsilon Gnet}$. The standard deviation of the error associated with the net ground-water seepage estimate, $\sigma_{\varepsilon Gnet}$, was computed as follows (Pollman and others, 1991):

$$\sigma_{\varepsilon Gnet} = \sqrt{[(P)(CV_P)]^2 + [(E)(CV_E)]^2 + [(\Delta V)(CV_{\Delta V})]^2}, \qquad (7)$$

where

$CV_\theta = \sigma_{\varepsilon\theta}/\theta$ is the coefficient of variation for the hydrologic variable θ (expressed as a fraction).

Pond-volume changes were assigned a coefficient of variation of 5 percent, and monthly precipitation was assigned a coefficient of variation of 15 percent based on studies by Winter (1981). Pond-evaporation estimates were assigned a coefficient of variation of 15 percent, based on studies by Sacks and others (1994), who determined that the monthly coefficient of variation for pond-evaporation estimates computed using an energy-budget method had a mean of 15 percent, a lower quartile of 11 percent, and an upper quartile of 17 percent.

Pond Pumping Tests

To assess the effect of changing pond stage on ground-water seepage rates, a pond pumping test was conducted at each site during a period of dry hydrologic conditions, considered to be the most likely period when the ponds would be utilized for irrigation. These tests involved pumping water out of the pond to lower stage by 1–2 ft while monitoring pumping rates, climatic conditions, and ground-water levels. Recovery rates were compared to changes in pond storage to determine estimates of net ground-water seepage. Water levels in wells surrounding each pond were monitored to determine changes in ground-water gradients near the pond and provide data for model calibration. Water pumped from each pond was discharged at distances sufficiently away from the pond to ensure no re-infiltration.

Ground-Water Flow Models

Pond-aquifer flow was simulated using the USGS digital, three-dimensional, finite-difference ground-water flow model, MODFLOW (McDonald and Harbaugh, 1988). Steady-state and transient simulations were used to evaluate changes in ground-water levels and seepage prior to and during pond pumping tests. The steady-state models provided initial hydraulic property values and boundary conditions for the transient models. Changes in recharge, pond stage, ground-water levels, and seepage over time were simulated using the transient models. Model development, calibration, and sensitivity analyses are described in Appendix A for the Glynn County pond site and in Appendix B for the Bulloch County pond site.

Following calibration, the ground-water flow models were used to determine rates of net ground-water seepage at each pond under a range of pond stages. Flows into and out of each pond were determined using the MODFLOW postprocessor ZONEBUDGET (Harbaugh, 1990).

Pond-Aquifer Flow and Water Availability

Pond-aquifer flow and water availability were evaluated at two pond test sites in areas of contrasting hydrologic, physiographic, and soil conditions in coastal Georgia—one at Brunswick in Glynn County, and one in southern Bulloch County. Information obtained from testing and analysis at the two sites can be used to assess the potential of seepage ponds as supplemental sources of water for irrigation throughout the coastal region. The testing program at each of the two sites was conducted during a period of prolonged drought in coastal Georgia—August 1999 through July 2001.

Glynn County Pond Site

The Glynn County site is a 5-acre pond located on the campus of Coastal Georgia Community College at Brunswick, Ga. (fig. 2). The area is generally urbanized and includes paved parking lots and streets, buildings and homes, open fields, and stands of pine trees. A second pond is located about 750 ft northeast of the Glynn County pond. Field studies at the site were conducted during August 1999 through October 2000. For 9 of the 15 months during this period, monthly precipitation at the nearby National Weather Service Station at Brunswick was below the long-term average for 1971–2001 (fig. 3).

To characterize the hydrogeology of the site, 24 test wells were installed and completed at various depths in the surficial aquifer (table 1)—three wells were completed at depths of 48.5–53.8 ft (from 36.0 to 41.8 ft below NAVD 88), one well at a depth of 23.0 ft (10.8 ft below NAVD 88), and 18 wells at depths of 8.4–10.4 ft (1.9 to 3.8 ft above NAVD 88). In addition, one well tapping the surficial aquifer (well 34H506) was completed in the pond at a depth of 15.0 ft (0.4 ft below NAVD 88). Pond stage and ground-water levels in selected wells were monitored continuously.

The Glynn County pond was constructed during the early 1970s by excavating to a maximum depth of about 21 ft (about 13 ft below NAVD 88) into the upper part of a 50- to 55-ft-thick sequence of fine quartz sand that is part of the surficial aquifer (fig. 4). A dense, low-permeability clay layer was penetrated at about 50 ft below land surface during drilling of several deep wells. Natural gamma logs, from wells located within 0.75 mile (mi) of the pond site, indicate that the clay layer is at similar depths throughout the area. Beck (1978) estimated that the permeability of surficial sands at two locations near Brunswick, Glynn County, ranged from 4.7 to 7.5 gallons per day per square foot (from 0.6 to 1.0 foot per day). Pond-bottom sediments are similar to the surficial aquifer, with the exception that a layer of organic material has been deposited over the years.

A bathymetric survey of the pond using a fathometer and a Global Positioning System (GPS) device was conducted during August 1999—the pond bottom ranges in altitude from about 8 ft above to about 13 ft below NAVD 88 (fig. 5). At the highest observed stage during October 1999 (8.52 ft above NAVD 88), the volume of water in the pond was about 2,343,000 cubic feet (ft^3) with a surface area of about 222,000 square feet (ft^2). The volume decreased to about 1,767,000 ft^3 and surface area decreased to about 172,000 ft^2 when observed pond stage was lowest (5.34 ft above NAVD 88) during June 2000.

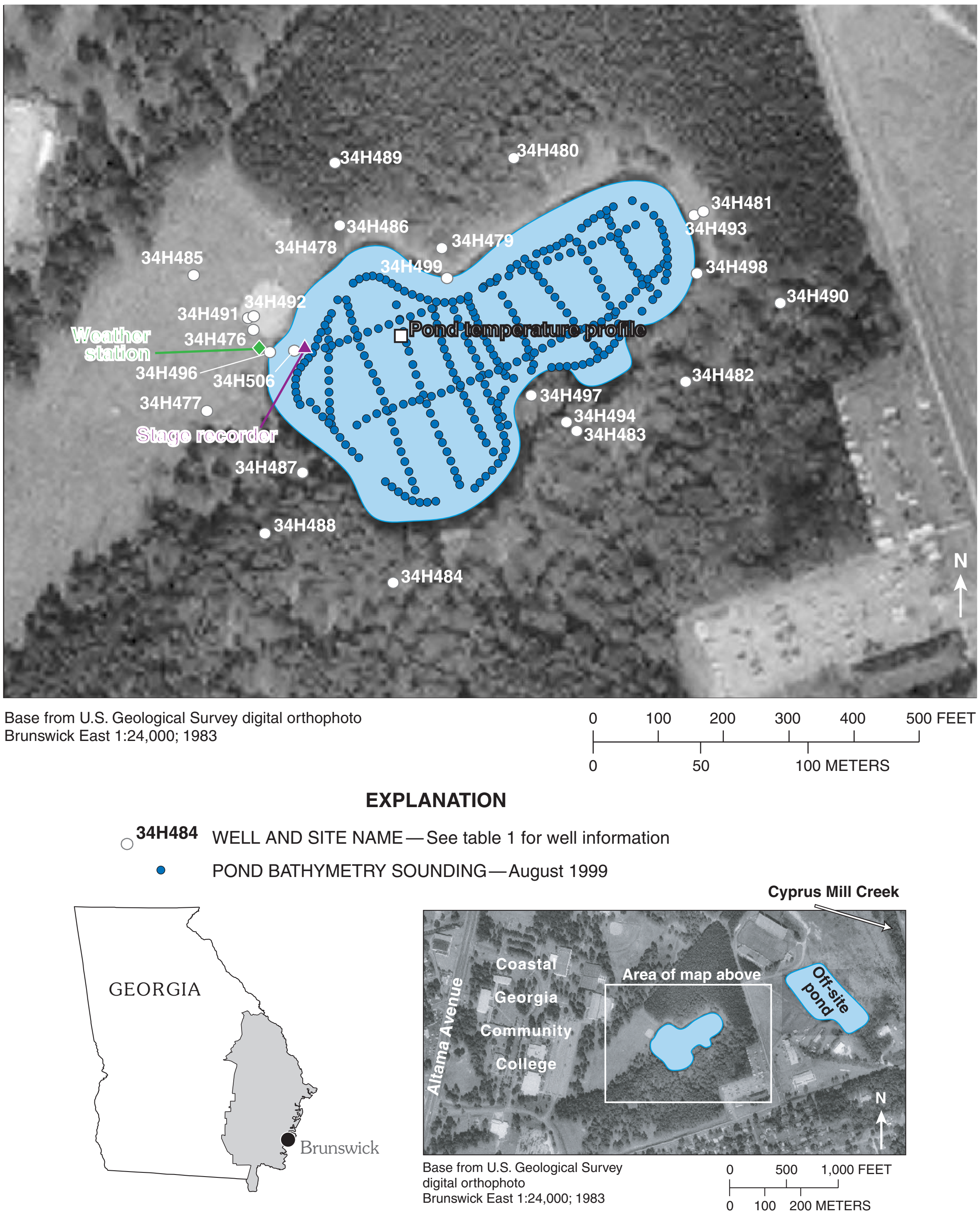


Figure 2. Glynn County pond site at Brunswick, Georgia, and locations of test wells, stage recorder, weather station, and bathymetry soundings.

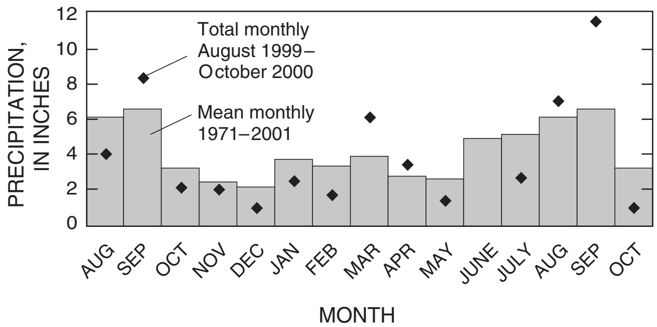


Figure 3. Mean monthly precipitation for 1971–2001, and total monthly precipitation for August 1999–October 2000, at the National Weather Service Station at Brunswick, Georgia.

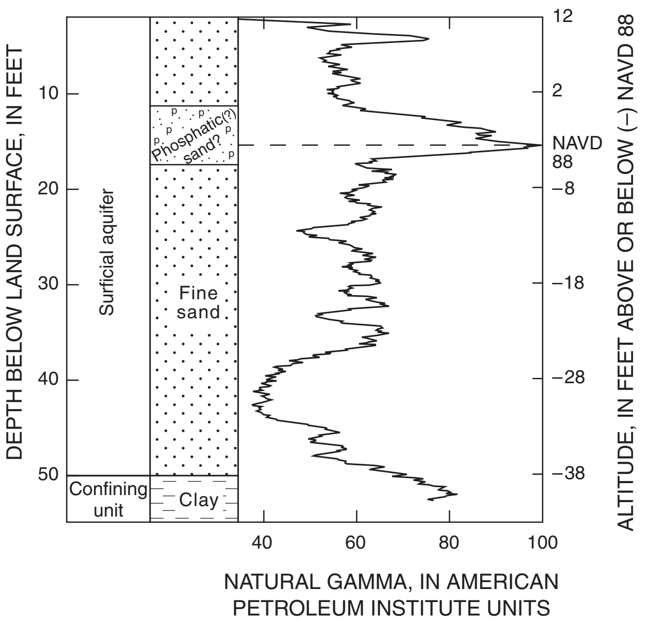


Figure 4. Subsurface geology at well 34H493 at the Glynn County pond site in Georgia.

To facilitate water-budget computations across a wide range of pond stages, polynomial regression models (fig. 6) were used to provide continuous relations between pond stage and pond volume, and between pond stage and pond area across a wide range of projected stages (from 14 ft below to 10 ft above NAVD 88). The relation for pond stage and pond area applies a second-order polynomial regression, whereas the relation for pond stage and pond volume applies a third-order polynomial regression (fig. 6).

Pond-Aquifer Flow

The sandy surficial aquifer is recharged by rainfall near the pond, and ground water flows toward the pond and discharges into it mostly along its western shoreline, with some flow entering along the pond bottom (fig. 7). Because of low relief and permeable soils, overland runoff is minimal at the site and water flows into the pond from the surficial aquifer. Water discharges from the pond primarily through evaporation or through ground-water seepage along the eastern shore of the pond toward an unnamed off-site pond and Cyprus Mill Creek.

Regionally, ground-water flow in the surficial aquifer is a subdued replica of land-surface topography. Water flows eastward from a topographic high located along Altama Boulevard, west of the pond site, toward Cyprus Mill Creek, a tidal estuary with elevations that are at or below NAVD 88 (see locations, fig. 2).

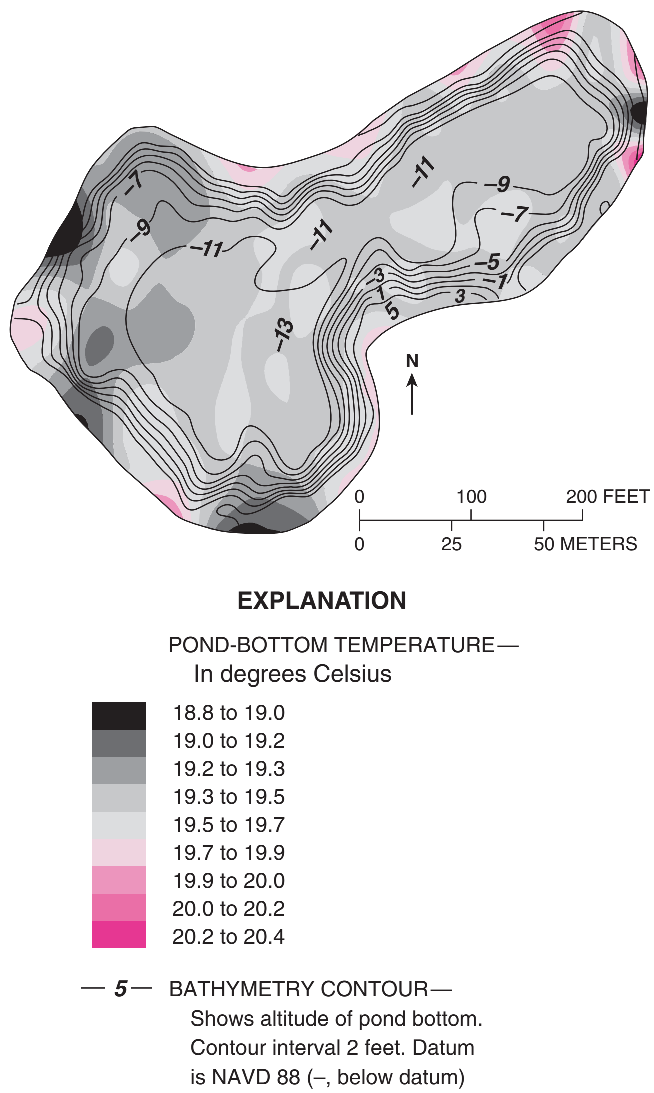


Figure 5. Pond bathymetry and pond-bottom temperature, Glynn County pond site in Georgia, August 1999.

Table 1. Well construction and location information at the Glynn County pond site in Georgia.

[degrees, °; minute, '; second, "]

Well number	Well name	Model layer	Latitude (NAD 83)	Longitude (NAD 83)	Altitude of land surface, in feet (NAVD 88)	Well depth in feet below land surface	Casing diameter (inches)	Open interval in feet below land surface		Water level on August 30, 2000 (feet below land surface)
								Top	Bottom	
34H476	CSSI Glynn Pond Test Site P-1	A1	31°10'59.15"	81°28'57.75"	12.12	8.4	2	3.4	7.09	8.4
34H477	CSSI Glynn Pond Test Site P-2	A1	31°10'57.90"	81°28'58.63"	12.60	9.8	2	4.8	7.39	9.8
34H478	CSSI Glynn Pond Test Site P-3	A1	31°11'00.36"	81°28'57.50"	13.63	9.8	2	4.8	7.26	9.8
34H479	CSSI Glynn Pond Test Site P-4	A1	31°11'00.37"	81°28'54.26"	11.79	10.0	2	5.0	6.37	10.0
34H480	CSSI Glynn Pond Test Site P-5	A1	31°11'01.76"	81°28'52.96"	11.36	9.8	2	4.8	5.40	9.8
34H481	CSSI Glynn Pond Test Site P-6	A1	31°11'00.83"	81°28'49.49"	12.11	10.0	2	5.0	6.32	10.0
34H482	CSSI Glynn Pond Test Site P-7	A1	31°10'58.20"	81°28'49.86"	12.44	10.3	2	5.3	6.11	10.3
34H483	CSSI Glynn Pond Test Site P-8	A1	31°10'57.46"	81°28'51.91"	11.79	10.0	2	5.0	6.10	10.0
34H484	CSSI Glynn Pond Test Site P-9	A1	31°10'55.15"	81°28'55.30"	13.39	9.8	2	4.8	6.43	9.8
34H485	CSSI Glynn Pond Test Site P-10	A1	31°11'00.03"	81°28'58.84"	13.82	10.0	2	5.0	7.72	10.0
34H486	CSSI Glynn Pond Test Site P-11	A1	31°11'00.76"	81°28'56.18"	12.34	10.4	2	5.4	6.61	10.4
34H487	CSSI Glynn Pond Test Site P-12	A1	31°10'56.91"	81°28'56.90"	12.82	10.4	2	5.4	6.58	10.4
34H488	CSSI Glynn Pond Test Site P-13	A1	31°10'45.97"	81°28'57.62"	12.84	10.2	2	5.2	6.89	10.2
34H489	CSSI Glynn Pond Test Site P-14	A1	31°11'01.75"	81°28'56.26"	12.99	10.0	2	5.0	6.91	10.0
34H490	CSSI Glynn Pond Test Site P-15	A1	31°10'55.96"	81°28'57.58"	11.87	9.9	2	4.9	6.28	9.9
34H491	CSSI Glynn Pond Test Site P-16	A5	31°10'59.34"	81°28'57.86"	12.21	23.0	2	18.0	7.17	23.0
34H492	CSSI Glynn Pond Test Site P-17	A8	31°10'59.37"	81°28'57.76"	12.54	48.5	2	43.5	7.20	48.5
34H493	CSSI Glynn Pond Test Site P-18	A8	31°11'00.76"	81°28'49.61"	11.96	53.8	2	48.8	6.02	53.8
34H494	CSSI Glynn Pond Test Site P-19	A8	31°10'57.62"	81°28'52.11"	12.00	49.6	2	44.6	6.40	49.6
34H496	CSSI Glynn Pond Test Site P-20	A1	31°10'58.75"	81°28'57.49"	9.81	10.0	2	5.0	6.71	10.0
34H497	CSSI Glynn Pond Test Site P-21	A1	31°10'58.05"	81°28'52.71"	10.03	10.0	2	5.0	6.31	10.0
34H498	CSSI Glynn Pond Test Site P-22	A1	31°10'59.91"	81°28'49.62"	9.39	10.0	2	5.0	6.29	10.0
34H499	CSSI Glynn Pond Test Site P-23	A1	31°10'59.90"	81°28'54.20"	10.60	10.0	2	5.0	4.13	10.0
34H506	CSSI Glynn Pond Test Site Dock Well	A3	31°10'58.82"	81°28'57.01"	14.59	15.0	2	11.0	7.28*	15.0

*Water level, in feet below top of casing, measured November 6, 1999

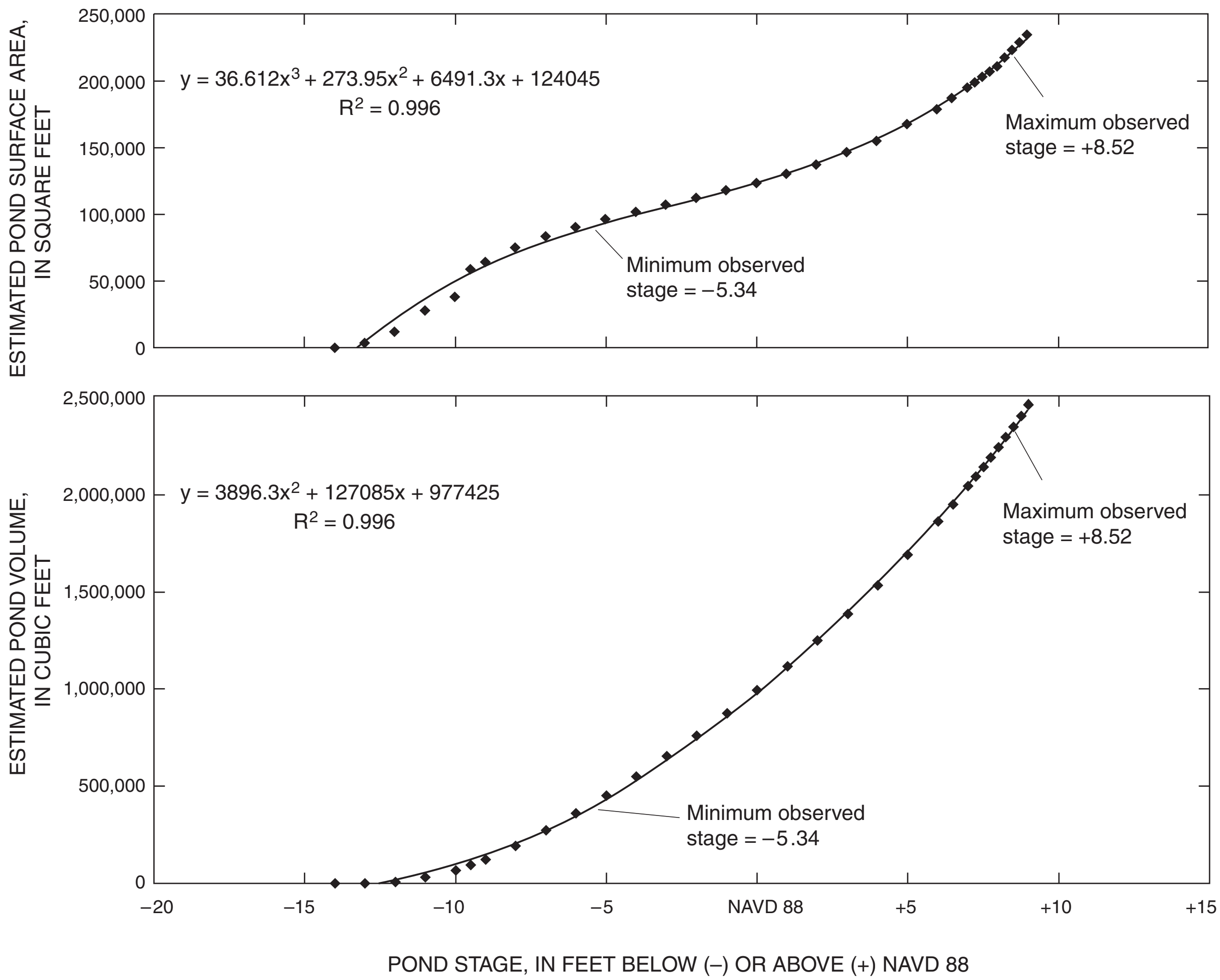


Figure 6. Regression models showing relation of pond stage to estimated surface area and estimated volume, Glynn County pond site in Georgia.

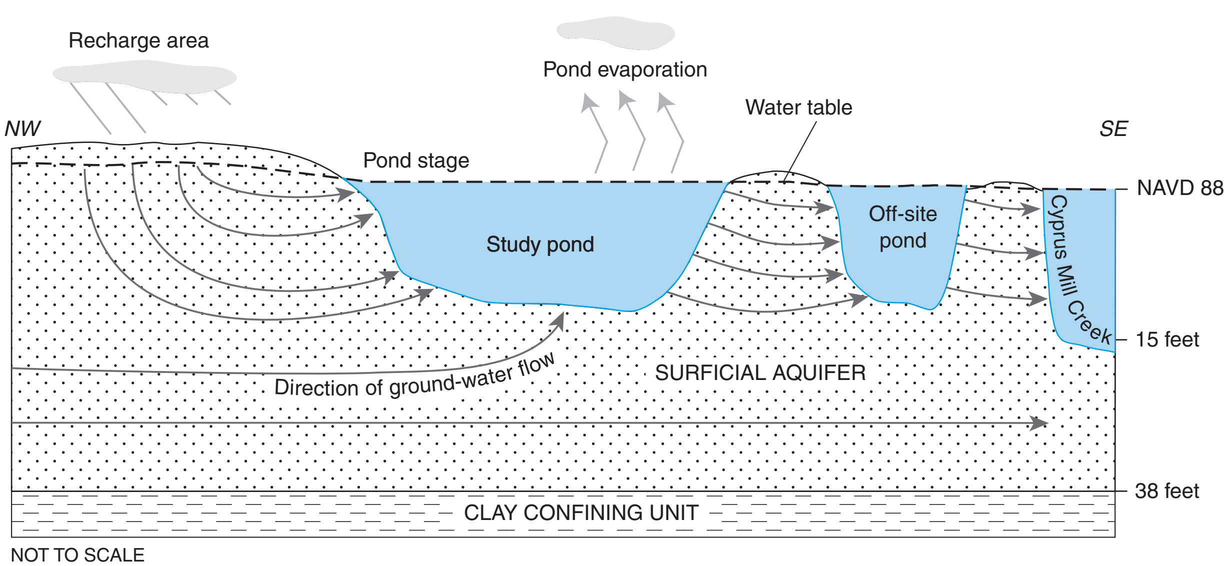


Figure 7. Conceptual model of the hydrogeologic framework and pond-aquifer flow for the Glynn County pond site in Georgia.

A water-table map for September 19, 1999, was constructed using data from 14 test wells completed in the uppermost part of the surficial aquifer (fig. 8). The map indicates that locally pond water recharges the aquifer along the northern, southern, and eastern shores, and aquifer water seeps into the pond along the western shore (fig. 8). A bottom-temperature survey of the pond water during August 1999 was conducted using a YSI Inc. temperature-specific conductance probe that was trolled at a depth of about 0.5 ft above the pond bottom with position recorded using a GPS device. Data from the survey indicate that pond-bottom temperatures ranged from 18.8 to 20.4°C and suggest that cooler ground water seeps into the pond along parts of the western shore (fig. 5). During September 1999, a ground-water high located about 50 ft west of the pond resulted in development of a local ground-water divide. Periodic and continuous water-level data at the pond site indicate that this divide is a temporary feature that is not present during most of the year.

Paired test wells completed in the upper and lower parts of the surficial aquifer indicate that vertical head gradients generally are small within the study area; thus, horizontal gradients to the pond are more dominant. This relation is demonstrated on a map showing vertical head differences at three paired well sites adjacent to the pond on August 30, 2000 (fig. 9).

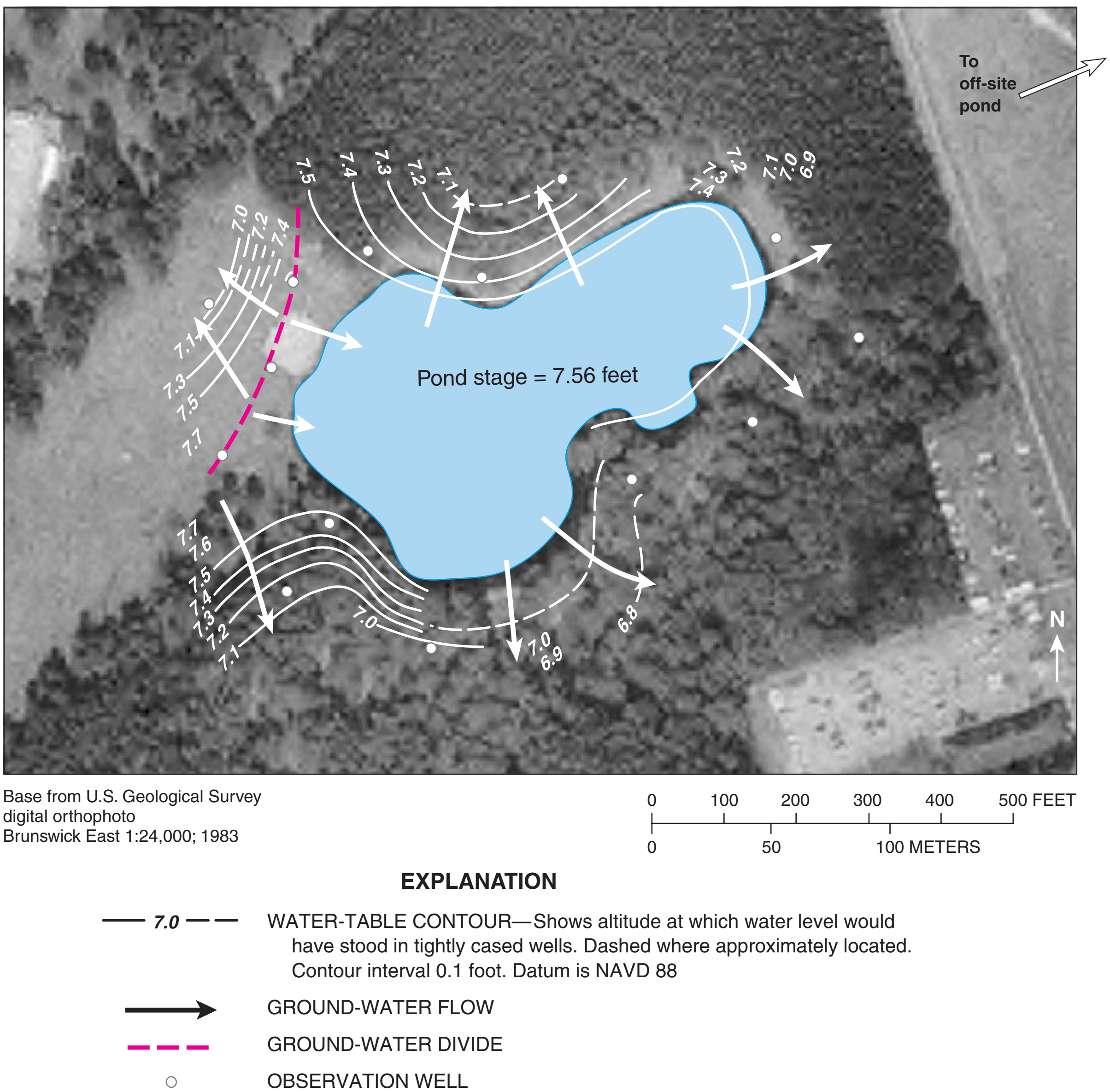


Figure 8. Water-table surface of the surficial aquifer at the Glynn County pond site in Georgia, September 19, 1999 (from Peck and others, 2001).

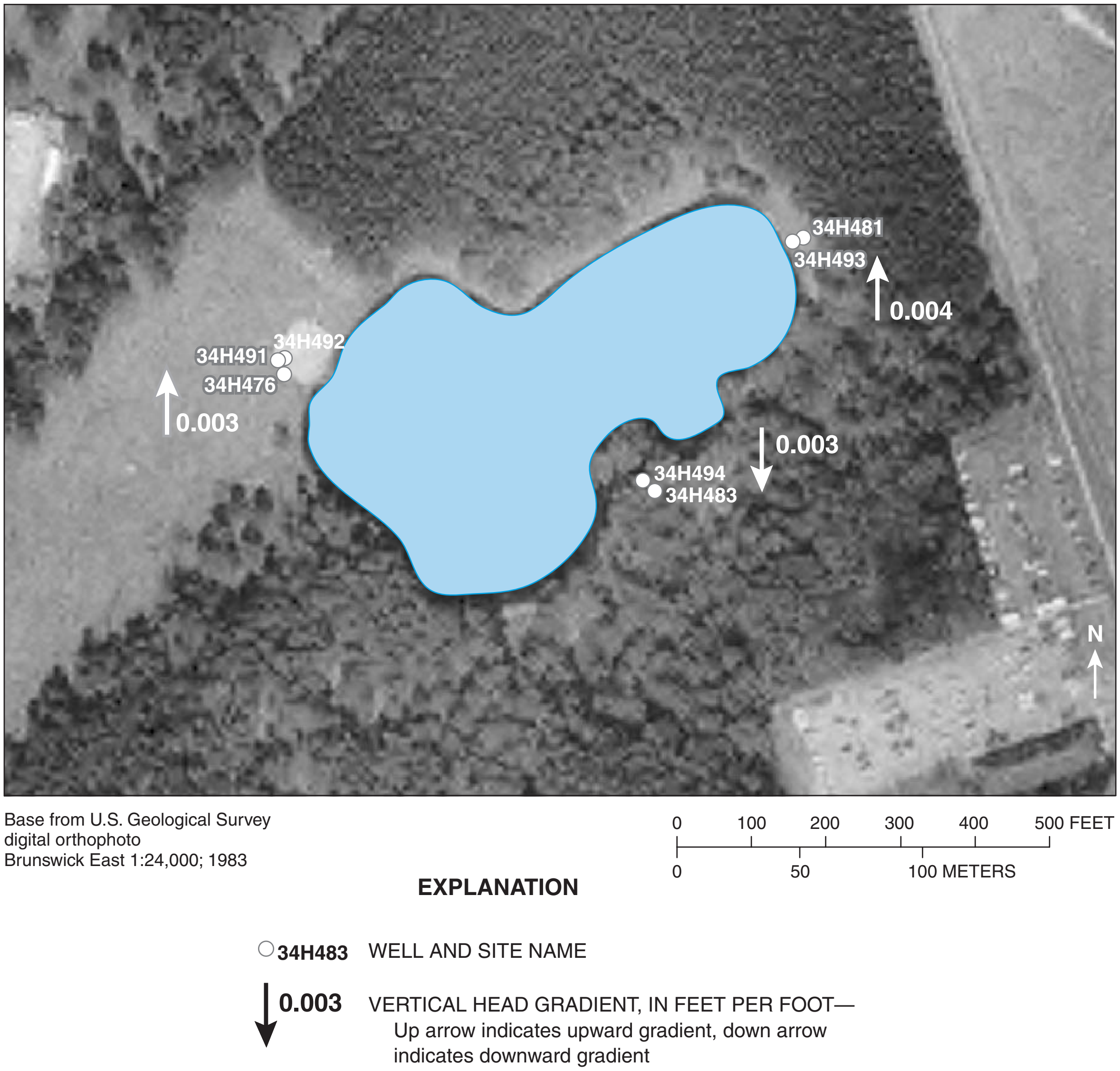


Figure 9. Vertical head gradient in well clusters near the Glynn County pond site in Georgia, August 30, 2000.

Pond stage and ground-water levels show a rapid response to precipitation events and a decline during dry periods in response to increased evapotranspiration. These responses are illustrated on hydrographs showing mean daily water levels in wells 34H476 and 34H492, pond stage, and cumulative net precipitation (precipitation minus evapotranspiration) (fig. 10).

Estimated Net Ground-Water Seepage

Net ground-water seepage rates were computed using water-budget analysis, model simulation, and results of a pond pumping test. The water-budget analysis was conducted at 10-day intervals from November 6, 1999, through April 24, 2000 (pretest period). The pond pumping test was conducted during May 1–3, 2000. Model simulations covered the period November 6, 1999, through May 3, 2000.

Water Budget

During November 1999–April 2000, maximum daily rainfall was 1.94 inches in March 2000; and average daily evapotranspiration ranged from 0.01 inch during March 2000 to 0.20 inch during April 2000 (average daily rate 0.08 inch) (fig. 11). Pond-stage altitude prior to the pumping test ranged from 7.73 ft during January 2000 to 8.39 ft during November 1999 (fig. 10), with a corresponding estimated volume change of about 125,000 ft^3 (based on polynomial regression, fig. 6).

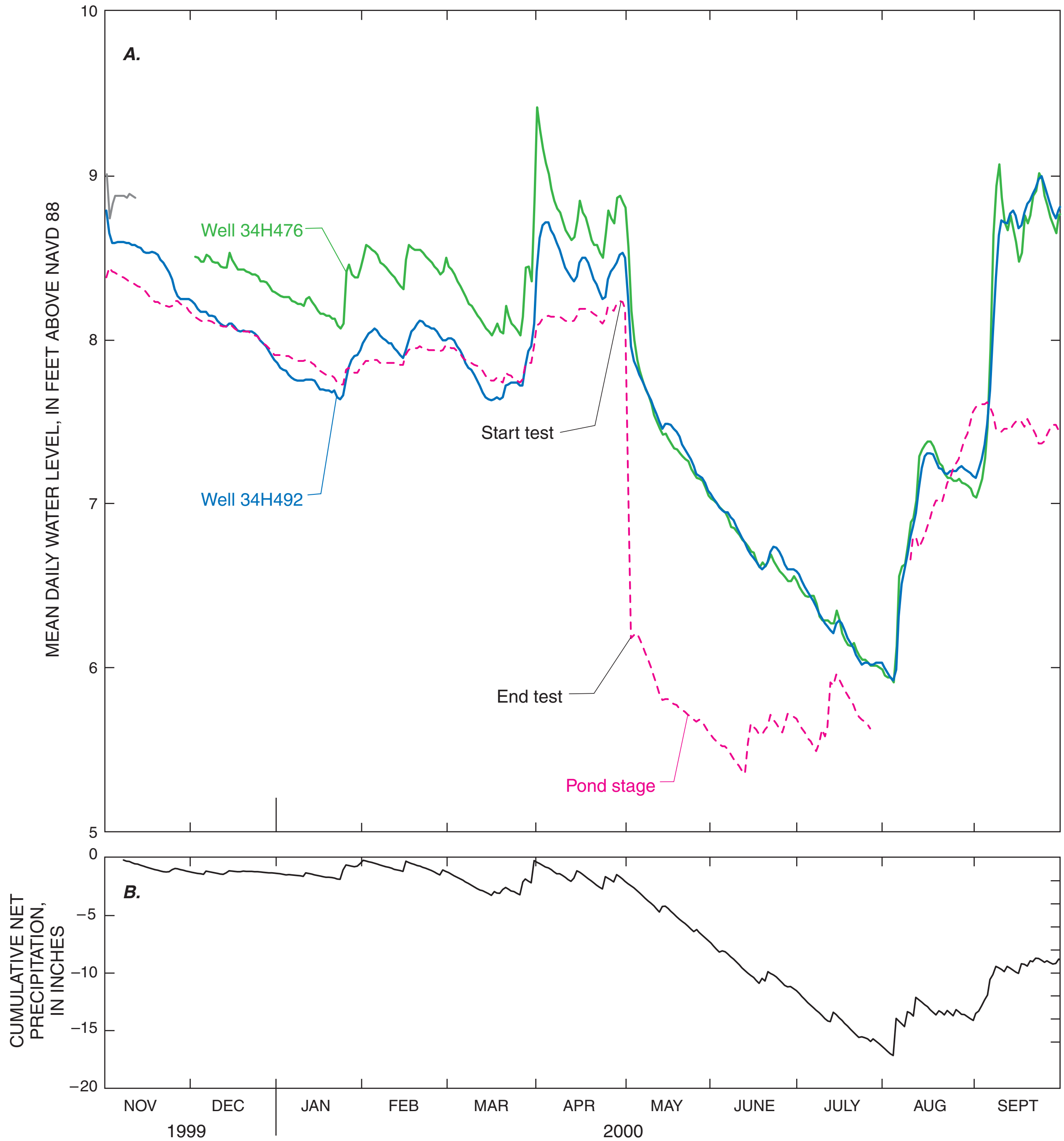


Figure 10. (*A*) Mean daily water levels in wells 34H476 and 34H492 and pond stage; and (*B*) calculated cumulative net precipitation (precipitation minus evapotranspiration), Glynn County pond site in Georgia, November 1999–September 2000.

Ground-water recharge to the shallow ground-water flow system can be approximated from net precipitation. Because overland runoff is negligible at the site, part of the precipitation remaining after evaporative loss (net precipitation) enters the shallow ground-water system, with an unknown amount lost to plant transpiration. The relation between cumulative net precipitation and ground-water levels is demonstrated in the hydrographs shown in figure 10. In general, when cumulative net precipitation is high, ground-water levels are high (indicating ground-water recharge), and when cumulative net precipitation is low, ground-water levels are low. The ground-water component of the water budget is illustrated by comparing plots showing cumulative daily net precipitation (precipitation minus evapotranspiration) and cumulative daily change in pond volume over time (fig. 12). With the assumption that surface runoff is negligible and errors in estimating atmospheric fluxes and pond volume changes are reasonably small and unbiased, the difference between the two lines represents cumulative net ground-water seepage.

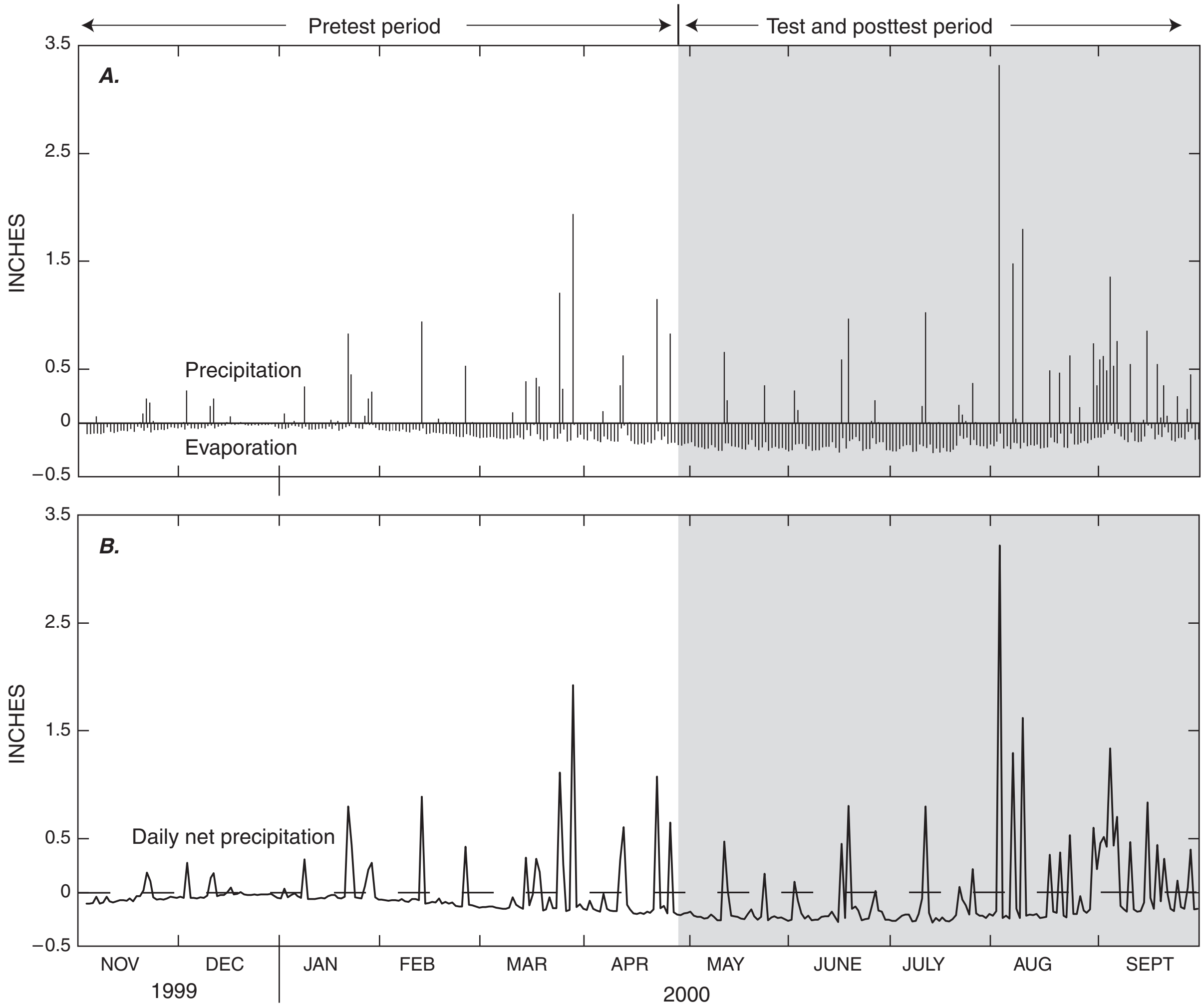


Figure 11. (*A*) Daily measured precipitation and estimated evaporation; and (*B*) estimated daily net precipitation (precipitation minus evapotranspiration) at the Glynn County pond site in Georgia, November 1999–September 2000.

The temporal distribution of net ground-water seepage computed using the water-budget method prior to the pumping test is related to patterns in precipitation (fig. 12). Net seepage values above the zero line on figure 12 represent periods of net seepage into the pond, whereas values below the zero line represent periods of net seepage out of the pond. Net seepage generally is positive during periods of high rainfall, indicating more ground water is entering the pond than leaving it. Conversely, net seepage generally is negative during periods of low rainfall, indicating that more ground water is leaving the pond than entering it. In general, net ground-water seepage was negative during the pretest period, corresponding to the observed decrease in pond stage. Computed net seepage per 10-day period ranged from –1,600 ft^3/d (-8.3 gal/min) during January 15–25, 2000, to 3,000 ft^3/d (15 gal/min) during March 26–April 4, 2000 (fig. 12). Confidence intervals shown on figure 12 were derived using equation 7 and error estimates derived from the hydrologic literature.

Pond Pumping Test

To estimate rates of net ground-water seepage under extreme conditions (dry, low pond stage), a pumping test was conducted in the pond during May 1–3, 2000. A large-capacity pump was used to lower the water level in the pond by 2 ft during a 32-hour period. Discharge water was piped about 0.1 mi away from the pond to a drainage ditch south of the pond. Following cessation of pumping, rates of recovery were monitored for 48 hours (fig. 13). During the test and recovery period, there was no precipitation and estimated evaporation was about 0.2 inch per day (in/d). Thus, changes in pond stage during the test were mainly due to the volume of water removed by pumping and contributed by ground-water seepage. Seepage estimates are limited by the accuracy of precipitation and discharge measurements, evaporation estimates, and pond-volume estimates determined using pond-stage and bathymetric data. Determination of seepage rates during the pumping test was not possible because the flowmeter measuring pumping rates was highly inaccurate and variable; however, estimated rates of seepage were computed following cessation of pumping.

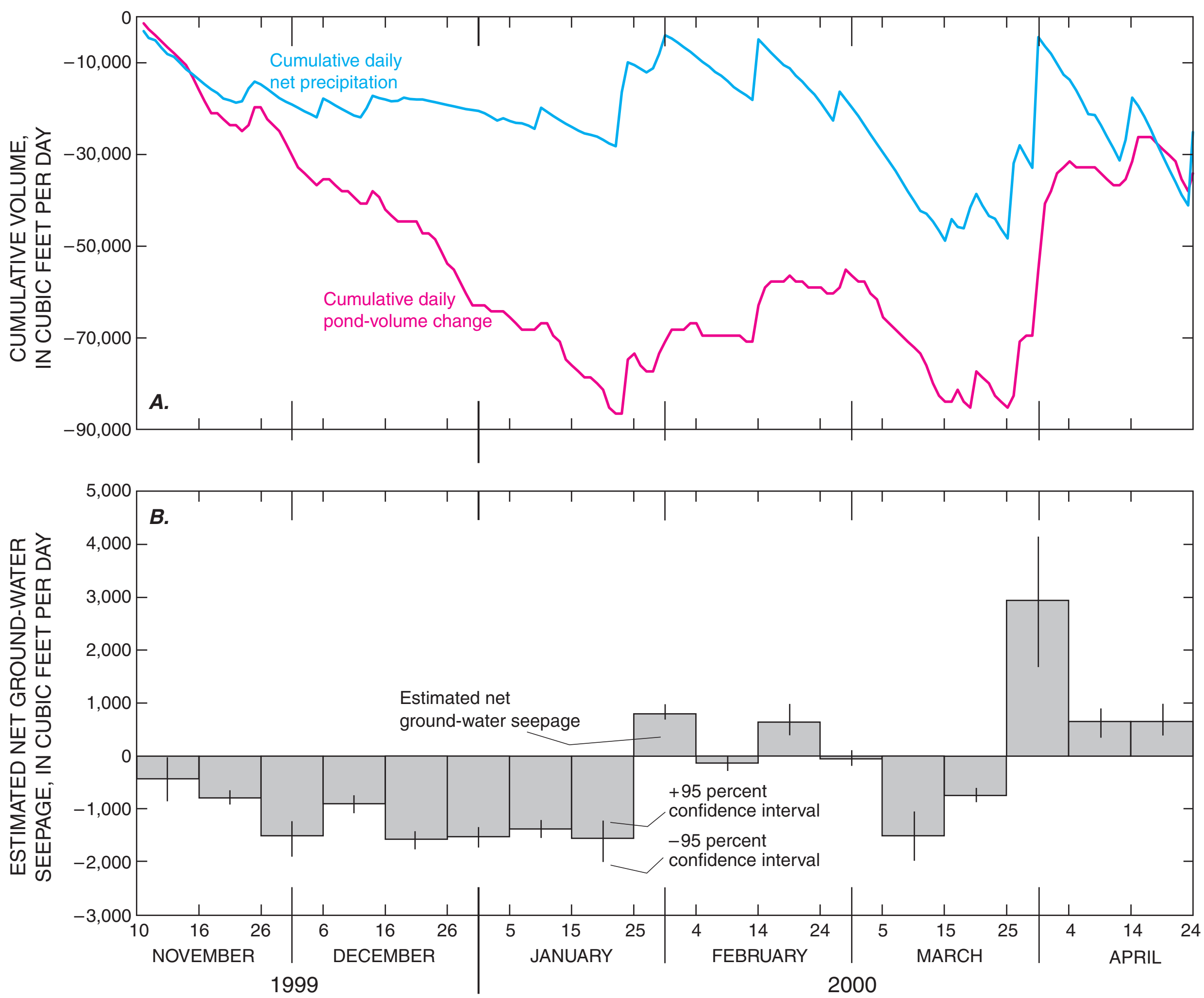


Figure 12. (*A*) Cumulative daily net precipitation (precipitation minus evapotranspiration) and cumulative daily pond-volume changes; and (*B*) estimated net 10-day average ground-water seepage, Glynn County pond site in Georgia, November 1999–April 2000.

Net ground-water seepage was estimated based on observed pond-volume changes during recovery and the relation:

$$\text{Net ground-water seepage} = \text{change in pond volume} + \text{evaporation} - \text{precipitation} \qquad (8)$$

Rates of ground-water seepage vary depending on pond stage and related changes in hydraulic gradient and cross-sectional area. Decreasing pond stage results in an increased hydraulic gradient toward the pond and increased rates of seepage to the pond. Following cessation of pumping, pond stage recovered about 0.1 ft in 48 hours (fig. 13), corresponding to a rate of about 8,100 ft^3/d (42 gal/min), which when combined with the estimated evaporation rate of about 4,300 ft^3/d (22 gal/min), equals a net seepage rate of about 12,400 ft^3/d or 64 gal/min. Applying an error analysis of precipitation, evaporation, and volume using equations 6 and 7 indicates that the net ground-water seepage estimate has a margin of error of +/–1,300 ft^3/d (6.8 gal/min). Values estimated using the recovery analysis compare favorably with the estimated seepage rate reported by Beck (1978) for a hypothetical 15-ft-deep, 100-ft-radius pond (69 gal/min) in a similar hydrogeologic setting.

In monitoring wells, the water-level response to lowered pond stage varied depending on distance from the pond. Wells located directly adjacent to the pond showed water-level declines of 1.0–1.5 ft during the test (well 34H496, fig. 13), whereas wells located farther away from the pond showed less pronounced responses of 0.5 ft or less (wells 34H476 and 34H485, fig. 13). Because there was no appreciable rainfall in the area for several weeks following the cessation of pumping, water levels in many of the wells continued to decline, reflecting evapotranspiration and transient drainage of the water table in response to the lowered pond stage (fig. 10).

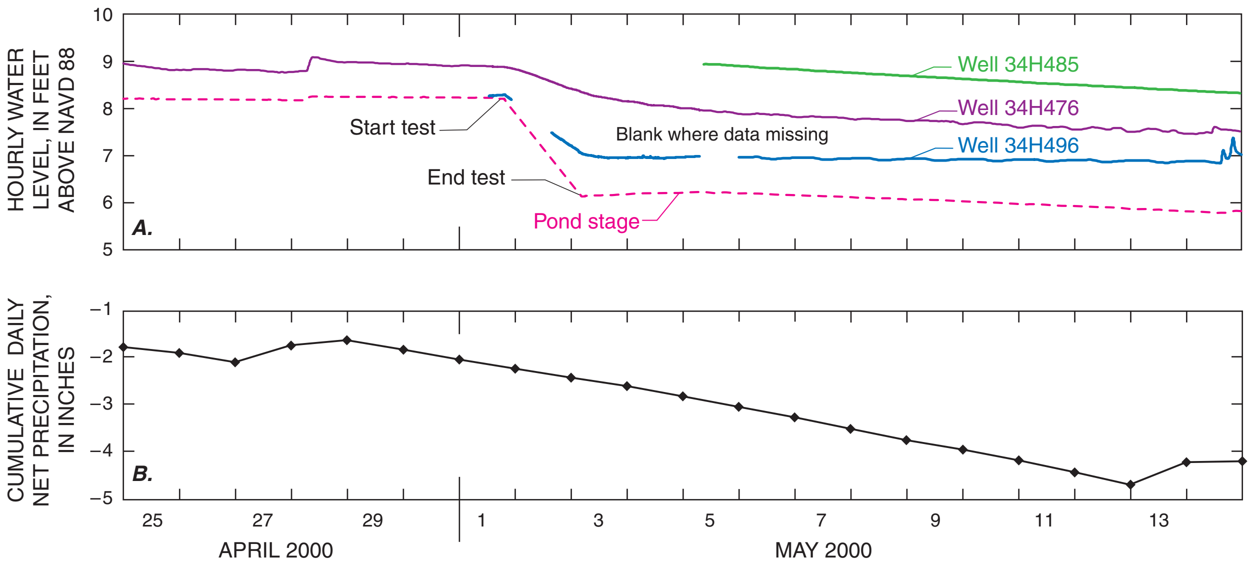


Figure 13. (*A*) Hourly water levels in wells 34H476, 34H485, and 34H496 and pond stage; and (*B*) cumulative daily net precipitation (precipitation minus evapotranspiration), Glynn County pond site in Georgia, April 25, 2000–May 14, 2000.

Ground-water levels continued to decline until several rainfall events during July 2000—almost 2 months after the pumping test—caused water levels to rise. Although pond stage showed some recovery following the test in response to rainfall during August and September, as of December 2000, pond stage remained about 0.8 ft below pretest conditions. Conversely, ground-water levels had recovered to pretest conditions by early September 2000.

Ground-Water Flow Model

The Glynn County pond site model utilized steady-state and transient simulations to evaluate changes in ground-water level and seepage to and from the pond prior to and during a 32-hour pumping test. Initial conditions were simulated as steady state, followed by simulation of transient changes in recharge, pond stage, ground-water levels, and seepage. Model development, calibration, and sensitivity are described in Appendix A.

For the initial steady-state simulation of pretest conditions, ground-water flow directions are from the western boundary and into the pond along the western and northern shores (fig. 14A). Pond water recharges the aquifer along the south-eastern shoreline. Some water discharging from the pond seeps into the second pond site, and the remaining water moves toward Cyprus Mill Creek, east of the simulated area. These flow patterns compare favorably to the conceptual model of ground-water flow (fig. 7), regional ground-water flowpaths as inferred from topography, and locally to water-table maps derived from test-well data (fig. 8). Some differences are apparent between the simulated and observed water-table maps. The observed-conditions map for November 1999 shows water flowing toward the pond from the western shore and discharging from all other directions, whereas the simulated map shows water entering from the western, northern, and southern shores, and discharging from the east-southeastern shores. In addition, the divide west of the pond site is evident on the observed-conditions map but not on the simulated map. These differences may reflect changes in water-table conditions during the two periods—water levels were lower during November 1999 than during May 2000, resulting in different flow conditions near the pond.

A map showing the simulated water table after 32 hours of pumping indicates a depression surrounding the study pond, with a steepened hydraulic gradient that captures flow along all shorelines (fig. 14B). This depression resulted in the development of a ground-water divide between the study pond and the off-site pond located east of the site.

The MODFLOW post-processor ZONEBUDGET (Harbaugh, 1990) was used to enable determination of simulated net ground-water seepage at the pond. In this procedure, the pond is designated as a separate “zone,” and flows into and out of that zone are summarized. For the pretest period, simulated 10-day-average net seepage values compare favorably with values estimated using the water-budget analysis, ranging from a low of –2,200 ft^3/d (–11.4 gal/min) during December 26, 1999–January 5, 2000, to a high of 2,600 ft^3/d (13.5 gal/min) during March 25–April 4, 2000, with a median rate of –360 ft^3/d (–1.9gal/min) (fig. 15). An exception occurs during January 15–25, 2000, when simulated net seepage rises 10 days earlier than determined through water-budget estimates. Despite this discrepancy, simulated values generally showed a good match to estimated values (see bar graph, fig. 15).

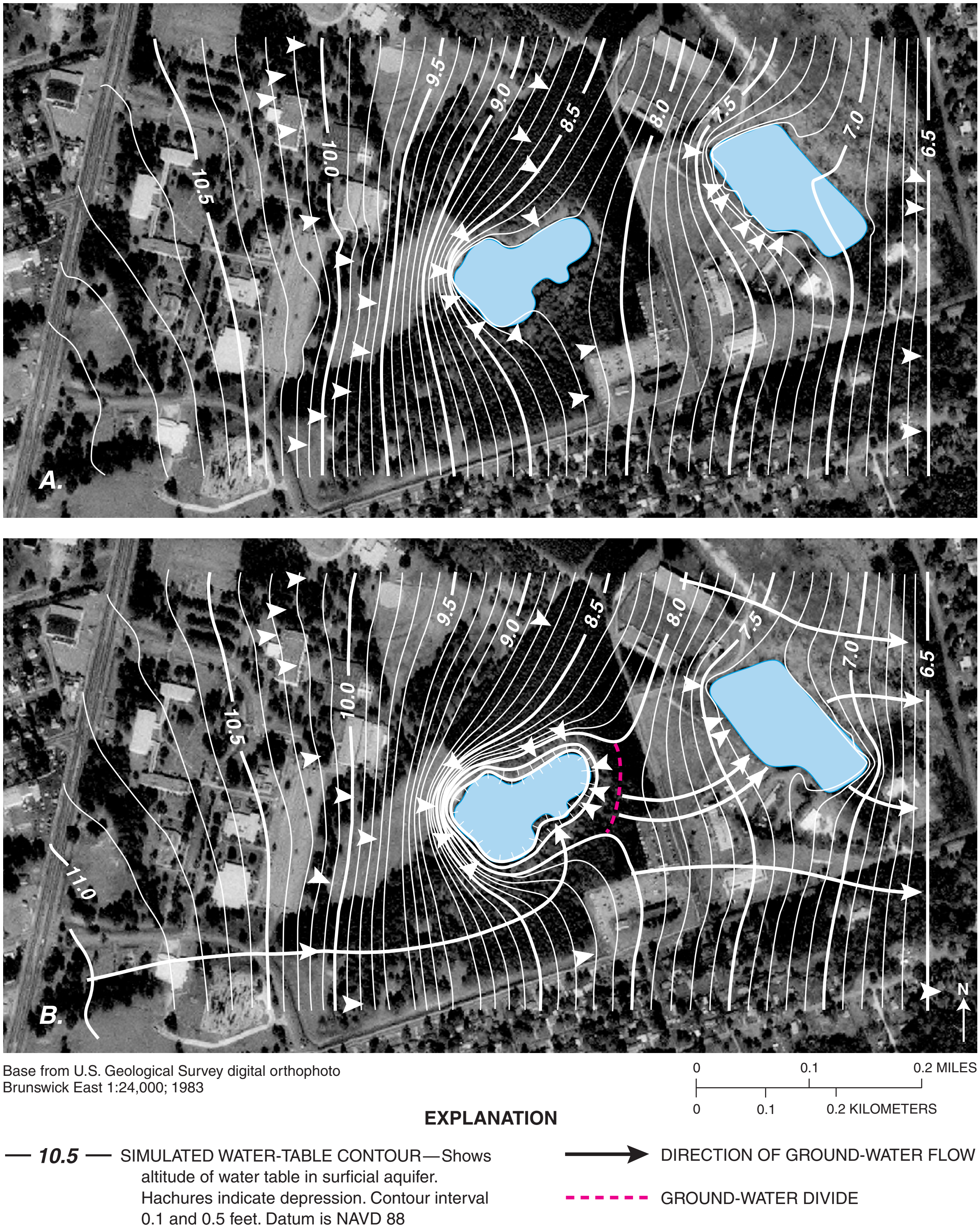


Figure 14. Simulated water-table contours of the surficial aquifer at the Glynn County pond site in Georgia (*A*) prior to pumping test on May 1, 2000; and (*B*) after pumping test on May 3, 2000.

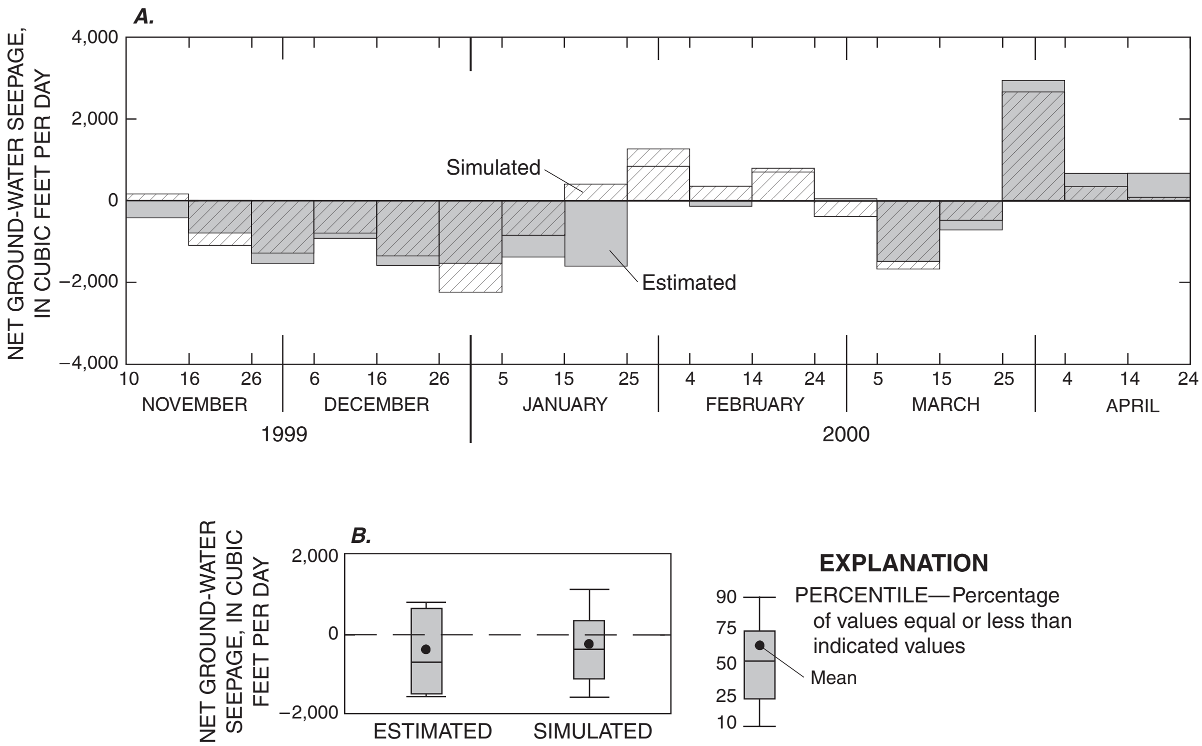


Figure 15. Estimated and simulated 10-day average net ground-water seepage at the Glynn County pond site in Georgia, November 1999–April 2000—(*A*) graph and (*B*) boxplot summarizing all values.

Rates of ground-water seepage vary depending on pond stage and related changes in hydraulic gradient and cross-sectional area. To evaluate the impact of changing hydraulic gradients on ground-water seepage, simulated transient net seepage was plotted with measured pond stage during the pumping test (fig. 16). Decreasing pond stage results in an increased hydraulic gradient toward the pond and increased rates of ground-water seepage into the pond. Simulated net ground-water seepage varied from 1,500 ft^3/d (7.8 gal/min) at the beginning of the test (high pond stage and low hydraulic gradient) to 19,900 ft^3/d (103 gal/min) at the end of the test (low pond stage and high hydraulic gradient). Median simulated net ground-water seepage during the pumping test was 12,100 ft^3/d (63 gal/min).

The calibrated ground-water flow model provided estimates of the vertical and horizontal hydraulic conductivity of the surficial aquifer. Initial values of hydraulic conductivity were adjusted during calibration based on observed head and calculated net ground-water seepage into the pond. Because estimates of hydraulic properties in the surficial aquifer are sparse, these estimates are useful to help guide development of the surficial aquifer and provide information to help development of other ground-water models in the area. Model-calibrated horizontal hydraulic conductivity ranged from 0.5 to 50 ft/d, and vertical hydraulic conductivity ranged from 0.5 to about 40 ft/d.

Water Availability

Available storage in the Glynn County pond ranged from about 1.8 to 2.4 million cubic feet (from 13.5 to 18 million gallons—Mgal) under the observed range of stage (from 5.34 to 8.75 ft) during 1999–2000 (figs. 6 and 10). Net ground-water seepage rates determined using the water-budget method and through flow-model simulation, indicate that the Glynn County pond was mostly losing water during November 1999–April 2000—more water moved from the pond than entered the pond (fig. 15). Most ground-water seepage entered the pond following major rainfall events that provided recharge to the surficial aquifer. This recharge raised water levels in the surficial aquifer and produced steepened hydraulic gradients toward the pond. Graphs of cumulative daily net precipitation, cumulative daily pond volume change, and estimated seepage demonstrate the relation between recharge events and estimated net ground-water seepage (fig. 12).

Net ground-water seepage rates vary in response to changing pond stage. Simulated values during a 32-hour pumping test indicate that ground-water seepage to the pond increases with decreased pond stage (fig. 16). A 2-ft drop in pond stage during the test resulted in an additional 18,400 ft^3/d (95 gal/min) of ground-water seepage into the pond. Note that these estimates are only appropriate for climatic and ground-water-level conditions similar to those observed during the test period. Different conditions could cause significant differences in hydraulic gradients near the pond and affect seepage rates.

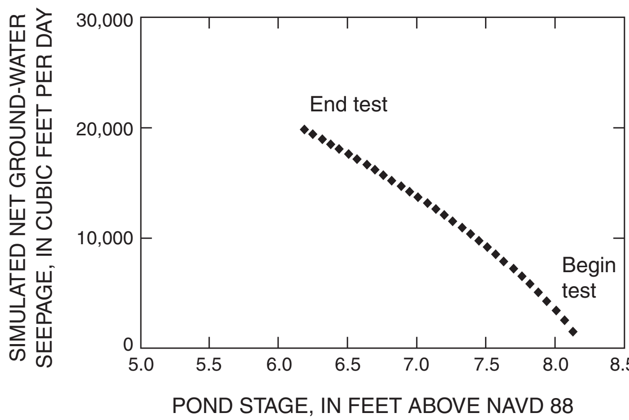


Figure 16. Pond stage and simulated net ground-water seepage, Glynn County pond site in Georgia, May 1–3, 2000.

Bulloch County Pond Site

The Bulloch County site is a 5-acre pond located in southern Bulloch County about 20 mi southeast of Statesboro, Ga. (figs. 1 and 17). The area generally is rural, and the site is located adjacent to a plowed cotton field adjacent to Interstate Highway 16. Field studies at the site were conducted during October 2000 through July 2001. For 8 of the 10 months during this period, monthly precipitation at the nearby National Weather Service Station at Brooklet was at or below the long-term average for 1971–2001 (fig. 18).

The pond was excavated as a borrow pit for road-fill material during construction of nearby Interstate Highway 16 during the 1970s. The pond was excavated into layers of clay and clayey sand and is underlain by a clayey sand layer that comprises the uppermost part of the surficial aquifer (fig. 19). The surficial aquifer is underlain by layers of clay and sandy clay that act as a semiconfining unit.

To characterize geologic and hydrologic conditions, eight shallow wells (from 5 to 16 ft deep) were installed, two of which were equipped with recorders to monitor ground-water levels continuously (table 2). In addition to the shallow wells, eight deeper (greater than 19 ft depth) test wells and one 62-ft-deep corehole were drilled around the pond to better define the site hydrogeology. Drill cuttings were collected and examined from each well, and borehole geophysical logs were collected in wells 33R036 and 33R037 to characterize subsurface geology (fig. 19).

A bathymetric survey conducted during October 2000, using a fathometer and GPS device, indicates pond-bottom altitude ranges from about 81 to 88 ft above NAVD 88 (fig. 20). The estimated volume of water in the pond at the highest observed stage during April 2001 (86.5 ft above NAVD 88) was about 774,000 ft^3 (5.79 Mgal) with a surface area of about 216,000 ft^2. When observed pond stage was lowest (83.7 ft above NAVD 88) during June 2001, the volume decreased to about 263,000 ft^3 (1.97 Mgal) and surface area decreased to about 149,000 ft^2 (fig. 21). To facilitate water-budget computations across a wide range of pond stages, polynomial regression models (fig. 21) were used to provide continuous relations between pond stage and pond volume, and between pond stage and pond area across a wide range of projected stages. The relation for pond stage and pond area applies a third-order polynomial regression, whereas the relation for pond stage and pond volume applies a second-order polynomial regression (fig. 21).

Pond-Aquifer Flow

The surficial aquifer is recharged by rainfall near the pond; ground water flows toward the pond and discharges into it where clayey surficial deposits are breached or thin (fig. 22). Water leaves the pond primarily through evaporation or through ground-water seepage.

Regionally, ground-water flow in the surficial aquifer is a subdued replica of land-surface topography. Water flows northward from a topographic high located along Interstate Highway 16, south of the pond site, toward Lower Black Creek (see locations, fig. 17).

Water-level data from 12 wells were used to construct a potentiometric-surface map of the surficial aquifer for April 27, 2001 (fig. 23); the map indicates that ground-water flow generally was toward the pond south and east of the pond or northward toward Lower Black Creek (see location, fig. 17), north of the pond. Steepened gradients, as indicated by closely spaced contours along the southern part of the map, may reflect modifications to the original topography of the area—fill material, used to build up depressed areas along Interstate Highway 16, increased land-surface altitudes and corresponding water-table altitudes, producing steepened hydraulic gradients. Despite this topography, overland runoff to the pond is minimal because of a berm surrounding the pond, drainage ditches along the eastern and southern shores, and an intermittent stream channel along the western shore. In addition, a plowed field to the north and east of the pond reduces quantities of runoff due to higher permeability and infiltration capacity of tilled soil. Two depressions are evident on the potentiometric-surface map—one beneath the western shore of the pond and one in the farmed area northeast of the pond (fig. 23). The depression beneath the pond is in an area where the course of an unnamed tributary was altered when the borrow pit was excavated. The depression in the farmed area occurs beneath a topographically low area.

The pond is hydraulically separated from the surficial aquifer across most of the pond area due to the low permeability of the upper soil layer; however, this low permeability layer was breached at the eastern end of the pond. At that location, an excavation was cut through the sandy clay layer and into an underlying clayey sand layer of higher permeability, which resulted in flooding of, and eventual abandonment of, the borrow pit. During the construction of shallow well 33R028 (see location, fig. 17), a sand layer was penetrated at a depth of about 9 ft and the water level in the well rose above land surface, indicating confined conditions near the pond. The clayey soil apparently acts as a confining or semiconfining unit to the uppermost part of the surficial aquifer in the vicinity of the pond.

Base from U.S. Geological Survey digital orthophoto
Lanier 1:24,000; 1993

0 500 1,000 FEET
0 100 200 METERS

EXPLANATION

WELL AND SITE NAME—See table 2 for well information

33R042 Test well

33R035 Existing well

Figure 17. Bulloch County pond site in Georgia and locations of test wells, stage recorder, and weather station.

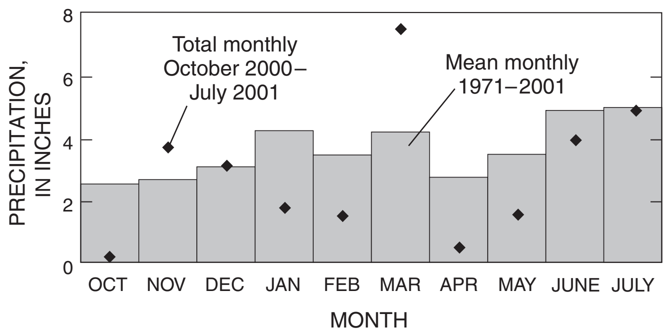


Figure 18. Mean monthly precipitation, 1971–2001, and total monthly precipitation, October 2000–July 2001, at the National Weather Service Station at Brooklet, Georgia.

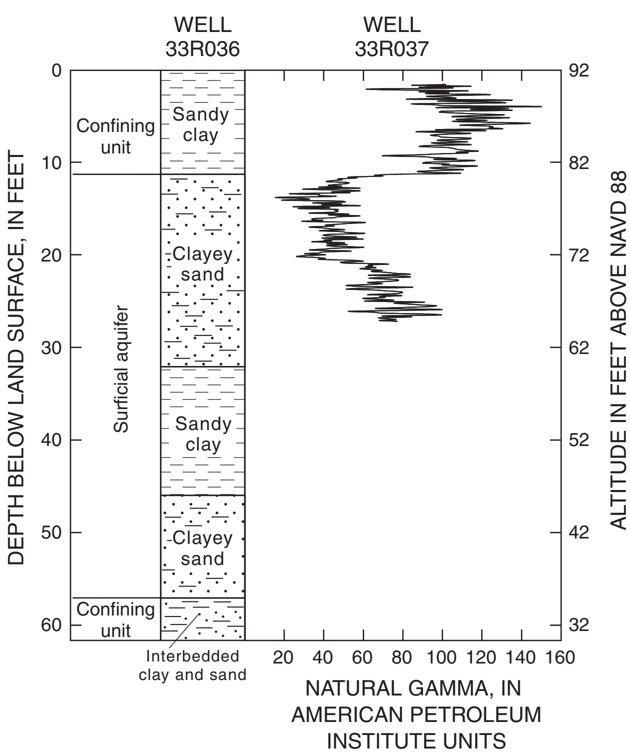


Figure 19. Subsurface geology at the Bulloch County pond site in Georgia.

Water levels from paired test wells completed in the upper and lower parts of the surficial aquifer during June 2001 indicate that vertical head gradients generally are downward within the study area, indicating a potential for aquifer recharge (fig. 24). Downward head gradients ranged from 0.02 to 0.06 feet per foot (ft/ft); only one site in the southwestern part of the area had an upward gradient of 0.02 ft/ft. Several of the paired wells are located within 20 ft of the pond, with downward gradients indicating that the "hinge line" separating areas of recharge (downward gradient) from areas of discharge (upward gradient) is close to the pond.

Pond stage and ground-water levels rise in response to precipitation and decline during dry periods in response to increased evapotranspiration. This relation is illustrated on a plot showing ground-water levels in wells 33R025 and 33R037, pond stage, and cumulative net precipitation (fig. 25). During March–June 2001 (immediately prior to a pumping test), pond stage declined about 1.1 ft and ground-water levels in well 33R025 declined about 3 ft, corresponding to a period when evaporation mostly exceeded precipitation (as indicated by decreasing cumulative net precipitation values). Water-level rises during March, June, and July 2001, corresponded to precipitation events.

Estimated Net Ground-Water Seepage

Net ground-water seepage rates were computed using water-budget analysis, model simulation, and results of a pond pumping test. The water-budget analysis was conducted during October 2000–June 2001, and was followed by a pond pumping test during June 4–5, 2001.

Water Budget

The water-budget analysis computed net ground-water seepage for 7-day periods during October 2000–June 2001, prior to the pumping test. During this period, average daily evaporation was 0.08 in/d, with a maximum daily rate of 0.22 in/d during May 2001 and minimum daily rate of 0.0003 in/d during January 2001 (fig. 26). Rainfall during this period had a daily maximum of 1.5 inches during December 2000. Pond-stage altitude ranged from 86.5 ft during March 2001 to 85.1 ft during June 2001 (figs. 21 and 25), with a corresponding volume change of 272,600 ft^3 (2 Mgal).

Ground-water recharge to the shallow ground-water flow system can be approximated from net precipitation. Because overland runoff is negligible at the site, part of the precipitation remaining after evaporative loss (net precipitation) enters the shallow ground- water system, with an unknown amount lost to plant transpiration. The relation between cumulative net precipitation and ground-water levels is demonstrated on the hydrographs shown in figure 25. In general, when cumulative net precipitation is high, ground-water levels are high (indicating ground-water recharge), and when cumulative net precipitation is low, ground-water levels are low. The ground-water component of the water budget is illustrated by comparing plots showing cumulative net precipitation (precipitation minus evapotranspiration) and cumulative pond-volume change over time (fig. 27). Assuming that surface runoff is negligible and errors in estimating atmospheric fluxes and lake volume changes are reasonably small and unbiased, the difference between the two lines represents cumulative net ground-water seepage.

Table 2. Well construction and location information at the Bulloch County pond site in Georgia.

[°, degrees; ', minute; ", second; —, no data]

Well number	Well name	Model layer	Latitude (NAD 83)	Longitude (NAD 83)	Altitude of land surface, in feet (NAVD 88)	Well depth in feet below land surface	Casing diameter (inches)	Open interval in feet below land surface		Water level, in feet below land surface	Date measured
								Top	Bottom		
33R023	CSSI Bulloch Pond Test Site P-1	A3	32°13'48.3"	081°36'19.9"	91.94	12.4	2.0	7.4	12.4	8.74	6/6/01
33R024	CSSI Bulloch Pond Test Site P-2	A3	32°13'48.8"	081°36'21.2"	89.15	5.4	2.0	2.4	5.4	4.01	6/6/01
33R025	CSSI Bulloch Pond Test Site P-3	A3	32°13'50.3"	081°36'16.0"	93.22	11.5	2.0	6.5	11.5	9.62	6/6/01
33R026	CSSI Bulloch Pond Test Site P-4	A3	32°13'47.9"	081°36'23.0"	96.59	14.1	2.0	9.1	14.1	11.71	6/6/01
33R027	CSSI Bulloch Pond Test Site P-5	A3	32°13'46.9"	081°36'16.7"	91.13	10.2	2.0	5.2	10.2	7.92	6/6/01
33R028	CSSI Bulloch Pond Test Site P-6	A3	32°13'47.6"	081°36'11.2"	87.27	8	2.0	6.0	8.0	3.19	6/6/01
33R029	CSSI Bulloch Pond Test Site P-7	A3	32°13'53.30"	081°36'09.80"	93.56	16.30	2.0	11.3	16.3	8.84	6/6/01
33R030	CSSI Bulloch Pond Test Site P-8	A3	32°13'46.04"	081°36'06.01"	91.79	14.1	2.0	9.1	14.1	6.72	6/6/01
33R031	CSSI Bulloch Pond Test Site 4-inch deep well	—	32°13'58.5"	081°36'17.3"	93.91	185	4.0	110.0	185.0	15.58	6/6/01
33R033	Ricky Denmark	A3	32°14'06"	081°36'08"	97.06	20.7	32.0	—	20.7	10.44	4/27/01
33R034	Leland Gregory	A3	32°13'58"	081°35'58"	98.35	20.2	30.0	—	20.2	14.32	6/6/01
33R035	Earl Nelson	A3	32°14'07"	081°35'54"	99.83	22.3	1.5	—	22.3	15.46	4/27/01
33R036	CSSI Bulloch Pond Test Site P-9 (Corehole)	—	32°13'50"	081°36'16"	92.43	62.00	—	—	62.0	—	—
33R037	CSSI Bulloch Pond Test Site P-10	A4	32°13'50"	081°36'16"	92.52	28	2.0	23.0	28.0	9.32	6/6/01
33R038	CSSI Bulloch Pond Test Site P-11	A4	32°13'49"	081°36'20"	90.82	29.20	2.0	24.20	29.2	8.63	6/6/01
33R039	CSSI Bulloch Pond Test Site P-12	A4	32°13'47"	081°36'17"	90.45	28.7	2.0	23.7	28.7	7.69	6/6/01
33R040	CSSI Bulloch Pond Test Site P-13	A4	32°13'48"	081°36'11"	90.59	27.8	2.0	22.8	27.8	7.18	6/6/01
33R041	CSSI Bulloch Pond Test Site P-14	A4	32°13'59"	081°36'17"	93.66	30.8	2.0	25.8	30.8	11.23	6/6/01
33R042	CSSI Bulloch Pond Test Site P-15	A4	32°13'42"	081°35'57"	96.08	28.4	2.0	23.4	28.4	8.97	6/6/01
33R043	CSSI Bulloch Pond Test Site P-16	A4	32°13'44"	081°36'26"	99.40	28.6	2.0	23.6	28.6	11.99	6/6/01
33R044	CSSI Bulloch Pond Test Site P-17	A3	32°13'44"	081°36'26"	99.40	19.3	2.0	18.9	19.3	12.06	6/6/01

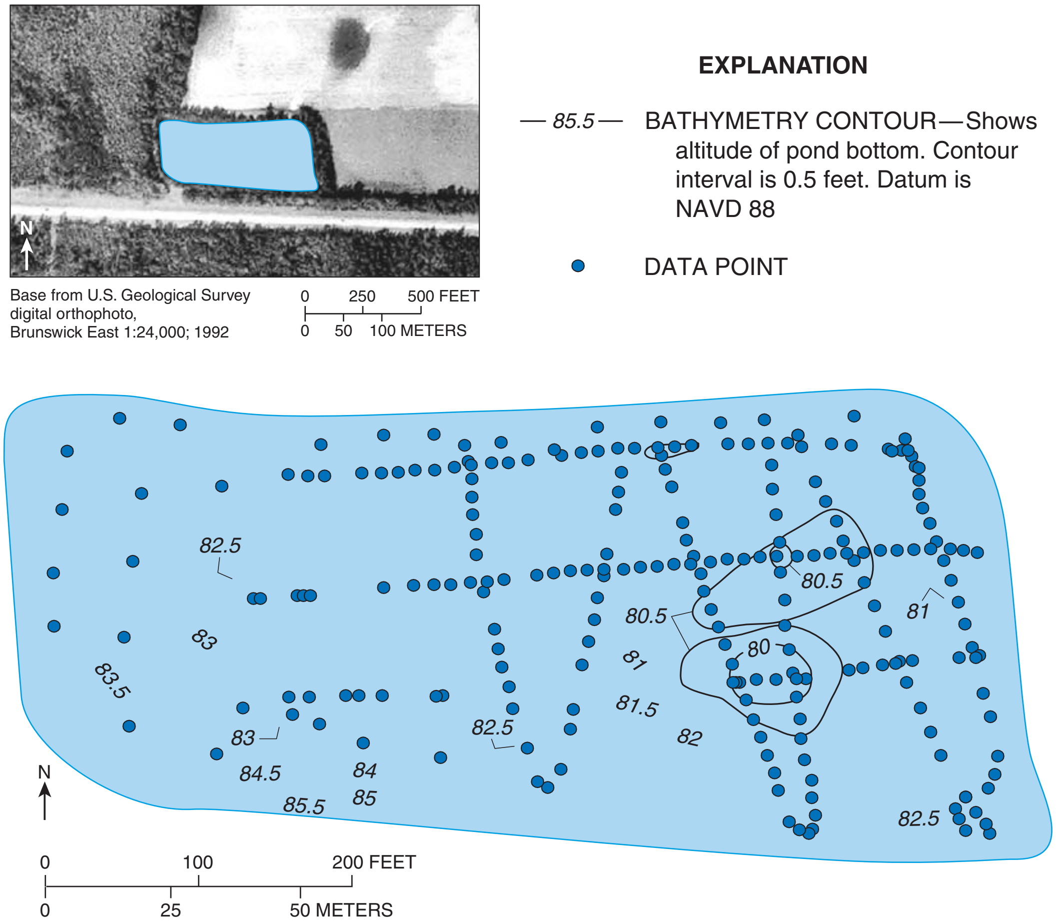


Figure 20. Pond bathymetry, Bulloch County pond site in Georgia, October 2000.

The temporal distribution of net ground-water seepage computed using the water-budget method prior to the pumping test is consistent with precipitation patterns (fig. 27). Net seepage values above the zero line in figure 27 represent periods of net seepage into the pond, whereas values below the zero line represent periods of net seepage out of the pond. Net seepage generally is positive during periods of high rainfall, indicating more ground water is entering the pond than leaving it. Conversely, net seepage generally is negative during periods of low rainfall, indicating that more ground water is leaving the pond than entering it. In general, net ground-water seepage was positive during the pretest period, ranging from –10,670 ft^3/d (–55 gal/min) immediately before the test during May 25–June 1, 2001, to 5,690 ft^3/d (30 gal/min) during March 16–23, 2001 (fig. 27). Confidence intervals shown on figure 27 were derived using equation 7 and error estimates derived from the literature.

Pond Pumping Test

To estimate rates of net ground-water seepage under extreme conditions (dry, low pond stage), a long-term pumping test was conducted in the pond during June 4–5, 2001 (fig. 28). A large-capacity pump was used to lower the water level in the pond by 1.74 ft during a 28-hour period. Discharge water was piped about 50 ft south of the pond to a concrete drainage culvert that passed beneath Interstate Highway 16. Following cessation of pumping, recovery was monitored for 72 hours (fig. 28). During the same period, there was no precipitation and estimated evaporation was about 0.23 in/d. Thus, changes in pond stage during the pumping test mainly were due to the volume of water removed by pumping and contributed by ground-water seepage. Seepage estimates are limited by the accuracy of precipitation measurements and evaporation estimates, and of pond-volume estimates determined using pond-stage and bathymetric data.

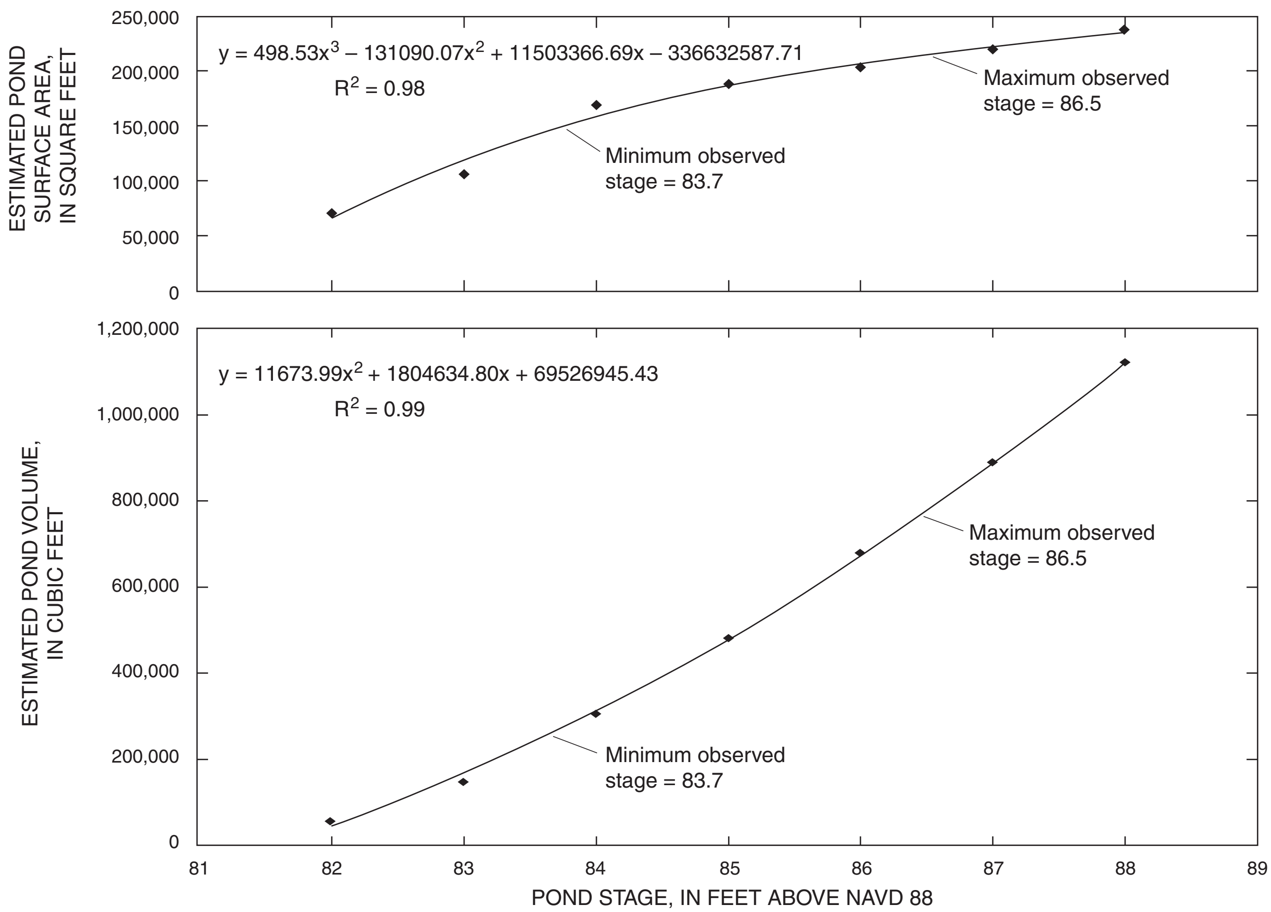


Figure 21. Regression models showing relation of pond stage to estimated surface area and volume, Bulloch County pond site in Georgia.

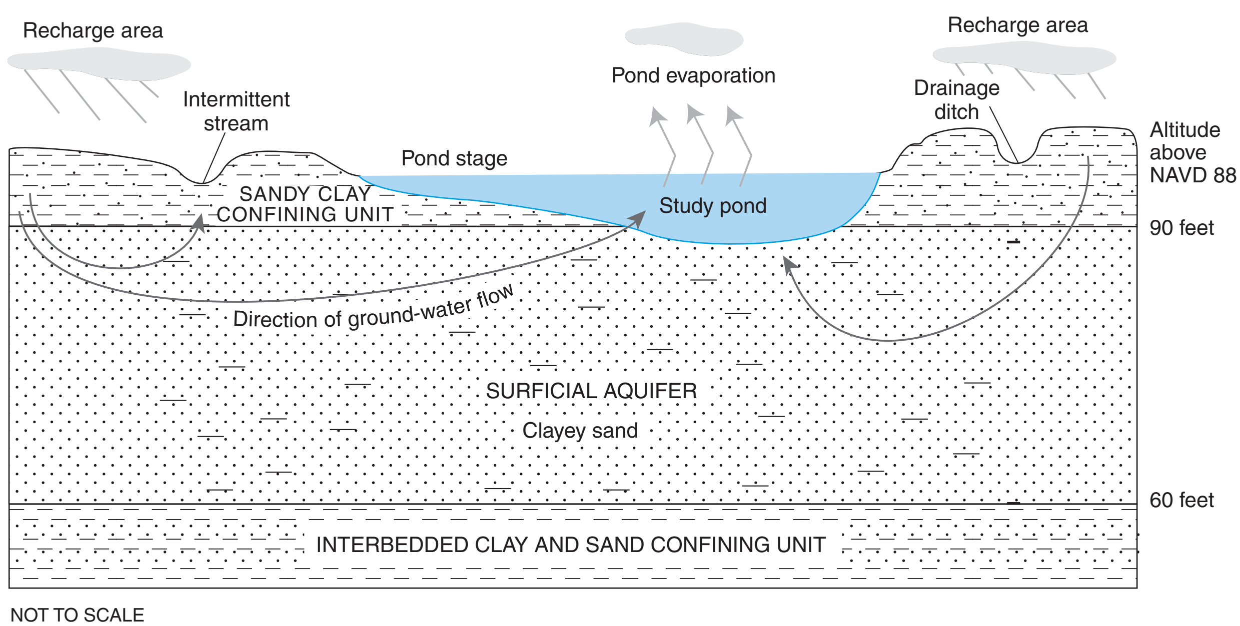
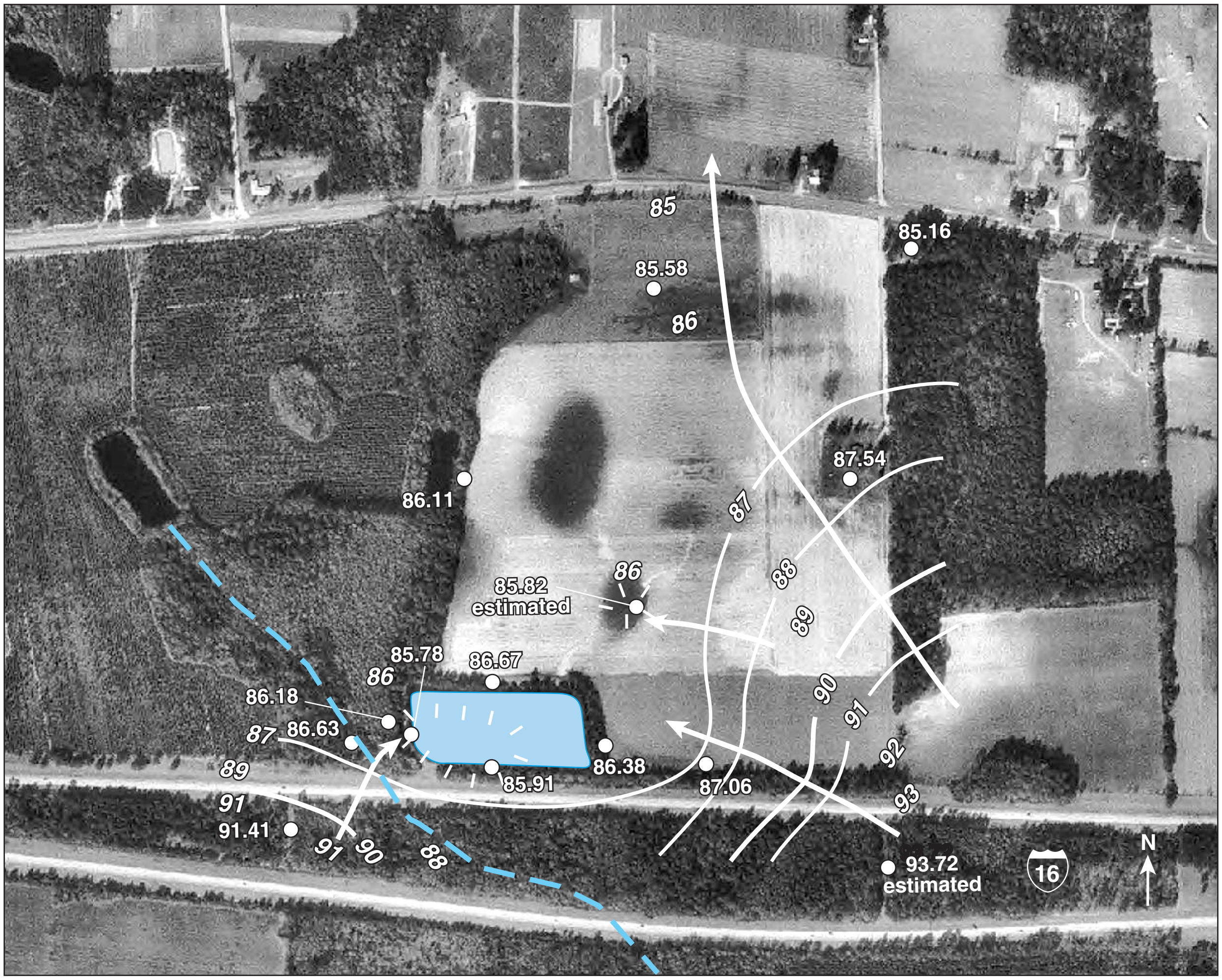


Figure 22. Conceptual model of the hydrogeologic framework and pond-aquifer flow at the Bulloch County pond site in Georgia.



Base from U.S. Geological Survey digital orthophoto
Lanier 1:24,000; 1993

0 500 1,000 FEET

0 100 200 METERS

EXPLANATION

— *90* — POTENTIOMETRIC CONTOUR—Shows altitude at which water table would have stood in tightly cased wells on April 27, 2001. Hachures indicate depression. Contour interval 1 foot. Datum is NAVD 88

— — INTERMITTENT UNNAMED TRIBUTARY TO ASH BRANCH CREEK

→ DIRECTION OF GROUND-WATER FLOW

91.41 ○ WELL—Number is altitude of potentiometric surface in feet above NAVD 88. Value estimated by comparing to water-level fluctuations in nearby well

Figure 23. Potentiometric surface of the surficial aquifer at the Bulloch County pond site in Georgia, April 27, 2001.

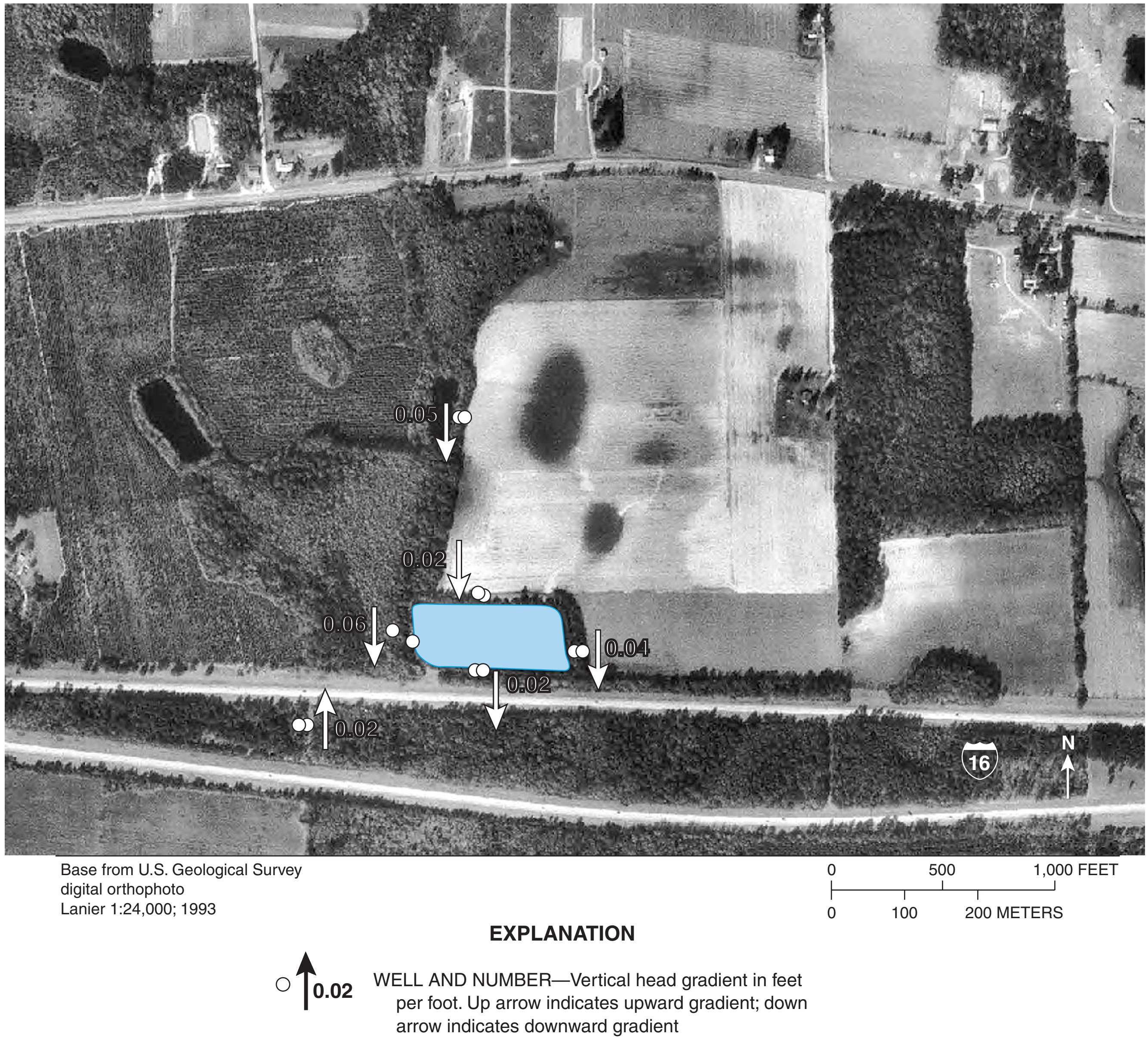


Figure 24. Vertical head gradient between the upper and lower part of the surficial aquifer, Bulloch County pond site in Georgia, June 6, 2001.

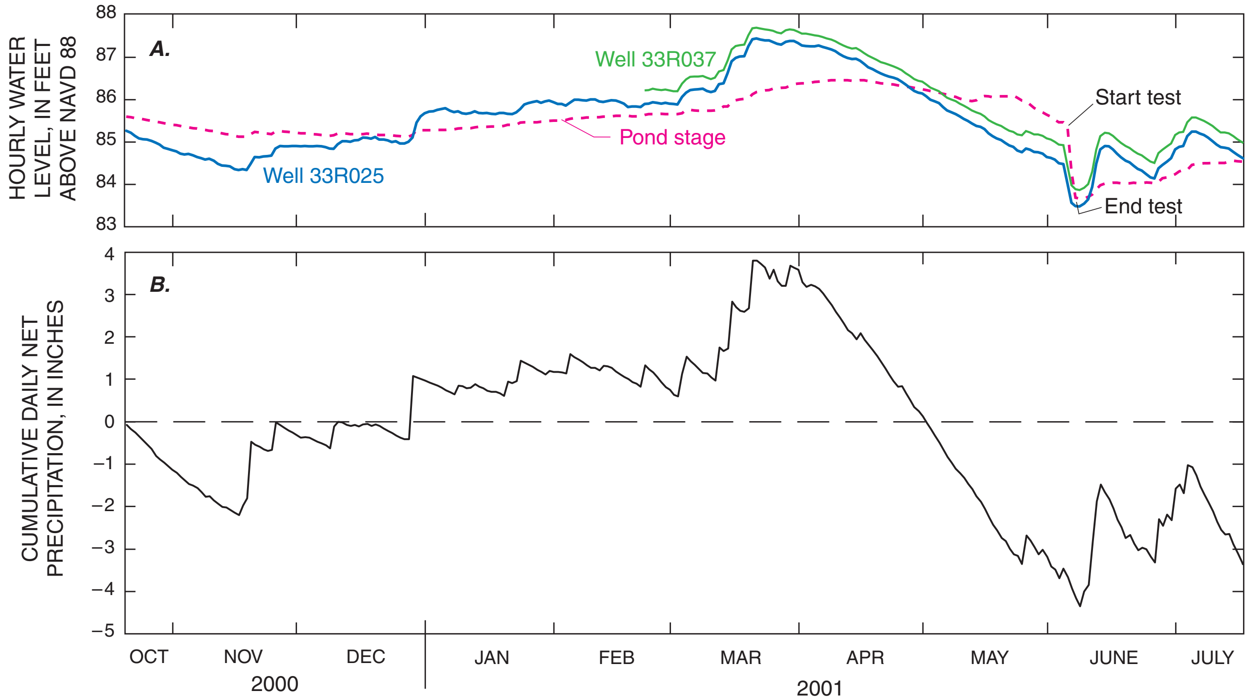


Figure 25. (*A*) Hourly water levels in wells 33R025 and 33R037 and pond stage; and (*B*) cumulative daily net precipitation (precipitation minus evapotranspiration), Bulloch County pond site in Georgia, October 2000–July 2001.

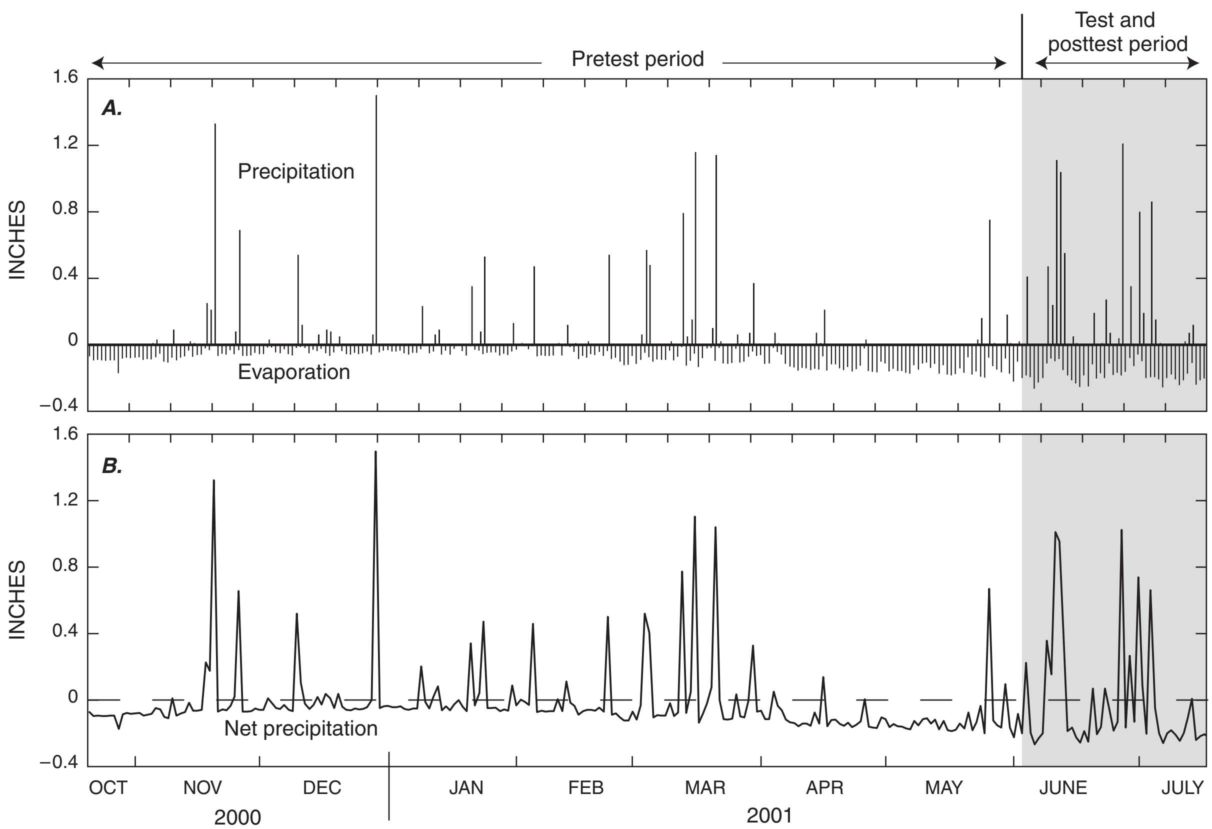


Figure 26. (*A*) Measured daily precipitation and estimated daily evaporation; and (*B*) estimated daily net precipitation (precipitation minus evapotranspiration) at the Bulloch County pond site in Georgia, October 2000–July 2001.

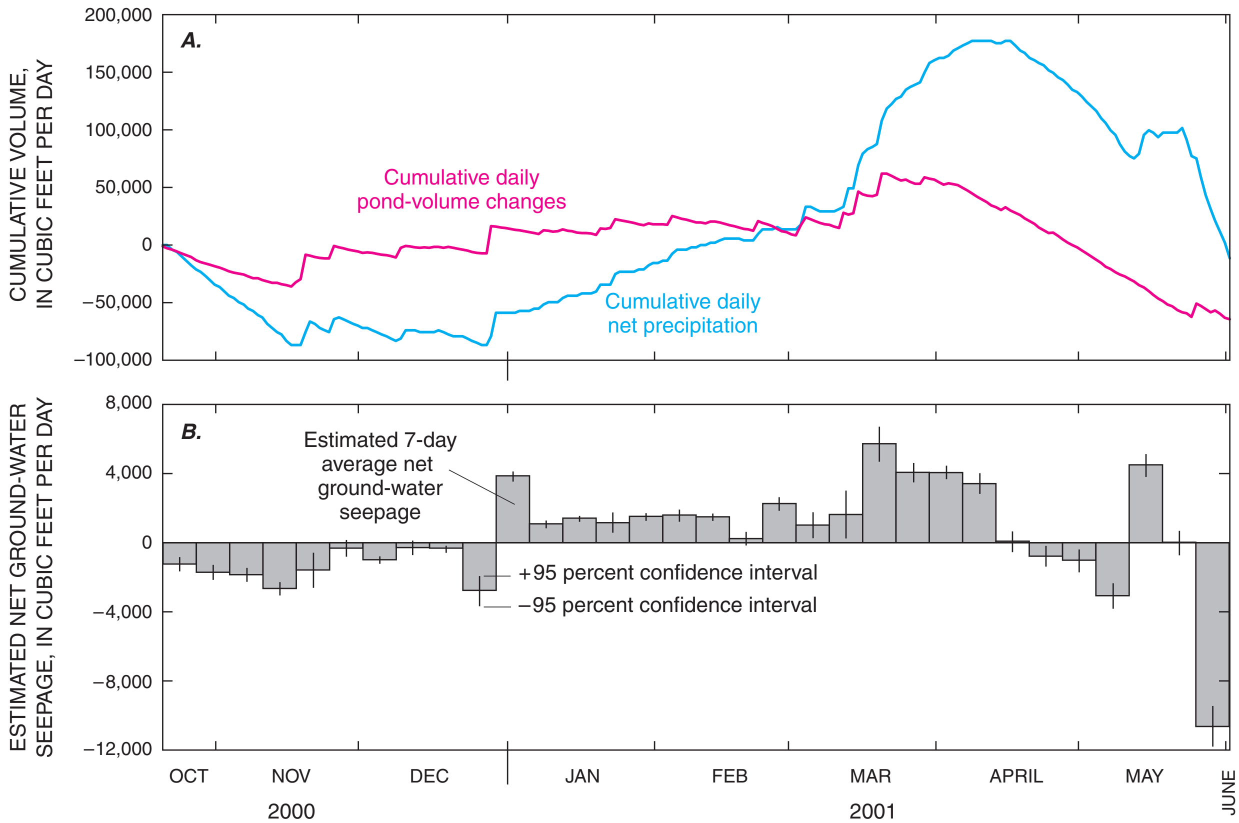


Figure 27. (*A*) Cumulative daily net precipitation (precipitation minus evapotranspiration) and cumulative daily pond-volume changes; and (*B*) estimated 7-day average net ground-water seepage, Bulloch County pond site in Georgia, October 2000–June 2001.

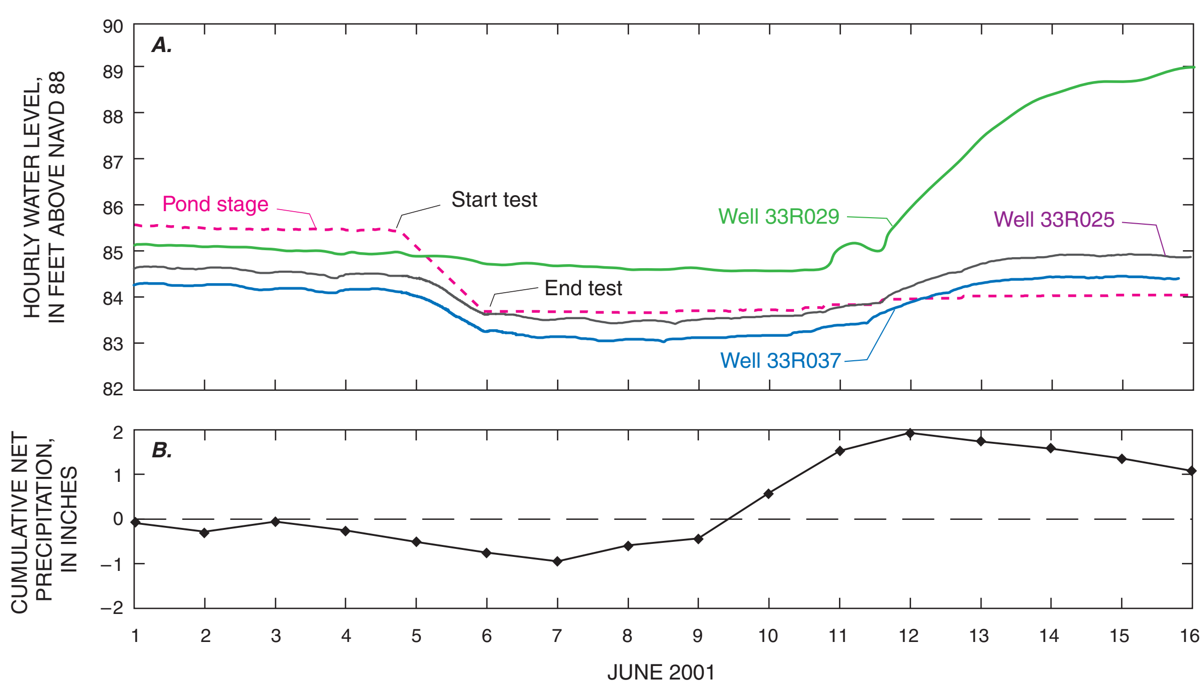


Figure 28. (*A*) Hourly water levels in wells 33R025, 33R029, and 33R037 and pond stage; and (*B*) cumulative net precipitation (precipitation minus evapotranspiration), Bulloch County pond site in Georgia, June 1–16, 2001.

Determination of seepage rates during the pumping test was not possible because pumping rates measured by flowmeter were highly inaccurate and variable; however, estimated rates of seepage were computed following cessation of pumping.

Net ground-water seepage was estimated based on observed pond-volume changes during recovery using equation 8. During June 7–10, 2001, pond stage rose about 0.09 ft, corresponding to a volume change of 13,500 ft^3. Evaporation removed about 6,100 ft^3, and precipitation added about 22,800 ft^3. Using equation 8, the computed net ground-water seepage rate is about 2,000 ft^3/d (10 gal/min). Applying an error analysis of precipitation, evaporation, and volume using equations 6 and 7 indicates that the net ground-water seepage estimate has a margin of error of +/–2,000 ft^3/d (10 gal/min). This high margin of error corresponded to a precipitation event that resulted in a large coefficient of variation for precipitation, limiting the utility of estimates derived using the recovery analysis.

Water-level responses in monitoring wells varied depending on distance from the pond. Wells located directly adjacent to the pond showed water-level declines of 0.82 ft during the test (wells 33R025 and 33R037, fig. 28), whereas wells located farther away from the pond showed less pronounced declines of 0.24 ft or less (well 33R029, fig. 28). Following the pumping test, water levels in the monitoring wells recovered to prepumping levels within 7–9 days. Several storms provided more than 3.4 inches of rain during this period, which quickly recharged the surficial aquifer (fig. 28). Despite this rainfall, pond stage recovered only slightly during this period. By the end of July 2001, the pond surface remained 0.6 ft below pretest stage.

Ground-Water Flow Model

The Bulloch County pond site model utilized steady-state and transient simulations to evaluate changes in ground-water level and seepage to and from the pond prior to and during the 28-hour pumping test. Initial conditions were simulated as steady state, followed by simulation of transient changes in recharge, pond stage, ground-water levels, and seepage. Model development, calibration, and sensitivity are described in Appendix B.

For the initial steady-state simulation of pretest conditions (June 4, 2001), ground water flows from the southern boundary northward (fig. 29A). Some water seeps into the pond along the southern shoreline and exits the pond along the northern shoreline. These flow patterns compare favorably to the conceptual model of ground-water flow (fig. 22), regional ground-water flowpaths as inferred from topography, and locally to potentiometric-surface maps derived from test-well data (fig. 23). Some differences are apparent between the simulated and observed-conditions maps. The observed-conditions map for April 2001 shows two cones of depression—one beneath the pond and one beneath a small depression located about 330 ft northeast of the pond—that do not appear on the simulated surface for June 2001. In addition, water levels generally are lower and the hydraulic gradient is steeper north of the pond on the simulated map than on the observed map. These differences may reflect changes in hydrologic conditions during the two periods—water levels were lower during June 2001 than during April 2001, resulting in different flow conditions near the pond. In particular, the relation between observed pond stage and ground-water levels in wells north of the pond was different during the two periods (fig. 25). During April 2001, pond stage was lower than ground-water levels in nearby wells north of the pond resulting in a more pronounced water-level gradient toward the pond as indicated on the observed-conditions map (fig. 23). Conversely, during June 2001, pond stage was higher than ground-water levels in nearby wells, resulting in a more pronounced gradient away from the pond, as indicated on the simulated map (fig. 29A).

A map showing the simulated potentiometric surface after 28 hours of pumping indicates a depression beneath the study pond, with a steepened hydraulic gradient along the southern shoreline (fig. 29B). The overall direction of ground-water flow remains northward toward Lower Black Creek.

The MODFLOW post-processor ZONEBUDGET (Harbaugh, 1990) was used to enable determination of simulated net ground-water seepage at the pond. In this procedure, the pond is designated as a separate “zone,” and flows into and out of that zone are summarized. For the pretest period, simulated net seepage compares favorably with values estimated using the 7-day water-budget analysis, ranging from –10,400 ft^3/d (–54 gal/min) immediately prior to the pumping test during May 25–June 1, 2001, to 6,000 ft^3/d (31 gal/min) during March 30–April 6, 2001, with a median rate of 800 ft^3/d (4.2 gal/min) (fig. 30). Rates of ground-water seepage vary depending on pond stage and related changes in hydraulic gradient and cross-sectional area. To evaluate the impact of changing hydraulic gradients on ground-water seepage, simulated net seepage was plotted with pond stage during the pumping test (fig. 31). Decreasing pond stage results in an increased hydraulic gradient toward the pond and increased rates of seepage to the pond. Simulated net ground-water seepage varied from net losing conditions at the beginning of the test (high pond stage and low hydraulic gradient) to net gaining conditions at the end of the test (low pond stage and high hydraulic gradient). Values ranged from –3,420 ft^3/d (–18 gal/min) at the beginning of the test to 2,880 ft^3/d (15 gal/min) at the end of the test. Median simulated net ground-water seepage during the pumping test was 1,270 ft^3/d (6.6 gal/min).

The calibrated ground-water flow model provided estimates of the vertical and horizontal hydraulic conductivity of the surficial aquifer. Initial values of hydraulic conductivity were adjusted during calibration based on observed head and calculated net ground-water seepage into the pond. Because hydraulic-property data for the surficial aquifer are sparse, these estimates are useful to help guide development of the surficial aquifer and provide information to help development of other ground-water models in the area. Calibrated horizontal hydraulic conductivity was lowest in the shallow, clayey soil zone with most values near 0.0005 ft/d, and highest in the surficial aquifer, with most values near 70 ft/d. Calibrated vertical hydraulic conductivity ranged from 0.05 in pond bed sediments to 10 ft/d in the surficial aquifer.

Water Availability

Available storage in the Bulloch County pond site ranged from 263,000 to 774,000 ft^3 (from 1.97 to 5.79 Mgal) under the observed range of stage (from 83.7 to 86.5 ft) during October 2000–June 2001 (fig. 21). Ground-water seepage provides a net increase in water to the pond during part of the year.

Net ground-water seepage rates determined using the water-budget method and flow- model simulation indicate that the Bulloch County pond was mostly gaining water during the study period—more water flowed into the pond than flowed out of the pond (fig. 30). Most ground-water seepage entered the pond following major rainfall events that provided recharge to the surficial aquifer. This recharge raised water levels in the surficial aquifer and produced slightly steepened hydraulic gradients toward the pond. The relation between recharge events and estimated net ground-water seepage is illustrated by graphs of cumulative daily net precipitation, cumulative daily pond-volume change, and estimated seepage (fig. 27).

Net ground-water seepage rates vary in response to changing pond stage. Simulated values during a 28-hour pumping test indicate that ground-water seepage to the pond increases with decreased pond stage (fig. 31). A 1.74-ft drop in pond stage during the test resulted in a pronounced change in flow conditions near the pond, transitioning ground-water seepage from a net losing to a net gaining condition. Examination of the graph shown on figure 31 indicates that net ground-water seepage was negative at pond stages greater than or equal to 84.9 ft and positive at stages less than 84.9 ft. Lowering pond stage by 1.2 ft beneath the 84.9-ft level resulted in a gain in ground-water seepage of 6,000 ft^3/d (31 gal/min). Note that these estimates are only appropriate for climatic and ground-water-level conditions similar to those observed during the test period. Different conditions could cause significant differences in hydraulic gradients near the pond and affect seepage rates.

Seepage Ponds as Sources of Irrigation Supply

Results at the two pond test sites indicate that the use of excavated seepage ponds as sources for irrigation supply is limited by pond-storage volume and low net ground-water seepage rates during periods of low precipitation. Although larger volumes of water initially could be available from deeper ponds encompassing larger areas, the rate of replenishment— dependent on net ground-water seepage—is low during dry periods and would not refill the pond quickly enough to provide a continuous reliable source.

At the Glynn County pond site, the volume of water stored in the pond at minimum observed stage (during the dry season) was 13.5 Mgal and the maximum simulated rate of replenishment during the pond pumping test was 103 gal/min. If 1,000 gal/min were withdrawn from the pond for 10 hours per day, it would take about 30 days to drain the pond completely (fig. 32). If the same pumping conditions were imposed at the Bulloch County pond site, the rate of depletion of pond volume would be even greater because of its lower storage volume (1.97 Mgal during the dry season) and lower net ground-water seepage rate (15 gal/min during pond pumping test). Under these conditions, it would take about 3.5 days to drain the pond completely (fig. 32). Note that different climatic conditions and pumping rates would influence the rate of pond-storage depletion, and that reducing pond stage beyond the range of observed test conditions also would increase rates of net ground-water seepage into the ponds. Despite these limitations, the aforementioned analysis gives some indication of the sustainability of pumping from excavated seepage ponds in the 24-county coastal Georgia area. Because the two pond test sites are considered to represent the extremes of likely conditions to be encountered the coastal Georgia area, it is likely that other seepage ponds would have similar storage-depletion rates. Thus, seepage ponds have limited utility as sources of irrigation water supply during dry conditions in coastal Georgia.

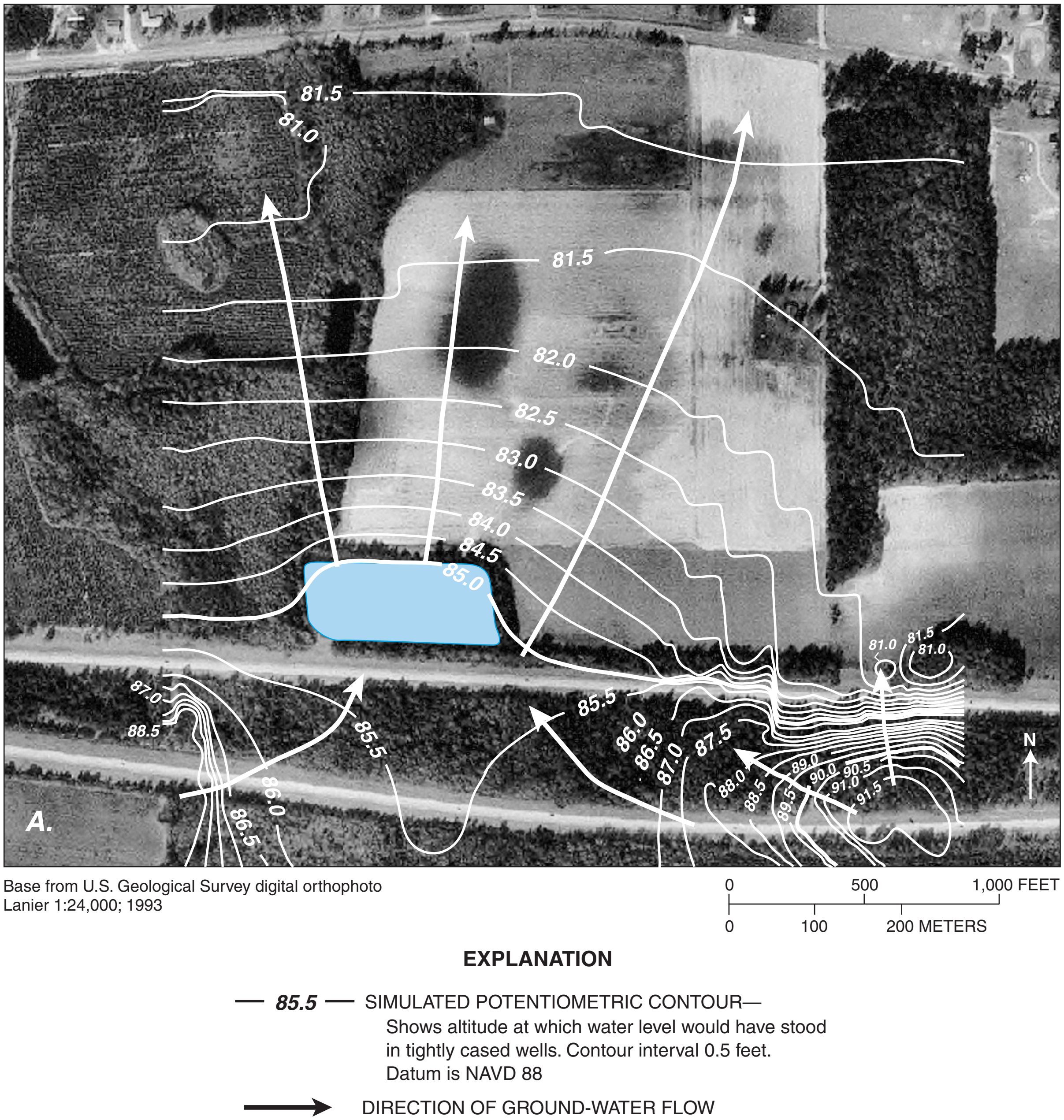
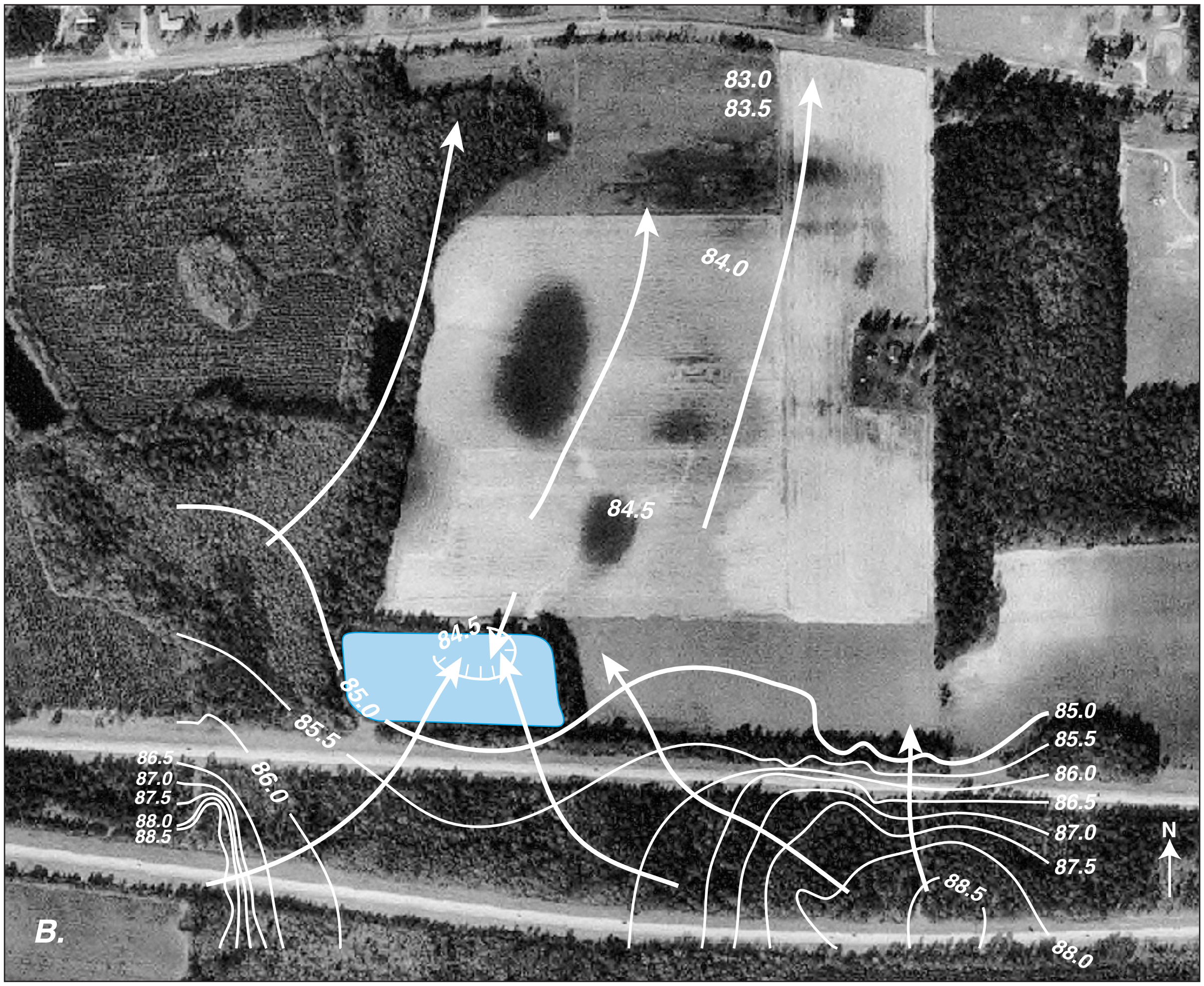


Figure 29. Simulated potentiometric surface of the surficial aquifer at the Bulloch County pond site in Georgia (*A*) prior to pumping test on June 4, 2001; and (*B*) after pumping test on June 5, 2001.



Base from U.S. Geological Survey digital orthophoto
Lanier 1:24,000; 1993

0 500 1,000 FEET
0 100 200 METERS

EXPLANATION

— 85.5 — SIMULATED POTENTIOMETRIC CONTOUR—
Shows altitude at which water level would have stood in tightly cased wells. Hachures indicate depression. Contour interval 0.5 feet. Datum is NAVD 88

→ DIRECTION OF GROUND-WATER FLOW

Figure 29. Simulated potentiometric surface of the surficial aquifer at the Bulloch County pond site in Georgia (*A*) prior to pumping test on June 4, 2001; and (*B*) after pumping test on June 5, 2001.—Continued

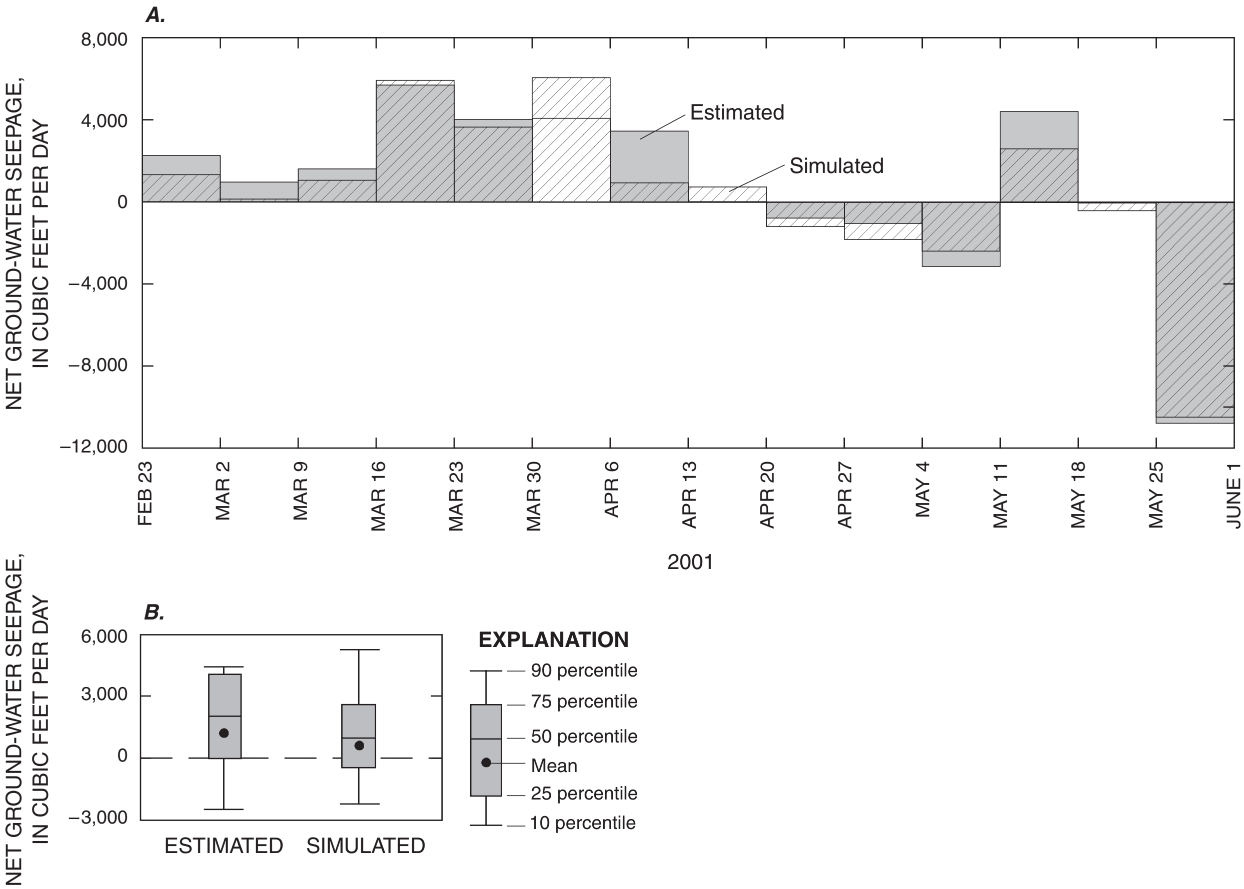


Figure 30. Estimated and simulated 7-day average net ground-water seepage at the Bulloch County pond site in Georgia, February–June 2001—(*A*) graph and (*B*) boxplot summarizing all values.

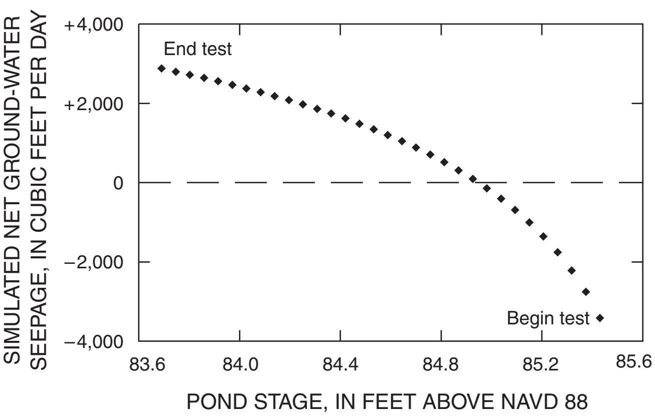


Figure 31. Pond stage and simulated net ground-water seepage (+, water from aquifer to pond; –, water from pond to aquifer), Bulloch County pond site in Georgia, June 4–5, 2001.

Summary

The availability of water from seepage ponds is controlled by the permeability of surficial deposits, the amount of precipitation recharging the ground-water system, and the volume of water stored in the pond. To develop a better understanding of these controls, two pond sites were selected based on contrasting hydrologic, physiographic, and soil conditions. The Glynn County pond site is located in the Coastal Lowlands physiographic division near the Atlantic Ocean in an area characterized by low relief and high-permeability sandy soil. The Bulloch County pond site is located in the Coastal Terraces physiographic division in an area also characterized by low relief, but having somewhat less-permeable clayey soils. During 1961–90, precipitation at the Glynn County site averaged about 49 in/yr and at the Bulloch County site averaged about 47 in/yr. The Glynn County site is typical of sites in the lower part of the coastal area, whereas the Bulloch County site is typical of sites in the upper part of the coastal area. Based on testing and analysis at the two sites, it appears that the viability of seepage ponds as supplies for irrigation is limited by low seepage rates and high dependence on climatic conditions.

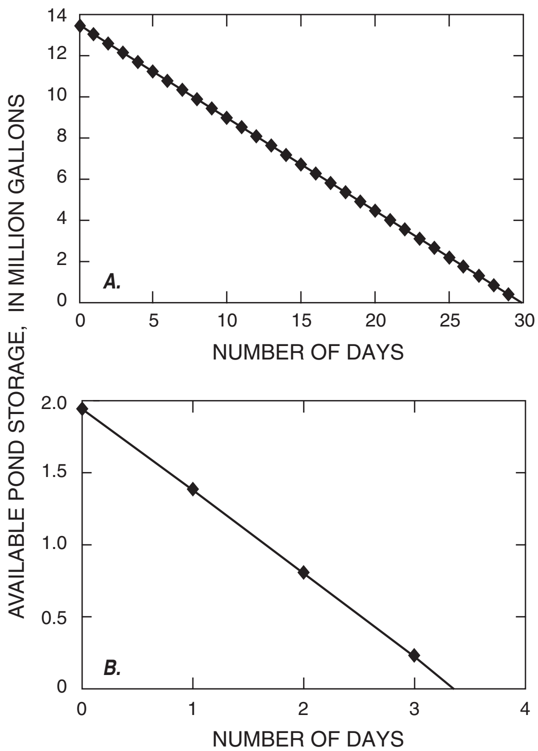


Figure 32. Hypothetical rate of depletion of pond storage at a pumping rate of 1,000 gallons per minute for 10 hours per day for climatic and hydrologic conditions similar to those observed during pond pumping tests at the (*A*) Glynn County and (*B*) Bulloch County pond sites in Georgia.

Although the Glynn County and Bulloch County seepage pond sites are located in areas of similar topography, some major differences exist in pond area and depth, permeability of the underlying sediments, and conditions under which ground water enters or exits each pond. The Glynn County pond encompasses about 5 acres and has a maximum depth of about 21 ft. Computed pond volume prior to a pond pumping test ranged from about 13.5 Mgal at minimum stage to 18 Mgal at maximum stage. The Bulloch County pond also encompasses about 5 acres but has a maximum depth of only 6 ft. The volume of water is considerably less than the Glynn County pond, with computed pond volume prior to a pond pumping test ranging from 1.97 Mgal at minimum stage to 5.79 Mgal at maximum stage.

Soil permeability is substantially different at the two pond sites. At the Glynn County site, the pond is excavated into a highly permeable 50- to 55-ft-thick layer of sand; whereas at the Bulloch County site, the pond is excavated into low-permeability clay throughout most of the pond's extent and depth, and incises clayey sand of the surficial aquifer in limited areas. Model-calibrated horizontal hydraulic conductivity for the surficial aquifer ranged from 0.5 to 50 ft/d at the Glynn County pond site and ranged from 0.0005 to 70 ft/d at the Bulloch County pond site. Calibrated vertical hydraulic conductivity ranged from 0.4 to 40 ft/d at the Glynn County pond site and from 0.05 to 10 ft/d at the Bulloch County pond site.

Pond-aquifer flow has different characteristics at the two pond sites: the Glynn County pond is influenced by both vertical and horizontal flow from the surficial aquifer, and the Bulloch County pond is influenced mostly by vertical flow in areas where the pond incises the surficial aquifer. Because the Bulloch County pond is mostly in low-permeability clay layers, ground water enters the pond mostly through vertical flow where the clay layers breach the surficial aquifer. Ground-water levels at both sites responded markedly to precipitation, rising rapidly in response to precipitation, and slowly declining during dry periods.

Ground-water seepage was estimated using a water-budget approach that utilized on-site climatic and hydrologic measurements, computing pond-volume changes during pond pumping tests, and by digital simulation using steady-state and transient ground-water flow models. During their respective study periods, the Glynn County pond was mostly losing water, whereas the Bulloch County pond was mostly gaining water. At both sites, most ground-water seepage entered the pond following major rainfall events that provided recharge to the surficial aquifer. This recharge raised water levels in the surficial aquifer and produced steepened hydraulic gradients toward the pond. Although higher ground-water seepage rates at the Glynn County pond might be expected due to more permeable soils and greater pond depth, net seepage rates were actually higher at the Bulloch site. During the period prior to a pond pumping test at the Glynn County pond, net ground-water seepage estimated using water-budget analysis and simulation ranged from –2,220 ft^3/d (–11.5 gal/min) to 2,950 ft^3/d (15 gal/min). Rates at the Bulloch County pond prior to a pond pumping test estimated using water-budget analysis and simulation ranged from –10,670 ft^3/d (-55 gal/min) to 6,000 ft^3/d (31 gal/min). This apparent discrepancy results because hydraulic gradients in the vicinity of the Bulloch County pond generally are steeper than at the Glynn County pond because of the relatively high relief along the southern part of the area near Interstate Highway 16 (see maps for each site, figs 8 and 23).

Net ground-water seepage rates vary in response to changing pond stage. Simulated values during pond pumping tests conducted at the two sites indicate that ground-water seepage to the pond increases with decreased pond stage. At the Glynn County pond site, simulated net ground-water seepage varied from 1,500 ft^3/d (7.8 gal/min) at the beginning of the test (high pond stage and low hydraulic gradient) to 19,850 ft^3/d (103 gal/min) at the end of the test (low pond stage and high hydraulic gradient). At the Bulloch County pond site, values ranged from -3,400 ft^3/d (–17.7 gal/min) at the beginning of the test to 2,880 ft^3/d (15 gal/min) at the end of the test. Pumping from the Glynn County pond produced steepened hydraulic gradients, which when combined with its generally higher permeability and deeper incision into the surficial aquifer, results in a higher net seepage rate than at the Bulloch County pond.

The availability of water to seepage ponds is highly dependent on climatic conditions—ponds will not refill unless there is adequate precipitation to recharge the surficial aquifer, which subsequently drains (seeps) into the pond. At the Glynn County pond, following a 32-hour pumping test in which pond stage was lowered by 2 ft, water levels in the pond and monitoring wells showed little recovery in the weeks following the test because there was no appreciable rainfall in the area. Water levels in many of the wells continued to decline until precipitation events during July 2000, almost 2 months after the pumping test. At the Bulloch County pond, following a 28-hour pumping test in which pond stage was lowered by 1.74 ft, water levels in the monitoring wells recovered to prepumping levels within 7–9 days in response to recharge from several storms. These storms provided more than 3.4 inches of rainfall, which quickly recharged the surficial aquifer. Despite this rainfall, pond stage only recovered slightly during this period. By the end of July 2001, the pond surface remained 0.6 ft below pretest stage. Lower permeability of surficial deposits at the Bulloch County pond site probably enabled less precipitation to infiltrate into the surficial aquifer than at the higher permeability Glynn County pond site.

Results at the two pond test sites indicate that the usage of excavated seepage ponds as sources for irrigation supply is limited by pond-storage volume and low net ground-water seepage rates during periods of low precipitation. Although larger volumes of water initially could be available from deeper ponds encompassing larger areas, the rate of replenishment—dependent on net ground-water seepage—is low during dry periods and would not refill the pond quickly enough to provide a continuous reliable source. Pumps withdrawing 1,000 gal/min for 10 hours per day at each site would eventually drain each pond under dry conditions similar to those observed during pond pumping tests—at the Glynn County site, the pond would drain within 30 days; at the Bulloch County site, the pond would drain within 3.5 days. Greater storage volume and net ground-water seepage rates at the Glynn County pond resulted in a longer pumping period than at the Bulloch County pond. Because the two pond test sites are considered to represent the extremes of likely conditions to be encountered in coastal Georgia, it is likely that other seepage ponds would have similar storage-depletion rates. Thus, seepage ponds have limited utility as sources of irrigation water supply during dry conditions in coastal Georgia.

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Appendix A. Ground-Water Model for the Glynn County Pond Site in Georgia

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Appendix A. Ground-Water Model for the Glynn County Pond Site in Georgia

Model Development

Pond-aquifer flow at the Glynn County pond site was simulated using the U.S. Geological Survey (USGS) digital, three-dimensional, finite-difference ground-water flow model, MODFLOW (McDonald and Harbaugh, 1988). Steady-state and transient simulations were used to evaluate changes in ground-water level and seepage to and from the pond prior to and during a 32-hour pond pumping test. Initial conditions on November 6, 1999, were simulated as steady state, followed by simulation of transient changes in recharge, pond stage, ground-water levels, and seepage from November 6, 1999, through the pond pumping test, May 1–3, 2000. ZONEBUDGET (Harbaugh, 1990) was used to estimate rates of ground-water seepage to the pond.

The model domain consists of a variably spaced grid having 75 rows and 106 columns, encompassing an area of 0.35 square mile (fig. A1). Cell size ranges from 20 by 20 feet (ft) near the pond to 100 by 120 ft at the outer margins of the model grid. Smaller cell sizes were used near the pond to better simulate steeper hydraulic gradients. In the model, the surficial aquifer is divided into eight layers—layer A1 is simulated as a water-table layer, whereas layers A2–A8 are simulated as confined layers (fig. A2). The pond incises the top five layers of the model in order to more accurately represent pond geometry and simulated fluxes into and out of the pond. Approximate altitudes of the top of each layer are shown on figure A2. Layer thicknesses are as follows: A1, from 1 to 14 ft; A2 through A6, 4.5 ft; A7, 16.5 ft, and A8, 5 ft.

Initial estimates of horizontal hydraulic conductivity were uniformly distributed by layer and are within estimated ranges for silty sand (Heath, 1983), ranging from 30 to 60 feet per day (ft/d). Vertical hydraulic conductivity was assigned an initial value of 20 ft/d, which is from about 1.5 to 3 times less than horizontal values. Pond bed sediments occur mostly in layer A6, and were assigned an initial vertical hydraulic conductivity of 30 ft/d, or a vertical to horizontal ratio of 1:1. Hydraulic property values were adjusted as part of the calibration process, which resulted in zonation of properties by layer and generally lower values (see “Calibrated Hydraulic Properties” section).

Lateral boundary conditions for the model were selected to coincide as closely as possible with natural no-flow boundaries (fig. A1). No-flow boundaries are assigned to the northern and southern sides of the model and correspond to flow lines in the surficial aquifer inferred from topographic maps. The eastern and western boundaries are simulated as specified head layers located at least 0.3 mile from the pond site to minimize influence on simulation results. Head at the western boundary is based on reported water levels at a gas station monitoring well located in the western part of the simulated area (Ron Wallace, Georgia Environmental Protection Division, written commun., November 2000). Head at the eastern boundary was assigned based on average tidal conditions in Cyprus Mill Creek, based on the USGS Brunswick East 7½-minute topographic quadrangle map. Water levels in the surficial aquifer were lower than normal during the period of simulation due to effects of a prolonged drought in the area.

The uppermost layer (A1) was simulated as (1) a free surface boundary in which recharge was applied to simulate the water table and (2) as a zone of specified head in the area of the pond. The base of the model (layer A8) is represented by a no-flow boundary at the top of the basal clay layer.

The recharge package of MODFLOW was used to simulate both recharge to the aquifer and water discharging from the aquifer as evapotranspiration. Net precipitation, representing the difference between precipitation and evapotranspiration, was estimated using continuous data from the weather station, averaged during 10-day periods—when positive, values represent net recharge; when negative, values represent net evapotranspiration. To reflect variations in soil infiltration capacity and uptake by plants (transpiration), the model was divided into four recharge zones (fig. A3):

- Zone 1: No recharge zone reflecting (buildings and surfaced parking lots and streets),
- Zone 2: Unlined drainage ditches that collect runoff from parking lots and fields (recharge applied as a line source),
- Zone 3: Wooded areas, and
- Zone 4: Field areas with grass or dirt (little vegetation).

The pond is simulated as a constant-head boundary in the first five layers of the model, with no recharge applied (fig. A2). The depth and geometry of the pond bottom were determined from a bathymetric survey conducted during August 1999. Pond-stage changes recorded by a continuous gage were applied to each stress period of the transient model. A second pond, located about 750 ft east of the study pond, is simulated as a constant-head boundary in the first three layers of the model. Stage for this pond was assigned based altitudes derived from the USGS Brunswick East 7½-minute topographic quadrangle map.

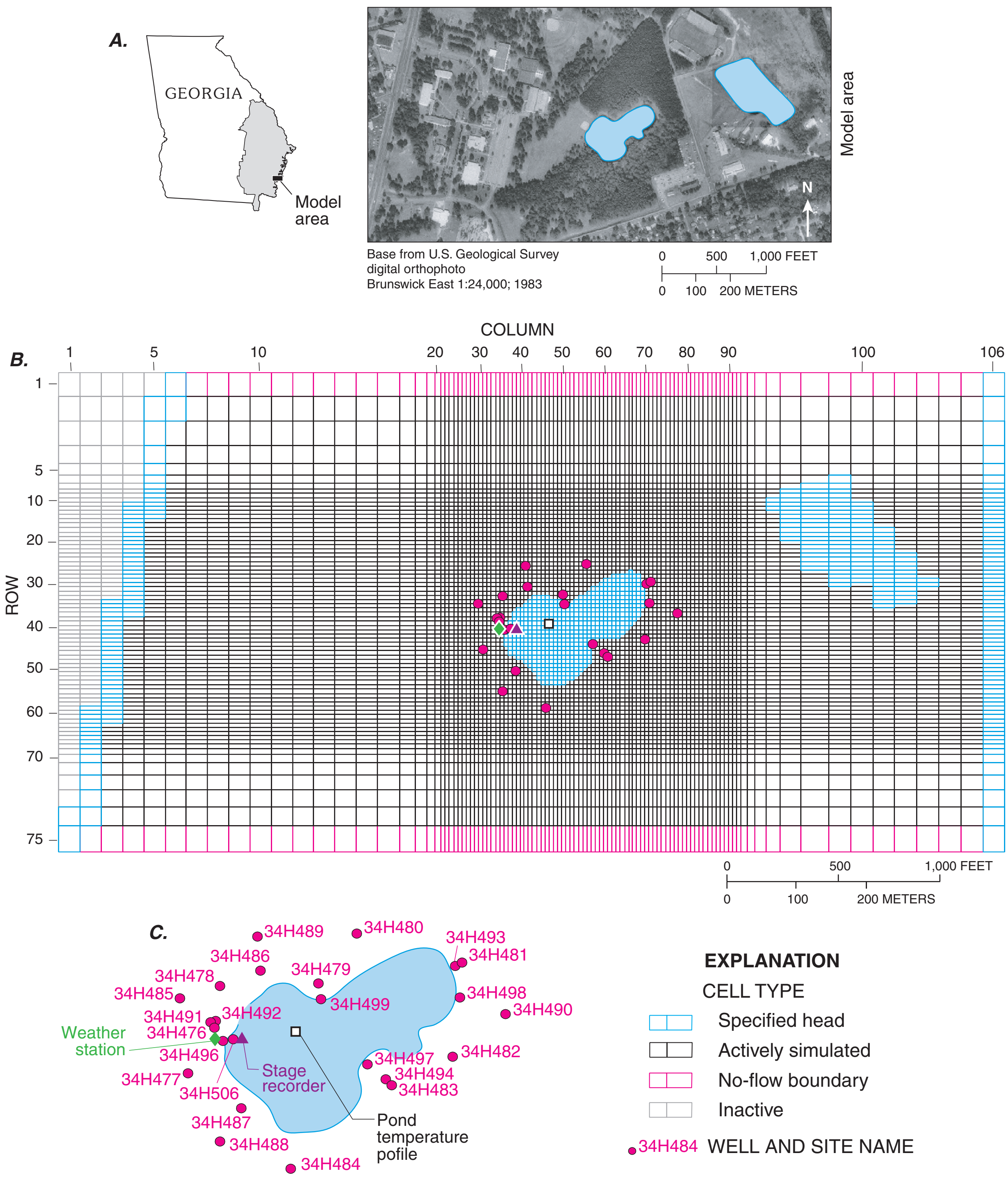

Figure A1. (*A*) Model area, (*B*) model grid and boundaries, and (*C*) well locations, Glynn County pond site in Georgia.

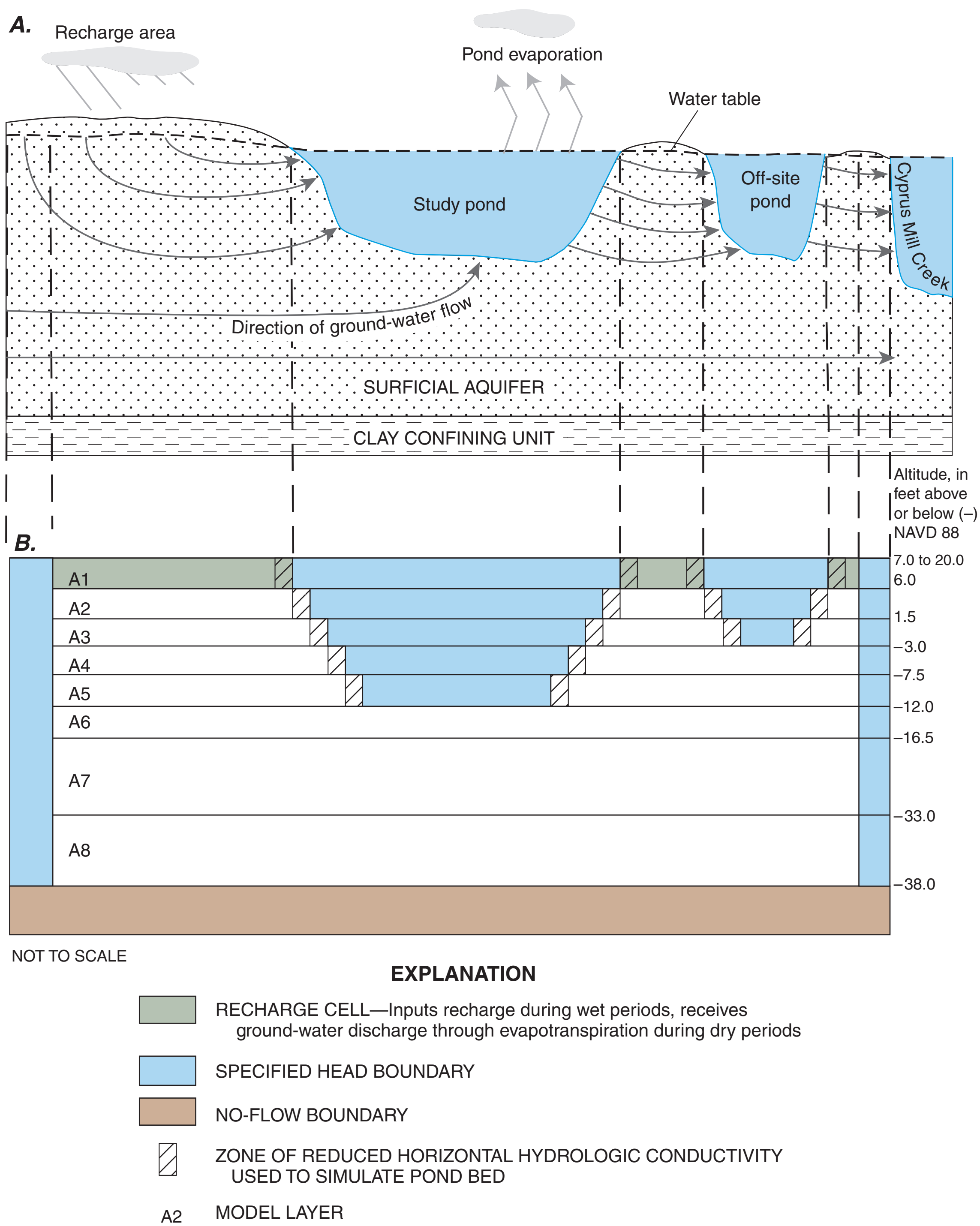

Figure A2. Diagram showing (*A*) hydrogeologic framework and pond-aquifer flow; and (*B*) model layers and boundary conditions for the Glynn County pond site model in Georgia.

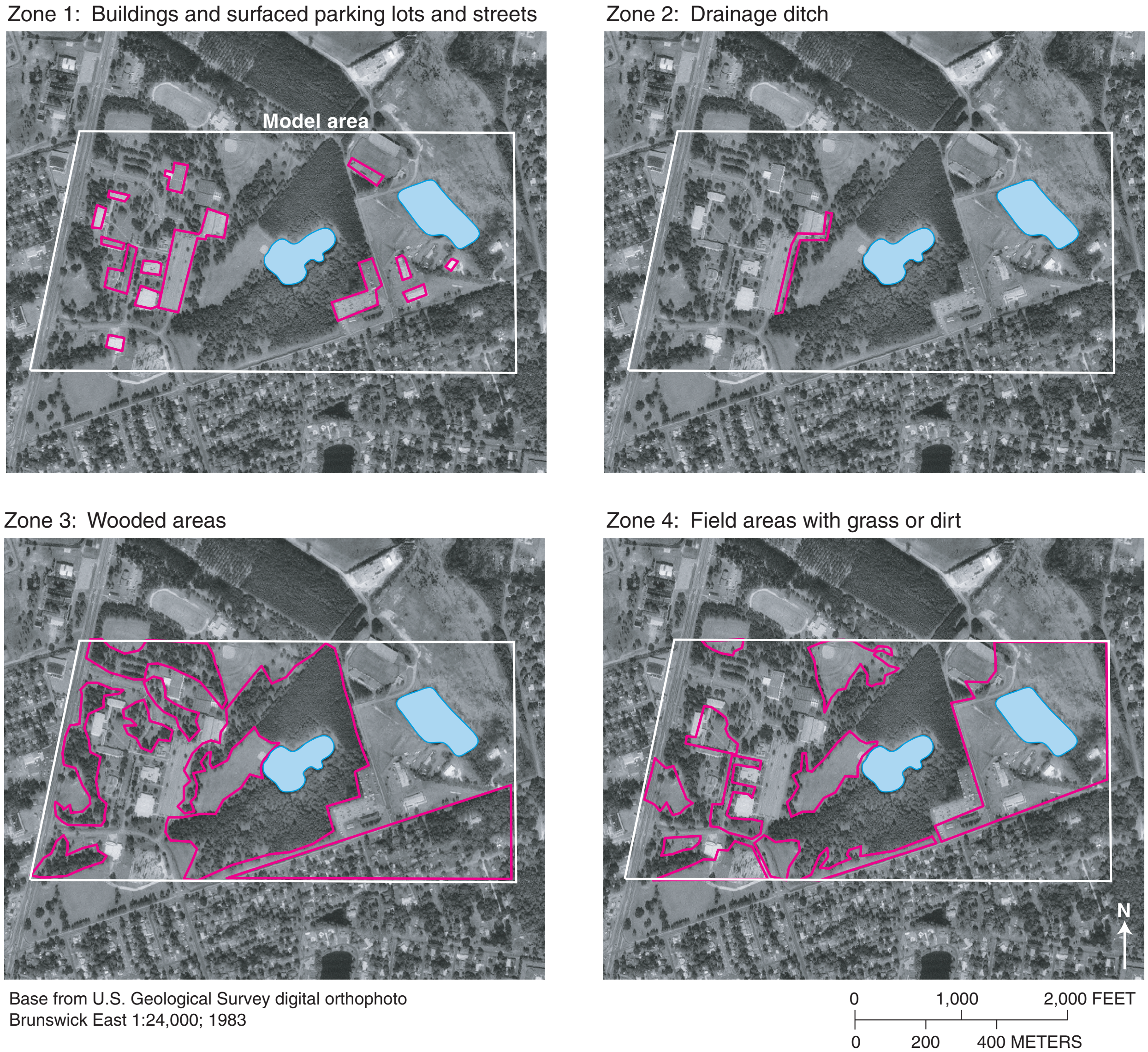

Figure A3. Recharge zones (shown in magenta) for the Glynn County pond site model in Georgia.

Steady-State Simulation

The steady-state model was used to (1) provide initial heads for transient simulations and (2) refine the initial estimates of hydraulic properties and their spatial distribution. The steady-state simulation was based on observed conditions during the 10-day period prior to November 6, 1999, a period when pond stage and ground-water levels were relatively stable, and net precipitation was near zero. Net precipitation rates of –0.0006 ft^3/d to zone 4, –0.001 ft^3/d to zone 3, and 0 ft^3/d to zones 1 and 2 were applied to the MODFLOW recharge package for the steady-state simulation.

Calibration was achieved by adjusting values of horizontal and vertical hydraulic conductivity and recharge (net precipitation) in order to match observed heads. Simulated head values from the calibrated steady-state model compared well to observed water levels, with residuals ranging from –1.0 to 0.6 ft, a root mean square of 0.38 ft, and a standard deviation of 0.38 ft in the 15 wells completed in layer A1. Water-level residuals are shown for each of the 15 wells in figure A4; well locations are plotted on figure A1.

The simulated steady-state water budget for the prepumping period indicates that inflows are derived mostly from specified head cells along the western boundary of the model (95 percent) and from the pond (5 percent) (table A1). Outflows from the model are mostly through recharge cells that simulate evapotranspiration (73 percent), and to specified head cells at the pond and along the eastern boundary of the model (27 percent).

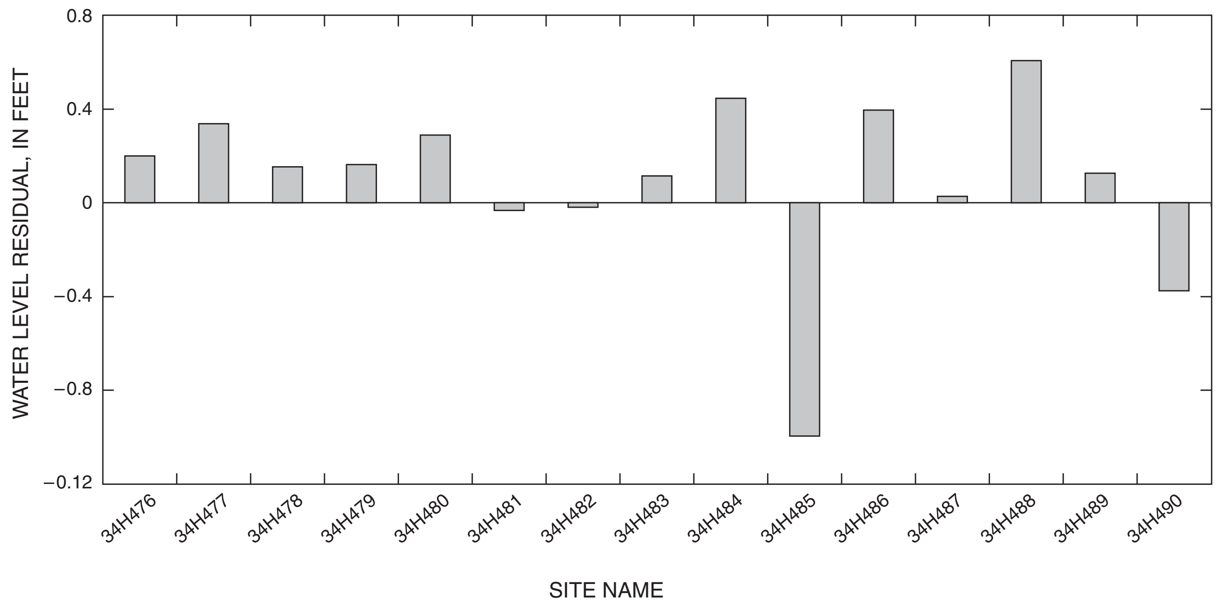

Figure A4. Difference between observed and simulated water levels (residual) for model layer A1, steady-state simulation, Glynn County pond site in Georgia, November 6, 1999.

Table A1. Simulated steady-state water budget, Glynn County pond site in Georgia, November 6, 1999.

[<, less than]

Component of budget	Inflow		Outflow	
	Cubic feet per day	Percent of flow	Cubic feet per day	Percent of flow
Specified head				
Lateral boundaries	6,778	95	27	<1
Pond	391	5	1,906	27
Recharge[1]	0		5,146	73
Total	**7,169**		**7,079**	

[1]Simulates recharge in inflow cells; evapotranspiration in outflow cells

Transient Simulation

Following the initial steady-state simulation, the model was used to simulate transient conditions from November 6, 1999, through the pond pumping test, May 1–3, 2000. Pond-aquifer flow was simulated using the model and rates of net ground-water seepage (flux) into or out of the pond were determined using the MODFLOW postprocessor ZONEBUDGET (Harbaugh, 1990) for selected periods prior to and during the pond pumping test.

The transient simulation consisted of 41 stress periods, based on 10-day precipitation patterns monitored at the on-site weather station (fig. A5). Before the pond pumping test, each stress period consisted of daily time steps, with the longest stress period before the pond pumping test having 20 time steps (days) and the shortest having one time step (day). During the pond pumping test, the model was discretized into one stress period divided into 32 one-hour time steps.

Each stress period was initially assigned a recharge rate (fig. A5) that reflected the net precipitation (precipitation minus evapotranspiration) based on observations at the weather station. In some instances, evapotranspiration exceeded precipitation; therefore, recharge was negative, representing discharge from the pond-aquifer system. Recharge rates were applied based on the four recharge zones described previously and were adjusted during model calibration when appropriate. No recharge was applied to the pond or to zone 1 because it represents paved areas with no inflow or outflow. With the exception of zone 2, which receives runoff from paved areas, calibrated values of recharge were at or below the estimated average net precipitation for each stress period (fig. A5). During rainfall events, values in zone 2 exceeded rates of net precipitation because it received runoff from an adjacent paved parking lot. Otherwise, recharge values assigned to zone 2 were similar to the other two areas.

Calibrated hydraulic conductivity values assigned to the transient model were identical to those assigned to the steady-state model, with the additional properties of specific yield and specific storage incorporated into the transient model. The uppermost layer (A1), simulated under water-table conditions, was assigned a specific yield of 0.15. Layers A2–A8, simulated as confined layers, were assigned a specific storage of 0.0003.

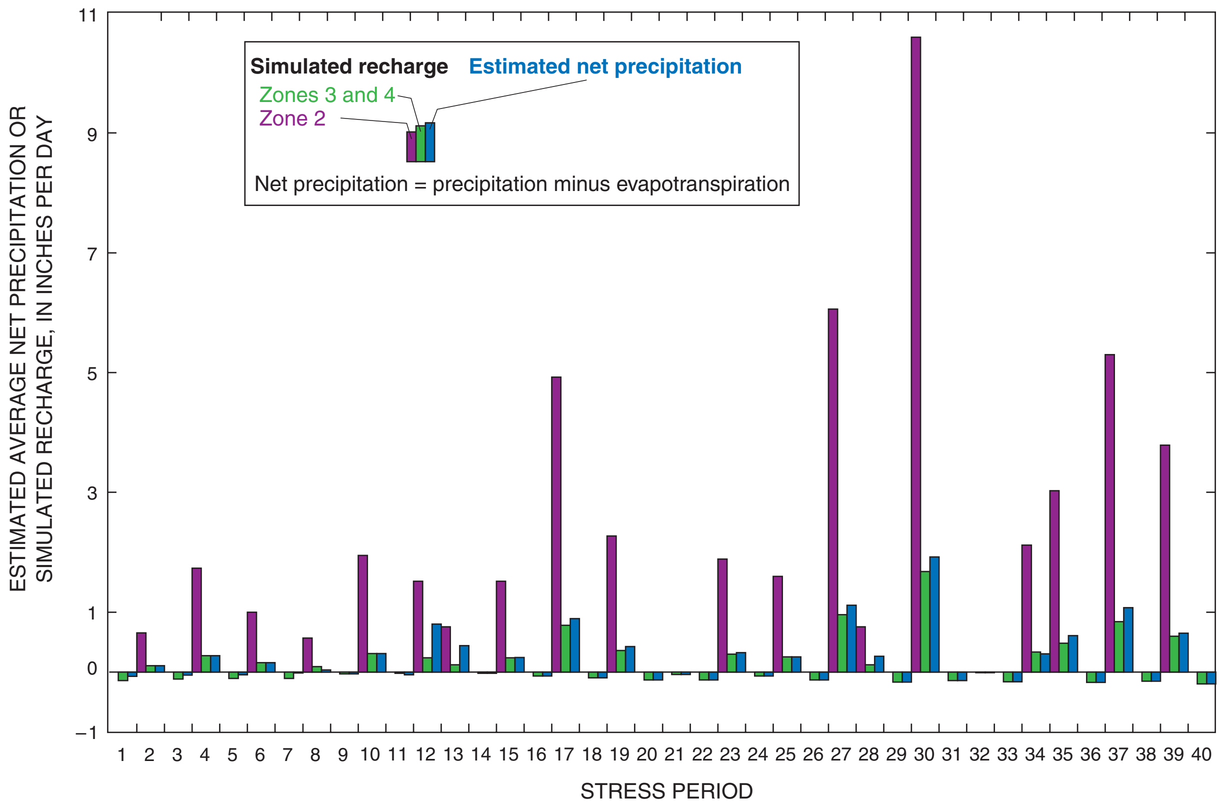

Figure A5. Comparison of estimated average net precipitation and simulated recharge by stress period for the transient model, Glynn County pond site in Georgia. When positive, values represent net recharge, when negative, values represent net evapotranspiration.

The transient model was calibrated by adjusting values of recharge and hydraulic conductivity in an effort to minimize the residuals between observed and simulated head and between the simulated and calculated net ground-water budget. All changes to hydraulic properties made during the transient calibration were also made in the steady-state model, so that both models contained identical hydraulic-property values.

Eighty percent of the simulated head values during the transient simulations were within –1.19 and 0.88 ft of observed values for layers A1 and A3 (fig. A6). Simulated water levels in the deeper layers (A5–A8) were generally higher than observed water levels; however, residuals were low with 80 percent of the values within –0.74 and 1.74 ft of observed values. There were no monitoring wells installed in layers A2 or A4. Graphs of simulated and observed water levels in selected wells indicate the model reasonably simulates water-level changes in the upper and lower parts of the surficial aquifer (fig. A7).

In addition to ground-water levels, the transient model was calibrated by adjusting aquifer parameters to minimize differences between simulated net ground-water seepage to the pond (as determined by summing fluxes into the pond using ZONEBUDGET) and estimated values from the water-budget approach (table A2). Simulated results showed a good comparison to estimated results—one-half of the values were within –39 and +34 percent of estimated values, and 80 percent of the values were within –65 and +128 percent of estimated values. The largest differences generally occurred when seepage estimates were near zero.

Simulated transient water budgets were computed for the stress period immediately prior to the pond pumping test (3-day period) and for the period immediately after the test (32-hour period). The simulated budgets indicate that ground-water storage provided most of the water flowing into the model, with 71 percent contributed prior to pumping and 67 percent contributed immediately after the cessation of pumping (table A3). Specified-head cells at the pond and along the western boundary provided the balance of inflow, with 29 percent contributed prior to the test and 33 percent contributed after the test. Ground-water discharge from the model was mostly to recharge cells representing evapotranspiration prior to the test (98 percent) and to specified-head cells at the pond after the test (62 percent). Lowering pond stage by pumping produced a steepened hydraulic gradient toward the pond, resulting in greater ground-water seepage.

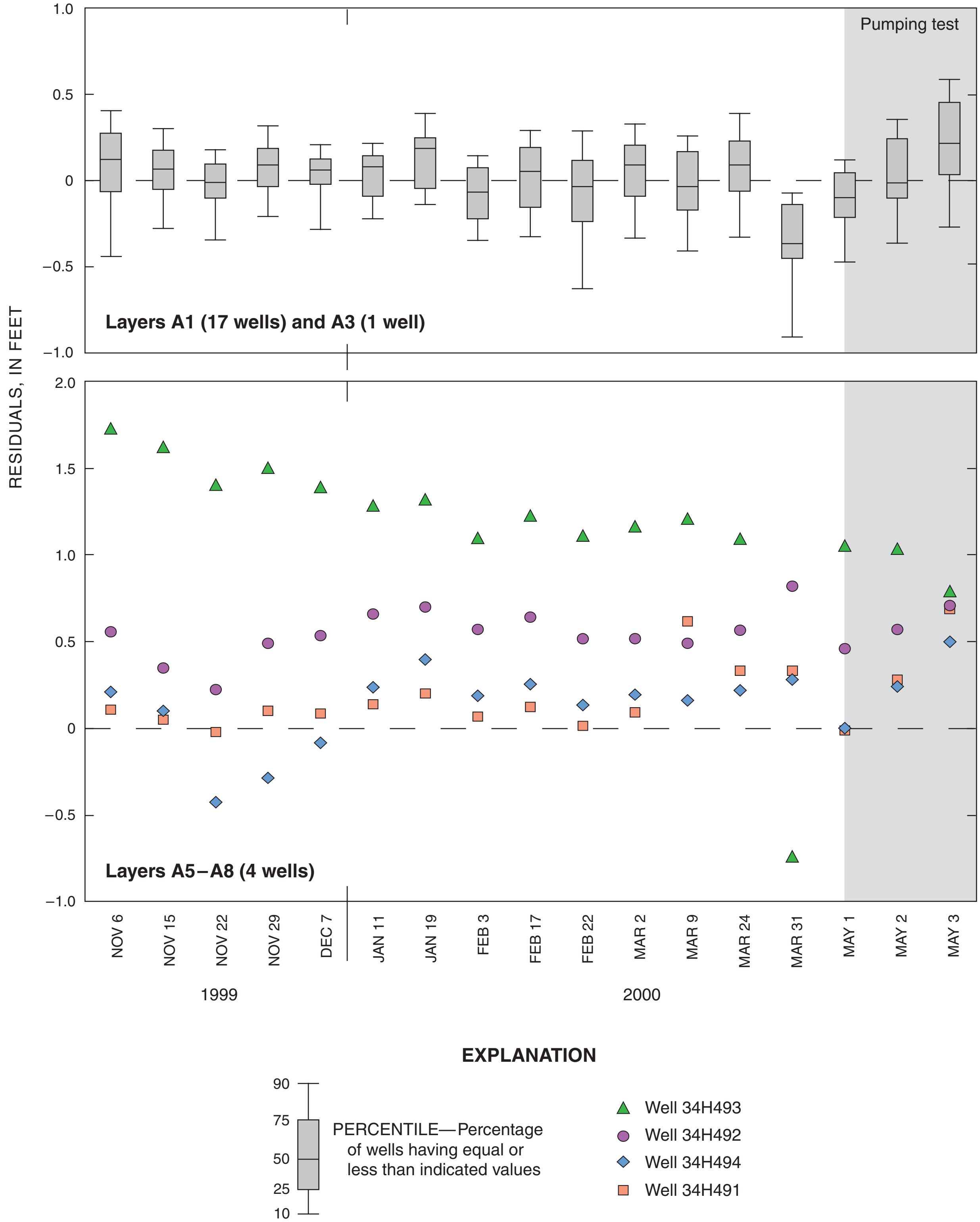

Figure A6. Difference between observed and simulated heads (residuals), transient model for Glynn County pond site in Georgia, November 6, 1999–May 3, 2000.

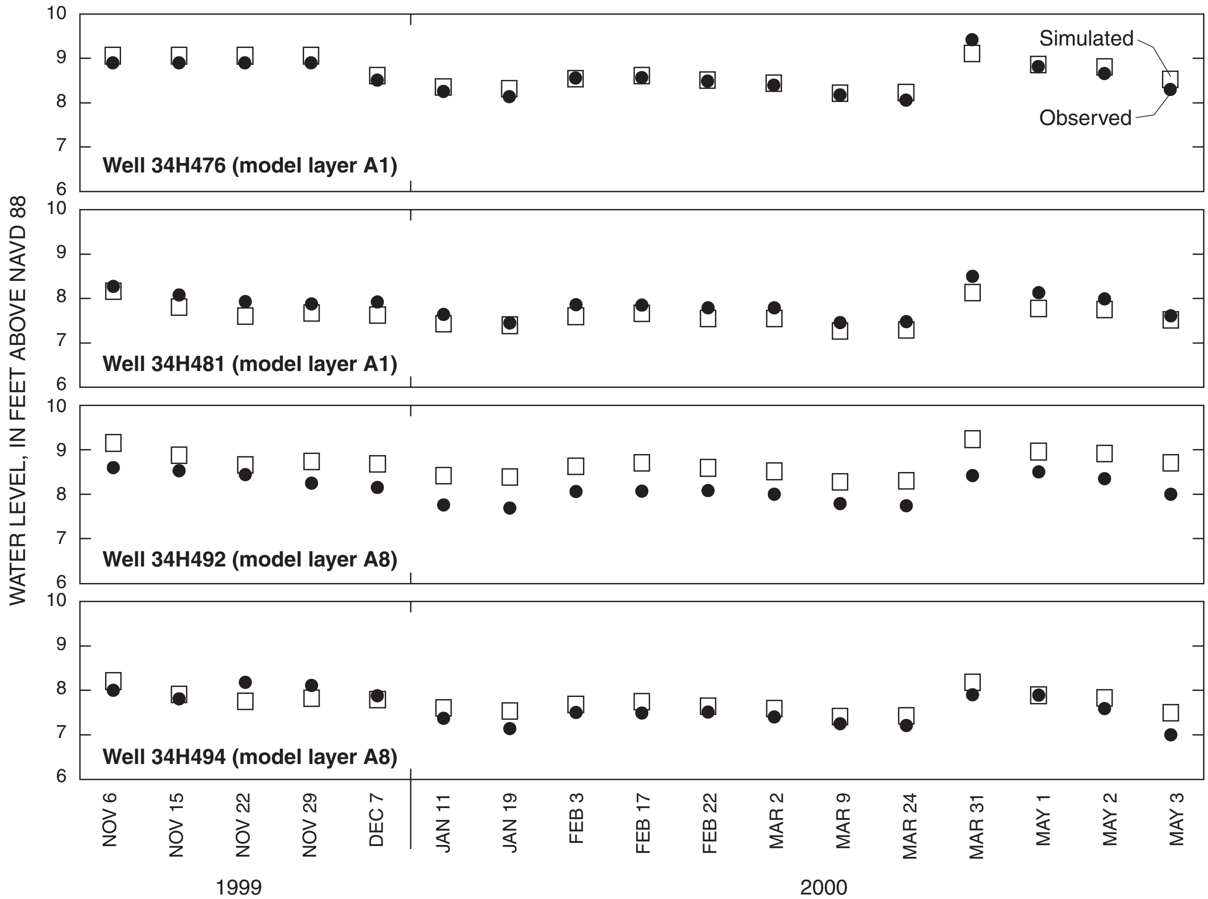

Figure A7. Observed and simulated water levels in selected wells at the Glynn County pond site in Georgia, November 6, 1999–May 3, 2000.

Calibrated Hydraulic Properties

Vertical and horizontal hydraulic conductivity was adjusted during calibration to provide a closer match of simulated values to observed ground-water levels and estimated ground-water seepage to the pond. Calibrated hydraulic conductivity for the Glynn County pond site is plotted in figures A8–A12. In general, calibrated values fall within the reported ranges for silty or fine sand (Heath, 1983) and are consistent with site observations of lithology and estimated permeability values for Glynn County reported by Beck (1978).

Values of hydraulic conductivity were zoned in layers A1 through A7 to reflect variations in hydraulic conductivity that might result from different types of vegetation and related depths of root penetration. The pond is surrounded by a wooded area consisting largely of pine trees and by open fields consisting largely of grassed areas (see figure A1). For layers A1 through A5, representing aquifer depths from 0 to about 32 ft, the influence of root penetration was believed to be more pronounced in the wooded area and less pronounced in the open fields. Three zones were delineated to reflect this variation (figs. A8, A10, and A11)—a western zone and eastern zone consisting largely of open fields, and a central zone consisting of wooded area surrounding the pond. The western zone includes the open-field area immediately surrounding the pond. In layers A6 and A7, representing depths from about 19 to 53 ft, two zones were delineated to the west and east of the pond. In layer A8, representing depths from 40 to 58 ft, a single zone was designated.

Simulated horizontal and vertical hydraulic conductivity was mostly higher in the western half of the simulated area and lower in the eastern half. In layers A1–A4, simulated horizontal hydraulic conductivity was 50 ft/d in the western zone, 5 ft/d in the central zone, and 0.5 ft/d in the eastern zone (fig. A8). In layer A5, horizontal conductivity was similarly distributed, with the exception that the central zone had a higher value of 30 ft/d (fig. A8). In layer A6, horizontal hydraulic conductivity was 40 ft/d in the western zone and 4 ft/d in the eastern zone; and in layer A8, a single value of 4 ft/d was simulated (fig. A9).

Simulated vertical hydraulic conductivity in layers A1 through A4 was from 30 to 40 ft/d in the western zone, 5 ft/d in the central zone, and 0.5 ft/d in the eastern zone (figs. A10 and A11). In layer A5, vertical hydraulic conductivity was similarly distributed, with the exception that the central zone had a higher value of 30 ft/d. In layer A6, vertical hydraulic conductivity was 40 ft/d in the western zone and 4 ft/d in the eastern zone; and in layer A8, a single value of 1 ft/d was simulated (fig. A12).

Table A2. Comparison of estimated and simulated net ground-water seepage, Glynn County pond site in Georgia.

[negative seepage values indicate net outflow from pond; positive numbers indicate net inflow]

Date	Net ground-water seepage in cubic feet per day		Difference	Percent difference
	Estimated	Simulated		
11/16/1999	−411	137	548	133
11/26/1999	−772	−1,071	−299	−39
12/6/1999	−1,536	−1,244	292	19
12/16/1999	−882	−765	117	13
12/26/1999	−1,567	−1,331	236	15
1/5/2000	−1,518	−2,224	−706	−46
1/15/2000	−1,359	−860	499	−37
1/25/2000	−1,578	384	1,962	124
2/4/2000	863	1,254	391	45
2/14/2000	−106	314	420	395
2/24/2000	716	764	48	7
3/5/2000	−10	−360	−350	−3,608
3/15/2000	−1,489	−1,640	−151	−10
3/25/2000	−694	−461	233	34
4/4/2000	2,950	2,622	−328	−11
4/14/2000	662	355	−307	−46
4/24/2000	714	42	−672	−94
Mean	−354	−240	114	−183
Tenth percentile	−1,548	−1,455	−479	−65
Twenty-fifth percentile	−1,489	−1,071	−307	−39
Median	−694	−360	117	7
Seventy-fifth percentile	662	355	391	34
Ninetieth percentile	775	960	519	128

Neither specific yield nor specific storage had any appreciable impact on simulated water levels or net ground-water seepage and required only minor adjustments during the transient simulation. Specific yield was 0.15 in layer A1 reflecting water-table conditions. Specific storage in layers A2–A8 was 0.0003 reflecting confined conditions.

Sensitivity Analysis

The sensitivity of the model to changes in model inputs was examined through a series of simulations whereby a single calibrated model parameter was varied while other parameters were held constant, and resulting simulated values for head and net ground-water seepage were compared to that of the calibrated model. Changes in the root mean square of residuals between observed and simulated hydraulic head are summarized in figures A13–A15. Changes in simulated net ground-water seepage are summarized in figure A13. Input parameters evaluated during the sensitivity analysis were:

- Steady-state model: horizontal hydraulic conductivity, vertical hydraulic conductivity, pond-bed hydraulic conductivity, and pond stage.
- Transient model: specific yield in the water-table zone (layer A1) and specific storage in the confined zone (layers A2–A8) was based on stress period 41, time step 16; net precipitation (recharge-evapotranspiration) was based on stress period 5, time step 1.

Stress period 41 was selected for evaluation of storage properties because lowering pond stage during the pond pumping test was considered to have the greatest impact on ground-water levels which are dependent, in part, on storage properties. Sensitivity of net precipitation could not be evaluated during this period, because it was near zero during the pumping test. Stress period 5 was a period of negative net precipitation (evapotranspiration exceeded precipitation).

Table A3. Simulated transient water budget immediately prior to and after pond pumping test, May 1–3, 2000, Glynn County pond site in Georgia.

Component of budget	Before pumping test, May 1, 2000				After pumping test, May 3, 2000			
	Inflow		Outflow		Inflow		Outflow	
	Cubic feet per day	Percentage of flow	Cubic feet per day	Percentage of flow	Cubic feet per day	Percentage of flow	Cubic feet per day	Percentage of flow
Storage	49,700	71	440	1	22,200	67	9,500	29
Specified head	19,900	29	1,000	1	10,800	33	20,500	62
Recharge	0	0	68,000	98	0	0	3,000	9
Total	**69,600**		**69,440**		**33,000**		**33,000**	

Figure A8. Simulated horizontal hydraulic conductivity in feet per day in model layers A1 through A5 at the Glynn County pond site in Georgia.

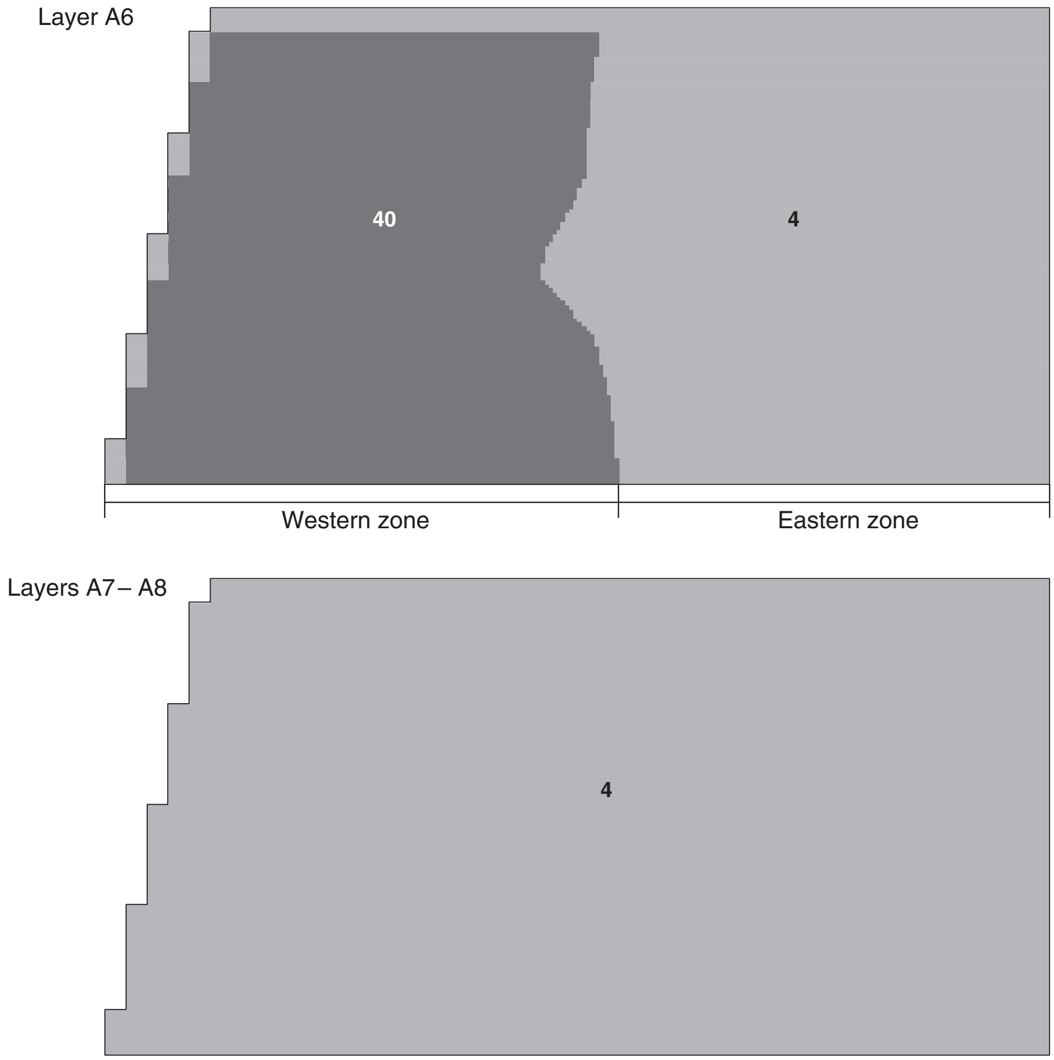

Figure A9. Simulated horizontal hydraulic conductivity in feet per day in model layers A6 through A8 at the Glynn County pond site in Georgia.

Figure A10. Simulated vertical hydraulic conductivity in feet per day in model layers A1 through A3 at the Glynn County pond site in Georgia.

Figure A11. Simulated vertical hydraulic conductivity in feet per day in model layers A4 and A5 at the Glynn County pond site in Georgia.

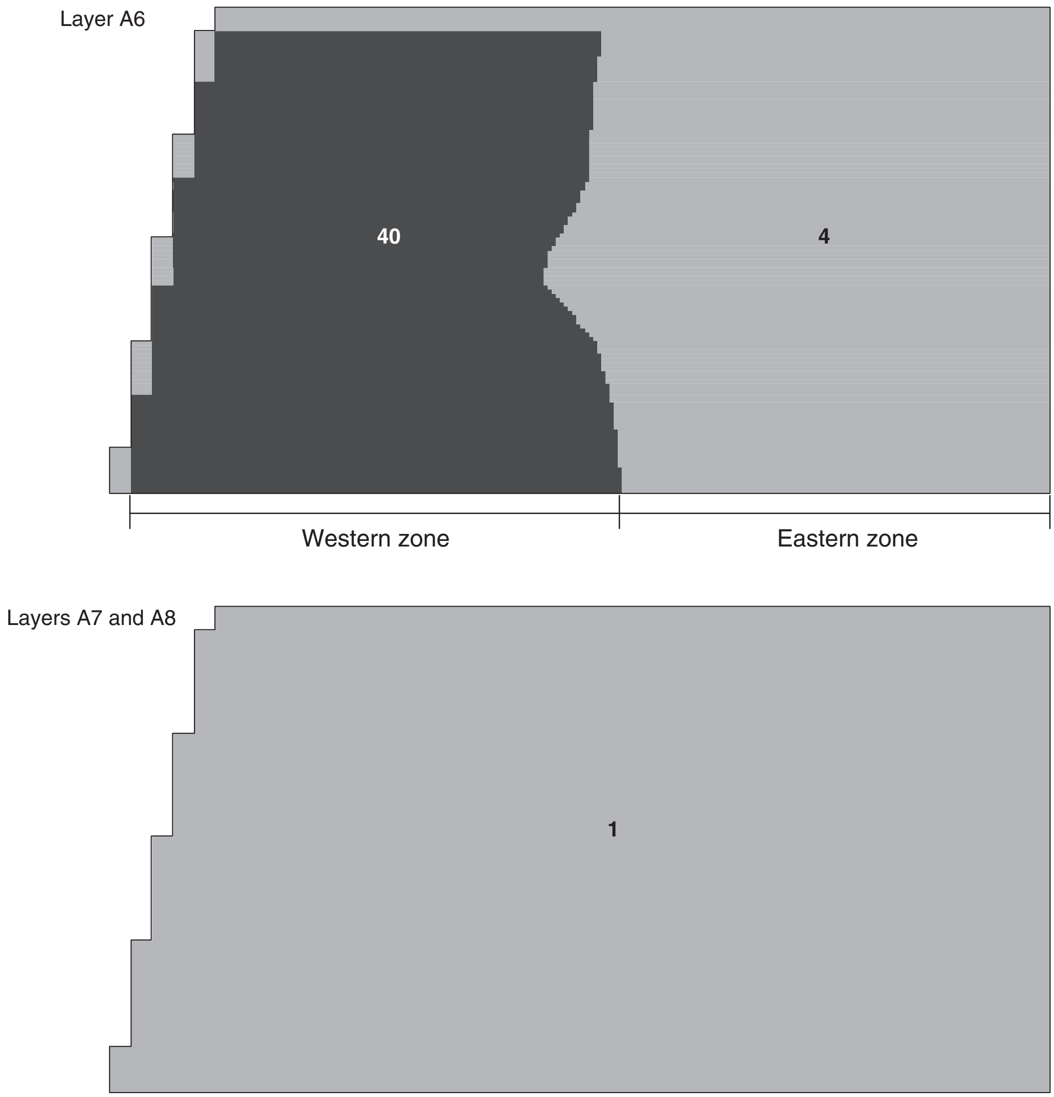

Figure A12. Simulated vertical hydraulic conductivity in feet per day in model layers A6 through A8 at the Glynn County pond site in Georgia.

Simulated ground-water levels are most sensitive to changes in horizontal, vertical, and pond-bed hydraulic conductivity (fig. A13A); simulated net ground-water seepage is most sensitive to changes in horizontal hydraulic conductivity, specific storage, and specific yield (fig. A13B). Decreasing horizontal, vertical, and pond-bed hydraulic conductivity had a similar impact on simulated ground-water levels (fig. A14). Increased horizontal hydraulic conductivity had a pronounced affect on simulated ground-water levels, while increased vertical and pond-bed hydraulic conductivity showed little effect. Simulated ground-water levels were highly sensitive to increases and decreases in pond stage (fig. A15). Changes in pond stage directly affect hydraulic gradients near the pond and impact head in the surficial aquifer, resulting in model sensitivity to this parameter.

Limitations of Digital Simulation

The digital ground-water flow model developed for the study area addresses questions related to ground-water flow through the surficial aquifer in the vicinity of Glynn County, Georgia. The conceptual model—supported by field measurement of ground-water levels, pond stage, and estimated water budget—is believed to represent flow-system dynamics accurately. Additional measurement of the vertical distribution of aquifer head near and beneath the pond would improve characterization of the conceptual model for the site.

The model is further limited by difficulty in obtaining sufficient measurements to account for all of the spatial variation in hydraulic properties and boundary conditions throughout the model area. The relative importance of hydraulic properties and selected boundary conditions on the calibrated model results are presented in the "Sensitivity Analysis" section. Simulated ground-water levels were sensitive to changes in pond stage and horizontal, vertical, and pond-bed hydraulic conductivity. Simulated net ground-water seepage was sensitive to horizontal hydraulic conductivity, specific storage, and specific yield.

Pond stage was adequately represented by field measurements; however, the model was unable to account for all of the spatial variation in hydraulic properties due to sparse field data on hydraulic properties, particularly vertical and horizontal hydraulic conductivity and pond-bed hydraulic conductivity. Additionally, because hydraulic conductivity and recharge are correlated in the mathematics of the ground-water flow equation on which MODFLOW is based, an overestimation of recharge would also result in an overestimation of hydraulic conductivity. Direct measurement of hydraulic conductivity through field or laboratory testing would decrease the level of uncertainty of the calibrated model.

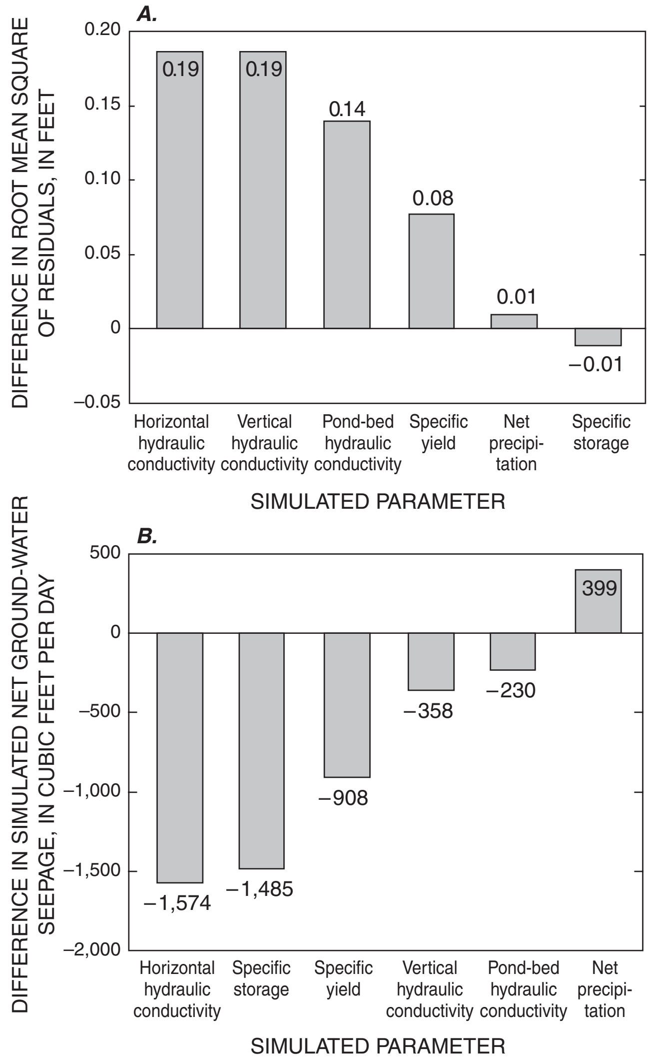

Figure A13. Sensitivity of simulated (*A*) ground-water levels; and (*B*) net ground-water seepage to changes in selected model parameters for the model, Glynn County pond site in Georgia. Calibrated parameters were modified by multiplying by 0.1 and rerunning the model to determine impact on simulated net ground-water seepage. Hydraulic conductivity based on steady-state model; specific storage and specific yield based on stress period 41, time step 16, transient model; net precipitation (precipitation minus evapotranspiration) based on stress period 5, time step 1, transient model.

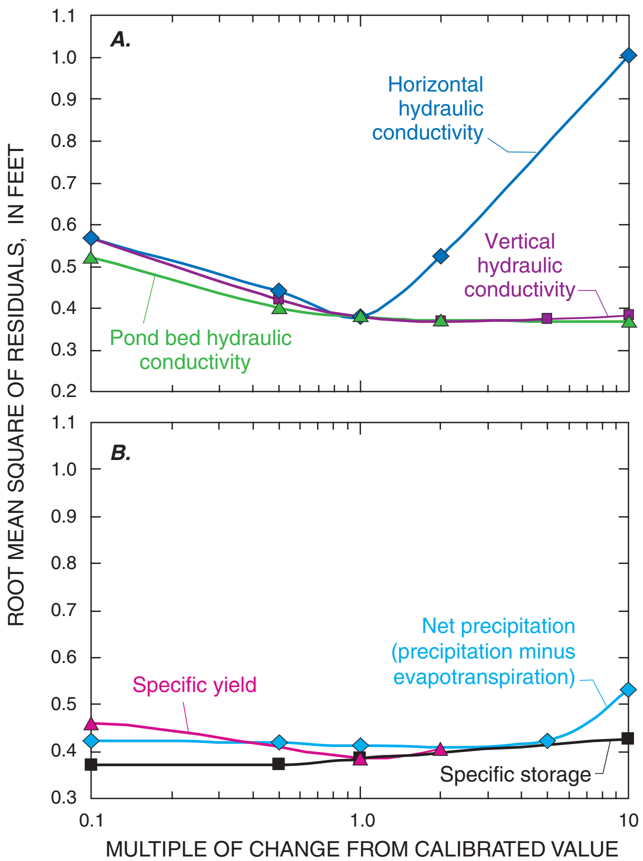

Figure A14. Sensitivity of simulated ground-water levels to selected parameters, Glynn County pond site in Georgia for the model—(*A*) steady-state model; and (*B*) transient model.

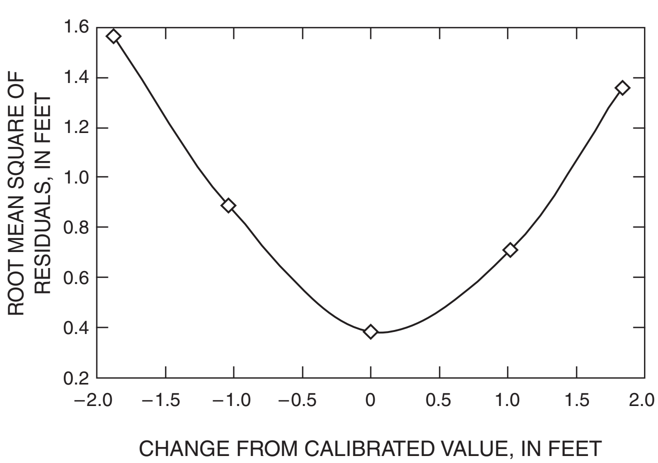

Figure A15. Sensitivity of simulated ground-water levels to changes in pond stage for the model, Glynn County pond site in Georgia. Based on steady-state simulation.

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Appendix B. Ground-Water Model for the Bulloch County Pond Site in Georgia

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Appendix B. Ground-Water Model for the Bulloch County Pond Site in Georgia

Model Development

Pond-aquifer flow at the Bulloch County pond site was simulated using the U.S. Geological Survey (USGS) digital, three-dimensional, finite-difference ground-water flow model, MODFLOW (McDonald and Harbaugh, 1988). Steady-state and transient simulations were used to evaluate changes in ground-water level and seepage to and from the pond prior to and during the 28-hour pond pumping test. Initial conditions on February 22, 2001, were simulated as steady state, followed by simulation of transient changes in recharge, pond stage, ground-water levels, and seepage from February 22, 2001, through July 4, 2001, including a pond pumping test, June 4–5, 2001. ZONEBUDGET (Harbaugh, 1990) was used to estimate rates of ground-water seepage to the pond.

The model domain consists of a variably spaced grid having 80 rows and 95 columns, encompassing an area of 0.36 square mile (fig. B1). Cell size ranges from 20 by 20 feet (ft) near the pond to 85 by 109 ft at the outer margins of the model grid. Smaller cell sizes were used near the pond to better simulate steeper hydraulic gradients and pond bathymetry. In the model, the surficial aquifer is divided into four confined layers (fig. B2). Layer A1 is the uppermost layer and was used to maintain specified heads in the pond and to provide recharge to, and evapotranspiration from, the surficial aquifer. Layer A2 is a thin layer that includes pond bed sediments and was used to control the flow of water to and from layer A1 and the pond. Flow in the surficial aquifer was simulated using two layers—layers A3 and A4, representing the top and bottom of the unit, respectively. Approximate altitudes of the top of each layer are shown on figure B2. Layer thicknesses are as follows: A1, from 6 to 13 ft; A2, 1 ft; A3, 4 ft, and A5, 5 ft.

Initial estimates of horizontal hydraulic conductivity, expressed in feet per day (ft/d) were assigned based on estimated ranges for various lithologies derived from the literature (Heath, 1983). In layer A1, initial horizontal hydraulic conductivity was subdivided into two zones—clayey soils encountered at depths from 0 to about 13 ft across most of the area were assigned a value of 0.0005 ft/d, and an intermittent stream valley in the southwestern part of the simulated area was assigned a value of 100 ft/d, representing coarse alluvial sand (see location, fig. B3). Initial horizontal hydraulic conductivity values for layer A2 were representative of coarse sand (75 ft/d). In layers A3 and A4, initial horizontal hydraulic conductivity was 50 ft/d (coarse sand).

Initial vertical hydraulic conductivity was also assigned on the basis of estimated ranges for various lithologies derived from the literature (Heath, 1983). For layer A1, an initial value of 1 ft/d, reflecting silty sand, was assigned in the vicinity of the intermittent stream valley. Layer A2 is a thin layer that was used to control the flow of water to and from layer A1. Initial vertical hydraulic conductivity for layer A2 was 0.1 ft/d. For layers A3 and A4, initial vertical hydraulic conductivity was 5 ft/d. Layers A1–A4, simulated as confined layers, were assigned a specific storage of 1 x 10^{-5}. Vertical and horizontal hydraulic conductivity values were adjusted as part of the calibration process (see “Calibrated Hydraulic Properties” section).

Lateral boundary conditions for the model were selected to coincide as closely as possible with natural no-flow boundaries (fig. B1). No-flow boundaries assigned to the western and eastern sides of the model correspond to flow lines in the surficial aquifer. An additional no-flow boundary along the southernmost part of the model area was located in a topographically high area along the Interstate Highway 16 median where flow conditions are poorly defined. The northern and part of the southern boundaries are simulated as specified-head layers located at least 0.1 mile from the pond site to minimize influence on simulation results. Head at the lateral boundaries were varied based on monitoring well observations (see boundary and well locations, fig. B1). Water levels in the surficial aquifer were lower than normal during the period of simulation due to effects of a prolonged drought in the area.

The uppermost layer (A1) was initially simulated as a largely inactive layer, with recharge cells designated in the vicinity of an intermittent stream valley in the southwestern part of the area, and specified-head cells designated in the vicinity of the pond. Boundary conditions in layer A1 were subsequently modified to include (1) a free-surface boundary in which recharge was applied to simulate the water table and (2) as a zone of specified head in the area of the pond (fig. B1). The base of the model is a no-flow boundary at the top of the basal clay layer, at the bottom of layer A4.

The recharge package of MODFLOW was used to simulate both recharge to the aquifer and water discharging from the aquifer as evapotranspiration. Net precipitation, representing the difference between precipitation and evapotranspiration, was estimated using continuous data from the weather station, averaged during 10-day periods—when positive, values represent net recharge; when negative, values represent net evapotranspiration. To reflect variations in soil infiltration capacity and uptake by plants (transpiration), the model was divided into two recharge zones (fig. B3):

- Zone 1: Wooded areas; and
- Zone 2: Field areas with grass or dirt (little vegetation).

The pond is simulated as a constant-head boundary in layer A1. The depth and geometry of the pond bottom were determined from a bathymetric survey conducted during fall 2000. Pond-stage changes recorded by a continuous gage were applied to each stress period of the transient model. A second pond, located about 0.13 mi north of the study pond, was deemed too small to impact the pond-aquifer flow system and was not included in the model simulation.

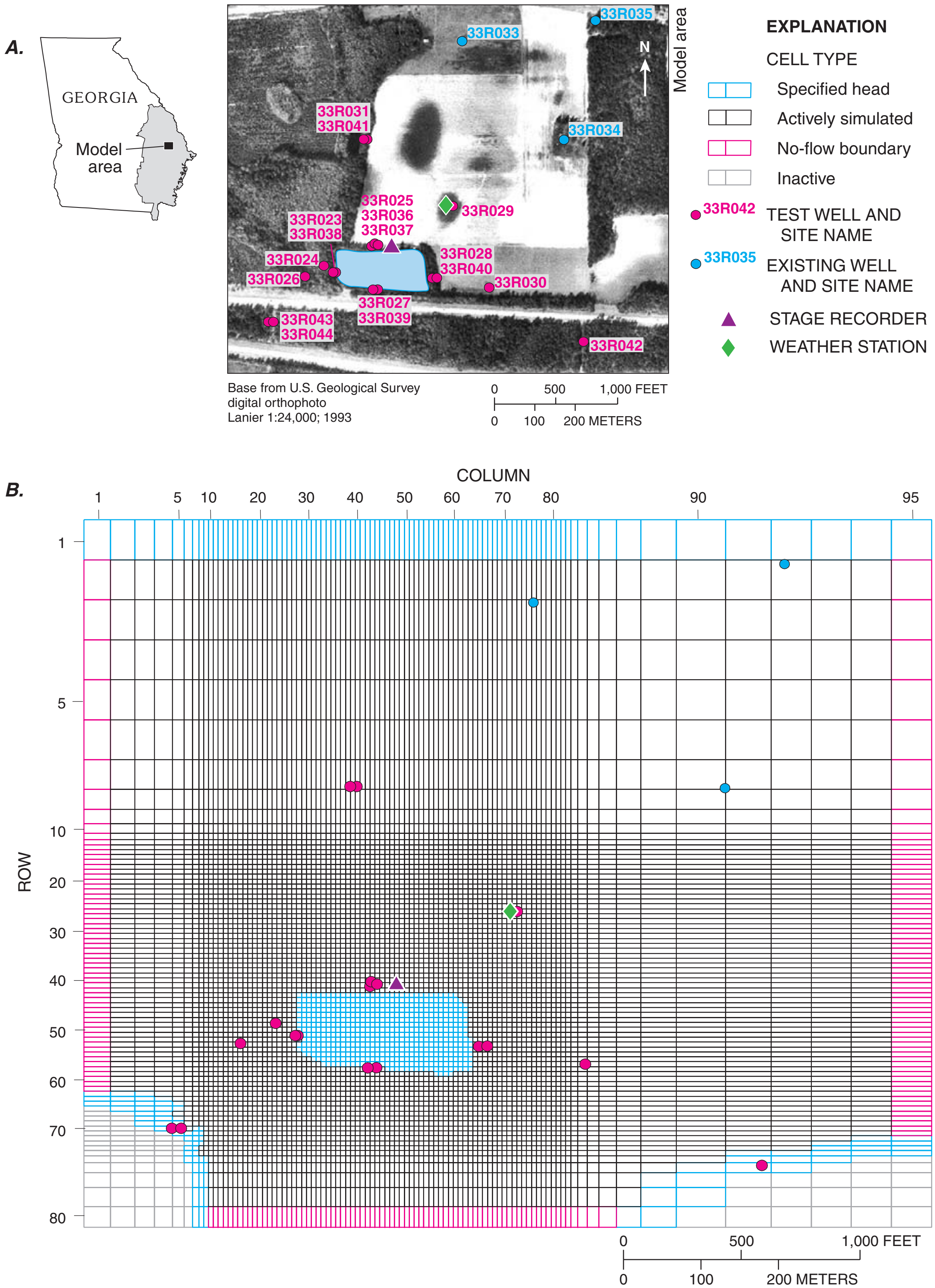
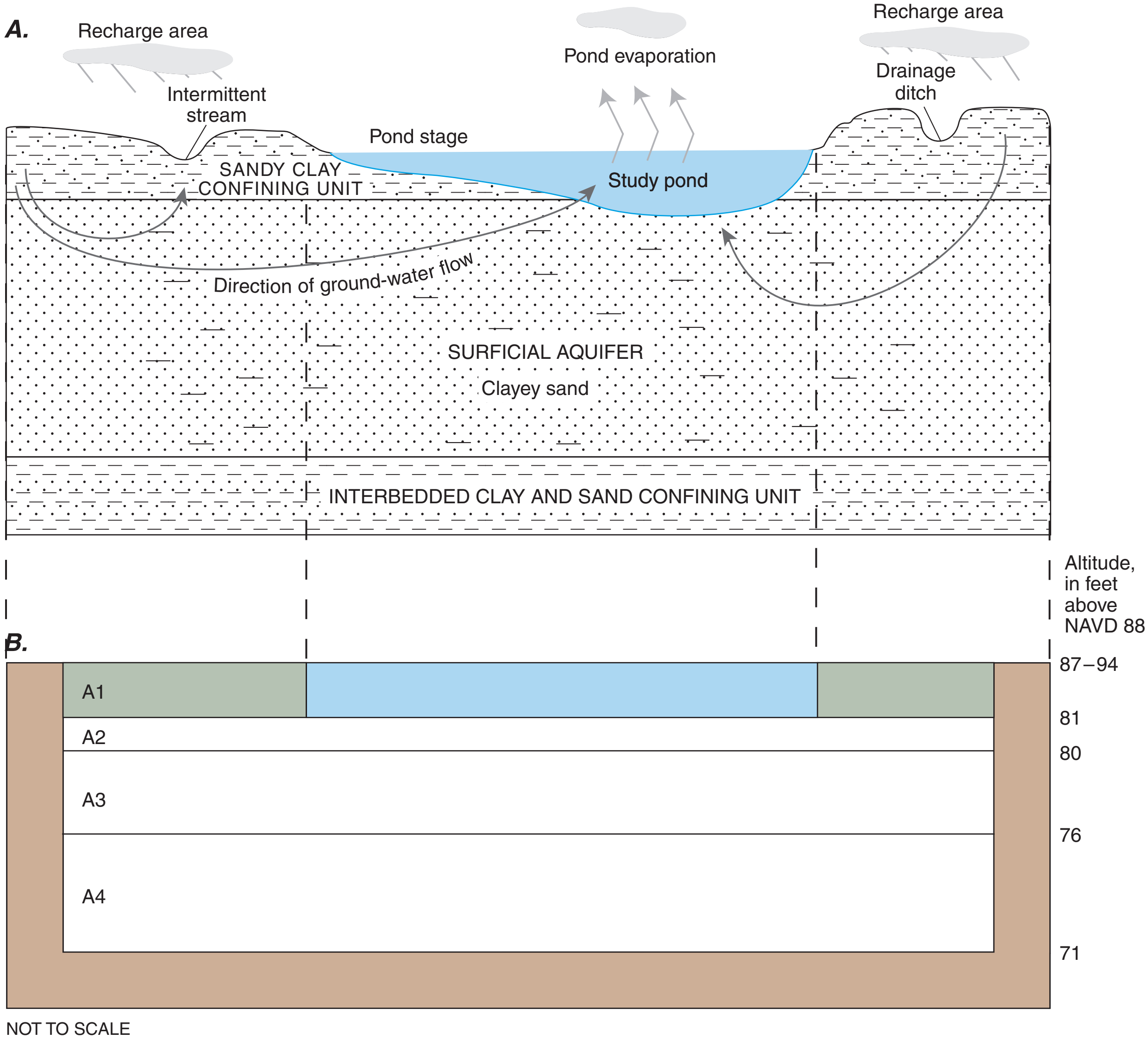


Figure B1. (*A*) Model area and well locations; and (*B*) model grid and boundaries, Bulloch County pond site in Georgia.



EXPLANATION

- RECHARGE CELL—Inputs recharge during wet periods, receives ground-water discharge through evapotranspiration during dry periods
- SPECIFIED HEAD BOUNDARY
- NO-FLOW BOUNDARY
- A2 MODEL LAYER

Figure B2. Diagram showing (*A*) hydrogeologic framework and pond-aquifer flow, and (*B*) model layers and boundary conditions for the Bulloch County pond site model in Georgia.

Figure B3. Recharge zones for the Bulloch County pond site model in Georgia.

Steady-State Simulation

The steady-state model was used to (1) provide initial heads for transient simulations and (2) refine the initial estimates of hydraulic properties and their spatial distribution. The steady-state simulation was based on observed conditions during February 22, 2001, a period of relatively stable ground-water levels. Because the period preceding February 22 was mostly dry, no recharge was applied for the steady-state simulation. In addition, because February is a winter month in which there is less active vegetation, losses by evapotranspiration were not included in the simulation.

The steady-state model was calibrated by adjusting values of horizontal and vertical hydraulic conductivity in order to match observed heads. The calibrated steady-state model showed a good comparison to observed heads, with residuals ranging from –0.6 to 0.59 ft, a root mean square error of 0.37 ft, and standard deviation of 0.38 ft, in the 14 wells completed in layers A3 and A4 at the time of the simulation. Water-level residuals are shown for the 14 wells on figure B4.

The simulated steady-state water budget for the prepumping period indicates that inflows are derived entirely from specified-head cells along the northern and southern boundaries of the model (table B1). Outflows are to specified-head cells at the pond (64 percent) and along the northern boundary of the model (36 percent). Net precipitation (precipitation minus evapotranspiration) during the prepumping period was near zero and was therefore not incorporated into the steady-state simulation.

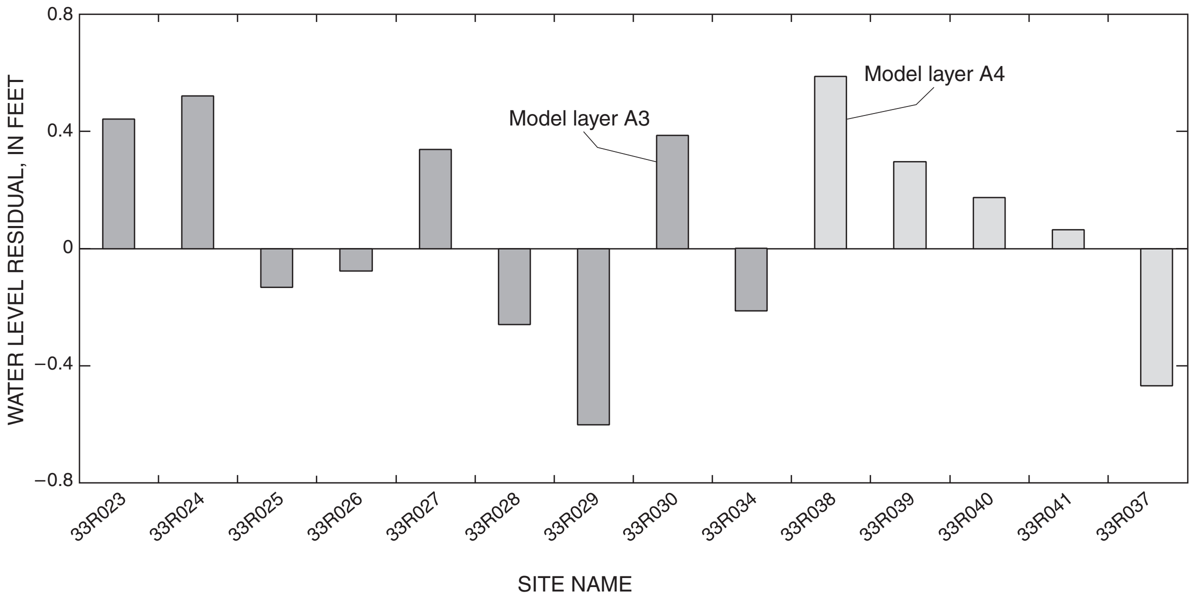


Figure B4. Difference between observed and simulated water levels (residual) for steady-state simulation, Bulloch County pond site in Georgia, February 22, 2001.

Table B1. Simulated steady-state water budget, Bulloch County pond site in Georgia, February 22, 2001.

Component of budget	Inflow		Outflow	
	Cubic feet per day	Percent of flow	Cubic feet per day	Percent of flow
Specified head				
Lateral boundaries	5,818	100	2,093	36
Pond	0	0	3,727	64
Recharge[1]	0	0	0	0
Total	**5,818**		**5,820**	

[1]Simulates recharge in inflow cells; evapotranspiration in outflow cells

Transient Simulation

Following the initial steady-state simulation, the model was used to simulate transient conditions from February 22, 2001, through the pond pumping test, June 4–5, 2001, and subsequent recovery through July 4, 2001. Pond-aquifer flow was simulated using the model and rates of net ground-water seepage were determined using the MODFLOW postprocessor ZONEBUDGET (Harbaugh, 1990) for selected periods prior to and during the pond pumping test.

The transient simulation consisted of 33 stress periods, based on precipitation patterns monitored at the on-site weather station. Before the pond pumping test, each stress period consisted of daily time steps, with the longest stress period before the pumping test having 25 time steps (days) and the shortest having one time step (day). During the 28-hour pumping test, the model consisted of one stress period divided into 32 time steps of 52.5 minutes each.

Each stress period was assigned an initial recharge rate that reflected the net precipitation (precipitation minus evapotranspiration) observed at the weather station. In some instances, evapotranspiration exceeded precipitation; therefore, recharge was negative, representing discharge from the pond-aquifer system. Recharge rates were applied based on the two recharge zones described previously. No recharge was applied to the pond because it is represented by specified-head model cells. Calibrated values of recharge were at or below the estimated average net precipitation for each stress period (fig. B5).

Initial hydraulic conductivity values used by the transient model were identical to those used by the steady-state model, with specific storage also incorporated into the transient model. Layers A1–A4, simulated as confined layers, were assigned a specific storage of 1×10^{-5}.

The transient model was calibrated by adjusting values of recharge and hydraulic conductivity in an effort to minimize the residuals between observed and simulated head and between the simulated and calculated net ground-water budget. All changes to hydraulic properties made during the transient calibration were also made in the steady-state model, so that both models contained identical hydraulic-property values. Eighty percent of simulated head values were within –3.4 and 1.5 ft of observed values during six transient stress periods (fig. B6). Graphs of observed water levels in selected wells are plotted together with simulated values in figure B7. The graphs indicate the model reasonably simulates water-level changes in the upper and lower parts of the surficial aquifer throughout the transient period.

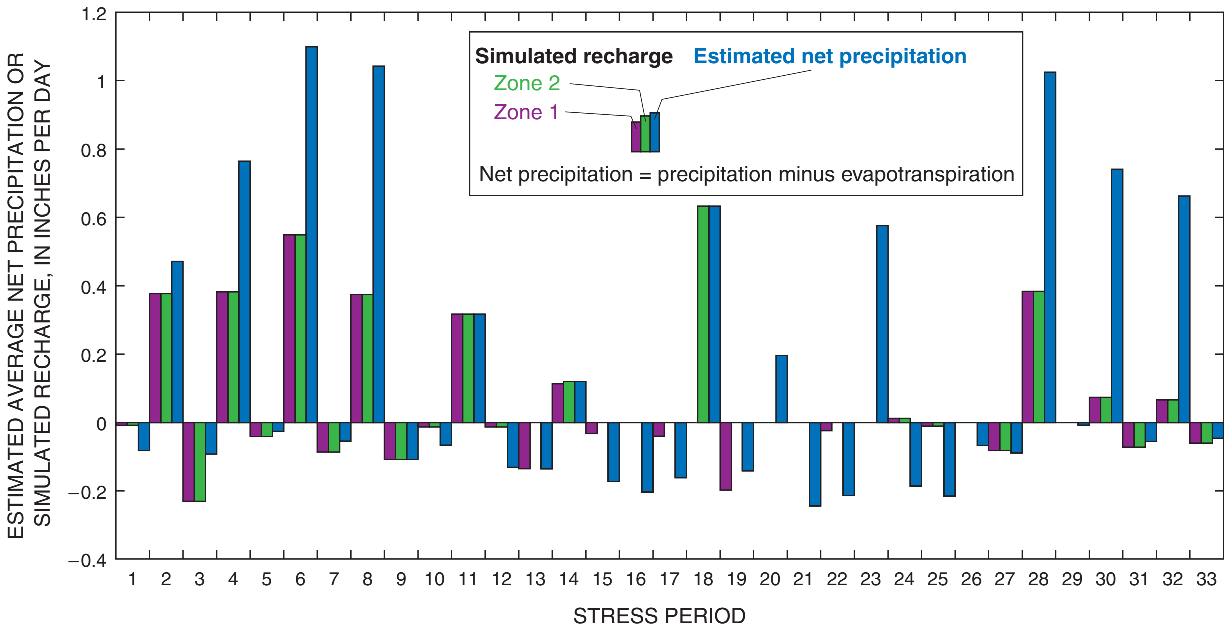


Figure B5. Comparison of estimated average net precipitation and simulated recharge by stress period for the transient model, Bulloch County pond site in Georgia. When positive, values represent net recharge, when negative, values represent net evapotranspiration.

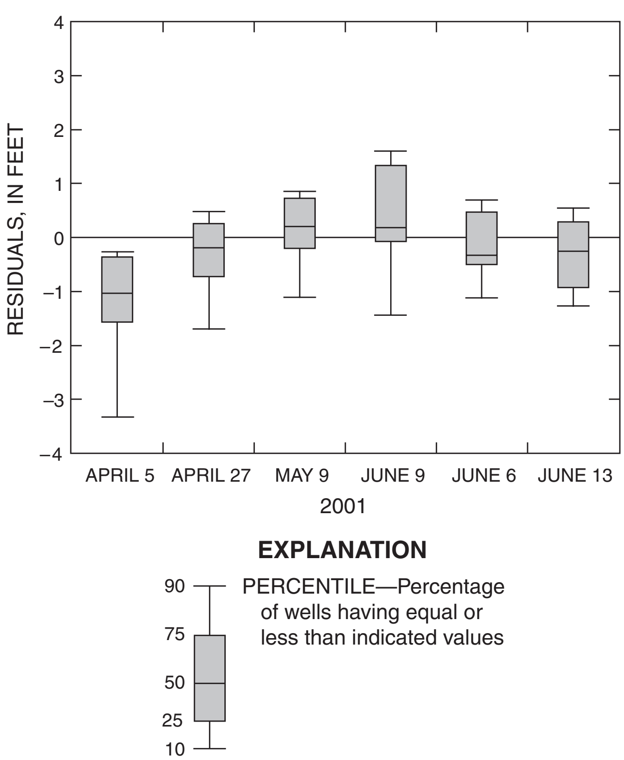


Figure B6. Difference between observed and simulated heads (residuals) for the transient model, Bulloch County pond site in Georgia.

In addition to ground-water levels, the transient model was calibrated by adjusting aquifer parameters to minimize differences between simulated net ground-water seepage (as determined by summing fluxes to the pond using ZONEBUDGET) and estimated values (table B2). Simulated results showed a good comparison to estimated results, with some exceptions—one-half of the values were within –42 to +38 percent of estimated values, and 80 percent of the values were within –75 to +515 percent of estimated values. The largest differences generally occurred when seepage estimates were near zero.

Simulated transient water budgets were computed for the stress period immediately before the pumping test (1-day period) and for the period immediately after the pumping test (28-hour period). Comparison of the pre- and postpumping test simulated transient water budget indicates that specified head cells at the pond and along the southern boundary provided most of the inflow to the model, with nearly 100 percent contributed prior to the test and 97 percent contributed immediately following the test (table B3). Outflow from the model was provided entirely from storage before the test and from specified-head cells at the pond and northern boundary (78 percent) and storage (22 percent) at the end of the test. Lowering head in the pond by pumping produced a steepened hydraulic gradient toward the pond, resulting in greater flow rates.

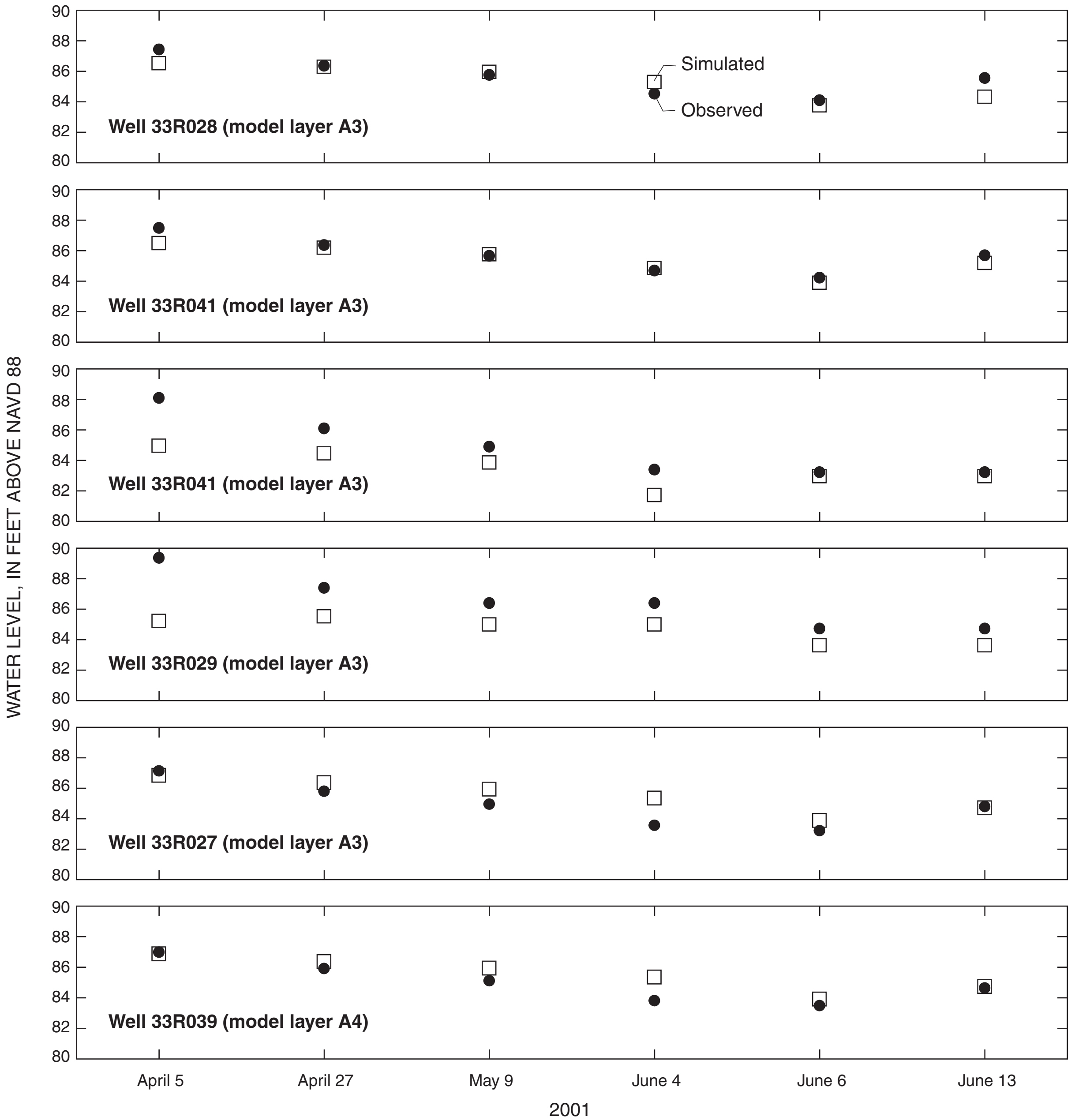


Figure B7. Observed and simulated water levels in selected wells at the Bulloch County pond site in Georgia, April 5–June 13, 2001.

Table B2. Comparison of estimated and simulated net ground-water seepage, Bulloch County pond site in Georgia.

[negative seepage values indicate net outflow from pond; positive numbers indicate net inflow]

Date	Net ground-water seepage in cubic feet per day		Difference	Percent difference
	Estimated	Simulated		
03/02/01	2,222	1,336	−886	−40
03/09/01	994	202	−792	−80
03/16/01	1,618	1,034	−584	−36
03/23/01	5,690	5,889	199	4
03/30/01	4,047	3,628	−419	−10
04/06/01	4,048	6,015	1,967	49
04/13/01	3,415	917	−2,498	−73
04/20/01	39	720	681	1,746
04/27/01	−802	−1,205	−403	50
05/04/01	−1,046	−1,777	−731	70
05/11/01	−3,089	−2,397	692	−22
05/18/01	4,464	2,581	−1,883	−42
05/25/01	−19	−314	−295	1,553
06/01/01	−10,666	−10,424	242	−2
06/15/01	2,987	−459	−3,446	−115
06/22/01	2,623	1,025	−1,598	−61
06/29/01	1,823	1,960	137	8
07/06/01	4,214	2,634	−1,580	−37
Mean	1,253	631	−622	164
Tenth percentile	−1,659	−1,963	−2,068	−75
Twenty-fifth percentile	−4	−423	−1,406	−42
Median	2,023	971	−502	−16
Seventy-fifth percentile	3,889	2,426	184	38
Ninetieth percentile	4,289	4,306	684	515

Calibrated Hydraulic Properties

Vertical and horizontal hydraulic conductivity was adjusted during calibration to provide a closer match of simulated values to observed ground-water levels and estimated ground-water seepage to the pond. Calibrated hydraulic properties at the Bulloch County pond site are plotted in figures B8 and B9. Calibrated horizontal hydraulic conductivity (fig. B8) was lowest in layer A1, representing the clayey soil zone (mostly 0.0005 ft/d), and greatest in layers A3 and A4, representing the surficial aquifer (mostly 70 ft/d). Horizontal hydraulic conductivity was also high in layers A1 and A2 (70 ft/d) in the vicinity of an intermittent stream channel in the southwestern part of the simulated area that breached the surficial aquifer (fig. B8).

Calibrated vertical hydraulic conductivity in layers A1 and A2 (fig. B9) was highest in the vicinity of the intermittent stream channel in the southwestern part of the simulated area (15 ft/d). In layers A3 and A4, calibrated vertical hydraulic conductivity was 10 ft/d across most of the simulated area. Beneath the pond, vertical hydraulic conductivity of layer A2 (pond-bed hydraulic conductivity) had a pronounced affect on simulated net ground-water seepage and was adjusted numerous times during the calibration process. Calibrated values were from 0.05 to 0.16 ft/d across much of the western half of the pond and were from 1 to 5 ft/d in isolated parts of the eastern half of the pond. The higher values may reflect areas where the pond bed was breached during construction of the pond and were infilled with more permeable sediments. Specific storage in the confined surficial aquifer (layers A3 and A4) had little impact on simulated water levels or net ground-water seepage and was held constant at 0.00001.

Table B3. Simulated transient water budget immediately before and after pond pumping test, June 4–5, 2001, Bulloch County pond site in Georgia.

Component of budget	Before pumping test, June 4, 2001				After pumping test, June 5, 2001			
	Inflow		Outflow		Inflow		Outflow	
	Cubic feet per day	Percentage of flow	Cubic feet per day	Percentage of flow	Cubic feet per day	Percentage of flow	Cubic feet per day	Percentage of flow
Storage	15	0.1	13,100	100	4,600	3.4	29,900	22.0
Specified head	13,100	99.9	0	0	13,1100	96.6	105,800	78
Recharge	0	0	0	0	0	0	0	0
Total	**13,115**		**13,100**		**135,700**		**135,700**	

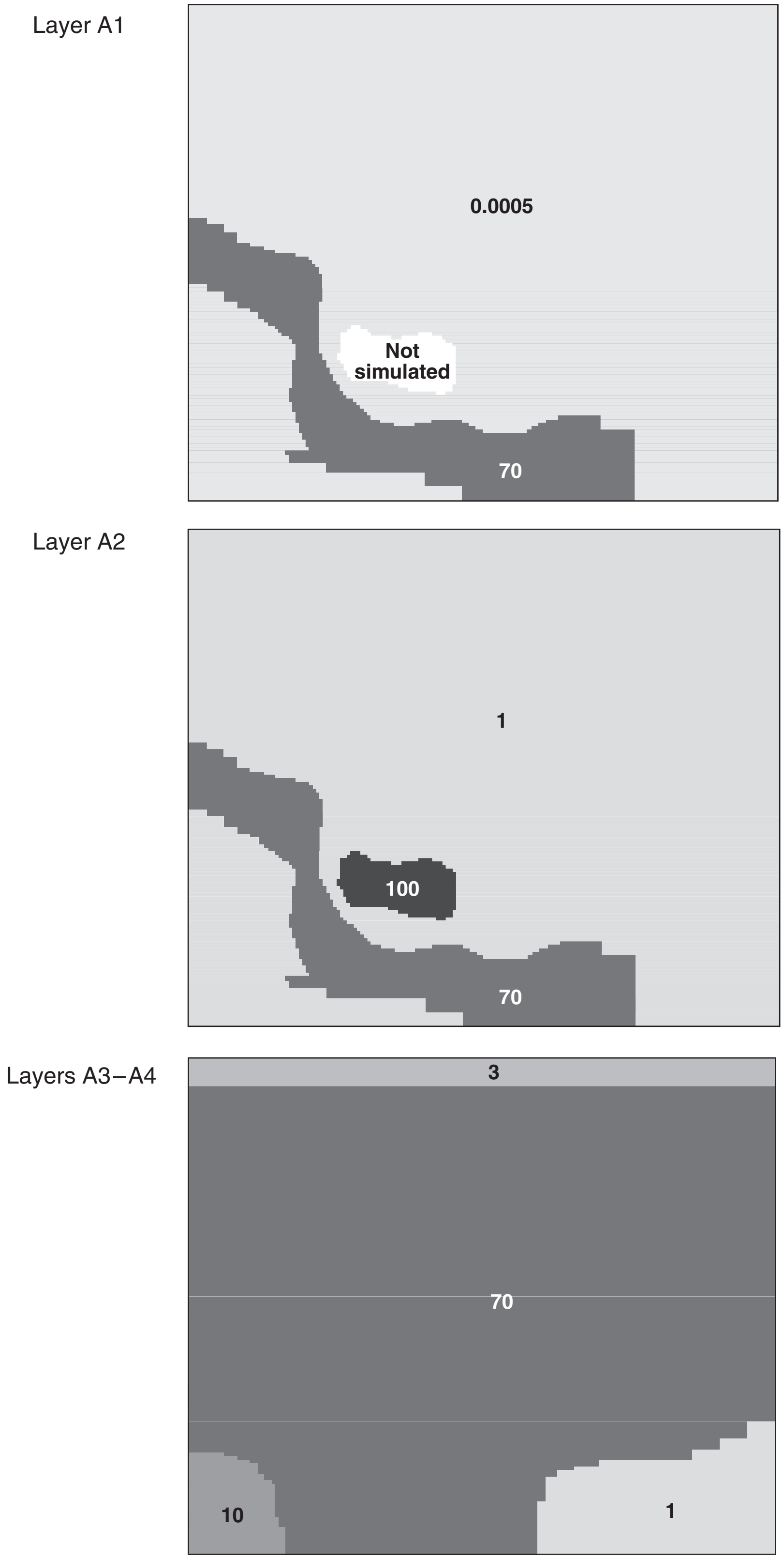


Figure B8. Simulated horizontal hydraulic conductivity in feet per day in model layers A1 through A4 at the Bulloch County pond site in Georgia.

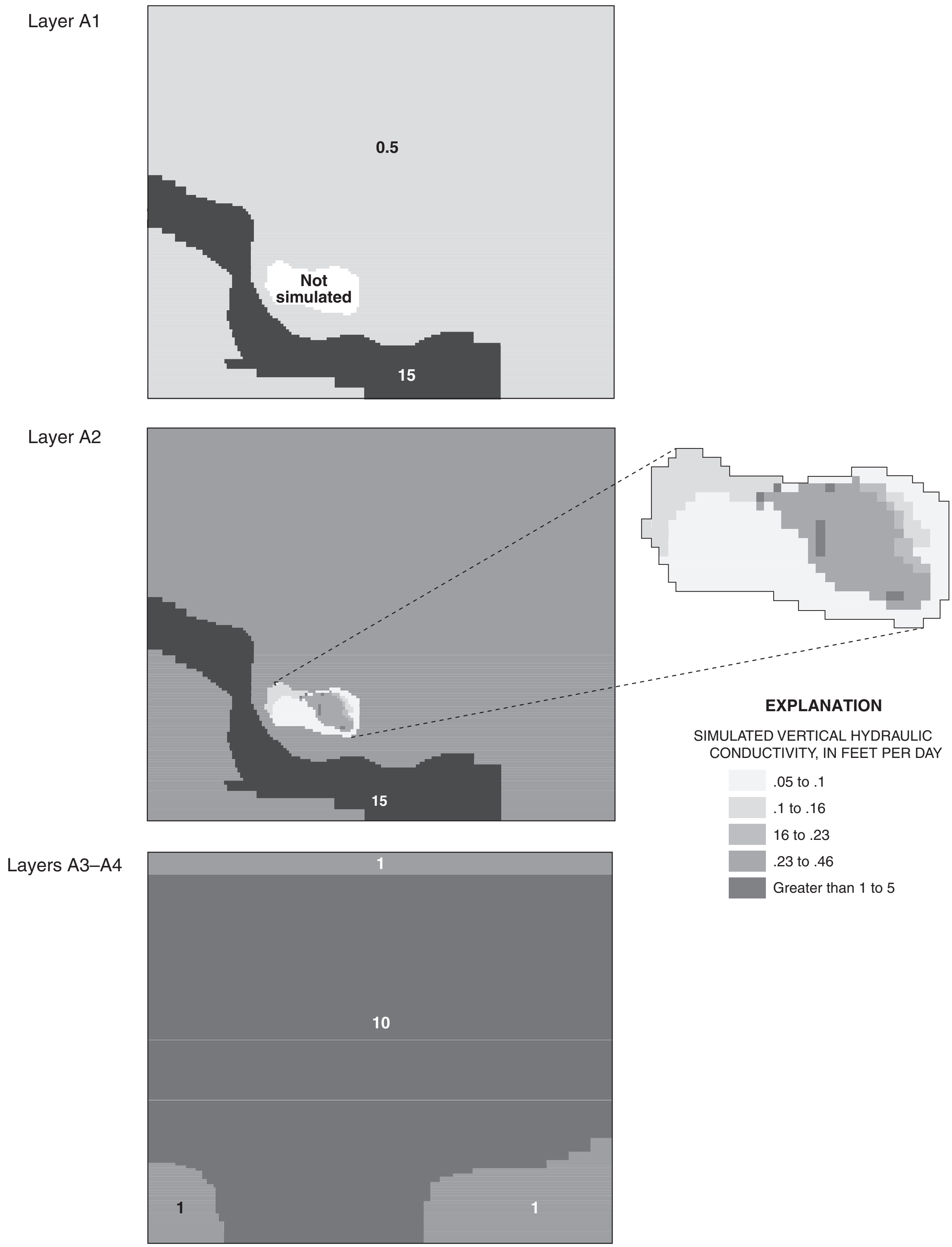


Figure B9. Simulated vertical hydraulic conductivity in feet per day in model layers A1 through A4 at the Bulloch County pond site in Georgia.

Sensitivity Analysis

The sensitivity of the model to changes in model inputs was examined by varying a single calibrated model parameter, running the model, and comparing the resulting simulated values for head and net ground-water seepage to that of the calibrated model. For each simulation, the value of a single input parameter was varied while other inputs were held constant. Changes in the root mean square of residuals between observed and simulated hydraulic head are summarized in figures B10–B12. Changes in simulated net ground-water seepage are summarized in figure B10. Input parameters evaluated during the sensitivity analysis were:

- Steady-state model: horizontal hydraulic conductivity, vertical hydraulic conductivity, pond-bed hydraulic conductivity, and pond stage.
- Transient model: recharge and specific storage (based on stress period 24, time step 1).

Simulated ground-water levels are most sensitive to changes in vertical and pond-bed hydraulic conductivity (fig. B10A); simulated net ground-water seepage is most sensitive to changes in horizontal hydraulic conductivity and net precipitation (fig. B10B). Decreases in vertical and pond-bed hydraulic conductivity have a pronounced affect on simulated ground-water levels, whereas increases show little effect (fig. B11). Increases in horizontal hydraulic conductivity had a more pronounced affect on simulated ground-water levels than decreases. Simulated ground-water levels were highly sensitive to increases and decreases in pond stage (fig. B12). Changes in pond stage directly affect hydraulic gradients near the pond and impact head in the surficial aquifer, resulting in model sensitivity to this parameter.

The sensitivity analysis for net precipitation was conducted during model stress period 24, time step 1, when simulated net precipitation was positive (fig. B11). Multiplying calibrated net precipitation by 0.1 resulted in decreased net ground-water seepage to the pond (fig. B10). Simulated ground-water levels are also sensitive to increases in net precipitation. Although increasing net precipitation by a factor of two had little effect, increasing by a factor of five had a pronounced affect on simulated ground-water levels (fig. B11).

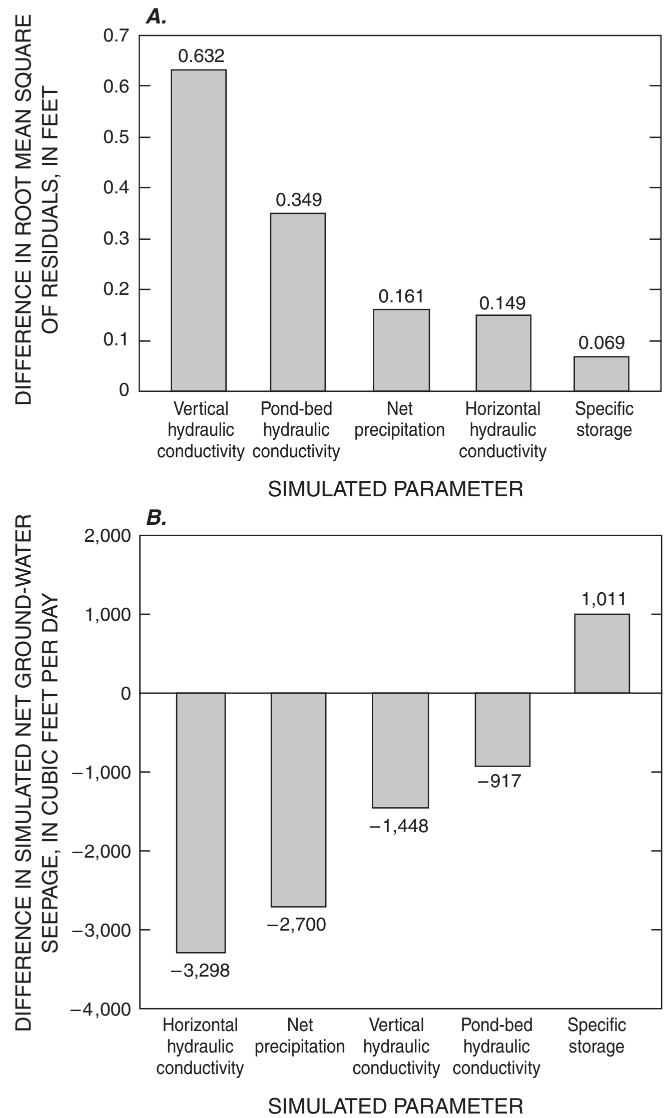


Figure B10. Sensitivity of simulated (*A*) ground-water levels; and (*B*) net ground-water seepage to changes in selected model parameters for the model, Bulloch County pond site in Georgia. Calibrated parameters were modified by multiplying by 0.1 and rerunning the model to determine impact on simulated net ground-water seepage. Hydraulic conductivity based on steady-state model; specific storage and net precipitation (precipitation minus evapotranspiration) based on stress period 24, time step 1 transient model.

Limitations of Digital Simulation

The digital ground-water flow model developed for the study area addresses questions related to ground-water flow through the surficial aquifer system in the vicinity of Bulloch County, Ga. The conceptual model—supported by field measurement of ground-water levels, pond stage, and estimated water budget—is believed to represent flow-system dynamics accurately. Additional measurement of the vertical distribution of aquifer head near and beneath the pond would improve characterization of the conceptual model for the site.

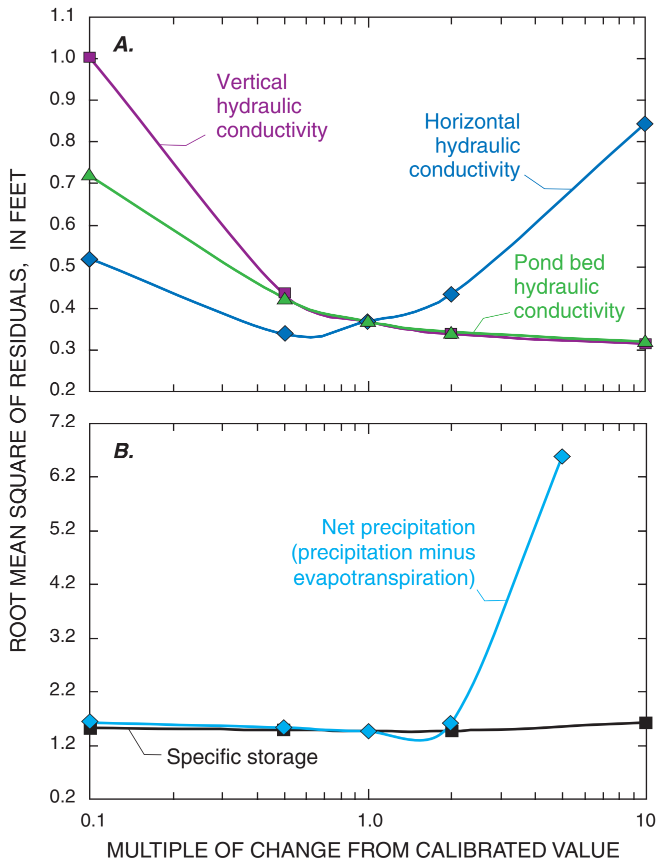


Figure B11. Sensitivity of simulated ground-water levels to selected parameters, Bulloch County pond site in Georgia—(*A*) steady-state model; and (*B*) transient model.

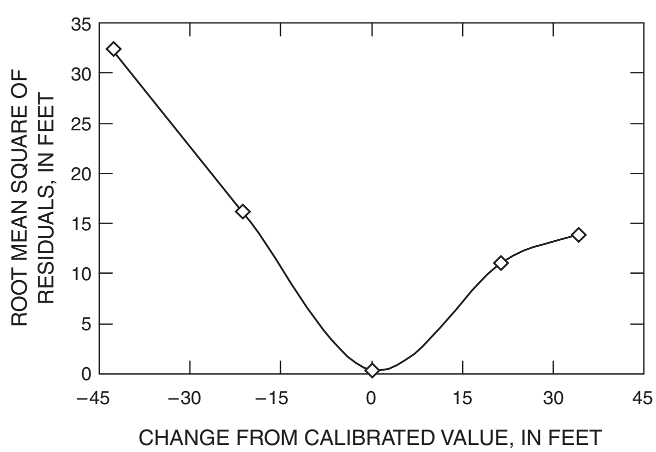


Figure B12. Sensitivity of simulated ground-water levels to changes in pond stage for the model, Bulloch County pond site in Georgia. Based on steady-state simulation.

The model is further limited by difficulty in obtaining sufficient measurements to account for all of the spatial variation in hydraulic properties and boundary conditions throughout the model area. The relative importance of hydraulic properties and boundary conditions on the calibrated model results are presented in the "Sensitivity Analysis" section. Simulated groundwater levels were sensitive to changes in pond stage, decreases in vertical and pond-bed hydraulic conductivity, and increases in horizontal hydraulic conductivity and net precipitation. Simulated net ground-water seepage was most sensitive to changes in horizontal hydraulic conductivity and net precipitation.

Pond stage was adequately represented by field measurements; however, the model was unable to account for all of the spatial variation in hydraulic properties due to sparse field data on hydraulic properties, particularly vertical and horizontal hydraulic conductivity and pond-bed hydraulic conductivity. Additionally, because hydraulic conductivity and recharge are correlated in the mathematics of the ground-water flow equation on which MODFLOW is based, an overestimation of recharge would also result in an overestimation of hydraulic conductivity. Direct measurement of hydraulic conductivity through field or laboratory testing would decrease the level of uncertainty of the calibrated model.

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