WATER AND PHOSPHORUS BUDGETS AND TROPHIC STATE, BALSAM LAKE, NORTHWESTERN WISCONSIN, 1987-1989

By William J. Rose

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CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	*By*	*To obtain*
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
foot (ft)	0.3048	meter
inch (in.)	25.4	millimeter
inch (in.)	0.0254	micrometer
mile (mi)	1.609	kilometer
pound (lb)	453.6	gram

Water-quality units: Chemical concentrations and water temperature are given in metric units. Chemical concentration is given in milligrams per liter (mg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter (µg/L) is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

Temperature can be converted to degrees Celsius (°C) or degrees Fahrenheit (°F) by the equations:

$$°C = 5/9\ (°F - 32)$$

$$°F = 9/5\ (°C) + 32$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum 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 and total-phosphorus budgets were determined for Balsam Lake in northwestern Wisconsin. All significant components of the lake's water budget were determined independently. The lake's trophic state was evaluated in relation to total-phosphorus loading from December 1, 1987 through November 30, 1989. The information obtained in the study can be used by local and State agencies to develop and assess lake- and watershed-management alternatives for maintaining or improving the water quality of the lake.

The three-basin, 1,900-acre drainage lake receives flow from two main tributary streams, Harder and Rice Creeks. Precipitation, ground-water levels, and streamflow were below normal during the study period and the year preceding the study. Precipitation was 6.09 inches below normal the first year of the study and 8.71 inches the second year.

Precipitation, the dominant water-budget inflow component, was followed in decreasing order by inflows from Rice Creek, ground water, Harder Creek, and near-lake drainage. Total inflows in the first and second years of the study were 11,040 and 11,650 acre-feet, respectively. Surface inflow was 23 percent greater in the second year of the study than in the first year.

The largest outflow from Balsam Lake was outflow to Balsam Branch, and the second largest outflow was evaporation. These outflows accounted for 98 percent of outflow from the lake. Recharge to ground water accounted for 2 percent.

Total-phosphorus input to the lake was 692 and 1,144 pounds in the first and second years of the study. Rice Creek and near-lake drainage accounted for 80 percent of phosphorus entering the lake. Outflow to Balsam Branch removed 30 percent of the phosphorus that entered the lake.

The main basin of the lake was mesotrophic, whereas the loading rates determined for the study period would have expected to result in oligotrophic conditions. Internal loading and below-normal external loading during the study are the likely explanation for this discrepancy. The northwest basin of the lake (locally called "Little Balsam Lake") received 66 percent of all external phosphorus that entered Balsam Lake. The trophic state of Little Balsam Lake ranged from upper mesotrophic to lower eutrophic. Phosphorus that entered Little Balsam Lake during the study period would have been expected to result in eutrophic conditions.

INTRODUCTION

The Polk, St. Croix, and Barron County area in northwestern Wisconsin was identified by Lillie and Mason (1983) as encompassing a disproportionately high percentage (44 percent) of the State's phosphorus-enriched lakes. In recent years, local residents and property owners have perceived an increase in algal blooms and a decrease in water clarity in Balsam Lake, a lake near the village of Balsam Lake in Polk County (fig. 1). These problems seemed to be worst during 1981-86 in the northwestern basin of the lake, locally called Little Balsam Lake (fig. 2).

Reliable information on phosphorus loading to Balsam Lake was not available. Rice Creek is the largest stream that discharges into Little Balsam Lake, and phosphorus from this creek was believed by some local residents to be a major cause of problems in Little Balsam Lake. Rice Creek and Harder Creek are the largest streams that discharge into Balsam Lake. On the basis of 1 year of data collected in the late 1970's, the Wisconsin Department of Natural Resources concluded that 64 percent of water entering the lake was ground water and that it contained 38 percent of phosphorus entering the lake (Wisconsin Department of Natural Resources, written commun., 1979).

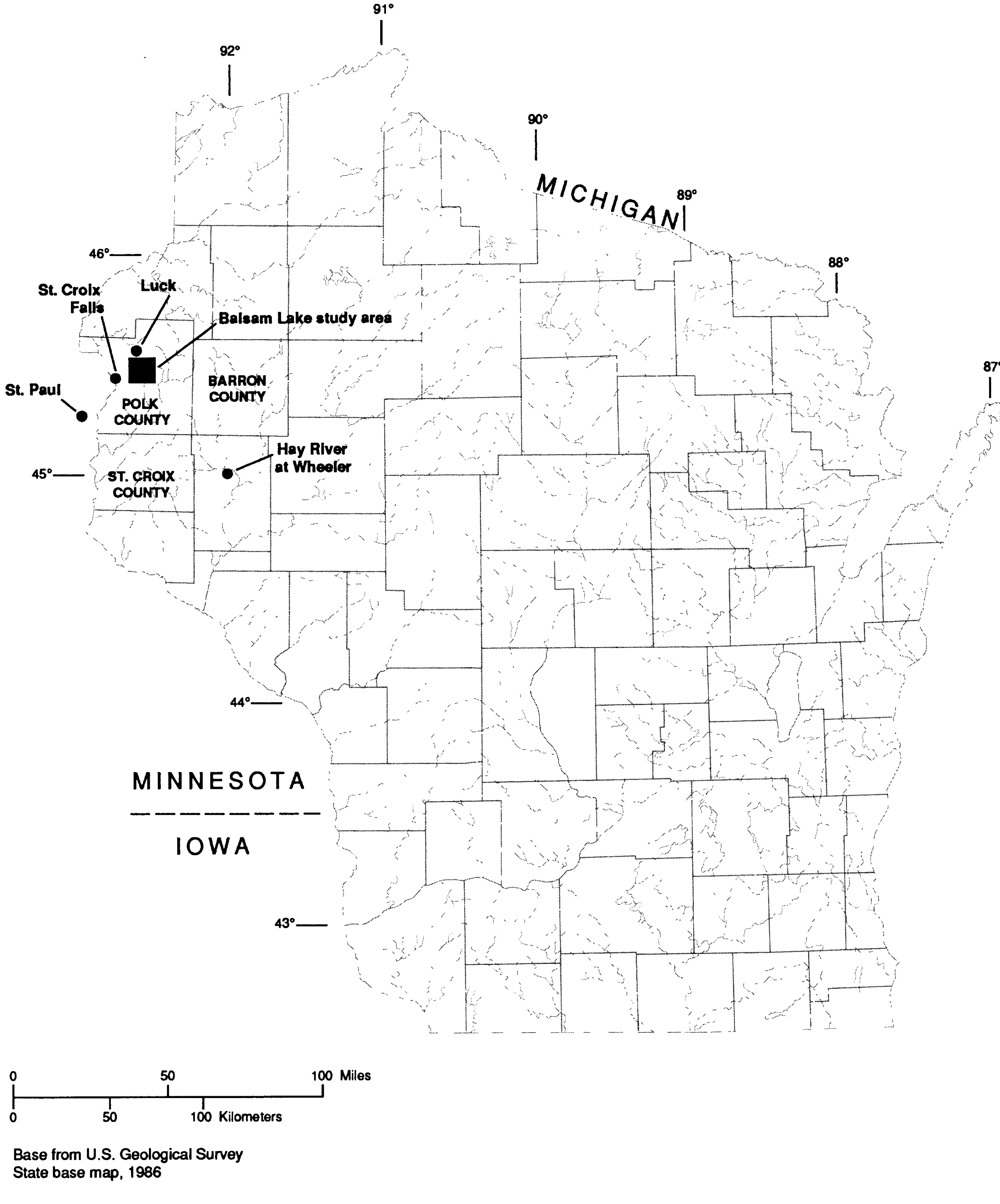


Figure 1. Location of Balsam Lake, Polk County, Wisconsin.

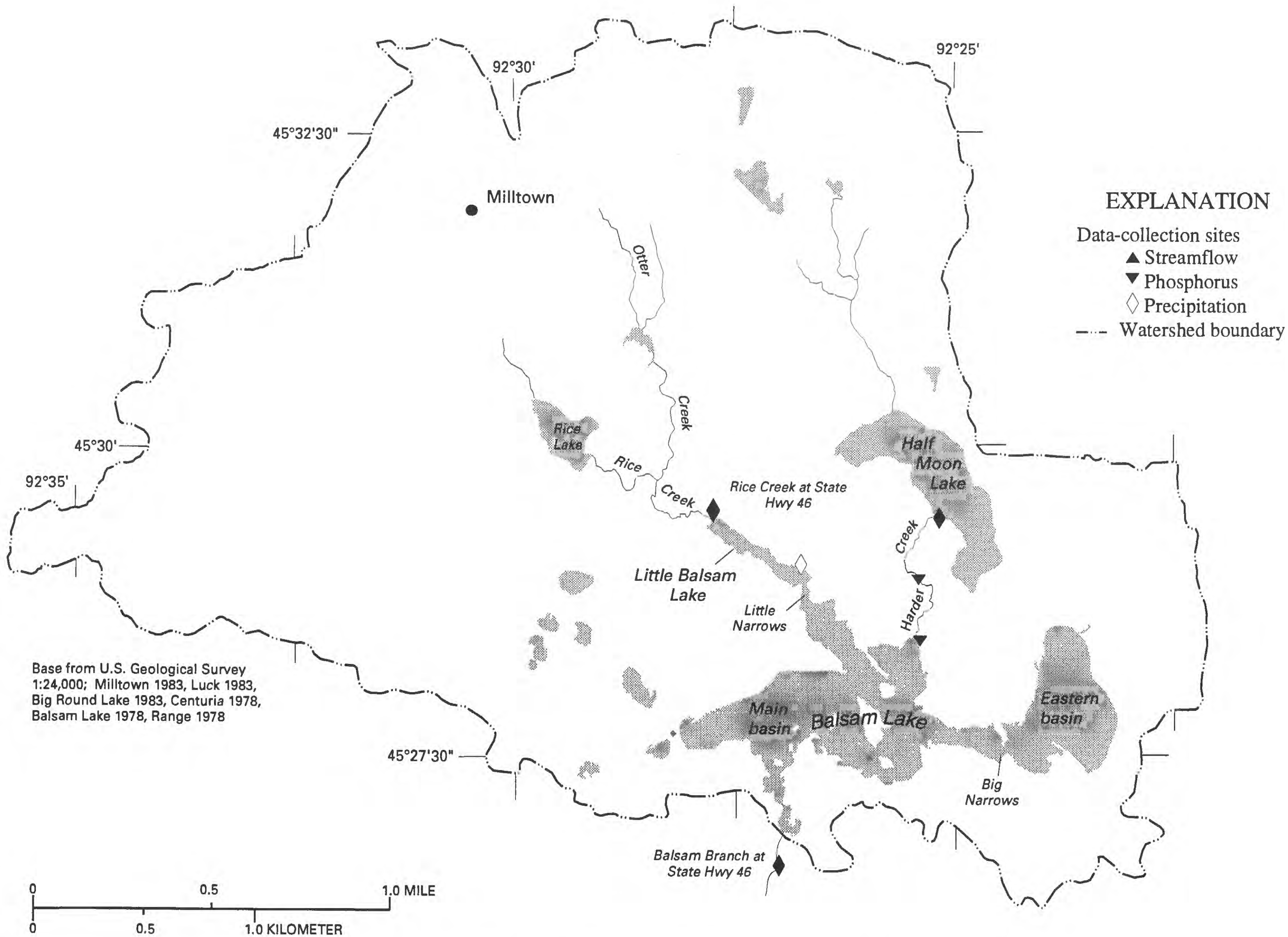


Figure 2. Locations of data-collection sites at and near Balsam Lake.

Identification of the amount and the sources of phosphorus entering Balsam Lake was needed to determine whether phosphorus loads were excessive. This information was needed to evaluate measures for reduction of phosphorus load that might be proposed. Beginning in October 1987, the U.S. Geological Survey, in cooperation with the Balsam Lake Rehabilitation and Protection District and the Wisconsin Department of Natural Resources, began a 2-year study to identify the amount and the sources of phosphorus entering the lake.

Purpose and Scope

This report presents water and phosphorus budgets for Balsam Lake, and describes the phosphorus loading in relation to the trophic state of the lake. The information can be used by local and State agencies to develop and assess lake- and watershed-management alternatives for maintaining or improving the water quality of the lake.

Water and total-phosphorus budgets were determined for a 2-year period beginning December 1, 1987, and ending November 30, 1989. The trophic state of the entire lake was evaluated by use of the water and phosphorus budgets and data on total-phosphorus concentration, chlorophyll *a* concentration, and secchi depth at a sampling point in the main basin of the lake. A separate evaluation of the trophic state was done for Little Balsam Lake, the northwestern basin of Balsam Lake.

Acknowledgments

The author thanks Robert Zuehlke (local observer at Balsam Lake) for collecting water samples and for measuring precipitation and lake stages. In addition, the author thanks Thomas Popowski and Jack Freshwaters (U.S. Geological Survey field office in Rice Lake, Wisconsin) for their extra effort in collecting storm-runoff samples and for maintaining and operating the data-collection network.

PHYSICAL SETTING

Balsam Lake is a drainage lake (a lake with a surface outlet). Its area is 1,900 acres, and its volume is 34,600 acre-ft. Maximum depth is 37 ft and average depth is about 16.8 ft. Total shore length is 22.7 mi. Little Narrows in the northwestern part of the lake and Big Narrows in the eastern part separate the lake into three basins (fig. 2). The areas of the northwestern basin (Little Balsam Lake), the main basin, and the eastern basin are about 86 acres, 1,270 acres, and 550 acres, respectively.

A dam at the outlet, built about 1850, raised the water level of the lake about 10 ft. The dam and an associated hydroelectric powerplant are used to regulate lake stage and water discharge into Balsam Branch.

Two main streams enter Balsam Lake. Rice Creek discharges into the northwestern end of Little Balsam Lake, and Harder Creek flows from Half Moon Lake into the north side of the main basin of Balsam Lake.

Watershed Characteristics

Thickness of glacial drift in the study area generally ranges from 100 to 150 ft (Young and Hindall, 1973). Most drift north and south of Balsam Lake is end moraine composed of till and stratified sand and gravel. Drift in areas east and west of the lake is pitted outwash composed of stratified sand and gravel. Sandstone of Cambrian age underlies the drift. A thin (0.5 to 2 ft thick) layer of loess overlying the drift is the parent material for most topsoil (Hole, 1950). Most soils are loams, silt loams, or peat (Hole and others, 1968).

Topography and drainage in the Balsam Lake watershed are typical for areas of end moraine and pitted outwash. Local relief is greatest (but usually less than 100 ft) in the area of end moraine near Balsam Lake and to the north. Many of the numerous closed depressions in the watershed contain wetlands or "pothole" lakes.

The area of Balsam Lake watershed upstream from the dam is 52.7 mi^2 (Henrich and Daniel, 1983). The watershed areas determined by Henrich and Daniel for topographically defined watersheds include areas of drainage to closed depressions or noncontributing area. Only about 42 percent of the Balsam Lake watershed contributes overland runoff to Balsam Lake. The remaining area supplies runoff to closed depressions. Watersheds and contributing and noncontributing areas are shown in figure 3.

Areas of Rice Creek and Harder Creek watersheds are 12.5 and 11.1 mi^2, respectively (Henrich and Daniel, 1983). About 49 percent of the Rice Creek watershed and 85 percent of the Harder Creek watershed contribute overland runoff to Balsam Lake. Runoff in the remainder of the watersheds is to closed basins. Only 22 percent, (6.55 mi^2) of the 29.1 mi^2 of land area outside the Rice Creek and Harder Creek watersheds contributes overland runoff to Balsam Lake. This area is referred to as "near-lake drainage area." The remaining area is considered to be noncontributing.

Rice and Harder Creeks flow through lakes. Rice Creek flows through Rice Lake, which is a shallow (less than 10 ft deep), 96-acre lake. Half Moon Lake in the Harder Creek watershed is a 60-foot deep, 579-acre lake.

Hydrologic Conditions During Study

Precipitation during the study (1987-88) and the year preceding the study was below normal (fig. 4). Precipitation was 12.54 in. below normal in the year preceding the study and was 6.09 in. and 8.71 in. below normal the first and second years of the study. Normal precipitation is defined as average values for the period 1951-80 at St. Croix Falls, about 11 mi southwest of the center of the Balsam Lake watershed (National Oceanic and Atmospheric Administration, 1989). Average annual precipitation at St. Croix Falls is 30.40 in.

Ground-water levels during the study were lower than they had been since about 1965. Water levels in well PK-40, which is in Milltown (fig. 2) near the upstream edge of Balsam Lake's watershed, are shown in figure 4. The well is screened in the sand and gravel aquifer. The water level in well PK-40 indicates the level of the water table. From January 1987 through January 1989, the water level dropped about 9 ft in response to the below-normal precipitation.

Streamflow in the region also was below normal during the study period. The Hay River at Wheeler, 40 mi southeast of Balsam Lake, drains an area of 418 mi^2. Average streamflow at this site during the study period was 265 ft^3/s, whereas long-term (1960-89) annual streamflow was 323 ft^3/s (fig. 4).

DATA-COLLECTION METHODS AND SITES

Surface inflow to the lake from the Rice Creek and Harder Creek watersheds was monitored at sites shown in figure 2. Flow at the Rice Creek site at State Highway 46 was determined by use of a continuous-recording gage. Flow in Harder Creek was determined from intermittent stage measurements in Half Moon Lake. Discharge was calculated by application of the stage readings to the stage-discharge relation of the Half Moon Lake outlet structure. Streamflow data were collected and were processed according to procedures outlined by Rantz and others (1982).

Three methods were used to obtain stream-water samples for determination of phosphorus concentration: (1) A local observer collected weekly "grab" (bottle-dipped) samples; (2) an automatic water sampler collected storm-runoff samples at the Rice Creek site; and (3) U.S. Geological Survey personnel collected intermittent and storm-runoff samples by the equal-width-increment (EWI) method (Edwards and Glysson, 1988). The representativeness of the grab and automatically collected samples was verified by comparison of total-phosphorus concentrations in concurrently collected grab or automatic samples with those of EWI samples.

Stream-sampling locations are shown in figure 2. Most Harder Creek samples were collected at the road crossing about one-half mile upstream from the mouth. A few samples were collected at the mouth of Harder Creek and at Half Moon Lake outlet.

Shallow piezometers were installed at depths ranging from 3.1 to 5.0 ft along the periphery of Balsam Lake to determine vertical hydraulic gradients and to collect samples of ground water for determination of total-phosphorus concentration. Locations of the sites are shown in figure 5. Piezometers of the type described by Lee and Cherry (1978) were constructed of 1/2-inch (outside diameter) polyethylene tubing.

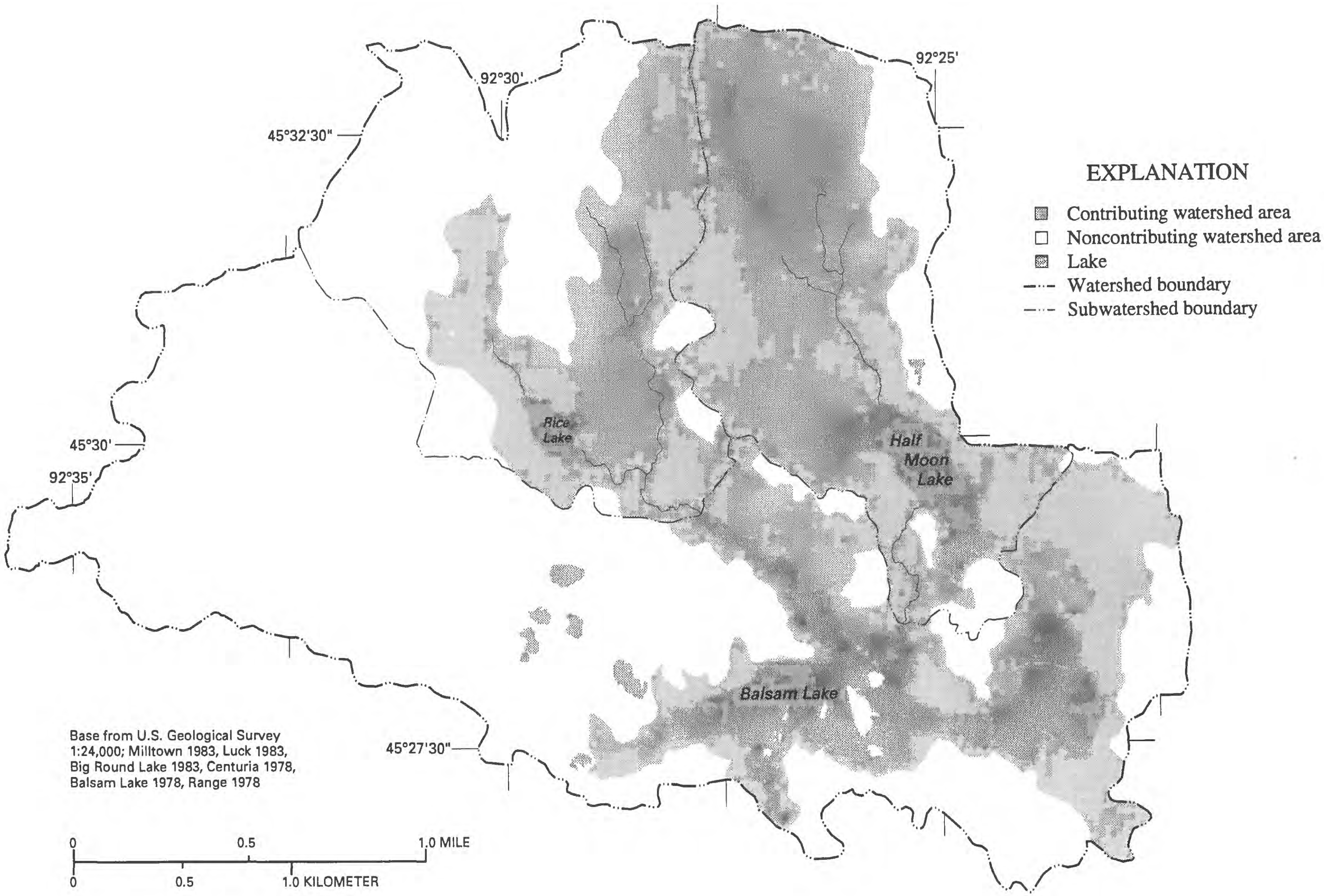


Figure 3. Contributing and noncontributing areas of Balsam Lake watershed.

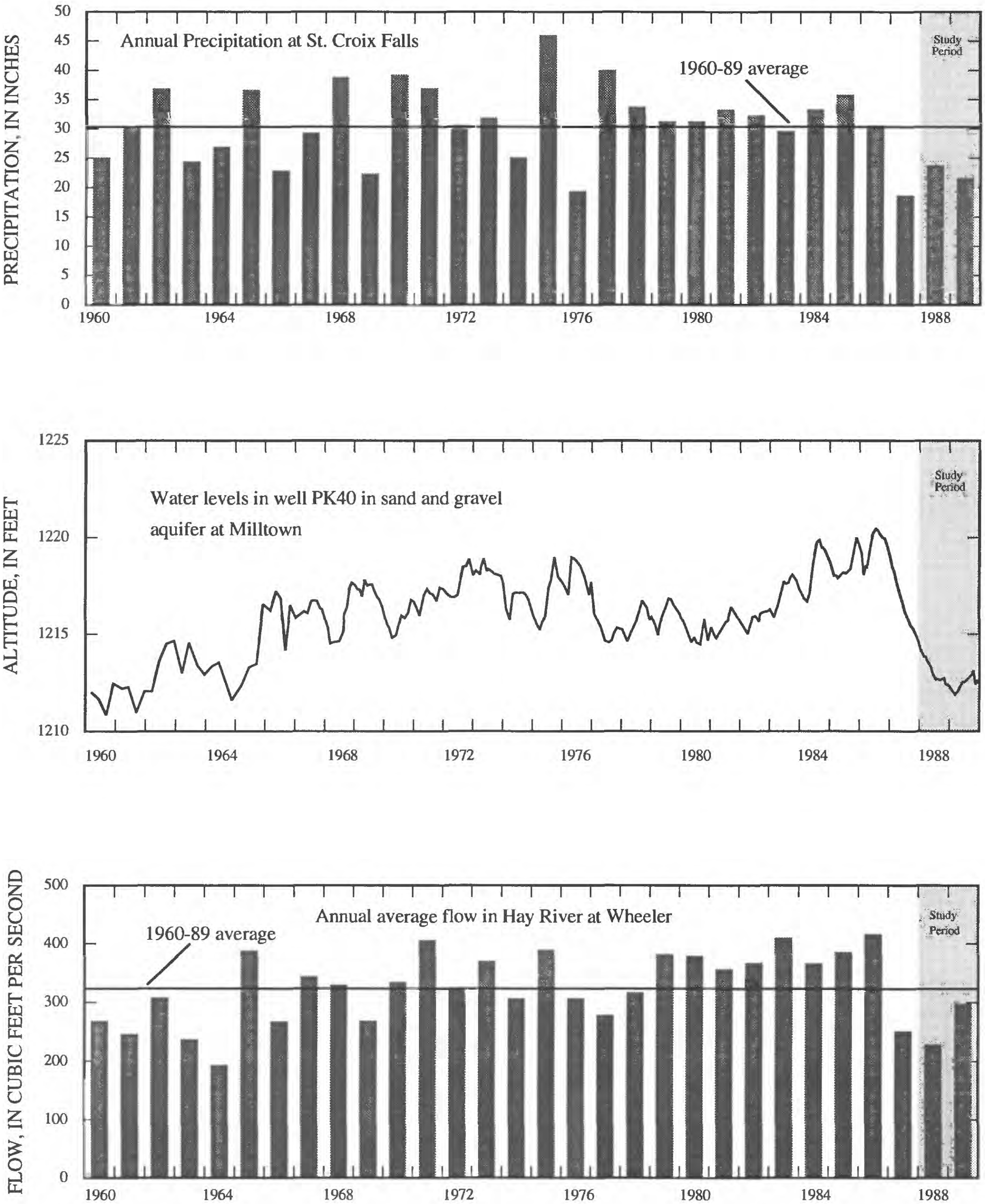
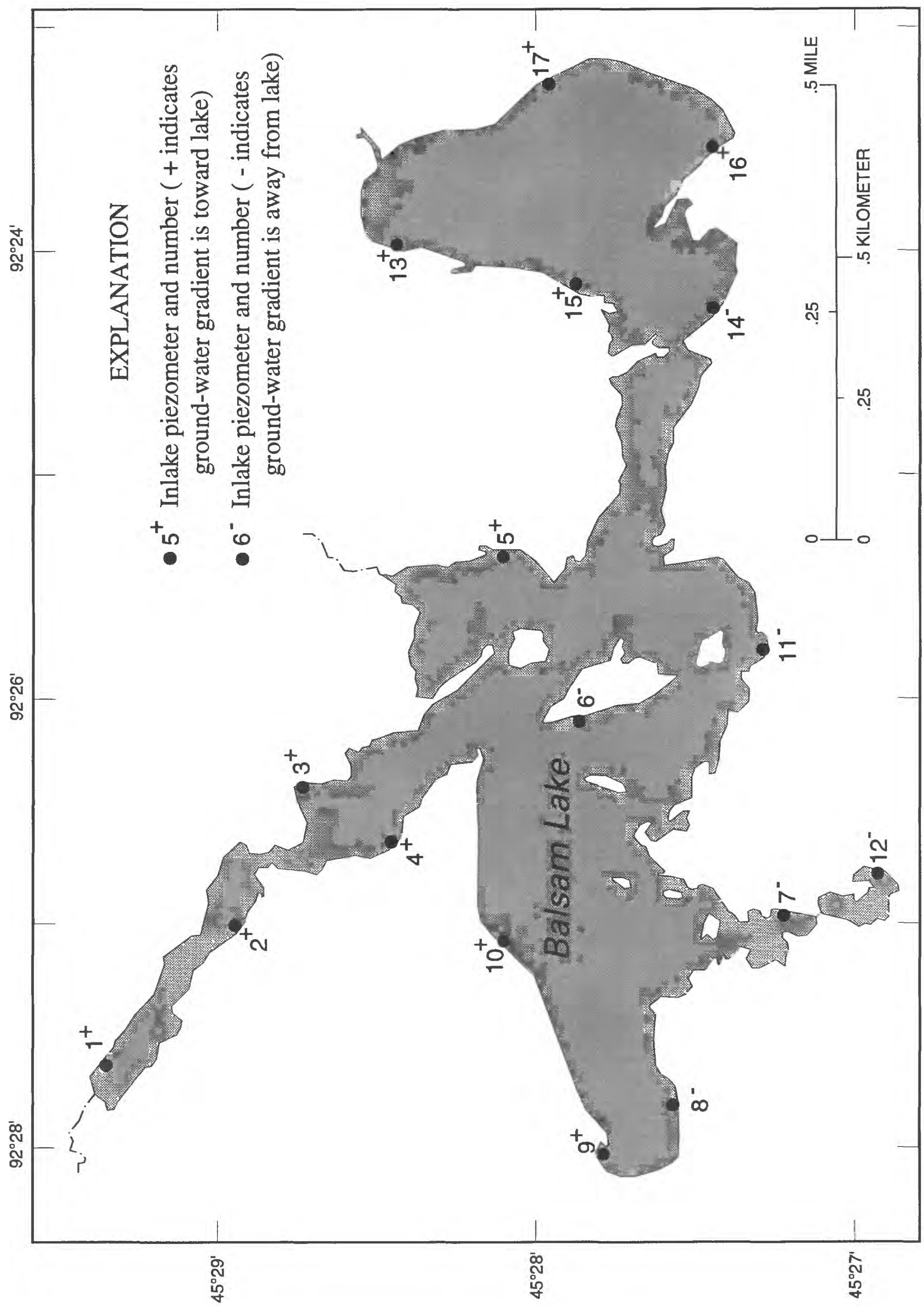


Figure 4. Annual and long-term averages of precipitation, ground-water levels, and streamflow before and during study period.



Base from U.S. Geological Survey
Balsam Lake, 1:24,000, 1978

Figure 5. Locations of in-lake piezometers at Balsam Lake.

Precipitation was measured daily by a local observer. Precipitation was collected in an 8-inch-inside-diameter gage near the northern shore of the lake at the site shown in figure 2. Data on phosphorus concentration in precipitation were obtained for a National Atmospheric Deposition monitoring site at Spooner, Wis., about 40 mi northeast of Balsam Lake.

Lake stage was measured weekly by a local observer and intermittently by U.S. Geological Survey personnel. Stage measurements were made at the site shown in figure 2 by use of a staff gage during open-water periods and by use of an underwater reference point during periods of ice cover.

WATER BUDGET

All significant components of Balsam Lake's water budget were determined independently. The general equation describing the lake's water budget is as follows:

$$DS = P + SI + GI - E - SO - GO, \quad (1)$$

where
- DS is change in lake storage,
- P is precipitation,
- SI is surface inflow to the lake,
- GI is ground-water discharge to the lake,
- E is evaporation from the lake surface,
- SO is surface-water outflow from the lake, and
- GO is ground-water recharge from the lake.

Volume units (L^3) are associated with each budget term.

Associated with each budget term are measurement and interpretation errors (Winter, 1981). A residual term, r, can be included in the above equation to aid in evaluating these errors and is calculated as follows:

$$r = P + SI + GI - E - SO - GO - DS, \quad (2)$$

The residual is the net error of all budget components and is zero if there is no error.

Budget Components

The greatest emphasis on data collection and analysis was directed to the components expected to have the greatest effect on the lake's phosphorus budget. By this criterion, surface inflow is the most important component and evaporation is the least important component.

Precipitation

Total precipitation at Balsam Lake was 28.75 in. during the first year of the study and 26.31 in. during the second year. Monthly precipitation at Balsam Lake and at two nearby sites, St. Croix Falls and Luck, is listed in table 1. Precipitation during both study years was greater at Balsam Lake than at St. Croix Falls or Luck. The differences are assumed to result from local variation in precipitation rather than from measurement error. The precipitation component of the lake's water budget is based on precipitation measured at Balsam Lake. The magnitude and temporal distribution of daily precipitation is shown in figure 6.

Surface Inflow

Surface inflow to the lake has three subcomponents, which are Rice Creek, Harder Creek, and near-lake drainage. Flow summaries are given in table 2.

Magnitude and temporal distribution of daily discharge in Rice and Harder Creeks is shown in figure 6. Flow in Rice Creek was continuous and was more responsive to storm runoff than flow in Harder Creek. Flow in Harder Creek was mostly controlled by the stage of Half Moon Lake; the creek was dry during five summer and fall months of 1988, but flow in the creek was intermittent during the summer and fall of 1989. Daily streamflow data for Rice Creek at State Highway 46 are published in annual data reports of the U.S. Geological Survey (Holmstrom and others, 1989 and 1990).

Surface inflow from the near-lake drainage area was estimated by a runoff and drainage-area comparison with Rice Creek. Storm runoff from the area of Rice Creek's watershed downstream from Rice Lake and the wetland in the Otter Creek watershed was estimated by hydrograph separation (Dunne

Table 1. *Precipitation at Balsam Lake, St. Croix Falls, and Luck, December 1987 through November 1989*

[All values in inches]

	First Year (December 1987 through November 1988)			Second Year (December 1988 through November 1989)		
	Balsam Lake	St. Croix Falls	Luck	Balsam Lake	St. Croix Falls	Luck
December	1.61	1.16	1.75	0.60	0.43	0.34
January	1.39	1.02	1.55	.85	.69	.67
February	.09	.05	.08	.58	.18	.43
March	1.89	1.28	1.35	1.59	1.11	1.41
April	.96	.62	.86	2.21	1.94	2.28
May	2.97	2.59	1.97	4.47	3.49	4.00
June	1.89	1.29	1.49	2.39	2.42	2.56
July	1.28	2.56	1.24	3.71	1.95	3.31
August	4.79	4.28	4.57	5.04	5.35	5.35
September	6.76	6.33	6.48	2.54	2.14	2.35
October	.72	.83	.98	.85	1.07	1.08
November	4.40	2.30	3.64	1.48	.92	1.15
	28.75	24.31	25.96	26.31	21.69	24.93

and Leopold, 1978, p. 287). It is assumed that this area of the Rice Creek watershed (fig. 7) generates the "rapid runoff" or peaked part of the storm hydrograph, and that runoff flowing through Rice Lake and the Otter Creek wetland is attenuated and delayed. An example of the hydrograph separation is shown in figure 8. Runoff characteristics of the Rice Creek watershed downstream from Rice Lake and the Otter Creek wetland are assumed to be similar to those of the near-lake drainage area.

Runoff from the near-lake drainage area (R) was calculated as follows:

$$R = \frac{\text{Near-lake drainage area}}{\text{Rice Creek "rapid-runoff" drainage area}} \times \text{Rice Creek "rapid runoff"}.$$

Ground-Water Inflow and Outflow

Ground-water inflow and outflow were estimated by use of the Darcy equation,

$$Q = KIA, \tag{3}$$

where Q is discharge (L^3/T),
K is hydraulic conductivity (L/T),
I is hydraulic gradient (L/L), and
A is the area through which the flow is passing (L^2).

Several simplifying assumptions and techniques were necessary because the scope of the study did not allow for a rigorous or detailed analysis.

Ground-water exchange with the lake was assumed to be steady state; that is, the rate and direction of flow through the lake bottom at any location does not change with time. This assumption was necessary because hydraulic gradient was known for only one date (March 9, 1988).

Vertical hydraulic gradient (I) was determined for each of the piezometer sites shown in figure 5. The piezometers typically were installed offshore in the lake bed in about 2 ft of water. Depth of penetration ranged from

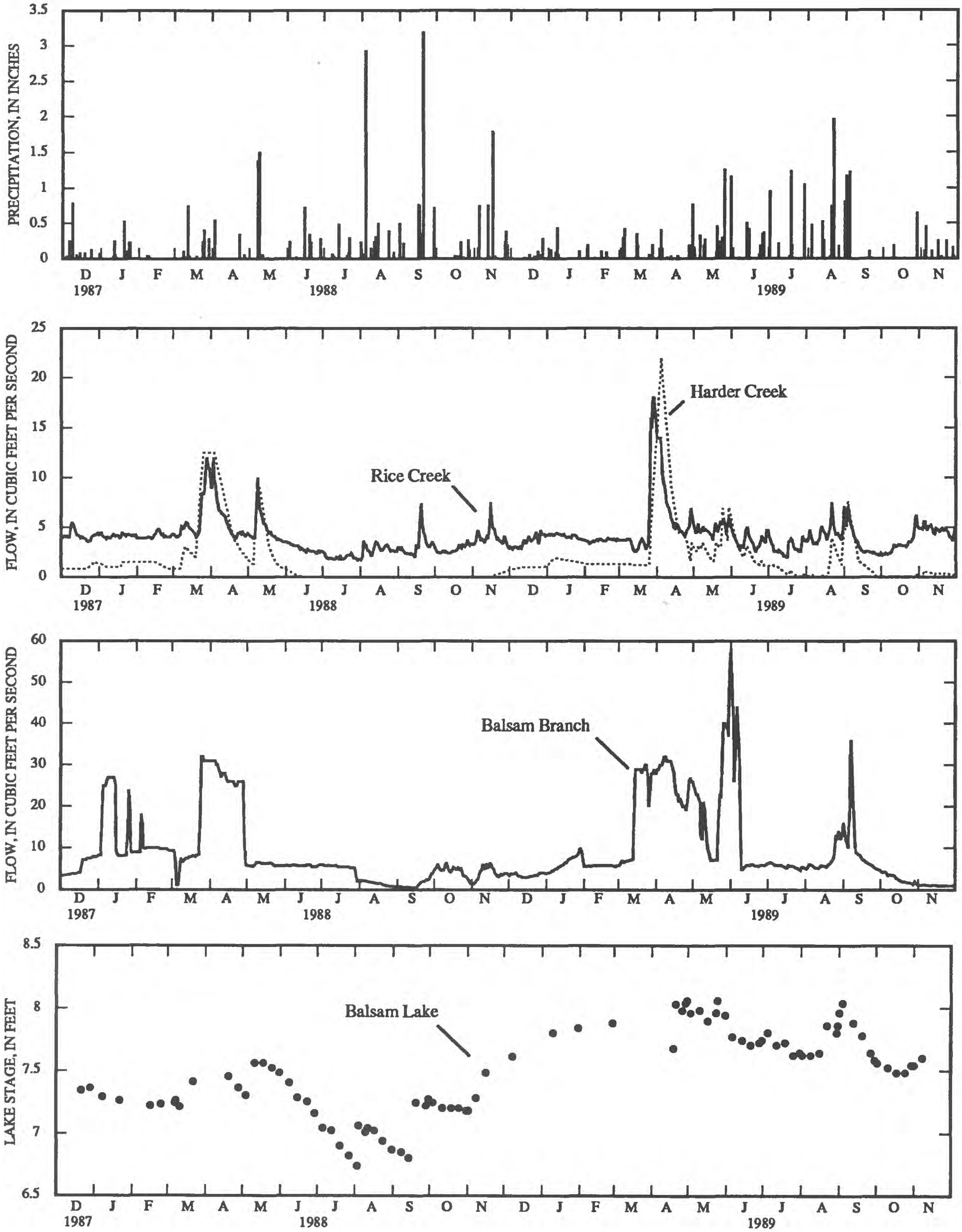


Figure 6. Precipitation at Balsam Lake, streamflow in Rice Creek, Harder Creek, and Balsam Branch; and stage of Balsam Lake, December 1987 through November 1989.

Table 2. *Summary of surface inflow to Balsam Lake, December 1987 through November 1989*

[ft^3/s, cubic feet per second; acre-ft, acre-feet; --, indicates value is unknown]

Stream or source	Year	Minimum instan-taneous streamflow (ft^3/s)	Maximum instan-taneous streamflow (ft^3/s)	Average streamflow (ft^3/s)	Streamflow volume (acre-ft)
Rice Creek	Dec. 1987-Nov. 1988	1.3	21	3.89	2,820
	Dec. 1988-Nov. 1989	1.7	29	4.28	3,100
Harder Creek	Dec. 1987-Nov. 1988	0	13	1.58	1,150
	Dec. 1988-Nov. 1989	0	20	2.16	1,570
Near-lake drainage	Dec. 1987-Nov. 1988	0	--	.41	297
	Dec. 1988-Nov. 1989	0	--	.83	600

3.1 to 5.0 ft and averaged 3.8 ft. Hydraulic gradient was calculated as follows:

$$I = \frac{H_L - H_P}{L}, \quad (4)$$

where H_L is water-surface altitude of the lake,
H_P is water-surface altitude in the piezometer, and
L is the distance between the lake bottom and the midpoint of the piezometer screen.

Hydraulic gradients for inflow areas ranged from 0.003 to 0.293 and, for outflow areas, from -0.007 to -1.269.

During winter months (December through March), evaporation is insignificant and can be assumed to be zero. For these months, eq. 1 can be simplified to

$$GI - GO = DS - P - SI + SO, \quad (5)$$

where GI - GO is net ground-water flow. Measurements of DS, P, SI, and SO were assumed to be errorless, and GI - GO, calculated as the residual, averaged 2.71 ft^3/s for the 8 winter months during the study.

Seventeen inflow and outflow regions of Balsam Lake were designated for calculation of ground-water flow by the Darcy equation. The regions were defined as strips paralleling the lake shore. Length of a strip is the distance between adjacent piezometers, and width of a strip is an unspecified distance (w). All seepage to and from the lake is assumed to be within the distance, w, of shore. Many studies, including those of McBride and Pfannkuch (1975), Lee (1977), and Fellows and Brezonik (1980), have shown that seepage decreases exponentially with distance from shore. The hydraulic gradient for a region is the average gradient at the piezometers at the ends of the region. Flow is into the lake for regions where the gradient is positive and out of the lake where negative.

The Darcy equations for specific regions for inflow (GI_r) and outflow (GO_r) are

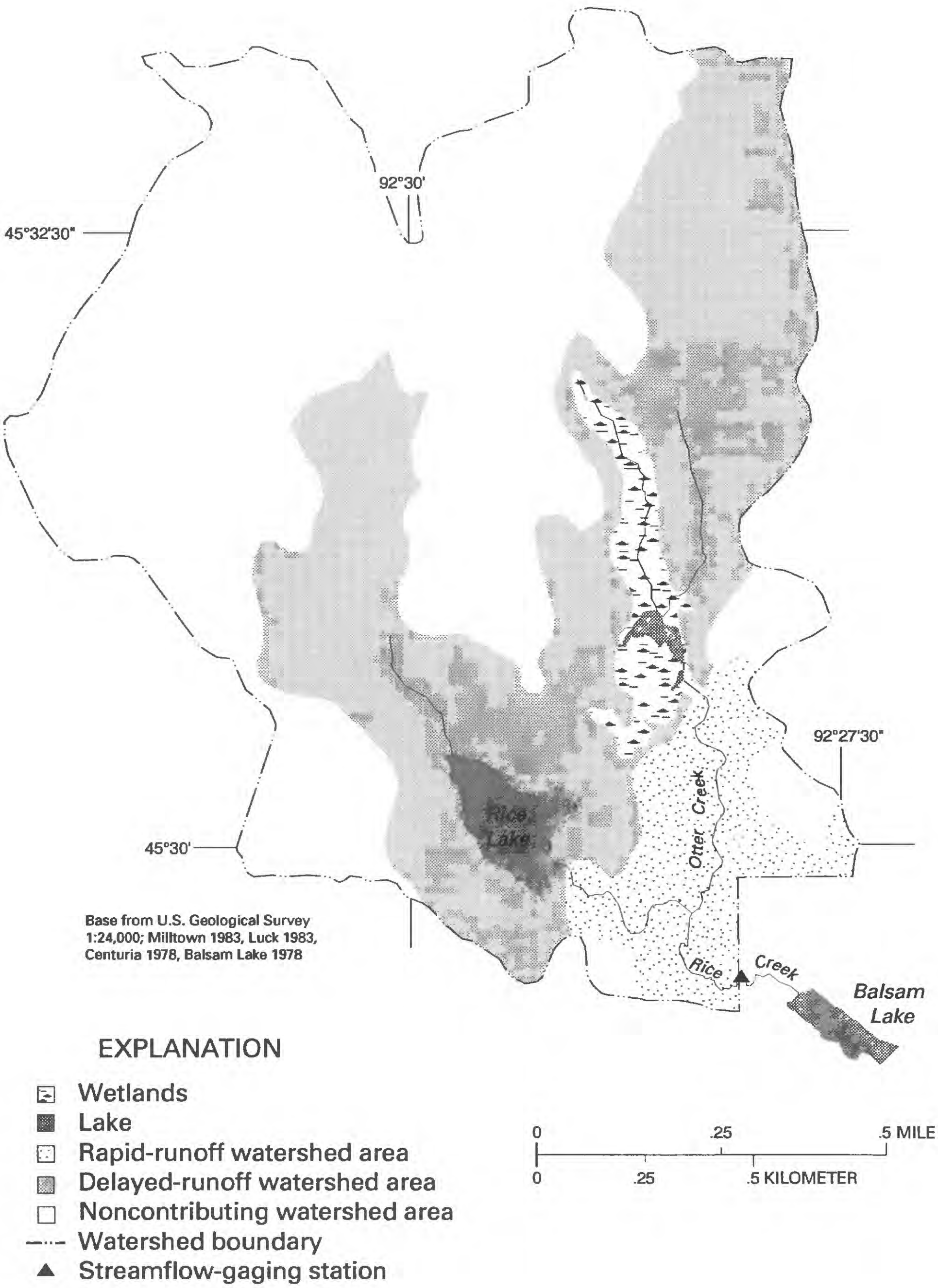


Figure 7. Rapid-runoff area of Rice Creek watershed upstream from the streamflow-gaging station at State Highway 46.

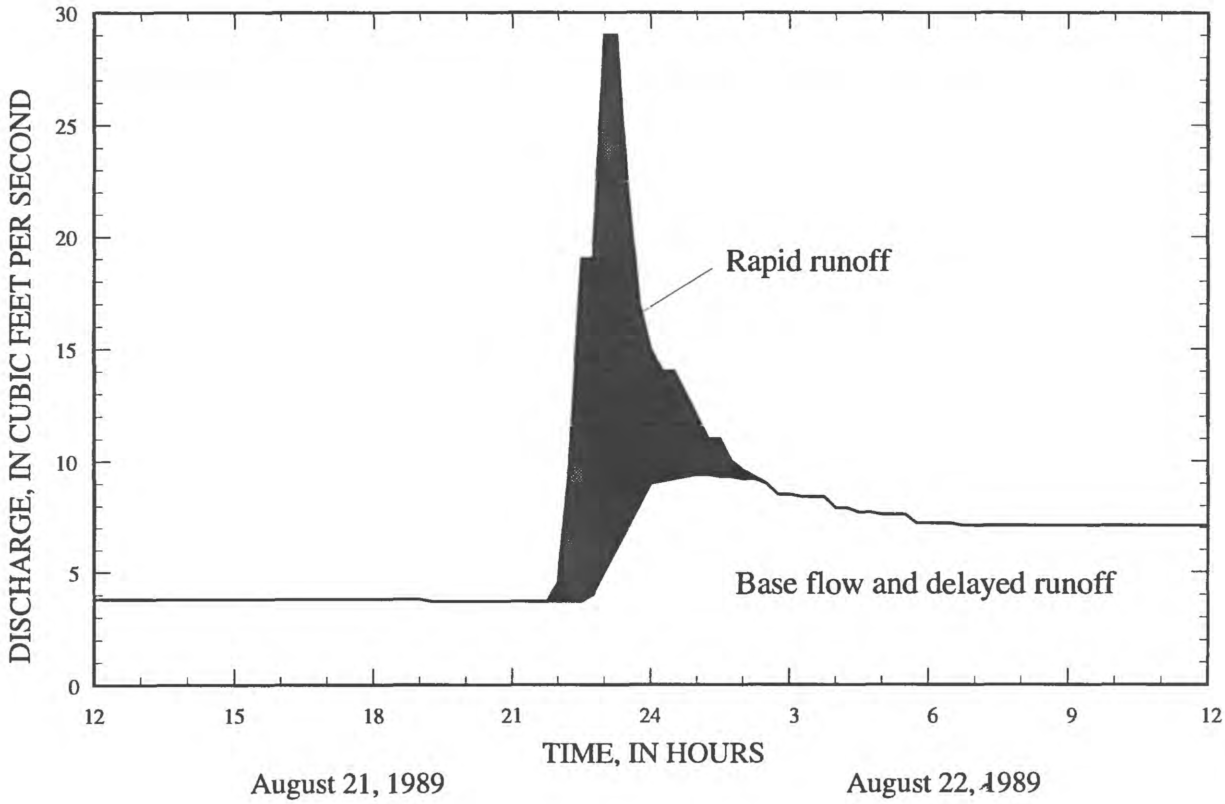


Figure 8. Separation of rapid and delayed runoff in Rice Creek for storm of August 21 and 22, 1989.

$$K_i I_r l_r w = GI_r \quad (6)$$

and

$$K_o I_r l_r w = GO_r \quad (7)$$

where K_i and K_o are the hydraulic conductivities of inflow and outflow regions,
I_r is the average hydraulic gradient,
l_r is the length, and
w is the width of a region.

Ten inflow and seven outflow regions were identified. The I_r and l_r terms are known for all regions. The sum of the product of I_r and l_r for inflow regions is 6,819, and for outflow regions is 7,572.

Net ground-water flow (*GI* - *GO*) can be expressed as follows:

$$K_i w\,(6819) - K_o w\,(7572) = 2.71\ \mathrm{ft}^3/\mathrm{s}, \quad (8)$$

The first term of eq. 8 is the sum of flow from the 10 inflow regions; the second term is the sum of flow from the 7 outflow regions; and 2.71 ft^3/s is net ground-water flow determined by use of eq. 5.

Hydraulic conductivities for inflow regions of lakes are greater than those for outflow regions. Lee (1977) confirmed this with experiments in a sand tank where he could control flow rate, hydraulic gradient, and flow direction. Wentz and Rose (1991) used hydraulic conductivities for ground-water-inflow regions an order of magnitude greater than those for outflow regions of Lakes Clara and Vandercook, Wis. Hence, for this study K_i was assumed to be 10 times K_o. By substitution of $10K_o$ for K_i in eq. 8, $K_o w$ is determined to be 0.0000447. Then, by substitution of 0.0000447 into the first and second terms of eq. 8, *GI* and *GO* are determined as follows:

$$GI = 10\,(0.0000447)\,(6819) = 3.05\ \mathrm{ft}^3/\mathrm{s}$$

and

$$GO = (0.0000447)\,(7572) = 0.34\ \mathrm{ft}^3/\mathrm{s}.$$

Evaporation

Estimates of lake evaporation were based on Class A evaporation pan data that were collected at St Paul, Minn., about 50 mi southwest of Balsam Lake. Greg Boden (Minnesota State Climatologist, written commun., 1990) provided the data.

Average pan evaporation for May through October, 1962-88 at St. Paul was 39.6 in., which is anomalously high for the region. On a map in Dunne and Leopold (1978, p. 102) showing lines of equal average annual pan evaporation for the United States, whole-year pan evaporation for the St. Paul area is shown to be about 40 in. Average evaporation from May through October for the St. Paul area is 81 percent of annual pan evaporation (Chow, 1964, p. 11-9) or 32.4 (0.81 x 40) in. St. Paul pan data were adjusted by the ratio of the May through October regional pan evaporation to the average annual May through October St. Paul pan evaporation. This ratio yields an adjustment coefficient of (32.4/39.6) or 0.82.

Lake evaporation for open-water periods was determined by multiplying St. Paul pan evaporation by the pan adjustment coefficient (0.82) by a lake-pan coefficient of 0.7. Lake evaporation during ice-covered periods was assumed to be zero. A summary of monthly lake evaporation follows.

Year and month	Lake evaporation (inches)	Lake evaporation (acre-feet)
1988		
April	1.80	285
May	5.96	943
June	6.76	1,070
July	6.73	1,065
August	5.13	812
September	2.96	469
October	2.26	359
November	.40	63
Total	32.00	5,066
1989		
April	2.15	340
May	3.71	587
June	4.48	709
July	5.11	810
August	4.16	659
September	3.35	531
October	1.65	261
November	.30	47
Total	24.91	3,944

(Note: Pan data were not available for parts of April, October, and November. Evaporation values for these months include estimates based on interpolation for periods in the spring from ice-out time to the beginning of pan measurement and in fall from the last pan measurement to lake freezeup.)

Surface-Water Outflow

Surface-water outflow was measured at the streamflow-gaging station on Balsam Branch about 500 ft downstream from the dam. The daily-flow hydrograph (fig. 6) shows flow fluctuations that result from regulation of the electric power plant and from gate manipulation. Minimum instantaneous discharge at the gaging station was 0.46 ft^3/s Sept. 15, 1988. Maximum instantaneous discharge was 76 ft^3/s May 31, 1989. Average flow during the study was 9.31 ft^3/s. Daily streamflow at the gaging station are published in U.S. Geological Survey annual data reports (Holmstrom and others, 1989 and 1990).

Flow measured at the gaging station was greater than surface-water outflow from the lake because of ground-water discharge to the reach of Balsam Branch between the dam and the gaging station. This discharge, about 0.4 ft^3/s, was subtracted from flow at the gaging station to calculate surface-water outflow from the lake. Flow volume of surface-water outflow from the lake during the first year (December 1987 through November 1988) was 5,692 acre-ft and during the second year (December 1988 through November 1989) was 7,229 acre-ft.

Lake Storage

Lake storage, which is directly related to lake stage (fig. 6), increased during both years of the study. Lake stage increased 0.43 ft and 0.17 ft during the first and second years, respectively, of the study. The volume of water in the lake increased by 820 acre-ft from December 1987 through November 1988 and by 320 acre-ft from December 1988 through November 1989. Change in lake storage was determined as the product of change in lake stage and lake area. Lake area was assumed to be constant during the study. This assumption is valid because the range of lake-stage fluctuation was only 1.32 ft.

Annual Water Budgets

Precipitation, the dominant water-inflow component, was followed in decreasing order by inflows from Rice Creek, ground water, Harder Creek, and near-lake drainage. Annual water budgets for each year of study are shown in table 3 and figure 9. Total inflow in the second year was about 5 percent greater than in the first year. Precipitation was 8.5 percent less the second year than in the first year. However, the combined surface inflow from Rice Creek, Harder Creek, and near-lake drainage was 23 percent greater in the second year than in the first year. Ground-water inflow was virtually the same for both years; the slight difference resulted from 1988 being a 366-day year.

The greater surface inflow during the second year than the first year reflects the considerably less evaporation the second year than the first year. Evaporation from lakes and wetlands within the contributing watersheds was at the expense of surface runoff. Storm intensity differences may also account for some of the surface inflow differences between the 2 years.

Greatest outflow from Balsam Lake during the 2 study years was into Balsam Branch. Outflow by evaporation was the second-ranked means by which water left the lake. In the first year, evaporation was only slightly less than flow into Balsam Branch owing to the much greater than normal evaporation that year. In the second year, evaporation was about 22 percent less and Balsam Branch flow was about 27 percent greater than in the first year. Flow to ground water was only 2 percent of total outflow both years.

Lake storage increased in both study years. Storage increase was about 8 percent of total inflow in the first year and about 3 percent in the second year.

The budget residual was negative for both study years. A negative residual indicates that inflow was underestimated or outflow was overestimated or both. The residual for the first year was about 7 percent of total inflow to the lake, and the residual for the second year was about 1 percent of total inflow to the lake.

PHOSPHORUS BUDGET

The equation for Balsam Lake's total-phosphorus budget is similar to eq. 1 for the water budget:

$$R_p = P_p + SI_p + GI_P - SO_p \,. \qquad (9)$$

The subscript "p" indicates that a quantity of

Table 3. *Annual water budgets for Balsam Lake, December 1987 through November 1989*

Budget item	December 1987 through November 1988		December 1988 through November 1989	
	Flow volume (acre-feet)	Percentage of total inflow or outflow	Flow volume (acre-feet)	Percentage of total inflow or outflow
Inflow:				
Precipitation	4,550	41	4,170	36
Rice Creek	2,820	26	3,100	27
Harder Creek	1,150	10	1,570	13
Near-lake drainage	300	3	600	5
Ground water	2,220	20	2,210	19
Total inflow	11,040	100	11,650	100
Outflow:				
Evaporation	5,070	46	3,940	35
Balsam Branch	5,690	52	7,230	63
Ground water	250	2	250	2
Total outflow	11,010	100	11,420	100
Lake-storage change:	820		320	
Budget residual:	-790		-90	

phosphorus is represented. Unlike water-budget eqs. 1 or 2, eq. 9 includes no terms for evaporation from the lake surface, change in storage, or ground-water outflow. Evaporation does not remove phosphorus. Independent determination of change in phosphorus stored in lake water and sediment and determination of the amount removed by ground-water outflow was beyond the scope of this study. The residual (R_p) is composed of change in phosphorus stored in lake water and in sediment, amount of phosphorus removed by ground-water outflow, and net error of all independently determined budget components.

Budget Components

The greatest emphasis on data collection and analysis was directed to the surface-water inflow and outflow components of the lake's phosphorus budget. These components were expected to be the largest components of the phosphorus budget.

Precipitation

Phosphorus inputs from precipitation were estimated from amounts of precipitation measured at Balsam Lake and from dissolved-phosphorus concentration in precipitation measured at the National Atmospheric Deposition Monitoring site at Spooner, Wis. Monthly average phosphorus concentration was multiplied by the monthly precipitation volume to calculate monthly total-phosphorus inputs. Monthly inputs were summed to obtain annual inputs. Dissolved-phosphorus concentration averaged 0.007 mg/L during the study period. Total-phosphorus input from precipitation could be somewhat higher than these estimates, because some phosphorus could be associated with particulates. A study by Murphy (1974) of phosphorus inputs from the atmosphere in the Chicago, Ill. area showed that total-phosphorus

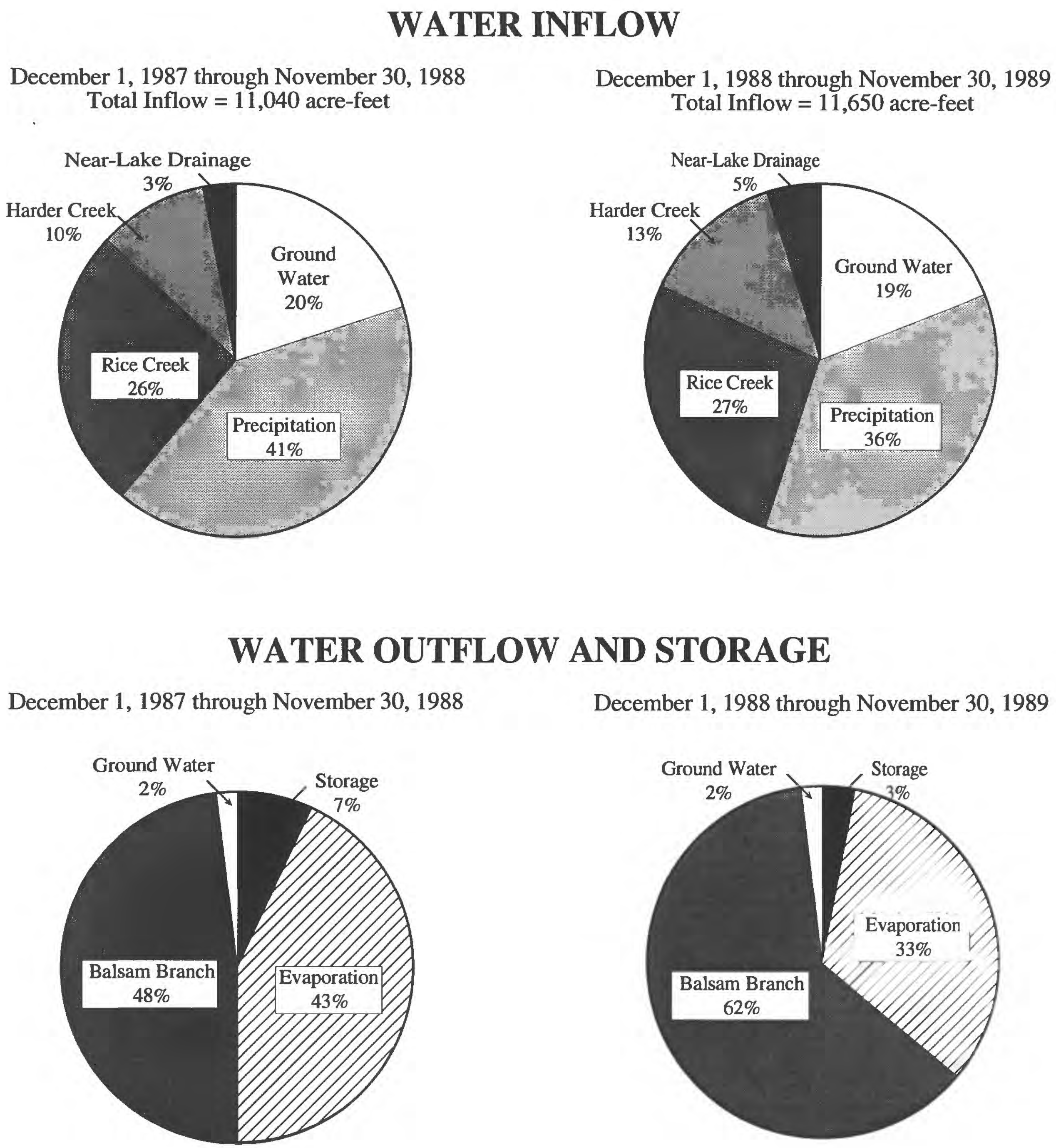


Figure 9. Annual water budgets for Balsam Lake, December 1, 1987, through November 30, 1989.

deposition from the atmosphere was almost twice as great as dissolved phosphorus in wet deposition.

Surface Inflow

Annual phosphorus inputs were calculated for each of the surface inflow sources (Rice Creek, Harder Creek, and near-lake drainage area). Phosphorus-concentration data is published in annual data reports of the U.S. Geological Survey (Holmstrom and others, 1989 and 1990).

Total-phosphorus concentration in Rice Creek generally was greater than and varied more than that in Harder Creek. Observed total-phosphorus concentration in Rice Creek ranged from 0.01 to 1.48 mg/L. Observed total-phosphorus concentration in Harder Creek ranged from 0.01 to 0.08 mg/L. The low phosphorus concentrations in Harder Creek indicate that Half Moon Lake with maximum depth of 60 ft is a sink to phosphorus in runoff from upstream areas of the watershed. Rice Lake in the Rice Creek watershed with a maximum depth of 6 ft is subject to mixing from wind, and is not an effective phosphorus sink (Sandy Engel, Wisconsin Department of Natural Resources, written commun., 1991).

Phosphorus inputs from Rice and Harder Creeks were calculated by use of techniques for integrating streamflow and concentration described by Porterfield (1972). Inputs from near-lake drainage area were determined as the product of the runoff volume and an estimate of average phosphorus concentration. The estimate used, 0.2 mg/L, was based on the findings of other studies of urban-rural drainage basins of sizes and land uses similar to those of the study basins. Annual mean concentrations of total phosphorus for Jackson Creek Tributary near Delavan were 0.12 and 0.17 mg/L for water years 1988 and 1989 (Holmstrom and others, 1989 and 1990). The geometric mean of total-phosphorus concentration of samples of runoff from medium-density residential areas in Milwaukee, Wis., was 0.25 mg/L (Bannerman and others, 1983, p. IV-37).

Ground-Water Inflow

Total-phosphorus concentration of ground-water inflow to the lake was based on analyses of water samples from 11 piezometers, one spring (ground-water seepage-emergence area), and one discharge pipe from an underground drainage field. Only piezometers in areas of ground-water discharge to the lake were sampled (fig. 5). The piezometers were placed at random in relation to the locations of domestic septic systems. It is possible that water sampled from some of the piezometers was influenced by nearby septic systems. Determination of the amount of phosphorus contributed by septic systems was beyond the scope of this study. The phosphorus data are summarized in table 4.

Phosphorus input to the lake was determined by multiplying the volume of ground-water inflow to the lake by the median concentration of phosphorus in sampled ground water. The median concentration (0.008 mg/L) was assumed to represent concentration of phosphorus in ground water flowing into the lake, and may include some contribution from domestic septic systems.

Surface-Water Outflow

Total-phosphorus output by surface outflow into Balsam Branch was calculated by use of techniques for integrating streamflow and concentration described by Porterfield (1972). Data on concentration of phosphorus is published in annual data reports of the U.S. Geological Survey (Holmstrom and others, 1989 and 1990). Total-phosphorus concentration ranged from <0.01 to 0.03 mg/L. This concentration range is approximately the same as that of the lake water.

Phosphorus output from the lake by surface-water outflow was slightly less than the load determined for the Balsam Branch gaging station. Loads were adjusted to account for ground-water seepage to the stream reach of Balsam Branch between the dam and the streamflow-gaging station. The adjustment was the product of seepage volume and total-phosphorus concentration of the seepage. The estimated concentration of 0.01 mg/L was based on analyses of two samples of streambank seepage.

Table 4. *Dissolved-phosphorus concentration in sampled ground water*

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter]

Site	Date	Specific conductance (µS/cm)	Dissolved phosphorus concentration (mg/L)
Piezometer 1	March 7, 1988	290	0.003
Piezometer 2	March 8, 1988	295	.035
Piezometer 3	March 8, 1988	250	.005
Piezometer 4	March 8, 1988	310	.006
Piezometer 5	March 8, 1988	229	.008
Piezometer 9	March 8, 1988	410	.013
Piezometer 10	March 8, 1988	320	.014
Piezometer 11	March 8, 1988	370	.002
Piezometer 13	March 8, 1988	279	.020
Piezometer 15	March 8, 1988	410	.045
Piezometer 17	March 8, 1988	223	.006
Drain-field pipe	March 7, 1988	218	.044
Spring	March 7, 1988	310	.006

Annual Total-Phosphorus Budgets

Principal sources of phosphorus input to Balsam Lake in decreasing order, were Rice Creek, near-lake drainage, precipitation, Harder Creek, and ground water. Annual phosphorus budgets for the study period are summarized in table 5 and in figure 10.

Total-phosphorus input from Rice Creek and near-lake drainage increased 81 and 102 percent, respectively, from the first year to the second. These increases probably resulted from greater storm runoff in the second year than in the first. In contrast to increases in total-phosphorus input from Rice Creek and near-lake drainage, input from Harder Creek increased by only 24 percent the second year, owing to the phosphorus-trapping ability of Half Moon Lake. Phosphorus inputs from precipitation and ground water were virtually the same in both years.

Total-phosphorus output from Balsam Lake into Balsam Branch, as a percentage of all phosphorus inputs, was 35 and 27 percent for the first and second years. Most of the phosphorus not discharged into Balsam Branch probably remained in the lake water or sediment, although a small amount discharged with ground-water outflow. Quantification of the amount of phosphorus associated with the lake water and sediment and ground-water outflow was beyond the scope of the study.

The total-phosphorus budgets for the two study years probably represent low-input years, particularly from stream sources. The study period was during the second and third years of a 3-year period of below normal precipitation, ground-water levels, and streamflow (fig. 4). Phosphorus inputs for a high-input year could be several times greater than those for a low-input year. For example, inputs to Delavan Lake in southeastern Wisconsin were about 11 times greater in 1986 than in 1988 (S.J. Field, U.S. Geological Survey, written commun., 1990).

TROPHIC STATE

The trophic-state index (TSI) developed by Carlson (1977) was used to evaluate in-lake water quality. The TSI is a numerical scale ranging from zero to 100. Lakes having TSI values less than 40 are oligotrophic, lakes

Table 5. *Annual total-phosphorus budgets for Balsam Lake, December 1987 through November 1989*

Budget item	December 1987 through November 1988		December 1988 through November 1989	
	Phosphorus amount (pounds)	Percentage of total inputs or outputs	Phosphorus amount (pounds)	Percentage of total inputs or outputs
Inputs:				
Precipitation	80	12	76	7
Rice Creek	392	57	712	62
Harder Creek	51	7	63	6
Near-lake drainage	121	17	245	21
Ground water	48	7	48	4
Total inflow	692	100	1,144	100
Outputs:				
Balsam Branch	248	36	307	27
Residual[1]	444	64	837	73

[1] The residual is composed of change in phosphorus stored in water and sediment, amount of phosphorus removed by ground-water outflow, and net error associated with all the independently determined phosphorus-budget components (precipitation, Rice Creek, Harder Creek, near-lake drainage, ground water and Balsam Branch).

having TSI values from 40 to 50 are mesotrophic, lakes having TSI values greater than 60 are eutrophic (fig. 11). Secchi depth, chlorophyll *a* concentration, and total-phosphorus concentrations were provided by the Wisconsin Department of Natural Resources.

The model developed by Vollenweider (1975) was used to estimate the trophic state likely to result from phosphorus loading during the study period. The model, shown graphically in figure 12, relates total-phosphorus loading rate per unit lake surface area to the lake's flushing rate. According to the model, "excessive" loading causes eutrophic lakes and "acceptable" loading causes oligotrophic lakes. The x axis of figure 12, "average lake depth/hydraulic residence time, in meters per year" is equivalent to Vollenweider's "mean lake depth, in meters/hydraulic residence time, in years."

Main Basin

The TSI for the main basin of Balsam Lake indicated a higher trophic state than would have been expected for the actual phosphorus loading during the study period. Most TSI values were in the mesotrophic range (fig. 11); however, the values ranged from upper oligotrophic in spring to lower eutrophic in late summer and fall.

Phosphorus loading during the two study years should have resulted in oligotrophic conditions in the lake, according to Vollenweider's model (fig. 12 and table 6). Internal loading (recycling of phosphorus from lake bottom sediment) may account for the discrepancy between the mesotrophic conditions indicated by the TSI and the oligotrophic conditions indicated by external phosphorus loading. Anoxic water in hypolimnions of both the main and northwest basins during summer months of 1988 is further evidence of internal loading. Associated with the anoxia were higher concentrations of phosphorus in the hypolimnion than at the surface as shown in table 7.

Phosphorus loading needed to produce mesotrophic conditions during an "average" runoff year was estimated using Vollenweider's

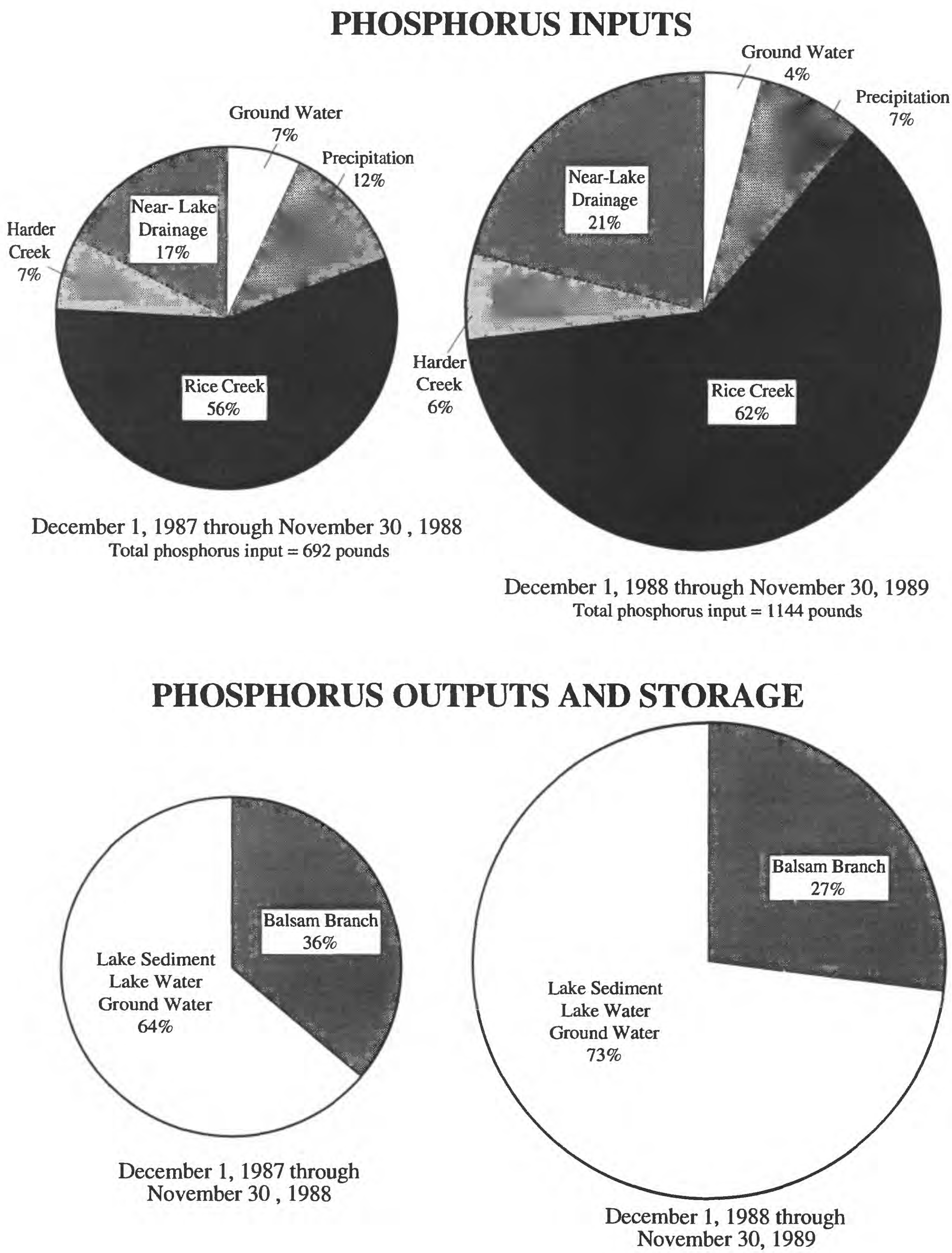


Figure 10. Annual phosphorus budgets for Balsam Lake, December 1, 1987, through November 30, 1989.

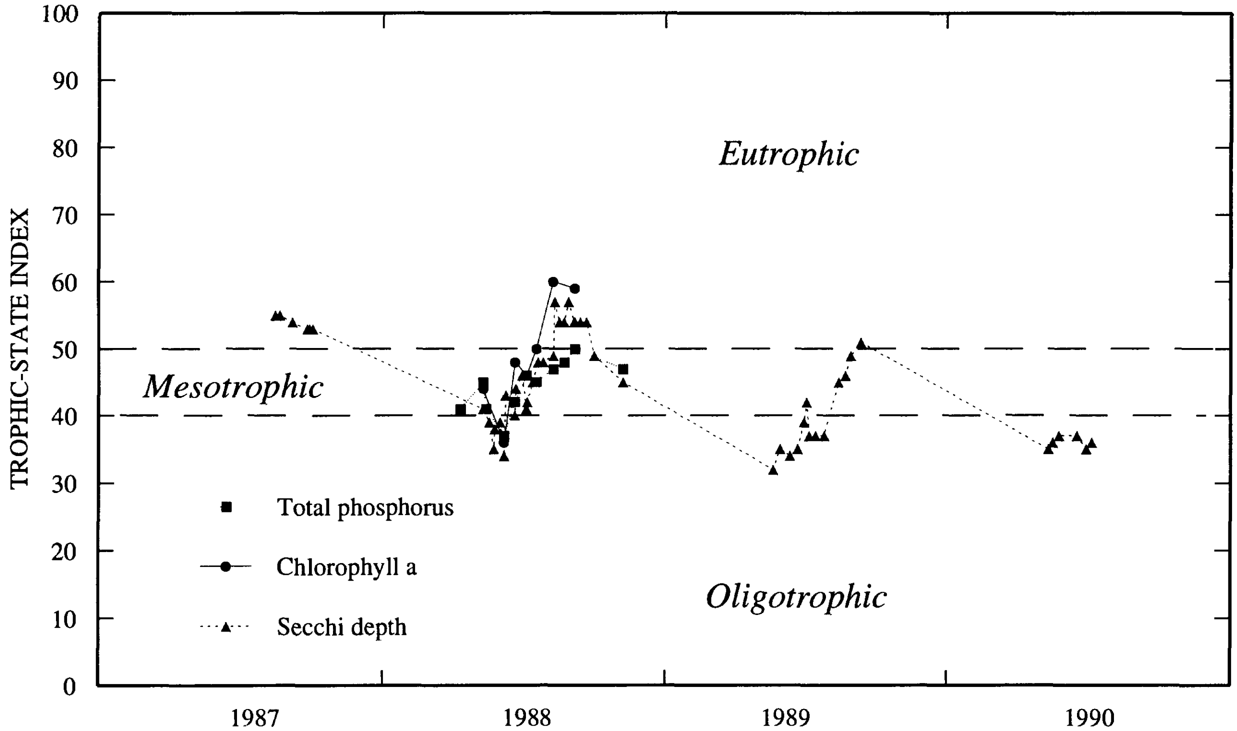


Figure 11. Trophic-state indices for the main basin of Balsam Lake, 1987-90.

model and estimated outflow from Balsam Lake. Average flow at Hay River at Wheeler during 1960 through 1989 was 23 percent greater than during the 2-year study period. Average surface outflow from Balsam Lake was assumed also to be 23 percent greater than during the study period. As shown in table 6, estimated external loading required to produce mesotrophic conditions in an average-runoff year ranges from 1,910 to 3,820 lb.

Northwest Basin (Little Balsam Lake)

The trophic state of Little Balsam Lake was higher than that of the main basin during the study period. Most TSI values were classified as upper mesotrophic and lower eutrophic, as shown in figure 13. Phosphorus-loading rates for the study years indicated eutrophic conditions according to the Vollenweider model (fig. 12). Average or above-normal loading rates would probably raise the TSI further into the eutrophic classification.

Effects of external loading probably are greater in Little Balsam Lake than in the main basin. Little Balsam Lake received 66 percent of all phosphorus loading to Balsam Lake during the study. Little Balsam Lake constitutes only 5 percent of the area and only 3 percent of the volume of Balsam Lake.

SUMMARY AND CONCLUSIONS

During the early 1980's, the severity of algal blooms had increased and water clarity had decreased in Balsam Lake in Polk County, northwestern Wisconsin. Water and total-phosphorus budgets were determined for a 2-year period (December 1, 1987 through November 30, 1989) of hydrologic monitoring.

Mean depth of the three-basin, 1,900-acre drainage lake is 16.8 ft. Two main streams, Harder and Rice Creeks, and near-lake drainage provide surface inflow to the lake. Outflow from the lake to Balsam Branch is regulated at a dam and a hydroelectric plant. Much of the lake's

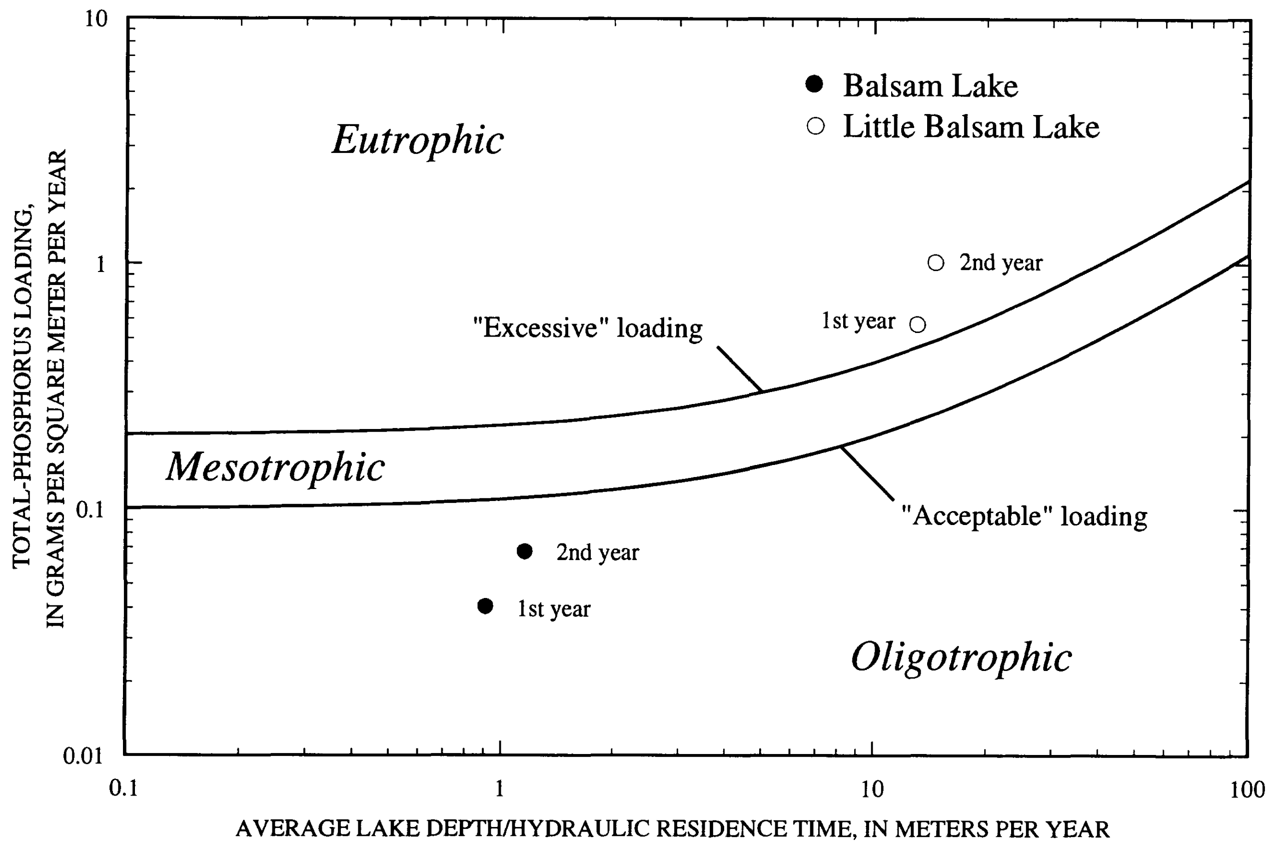


Figure 12. Phosphorus-loading classification for Balsam Lake and Little Balsam Lake (Vollenweider model).

watershed contains pitted glacial-outwash deposits resulting in many closed depressions containing wetlands and "pothole" lakes. Only about 42 percent of Balsam Lake's topographically defined watershed contributes overland flow to Balsam Lake.

Precipitation, ground-water levels, and streamflow were below normal during the study period and year preceding the study. Precipitation was 6.09 in. below normal during the first year of the study and 8.71 in. during the second year. Ground-water levels in the upstream part of the watershed dropped about 9 ft from January 1987 through January 1989. Streamflow at Hay River at Wheeler averaged 265 ft^3/s during the study compared to the long-term (1960-89) average of 323 ft^3/s.

All significant components of the lake's water budget were determined independently. Monitoring and analysis were predominantly focused on surface-water inflow and outflow components because these components were expected to have the greatest effect on the lake's phosphorus budget.

Precipitation, the dominant water-budget inflow component, was followed in decreasing order by inflows from Rice Creek, ground water, Harder Creek, and near-lake drainage. Total inflow in the first and second years of the study was 11,040 and 11,650 acre-ft, respectively. Surface inflow was 23 percent greater in the second than in the first year.

The largest lake-water outflow from Balsam Lake was into Balsam Branch, and the second largest outflow was evaporation. These outflows accounted for 98 percent of lake outflow. Recharge to ground water accounted for 2 percent. Water storage in the lake increased in

Table 6. *Vollenweider model variables for Balsam Lake and the northwestern basin of Balsam Lake*

[--, nonexistent]

Loading period	Average lake depth (feet)	Hydraulic residence time (years)	Phosphorus loading: Actual (pounds)	Phosphorus loading: Range likely to result in mesotrophic conditions (pounds)
Balsam Lake (whole lake):				
Dec. 1, 1987-Nov. 30, 1988	18.2	6.08	692	1,850 - 3,700
Dec. 1, 1988-Nov. 30, 1989	18.2	4.78	1,144	1,890 - 3,780
Estimated "average" year during 1960-89	18.2	4.38	--	1,910 - 3,820
Northwestern basin of Balsam Lake (Little Balsam Lake):				
Dec. 1, 1987-Nov. 30, 1988	12.4	.29	440	177 - 354
Dec. 1, 1988-Nov. 30, 1989	12.4	.26	780	188 - 376

both years of the study and caused outflow to be less than inflow. The water-budget residual was 7 and 1 percent of total inflow in the first and second years, respectively.

Total-phosphorus inputs to the lake were 692 and 1,144 lb in the first and second years of the study. Phosphorus loading was probably below normal both years, reflecting below-normal streamflow. Rice Creek and near-lake drainage accounted for 80 percent of phosphorus entering the lake. Outflow to Balsam Branch removed 30 percent of the phosphorus that entered the lake.

Carlson's TSI indicates that the main basin of the lake was mesotrophic during the study. Vollenweider's model indicates that the loading rates during the study would result in oligotrophic conditions. Internal loading and below-normal external loading during the study are the likely explanation for the discrepancy between results derived by the two methods.

Little Balsam Basin received 66 percent of all external phosphorus loading to Balsam Lake during the study. The TSI of Little Balsam Lake was in the lower eutrophic/upper mesotrophic classification. Phosphorus-loading rates for the study period indicated eutrophic levels (according to Vollenweider's model). Normal or above-normal external phosphorus loading would probably raise the TSI further into the eutrophic classification.

Table 7. *Summary of in-lake dissolved oxygen and phosphorus data, April through November 1988*

[These data were provided by the Wisconsin Department of Natural Resources. ft, feet; mg/L, milligrams per liter; --, indicates value is unknown]

	Main Basin				Northwest basin (Little Balsam Lake)			
Date	Sampling depth (ft)	Dissolved oxygen (mg/L)	Dissolved reactive phosphorus (mg/L)	Total phosphorus (mg/L)	Sampling depth (ft)	Dissolved oxygen (mg/L)	Dissolved reactive phosphorus (mg/L)	Total phosphorus (mg/L)
4-11-88	0	--	--	0.013	--	--	--	--
5-10-88	0	9.6	0.003	.017	--	--	--	--
	33	7.5	.012	.032	--	--	--	--
5-24-88	0	9.5	.004	.013	--	--	--	--
	33	4.8	.010	.044	--	--	--	--
6-06-88	0	8.3	.004	.010	--	--	--	--
	33	0.4	.020	.108	--	--	--	--
6-20-88	0	8.3	.005	.014	0	9.9	0.005	0.016
	33	.6	.019	.087	20	5.5	.004	.063
7-05-88	0	8.2	.008	.018	0	9.8	.007	.024
	33	3.0	.027	.210	20	0	.007	.072
7-18-88	0	8.5	.006	.017	0	8.6	.008	.023
	33	0	.024	.268	20	1.2	.007	.122
8-09-88	0	8.3	.005	.020	0	9.6	.007	.029
	33	.2	.026	.304	20	0	.007	.145
8-23-88	0	6.6	.005	.021	0	5.6	.007	.029
	33	0	.016	.490	20	0.1	.005	.191
9-06-88	0	9.0	.005	.024	0	8.1	.004	.022
	33	5.3	.005	.023	20	6.8	.006	.027
10-03-88	0	7.8	.007	.043	0	7.5	.005	.024
	33	8.0	.009	.042	20	7.3	.005	.030
11-07-88	0	10.4	.008	.020	0	10.4	.004	.020
	33	10.6	.008	.025	20	9.5	.005	.020

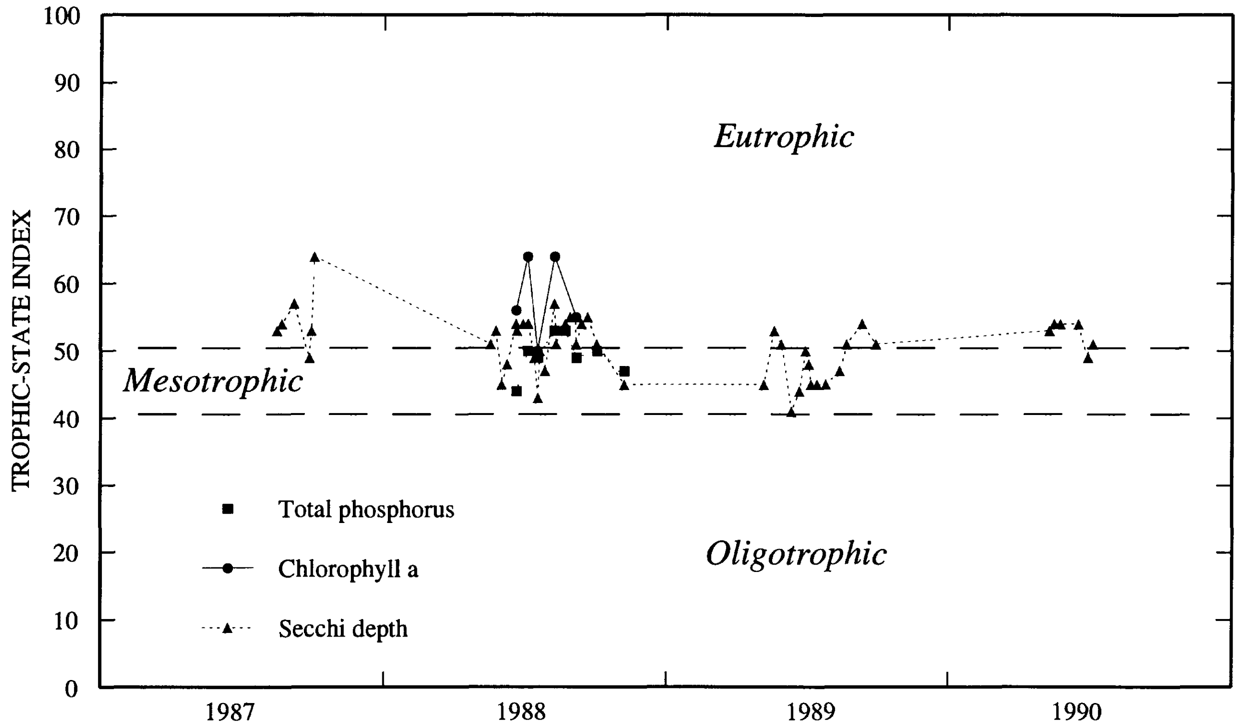


Figure 13. Trophic-state indices for Little Balsam Lake, 1987-90.

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