HYDROLOGY AND WATER QUALITY OF LAUDERDALE LAKES, WALWORTH COUNTY, WISCONSIN, 1993–94

By Herbert S. Garn, Daniel L. Olson, Tracy L. Seidel, and William J. Rose

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To Obtain
inch (in.)	25.4	millimeter
inch (in.)	25,400	micrometer
mile (mi)	1.609	kilometer
pound (lb)	453.6	gram
acre	0.4048	hectare
foot (ft)	0.3048	meter
acre-foot (acre-ft)	1,233	cubic meter
square mile (mi^2)	2.590	square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
pound per square mile (lb/mi^2)	0.175	kilogram per square kilometer
gallon per day (gal/d)	3.785	liter per day
gram per square meter per year ($g/m^2/yr$)	0.0002	pound per square foot per year

Temperature can be converted to degrees Celsius (°C) or degrees Fahrenheit (°F) by use of 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 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Abbreviated 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. Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm).

Hydrology and Water Quality of Lauderdale Lakes, Walworth County, Wisconsin, 1993–94

By Herbert S. Garn, Daniel L. Olson, Tracy L. Seidel, *and* William J. Rose

Abstract

Water and phosphorus budgets were determined for the Lauderdale Lakes (the interconnected Green, Middle, and Mill Lakes) in Walworth County, southeastern Wisconsin to provide background information for a wastewater management plan to limit the input of phosphorus to the lakes. The most significant components of the water and phosphorus budgets were determined independently by intensive data collection from November 1993 through October 1994. In addition to development of the water and phosphorus budgets, in-lake water quality, and trophic state of the lakes were evaluated.

The lakes (treated as one lake with three basins) have a total surface area of 807 acres. The lakes have a surface-water outlet, but have no major surface inlets. Lake level is controlled by a dam and weir at the outlet. Maximum depths of Green, Middle, and Mill Lakes are about 60, 50, and 50 feet, respectively. The total drainage area of the lakes measured from the outlet is 16.1 square miles; only about 2.5 square miles, however, contribute surface runoff directly to the lake. About 70 percent of the 14.7-mile shoreline length is developed. Shoreline development includes 1,010 houses, of which about 30 percent are used year-round.

Ground water and precipitation are the primary water-budget inflow components, and during the study period represented 72 and 24 percent of the total annual inflow, respectively. Surface-water inflow from the small nearshore contributing drainage area accounted for only 4 percent of the inflow budget. Total annual phosphorus input to the lakes was 846 pounds. Although surface water accounted for only 4 percent of the water budget, it represented 51 percent of the total annual phosphorus input. Phosphorus input from septic systems was the second largest source, with a probable annual input of 210 pounds, accounting for 25 percent of the total. Positive ground-water gradients to the lake and phosphorus concentrations in ground water were verified by data from nearshore observation wells. Phosphorus concentrations in ground water exceeded background concentrations of 0.008 milligrams per liter in three out of six observation wells in the inflow area of the lakes. Overall, the phosphorus loading to the lakes is small and lake-water quality is good. The trophic state indices calculated for the lakes ranged from oligotrophic to mesotrophic but were in the mesotrophic class for most of the year. An equation to predict phosphorus concentration at spring turnover from loading estimates was fairly accurate in predicting the measured phosphorus concentration for Lauderdale Lakes.

INTRODUCTION

The Lauderdale Lakes are a chain of three interconnected lakes—Green, Middle, and Mill Lakes—in north-central Walworth County in southeastern Wisconsin (fig. 1). The lakes are about 6.5 mi north of Elkhorn and 9 mi southeast of Whitewater, Wis.

Residents along the shore have expressed concern about water quality of the lakes, including problems with increased macrophyte growth since about 1990. Macrophytes (rooted aquatic plants) grow in high densities that interfere with boating and swimming in the shallower bays of the lakes. About 60 percent of macrophytes are Eurasian watermilfoil (G.T. Petersen, Lauderdale Lakes Lake Management District, oral commun., 1993). Macrophytes have been harvested since 1991 in the areas of heavy growth, primarily in Middle and Mill Lakes. In 1994, an estimated wet weight of 565.6 tons of plant material was removed from the lakes (Douglas Rubnitz, Lauderdale Lakes

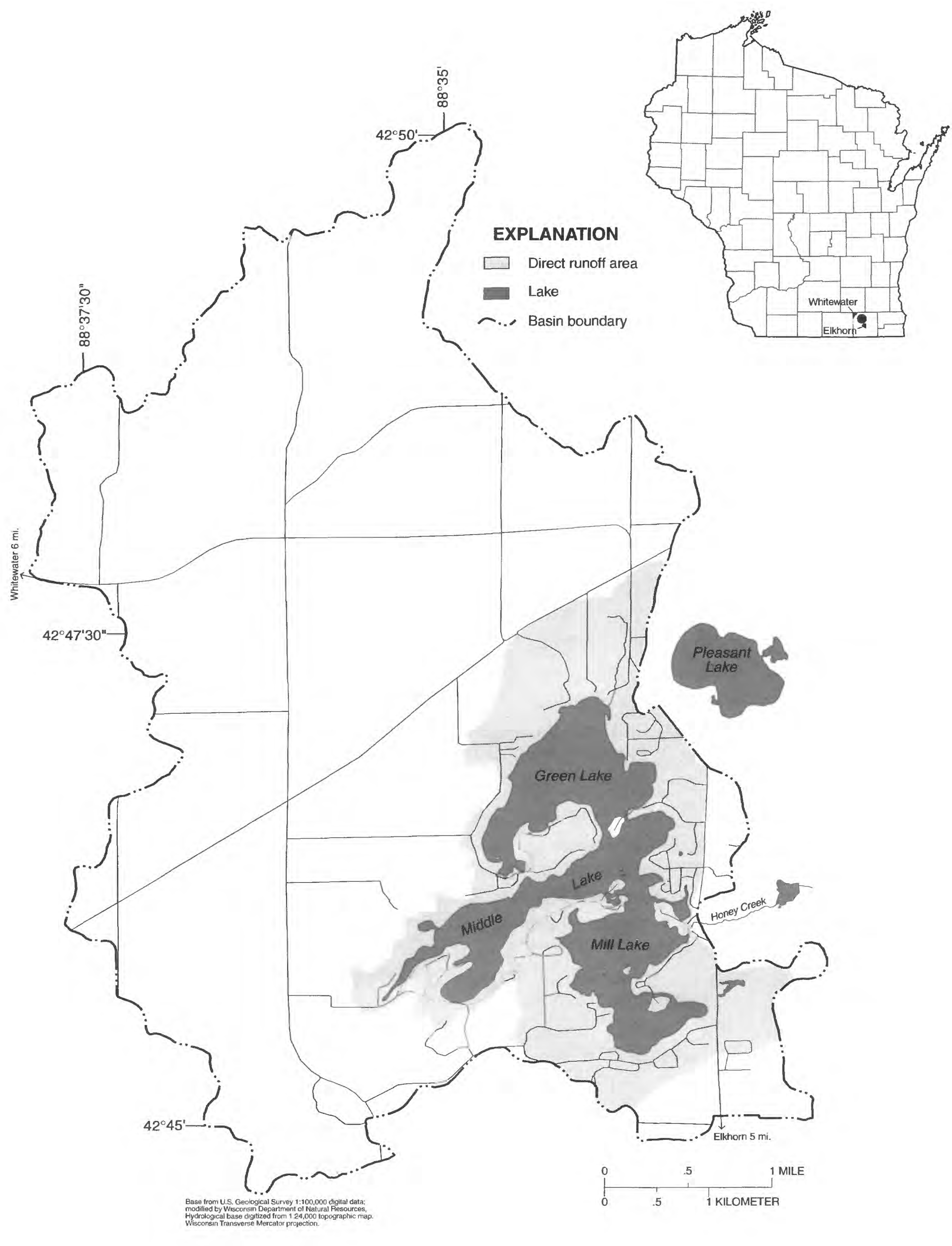

Figure 1. Location of Lauderdale Lakes (Green, Middle, and Mill) drainage basin, Walworth County, Wisconsin, and direct-runoff area.

Lake Management District, written commun., 1995). The Lauderdale Lakes Lake Management District began large-scale harvesting of macrophytes in 1991, which had not been necessary since the 1950's (Southeastern Wisconsin Regional Planning Commission, 1991). The Lake District also began inspections of individual wastewater systems around the lake and was concerned over the number of failing septic systems.

The Lauderdale Lakes Improvement Association has been conducting periodic lake monitoring since the late 1970's. Historical in-lake water-quality data are available for the lakes beginning in 1979, and earlier in-lake data collected by others are available back to 1973 (G.T. Petersen, written commun., 1993). The lake association had contracted with a consultant to collect chemical data during spring turnover every 3 years. This triennial sampling indicated that total phosphorus concentrations in the spring for the three lakes ranged from 10 to 37 µg/L. Concentrations greater than 20 µg/L are commonly considered indicative of eutrophic conditions. Secchi-disc depth measurements ranged from 6.1 to 14.3 ft.

The Lake Management District intends to prepare a wastewater-management plan to limit the input of phosphorus to the lake. Additional information on the hydrology of the lakes and on sources and amounts of phosphorus entering the lakes is needed. Moreover, determination of the trophic state of the lakes is needed for evaluating the effectiveness of the plan. To collect and interpret the necessary information, the U.S. Geological Survey (USGS), in cooperation with the Lauderdale Lakes Lake Management District, studied the lakes during 1993–94. Results of this study may be useful to local and State agencies for developing and assessing lake and watershed management plans and for maintaining or improving lake-water quality.

Purpose and Scope

This report describes the water budget of the lakes, current lake-water quality, major phosphorus loads and a phosphorus budget for the lakes, and the trophic state of the lakes. The report gives water and total phosphorus budgets for Lauderdale Lakes from November 1, 1993, through October 31, 1994, and describes the phosphorus loading in relation to the trophic state of the lakes. Data were collected from October 1993 through October 1994. Specific data collected during the study have been published separately (Holmstrom and others, 1995; Wisconsin District Lake-Studies Team, 1995).

Acknowledgments

The authors thank Gerald T. Petersen and Charles H. Sharpless of the Lauderdale Lakes Lake Management District for their support and assistance during the study. Many thanks also go to local observers Curt Rinda, Robert Skor, Frank Bell, and Joseph Volpe. Curt Rinda recorded daily precipitation and pan evaporation and collected runoff samples; Robert Skor, Frank Bell, and Joe Volpe watched for storms and assisted in collecting runoff samples. Partial funding for this study was provided by the Lake Planning Grant Program of the Wisconsin Department of Natural Resources.

LAKE AND DRAINAGE-BASIN CHARACTERISTICS

The Lauderdale Lakes are ground-water drainage lakes; that is, inflow is primarily from ground water and outflow is by a surface outlet (Shaw and others, 1993). The drainage area of the lakes measured from the outlet is 16.1 mi^2 (Henrich and Daniel, 1983); most of this area, however, does not contribute surface runoff to the lake. Some of the listed drainage areas for these topographically defined watersheds include areas of closed depressions, or noncontributing areas. The area contributing surface runoff to the lakes—called the direct-runoff area in this report—was delineated on a topographic map on the basis of field observations and was digitized to compute area, which (excluding the lakes) is 1,580 acres (fig. 1).

Topography of the basin is generally hilly to rolling, and local relief is 50 to 100 ft. Most of the area is used for agriculture (Southeastern Wisconsin Regional Planning Commission, 1991). Surface materials in the basin are typical of glacier end moraines and glaciated uplands, with pitted outwash and other ice-contact deposits (Borman, 1976; Haszel, 1971). Moderately deep to deep soils are well drained and are underlain by a subsoil of clay loam. Unconsolidated surface deposits are mainly sand and gravel that are extremely well drained but poorly sorted and stratified. The deposits are relatively thick, generally about 100 to 400 ft thick over dolomite bedrock (Mudrey and others, 1982; Borman, 1976). The saturated thickness of the sand and

Table 1. Physical characteristics of Lauderdale Lakes, Walworth County, Wis.

Characteristic	Amount
Lake type: Ground-water drainage lake	
Lake surface area	807 acres[1]
Total drainage basin area	9,500 acres
- Contributing area of direct surface runoff	1,600 acres[2]
Shoreline length	14.7 miles
- Shoreline developed	70 percent
Volume	11,560 acre-feet[3]
Mean depth	14.3 feet
Maximum depth	57 feet

[1]Excludes islands; digitized from 1:24,000-scale topographic map.

[2]See text for explanation.

[3]For water-surface elevation of 884.60 feet above sea level.

gravel materials in the drainage area of the lakes ranges from less than 100 to 300 ft. Hydraulic conductivities for the sand and gravel aquifer range from about 80 to 400 ft/d. The general direction of ground-water flow in the vicinity of Lauderdale Lakes is eastward. Concentrations of dissolved solids and hardness in ground water in the sand and gravel aquifer are very high; median concentrations are about 350 and 330 mg/L, respectively.

The revised total surface area of the lakes is 807 acres (excluding islands): Green Lake, about 298 acres; Middle Lake, 245 acres, including a 120-acre shallow marshy area at the west end; and Mill Lake, 264 acres. The large bay (Don Jean Bay) on the south end of Mill Lake is less than 5 ft deep. A bathymetric map of the lakes surveyed in 1966 listed the lakes' surface area as 834 acres and volume as 12,700 acre-ft (Wisconsin Department of Natural Resources, written commun., 1993). Depth contour lines on this map were digitized and areas and volumes were recalculated. The physical characteristics of the lakes are summarized in table 1. Maximum depths of Green, Middle, and Mill Lakes are about 60, 50, and 50 ft, respectively. About 60 percent of Middle Lake and 47 percent of Mill Lake is equal to or less than 5 ft deep.

The lakes have a surface-water outlet on the southeast side (Honey Creek) but no major inlets. Surface water enters the lakes from the direct runoff area by way of a few ephemeral drainageways or as overland flow. Lake level is controlled by a dam and flow over a weir at the outlet. The lake level, which fluctuates little, is maintained at a minimum elevation of 883.96 ft set by the Wisconsin Department of Natural Resources (Joseph Skidmore, WDNR, written commun., 1994). The original dam was constructed in the mid-1800's for the operation of a sawmill; the present-day dam was constructed in 1962.

The 14.7 mi shoreline is about 70 percent developed, primarily as single-family housing units on small lots (Southeastern Wisconsin Regional Planning Commission, 1991). Shoreline developments include 1,010 houses, of which about 30 percent are year-round residences (1990 census data); the remainder are seasonal homes (G.T. Petersen, oral commun., 1995; Tim McCauley, Southeastern Wisconsin Regional Planning Commission, written commun., 1995). Other developments around the lakes include a golf course, a boat marina, and condominiums on Mill Lake; and a Girl Scout camp, a large Bible camp, a densely developed trailer park, and condominiums on Green Lake. The area is a focus for significant urban development, which is accelerating. In many cases, land some distance from the lake has been subdivided and developed. An aerial photograph of the Lauderdale Lakes area is included at the front of this report.

METHODS OF DATA COLLECTION AND ANALYSIS

The general equation describing the water budget of Lauderdale Lakes can be stated as "Inflow plus precipitation equals outflow plus evaporation plus change in storage," and can be written as follows:

$$\Delta S = P + S_i + G_i - E - S_o - G_o, \quad (1)$$

where

ΔS is change in lake storage,
P is precipitation on the lake,
S_i is surface-water inflow to the lake,
G_i is ground-water inflow to the lake,
E is evaporation from the lake,
S_o is surface-water outflow from the lake, and
G_o is ground-water outflow from the lake.

The significant components of the lake's water budget were measured directly. The greatest emphasis on data collection was directed toward those components that were expected to be the most important in the phosphorus budget.

Data-collection sites used in the study are shown in figure 2. Data collection began in October 1993 and continued through October 1994, with emphasis on the open-water period. Budget components that were not

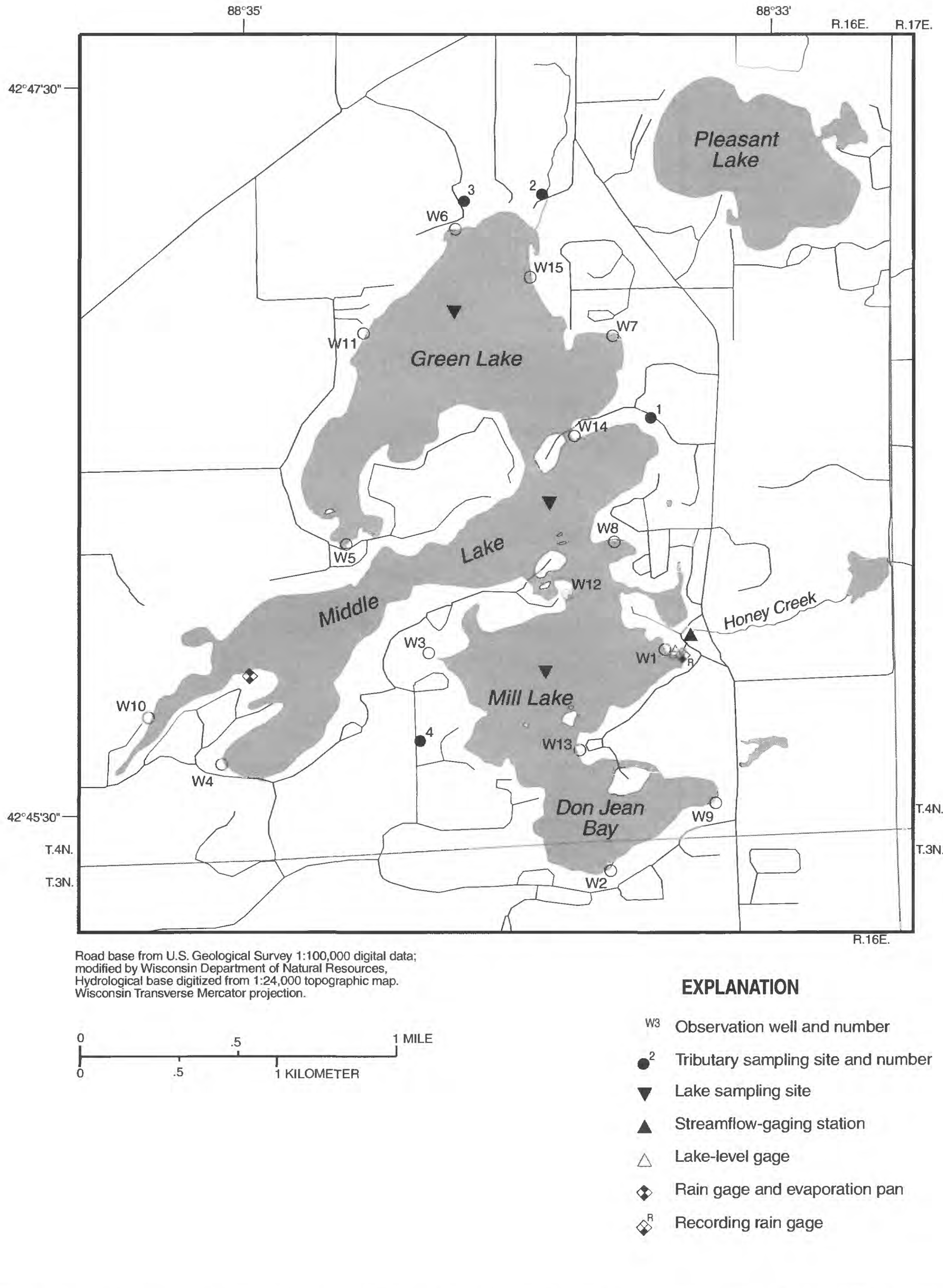

Figure 2. Location of data-collection sites at Lauderdale Lakes, Walworth County, Wisconsin, October 1993–October 1994.

measured directly were estimated from data collected at nearby sites, data from the scientific literature, and reconnaissance data or observations from the study area.

Measurement of Precipitation and Evaporation

Precipitation was measured with rain gages at two sites from June through October 1994 (fig. 2). One of the gages, an 8-in.-diameter recording rain gage, at the lake-level gage near the outlet, recorded rainfall at 15-minute intervals. The other, a nonrecording gage on the west end of Middle Lake, was read daily by a local observer. An average of the two gages was used. Precipitation records from the National Weather Service stations at Whitewater and Eagle (National Oceanic and Atmospheric Administration, 1994) were used for the remainder of the year when these gages were not operating.

Lake-evaporation estimates were based on evaporation from a Class A evaporation pan at the nonrecording rain gage on the west side of Middle Lake and from pan evaporation data at the National Weather Service station at Arlington University Farm. A local observer recorded pan readings daily from June through October 1994. A pan coefficient of 0.77 was used to convert pan evaporation to lake evaporation (Farnsworth and others, 1982).

Measurement of Lake Stage and Contents

The water level of Lauderdale Lakes was recorded at 15-minute intervals at a gage in the bay near the dam. The datum at 0.00 ft gage height of the gage is at an elevation of 879.57 ft above mean sea level. Lake-storage volume and a lake-stage/lake-volume relation were derived by digitizing the bathymetric map of the lake basin. Changes in lake storage were computed by use of lake stage measurements from the recording gage.

Measurement of Streamflow and Estimation of Runoff

Although no major streams flow into the lakes, direct runoff can flow into the lakes during snowmelt and heavy rainfall. Runoff from small ephemeral streams enters Green Lake on the north side (site 2, drainage area of 79 acres; site 3, drainage area of 91 acres), Middle Lake on the east side (site 1, drainage area of 35 acres), and Mill Lake (site 4, drainage area of 11 acres); drainageways in the remaining areas are absent or poorly defined. A constructed drain in a large swale area (about 80 acres) on the south side of Don Jean Bay that was not monitored directs surface runoff from lawns and streets directly into the lake (fig. 3). Runoff was monitored at four sites tributary to the lakes (fig. 2) by observers who recorded flow depths and velocities and by multistage point samplers (J.D. Dewey, U.S. Geological Survey, written commun., 1978). Estimates of surface runoff were estimated on the basis of observations of magnitude and duration of runoff at these sites and comparison with data from nearby USGS recording streamflow gages. Hydrograph separation into base flow and direct runoff components (Chow, 1964, p. 14–11) was applied to the discharge records (Holmstrom and others, 1995) from the USGS gaging stations on Jackson Creek near Elkhorn (05431014) and Jackson Creek Tributary near Elkhorn (054310157).

Surface water leaves the lake through the weir at Lauderdale into Honey Creek. Surface-water outflow from Lauderdale Lakes was monitored by a continuous-recording gage on Honey Creek immediately downstream from the dam. Streamflow data were collected and were processed according to procedures described by Rantz and others (1982).

Estimation of Ground-Water Flow

Fifteen shallow, 1/2-in.-small-diameter piezometers (observation wells) were installed along the shoreline of Lauderdale Lakes (fig. 2) to determine vertical hydraulic gradients and to collect samples of ground water for the determination of dissolved phosphorus concentrations. Piezometers were installed within 14 ft of the water's edge—on the average, 4 ft from the water's edge. Water levels in the piezometers were measured monthly.

Ground-water inflow and outflow were estimated by use of the Darcy equation according to a method used by Rose (1993) in a similar study of Balsam Lake in northwestern Wisconsin, and by Goddard and Field (1994) in a study of Whitewater and Rice

Figure 3. Constructed drain that carries surface runoff into Don Jean Bay of Mill Lake.

Lakes in southeastern Wisconsin. A detailed description of the method is given by Rose (1993).

Several simplifying assumptions about ground-water flow and its relation to the lakes were necessary because the scope of the study did not allow for more vigorous analysis. Ground-water exchange with the lake was assumed to be at a steady state; that is, the rate and direction of flow through the lake bottom at any location did not vary with time. This assumption was justified because the hydraulic gradient was determined for 5 to 12 dates at the piezometer sites and the gradients did not vary significantly with time.

The method that was used to calculate ground-water flow requires a value for the hydraulic conductivity ratio (k_i/k_o), where k_i is the vertical hydraulic conductivity of inflow areas and k_o is the vertical hydraulic conductivity of outflow areas. A ratio of 5 was used for this study. The rationale for using different values for inflow and outflow areas is explained in Rose (1993).

Sampling of Lake Water, Streamwater, and Ground Water for Determination of Water Quality

Physical and chemical sampling of Lauderdale Lakes was done once each month in November 1993 and April, October, and November 1994 and twice each month in May through September 1994. Three sites were sampled (fig. 2) at the deepest part of each lake: Green Lake has a depth of 57 ft; Middle Lake, a depth of 52 ft; and Mill Lake, a depth of 52 ft. All water samples were analyzed by the Wisconsin State Laboratory of Hygiene using standard analytical methods (Wisconsin State Laboratory of Hygiene, 1993).

Depth profiles of water temperature, specific conductance, pH, and dissolved oxygen were determined at all lake sites by use of a multiparameter water-quality meter. The meter was calibrated to known standards before lake monitoring began. The dissolved-oxygen function of the meter was calibrated by use of the air-calibration method and was checked on the lake by the Winkler method. Depth-profile readings were made at 3-ft intervals.

Discrete water samples were collected 1.5 ft below the lake surface by use of a Kemmerer-type water sampler and at 1.5 ft above the lake bottom by use of a horizontal (alpha) Van Dorn-type sampler. Two additional samples were collected at depths based on thermal stratification—one near the bottom of the epilimnion (the upper warmer, mixed layer) and the other near the middle of the hypolimnion (the lower, cooler layer of the lake). Samples collected for dissolved constituents were filtered in the field with a filtering unit equipped with a 0.45-µm-pore-size filter. Samples for determination of chlorophyll *a* concentration were collected from the top 1.5 ft of the lakes at each site by use of a Kemmerer-type sampler and filtered through a 5.0-µm-pore-size filter.

Water outflow from Lauderdale Lakes was sampled for determination of total phosphorus concentration. Flow-integrated samples were collected manually by use of the equal-width-increment (EWI) method (Edwards and Glysson, 1988). Water samples were collected approximately monthly at the lakes' outlet to determine the amount of phosphorus leaving the lakes in surface outflow. Total phosphorus discharge in the outflow was calculated by use of the streamflow and concentration integrating technique described by Porterfield (1972).

Water samples for determination of total phosphorus were collected by local observers and USGS personnel at the mouths of four ephemeral streams entering the lakes. Surface runoff to Lauderdale Lakes was sampled for total phosphorus concentration during storm and snowmelt runoff. Two sites tributary to Green Lake, one site tributary to Middle Lake, and one site tributary to Mill Lake were monitored (fig. 2). Samples at these sites were obtained by observers taking "grab" (bottle-dipped) samples and by the use of multistage point samplers.

Water samples for determination of dissolved phosphorus concentration were collected approximately monthly from the observation wells by use of a peristaltic pump. Samples were filtered in the field with a filtering unit equipped with a 0.45-µm-pore-size filter.

HYDROLOGY

Precipitation and Evaporation

The total precipitation for the study year was 25.65 in. (fig. 4), about 83 percent of the long-term (1961–90) average annual precipitation based on the record at Whitewater. The long-term average annual precipitation at Whitewater is 32.44 in. (Pamela Naber-Knox, Wisconsin State Climatologist, University of Wisconsin-Extension, written commun., 1995). Evaporation for the study period was 26.23 in.

Lake Storage

Water-level fluctuations for Lauderdale Lakes are shown in figure 4. Stage is referenced to the datum of the gage (879.57 ft above sea level). During November 1993 through October 1994, stage fluctuated 0.63 ft, from a low of 4.79 ft on January 21, 1994 to a high of 5.42 ft on December 6 and 10, 1993. The corresponding lake storage fluctuated 494 acre-ft, from 11,390 to 11,880 acre-ft.

Streamflow and Runoff

Because no perennial streams flow into Lauderdale Lakes, ephemeral surface runoff from the nearshore contributing drainage area and drainageways was estimated for November 1993 through October 1994 by a runoff and drainage-area comparison with Jackson Creek and Jackson Creek Tributary near Elkhorn (Holmstrom and others, 1995). These creeks, whose drainage areas are 8.96 and 4.34 mi^2, respectively, have a base-flow component, and their hydrographs were separated to determine the direct-runoff component. Runoff periods so identified compared well with precipitation periods measured at Lauderdale Lakes.

Two methods were used to estimate runoff to the lakes from results of the hydrograph separation. In the first method, the unit-area direct runoff from the hydrograph separation of the comparison drainages was applied to the nearshore contributing area, resulting in an estimated 370 acre-ft of runoff. In the second method, results from the hydrograph separation were combined with observations and estimates of peak flows at the four monitored ephemeral drainages. On

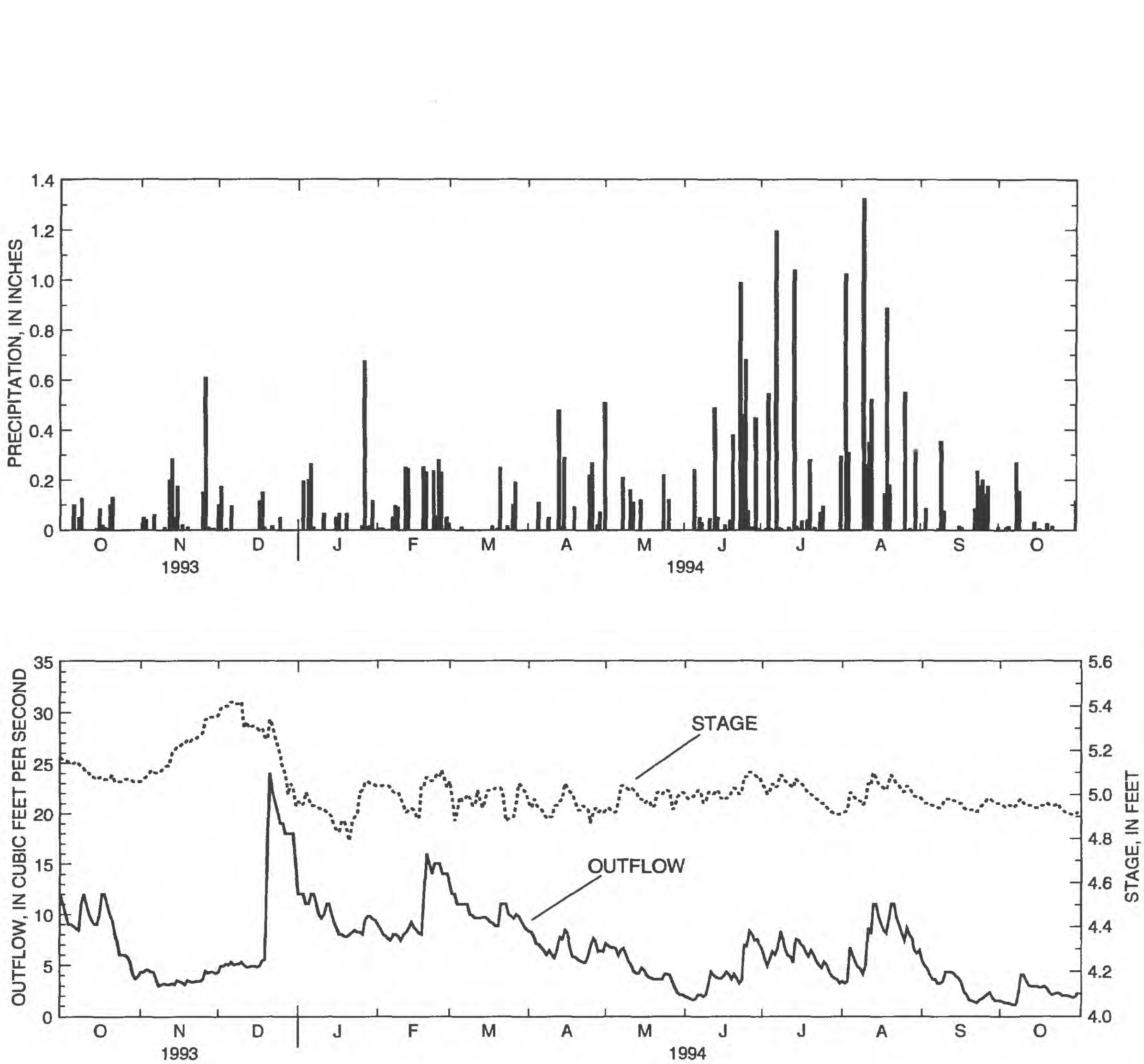

Figure 4. Daily precipitation, outflow from, and stage for Lauderdale Lakes, Walworth County, Wis., October 1993–October 1994.

the basis of the runoff at Jackson Creek, a major event on February 18–20, 1994, represented as much as 70 percent of the annual direct runoff. Rainfall and snowmelt depleted the entire snowpack of about 2.1 in. of water equivalent in 2 days and resulted in heavy runoff over frozen soils. Estimates of peak flow from this event and the duration of flow at the monitored drainages were made in the field, and volumes were calculated by assuming a simple triangle hydrograph. Total runoff volume for this February event was then adjusted to an annual volume of 310 acre-ft. This value was thought to be more representative than that resulting from the first estimating method and was used in subsequent analysis.

Surface-water inflow was the smallest component in the water budget for Lauderdale Lakes. The runoff observed in February on frozen ground is probably typical for this area and represents most of the annual surface-water inflow. Little runoff was observed during the summer in response to rainfall. Rainfall would have to exceed an estimated 3 to 4 in/hr (the infiltration capacity of the soils) before surface runoff would begin on unfrozen ground.

Streamflow from the outlet of Lauderdale Lakes is shown in figure 4. Mean daily outflow ranged from 1.1 ft^3/s on October 6–7, 1994 to 24.0 ft^3/s on December 21, 1993. Total outflow from the lake for the study period was 4,700 acre-ft.

Ground-Water Flow

Knowledge of the direction of ground-water flow is essential for determining those areas where contaminant transport to the lakes by ground water is possible. Any contamination from ground-water sources normally occurs where the ground-water gradients are positive, or into the lake. A water-table map prepared by Borman (1976) shows that regional ground-water movement is from west to east. Data from the near-shore observation wells installed for this study support Borman's findings. Water levels were higher than the lake surface in wells on the west side of the lakes, indicating positive gradients and flow into the lakes in these regions (fig. 5). Along the eastern shores of the lakes, water levels in the wells were generally lower than the lake surface, indicating negative gradients or outflow from the lakes in these regions. Wells W6 and W9 were in transition regions where flow directions changed during the year. Ground-water flow was always toward the lake along 54 percent of the lakes' shoreline, flow was always away from the lakes along 39 percent of their shoreline, and 7 percent of shorelines were in the transitional regions where flow direction reversed during the year.

Total ground-water inflow was about six times greater than ground-water outflow during the study period. Annual inflow to the lakes was estimated to be 5,160 acre-feet; outflow was estimated to be 850 acre-feet. Water levels in well WK-31 (Holmstrom and others, 1995), a well in Niagara Dolomite in Waukesha County, 23 mi northeast of Lauderdale Lakes, were slightly above the long-term average in November 1993, but were below average from May to December 1994. The record for this monitoring well began in 1947. Ground-water discharge to lakes is generally correlated with ground-water levels; thus, the computed inflow is probably near or slightly below the long-term average based on the water-level record at well WK-31.

Annual Water Budget

The annual water budget for the year of study (November 1993–October 1994) is shown in table 2 and figure 6. Ground water was the dominant inflow component, accounting for 72 percent of the total inflow; precipitation accounted for 24 percent. Surface-water inflow accounted for only about 4 percent of the total.

Table 2. Annual water budget for Lauderdale Lakes, Walworth County, Wisconsin, November 1993–October 1994

Budget item	Flow volume (acre-feet)	Percentage of total inflow or outflow
Inflow:		
Precipitation	1,725	24
Surface inflow	310	4
Ground water	5,160	72
Total inflow	7,195	100
Outflow:		
Evaporation	1,764	24
Surface outflow	4,700	64
Ground water	850	12
Total outflow	7,314	100
Change in lake storage	-115	
Budget residual	-4	

Surface-water outflow from the lakes into Honey Creek, the dominant outflow component in the budget, accounted for 64 percent of the total outflow volume. Evaporation, the next largest component, accounted for 24 percent of the total outflow.

The hydraulic residence time of the lakes (the average length of time water remains in the lake or the time required to replace the volume of the lake, calculated by dividing the lake volume by the volume of water passing through the lake) was about 1.6 years. Knowledge of the hydraulic residence time is important for determining the response time of the lake to changes in nutrient loading (Garn and Parrott, 1977) and is used in various lake loading models such as that by Vollenweider (1975). Flushing rate, another commonly-used term (the average number of times per year that the lake volume is replaced), is the inverse of residence time.

As mentioned previously, precipitation during the study period was about 83 percent of the normal annual precipitation. Runoff in the region also was below normal during the study year (Holmstrom and others, 1995). At the Mukwonago River at Mukwonago, northeast of the study area, streamflow for the year was 90 percent of the long-term (1973–94) average. Runoff for the year at Jackson Creek Tributary near Elkhorn was 61 percent of the 1984–94 average.

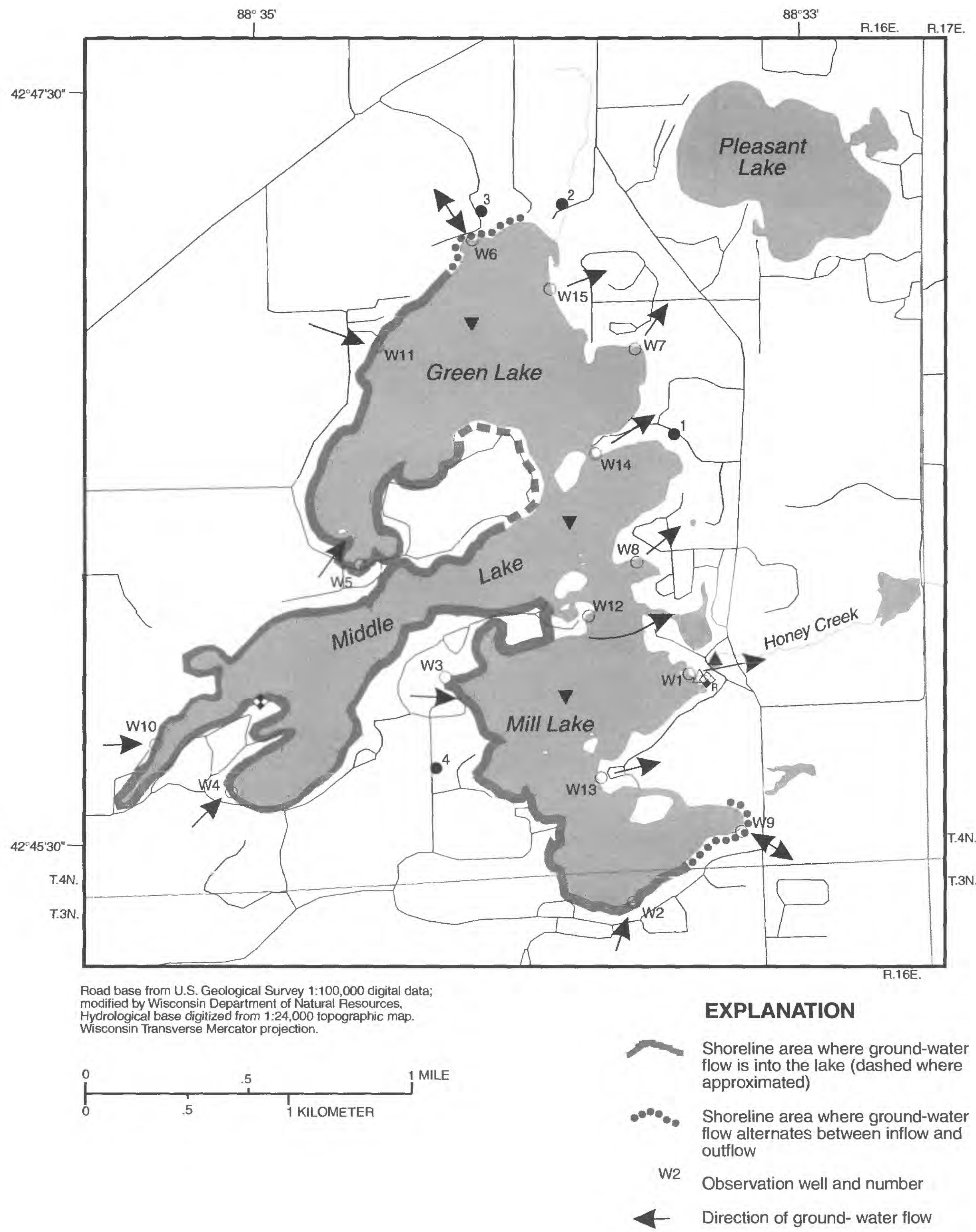

Figure 5. Location of observation wells and direction of ground-water flow at Lauderdale Lakes, Walworth County, Wisconsin.

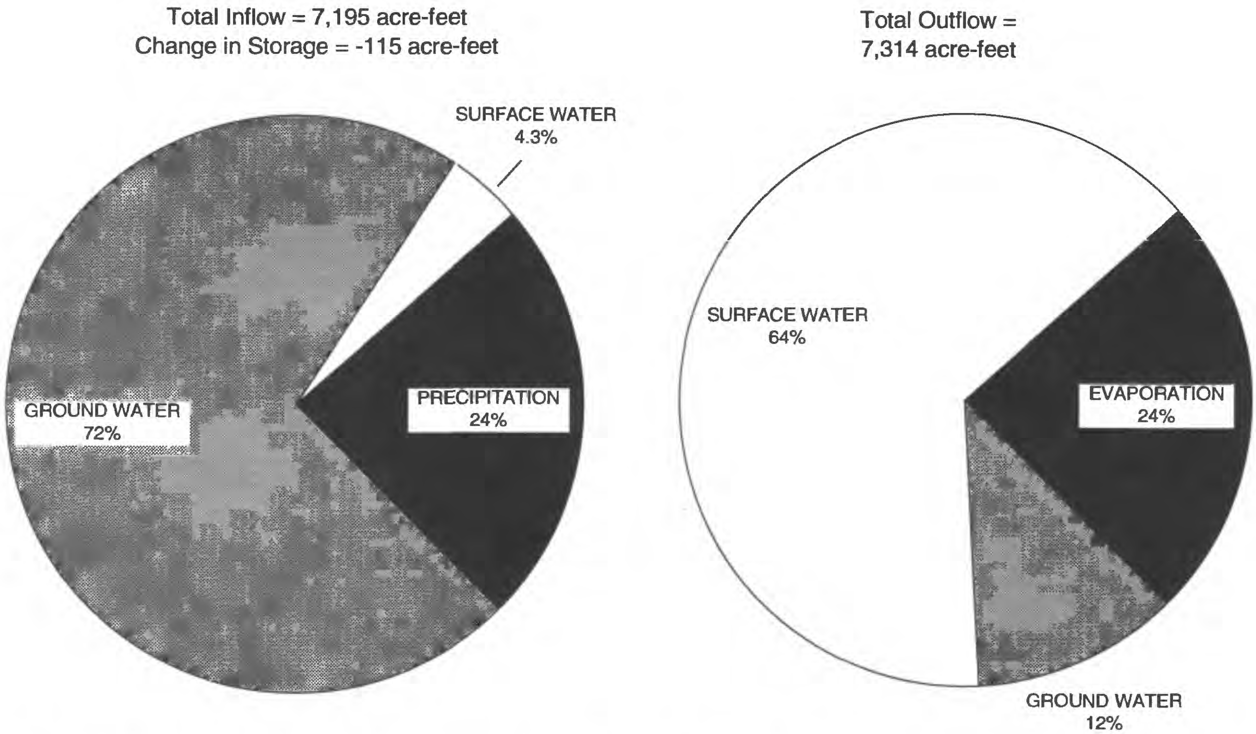

Figure 6. Annual inflows and outflows for Lauderdale Lakes, Walworth County, Wis., November 1, 1993, through October 31, 1994.

WATER QUALITY

Physical and Chemical Characteristics

Water-quality data were collected at the three Lauderdale Lakes 15 times during open-water periods between November 1, 1993 and November 30, 1994. For each sample date and lake, the data consist of water samples for total phosphorus at various depths and a surface chlorophyll *a* sample, Secchi-disc depth reading, lake-stage reading, and a depth profile of the water temperature, pH, specific conductance, and dissolved oxygen. Concentrations of major cations and anions were determined for samples collected on 3 of the 15 dates, during spring and fall turnover when the lakes were mixed. The data, including temperature and dissolved oxygen profiles, were published in the U.S. Geological Survey's annual data reports (Holmstrom and others, 1995; Wisconsin District Lake-Studies Team, 1995).

Water Temperature

Of all the sampling dates, complete water-column mixing in all three lakes was observed only on November 10, 1993, and in Middle and Mill Lakes on November 2, 1994. Almost complete mixing was observed in Green and Middle Lakes on April 18, 1994. Lauderdale Lakes are thermally stratified during the summer. In July, the epilimnion in Green, Middle, and Mill Lakes extended to a depth of about 20, 15, and 15 ft, respectively. The metalimnion in the three lakes extended to 36, 34, and 33 ft, respectively. The metalimnion is the layer of water that includes the thermocline, the zone where the greatest temperature gradient occurs, usually greater than 1°C per meter of depth (Wetzel, 1983, p. 75). The thermocline develops in the spring and reaches its maximum gradient in late summer. The hypolimnion extends from the bottom of the metalimnion to the lake bottom.

Dissolved Oxygen

In Lauderdale Lakes, dissolved oxygen concentrations at most depths and times are sufficient to support all aquatic life. At various times during the summer and at various depths in the hypolimnion, however, dissolved oxygen concentrations become insufficient for most aquatic life.

When the thermocline develops in early summer and prevents the mixing of surface and bottom water, the supply of dissolved oxygen to the hypolimnion may be cut off. The oxygen demand of decaying organic matter on the lake bottom depletes the dissolved oxygen in water near the bottom. This oxygen depletion (anoxia) begins at the lake bottom and progresses upward. The period of stratification for Green and Middle Lakes began in late May 1994, and for Mill Lake began about mid-April 1994. The stratification period ended with mixing in all three lakes about mid-October 1994. During the late summer, the hypolimnion in all three lakes became anoxic and unable to support aquatic life. The hypolimnion in Middle and Mill Lakes became anoxic on July 5, and it became anoxic in Green Lake on July 22. The anoxic zone reached a maximum of 27 feet in Green Lake on September 15, a maximum of 24 feet in Middle Lake on August 31, and 30 feet in Mill Lake on August 2 and 31.

Hypolimnetic anoxia is common in thermally-stratified eutrophic lakes. One of the concerns associated with anoxia is that phosphorus may be released internally from bottom sediments (if phosphorus concentration in the sediments is sufficiently high) during periods of anoxia and that this internal loading may represent a significant proportion of the total phosphorus load. If phosphorus concentration of the near-lake-bottom water samples is much greater than that of surface samples and increases during the summer, internal phosphorus loading is the probable cause.

Hardness

Average hardness on turnover dates for each of the three lakes, in milligrams per liter as $CaCO_3$, are given below:

Lake	11-10-93	4-18-94	11-02-94
Green	225	240	245
Middle	260	280	260
Mill	250	275	240

The overall average hardness for Lauderdale Lakes was 253 mg/L as $CaCO_3$. Water whose hardness exceeds 180 mg/L as $CaCO_3$ is described as very hard (Hem, 1985, p. 159). Hardness is caused primarily by the presence of calcium and magnesium. Calcium concentrations ranged from 38 to 42 mg/L in Green Lake, 44 to 55 mg/L in Middle Lake, and 37 to 50 mg/L in Mill Lake; magnesium concentrations ranged from 32 to 34 mg/L in Green Lake, 34 to 36 mg/L in Middle Lake, and 32 to 36 mg/L in Mill Lake. Sulfate concentrations were fairly constant for the three sampling times, averaging 30, 33, and 31 mg/L as SO_4, respectively, for each of the lakes. Chloride concentrations also were fairly consistent, averaging 19, 19, and 20 mg/L for each lake, respectively.

Hardness and concentrations of calcium and magnesium were greatest at Middle Lake because of significant discharge of ground water concentrated in several springs in the northwest shallow arm of the lake. Calcium and magnesium concentrations measured in the shallow arm were as high as 74 and 37 mg/L; hardness was 330 mg/L as $CaCO_3$, and specific conductance was about 680 µS/cm. These measurements are fairly close to those for inflowing ground water, whose specific conductance was 740 µS/cm and calcium and magnesium concentrations were 87 and 38 mg/L. Historically, residents have complained about the development of a grayish or milky coloration in the bay, usually in spring (Peter Donoghue, Lauderdale Lakes Lake Management District, oral commun., 1994; and Albert Marth, resident, oral commun., 1995), a phenomenon that was also observed in late May 1994 during this study. This recurring "whitening" of the bay is probably caused by the precipitation of calcite ($CaCO_3$) or "marl" when the photosynthesis of intensively growing macrophytes in the bay upsets the chemical equilibrium of dissolved $CaCO_3$ and CO_2 in the water (Wetzel, 1983, p. 205–206). The photosynthetic use of CO_2 by submersed aquatic plants and the resulting increase in pH is a common mechanism that induces the precipitation of $CaCO_3$ in hardwater, calcareous lakes. Artificially raising the pH in a bay-water sample by titration techniques resulted in precipitation and milky turbidity at pH of 9.5 to 10. In an intensive study at the inlet of Delavan Lake at Delavan, 10 mi south of Lauderdale Lakes, from April through September 1994, pH values in the shallow, heavily vegetated inlet to the lake commonly exceeded 9.5 in May and June and at times exceeded 10 (Holmstrom and others, 1995). The concentration of calcium and precipitation of calcite may be important in limiting the solubility of phosphate (Wetzel, 1983) and thus influencing plankton productivity. The availability of phosphorus may also be decreased by its co-precipitation with calcite.

Phosphorus

Historical phosphorus data provided by the Improvement Association for Lauderdale Lakes (G.T. Petersen, written commun., 1993) are shown in figure 7. Monitoring in the past was usually done triennially, during spring turnover. Monthly total phosphorus concentrations at the lake surface for Lauderdale Lakes, in micrograms per liter, for November 1993 through October 1994 were the following:

Month	Green Lake	Middle Lake	Mill Lake
November	12	10	11
April	5	6	9
May	8	14	10
June	9	10	13
July	8	10	14
August	7	9	13
September	10	10	14
October	14	8	11
Average	9	10	12

Total phosphorus concentrations at the lake surface were lowest in the spring and highest in the summer and fall.

Monthly concentrations of total phosphorus, in micrograms per liter, 1.5 ft above the lake bottom in Lauderdale Lakes for November 1993 through October 1994, were the following:

Month	Green Lake	Middle Lake	Mill Lake
November	13	9	10
April	8	8	46
May	16	22	66
June	25	40	80
July	40	46	108
August	53	46	44
September	42	35	38
October	([1])	87	53
Average	28	37	56

[1]Not available

Concentrations near the bottom were lowest in the spring and highest in the summer and fall. Mill Lake is the most nutrient-enriched of the three lakes. These relatively low concentrations, however, indicate that only minor amounts of phosphorus are being released from the sediments during anoxia in the summer.

The following nitrogen:phosphorus ratios were computed from concentrations in the surface samples for the three turnover dates:

Lake	11-10-93	4-18-94	11-02-94
Green	76:1	196:1	61:1
Middle	133:1	333:1	116:1
Mill	93:1	136:1	80:1

The average ratios for Green, Middle, and Mill Lakes were 111:1, 194:1, and 103:1; respectively. The data indicate that the lake is phosphorus limited. In general, a nitrogen:phosphorus ratio greater than 15:1 indicates that phosphorus is the nutrient limiting plant growth (Lillie and Mason, 1983, p. 63).

Chlorophyll *a*

Chlorophyll *a* is a green photosynthetic pigment in plant cells, including algae. Its concentration in water is commonly used as an indicator of algal biomass in lakes. Few historical data are available for chlorophyll *a* in Lauderdale Lakes. The Southeastern Wisconsin Regional Planning Commission (1991, p. 36) reported results from two studies done in 1972 and 1979. Chlorophyll *a* in Middle Lake samples collected during June, August and November 1972 ranged from 4.1 to 5.2 µg/L. Chlorophyll *a* concentrations in August 1979 were 2.8 µg/L in Green Lake, 3.2 µg/L in Middle Lake, and 3.8 µg/L in Mill Lake.

During this study, chlorophyll *a* concentration in Green Lake ranged from 0.8 to 6.9 µg/L; in Middle Lake, concentration ranged from 1.1 µg/L to 6.2 µg/L; and in Mill Lake, concentration ranged from 1.2 to 8.0 µg/L. Following are monthly chlorophyll *a* concentrations, in micrograms per liter, in Green, Middle, and Mill Lakes during the study period:

Month	Green Lake	Middle Lake	Mill Lake
November	5.6	2.0	1.9
April	0.8	2.3	4.6
May	1.4	1.4	1.8
June	5.1	4.7	4.5
July	3.4	3.6	6.7
August	2.7	3.3	7.8
September	2.2	3.4	5.1
October	6.0	3.0	5.3
Average	3.4	3.0	4.7

The average concentrations are low compared to those in other southeastern Wisconsin lakes.

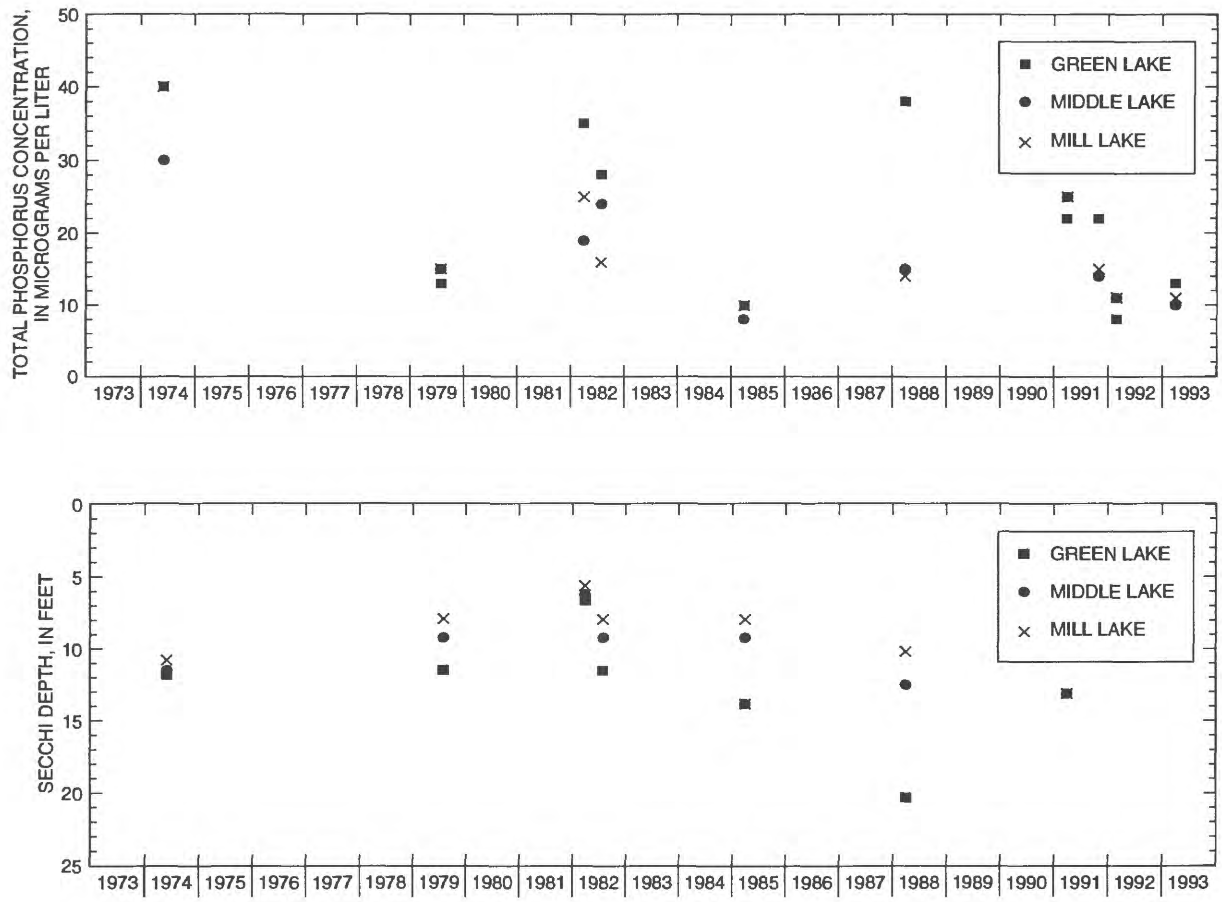

Figure 7. Historical total phosphorus concentrations at lake surface and Secchi depths for Lauderdale Lakes, Walworth County, Wis., 1973–93 (1974 value is a 3-year average for 1973–75; see text).

Water Clarity

The depth of photosynthetic activity in a lake depends on the depth of light penetration, which is influenced largely by water clarity, or transparency of the water. The Secchi disc is commonly used to measure water clarity. This device is usually an 8-in.-diameter disc with black and white alternating quadrants. The Secchi depth is the average of the depth at which the disc is no longer visible from the water surface as it is being lowered into the water and the depth at which the disc becomes visible when raised again. This measurement is made on the shady side of the boat. Factors that affect water clarity include water color, algae populations, and suspended sediment. Algae concentration is usually the dominant factor affecting clarity in most lakes; therefore, Secchi depth is commonly inversely related to chlorophyll *a*. Generally, Secchi depths are greatest in the spring, fall, and winter, and least in the summer when algae populations are the greatest. Average monthly Secchi depths for November 1993 through October 1994, in ft, for Green, Middle, and Mill Lakes were the following:

Month	Green Lake	Middle Lake	Mill Lake
November	11.8	14.4	13.1
April	17.7	11.2	8.5
May	19.7	17.1	13.1
June	8.5	7.5	6.9
July	9.2	7.2	6.2
August	11.5	8.9	6.2
September	13.8	10.5	7.2
October	13.1	14.8	11.8
Average	13.2	11.4	9.1

During the study period, Secchi depth generally was greatest in Green Lake, the largest and deepest lake, and least in Mill Lake, the smallest and shallowest lake.

Historical data for Secchi depth from 1973 to 1991, provided by the Lauderdale Lakes Improvement Association, are shown in figure 7. These data also show an increasing Secchi depth from Mill Lake to Middle Lake to Green Lake. Most of the measurements were made in April, the time of year when Secchi depth is usually greatest. Measurements in 1979 and also 1982 were made in August, and the depth shown for 1974 is a 3-year average (1973–75). In comparing the April and May 1994 depths with the historical data, the 1994 Secchi depths are greater than most of the historical depths, and it appears that water clarity may have improved slightly since the 1970's, as was also indicated by the historical total phosphorus data.

Phosphorus Budget

A lake's phosphorus budget includes an evaluation of the following terms, which may be expressed in pounds per year: Inflow loading = Outflow loading + Net Sedimentation + Change in storage (Moore and Thornton, 1988). The equation for the total phosphorus budget is similar to that for the water budget (eq. 1), which may be rewritten as

$$P+S_i+G_i = S_o+G_o+\Delta S, \qquad (2)$$

each of the components having a quantity of phosphorus associated with it. The amount of phosphorus leaving by evaporation is assumed to be zero and is omitted from the equation. Net sedimentation is the result of all physical, chemical, and biological processes causing transfer of phosphorus between the lake water and bottom sediments. Generally, it is not feasible to measure net sedimentation directly, so it was estimated in this study by a mass-balance approach. Independent determination of the change in phosphorus stored in lake water and sediment and of the amount leaving by ground-water outflow was beyond the scope of this study. The inflow components of the budget were of particular interest for evaluating the relative sources of phosphorus contributing to the total loading of the lakes. Because of the limitations of evaluating some of the outflow components (in particular, ground-water outflow), all outflow loadings were not computed.

Budget Components

Phosphorus inputs from precipitation were estimated from amounts of precipitation measured at the Lauderdale Lakes rain gages and National Weather Service Whitewater station and from average phosphorus concentration in precipitation measured at Delavan. Field and Duerk (1988), in their study of nearby Delavan Lake, reported a volume-weighted average concentration of 0.02 mg/L total phosphorus in precipitation. The total phosphorus loading to Lauderdale Lakes from precipitation was estimated to be 94 lb for the study year.

Samples of runoff for analysis of total phosphorus concentrations were collected near the mouths of four ephemeral drainages flowing into the lakes (fig. 2). Grab samples were obtained by observers during storms in February, March, April, and July. No runoff during spring and summer was of sufficient magnitude to trigger sample collection by the multistage point samplers installed in these drainages. Two samples were obtained at site 1, two at site 2, and three at site 4; none were obtained from site 3 because of the lack of runoff in this tributary. Total phosphorus concentrations in runoff samples ranged from 0.113 to 0.84 mg/L; the highest concentrations were found early in the year (Holmstrom and others, 1995). The greatest concentration was measured at site 2; the drainage area contributing to this site has a high proportion of agricultural land and also produces the greatest amount of runoff.

Total phosphorus load from the direct-runoff area was estimated by using a mean concentration of 0.53 mg/L for the runoff in February and March and a mean concentration of 0.30 mg/L for runoff later in the spring and in summer. According to the runoff estimates, more than 90 percent of the annual phosphorus load was transported in February and March. The total annual estimated phosphorus loads from the identified tributary drainage areas were the following:

Site and acreage:	*Pounds of phosphorus per year*
Site 1 (35 acres)	12.2
Site 2 (79 acres)	38.3
Site 3 (91 acres)	16.6
Site 4 (11 acres)	4.8
Swale, Don Jean Bay (80 acres, not monitored)	37.8

The greatest loads were produced by the contributing drainage areas at site 2 and the swale on Don Jean Bay.

Total annual phosphorus load from the direct-runoff area to the lakes (including the tributaries and shoreline drainage) was estimated to be 430 lb, which is equivalent to a yield of 175 lb/mi^2. This yield is somewhat lower than the phosphorus-export coefficients recommended by Panuska and Lillie (1995), possibly because of the mixture of land uses and soils that yield less runoff.

Observation wells installed around the lakeshore were sampled to determine the concentrations of dissolved phosphorus in ground water entering and leaving the lake (table 3). An average background concentration of 0.008 mg/L was used to estimate the background phosphorus load from ground-water inflow for the area where gradients were into the lake (fig. 5). The annual total phosphorus load contributed by ground water (for this background concentration) was estimated to be 112 lb. Phosphorus concentrations in water from some of the observation wells greatly exceeded the background level and were probably affected by septic tank effluent and other sources; therefore, loading estimates were made separately for that from "background" ground water and that from septic systems. The number of observation wells and their spacing were not sufficiently detailed for the purpose of directly calculating the combined load from unaffected ground water and septic systems by use of all of the concentration data.

Lakeshore septic systems may be a significant source of phosphorus loading to lakes. Phosphorus loading from nearshore septic systems was estimated separately by applying per capita export coefficients from households to onsite septic systems and from septic systems to the lake. Positive ground-water gradients to the lake and phosphorus concentration in ground water were verified by data from the nearshore observation wells. The latest population and occupancy information; site-specific soil, topography, and environmental information; and septic-system characteristics were evaluated and used to estimate the quantity of phosphorus from near-lake systems that entered the lakes.

The total annual mass of phosphorus entering the lake was estimated as the sum of contributions from all the systems by use of procedures outlined in Garn and Parrott (1977) and Reckhow and others (1980). The following general expression (after Reckhow and others, 1980) was used in the calculations:

$$M = E_s \text{ (\#capita-years) } (1\text{-}SR), \qquad (3)$$

where

M is the annual mass (load) of phosphorus entering the lake from septic systems (lb/yr),

E_s is the export coefficient to septic tank systems (per capita export from household to septic tank, (lb/capita-yr),

#capita-years is the number of people using septic systems affecting the lake multiplied by the fraction of year occupying the residence, and

SR is the soil-retention coefficient, the fraction of phosphorus retained between the septic system and the lake.

Population and occupancy information were obtained from 1990 census data and local information. Of the approximately 1,010 housing units around Lauderdale Lakes, about 30 percent are year-round residences (G.T. Petersen, oral commun., 1995). Of the 70 percent seasonal residences, 60 percent of the total were assumed to be occupied during the summer and on weekends (160 days) and 10 percent to be occupied during summer only (92 days). The average number of persons per household for Lauderdale was assumed to be 2.60, on the basis of 1990 census data (Tim McCauley, Southeastern Wisconsin Regional Planning Commission, written commun., 1995).

Not all households and facilities around the lake are likely to affect the lake, however, because ground-water gradients in part of the area are out of and away from the lakes. In this study, the number of residences potentially affecting the lake was determined for the area within 250 ft of the shoreline where ground-water gradients were into the lake. Residences with drainfields greater than 250 ft from the shoreline were assumed not to affect the lake on the basis of soils information and information from Reckhow and others (1980). The number of residences within this 250-ft zone was determined from 1992 aerial photos obtained from Walworth County Agricultural Stabilization and Conservation Service (written commun., 1995). The number of residences in this zone used in the calculations was 374 of the 1,010. Number of residences obtained from a more detailed septic survey would probably be more accurate. Number of capita-years was calculated by multiplying

Table 3. Water levels and dissolved phosphorus concentrations in samples from observation wells near Lauderdale Lakes, Walworth County, Wis., 1993–94

[Water levels referenced to lake stage gage; datum of gage is 879.57 ft above sea level; mg/L, milligrams per liter; --, data not available; <, less than. Well locations shown in fig. 5]

Well number	Date	Water level (feet)	Lake stage (feet)	Phosphorus ortho-phosphate as P, dissolved (mg/L)
Flow direction: out of lake				
1	11/30/93	4.27	5.37	--
	12/21/93	4.32	5.34	--
	02/01/94	3.91	5.04	--
	03/16/94	4.23	5.02	--
	05/05/94	4.23	5.00	--
	05/12/94	4.20	5.00	0.039
	06/13/94	4.10	5.00	.052
	07/21/94	4.05	4.99	.099
	08/24/94	4.04	5.02	.119
	09/28/94	3.89	4.97	.103
	11/01/94	3.79	4.93	.088
7	12/01/93	5.18	5.38	--
	12/21/93	5.24	5.34	--
	02/01/94	4.71	5.04	--
	03/16/94	5.29	5.02	.005
	05/05/94	5.02	5.00	--
	05/12/94	4.82	5.00	.002
	06/13/94	4.40	5.00	.002
	07/21/94	4.30	4.99	.005
	08/24/94	4.39	5.02	<.002
	09/28/94	4.21	4.97	<.002
	11/01/94	4.27	4.93	<.002
8	12/01/93	4.50	5.38	--
	12/21/93	4.58	5.34	--
	02/01/94	4.15	5.04	--
	03/16/94	4.56	5.02	--
	05/05/94	4.53	5.00	--
	05/12/94	4.50	5.00	.010
	06/13/94	4.38	5.00	.008
	07/21/94	4.32	4.99	.004
	08/24/94	4.28	5.02	.002
	09/28/94	4.13	4.97	.002
	11/01/94	4.04	4.93	<.002
12	06/16/94	4.72	5.00	.004
	07/21/94	4.74	4.99	.006
	08/24/94	4.72	5.02	.120
	09/28/94	4.62	4.97	.002
	11/01/94	4.55	4.93	<.002

Table 3. Water levels and dissolved phosphorus concentrations in samples from observation wells near Lauderdale Lakes, Walworth County, Wis., 1993–94—Continued

Well number	Date	Water level (feet)	Lake stage (feet)	Phosphorus ortho-phosphate as P, dissolved (mg/L)
		Flow direction: out of lake—continued		
13	06/16/94	4.83	5.00	.008
	07/21/94	4.92	4.99	.002
	08/24/94	5.00	5.02	.002
	09/28/94	4.87	4.97	.004
	11/01/94	4.86	4.93	<.002
14	06/13/94	4.28	5.00	.003
	07/21/94	4.20	4.99	.005
	08/24/94	4.16	5.02	.007
	09/28/94	4.02	4.97	.003
	11/01/94	3.89	4.93	.005
15	06/16/94	4.23	5.00	.011
	07/21/94	4.14	4.99	.005
	08/24/94	4.06	5.02	.003
	09/28/94	3.92	4.97	.006
	11/01/94	3.78	4.93	.005
		Flow direction: into lake		
2	12/01/93	5.76	5.38	.018
	12/21/93	5.82	5.34	--
	02/01/94	5.42	5.04	--
	05/05/94	5.49	5.00	--
	05/12/94	5.46	5.00	.010
	06/13/94	5.40	5.00	.014
	07/21/94	5.43	4.99	.415
	08/24/94	5.51	5.02	.023
	09/28/94	5.37	4.97	.032
	11/01/94	5.29	4.93	.021
3	12/01/93	6.08	5.38	.003
	12/21/93	6.12	5.34	--
	03/16/94	5.99	5.02	.004
	05/05/94	5.82	5.00	--
	05/12/94	5.79	5.00	<.002
	06/16/94	5.63	5.00	.003
	07/21/94	5.59	4.99	.010
	08/24/94	5.57	5.02	.004
	09/28/94	5.47	4.97	.007
	11/01/94	5.42	4.93	.004

Table 3. Water levels and dissolved phosphorus concentrations in samples from observation wells near Lauderdale Lakes, Walworth County, Wis., 1993–94—Continued

Well number	Date	Water level (feet)	Lake stage (feet)	Phosphorus ortho-phosphate as P, dissolved (mg/L)
Flow direction: into lake—continued				
4	12/01/93	5.40	5.38	.042
	12/21/93	5.43	5.34	--
	02/01/94	4.96	5.04	--
	03/16/94	5.17	5.02	.036
	05/05/94	5.12	5.00	--
	05/12/94	5.10	5.00	.032
	06/16/94	5.02	5.00	.036
	07/21/94	5.05	4.99	.048
	08/24/94	5.05	5.02	.041
	09/28/94	5.03	4.97	.044
	11/01/94	5.00	4.93	.043
5	12/01/93	6.09	5.38	.003
	12/21/93	6.11	5.34	--
	02/01/94	5.75	5.04	--
	03/16/94	5.21	5.02	.009
	05/05/94	5.82	5.00	--
	05/12/94	5.79	5.00	<.002
	07/21/94	5.66	4.99	.008
	08/24/94	5.69	5.02	.006
	09/28/94	5.54	4.97	.002
	11/01/94	5.49	4.93	.003
10	12/21/93	6.28	5.34	--
	02/01/94	5.90	5.04	--
	03/16/94	6.08	5.02	.023
	05/05/94	5.94	5.00	--
	05/12/94	5.91	5.00	.013
	06/16/94	5.78	5.00	.023
	07/21/94	5.74	4.99	.390
	08/24/94	5.73	5.02	.062
	09/28/94	5.66	4.97	.029
	11/01/94	5.62	4.93	.025
11	12/21/93	5.71	5.34	--
	03/16/94	5.61	5.02	.013
	05/05/94	5.44	5.00	--
	05/12/94	5.39	5.00	.003
	06/13/94	5.25	5.00	.012
	07/21/94	5.16	4.99	.147
	08/24/94	5.11	5.02	.009
	09/28/94	4.99	4.97	.016
	11/01/94	4.92	4.93	.012

Table 3. Water levels and dissolved phosphorus concentrations in samples from observation wells near Lauderdale Lakes, Walworth County, Wis., 1993–94—Continued

Well number	Date	Water level (feet)	Lake stage (feet)	Phosphorus ortho-phosphate as P, dissolved (mg/L)
		Flow direction: transition		
6	12/01/93	5.38	5.38	--
	12/21/93	5.43	5.34	--
	03/16/94	5.28	5.02	.049
	05/05/94	5.15	5.00	--
	05/12/94	5.11	5.00	.048
	06/13/94	4.99	5.00	.545
	07/21/94	4.84	4.99	.435
	08/24/94	4.79	5.02	.165
	09/28/94	4.70	4.97	.094
	11/01/94	4.61	4.93	.083
9	12/21/93	5.42	5.34	--
	03/16/94	5.26	5.02	.005
	05/05/94	5.08	5.00	.007
	05/12/94	5.03	5.00	.004
	06/16/94	4.81	5.00	.012
	07/21/94	4.78	4.99	<.002
	08/24/94	4.90	5.02	.004
	09/28/94	4.77	4.97	.002
	11/01/94	4.72	4.93	--

the number of residences by the number of persons per household by the fraction of year occupied.

The major sources of wastewater to septic tanks are sinks, bathtubs and showers, appliances, garbage disposals, and toilets. Each source contributes different amounts of nutrients. Phosphorus in wastewater originates mainly from toilet wastes and phosphate detergents.

E_s, the per capita export of phosphorus from the household to the onsite septic system, was estimated from coefficients given in the literature (Garn and Parrott, 1977; Reckhow and others, 1980). The selected coefficients are slightly on the low side of those in the literature to account for the ban on sale of phosphate-based detergents. Reckhow and others (1980, p. 56) reported that in areas where a phosphate detergent was banned, median phosphorus loading was 0.8 to 1.2 lb/capita-yr. Per capita load without a ban ranged from about 1.8 to 6.6 lb; the median was about 2.9 lb. Although a phosphate ban indicates that a loading approaching 1.0 lb would be likely, the increasing use of automatic dishwashers and garbage disposals may offset the effectiveness of a ban. Automatic dishwasher detergents are not included in the ban, and their phosphate content typically is 3 to 9 percent phosphate by weight, equivalent to 0.6 to 1.1 g of phosphorus per tablespoon of detergent. A most likely median loading of 1.8 lb/capita-yr was selected for subsequent calculations. Reckhow and others (1980) also recommend selecting a low and a high value to account for the wide range and uncertainty in selecting values; therefore, a low of 1.1 and a high of 2.2 lb/capita-yr were selected for the estimates.

Many factors influence the quantity of phosphorus eventually reaching the lake from the septic systems. The factors involve physical and biological site characteristics, properties of the soil, and properties of the septic system (Reckhow and others, 1980). These factors include

- phosphorus-adsorption capacity of soil,
- drainage of soil (depth to water table or impermeable material),

- permeability of soil,
- land slope,
- distance from lake,
- uptake of phosphorus by plants,
- age of system, and
- use and maintenance of system.

Septic systems, if working properly, are effective in removing phosphorus. Generally, removal capacity increases with decreasing particle size of soil, decreasing pH of soil, increasing content of clay and amounts of iron and aluminum in soil, increasing reaction time, and increasing depth to water table (Garn and Parrott, 1977). A soil has a finite adsorption capacity, which may be reduced by drainfield effluent over time; new septic systems provide more soil retention of phosphorus than old systems. In addition to age, maintenance of septic systems also influences the effectiveness of the system. If scum and sludge are allowed to build up in the tank to a point at which solids are carried out into the drainfield, soil spaces may become plugged, and system failure may result. Septic-system failures and water contamination are most likely in soils where water tables are high, or perched; in shallow soils over bedrock; on steep slopes that allow effluent to surface; and in very coarse-textured soils that are low in organic matter, high in permeability, and low in phosphorus-retention capacity.

SR, the soil-retention coefficient (the fraction of phosphorus retained by the soil or otherwise retained between the septic system and lakeshore), was estimated on the basis of these various site-specific factors. The coefficient may range from 0 to 1.0. If all phosphorus from septic systems is assumed to reach the lake, then *SR*=0; if no phosphorus is assumed to reach the lake, then *SR*=1.0. In this evaluation, systems greater than 250 ft from the lakeshore were assumed to have no effect on the lake (*SR*=1.0). For septic systems that were determined to be failing within the 250-ft zone, *SR*=0.25. The Lake Management District has a septic inspection, pumping, and corrective action program; it has been inspecting septic systems since 1991. The inspections are nearly completed, and replacement or repairs to many systems are planned to be completed in 1997. On the basis of inspection data, a failure rate of 10 percent of the systems was used in the calculations (Charles H. Sharpless, Lauderdale Lakes Lake Management District, written commun., 1995).

The factors considered in estimating *SR* included primarily phosphorus-adsorption capacity of the soils in the area and drainage, permeability, and slope of the soils. In the nearshore area, soils consist predominantly of the Casco-Rodman Complex, Rodman-Casco Complex, and Casco-Fox Silt Loam (Haszel, 1971; Natural Resources Conservation Service, Walworth County, written commun., 1995). These are loamy soils over sand and gravel; they are excessively drained—subsoil permeabilities are greater than 20 in/hr—and they are classified as a poor filter and as having severe limitations for septic-tank absorption fields. *SR* coefficients for these types of soils may range from 0.2–0.6. *SR* also includes a fraction of the phosphorus that is removed through storage in sludge in the septic tank, which amounts to about 20 to 30 percent of the incoming wastewater (Doenges and others, 1990). Therefore, as with the selection of an E_s value, a "most likely" *SR* of 0.85 was used in the calculations for the "most likely" case, and a low value of 0.5 and high value of 0.9 also were evaluated.

In summary, the following "most likely," low, and high annual phosphorus loads from septic systems were estimated by use of the "most likely," low, and high values for the coefficients:

Estimate	E_s, in pounds per capita-yr	1-*SR*	Phosphorus load, in pounds per year
"Most likely"	1.8	0.15	210
Low	1.1	.10	95
High	2.2	.50	670

The "most likely" load estimate of total phosphorus that reaches the lakes annually from near-lake septic systems is 210 lb. Because of the uncertainties associated with this load, low and high estimates also are presented to suggest the possible range of loads. The low and high estimates represent 13 and 51 percent, respectively, of the total annual phosphorus input to Lauderdale Lakes. The most likely estimate was used as the most probable loading in the evaluation. In the future, assuming all failed systems are corrected and a proposed systematic pumping program is in place, the load from septic systems is estimated to be about 100 lb annually; this is less than one-half of the present load.

Phosphorus concentration in ground water from the nearshore observation wells verified that septic systems and possibly other sources (perhaps fertilizer applications) were affecting ground water. Phosphorus concentrations in ground water (table 3) greatly exceeded 0.008 mg/L in three out of six wells located in the inflow area of the lakes. Concentrations at wells

2, 10, and 11 (fig. 2) were unusually high (15 to 50 times the background concentration) in July, corresponding to the heavy use season. At well 6, in the transition zone on the north side of Green Lake, the extremely high phosphorus concentrations could not be explained by the information available; the high concentrations occurred during the summer when the flow direction was primarily out of the lake. The high phosphorus concentrations in the ground water were almost as great as those measured in surface runoff. Wells 11 and 4 (where concentrations also were above normal) are in an area of failed septic systems identified by the inspections (Charles H. Sharpless, written commun., 1995).

Annual Total Phosphorus Budget

The total annual phosphorus input to Lauderdale Lakes for the study year was estimated to be 846 lb. The greatest sources of phosphorus input to the lakes were surface runoff and septic systems (table 4; fig. 8). Total phosphorus input for the study year probably represents a below-average input, particularly from surface runoff, because precipitation during the year was below average.

Not included in the preceding estimate of annual phosphorus load to the lakes is the nutrient contribution from waterfowl. Nutrients added by waterfowl are generally thought to be relatively unimportant and are seldomly estimated; moreover, behavior of aquatic birds is variable, and population data are difficult to obtain. For these reasons, a detailed estimate of the loading from this source was not within the scope of this study. Phosphorus loading from waterfowl droppings may, however, be a significant fraction of the total phosphorus loading from all sources where waterfowl populations are large (Scherer and others, 1995; Manny and others, 1994). An escalating population of resident geese is a growing problem in many areas. The increasing numbers of geese are resulting in more complaints about nuisance geese, which are becoming common in urbanized areas where grassy lawns of lakefront homes, golf courses, and parks furnish ideal grazing and resting sites. A newspaper article in the Wisconsin State Journal (December 23, 1995, "Nuisance Geese To Hear Explosions") related the growing problems of nuisance populations at Oconomowoc and Beaver Dam Lakes in Wisconsin.

Approximately 550 Canada geese were concentrated in the ice-free, open-water area of the springs on the west end of Middle Lake in March 1994. High densities of geese were also observed in the summer and fall during the study. Because geese spend much of the day feeding on land near the lake or returning to the lake to roost, a significant proportion of their droppings may be deposited directly into the water or washed in from lakeshore areas and boat docks. Manny and others (1994) estimated that a goose produces about 33 g dry weight of droppings per day and that the mean proportion of phosphorus by weight was 0.015, resulting in a mean daily phosphorus loading of 0.49 g per goose. The mean daily loading rate for ducks was assumed to be 0.46 (the mean duck/goose weight ratio) of that for geese, or 0.22 g of phosphorus per duck. Although no other waterfowl population data are available for Lauderdale Lakes, a conservative estimate of number of geese and ducks times number of days that they were present might be about 400,000 and 275,000, respectively. These numbers are based on the few observations, a maximum assumed population of 5,000 geese during migration, and information from Manny and others (1994). A total annual loading by waterfowl based on these assumptions could be as much as 560 lb. Even with the application of a factor of 0.5 to account for time that the waterfowl were not on the lakes, or phosphorus not entering the lakes, the annual loading by waterfowl could potentially still be as much as 280 lb, or about 25 percent of all inputs.

Scherer and others (1995) also present a procedure for estimating phosphorus loading from waterfowl. They found that total phosphorus from waterfowl droppings was 25 to 34 percent of the annual load to an urban lake; almost all of this loading, however, originated from food within the lake and probably represented internal recycling because the surrounding urban setting contained no feeding areas.

Total phosphorus output from the lakes, measured at the dam outlet, was 162 lb for November 1993

Table 4. Annual total-phosphorus inputs for Lauderdale Lakes, Walworth County, Wis., November 1993–October 1994

Budget item	Total phosphorus load (pounds)	Percent of total inputs
Inputs:		
Precipitation	94	11
Surface runoff	430	51
Ground water	112	13
Septic systems	210	25
Total inputs	846	100

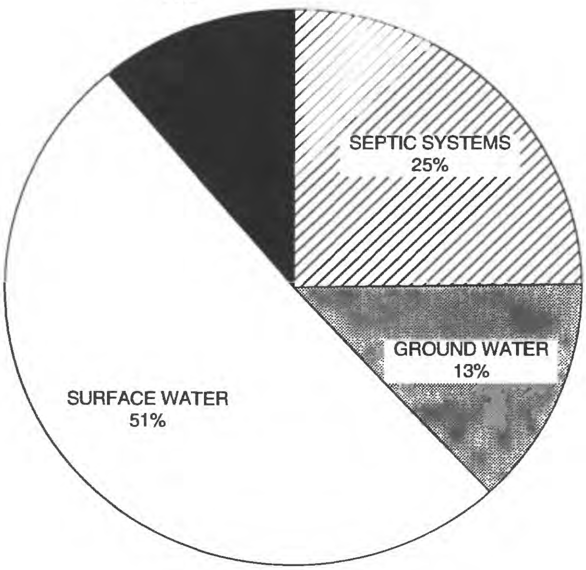

Figure 8. Annual phosphorus inputs for Lauderdale Lakes, Walworth County, Wis., November 1, 1993, through October 31, 1994.

through October 1994 (Holmstrom and others, 1995), or 19 percent of all estimated inputs. A small amount of phosphorus not estimated probably discharges with ground-water outflow. A considerable quantity of phosphorus was removed from the lakes by the macrophyte-harvesting program. In 1994, a total of 565.6 tons (wet weight) of weeds were harvested during the season (Douglas D. Rubnitz, Lauderdale Lakes Improvement Association, written commun., 1995). Eurasian watermilfoil was the dominant submerged aquatic macrophyte species in the lakes. If average dry-weight percentage is assumed to be 7.0 percent of the wet weight (Michael R. Martin, Adirondack Aquatic Institute, N.Y., written commun., 1995; Peterson and others, 1974) and the average phosphorus content is assumed to be 0.30 percent of dry weight (Peterson and others, 1974), then about 240 lb of phosphorus was removed from the lakes by the harvesting program.

Internal Recycling of Phosphorus

Release of phosphorus from the bottom sediments to the overlying water in a lake can be a major component of the phosphorus budget in nutrient-rich lakes. Phosphorus can be released from sediments by a number of mechanisms, including hypolimnetic anoxia, macrophytes, fish, benthic invertebrates (Wetzel, 1983, p. 259–269), and disturbance by motorboats and wave action. Concentrations of phosphorus near the sediments of stratified lakes may equal or exceed 1,000 µg/L (Wisconsin District Lake-Studies Team, 1995, 1996).

Internal recycling and sedimentation of total phosphorus (TP) were evaluated by use of a mass-balance approach according to the following calculation: Net internal recycling or sedimentation = (total inflow TP mass) - (outflow TP mass) - (change in water-column TP mass). Net internal recycling or sedimentation were calculated for each water-quality sampling interval during the study year. Net sedimentation for the year was estimated to be 607 lb. The calculations indicate that sedimentation dominates and that internal recycling, or release of phosphorus from sediments during anoxia, is not a large component of the phosphorus budget. This conclusion is also supported by the relatively low concentrations of phosphorus (usually less than 100 µg/L) measured near the lake bottom (see the section on "Phosphorus" under "Water Quality").

Evaluation of Lake Condition

The water quality of Lauderdale Lakes was evaluated by use of two commonly employed methods: Lillie and Mason's (1983) water-quality evaluation for Wisconsin lakes, and Carlson's (1977) Trophic State Index, or TSI. Vollenweider's (1975) model and Dillon and Rigler's (1974) model were used to evaluate the phosphorus loading to the lakes.

Lillie and Mason's Classification

Lillie and Mason (1983) used a random data set consisting of total phosphorus concentration, chlorophyll *a* concentration, and Secchi depths collected during summer (July–August) to classify Wisconsin lakes. They devised the following classification:

Water-quality index	Approximate total phosphorus range (micrograms per liter)	Approximate chlorophyll *a* range (micrograms per liter)	Approximate water-clarity range (Secchi depth, in feet)
Excellent	<1	<1	>19.7
Very good	1–10	1–5	9.8–19.7
Good	10–30	5–10	6.6–9.8
Fair	30–50	10–15	4.9–6.6
Poor	50–150	15–30	3.3–4.9
Very poor	>150	>30	<3.3

Green Lake's mean 1994 summer total phosphorus and chlorophyll *a* concentration and Secchi depth were 8 µg/L, 3.0 µg/L, and 10.4 ft, respectively, all in the "very good" category. Middle Lake's mean total phosphorus and chlorophyll *a* concentration and Secchi depth were 10 µg/L, 3.4 µg/L, and 8.0 ft, respectively, in the "good" to "very good" category. Mill Lake's mean total phosphorus and chlorophyll *a* concentration and Secchi depth were 14 µg/L, 7.2 µg/L, and 6.2 ft, respectively, in the "good" category. In comparing the 1994 data to a long-term record (1986–95) that is available for Powers Lake, a lake of similar quality on the Walworth-Kenosha County line, the 1994 data are fairly representative of the long-term average (Wisconsin District Lake-Studies Team, 1996).

Carlson's Trophic State Index

Carlson's (1977) Trophic State Index or TSI, also is computed by use of total phosphorus and chlorophyll *a* concentrations and Secchi depths for ice-free periods. Carlson's TSI equations for total phosphorus and chlorophyll *a,* as modified by Lillie and others (1993) to apply to Wisconsin lakes, were used for the evaluation. The Wisconsin Department of Natural Resources has adopted the following TSI ranges to classify the condition of lakes:

TSI	Condition
<40	oligotrophic
40–50	mesotrophic
51–70	eutrophic
>70	hypereutrophic

These ranges are commonly used to make consistent comparisons in lake trophic-state evaluations.

The computed TSI's for the three characteristics of each of the Lauderdale Lakes follow similar patterns for the duration of the study period (fig. 9). TSI's in April and May are generally in the oligo-mesotrophic range; by June and for the remainder of the summer, the TSI's are generally in the mesotrophic range, and some approach the eutrophic range. Overall, these TSI's are low relative to those for other southeastern Wisconsin lakes (Wisconsin District Lake-Studies Team, 1995, 1996) and representative of comparatively "good" trophic conditions.

Vollenweider's Model

Vollenweider (1975) formulated a relation for predicting the trophic state likely to result from external phosphorus loading to lakes. The model, shown graphically in figure 10, relates total phosphorus loading per unit lake surface area to the lake's mean depth and hydraulic residence time. This relation may be used as a general guide for determining phosphorus loading limits to lakes and for predicting changes in the trophic state of lakes. The model illustrates the importance of hydraulic residence time. The loading rate at which a lake may become eutrophic (representing a spring phosphorus concentration of about 20 µg/L) is termed "dangerous," and the loading rate at which a lake may become mesotrophic (representing a spring phosphorus concentration of about 10 µg/L) is termed "permissible." For 1994 data, the Lauderdale Lakes plot near the "permissible" line.

Dillon and Rigler's Model

Loading estimates may be used to predict a lake's phosphorus concentration at spring turnover by use of Dillon and Rigler's (1974a) formula,

$$P = L\,(1\text{-}R_p)/q_s,$$

where P is the predicted phosphorus concentration (g/m^3 or mg/L), L is the areal phosphorus load (g/m^2/yr), R_p is the phosphorus-retention coefficient (calculated from actual data or estimated by various methods described by Canfield and Bachman, 1981, and Nurnberg, 1984), and q_s is the areal water load (total inflows divided by lake surface area, in meters per year). Using the data for Lauderdale Lakes, where $L = 0.12$ g/m^2/yr, $R_p = 0.81$ ([846 lb TP input - 162 lb TP output] / 846 lb), and $q_s = 2.72$ m, one obtains a mean spring total phosphorus concentration of 8 µg/L. The measured average total phosphorus concentration for the three lakes in spring 1994 was 8.5 µg/L; therefore, the equation accurately predicted phosphorus concentration for spring turnover. Phosphorus concentrations at spring turnover are usually less than those during the summer; thus, the equation may underestimate the summertime phosphorus concentration.

Dillon and Rigler (1974b) also developed a relation to predict summer chlorophyll *a* concentration (chl *a*) from the spring total phosphorus concentration. The equation has the form

$$\log_{10}[\text{chl } a] = 1.45 \log_{10}[\text{TP}] - 1.14.$$

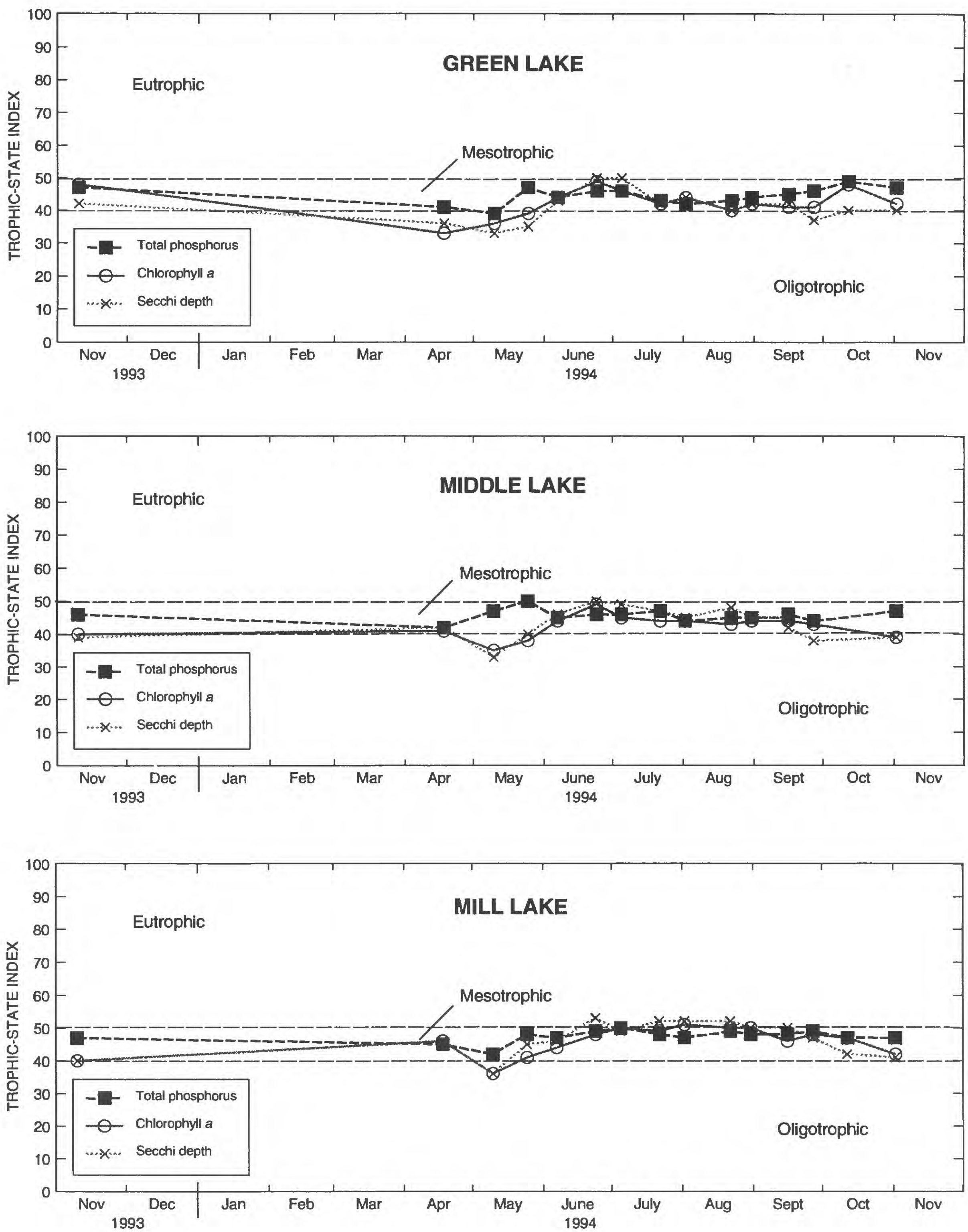

Figure 9. Trophic State Indices for Lauderdale Lakes, Walworth County, Wis., November 1, 1993, through November 30, 1994.

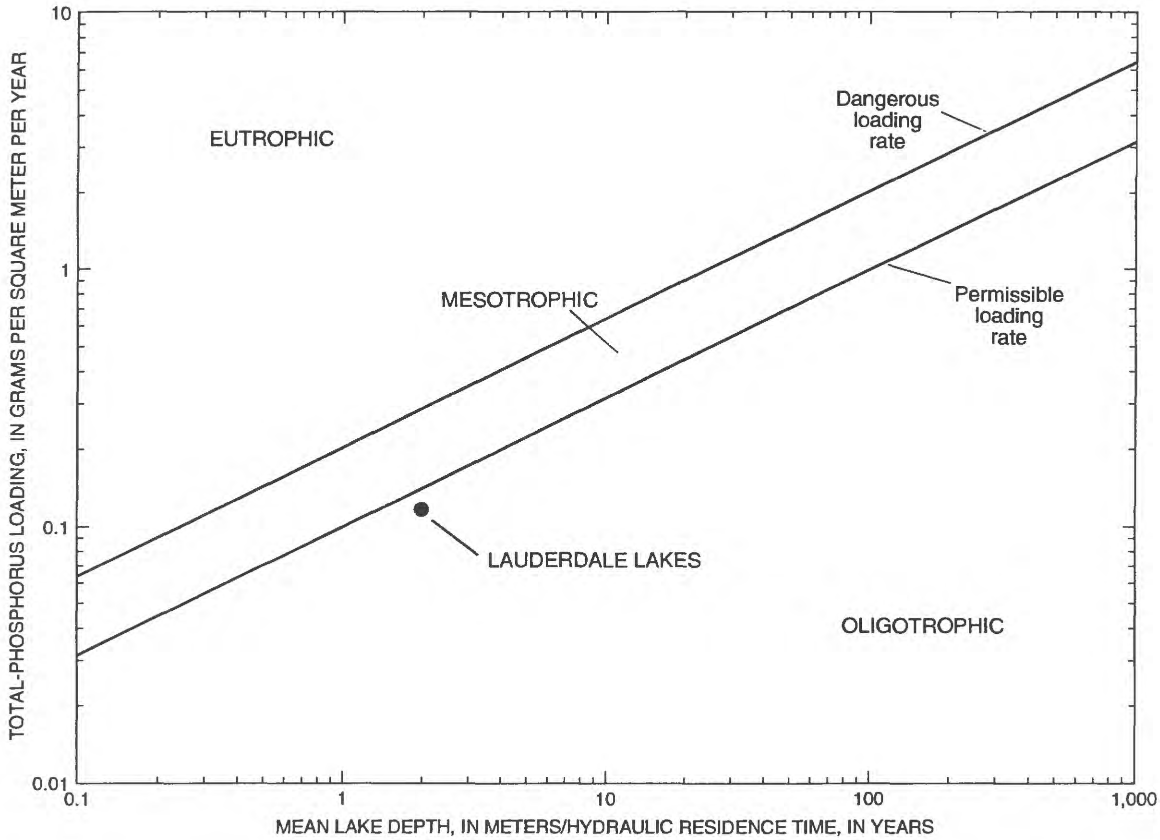

Figure 10. Vollenweider (1975) phosphorus-loading classification for Lauderdale Lakes, Walworth County, Wis., November 1993–October 1994.

Applying the above equation to the spring total phosphorus concentration of 8.5 µg/L for Lauderdale Lakes results in a predicted summer chlorophyll *a* concentration of 1.6 µg/L. This predicted concentration is lower than those observed during June–August (2.7–7.8 µg/L) but close to those observed in the spring (0.8–1.8 µg/L).

CONCLUSIONS

Water and phosphorus budgets were determined for Lauderdale Lakes for the period November 1993 through October 1994. Significant components of the water and phosphorus budgets were measured independently, and other components were estimated. Findings of this study are summarized as follows:

1. Lauderdale Lakes are classified as ground-water drainage lakes; ground water supplied 72 percent of the total inflow. Only 4 percent of the total inflow was from surface water. The total inflow to the lakes was estimated to be about 7,200 acre-ft for the study year. A surface outlet accounted for 64 percent of the total outflow from the lakes.
2. In terms of total phosphorus concentration, chlorophyll *a* concentration, and Secchi depth, and in comparison to other Wisconsin lakes, water quality of Lauderdale Lakes was good to very good. The lakes are thermally stratified in the summer, and the lower depths become anoxic. Phosphorus release from the bottom sediments during anoxia, however, did not seem to be a major problem.
3. Near-lake surface runoff and septic systems were the dominant sources of total phosphorus loading to the lakes. Total annual phosphorus input to the lakes from November 1993 through October 1994 was estimated to be 846 lb. Direct runoff from the near-lake

drainage area made up 51 percent of the total phosphorus loading; septic systems accounted for 25 percent of the total loading. The greatest individual loads were from the contributing drainage areas to site 2, including farm land on the northeast side of Green Lake, and the residential swale area on the southern shore of Don Jean Bay. Phosphorus concentrations in ground water were elevated above background concentrations at three of six observation wells in the area of ground-water inflow, a strong indication that ground water was a source of phosphorus loading.

4. The range of trophic state indices for the lakes was from oligotrophic to mesotrophic, but most were in the mesotrophic class throughout the year.
5. An equation used to predict phosphorus concentration at spring turnover from loading estimates fairly accurately predicted the actual phosphorus concentration for Lauderdale Lakes at the 1994 spring turnover.

REFERENCES CITED

Borman, R.G., 1976, Ground-water resources and geology of Walworth County, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 34, 45 p.

Canfield, D.E., and Bachman, R.W., 1981, Prediction of total phosphorus concentrations, chlorophyll *a*, and Secchi depths in natural and artificial lakes: Canadian Journal of Aquatic Science, v. 38, p. 414–423.

Carlson, R.E., 1977, A trophic state index for lakes: Limnology and Oceanography, v. 22, no. 2, p. 361–369.

Chow, Ven Te, ed., 1964, Handbook of applied hydrology: New York, McGraw-Hill Book Co. [variously paged].

Dillon, P.J. and Rigler, F.H., 1974a, A test of a simple nutrient budget model predicting the phosphorus concentration in lake water: Journal of the Fisheries Resources Board of Canada, v. 31, p. 1771–1778.

Dillon, P.J. and Rigler, F.H., 1974b, The phosphorus-chlorophyll relationship in lakes: Limnology and Oceanography, v. 19, no. 5, p. 767–773.

Doenges, J.M., and others, 1990, Carrying capacity of public water supply watersheds—a literature review of impacts on water quality from residential development: Connecticut Department of Environmental Protection Bulletin 11 [variously paged].

Edwards, T.K., and Glysson, D.G., 1988, Field methods for measurement of fluvial sediment: U.S. Geological Survey Open-File Report 86-531, 118 p.

Farnsworth, R.K., Thompson, E.S., and Peck, E.L., 1982, Evaporation atlas for the contiguous 48 United States: National Oceanic and Atmospheric Administration Technical Report NWS 33, 26 p.

Field, S.J., and Duerk, M.D., 1988, Hydrology and water quality of Delavan Lake in southeastern Wisconsin: U.S. Geological Survey Water-Resources Investigations Report 87-4168, 61 p.

Garn, H.S. and Parrott, H.A., 1977, Recommended methods for classifying lake condition, determining lake sensitivity, and predicting lake impacts: U.S. Department of Agriculture, Forest Service, Hydrology Paper 2, 49 p.

Haszel, O.L., 1971, Soil survey of Walworth County, Wisconsin: U.S. Department of Agriculture, Soil Conservation Service [variously paged].

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Henrich, E.W., and Daniel, D.N., 1983, Drainage area data for Wisconsin streams: U. S. Geological Survey Open-File Report 83-933, 322 p.

Holmstrom, B.K., and others, 1995, Water resources data, Wisconsin, water year 1994: U.S. Geological Survey Water-Data Report WI-94-2, 388 p.

Lillie, R.A., Graham, S., and Rasmussen, P., 1993, Trophic state index equations and regional predictive equations for Wisconsin lakes: Wisconsin Department of Natural Resources Research Management Findings, no. 35, 4 p.

Lillie, R.A., and Mason, J.W., 1983, Limnological characteristics of Wisconsin Lakes: Wisconsin Department of Natural Resources Technical Bulletin 138, 116 p.

Manny, B.A., Johnson, W.C., and Wetzel, R.G., 1994, Nutrient additions by waterfowl to lakes and reservoirs—predicting their effects on productivity and water quality: Hydrobiologia, v. 279/280, p. 121–132.

Moore, L., and Thornton, K., eds., 1988, Lake and reservoir restoration guidance manual: U.S. Environmental Protection Agency, EPA 440/5-88-002 [variously paged].

Mudrey, M.G., Jr., Brown, B.A., and Greenberg, J.K., 1982, Bedrock geologic map of Wisconsin: University of Wisconsin-Extension, Geological and Natural History Survey, scale 1:1,000,000.

National Oceanic and Atmospheric Administration, 1994, Climatological data—Wisconsin: Asheville, N.C., National Climatic Data Center, published monthly [variously paged].

Nurnberg, G.K., 1984, The prediction of internal phosphorus load in lakes with anoxic hypolimnia: Limnology and Oceanography, v. 29, no. 1, p. 111–124.

Panuska, J.C., and Lillie, R.A., 1995, Phosphorus loadings from Wisconsin watersheds—recommended phosphorus export coefficients for agricultural and forested watersheds: Wisconsin Department of Natural Resources Research Management Findings, no. 38, 8 p.

Peterson, S.A. Smith, W.L., and Malueg, K.W., 1974, Full-scale harvest of aquatic plants—nutrient removal from a eutrophic lake: Journal of Water Pollution Control Federation, v. 46, no. 4, p. 697–707.

Porterfield, George, 1972, Computation of fluvial-sediment discharge: U.S. Geological Survey Techniques of Water- Resources Investigations, book 3, chap. C3, 66 p.

Rantz, S.E., and others, 1982, Measurement and computation of streamflow: U.S. Geological Survey Water-Supply Paper 2175, 2 v., 631 p.

Reckhow, K.H., Beaulac, M.N., and Simpson, J.T., 1980, Modeling phosphorus loading and lake response under uncertainty—a manual and compilation of export coefficients: Washington, D.C., U.S. Environmental Protection Agency, EPA440/5-80-011, 214 p.

Rose, W.J., 1993, Water and phosphorus budgets and trophic state, Balsam Lake, northwestern Wisconsin, 1987–89: U.S. Geological Survey Water-Resources Investigations Report 91-4125, 28 p.

Scherer, N.M., Gibbons, H.L., Stoops, K.B., and Muller, M., 1995, Phosphorus loading of an urban lake by bird droppings: Lake and Reservoir Management, v. 11, no. 4, p. 317–327.

Shaw, B., Mechenich, C., and Klessig, L., 1993, Understanding lake data: Madison, Wis., University of Wisconsin Extension, Pub. G3582, 20 p.

Southeastern Wisconsin Regional Planning Commission, 1991, A land use plan for the town of La Grange—2010: Waukesha, Wis., Report 168, 124 p.

Vollenweider, R.A., 1975, Input-output models with special reference to the phosphorus loading concept in limnology: Schweizerische Zeitschrift fur Hydrologie, v. 37, no. 1, p. 53–84.

Wetzel, R.G., 1983, Limnology (2d ed.): New York, Saunders College Publishing, 767 p.

Wisconsin District Lake-Studies Team, 1995, Water-quality and lake-stage data for Wisconsin lakes, water year 1994: U.S. Geological Survey Open-File Report 95-190, 157 p.

____1996, Water-quality and lake-stage data for Wisconsin lakes, water year 1995: U.S. Geological Survey Open-File Report 96-168, 123 p.

Wisconsin State Laboratory of Hygiene, 1993, Manual of analytical methods, inorganic chemistry unit: Wisconsin State Laboratory of Hygiene, Environmental Sciences Section [variously paged].