HYDROLOGY OF LITTLE ROCK LAKE IN VILAS COUNTY, NORTH-CENTRAL WISCONSIN

By William J. Rose

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 93-4139

Prepared in cooperation with the
WISCONSIN DEPARTMENT OF NATURAL RESOURCES

Madison, Wisconsin
1993

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	*By*	*To obtain*
millimeter (mm)	0.03937	inch
millimeter per year (mm/yr)	0.03937	inch per year
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
hectare (ha)	2.471	acre
square meter (m^2)	10.76	square foot
square kilometer (km^2)	0.3861	square mile
cubic meter (m^3)	35.31	cubic foot
meter per day (m/d)	3.281	foot per day
meter per kilometer (m/km)	5.280	foot per mile

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:

$$°F = 9/5\ (°C) + 32$$

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

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ABSTRACT

Water budgets were developed for Little Rock Lake for October 1983 through September 1990 as part of a study to evaluate the chemical and biological effects of artificially acidifying one basin of the two-basin lake. The 17.9-hectare seepage lake is situated in 60- to 90-meter-thick, predominantly sand and gravel glacial deposits of Vilas County, north-central Wisconsin. Annual precipitation during the study varied from 647 to 926 mm (millimeters). Average annual precipitation during 1951-80, based on nearby National Weather Service stations, was 825 mm. Annual evaporation from the lake surface ranged from 495 to 648 mm. Total lake-stage fluctuation was 930 mm during the study. Lake volume at the maximum stage was 31 percent greater than at the minimum lake stage. Inflow to the lake was dominated by precipitation, which was about 99 percent of total inflow. Ground-water inflow to the lake was transient, occurring only intermittently during October 1983 through September 1986, and amounted to only about 1 percent of total inflow. No ground water flowed into the lake from October 1986 through September 1990. Evaporation accounted for about two-thirds of total outflow from the lake, and lake water discharging to the underlying aquifer accounted for the remainder. The average hydraulic residence times for the 7-year study period were 3.9, 3.3, and 4 years for the entire lake, the south basin, and the north basin, respectively; corresponding chemical residence times were 10.9, 9.3, and 10 years.

INTRODUCTION

Studies of Little Rock Lake began in 1983 as part of the U.S. Environmental Protection Agency's National Acid Precipitation Assessment Program. Many aspects of Little Rock Lake's ecosystem were studied by a multiagency group to gain an improved understanding of the chemical and biotic effects of lake acidification. The studies featured the artificial acidification of the north basin of the two-basin lake, and the use of the south basin as a control. The lake basins were separated by a vinyl curtain in August 1984, and acidification of the north basin was begun in April 1985. Details of the design and scope of the acidification are outlined by Brezonik and others (1986).

The primary focus of the studies was on chemical and biological elements of the lake's ecosystem. However, a thorough understanding of the lake's hydrology was needed to help interpret some chemical and biological observations. Water budgets were required to compute chemical-constituent budgets, which were then used to evaluate some of the changes in lake-water quality that occurred in both the acidified and control basins during the studies.

The lake's hydrology and its water budget were the principal focus of the study of the lake by the U.S. Geological Survey (USGS) in cooperation with the Wisconsin Department of Natural Resources.

Purpose and Scope

This report describes the hydrology of Little Rock Lake and includes a detailed analysis of each of the lake's primary water-budget components--lake storage, precipitation, evaporation, and ground-water flow. Annual water budgets are presented for water years 1984-90 (October 1983 through September 1990). Separate water budgets are presented for the entire lake and for each basin. A general description of the method used for computing the exchange of water between the lake and aquifer is presented. This report provides an assessment of the lake's hydrology during a 7-year study that encompassed periods of near-, above-, and below-average precipitation.

Physical Setting

Little Rock Lake, a small (17.9 ha) seepage lake with no inflowing or outflowing streams, has two main basins that are separated by a 60-m-wide narrows. The maximum depth of the northernmost basin or "north basin" is 10.5 m, and the average depth is 3.9 m. The southernmost basin or "south basin" is 6.5 m deep, with an average depth of 3.1 m. Areas of the north and south basins are 9.8 and 8.1 ha, respectively.

The lake, which is in the Northern Highland Lake District of north-central Wisconsin, is part of the American Legion State Forest in Vilas County (fig. 1) and has no shoreline development. Terrestrial vegetation near the lake is predominantly a mixture of deciduous and coniferous trees. The hummocky topography, with a local relief of about 25 m, was formed by glacial processes during the last part of Wisconsin glaciation, about 10,000 to 25,000 years ago (Attig, 1985).

The glacial deposits consist of predominantly sand and gravel. This material was deposited initially as braided stream sediment, which formed a sloping plain over stagnant ice. The deposits were very well sorted to moderately sorted, very well stratified to poorly stratified. Subsequently, the buried ice melted, and the overlying deposits collapsed, destroying the original depositional surface and disrupting the stratification (Attig, 1985).

Precambrian bedrock underlies the glacial deposits 60 to 90 m below land surface. Little Rock Lake is situated near the margin between areas underlain mafic, metavolcanic rock and metasedimentary bedrock (Attig, 1985). A generalized contour map of the thickness of Pleistocene sediment in Vilas County indicates that the depth to bedrock in the Little Rock Lake area is about 60 m (Attig, 1985). However, a single seismic-refraction survey line done for this study near the northern side of the lake indicates that depth to bedrock is about 90 m.

Climate in the area is continental. January (average temperature, -12.6°C) was the coldest month during water years[1] 1951-80 as measured at the National Weather Service (NWS) station at Minocqua Dam 15 km south of Little Rock Lake; July (average temperature, 19.1°C) was the warmest month. Average precipitation for 1951-80 was 825 mm based on interpolation of data from nearby NWS stations (D.R. Clark, University of Wisconsin, Madison, written commun., 1989). Average annual snowfall for 1949-77 was approximately 1.8 m (Wisconsin Agricultural Reporting Service, 1978).

[1]Water year is the 12-month period from October 1 through September 30. It is designated by the calendar year in which it ends. In this report, years are water years unless otherwise specified.

METHODS OF STUDY

The general approach to determining the hydrology of Little Rock Lake was to quantify each of the major components of the lake's water budget. The water budget or mass balance for Little Rock Lake is described by the relation

$$\Delta S=P-E+GI-GO, \quad (1)$$

where

ΔS is the change in lake storage,
P is precipitation on the lake surface,
E is lake evaporation,
GI is ground-water inflow to the lake, and
GO is ground-water outflow from the lake.

All units of the equation are expressed in terms of length and time (L/T). Surface runoff was not included in equation 1 because the watershed is small (about 50 ha) and forested, and has very permeable soils. Inflow to the lake as interflow (subsurface flow in the unsaturated zone), and outflow by aquatic plant transpiration was considered negligible and outside the scope of this study. Various kinds of hydrologic monitoring were done to obtain the data needed to quantify the components of the annual water budgets and will be discussed in detail in subsequent sections. The location of data-collection sites is shown in figure 2.

Determination of Lake Storage

Lake stage was monitored continuously by means of a bubble-gage equipped with a digital recorder (Rantz and others, 1982) during the study at a site near the northeast end of the south basin (fig. 2). Lake-stage values were recorded at hourly intervals. The flexible barrier curtain separating the north and south basins did not prevent the equalization of water levels between the two basins. Hence, water levels in the two basins were assumed to be equal during the study. Lake stage was converted to lake volume through the use of stage-volume curves constructed from bathymetric maps (not shown). Bathymetric data were collected August 26, 1983 (Wisconsin Department of Natural Resources, written commun., 1983).

Figure 1. Location of Little Rock Lake in Vilas County, north-central Wisconsin.

Change in lake storage (ΔS) for a given time period, expressed as the amount of water on the lake surface, is the stage at the end of the time period minus the stage at the start of the time period. The precision of the lake stage measuring equipment is about 3 mm (Rantz and others, 1982). Hence, the error of ΔS values (as a percentage of actual ΔS) calculated from stage measurements decreases with increasing ΔS.

Measurement of Precipitation

A recording rain gage continuously measured rainfall during the freeze-free season (generally April through October). The gage was located in a small clearing about 100 m northeast of the lake (fig. 2). A 200-mm-diameter collector funnel on the roof of a shelter collected the rainfall that then flowed into a measuring and recording device inside the shelter. Rainfall amounts were recorded at 15-minute intervals. Additional precipitation data were collected daily (year round) by a 200-mm-diameter nonrecording gage near Vandercook Lake about 2.5 km southeast of Little Rock Lake; during freezing periods (November through March) a nonrecording gage was maintained at Little Rock Lake. Both of these nonrecording precipitation gages were maintained by local observers.

Estimation of Lake Evaporation

Estimates of lake evaporation were based on Class-A evaporation-pan data collected near Vandercook Lake (fig. 2). The evaporation pan was maintained, and its water level measured daily by a local observer during nonfreezing periods. Pan evaporation was converted to lake evaporation by applying lake-pan coefficients developed from data collected at Rainbow Reservoir, about 20 km southeast of Little Rock Lake. Floating and land-based evaporation pans are maintained at Rainbow Reservoir by the Wisconsin Valley Improvement Company. It was assumed that evaporation from the surface of the floating pan was the same as that from the surface of Rainbow Reservoir. Thus, the coefficient was the ratio of floating-pan evaporation to land-

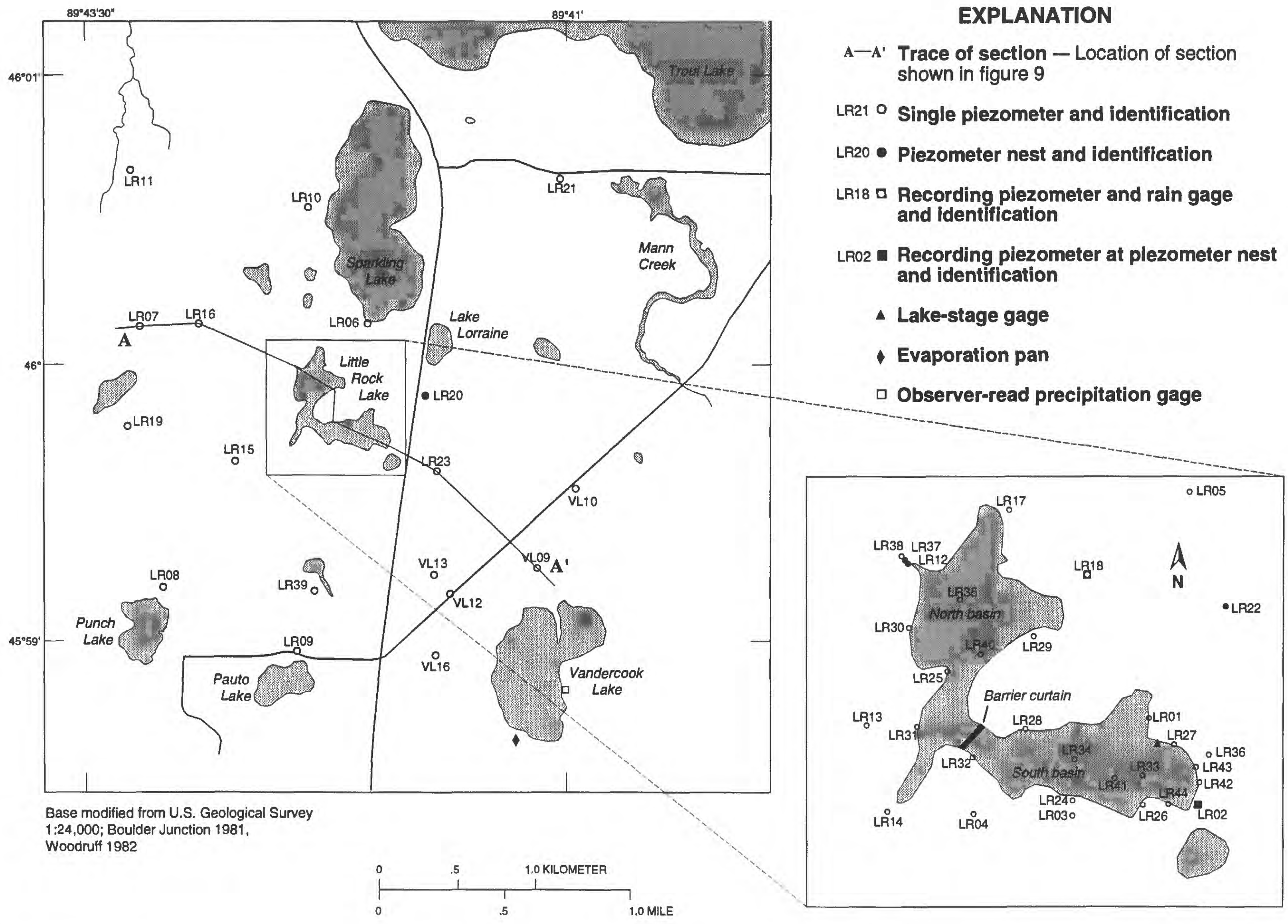

Figure 2. Hydrologic data-collection sites in Little Rock Lake study area.

based pan evaporation. Mean monthly coefficients determined by Wentz and Rose (1991), which were based on 1971-83 data from Rainbow Reservoir, were used for this study. These coefficients ranged from 0.75 (May) to 1.17 (October). Lake evaporation was assumed to be zero during winter periods, when the lake was completely ice-covered.

Evaporation-pan data were not available for parts of April, October, and November when the lake was not ice-covered. Evaporation values for these months were estimated by interpolation for periods in the spring from the time ice left the lake to the beginning of pan measurement and in fall from the last pan measurement to lake freezeup.

Measurement and Analysis of Ground-Water Levels

Water levels were measured monthly in 59 piezometers at 49 sites within a 10-km^2 area surrounding and in the lake. The piezometers ranged in depth from 2 to 30 m. Nests of two to five piezometers were located at five sites (fig. 2). About 80 percent of the piezometers were installed in 100-mm-diameter auger holes, and the boreholes allowed to collapse around the piezometer screens; the remainder were installed by hand driving or water jetting. Five piezometers were hand driven into the lakebed and screened in the aquifer just beneath the lake sediment 1.8 to 11 m below the lakebed. About half of the piezometers were constructed of 38-mm nominal inside-diameter polyvinyl chloride (PVC) pipe and screen; most of the remaining piezometers were 32-mm nominal inside-diameter galvanized steel pipe and stainless-steel screen. The stainless-steel screens were 0.46 m long, and the PVC screens were 0.61 m long. The two instrumented piezometers shown in figure 2 were constructed of 76-mm nominal-diameter PVC pipe and screen and were equipped with water-level recorders that recorded at hourly intervals.

Slug tests were done on selected piezometers to determine estimates of aquifer hydraulic conductivity. Removal of a "slug" of water was accomplished by lowering a solid rod of known volume into the piezometer, allowing the water level to equilibrate, and then rapidly removing the rod. The procedure outlined by Bouwer and Rice (1976) was used to analyze the data.

The exchange of water between the lake and the aquifer was calculated by use of the Darcy equation and the assumption that flow is vertical through the lake bottom. The method of calculating ground-water exchange is similar to that used for studies of Vandercook Lake and described in detail by Wentz and Rose (1989, 1991). The lakebed area was divided into a grid composed of 12.7-m-square cells. Each cell on the lakebed was the top end of a vertical flow tube. Flow through each tube was calculated by the equation,

$$q = \frac{K(h_s - h_L)A}{L} \quad , \qquad (2)$$

where

q is the discharge through a flow tube,

K is the vertical hydraulic conductivity of the fine-grained lake sediment (if present) or sand and gravel aquifer within the tube,

h_s is the hydraulic head at the lower boundary surface of the tube (in the aquifer),

h_L is the hydraulic head at the upper boundary surface (lake bottom) and is equal to the measured lake stage,

A is the horizontal cross-sectional area of the tube (161.3 m^2), and

L is the flow-tube length and is equal to the distance between the lake bottom and the lower boundary surface (described below).

In areas where fine-grained organic lake sediment was present, the lower boundary surface of a flow tube coincided with the sediment-aquifer interface. Organic sediment presence and thickness was mapped by a combination of coring, probing, and continuous marine seismic-reflection profiling of the type described by Sylwester (1983). Where organic sediment was absent, the lower boundary surface of the tube was at a depth equal to the depth of penetration midpoints of screens of nearshore piezometers.

Hydraulic-head (h_s) values were determined by interpolation between head values obtained from in-lake and near-shore piezometers whose screened intervals intersected the lower boundary surface or a near-lake extrapolation of the lower boundary surface. A computer interpolation program (Kontis and Mandle, 1980) was used to calculate the h_s values.

The magnitude of vertical hydraulic-conductivity values assigned to each flow tube depended on lakebed composition and whether flow in the tube was toward or away from the lake. Flow tubes in areas of fine-grained sediment were assigned values two to three orders of magnitude smaller than areas having coarse-grained sediment. It was necessary to assign smaller hydraulic conductivities to flow tubes in outflow regions of the lake than in inflow regions as was done by Wentz and Rose (1989) in determining ground-water exchange with Vandercook Lake. One explanation for lower hydraulic-conductivity in outflowing than in inflowing regions of the lakebed is that in outflowing regions, fine-grained-sediment particles on the lake bottom advect into and clog the pores of sand and gravel beneath the lakebed. Inflowing ground water in a similar lakebed environment would tend to unclog pore spaces. Lee (1977) observed that the hydraulic conductivity was lower with downward flowing than with upward flowing water in an experimental sand tank where flow rate, hydraulic gradient, and flow direction could be controlled. For initial calculations of ground-water-flow volume, fixed, but different, vertical hydraulic-conductivity values were used for each of three different lakebed and hydraulic environments. The three environments were (1) lakebed composed of fine-grained organic and mineral sediment where flow is from the lake to the aquifer; (2) nearshore areas underlain by sand and gravel where flow is from the lake to the aquifer; and (3) nearshore areas underlain by sand and gravel where flow is from the aquifer to the lake. Initial calculations were made using vertical hydraulic conductivity values one to three orders of magnitude smaller than the median horizontal hydraulic conductivity (2.1 m/d) based on results of 50 slug tests. These values were modified in order to obtain reasonable water-budget balances, as is discussed later in this report.

Ground-water inflow and outflow rates were calculated by summing the flows in inflowing and outflowing tubes, respectively. A tube is inflowing when its gradient $[(h_S-h_L)/L]$ is positive, and outflowing when its gradient is negative. Ground-water inflow and outflow rates were calculated for dates (about monthly) when ground-water levels were measured. Ground-water inflow and outflow rates were assumed to vary linearly with time between the calculated flow rate values. Ground-water inflow and outflow rate versus time relations were numerically integrated to yield annual ground-water inflows and outflows.

HYDROLOGY

Lake Storage

Total lake-stage fluctuation, as monitored in the south basin, was 0.93 m from October 1, 1983 through September 30, 1990. The maximum lake stage (496.24 m above sea level) occurred April 7-9, 1986; the minimum lake stage (495.32 m above sea level) occurred August 8, 1990. Generally, lake stage increased during spring, declined during summer, and held fairly steady during fall and winter. As shown in figure 3, there was a general decline during a 4-year period from about mid-1986 to mid-1990.

Changes in lake area and volume were associated with stage changes. The relations of lake stage to area and volume are shown in figures 4 and 5, respectively. The bathymetric survey on which these relations were based was done in August 1983. The lake's stage at the time of the survey was 496.08 m above sea level, or 0.16 m below the peak stage, and 0.76 m above the minimum stage experienced during the study. The lake's area at the maximum stage was 13 percent greater than at the minimum stage. The lake's volume at maximum stage was 31 percent greater than at minimum stage.

Precipitation

Precipitation from October 1983 through September 1990 averaged 783 mm per year, or about 42 mm below the long-term (1951-80) average (825 mm based on interpolation from nearby NWS stations) for the area. Precipitation was near average in water year 1984, above average in water years 1985 (12 percent) and 1986 (11 percent), well below average in water years 1987-89 (22, 13, and 21 percent, respectively), and near average in water year 1990 (fig. 6).

Seasonal distribution of precipitation at Little Rock Lake during the study period differed

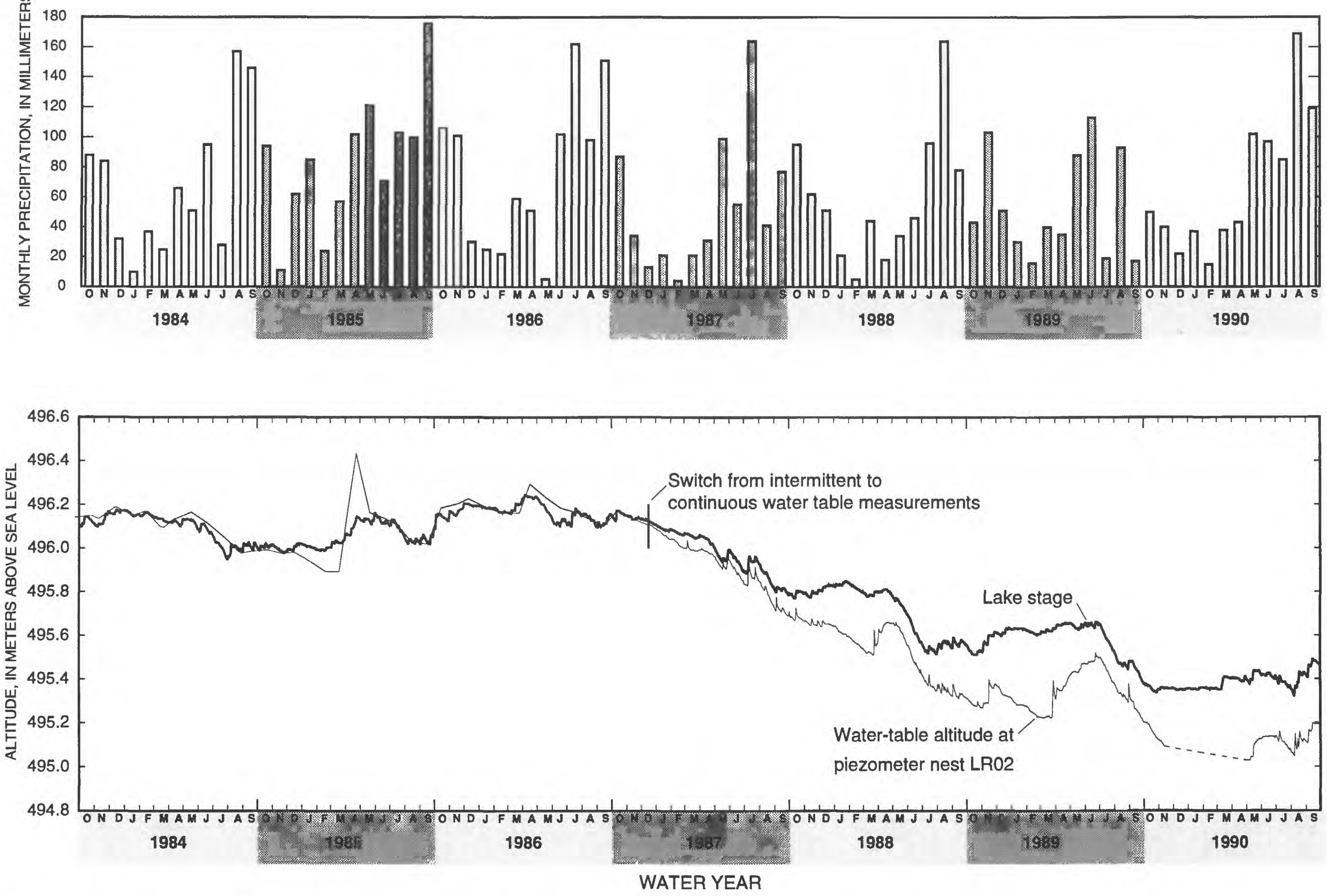

Figure 3. Precipitation, lake stage, and water table at Little Rock Lake, Wisconsin, water years 1984-90.

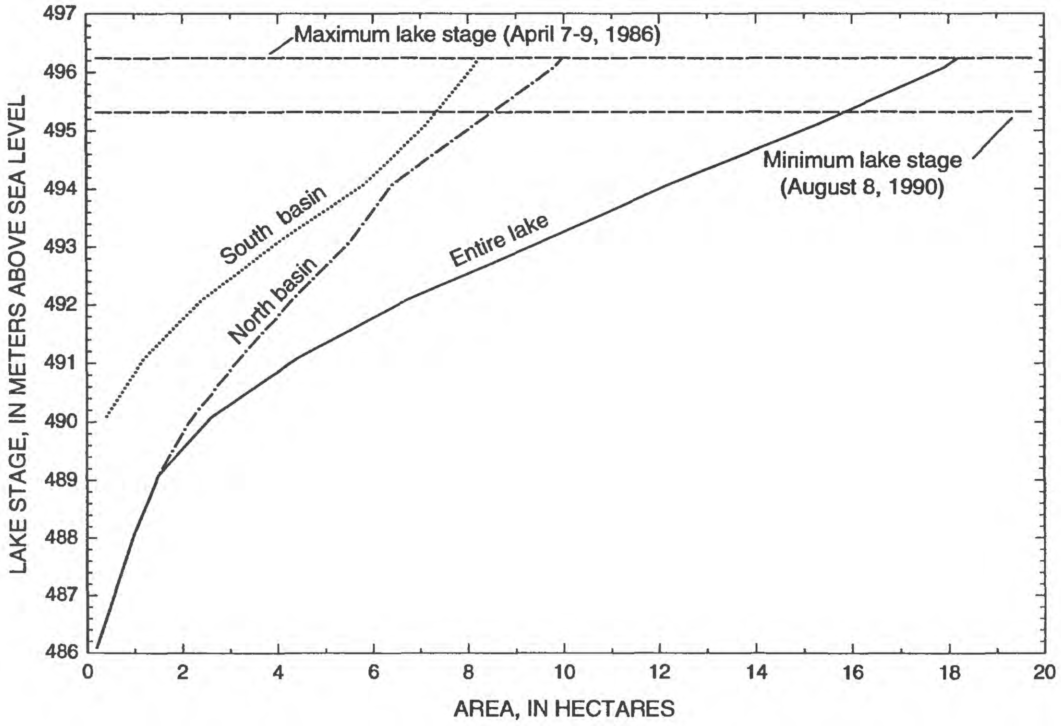

Figure 4. Relation of stage to area of Little Rock Lake.

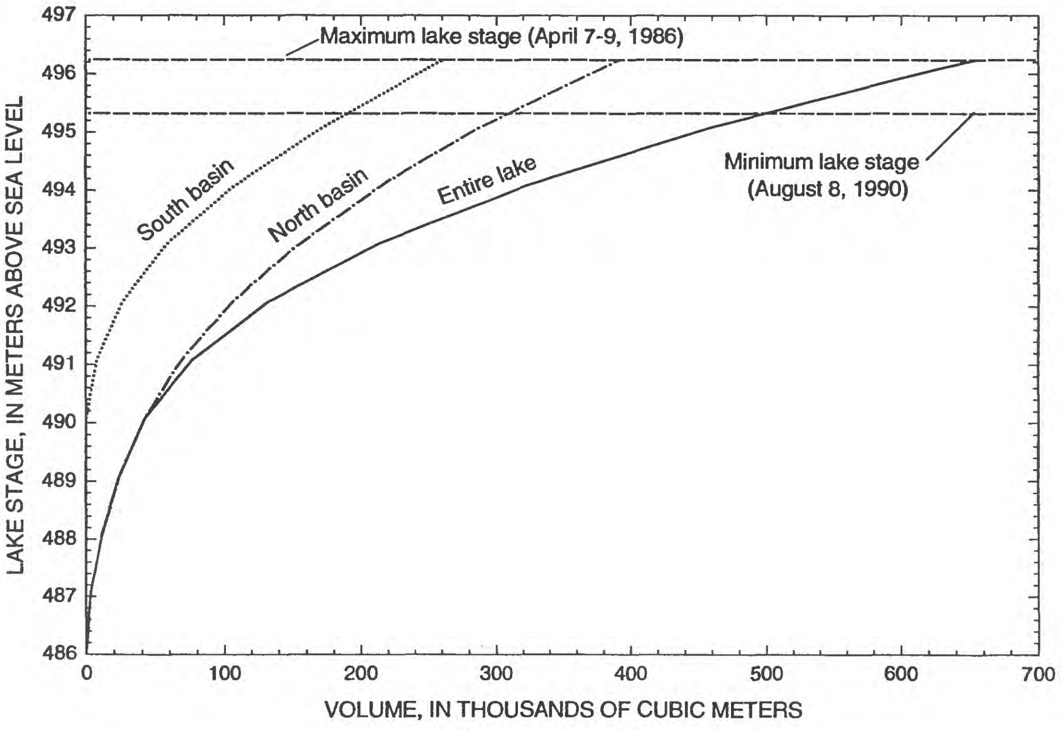

Figure 5. Relation of stage to volume of Little Rock Lake.

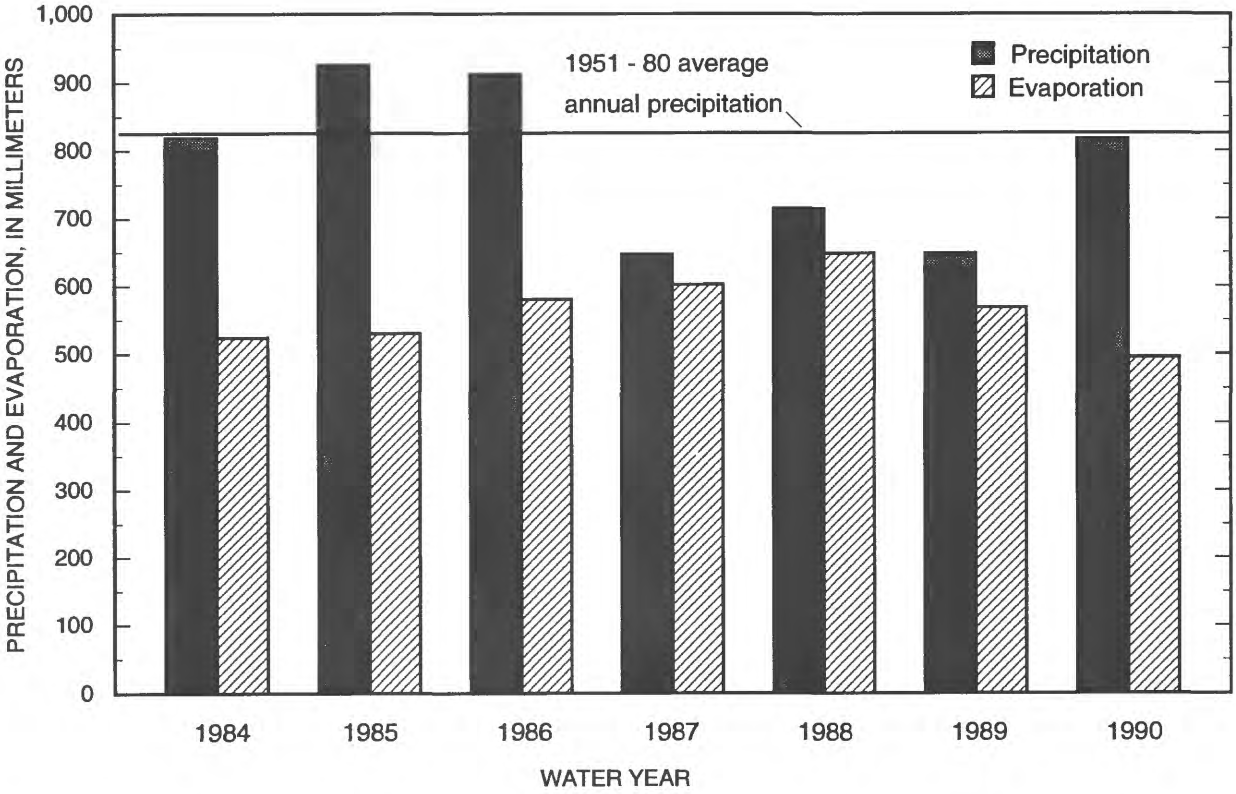

Figure 6. Annual precipitation and evaporation at Little Rock Lake, water years 1984-90.

from that for the long-term (1951-80) period at Minocqua Dam (fig. 7). Precipitation during September through December at Little Rock Lake comprised 37 percent of the average annual precipitation during water years 1984-90, whereas average monthly precipitation for September through December during 1951-80 at Minocqua Dam was 27 percent of the total average annual precipitation for 1951-80. During the remaining months, average monthly precipitation at Little Rock Lake for the study period was equal to or less than the average monthly precipitation for 1951-80 at Minocqua Dam. About 71 percent of the average annual precipitation for October 1983 through September 1990 occurred during the six warmest months, May through October.

Evaporation

Annual lake evaporation during water years 1984-90 varied from 495 mm in water year 1990 to 648 mm in water year 1988. Average annual lake evaporation during the study period was 564 mm. Evaporation tended to be less in years of average to above-average precipitation than in years of below-average precipitation as shown in figure 6.

Ground-Water Flow

Water moves from southeast to northwest in the regional ground-water system in which Little Rock Lake is situated, as is shown in figure 8. The horizontal gradient of the water table in the vicinity of the lake is about 0.0008. The vertical gradient between shallowest and deepest piezometers was downward most of the time at piezometer nest LR02 and was downward all of the time at nest LR12 (fig. 2). At piezometer nest LR02 the downward vertical gradient between the water table and deepest piezometer screen, which was about 25 m below the water table, was generally about 0.006; at piezometer nest LR12 the downward gradient was generally about 0.013.

The relation of the lake surface to the ground-water table is shown for two dates in the section view along A-A' in figure 9. On May 21, 1986, the lake-water surface in the entire north basin and in most of the south basin is hydraulically mounded above the water table. On March 20, 1989, both basins are entirely mounded above the water table. No ground water flowed into the north basin, but some ground water flowed into

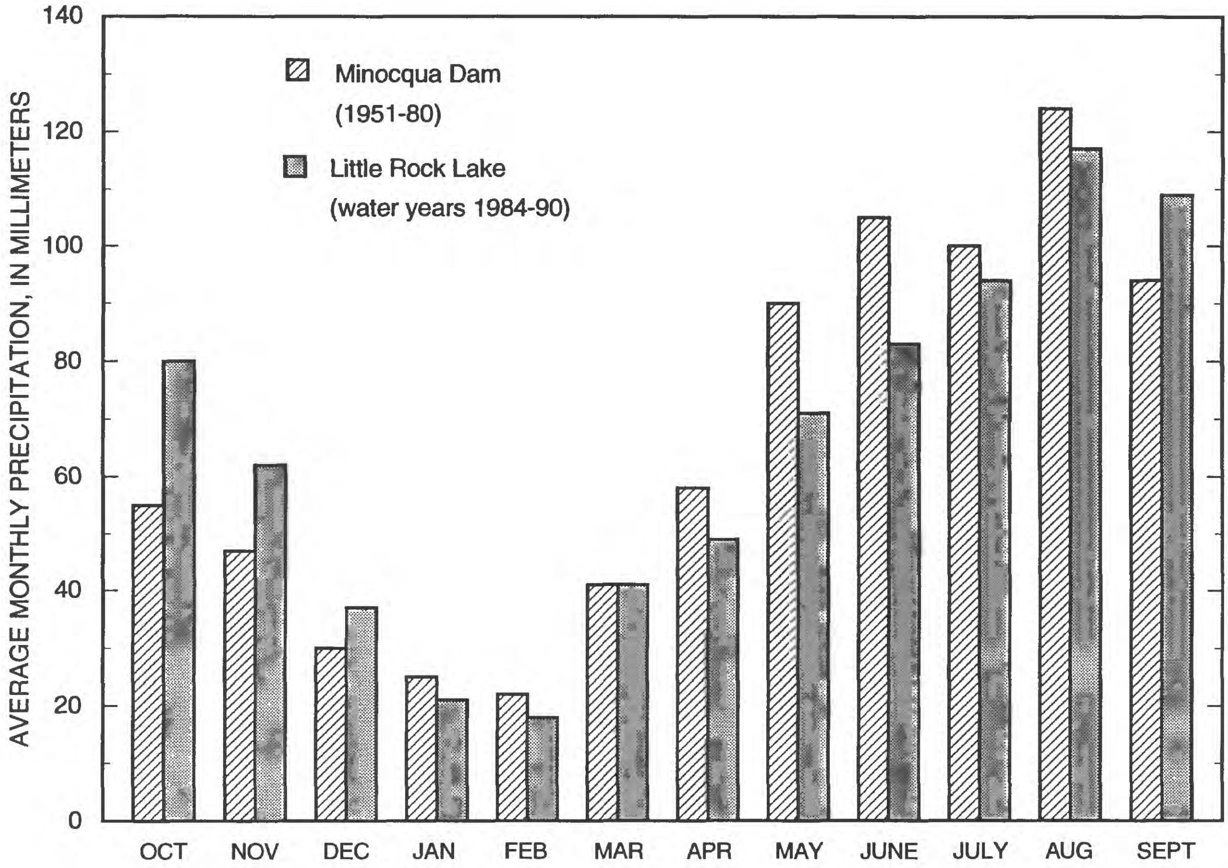

Figure 7. Comparison of average monthly precipitation for study period with long-term average monthly precipitation at Minocqua Dam.

the south basin on May 21, 1986. No ground water flowed into either basin on March 20, 1989.

The rate of the ground-water inflow and area of the south basin through which it passes are transient, depending on the relative altitudes of the water table and the lake surface. Water levels in piezometers penetrating 2 to 3 m at piezometer nest LR02 indicate the altitude of the water table at this most-upgradient edge of the lake. The altitude of the water table at piezometer nest LR02 relative to the lake water-surface altitude is shown in figure 3. Before December 1986, water levels were measured to monitor the altitude of the water table at about monthly intervals. Since December 1986, a recorder continuously monitored the water table. Whenever the water table at piezometer nest LR02 was higher than the lake-water surface, ground water was flowing into the lake. Ground water discharged to the lake intermittently only during water years 1984-86. During the remainder of the study, the entire lake-water surface was hydraulically mounded above the water table, and no ground water flowed into the lake.

Water Budgets

Annual water budgets were determined for the entire lake and for the north and south basins by doing monthly calculations of all the water-budget components and summing the monthly values by water year.

Measurement and interpretation errors are associated with each water-budget component (Winter, 1981). Rewriting equation (1) as follows with a residual term (r) provides a means of evaluating errors and the accuracy of the water budget:

$$r = P - E + GI - GO - \Delta S. \quad (3)$$

The value of the term, P - E + GI - GO in equation 3 can be regarded as the calculated change in storage. Hence, the residual is equal to the difference between calculated and observed change in storage (ΔS). Errors in determining individual budget terms and any inflow, such as overland flow and interflow, which are believed to be insig-

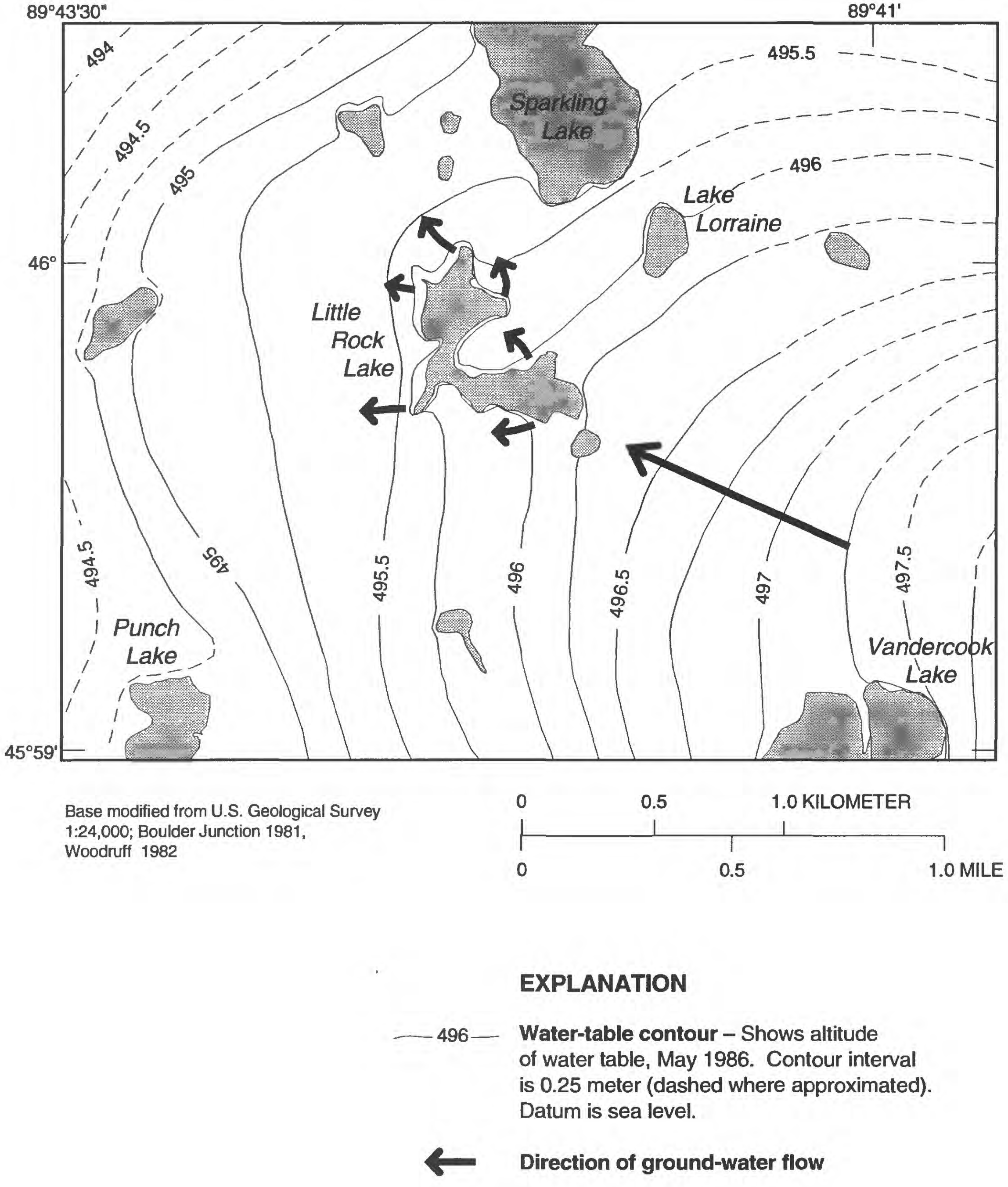

Figure 8. Water-table configuration near Little Rock Lake, May 1986.

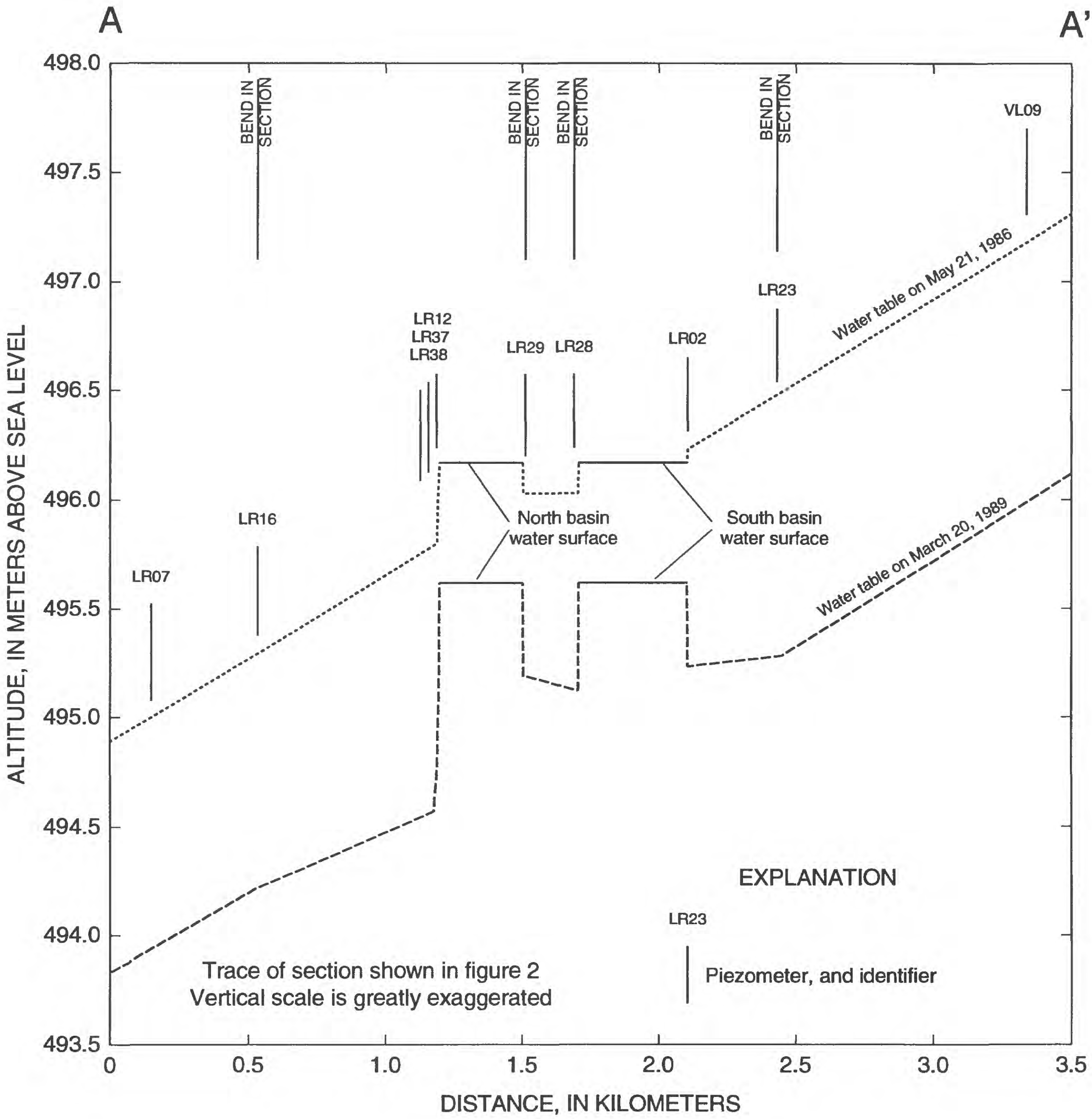

Figure 9. Cross section showing relation of Little Rock Lake's water surface to regional water table on May 21, 1986 and on March 20, 1989.

nificant at Little Rock Lake, are included in r. Overland flow was not observed, and quantification of interflow was beyond the scope of this study.

The effect of the vinyl-curtain barrier separating the basins was disregarded in the computation of whole-lake water budgets. In actuality, the barrier prevented free mixing of water between basins but did not prevent net flow or leakage past the curtain, which was necessary to maintain lake-stage equilibrium across the curtain.

Water-budget residuals calculated by equation 3 were reasonably small for water years 1984-87. However, residuals became increasingly large in coincidence with decreasing lake stage during water years 1988-90.

Vertical flow-tube positions were based on the lake-surface area for the lake stage at the time of the bathymetric survey in August 1983. As lake stage decreased below the level of the lake at the time of that survey, only part of the flow tubes along the perimeter of the lake (lake-perimeter flow tubes) were covered by water. To compensate for this, the areas of the lake-perimeter flow tubes were adjusted as a function of lake stage. Perimeter flow-tube area-adjustment factors varied from a minimum of 0.44 in December 1989 (low lake stage) to a maximum of 1.06 in April 1986 (high lake stage). Water-budget residuals after this adjustment was applied were smaller in magnitude than before but still were large in comparison with the magnitude of individual water-budget components for water years 1988-90.

In determining water budgets for Vandercook Lake, Wentz and others (U.S. Geological Survey, written commun., 1993) found it necessary to vary hydraulic conductivity for nearshore ground-water-outflow regions of the lake as a function of lake stage in order to get reasonable water-budget balances. The rationale for this is that lakebed sediment becomes increasingly finer grained in the lakeward direction from the lakeshore. Hence, as the lake stage decreases, the average hydraulic conductivity at the increasingly smaller lake-perimeter flow tubes decreases.

The method used to determine the function to vary hydraulic conductivity with lake stage follows. Total ground-water outflow (GO in equation 3) was divided into two components--(1) ground-water outflow through all lake-perimeter flow tubes (GO_p), and (2) ground-water outflow through all flow tubes except lake-perimeter flow tubes. Annual lake water budgets were recalculated using a fixed hydraulic conductivity for lake-perimeter flow tubes that yielded near-zero residuals for water years 1988-90, but quite large residuals for the high lake-stage water years 1984-87. For the purpose of determining the functional relation of hydraulic-conductivity adjustment coefficient and lake stage, it was assumed that all of the residuals in the annual water budgets were caused by use of an incorrect hydraulic-conductivity value for lake-perimeter flow tubes. Because ground-water discharge is directly proportional to hydraulic conductivity in the Darcy equation, a hydraulic-conductivity adjustment coefficient (C) needed to yield a zero residual (r) for a given year is the ratio

$$C = \frac{GO_p + r}{GO_p} \quad , \qquad (4)$$

The relation of the adjustment coefficient to lake stage is shown in figure 10. Final ground-water-flow values were obtained by applying the adjustment coefficient function in figure 10 to obtain hydraulic-conductivity values for lake- perimeter flow tubes.

Hydraulic-conductivity values, which were used for final ground-water-flow calculations for the various lakebed sediment and hydraulic environments, are summarized below.

Final water budgets for the entire lake are given in table 1 and shown in figure 11. The absolute value of the water-budget residuals varied from 20 mm in water years 1985 and 1990 to

Lakebed composition	Direction of ground-water flow	Vertical hydraulic conductivity (meter per day)
Fine-grained organic and mineral sediment	Toward or away from lake	0.0013
Fine-grained sediment absent	Toward lake	0.26
Fine-grained sediment absent and flow tube not on lake perimeter	Away from lake	0.013
Fine-grained sediment absent and flow tube is on lake perimeter	Away from lake	0.013 to 0.034

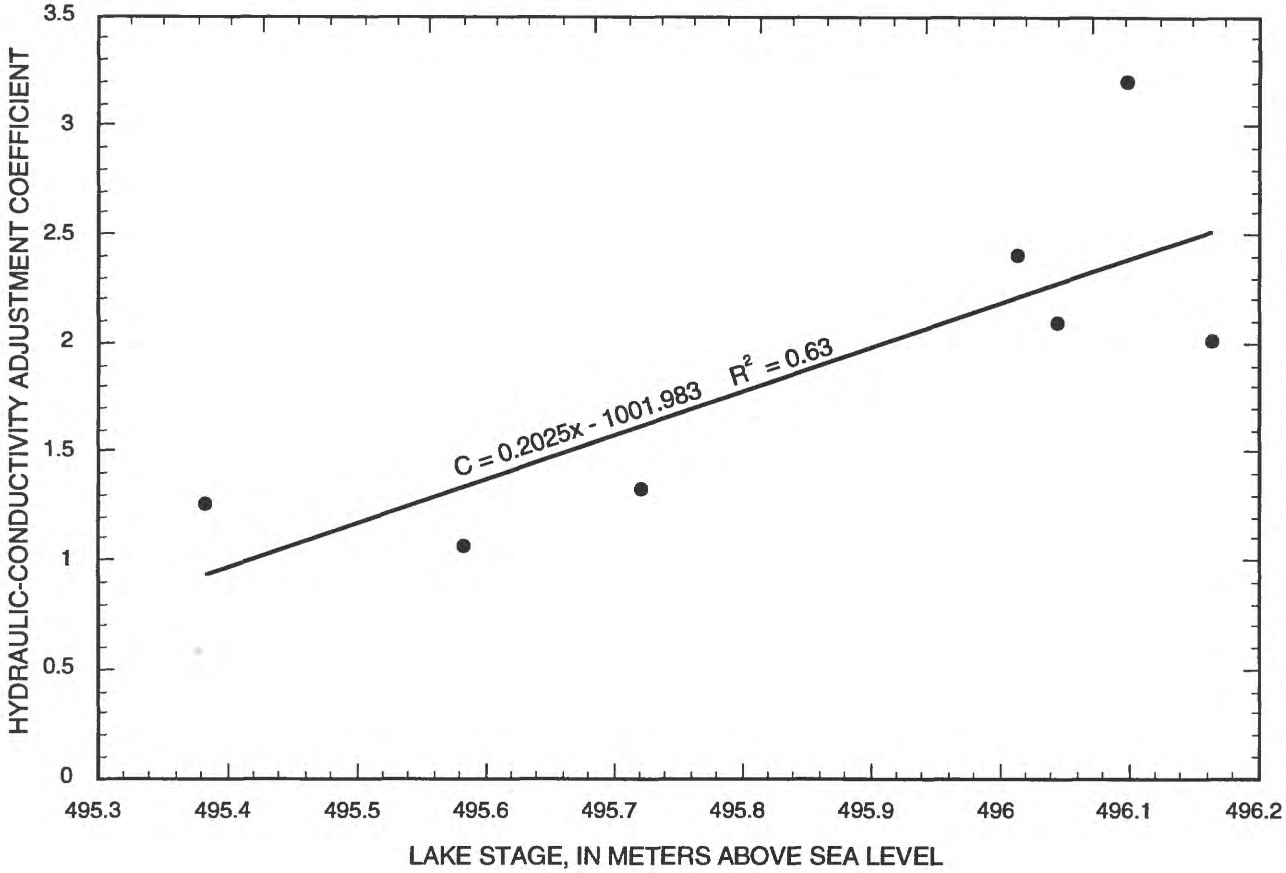

Figure 10. Relation of hydraulic-conductivity adjustment coefficient to stage of Little Rock Lake.

Table 1. Annual water budgets for Little Rock Lake (both basins), water years 1984-90

[Units of measurement are in millimeters]

	Inflow		Outflow		Change in lake storage		
Water year	Precipitation	Ground-water inflow	Evaporation	Ground-water outflow	Calculated	Observed	Residual
1984	819	8	524	327	- 24	-100	76
1985	926	5	530	341	60	80	-20
1986	912	7	580	314	25	71	-46
1987	647	0	602	388	-343	-366	23
1988	714	0	648	340	-274	-233	-41
1989	648	0	568	287	-207	-174	-33
1990	817	0	495	225	97	77	20

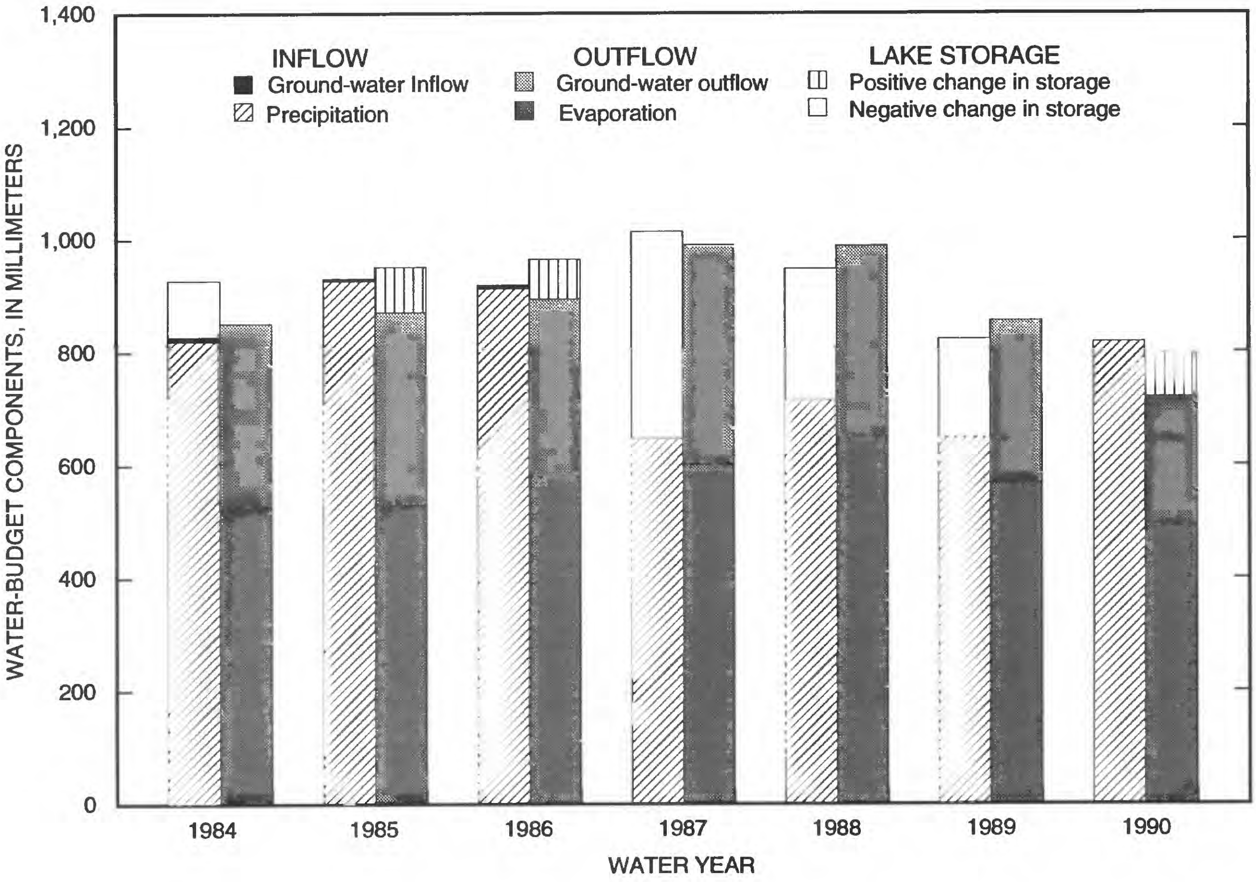

Figure 11. Annual water budgets for Little Rock Lake (both basins) for water years 1984-90.

76 mm in water year 1984. When inflows plus the absolute value of negative change in storage were greater than outflow plus positive change in storage, the residual was positive. Likewise, when outflows plus positive change in storage were greater than inflow plus absolute value of negative change in storage, the residual was negative. The difference between heights of paired bars in figure 11 is the water-budget residual.

Precipitation dominated inflow to the entire lake, and evaporation dominated outflow. Precipitation accounted for 99 to 100 percent of total inflow (table 2). Ground-water inflow was about 1 percent of total inflow in water years 1984 and 1986, and 0.5 percent in water year 1985; no ground-water inflow occurred during water years 1987-90. The accuracy of the ground-water-inflow estimates for water years 1984-86 are subject to question because the absolute values of the residuals were from about 4 to 10 times greater than ground-water inflow. The estimate of zero ground-water inflow for water years 1987-90 is supported by hydraulic-head measurements that show that the entire lake-water surface was hydraulically mounded above the water table. On the average, evaporation accounted for about two-thirds of total outflow, and the remainder was ground-water outflow. However, ground-water outflow decreased during water years 1988-90 even though the hydraulic-head difference between the lake and water table increased compared to earlier years of the study, as seen in figure 3. Declining lake stage and the accompanying decreased lakebed area underlain by very permeable coarse-grained sediment more than offset the effect of increased gradient.

Water budgets for the south and north basins have a component to account for south-to-north basin leakage past the vinyl-curtain barrier. This leakage is an outflow component for the south basin and is an inflow component for the north

Table 2. Percentage composition of Little Rock Lake inflow and outflow, water years 1984-90

[--, nonexistent]

Lake or lake basin	Water year	Inflow			Outflow		
		Precipitation	Ground-water inflow	South-to-north basin leakage	Evaporation	Ground-water outflow	South-to-north basin leakage
Entire lake:	1984	99.0	1.0	--	62	38	--
	1985	99.5	.5	--	61	39	--
	1986	99.2	.8	--	65	35	--
	1987	100	0	--	61	39	--
	1988	100	0	--	66	34	--
	1989	100	0	--	66	34	--
	1990	100	0	--	69	31	--
	Average	99.7	.3	--	64	36	--
South basin	1984	97.7	2.3	--	61	26	13
	1985	98.9	1.1	--	60	27	13
	1986	98.3	1.7	--	64	24	13
	1987	100	0	--	61	29	10
	1988	100	0	--	66	27	7
	1989	100	0	--	66	27	7
	1990	100	0	--	69	24	7
	Average	99.3	.7	--	64	26	10
North basin:	1984	90	0	10	56	44	--
	1985	91	0	9	55	45	--
	1986	90	0	10	58	42	--
	1987	88	0	12	56	44	--
	1988	92	0	8	62	38	--
	1989	93	0	7	63	37	--
	1990	95	0	5	65	35	--
	Average	91	0	9	59	41	--

basin. Leakage is a function of the volumes of ground-water flow into and out of the basins and the surface areas of the basins. Assuming that water-surface elevation, precipitation, and evaporation are the same for each basin, it can be shown that

$$L_b = \frac{GI_s - GO_s + A_s/A_n\left(GO_n - GI_n\right)}{1 + A_s/A_n}, \quad (5)$$

where

L_b is south-to-north basin leakage (L^3),

GI_s is ground-water inflow to the south basin (L^3),

GO_s is ground-water outflow from the south basin (L^3),

GI_n is ground-water inflow to the north basin (L^3),

GO_n is ground-water outflow from the north basin (L^3),

A_s is area of south basin (L^2), and

A_n is area of north basin (L^2).

Equation 5 reduces to

$$L_b = \frac{GI_s - GO_s + 0.8355\left(GO_n - GI_n\right)}{1.8355}, \quad (6)$$

when areas of the south and north basins are substituted for A_s and A_n, respectively. L_b was divided by the surface areas of the basins to express south-to-north leakage as an equivalent amount of water on the surfaces of the basins. Water budgets for the south and north basins are given in tables 3 and 4, respectively, and are shown graphically in figures 12 and 13, respectively.

All ground-water inflow to the lake is to the south basin. Hence, as shown in table 2, ground-water inflow as a percentage of total inflow to the south basin for water years 1984 and 1986 is about 2 percent, and for water year 1985 is 1.1 percent or about twice that for the entire lake. For water years 1984-90, average outflow was distributed as follows: evaporation, 64 percent; ground-water outflow, 26 percent; and south-to-north basin leakage, 10 percent.

During water years 1984-90 (table 2), precipitation accounted for an average of 91 percent of the total inflow to the north basin. South-to-north basin leakage accounted for the remaining 9 percent of total inflow. There was no ground-water inflow to the north basin. Evaporation averaged 59 percent of the total outflow during water years 1984-90. Ground-water outflow averaged 41 percent of total outflow.

Hydraulic and Chemical Residence Times

Hydraulic and chemical residence times were calculated for each year for the entire lake and for the south and north basins. Hydraulic residence time (HRT), the average time a parcel of water spends in the lake, was calculated by dividing the annual average lake (or basin) volume by the annual outflow. Chemical residence time (CRT), the average time a conservative chemical constituent spends in the lake, was calculated by dividing annual average lake (or basin) volume by the annual sum of all outflow components except evaporation. Evaporation was assumed to be pure water and, hence, did not remove chemical constituents.

Year-to-year trends in HRT and CRT for the whole lake and for the southern and northern basins were similar (table 5). The average HRT's for the 7-year study period were 3.9, 3.3, and 4.0 years for the entire lake, the south basin, and the north basin, respectively; corresponding CRT's were 10.9, 9.3, and 10.0 years. CRT's were about 2.8 times greater than HRT's for the entire lake and south basin. CRT's were about 2.5 times greater than HRT's for the north basin. Absolute values of HRT and CRT were generally smaller for the south basin than for the entire lake or the north basin because south-to-north basin leakage was an outflow component in addition to evaporation and ground-water outflow.

SUMMARY

A hydrologic study of Little Rock Lake in north-central Wisconsin was made during water

Table 3. Annual water budgets for Little Rock Lake's south basin, water years 1984-90

[Units of measurement are in millimeters]

	Inflow		Outflow			Change in lake storage		
Water year	Precipitation	Ground-water inflow	Evaporation	Ground-water outflow	South-to-north basin leakage	Calculated	Observed	Water budget residual
1984	819	19	524	225	112	-23	-100	77
1985	926	10	530	235	110	61	80	-19
1986	912	16	580	204	122	22	71	-49
1987	647	0	602	289	101	-345	-366	21
1988	714	0	648	265	74	-273	-233	-40
1989	648	0	568	230	57	-207	-174	-33
1990	817	0	495	177	49	96	77	19

Table 4. Annual water budgets for Little Rock Lake's north basin, water years 1984-90

[Units of measurement are in millimeters]

	Inflow			Outflow		Change in lake storage		
Water year	Precipitation	Ground-water inflow	South-to-north basin leakage	Evaporation	Ground-water outflow	Calculated	Observed	Residual
1984	819	0	96	524	413	-22	-100	78
1985	926	0	91	530	428	59	80	-21
1986	912	0	101	580	412	21	71	-50
1987	647	0	86	602	476	-345	-366	21
1988	714	0	63	648	402	-273	-233	-40
1989	648	0	47	568	335	-208	-174	-34
1990	817	0	44	495	268	98	77	21

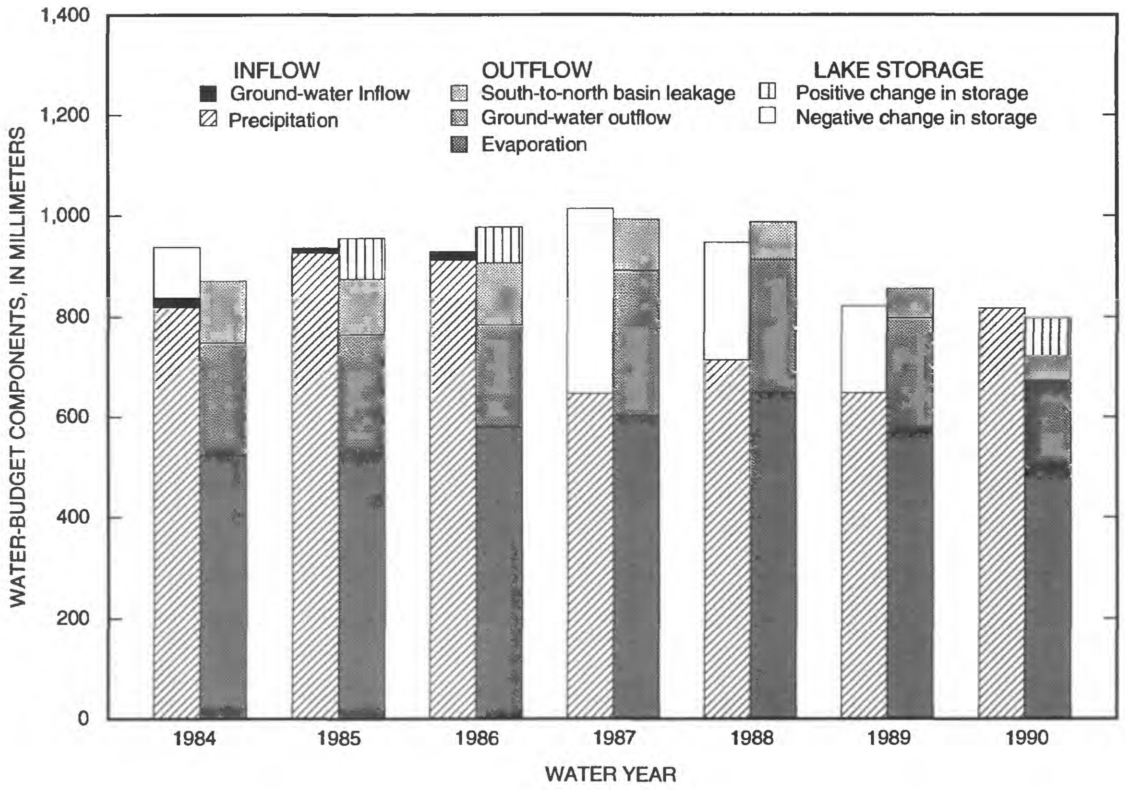

Figure 12. Annual water budgets for Little Rock Lake's south basin for water years 1984-90.

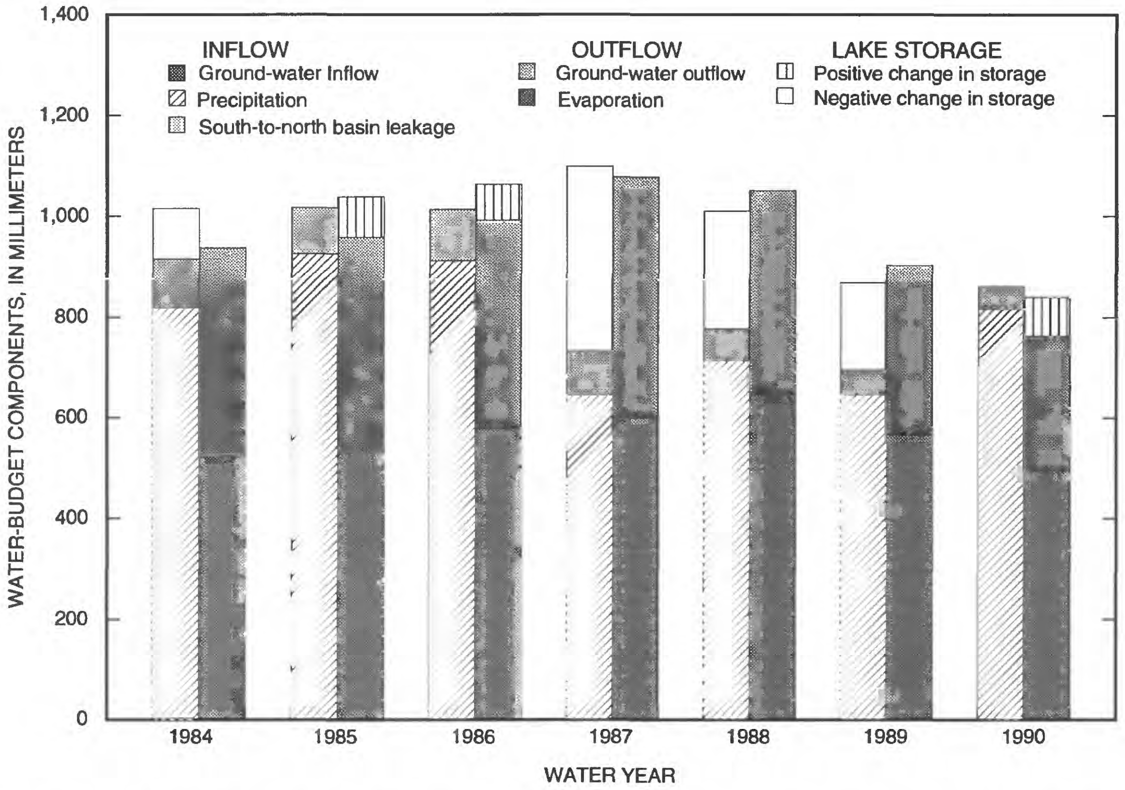

Figure 13. Annual water budgets for Little Rock Lake's north basin for water years 1984-90.

Table 5. Hydraulic and chemical residence times in Little Rock Lake, water years 1984-90

[--, nonexistent]

Lake or basin	Water year	Average annual stage (meters)	Average annual area (hectares)	Average annual volume (cubic meters)	Hydraulic residence time (years)	Chemical residence time (years)
Entire lake:	1984	496.012	17.9	629,100	4.1	10.7
	1985	496.047	17.8	619,700	4.0	10.2
	1986	496.166	18.1	640,400	4.0	11.3
	1987	496.016	17.7	614,600	3.5	8.9
	1988	495.724	16.9	566,200	3.4	9.8
	1989	495.587	16.6	543,500	3.8	11.4
	1990	495.385	16.0	510,000	4.4	14.1
	Average	--	--	--	3.9	10.9
South basin:	1984	496.012	8.1	250,000	3.6	9.1
	1985	496.047	8.1	245,600	3.5	8.8
	1986	496.166	8.2	255,200	3.4	9.6
	1987	496.016	8.0	243,300	3.1	7.8
	1988	495.724	7.7	221,000	2.9	8.4
	1989	495.587	7.6	210,600	3.2	9.6
	1990	495.385	7.4	195,200	3.7	11.7
	Average	--	--	--	3.3	9.3
North basin:	1984	496.012	9.8	379,200	4.1	9.3
	1985	496.047	9.7	374,100	4.0	9.0
	1986	496.166	9.9	385,200	3.9	9.4
	1987	496.016	9.7	371,300	3.6	8.0
	1988	495.724	9.2	345,200	3.6	9.3
	1989	495.587	9.0	332,900	4.1	11.1
	1990	495.385	8.6	314,800	4.8	13.6
	Average	--	--	--	4.0	10.0

years 1984-90. The main purpose of the study was to provide water-budget information needed by investigators studying the chemical and biological effects of artificial acidification of one basin of the two-basin lake.

Total lake-stage fluctuation was 0.93 m; the highest stages occurred during the first 3 years of the study. Stage declined from mid-1986 to mid-1990, primarily because of a decrease in precipitation and an increase in evaporation than during the early part of the study. The lake's area at maximum stage was 13 percent greater than it was at minimum stage, and lake volume at maximum stage was 31 percent greater than it was at minimum stage.

Precipitation was near the long-term (1951-80) average (825 mm) in water years 1984 and 1990; 12 and 11 percent above average in water years 1985 and 1986 respectively; and 22, 13, and 21 percent below average in water years 1987, 1988, and 1989, respectively. Annual lake evaporation ranged from 495 mm in water year 1990 to 648 mm in 1988, and average annual evaporation during the study period was 564 mm. Evaporation was generally less during years of above-average precipitation than it was during years of below-average precipitation.

Ground-water flow in the Little Rock Lake region is from southeast to northwest. The lake-water surface in the entire north basin and most of the south basin of the lake is hydraulically mounded above the water table, indicating that water flows from the lake to the aquifer. Ground-water inflow to the lake and the area of the south basin through which it passes are transient, depending on the relative altitudes of the water table and the lake surface. Ground water discharged into the lake intermittently during water years 1984-86. During water years 1987-90, the entire lake-water surface was mounded above the water table, and no ground water flowed into the lake.

Precipitation dominated inflow to the entire lake, accounting for 99 to 100 percent of total inflow. Ground-water inflow was about 1 percent of total inflow in water years 1984 and 1986, and 0.5 percent in water year 1985. During water years 1987-90, no ground water flowed into the lake. Evaporation was, on the average, about two-thirds of total lake outflow; the remainder was ground-water outflow.

Ground-water inflow accounted for about 2 percent of total inflow to the southern basin during water years 1984 and 1986, and about 1.1 percent during water year 1985, or about twice that for the entire lake--the remaining 98 percent was from precipitation. No ground water flowed into the south basin during 1987-90. Average outflow from the south basin was evaporation, 64 percent; ground-water outflow, 26 percent; and south-to-north basin leakage, 10 percent. No ground water flowed into the north basin. Precipitation accounted for an average of 91 percent of total inflow to the north basin and south-to-north basin leakage accounted for an average of 9 percent. Average outflow from the north basin was evaporation, 59 percent, and ground-water outflow, 41 percent.

Average hydraulic residence times for the 7-year study period were 3.9, 3.3, and 4.0 years for the entire lake, south basin, and north basin, respectively. Chemical residence times were 10.9, 9.3, and 10.0 years for the entire lake, south basin, and north basin, respectively.

REFERENCES

Attig, J.W., 1985, Pleistocene geology of Vilas County, Wisconsin: Wisconsin Geological and Natural History Survey, Information Circular 50, 32 p.

Bouwer, H., and Rice, R.C., 1976, A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells: Water Resources Research, v. 12, p. 423-428.

Brezonik, P.L., Baker, L.A., Eaton, J.G., Frost, T.M., Garrison, P.J., Kratz, T.K., Magnuson, J.J., Perry, J.A., Rose, W.J., Shepherd, B.K., Swenson, W.A., Watras, C.J., and Webster, K.E., 1986, Experimental acidification of Little Rock Lake, Wisconsin--Baseline studies and predictions of lake responses to acidification: Minneapolis, University of Minnesota, Water Resources Research Center, Special Research Report 7, 43 p.

Kontis, A.L., and Mandle, R.J., 1980, Data-base system for Northern Midwest regional aquifer-system analysis: U.S. Geological Survey Water-Resources Investigations 80-104, 23 p.

Lee, D.R., 1977, A device for measuring seepage flux into lakes and estuaries: Limnology and Oceanography, v. 22, no. 1, p. 140-147.

Rantz, S.E., and others, 1982, Measurement and computation of streamflow: U.S. Geological Survey Water-Supply Paper 2175, 631 p.

Sylwester, R.E., 1983, Single-channel, high-resolution, seismic-reflection profiling: A review of the fundamentals and instrumentation: *in* Geyer, R.A., Handbook of geophysical exploration at sea, West Palm Beach, Fla., CRC Press, Inc., 122 p.

Wentz, D.A., and Rose, W.J., 1989, Interrelationships among hydrologic-budget components of a northern Wisconsin seepage lake and implications for acid-deposition modeling: Archives of Environmental Contamination and Toxicology, v. 18, p. 147-155.

_____1991, Hydrology of Lakes Clara and Vandercook in north-central Wisconsin: U.S. Geological Survey Water-Resources Investigations Report 89-4204, 24 p.

Winter, T.C., 1981, Uncertainties in estimating the water balance of lakes: American Water Resources Association, Water Resources Bulletin, v. 17, no. 1, p. 82-115.

Wisconsin Agricultural Reporting Service, 1978, Snow and frost in Wisconsin, 1961-77: Madison, Wisconsin Agricultural Reporting Service, 38 p.