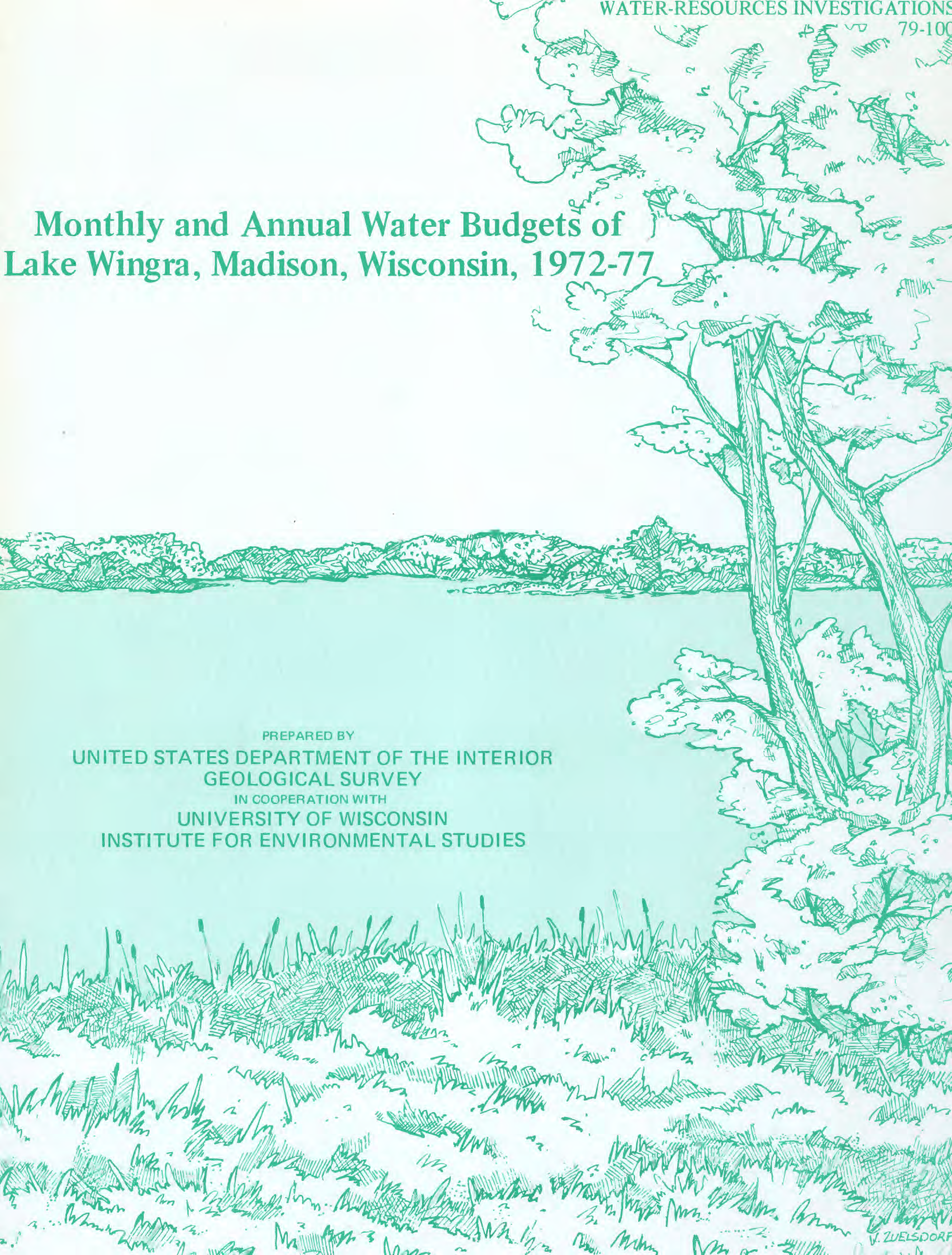
WATER-RESOURCES INVESTIGATIONS
79-100

Monthly and Annual Water Budgets of Lake Wingra, Madison, Wisconsin, 1972-77



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This report presents estimated annual and monthly water budgets for Lake Wingra and the adjacent wetland area for January 1972 through September 1977. Annually, inputs from precipitation, surface runoff, and ground-water inflow are approximately equal (31, 34, and 35 percent, respectively). Outputs include outflow from the lake into Murphy Creek (70 percent), evapotranspiration from the lake and wetland (26 percent), and ground-water outflow (4 percent).

The inputs and outputs vary seasonally. In months when snowmelt occurs, surface runoff is a major input (56 percent in March; 46 percent in April). In fall and winter, ground-water inflow is a major input (57 percent in November). Precipitation is 41 percent of the inflow in August, but only 18 percent in January. Lake outflow is the major output except in July, August, and September. Combined evaporation and evapotranspiration is a major output in summer (45 to 58 percent) but minor in winter (less than 13 percent). Ground-water outflow is a small part of the budget each month, ranging from 2 percent in March and April to a maximum of 7 percent in September.

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R. P. NOVITZKI AND B. K. HOLMSTROM

U. S. GEOLOGICAL SURVEY
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Prepared in cooperation with the
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TO INCH-POUND UNITS

Divide SI unit	By	To obtain inch-pound unit
millimeter (mm)	25.4	inch (in.)
meter (m)	0.0254	inch (in.)
meter (m)	0.3048	foot (ft)
kilometer (km)	1.609	mile (mi)
square kilometer (km^2)	2.590	square mile (mi^2)
liter (L)	3.785	gallon (gal)
liter per second (L/s)	0.06309	gallon per minute (gal/min)
kilogram (kg)	0.4536	pound (lb)
cubic meter per second (m^3/s)	0.02832	cubic foot per second (ft^3/s)
cubic meter per day per square meter $\{(m^3/d)/m^2\}$	0.3048	cubic foot per day per square foot $\{(ft^3/d)/ft^2\}$

Monthly and Annual Water Budgets of Lake Wingra, Madison, Wisconsin, 1972-77

R. P. NOVITZKI AND B. K. HOLMSTROM

ABSTRACT

This report presents estimated annual and monthly water budgets for Lake Wingra and the adjacent wetland area for January 1972 through September 1977. Annually, inputs from precipitation, surface runoff, and ground-water inflow are approximately equal (31, 34, and 35 percent, respectively). Outputs include outflow from the lake into Murphy Creek (70 percent), evapotranspiration from the lake and wetland (26 percent), and ground-water outflow (4 percent).

The inputs and outputs vary seasonally. In months when snowmelt occurs, surface runoff is a major input (56 percent in March; 46 percent in April). In fall and winter ground-water inflow is a major input (57 percent in November). Precipitation comprises 41 percent of the input in August but only 18 percent in January. Lake outflow is the major output except from July through September. Combined evaporation and evapotranspiration is a major output in summer (45 to 58 percent) but minor in winter (less than 13 percent). Ground-water outflow is a small part of the budget each month, ranging from 2 percent in March and April to a maximum of 7 percent in September.

The water budget is based on field data collected from January 1972 through June 1973, and on fragmentary data and estimates for July 1973 through September 1977. The budget terms differ from those published by Oakes, Hendrickson, and Zuehls (1975, table 10) because springflow has been included in total ground-water inflow and estimated on a monthly basis in this report. Previously only annual estimates were provided.

INTRODUCTION

This report provides estimated water budgets for Lake Wingra. The water budget is the framework upon which chemical and biological models of the Lake Wingra ecosystem can be based. It is particularly important in determining nutrient input budgets for the system. This report presents monthly and annual water budgets for Lake Wingra and the wetland areas along the west and south sides of the lake (fig. 1). The budgets are for January 1972 through September 1977. Inputs include precipitation, surface runoff, and ground-water inflow. Outputs include streamflow, evapotranspiration, and ground-water outflow. The budgets are presented in terms of cubic meters of water (m^3).

The water budgets are based on field data collected from January 1972 through September 1977 at three precipitation gages, two storm-sewer gaging stations, a lake-level gage on Lake Wingra, and a stream-gaging station at the lake outlet. Additional data were collected at 5 precipitation gages, 3 storm-sewer gaging stations, 3 springflow gaging stations, 14 wells, and evaporation pans at Lake Wingra and the Nevin State Fish Hatchery for various periods during the project. The data sites (shown in figure 1) are described by Oakes, Hendrickson, and Zuehls (1975) and by Novitzki (1978). These data were used to estimate the monthly input and output components of the budgets.

The data used for the budgets are subject to different levels of measurement error, and this must be considered when using the estimated water budgets. Errors in precipitation, streamflow, lake outflow, and lake-level measurements should be less than 10 percent. Errors in estimates of lake evaporation and wetland evapotranspiration may be as great as 20 percent. However, errors in estimates of runoff from ungaged areas and ground-water flow may be 20 to 100 percent or even more.

WATER BUDGETS

Inputs include precipitation, surface runoff, and ground-water inflow. Annually, these average about 31, 34, and 35 percent, respectively (table 9). Surface runoff is the major input in the months when snowmelt occurs (56 percent in March, 46 percent in April). Ground-water inflow is the major input (57 percent) in November when surface runoff is minimal (14 percent). The monthly inputs are shown in table 8.

Outputs include lake outflow, evaporation from the lake, evapotranspiration from the wetland, and ground-water outflow. Annually, the major output is lake outflow (70 percent), compared to evaporation from the lake (16 percent), evapotranspiration from the wetland (10 percent), and ground-water outflow (4 percent). Combined evapotranspirative losses from the lake and wetland areas are a large part of the output in summer (45 to 58 percent) but only a small part (less than 13 percent) in the winter. Ground-water outflow is a small part of the output in each month, ranging from a minimum of 2 percent in March and April to a maximum of 5 to 7 percent in late summer. The monthly outputs are shown in table 8.

The water budget for the lake can be written as:

$$V = P + SR + GWI - SO - E - ET - GWO \tag{1}$$

where:
V = change in lake volume,
P = precipitation on lake,
SR = surface runoff into lake,
GWI = ground-water inflow,
SO = streamflow out of lake,
E = evaporation from lake surface,
ET = evapotranspiration from wetlands, and
GWO = ground-water outflow.

The volume of the lake at any time, "t", then can be written:

$$V_t = V_{t-1} + P_t + SR_t + GWI_t - SO_t - E_t - ET_t - GWO_t \tag{2}$$

where the terms are the same as before and the subscript "t-1" for lake volume means the volume at the end of the preceding time step, and the subscript "t" with the remaining terms means, for example, that P_t is the precipitation P falling within the time interval from "t-1" to "t". The term V_{t-1} is the lake volume at the beginning of the computation period; $V = 3,405\ m^3$ at the end of December 1971.

A modification in the water budget (2) was necessary to account for discrepancies in calculated and observed lake volumes. Precipitation from October through March does not produce a proportional change in lake volume. (See discussion in Precipitation section.) During this period it appears that precipitation (P_t) is stored in the sand and gravel surrounding the lake and wetland, and that part of this stored ground water is released each subsequent month as long as a positive ground-water storage balance (GWS_t) remains. Then the water budget for the period April through Septembe is:

$$V_t = V_{t-1} + P_t + 0.15GWS_{t-1} + SR_t + GWI_t - SO_t - E_t - ET_t - GWO_t \tag{3}$$

where: $$GWS_t = GWS_{t-1} - 0.15GWS_{t-1} \tag{3A}$$

and the water budget for the period October through March is:

$$V_t = V_{t-1} + 0.15GWS_{t-1} + SR_t + GWI_t - SO_t - E_t - ET_t - GWO_t \tag{4}$$

where: $$GWS_t = GWS_{t-1} + P_t - 0.15GWS_{t-1} \tag{4A}$$

The term GWS_{t-1} is assumed to be zero at the beginning of the computation shown in table 8.

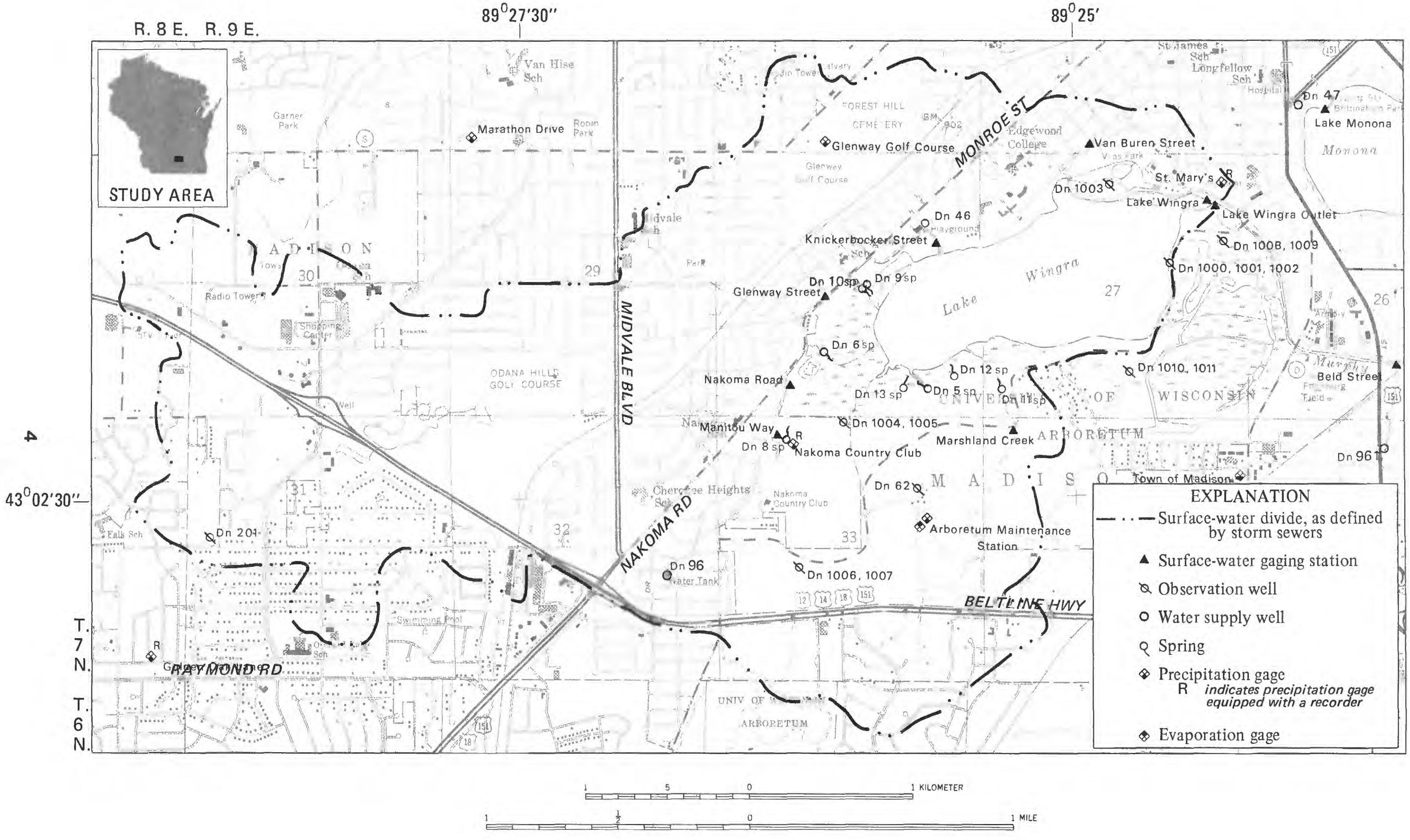

Figure 1. Hydrologic data sites in the Lake Wingra area, Wisconsin.

Following is a discussion of how each of the budget terms was estimated. The estimated monthly water budgets for Lake Wingra and the adjacent wetland area from January 1972 through September 1977 are presented in table 8 at the end of the report. The 6-year average monthly and annual water-budget terms are summarized in table 9.

Inputs

PRECIPITATION

Precipitation was measured at three locations from January 1972 through September 1977, and at five additional locations for various periods during this time (fig. 1). The monthly values, shown in table 1, are basin averages weighted by appropriate factors depending upon which stations had records. The precipitation falling on the 2.17 km^2 lake and wetland surface (P_t in equation 3) is converted to volumes in table 8.

Precipitation from October through March does not produce a direct proportional change in lake level. During this period, part of the precipitation probably is stored temporarily at the surface as ice and snow and part of it moves into the wetland soils to replenish soil moisture after the growing season. Also, part of the lake water probably moves into the sand and gravel adjacent to the lake and wetland, analagous to bank storage in river systems (Rorabaugh, 1963) as lake levels rise. This ground-water storage appears reasonable when compared to ground-water levels in well Dn-1005 (fig. 1) within the Lake Wingra basin and in well Dn-441, which is 3 mi northeast of the Lake Wingra basin but represented trends in the local shallow ground-water system through the study period. Ground-water levels rose in 1973, remained high for 2 years, and have been declining since 1975. The cumulative ground-water storage (GWS) calculated from equation 4 for the period of the study has a similar trend (fig. 2). Precipitation for October through March is removed from the water budget, added into ground-water storage, and then returned to the water budget each succeeding month at the rate of 15 percent of the total amount in ground-water storage (table 8). Fifteen percent was estimated on the basis of the best balance between calculated and observed lake volumes.

SURFACE RUNOFF

Surface runoff was measured from 1972 through 1973 at six locations (fig. 1 and Oakes and others, 1975, table 3), representing 10.85 km^2 of the 13.50 km^2 of upland. Two stations were operated from January 1972 through September 1977. Four additional stations were operated from January 1972 through October 1973. Surface runoff at discontinued sites for November 1973 through September 1977 was estimated by correlation with the records at the sites operated throughout the period. The monthly surface runoff and relations used to extend records are shown in table 2.

Surface runoff from the 2.65 km^2 ungaged part of the watershed (table 3) was estimated from a relation between runoff and drainage area defined at five of the gaged sites. The Marshland Creek data were not used because that basin is least similar to the ungaged area. Measured discharge was

Table 1.--Monthly precipitation in the Lake Wingra basin from January 1972 through September 1977. Weighting factors provide average precipitation over the basin, depending upon which stations were in operation

(Units in millimeters)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1972	7	7	43	57	70	26	87	194	113	82	26	51	763
1973	39	41	129	194	160	42	41	54	116	67	41	60	984
1974	67	37	89	104	138	91	61	82	21	90	56	51	887
1975	28	44	81	103	91	169	121	108	23	16	75	8	867
1976	12	67	123	118	56	44	25	51	15	47	4	11	573
1977	12	35	98	73	43	77	218	93	64	--	--	--	---

Weighting Factors

Stations operated	Charmany	Golden Oak Lane	Marathon Drive	Glenway Golf Course	Nakoma Country Club	St. Mary's	Town of Madison	Arboretum
8	0.1066	0.1069	0.0616	0.1685	0.2795	0.0932	0.0035	0.1802
7	.1076	.1162	.1082	.2134	------	.0930	.0035	.3581
4	.2047	------	.0799	------	.4374	------	------	.2780
3	.2062	------	.1989	------	------	------	------	.5949

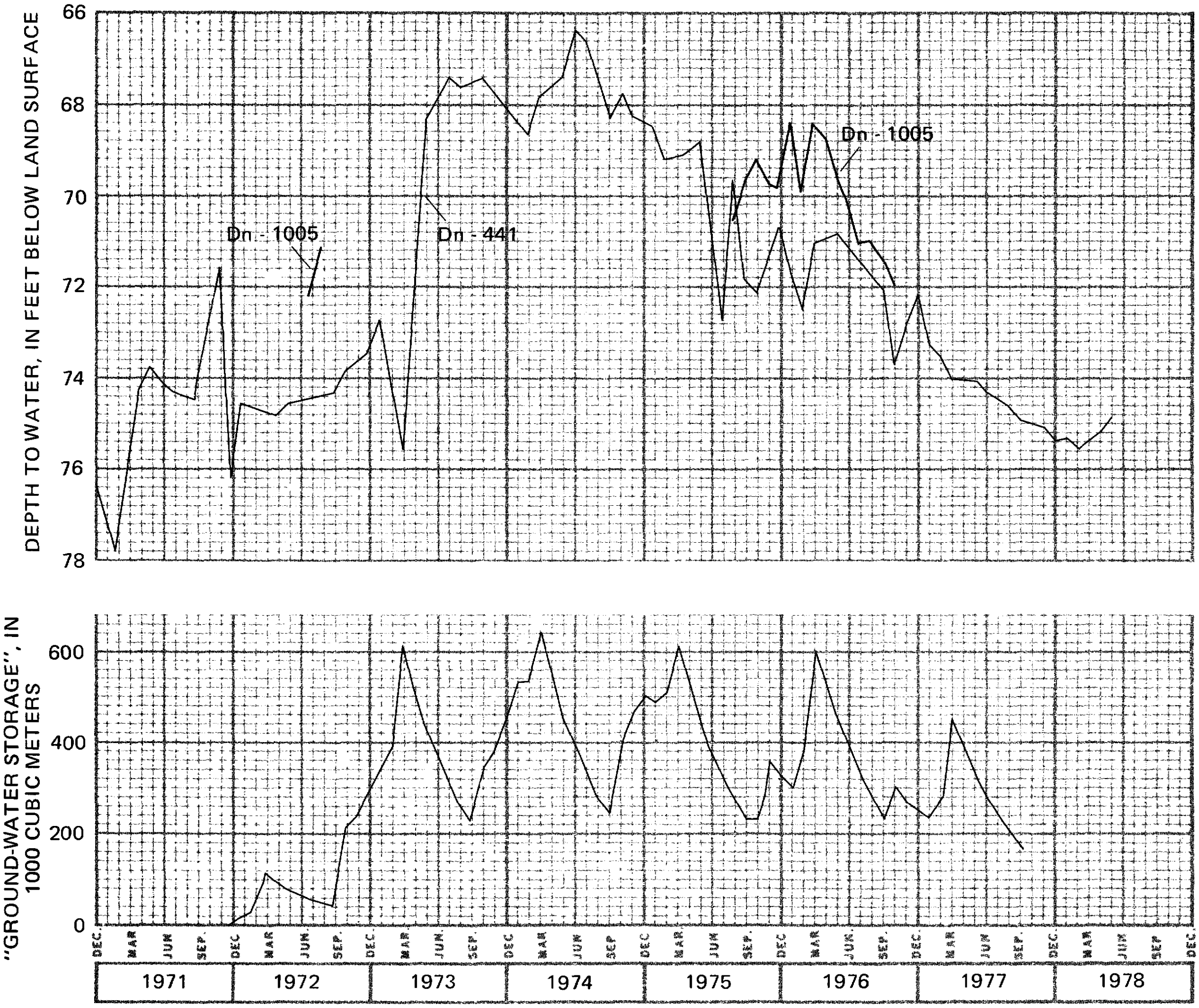

Figure 2. Ground-water storage in the Lake Wingra water budget compared to ground-water levels.

related to drainage area for each month from October 1972 through September 1973. (An example of the October relationship defined by runoff measured in October 1972 and 1973 is shown in figure 3.) Then, for each month from October 1974 through September 1977 the reported discharges for the Nakoma and Manitou Way storm sewers were plotted and used to adjust the position of the relation line, retaining the original slope (see example for October 1974, 1975, and 1976 in figure 3). Monthly surface runoff from the ungaged area was estimated from the adjusted relation line. This technique was used to estimate flow in Marshland Creek for the winter months (December-April) 1974 through 1977 (table 2). The estimated monthly surface runoff from ungaged areas is shown in table 3.

The combined monthly surface runoff (SR_t in equation 3), the sum of values from tables 2 and 3, are shown in table 8.

Table 2.--Measured and estimated surface runoff from gaged areas (10.85 km^2) in the Lake Wingra basin[1]

(Units in 1,000 m^3)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
					1972							
Manitou Way storm sewer-------------	0.4	0.7	12.3	21.7	4.6	0.7	4.5	13.5	7.9	4.3	1.4	2.6
Nakoma Road storm sewer-------------	4.6	58.1	308	78.4	44.8	2.9	15.5	161	79.8	53.6	12.3	39.0
Glenway Street storm sewer-------	1.5	10.1	27.0	9.2	8.6	2.1	11.0	41.5	22.2	9.7	4.9	10.8
Knickerbocker Street storm sewer-------	.3	.5	17.5	4.6	2.0	.3	4.6	12.8	4.8	2.7	.8	.7
Van Buren Street storm sewer-------	.5	.8	4.8	2.1	1.3	.2	1.4	3.7	2.0	1.4	.6	1.5
Marshland Creek-----	.0	.0	65.5	29.1	15.8	.1	.0	31.6	11.8	13.7	.1	1.2
Total monthly surface runoff------	7.3	70.2	435	145	77.1	6.3	37.0	264	128	85.4	20.1	55.8
					1973							
Manitou Way storm sewer-------------	5.6	8.9	17.1	16.2	11.2	2.2	2.0	2.8	6.2	4.9	2.7	4.1
Nakoma Road storm sewer-------------	84.4	94.2	222	194	188	15.4	15.0	21.7	81.9	49.3	22.1	60.0
Glenway Street storm sewer-------	17.8	15.6	38.3	26.3	30.2	11.7	5.7	7.5	9.8	13.4	7.3	10.9
Knickerbocker Street storm sewer-------	3.9	6.6	11.6	11.5	8.7	.9	2.8	1.5	4.2	1.4	1.7	2.6
Van Buren Street storm sewer-------	3.0	2.7	2.5	4.0	5.2	1.8	1.1	.9	2.2	2.0	1.2	1.7
Marshland Creek-----	20.9	30.9	125	82.5	75.7	5.3	.6	2.6	6.1	12.5	5.8	10.4
Total monthly surface runoff------	136	159	417	334	319	37.3	27.2	37.0	110	83.5	40.8	89.7

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
					1974							
Manitou Way storm sewer-------------	12.6	0.9	13.2	7.3	7.7	6.4	3.8	5.1	0.1	6.4	2.9	2.0
Nakoma Road storm sewer-------------	170	22.6	190	101	138	67.2	37.1	50.7	7.8	39.7	24.0	25.5
Glenway Street storm sewer-------	54.4	9.8	31.4	18.1	19.0	16.2	10.2	13.0	.4	16.1	7.9	5.7
Knickerbocker Street storm sewer-------	10.5	1.6	6.0	4.9	5.3	4.3	2.4	3.3	.1	4.2	1.7	1.2
Van Buren Street storm sewer-------	6.8	.0	3.6	2.4	2.5	2.2	1.6	1.8	.1	2.1	1.2	.9
Marshland Creek-----	39.6	6.7	55.6	39.8	46.7	17.7	3.7	8.4	.1	11.0	2.9	9.5
Total monthly surface runoff------	294	41.6	300	174	219	114	58.8	82.3	8.6	79.5	40.6	44.8
					1975							
Manitou Way storm sewer-------------	1.9	1.3	42.0	69.9	23.2	14.1	10.3	5.3	1.4	1.4	6.0	1.7
Nakoma Road storm sewer-------------	20.0	7.4	305	108	65.5	272	127	96.8	37.0	28.8	35.0	10.6
Glenway Street storm sewer-------	5.4	3.8	86.4	137	50.9	32.7	24.7	13.5	4.2	4.1	15.1	4.9
Knickerbocker Street storm sewer-------	1.1	.7	34.5	60.7	17.8	10.3	7.3	3.5	.8	.8	4.0	1.0
Van Buren Street storm sewer-------	.9	.7	8.2	11.8	5.4	3.8	3.0	1.9	.7	.7	2.1	.9
Marshland Creek-----	7.9	3.9	156	90.7	11.3	62.4	25.0	17.9	.3	.1	6.5	5.9
Total monthly surface runoff------	37.2	17.8	632	478	174	395	197	139	44.4	35.9	68.7	25.0

Table 2.--Measured and estimated surface runoff from gaged areas (10.85 km^2) in the Lake Wingra basin--Continued[1]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
					1976							
Manitou Way storm sewer-------------	0.0	11.1	17.2	26.1	20.8	2.9	2.2	2.4	0.5	2.2	0.0	0.0
Nakoma Road storm sewer-------	.3	158	245	110	50.7	9.6	4.2	9.3	1.5	12.3	.0	.0
Glenway Street storm sewer-------	.0	26.3	39.0	56.6	46.3	7.8	6.2	6.8	1.7	6.4	.0	.0
Knickerbocker Street storm sewer-------	.0	7.8	12.8	20.3	15.8	1.7	1.3	1.5	.3	1.4	.0	.0
Van Buren Street storm sewer-------	.0	3.2	4.4	5.9	5.0	1.2	1.0	1.1	.3	1.1	.0	.0
Marshland Creek-----	.1	56.2	88.1	68.5	2.9	1.4	.3	2.3	.1	1.7	.0	.0
Total monthly surface runoff------	0.4	263	406	287	142	24.6	15.2	23.4	4.4	25.1	0.0	0.0
					1977							
Manitou Way storm sewer-------------	0.0	3.3	6.6	49.9	2.2	4.5	15.4	0.6	4.8	----	---	---
Nakoma Road storm sewer-------------	.0	67.9	73.4	58.1	9.7	29.4	215	56.7	15.9	----	---	---
Glenway Street storm sewer-------	.0	8.9	16.5	101	6.3	11.7	15.6	4.5	6.9	----	---	---
Knickerbocker Street storm sewer-------	.0	2.1	4.4	41.6	1.3	2.8	10.7	4.0	2.4	----	---	---
Van Buren Street storm sewer-------	.0	1.4	2.2	9.2	1.1	1.7	1.3	2.0	1.8	----	---	---
Marshland Creek-----	.0	19.6	31.8	53.8	1.4	13.7	77.8	1.6	11.8	----	---	---
Total monthly surface runoff------	0.0	103	135	314	22.0	63.8	336	69.4	43.6	----	---	---

[1]Runoff was measured at all sites from January 1972 through October 1973. Subsequent figures are based on fragmentary station records or estimates based on relations defined below:

Glenway Street storm sewer $(1{,}000\ m^3) = 6.83Q^{0.804}$ where Q = total monthly runoff (ft^3/s) from Manitou Way storm sewer (correlation coefficient = 0.95).

Knickerbocker Street storm sewer $(1{,}000\ m^3) = 1.47Q^{1.11}$ where Q = total monthly runoff (ft^3/s) from Manitou Way storm sewer (correlation coefficient = 0.94).

Van Buren Street storm sewer $(1{,}000\ m^3) = 1.11Q^{0.705}$ where Q = total monthly runoff (ft^3/s) from Manitou Way storm sewer (correlation coefficient = 0.88).

Marshland Creek (May-Nov.)$(1{,}000\ m^3) = 0.323P^{2.78}$ where P = average monthly precipitation for Lake Wingra basin using Thiessen factor (correlation coefficient = 0.85).

(Dec.-Apr.)$(1{,}000\ m^3)$: estimated from drainage area-discharge relations defined by five sites.

Table 3.--Estimated surface runoff from ungaged areas (2.65 km^2) in the Lake Wingra basin

(Units in cubic meters)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1972	2.2	15.2	100	29.4	19.1	1.9	12.2	77.2	38.6	22.2	6.4	15.2
1973	34.2	37.4	96.8	77.1	71.5	9.1	8.6	11.2	31.8	21.1	10.5	22.7
1974	66.1	11.0	73.4	39.1	46.5	26.9	15.2	22.7	1.6	25.7	11.2	10.2
1975	8.3	4.4	164	93.3	51.4	78.3	46.5	31.8	12.4	8.8	19.6	6.1
1976	.2	58.8	97.6	78.3	44.1	6.6	3.6	6.4	1.2	7.3	0	0
1977	0	21.5	31.8	53.8	6.6	14.4	83.9	24.5	12.3	----	----	----

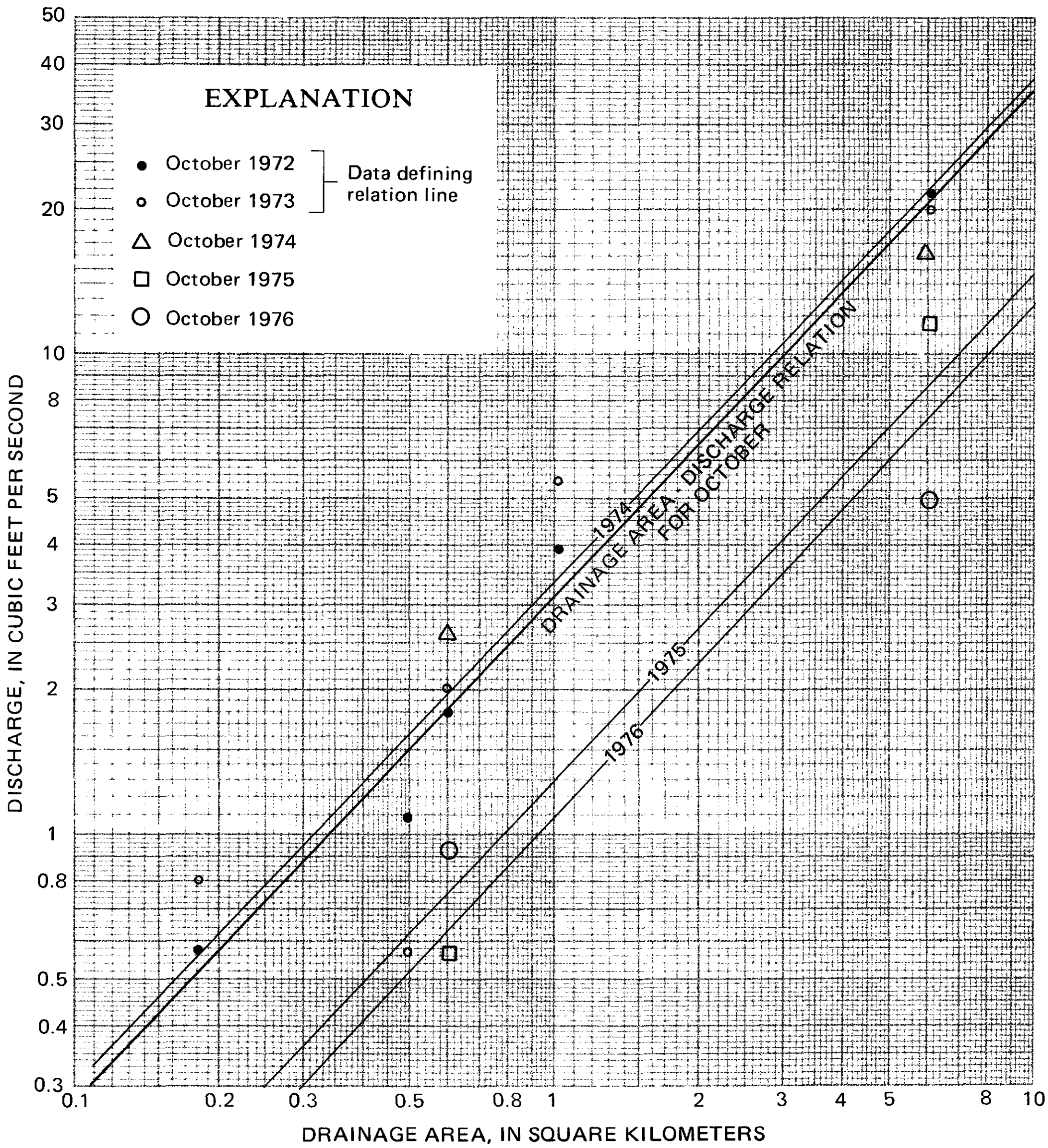

Figure 3. An example of relations between surface runoff and drainage area used to estimate runoff from ungaged areas.

GROUND-WATER INFLOW

Ground-water inflow includes springflow and upward leakage through the wetland soils and through the lake bottom. Springflow (included in "ground-water inflow", tables 8 and 9) was measured at three sites, Dn-5, Dn-6, and Dn-8 (fig. 1 and Oakes and others, 1975, table 4) from January 1972 through June 1973. Intermittent measurements were obtained at Dn-5 and Dn-8 from July 1973 to October 1976. For periods when two springs were measured, flow from the third was estimated from flow hydrographs at the measured sites. This technique also was used to correct data obtained when

Table 4.--Measured and estimated springflow, in cubic meters per second, from springs Dn-5, Dn-6, and Dn-8

(Underscored values are those used in table 1)

(3 = total of measurements at all three sites; 2 = missing data estimated from hydrographs based on available measurements; 1 = estimate based on ratio of available measurements; 0 = estimate based on correlation with monthly departure of precipitation from normal)

Basis for estimate (see note above)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						1972						
3	0.040	-----	0.042	0.045	0.041	0.032	0.029	0.036	[1]0.037	[1]0.036	[1]0.035	[1]0.035
2		0.037							.040	.040	.039	.038
1												
0	.036	.035	.033	.031	.030	.029	.029	.033	.037	.038	.037	.037
						1973						
3	[1].039	[1].036	[1].040	[1].043	.048	.044						
2	.040	.041	.044	.046			.042	.039	.044	.046	.044	.046
1							.033	.032	.036	.037	.042	.044
0	.037	.037	.040	.045	.048	.045	.044	.039	.042	.043	.043	.043
						1974						
3												
2	.044	.047	.051	.049	.053	.051		.051	.048			
1	.043	.046	.049	.048	.052	.048	.048			.048	.046	.042
0	.045	.045	.046	.046	.050	.052	.051	.052	.045	.050	.050	.051

1975												
3												
2												
1	.044	.045	.050	.049	.050	.045	.049	.052	.056	.061	.060	.059
0	.050	.051	.051	.052	.053	.056	.059	.061	.058	.056	.058	.056
1976												
3												
2												
1				[1].050	.054	.046	[1].035	[1].041	[1].037	[1].044		
0	.055	.056	.058	.060	.057	.056	.053	.050	.046	.046	.043	.041
1977												
3												
2												
1								[1].046				
0	.040	.041	.041	.039	.037	.037	.042	.044	.044	.043	.043	.043

[1]Part of the flow was measured and part bypassed the weir or flume, so springflow is estimated from other available data.

a flume or weir malfunctioned. When only one site was measured, total flow was estimated as a ratio of total flow to that at the measured site, determined for months when all three sites were measured and flows were similar. When no measurements were available, total flow was estimated on the basis of the cumulative departure of precipitation from normal. The estimated springflow is shown in table 4. These values are used in the calculation of total monthly ground-water inflow (GWI_t in equation 3) shown in table 8, as discussed below.

Ground-water inflow from ungaged springs and by diffuse upward leakage through the wetland soils and through the lake bottom was estimated from vertical gradients and vertical hydraulic conductivity. For the period October 1974 through September 1976, Huff and Young (1979, unpublished data) reported ground-water inflow of 49 m^3/d for 0.098 km^2 of the wetland on the west side of Lake Wingra (0.0005 $(m^3/d)/m^2$). Assuming that this inflow rate also represented the remaining wetland area (0.712 km^2) for January 1972 through September 1977, the volume of ground-water inflow in the marsh area was calculated as 400 m^3/d. For January 1972 through June 1973 Oakes, Hendrickson, and Zuehls (1975, p. 26) reported ground-water inflow through the lake bottom sediments of 0.0048 $(m^3/d)/m^2$. This rate is approximately 10 times as great as that for the wetland soils, and probably reflects the greater hydraulic conductivity of the predominantly mineral lake-bottom sediments compared to the predominantly organic wetland soils. They assumed that this infiltration occurred over approximately 0.26 km^2 of the lake area. Assuming that this inflow rate represented the average value during the period January 1972 through September 1977, ground-water inflow along the lakeshore was estimated as 1,250 m^3/d. The combined ground-water inflow was then calculated as 1,650 m^3/d. Variations of ground-water inflow were not adequately defined by ground-water-level measurements, so it was assumed to vary as springflow did. Springflow averaged 0.046 m^3/s (table 4) or 3,970 m^3/d. Monthly springflow times (1.0 plus 1650/3970) provided the estimated monthly ground-water inflow (GWI_t in equation 3) entered in table 8.

Outputs

LAKE OUTFLOW

Lake outflow has been measured from October 1970 to the present. The values are published annually in the U.S. Geological Survey report series "Water Resources Data for Wisconsin". The site is identified as station 05429120, Lake Wingra outlet at Madison, Wis. The monthly lake outflow (SO_t in equation 3) is shown in table 8.

LAKE EVAPORATION

Evaporation from the lake surface was computed using a technique developed by Lamoreaux (1962) using climatological data (Environmental Data Service, 1972-77) and solar radiation measurements (Val Mitchell, State Climatologist, written commun., 1978) for Truax Field. Monthly lake evaporation rates are shown in table 5. These rates are converted to total monthly evaporation (E_t in equation 3) in table 8.

Table 5.--Calculated evaporation rates for Lake Wingra

(Units in millimeters)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1972	6	10	33	52	106	126	110	87	50	30	9	3
1973	9	12	33	49	72	113	126	104	53	34	12	4
1974	8	10	29	69	78	110	129	87	68	39	12	5
1975	5	11	25	43	96	95	112	75	58	46	14	4
1976	5	17	31	67	99	141	150	126	74	36	15	5
1977	3	12	35	77	135	118	140	72	44	30	9	4

WETLAND EVAPOTRANSPIRATION

Evapotranspiration from the wetland area was estimated from recorded pan evaporation. Studies by Sturges (1968) in Wyoming and by Bay (1966) in Minnesota showed that evapotranspiration in wetlands where water is available throughout the growing season usually equals or exceeds (by as much as 27 percent) measured pan evaporation. No information was available to adjust measured pan evaporation, so ET was assumed equal to pan evaporation, although this estimate may be 10 to 20 percent low. This technique was adequate for estimating ET in the water budget for the Nevin wetland (Novitzki, 1978), approximately 4 km south of Lake Wingra. Pan evaporation was measured in the Lake Wingra basin (fig. 1 and Oakes and others, 1975, table 2) from April 1971 through September 1972. Pan evaporation was measured at the Nevin State Fish Hatchery (fig. 1 and Novitzki, 1978, p. 3, 15), approximately 4 km south of Lake Wingra, from June 1973 through October 1976. Pan evaporation measurements were not available for October 1972, May 1973, May 1975, and all of 1977, so ET was estimated to be equal to potential ET calculated by the Thornthwaite and Mather technique (1957). Measured pan evaporation and calculated potential ET are shown in table 6. These values are converted to total monthly evapotranspiration (ET_t in equation 3) in table 8.

GROUND-WATER OUTFLOW

Ground-water seepage from the lake into the ground-water system was reported by Oakes, Hendrickson, and Zuehls (1975, p. 17, 27). They report an average seepage rate of 0.0016 $(m^3/d)/m^2$. (This outflow rate is one-third the inflow rate they report because their data indicated that the hydraulic gradient toward the lake on the west was three times as great as the hydraulic gradient away from the lake on the east.) They assumed that seepage occurs over the entire lake bottom except that through which ground-water inflow occurs. McBride and Pfannkuch (1975) show that most seepage

Table 6.--Pan evaporation measured in the Lake Wingra basin and at the Nevin State Fish Hatchery, and calculated potential ET (Thornthwaite and Mather, 1957)

(Units in millimeters)

	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Total
1972										
Wingra	---	---	103	125	131	100	80	---	---	539
Potential ET	---	26	86	107	128	119	79	36	6	587
1973										
Nevin	---	---	---	148	157	141	84	78	---	608
Potental ET	23	34	67	127	138	128	79	51	6	653
1974										
Nevin	---	---	130	119	159	125	93	70	---	696
Potential ET	---	51	67	107	147	119	71	43	12	617
1975										
Nevin	---	---	---	151	178	144	88	93	---	654
Potential ET	---	17	96	127	147	128	71	43	19	648
1976										
Nevin	---	114	136	189	204	168	114	77	---	1,002
Potential ET	8	51	67	127	147	119	71	29	---	619
1977										
Nevin	---	---	---	---	---	---	---	---	---	---
Potential ET	15	51	106	107	147	101	71	36	61	---

occurs near the lakeshore and little occurs through the rest of the lake bottom. Springs occur around much of the west and south sides of the lake, indicating that ground water is flowing into about half of the potential area where seepage may occur. Under normal conditions it would appear that only ground-water inflow to Lake Wingra would occur, and that seepage out of the lake is recharge induced by pumpage. Although ground-water levels are above lake level around most of the lake, ground-water levels near the east side of the lake were below lake level and declined with depth. Because this is not a natural condition, the area in which outflow occurs may be somewhat larger than the potential seepage area in a natural lake aquifer system. It is arbitrarily assumed that the outflow area is 1.5 times as large as the inflow area (1.5 X 0.26 = 0.39 km^2). Then outflow averages 390,000 m^2 X 0.0016 m^3/m^2 = 624 m^3/d, or 18,700 m^3/month.

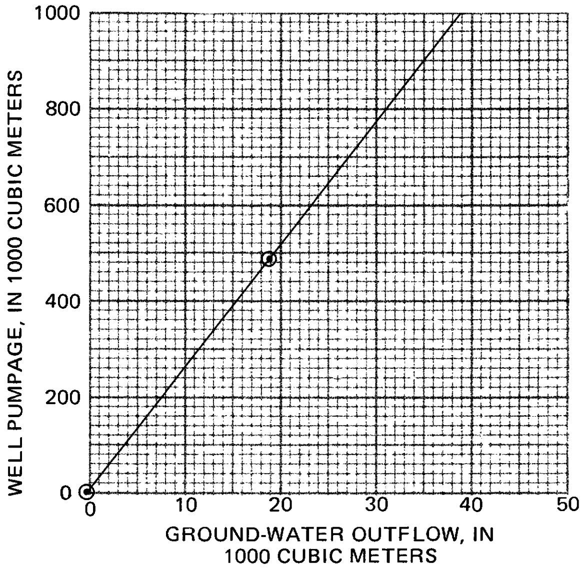

Figure 4. Estimated monthly ground-water outflow from Lake Wingra related to monthly pumpage from Madison public water-supply wells in the lake basin.

Outflow will vary as the hydraulic gradient varies, but intermittent ground-water-level measurements were inadequate to define these variations throughout the study period. However, assuming that outflow is the result of recharge induced by pumpage from Madison public water-supply wells (Oakes and others, 1975, p. 17), it may be assumed that it varies proportionally as city well pumpage varies. Monthly pumpage from four city wells within the Lake Wingra basin (Dn-46, Dn-47, Dn-96, and Dn-961, fig. 1) varied from 253,000 to 950,000 m3 (table 7, Larry Deibert, written commun., 1978) and averaged 491,000 m^3. Plotting the average monthly pumpage against average monthly outflow (18,700 m^3) and assuming that outflow is induced by pumpage and would be zero if pumpage were zero defines the relation shown in figure 4. This straight-line relation is unlikely, but no additional data is available to better define the relation. Consequently, monthly ground-water outflow (GWO_t in equation 3) is assumed to vary proportionally to pumpage, and is calculated from monthly pumpage (table 7) and figure 4. Monthly ground-water outflow is presented in table 8.

DISCUSSION

The monthly inputs and outputs to Lake Wingra, estimated by the techniques described above, are presented in table 8. Average monthly and annual budgets are summarized in table 9. Comparing monthly lake volumes calculated from the water budget (V_t from equation 3) to those calculated from observed lake stages indicates that the water-budget terms are reasonable. The volume of water in Lake Wingra was determined from a stage-volume relation (fig. 5) modified from a depth-volume relation reported by Patterson, Wagner, Hoopes, and Woloshuk (1972). Lake Wingra stages are published annually in the U.S. Geological Survey water-data reports (station 05429118,

Table 7.--Total monthly pumpage from Madison city wells in the Lake Wingra basin (wells 1, 2, 10, and 18, figure 1)

(Units in 1,000 m^3)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1972	328	306	330	342	553	625	772	598	522	439	443	325	5,583
1973	466	428	454	583	693	863	950	757	519	401	327	325	6,766
1974	342	303	332	323	390	526	746	644	659	621	519	439	5,844
1975	485	469	485	485	594	621	685	613	454	416	287	253	5,847
1976	329	322	338	353	549	829	837	591	500	347	354	366	5,715
1977	364	323	359	405	572	526	606	526	450	---	---	---	4,131

Table 8.--Monthly water budgets for Lake Wingra and adjacent wetland areas from January 1972 through September 1977

(Units in 1,000 m^3)

	Terms in equations 3 and 4	1972 Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
INPUTS													
PRECIPITATION (P)	P_t	15	15	93	123	152	56	189	421	245	178	56	111
Flow to ground-water storage	P'_t	15	15	93	---	---	---	---	---	---	178	56	111
Return from ground-water storage	$0.15GWS_{t-1}$	0	2	4	18	15	13	11	9	8	6	32	36
Ground-water storage balance[1]	GWS_t	(15)	(28)	(117)	(99)	(84)	(71)	(60)	(51)	(43)	(215)	(239)	(314)
SURFACE RUNOFF	SR_t	10	85	535	174	96	8	49	341	167	108	26	71
GROUND WATER	GWI_t	153	127	157	166	157	119	109	136	147	153	149	144
TOTAL INPUT		163	214	696	481	420	196	358	907	567	267	207	251
OUTPUTS													
LAKE OUTFLOW	SO_t	193	120	625	547	355	0	0	331	322	224	152	99
EVAPOTRANSPIRATION													
Lake	E_t	8	14	45	71	145	173	151	119	68	41	12	4
Wetland	ET_t	---	---	---	---	82	100	105	80	64	[2]29	---	---
GROUND WATER	GWO_t	12	12	13	13	21	24	30	23	20	17	17	12
TOTAL OUTPUT		213	146	683	631	603	297	286	553	474	311	181	115
LAKE VOLUME													
From water-budget calculations	V_t	3,336	3,404	3,417	3,267	3,084	2,983	3,055	3,409	3,502	3,458	3,484	3,620
From observed lake levels	V_t	3,355	3,333	3,399	3,390	3,280	3,193	3,197	3,412	3,386	3,360	3,298	3,386

Table 8.--Monthly water budgets for Lake Wingra and adjacent wetland areas from January 1972 through September 1977--Continued

(Units in 1,000 m^3)

	Terms in equations 3 and 4	1973											
		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
INPUTS													
PRECIPITATION (P)	P_t	85	89	280	421	347	91	89	117	252	145	89	130
Flow to ground-water storage	P'_t	(85)	(89)	(280)	---	---	---	---	---	---	(145)	(89)	(130)
Return from ground-water storage	$0.15GWS_{t-1}$	47	53	58	92	78	66	56	48	40	34	51	57
Ground-water storage balance[1]	GWS_t	(352)	(388)	(610)	(518)	(440)	(374)	(318)	(270)	(230)	(341)	(379)	(452)
SURFACE RUNOFF	SR_t	170	196	514	411	390	46	36	48	142	105	51	112
GROUND WATER	GWI_t	151	140	167	170	181	161	161	149	161	174	161	174
TOTAL INPUT		368	389	739	1,094	996	364	342	362	595	313	263	343
OUTPUTS													
LAKE OUTFLOW	SO_t	365	377	860	732	773	217	7	7	141	361	235	357
EVAPOTRANSPIRATION													
Lake	E_t	12	16	45	67	99	155	173	142	73	47	16	5
Wetland	ET_t	---	---	---	---	[2]54	118	126	112	67	62	---	---
GROUND WATER	GWO_t	18	16	17	22	27	33	37	29	20	15	12	12
TOTAL OUTPUT		395	409	922	821	953	523	343	290	301	485	263	374
LAKE VOLUME													
From water-budget calculations	V_t	3,593	3,573	3,390	3,663	3,706	3,547	3,546	3,618	3,912	3,740	3,740	3,709
From observed lake levels	V_t	3,359	3,342	3,350	3,439	3,434	3,298	3,271	3,302	3,430	3,350	3,359	3,364

Table 8.--Monthly water budgets for Lake Wingra and adjacent wetland areas from January 1972 through September 1977--Continued

(Units in 1,000 m^3)

	Terms in equations 3 and 4	1974											
		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
INPUTS													
PRECIPITATION (P)	P_t	145	80	193	226	299	197	132	178	46	195	122	111
Flow to ground-water storage	P'_t	145	80	193	---	---	---	---	---	---	195	122	111
Return from ground-water storage	$0.15GWS_{t-1}$	68	79	80	96	82	70	59	50	43	36	60	70
Ground-water storage balance[1]	GWS_t	(529)	(530)	(643)	(547)	(465)	(395)	(336)	(286)	(243)	(402)	(464)	(505)
SURFACE RUNOFF	SR_t	360	53	373	213	266	141	74	105	10	105	52	55
GROUND WATER	GWI_t	167	160	194	181	200	185	193	193	177	180	167	157
TOTAL INPUT		595	292	647	716	847	593	458	526	276	321	279	282
OUTPUTS													
LAKE OUTFLOW	SO_t	535	408	686	763	766	412	23	50	6	266	317	304
EVAPOTRANSPIRATION													
Lake	E_t	11	14	40	95	107	151	177	119	93	53	16	7
Wetland	ET_t	---	---	---	---	104	95	127	100	74	56	---	---
GROUND WATER	GWO_t	13	12	13	12	15	20	29	25	25	24	20	17
TOTAL OUTPUT		559	434	739	870	992	678	356	294	198	399	353	328
LAKE VOLUME													
From water-budget calculations	V_t	3,745	3,603	3,511	3,357	3,212	3,127	3,229	3,461	3,539	3,461	3,387	3,341
From observed lake levels	V_t	3,494	3,386	3,471	3,394	3,394	3,315	3,280	3,324	3,289	3,360	3,359	3,346

Table 8.--Monthly water budgets for Lake Wingra and adjacent wetland areas from January 1972 through September 1977--Continued

(Units in 1,000 m^3)

	Terms in equations 3 and 4	1975											
		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
INPUTS													
PRECIPITATION (P)	P_t	61	95	176	224	197	367	263	234	50	35	163	17
Flow to ground-water storage	P'_t	61	95	176	---	---	---	---	---	---	35	163	17
Return from ground-water storage	$0.15GWS_{t-1}$	76	74	77	92	78	66	56	48	40	34	35	54
Ground-water storage balance[1]	GWS_t	(490)	(511)	(610)	(518)	(440)	(374)	(318)	(270)	(230)	(231)	(359)	(322)
SURFACE RUNOFF	SR_t	46	22	796	571	225	473	244	171	57	45	88	31
GROUND WATER	GWI_t	167	154	190	180	190	166	185	195	205	229	221	222
TOTAL INPUT		289	250	1,063	1,067	690	1,072	748	648	352	308	344	307
OUTPUTS													
LAKE OUTFLOW	SO_t	204	151	859	802	637	891	628	270	161	127	280	328
EVAPOTRANSPIRATION													
Lake	E_t	7	15	34	59	132	130	153	103	79	63	19	5
Wetland	ET_t	---	---	---	---	[2]77	121	142	115	70	76	---	---
GROUND WATER	GWO_t	18	18	18	18	23	24	26	24	17	16	11	10
TOTAL OUTPUT		229	184	911	879	869	1,166	949	512	327	282	310	343
LAKE VOLUME													
From water-budget calculations	V_t	3,401	3,467	3,619	3,807	3,628	3,534	3,333	3,469	3,494	3,520	3,554	3,518
From observed lake levels	V_t	3,315	3,333	3,453	3,600	3,466	3,494	3,337	3,368	3,328	3,333	3,443	3,342

Table 8.--Monthly water budgets for Lake Wingra and adjacent wetland areas from January 1972 through September 1977--Continued

(Units in 1,000 m^3)

	Terms in equations 3 and 4	1976											
		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
INPUTS													
PRECIPITATION (P)	P_t	26	145	267	256	122	95	54	111	33	102	9	24
Flow to ground-water storage	P'_t	26	145	267	---	---	---	---	---	---	102	9	24
Return from ground-water storage	$0.15GWS_{t-1}$	48	45	60	91	77	66	56	48	40	34	45	39
Ground-water storage balance[1]	GWS_t	(300)	(400)	(607)	(516)	(439)	(373)	(317)	(269)	(229)	(297)	(261)	(246)
SURFACE RUNOFF	SR_t	1	322	504	365	186	31	19	30	6	32	0	0
GROUND WATER	GWI_t	208	190	219	219	205	170	200	188	137	173	159	156
TOTAL INPUT		257	557	783	931	590	362	329	377	216	239	204	195
OUTPUTS													
LAKE OUTFLOW	SO_t	224	481	1,014	718	436	59	2	0	0	0	56	184
EVAPOTRANSPIRATION													
Lake	E_t	7	23	42	92	136	193	206	173	101	49	21	7
Wetland	ET_t	---	---	---	---	109	151	163	134	91	61	---	---
GROUND WATER	GWO_t	12	12	13	13	21	32	32	23	19	13	13	14
TOTAL OUTPUT		243	516	1,069	823	702	435	403	330	211	123	90	205
LAKE VOLUME													
From water-budget calculations	V_t	3,532	3,573	3,287	3,395	3,283	3,210	3,136	3,183	3,188	3,304	3,418	3,408
From observed lake levels	V_t	3,333	3,457	3,439	3,457	3,342	3,311	3,240	3,227	3,201	3,289	3,333	3,328

Table 8.--Monthly water budgets for Lake Wingra and adjacent wetland areas from January 1972 through September 1977--Continued

(Units in 1,000 m^3)

	Terms in equations 3 and 4	1977 Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
INPUTS													
PRECIPITATION (P)	P_t	26	76	213	158	93	167	473	202	139	---	---	---
Flow to ground-water storage	P'_t	26	76	213	---	---	---	---	---	---	---	---	---
Return from ground-water storage	$0.15GWS_{t-1}$	37	35	41	67	57	49	41	35	30	---	---	---
Ground-water storage balance[1]	GWS_t	(235)	(276)	(448)	(381)	(324)	(275)	(234)	(199)	(169)	---	---	---
SURFACE RUNOFF	SR_t	0	124	167	368	29	78	420	94	56	---	---	---
GROUND WATER	GWI_t	153	140	154	143	140	137	160	176	160	---	---	---
TOTAL INPUT		190	299	362	736	319	431	1,094	507	385	---	---	---
OUTPUTS													
LAKE OUTFLOW	SO_t	215	328	539	545	91	190	620	190	172	---	---	---
EVAPOTRANSPIRATION													
Lake	E_t	4	16	48	105	185	162	192	99	60	---	---	---
Wetland	ET_t	---	---	---	---	[2]85	[2]86	[2]118	[2]81	[2]57	---	---	---
GROUND WATER	GWO_t	14	12	14	15	22	20	23	20	17	---	---	---
TOTAL OUTPUT		233	356	601	665	383	458	953	390	306	---	---	---
LAKE VOLUME													
From water-budget calculations	V_t	3,365	3,308	3,069	3,140	3,076	3,049	3,190	3,307	3,386	---	---	---
From observed lake levels	V_t	3,333	3,406	3,453	3,355	3,306	3,218	3,218	3,245	3,210	---	---	---

[1]Ground-water storage (GWS_t) does not enter water-budget calculations, except that 15 percent of the storage balance is added to the budget in the following month.

[2]Pan evaporation data missing; value is potential ET calculated by the Thornthwaite and Mather technique (1957).

Table 9.--Six-year average monthly and annual water budgets for Lake Wingra and adjacent wetland areas (Units in 1,000 m^3; numbers in parentheses indicates percentage)[1]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Precipitation	60 (18)	83 (23)	204 (23)	235 (31)	202 (35)	162 (36)	200 (39)	210 (41)	127 (35)	131 (33)	88 (29)	79 (26)	1,781 (31)
Surface runoff	98 (30)	134 (36)	481 (56)	350 (46)	199 (34)	129 (29)	140 (28)	131 (25)	73 (20)	79 (20)	43 (14)	54 (18)	1,911 (34)
Ground-water inflow	167 (52)	151 (41)	180 (21)	177 (23)	177 (31)	156 (35)	168 (33)	173 (34)	164 (45)	181 (47)	171 (57)	171 (56)	2,036 (35)
Total input	325 (5.7)	368 (6.4)	--- (15)	762 (13)	578 (10)	447 (7.8)	508 (8.9)	514 (9.0)	364 (6.4)	391 (6.8)	302 (5.3)	304 (5.3)	5,728 ---
Lake outflow	289 (92)	311 (92)	764 (93)	684 (88)	510 (68)	295 (51)	213 (39)	141 (36)	134 (44)	196 (59)	208 (87)	254 (93)	3,999 (70)
Evapotranspiration													
Lake	8 (3)	16 (5)	42 (5)	81 (10)	134 (18)	148 (26)	175 (32)	126 (32)	79 (26)	51 (15)	17 (7)	6 (2)	883 (16)
Wetland	--- ---	--- ---	--- ---	--- ---	85 (11)	112 (19)	130 (24)	104 (26)	70 (23)	68 (21)	--- ---	--- ---	569 (10)
Ground-water	14 (5)	12 (3)	15 (2)	15 (2)	21 (3)	25 (4)	29 (5)	24 (6)	20 (7)	17 (5)	15 (6)	13 (5)	220 (4)
Total output	311 (5.5)	339 (6.0)	821 (15)	780 (14)	750 (13)	580 (10)	547 (9.6)	395 (7.0)	303 (5.3)	332 (5.9)	240 (4.2)	273 (4.8)	5,671 ---

[1]Percentage figure is the percentage of the input or output from each source compared to the total input or output for the month or the percentage of the total monthly input or output compared to the total annual input or output.

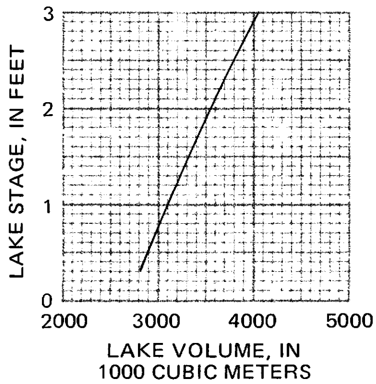

Figure 5. Stage-volume relation for Lake Wingra.

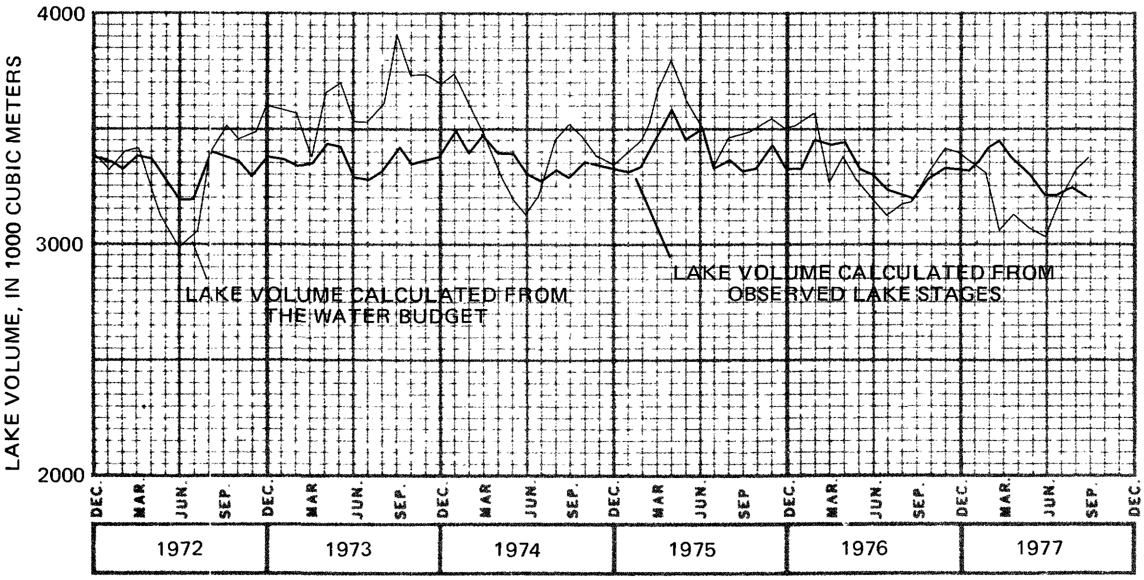

Figure 6. Monthly lake volumes indicated by the water budget compared to those calculated from observed lake stages.

Lake Wingra at Madison, Wis.). In figure 6 the lake volume defined by the lake stage on the last day of each month is compared to the lake volume indicated by the water budget (table 8).

The lake volumes calculated from the water budget are typically higher than those observed in the fall and winter, but lower than those observed in spring and summer (fig. 6). This indicates that precipitation stored as snow and ice in the basin during the winter, subsequently released following snowmelt, is independent of the ground-water storage described in the discussion of precipitation. However, a refinement in the budget to account for this phenomenon is not justified because of the approximate nature of the other water-budget terms. This refinement could be based on some other parameter (such as a nutrient budget) that would confirm independently an improvement in the water budget. However, such refinement is beyond the scope of this report.

Although the lake-volume comparison indicates that the water-budget terms are reasonable, some are considerably more accurate than others. Precipitation, lake volume, and lake outflow are based on direct measurements and are the most precise values in the water budget (although the ground-water storage reduces the accuracy of estimated precipitation input). Surface runoff, lake evaporation, and evapotranspiration are based on accepted estimation techniques and are probably good estimates. Ground-water inflow and outflow estimates, based on fragmentary hydraulic gradient data, approximate determinations of inflow and outflow areas, and an arbitrary relation between estimated monthly springflow and reported monthly pumpage are the least accurate.

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