U.S DEPARTMENT OF THE INTERIOR
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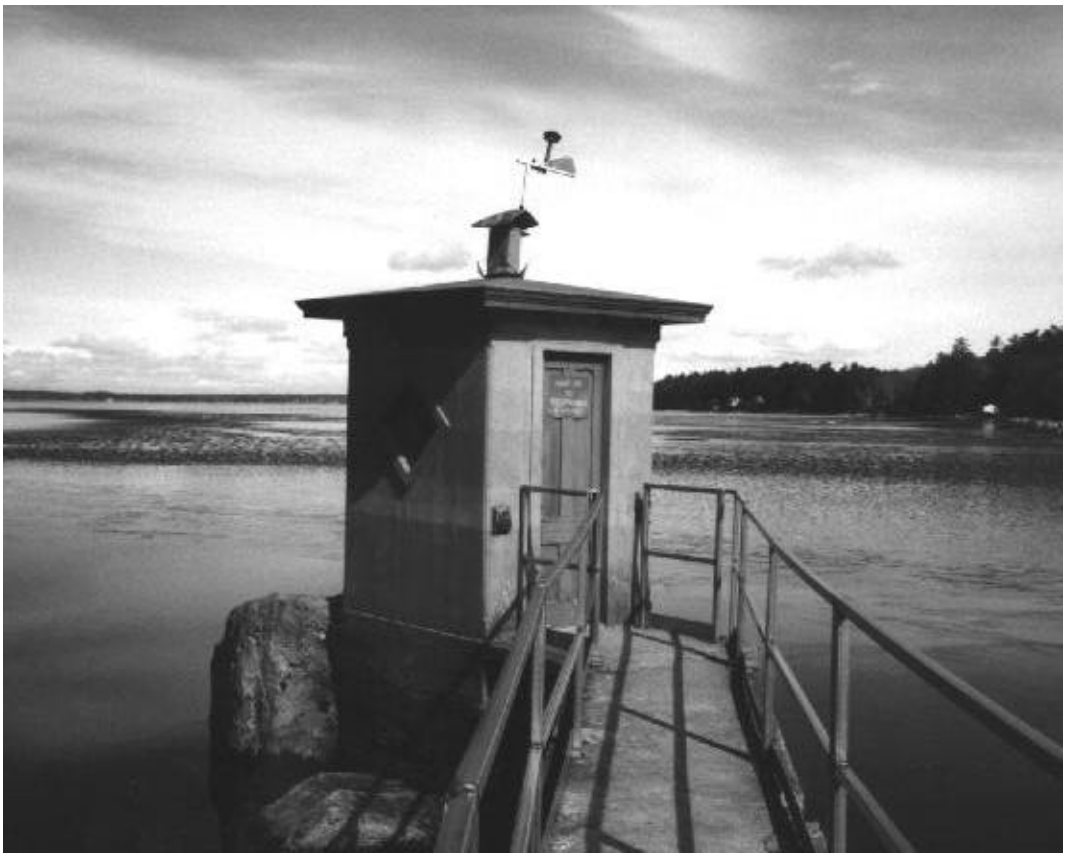
Water Budget for Sebago Lake, Maine, 1996-99

Water-Resources Investigations Report 01-4235



Prepared in cooperation with the
PORTLAND WATER DISTRICT,
TOWN OF WINDHAM,
MAINE DEPARTMENT OF HEALTH, AND
MAINE GEOLOGICAL SURVEY

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Cover Photograph. Gage at Sebago Lake (photo courtesy Robert Johnston).

Water Budget for Sebago Lake, Maine, 1996-99

By Robert W. Dudley, Glenn A. Hodgkins, and Joseph P. Nielsen

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PORTLAND WATER DISTRICT
TOWN OF WINDHAM
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MAINE GEOLOGICAL SURVEY

Augusta, Maine
2001

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

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CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot (ft^3)	0.02832	cubic meter
cubic foot (ft^3)	0.134	gallon
foot (ft)	0.3048	meter
gallon per minute (gal/min)	3.785	liter per minute
inch (in.)	2.54	centimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.59	square kilometer

Temperature in degrees Fahrenheit (^oF) may be converted to degrees Celsius (^oC), by using the following equation:

$$^oC = 5/9\ (^oF - 32)$$

Vertical datum: 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.

Other abbreviations: Mgal, million gallons; Mgal/d, million gallons per day

Water Budget for Sebago Lake, Maine Water Years 1996-99

by Robert W. Dudley, Glenn A. Hodgkins, and Joseph P. Nielsen

ABSTRACT

Annual water budgets were developed for Sebago Lake in southwestern Maine. The inflow components of the water budget are direct precipitation to the surface of the lake and surface-water inflow. Mean annual inflow to Sebago Lake during water years 1996-99 was 35,100 million cubic feet. The outflow components of the water budget are evaporation from the surface of the lake, municipal water-supply withdrawals by the Portland Water District, and surface-water outflow. Mean annual outflow during water years 1996-99 was 28,200 million cubic feet. The two largest components of the water budgets are the surface-water components—surface-water inflow was 84.0 percent of the mean annual inflow budget and surface-water outflow was 87.3 percent of the mean annual outflow budget. Changes in lake storage also were included in the water budgets.

The sum of inflow minus outflow volumes, adjusted for changes in lake storage, do not balance for each water year. This remainder volume is the residual in the water budget calculation. The mean annual residual for the 4 years is 5,860 million cubic feet and is relatively consistent in magnitude and sign (positive) each water year, indicating either a systematic overestimation of inflows to or underestimation of outflows from Sebago Lake. The residual also could be partially composed of ground-water flow, a budget component not accounted for in this study.

Errors associated with budgeting precipitation, evaporation, and net changes in storage are relatively small. The largest potential errors in calculating the water budget for Sebago Lake are those associated with surface-water inflow and outflow, because they are the two largest elements of the budget, and ground-water flow (net in or out) because it was not computed.

INTRODUCTION

Sebago Lake, in southwestern Maine, is the second largest lake in the State (fig. 1) and the principal water supply for about 170,000 people in southern Maine. The Portland Water District (PWD) withdraws about 8,500 Mgal annually from the lake and distributes water to residents of the greater Portland area. The city of Portland is about 15 mi southeast of the lake and is Maine's largest city, with a 1999 population of 64,000 (Maine Register, 2000). PWD customers in the greater Portland area (city of Portland and towns of Standish, Gorham, Windham, Scarborough, Westbrook, Falmouth, Cumberland, South Portland, and Cape Elizabeth (fig. 2)) are supplied with about 23 Mgal/d, of which more than 99 percent comes from Sebago Lake, supplemented by a well system in Standish (Phillip Boissonneault, Portland Water District, oral commun., 2001).

The PWD also is responsible for maintaining an adequate water supply and the protection of the quality of that supply. To protect the quality of the water supply, the PWD owns and protects more than 2,000 acres of land around its water intake. They also collect flow and water-quality data on nine tributaries to Sebago Lake (fig. 2). This information is used to ensure source-water quality and to estimate constituent loads and mass balances for the lake.

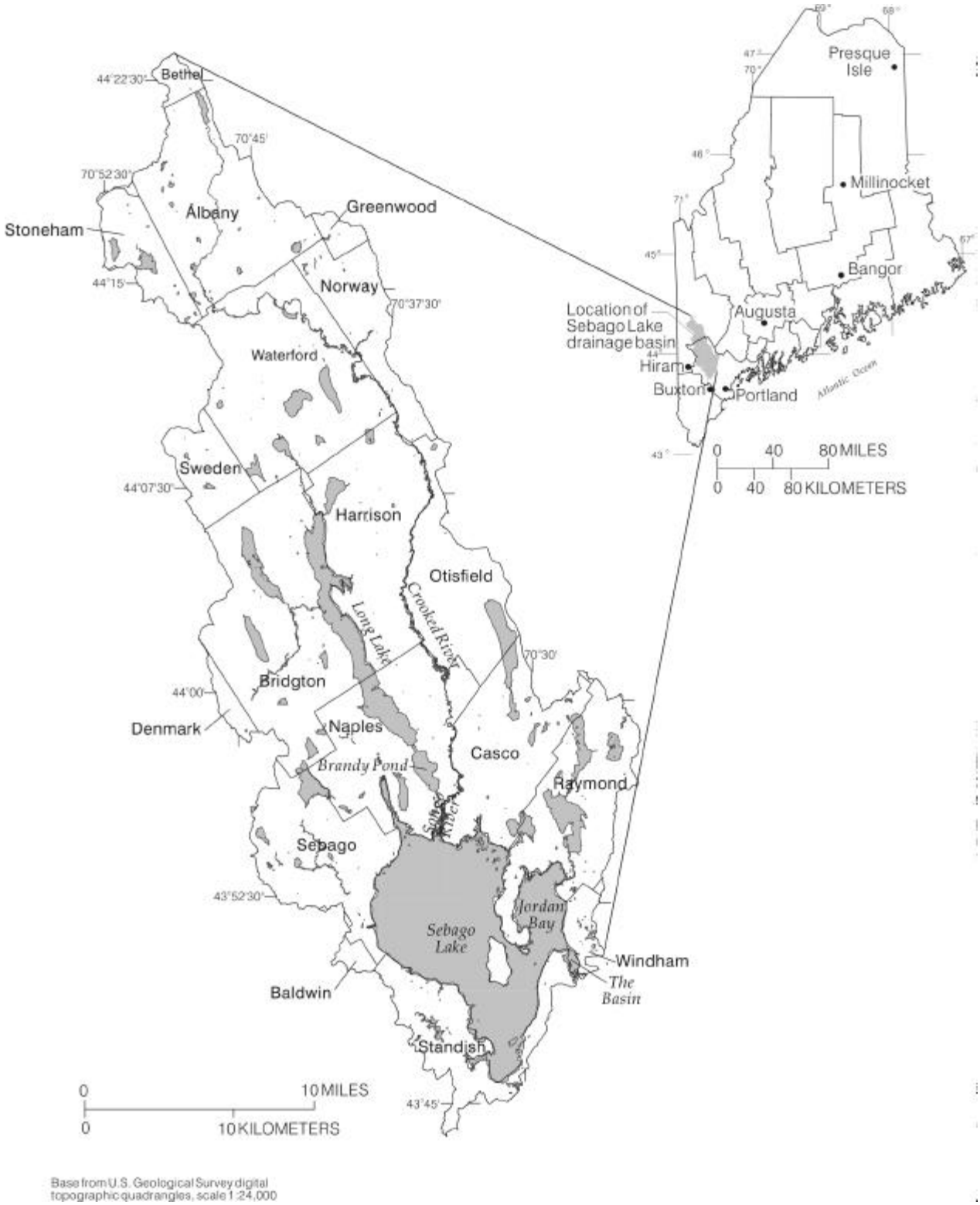

Figure 1. Sebago Lake drainage basin, southwestern Maine.

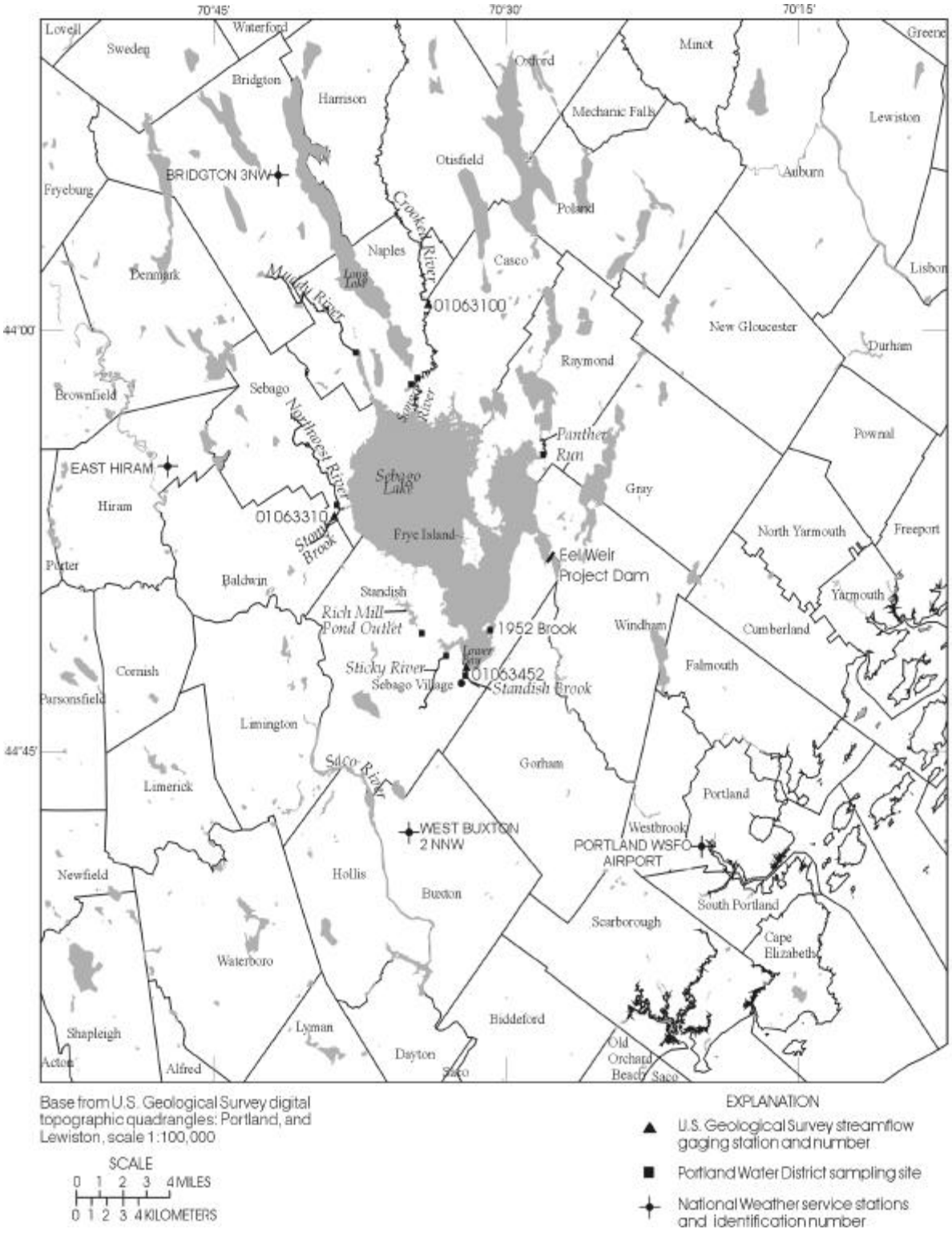

Figure 2. Sebago Lake and the greater Portland area.

The U.S. Geological Survey (USGS), in cooperation with the Portland Water District, the Town of Windham, the Maine Department of Health, and the Maine Geological Survey, began a study in 1995 to assess the water resources of the Sebago Lake watershed. Hydrologic, geologic, and water-quality data collected in the Presumpscot River Basin from April 1995 to September 1996 were summarized by Nichols and Silverman (1998). The report includes locations and streamflow data for surface-water sites, water-level data, water-quality data, grain-size data and lithologic logs of aquifer material associated with observation wells and test borings, and surface-water elevations for ponds, lakes, and streams in Windham.

The USGS also evaluated the existing streamflow-gaging stations and water-sampling networks operated by the PWD in terms of their applicability for computing total phosphorous loads for tributaries of Sebago Lake (Hodgkins, 2001). The locations and frequency of flow measurements, length of flow records, and the locations and frequency of water-quality sampling were examined in the evaluation. Hodgkins (2001) concluded that if all tributaries gaged by the PWD had adequate streamflow data, the current PWD tributary-monitoring program would likely produce data on total phosphorous loads that were representative of all gaged and ungaged tributaries to Sebago Lake.

This report has been modified from the original version to eliminate minor technical errors.

Purpose and Scope

This report presents an annual water budget for Sebago Lake for water years[1] 1996 through 1999. The report presents the computation and associated uncertainty of the following major water-budget components: (1) inflows, including direct precipitation on the lake surface and all major surface-water tributary inflows; (2) outflows, including evaporation, surface-water outflow, and municipal water-supply withdrawals; and (3) changes in lake storage.

[1] The term "water year" denotes the 12-month period from October 1 through September 30 and is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year beginning October 1, 1995 and ending September 30, 1996 is called "water year 1996."

Description of the Study Area

Sebago Lake has a surface area of 45.6 mi^2, a mean depth of 101 ft, a maximum depth of 316 ft (49 ft below sea level), and a mean hydraulic retention time of 5.4 years (Pacific Northwest Environmental Research Laboratory, 1974). Lake levels at Sebago Lake are governed at The Basin Dam (fig. 2), also referred to as the Eel Weir Project Dam, by a water-level management plan developed by South African Pulp and Paper, Inc. (SAPPI), the Federal Energy Regulatory Commission (FERC), the PWD, various State agencies, and local citizen groups. The Basin Dam is a stone masonry, concrete, and earth structure constructed in 1830 by the Cumberland and Oxford Canal Company to provide for better navigation and to divert water to a canal (Wheeler, 1994). The dam currently has a 115-ft long masonry spillway for uncontrolled flow when lake levels exceed the crest elevation of 266.65 ft above sea level. The dam provides water to a power canal, Eel Weir Hydroelectric Project, via 4 wooden gates with an additional 5 wooden gates to bypass flow. The dam raises the water-surface elevation of Sebago Lake by about 12 ft over what would be its natural level (Robert Johnston, Maine Geological Survey, written comm., 2000).

Physiography and Geology

Throughout Maine, bedrock typically consists of crystalline and sedimentary rocks that are overlain by glacial deposits. Localized, discontinuous sand and gravel aquifers containing glacial ice-contact and outwash deposits are scattered throughout the State. Where these aquifers are not present, wells typically draw their water supply from fractured bedrock. The inland area of the Sebago Lake drainage basin is underlain by 40 significant sand and gravel aquifers; that is, aquifers capable of yielding 10 or more gal/min to a typical private well (U.S. Department of Agriculture, 1995).

The Sebago Lake drainage basin has an area of 440 mi^2 (Cowing and McNelly, 1978) including the 45.6 mi^2 of lake surface area (fig. 1). The drainage basin is long, hilly, and narrow and spans 50 mi in a north-south direction. The basin is predominately rural and forested with some farmland, timber operations, and residential development. Many lakes and ponds are

interspersed throughout the basin. The surficial geology of the drainage basin consists primarily of glacial till (a mixture of sand, silt, clay, and stones), except near the Crooked River where it is mostly sand and gravel glacial outwash deposits (Thompson and Borns, 1985).

Climate

The temperate climate in the Sebago Lake Basin is typified by mild summers and cold winters. Based on records from National Weather Service (NWS) stations in Maine's southern interior at Bridgton and West Buxton and on the coast in Portland, the mean annual temperature (1961-99) is 44°F, and the mean monthly temperatures range from 19°F in January to 68°F in July (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, 1999). The mean annual precipitation in the Sebago Lake drainage basin is 44 in. and is fairly evenly distributed throughout the year (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, 1999).

Surface-Water Hydrology

The USGS and the PWD have collected streamflow information on tributaries to Sebago Lake (fig. 2). The USGS, using the techniques described by Rantz and others (1982), has collected streamflow data on three tributaries. Data have been collected at Crooked River near Naples (at State Highway 11, USGS gaging station number 01063100) and Stony Brook at East Sebago (at State Highways 114 and 11, USGS gaging station number 01063310) since October 1995. Data also were collected at the Crooked River gaging station seasonally from 1975 to 1977. Data have been collected at Standish Brook at the mouth, at Sebago Lake (USGS gaging station number 01063452) since August 1999. Daily mean streamflows are published annually (Nielsen and others, 1997-00).

The principal tributary to Sebago Lake is the Songo River. The Songo River drains 275 mi^2 including the drainage area of the Crooked River (154 mi^2), which flows into the Songo River about 2 mi upstream from Sebago Lake. The Songo River flows out of Brandy Pond (also known as the Bay of Naples) about 1 mi upstream from its confluence with the Crooked River. After the Songo River, the next largest tributaries to Sebago Lake are Panther Run (30.6 mi^2) and Northwest River (23.5 mi^2) (Cowing and McNelly, 1978).

DATA COMPILATION AND ANALYSIS

Annual water budgets were computed for water years 1996 through 1999. The major water budget components used to compute the annual water budgets for Sebago Lake include direct precipitation to the lake surface, evaporation from the lake surface, major tributary surface-water inflows, major surface-water outflows, municipal water-supply withdrawals by PWD, and changes in lake storage.

Precipitation

Precipitation data were obtained from four NWS stations around Sebago Lake—East Hiram, Bridgton, and West Buxton in Maine's southern interior, and Portland near the coast. The mean annual precipitation for the four stations during the 4-year period of the study was 52.82 in. (table 1), which is substantially higher than the long-term mean of 44 in. for the Sebago Lake drainage basin. The precipitation for Sebago Lake was computed as the unweighted mean of all four NWS stations around the lake (fig. 2).

During the 1996-99 period, October was the wettest month, with a mean of 7.7 in. This high mean rainfall can be attributed to a precipitation event in the region from October 20-22, 1996 (in water year 1997), when a maximum-recorded rainfall of 19.19 in. fell in the Camp Ellis area of Saco, Maine (Hodgkins and Stewart, 1997). The NWS station at Portland recorded total monthly rainfall of 16.83 in. for October 1996.

Evaporation

Evaporation was computed on a monthly basis for the annual water budgets, using mean monthly air temperatures and monthly hours of daylight. Mean monthly air temperature data were obtained from four NWS stations and were arithmetically averaged (unweighted) to estimate air temperatures at Sebago Lake. The monthly hours of daylight were interpolated from data presented by Dunne and Leopold (1978) that relate duration of daylight to latitude.

Table 1. Annual precipitation at selected locations and mean annual precipitation and evaporation for Sebago Lake, 1996-99

[Temperature and precipitation data from the National Weather Service; all data in inches; inc., incomplete precipitation record for the year - record is missing some monthly values]

Water year	National Weather Service Stations				Sebago Lake	
	East Hiram	Bridgton	Portland	West Buxton	Precipitation	Evaporation
1996	inc.	inc.	49.61	50.73	51.84	22.52
1997	54.74	55.69	53.42	55.74	54.90	22.10
1998	53.69	inc.	50.08	54.07	51.89	23.67
1999	56.89	55.55	46.40	51.73	52.64	24.68
Mean	55.11	55.62	49.88	53.07	52.82	23.24

The Hamon equation was used to compute daily evaporation from Sebago Lake (Hamon, 1961). The Hamon equation uses saturation vapor density and hours of daylight to compute evaporation in centimeters per day. Saturation vapor density is a function of air temperature and was computed on the basis of the mean monthly air temperatures described above. The hours of daylight used in the Hamon equation were the mean monthly values. Monthly evaporation was then computed by multiplying the daily evaporation yielded by the Hamon equation by the number of days in each month. Monthly evaporation values were summed to compute evaporation totals for the year (table 1). Monthly evaporation values were converted to volumes by multiplying by the surface area of Sebago Lake.

Surface-Water Inflows and Outflows

Surface-water inflows to Sebago Lake were calculated using several different techniques because of the variety of data available for different tributaries to the lake. Inflows from Crooked River and Stony Brook (table 2) were calculated using data from USGS streamflow-gaging stations (Nielsen and others, 1997-00). USGS streamflow-gage data were computed using the techniques in Rantz and others (1982).

Inflows from five tributaries with noncontinuous flow record—Panther Run, Northwest River, Rich Mill Pond Outlet, Sticky River, and Muddy River (table 2)—were calculated using the Maintenance of Variance-Extension, type 1, (MOVE.1) method; also known as the Line of Organic Correlation (Hirsch, 1982; Helsel and Hirsch, 1992). MOVE.1 is a method of estimating flows at a stream on days when no data are collected. The explanatory (independent) variable, as used here, is daily streamflow from a continuous-record USGS streamflow-gaging station. The response (dependent) variable is streamflow data from a stream without continuous flow records (Portland Water District, written commun., 1998; Nichols and Silverman, 1998). Streamflow estimates from MOVE.1, unlike estimates from standard regression equations, will have a statistical distribution similar to that expected if the streamflows had actually been measured on a continuous basis (Helsel and Hirsch, 1992). MOVE.1 was analyzed for its applicability at the five tributaries for water years 1996-99. MOVE.1 assumes a linear relation between the concurrent logarithms of streamflows at the continuous-record gaging sites and the non-continuous sites.

The logarithms of streamflow values at the five noncontinuous-record sites were plotted against the logarithms of flow values for Crooked River and Stony Brook. The best plots for each site were analyzed for curvature, for outliers that may have a large effect on the relation between the variables, and for constant variance. The plots for Northwest River against Crooked River and for Rich Mill Pond Outlet against Stony Brook were judged to be acceptable. The plots for Panther Run against Crooked River, and for Sticky River and Muddy River against Stony Brook indicated some problems with curvature, outliers, or nonconstant variance. The MOVE.1 method, however, was assumed to be more accurate than alternative methods of flow estimation for these sites.

Table 2. Annual surface-water inflows and outflows to and from Sebago Lake for gaged (continuous record) and ungaged (noncontinuous record) tributaries, 1996-99

[Values are in cubic feet per second]

Surface-water body	Water year 1996	Water year 1997	Water Year 1998	Water year 1999	Average (1996-99)
Crooked River inflow	404	374	362	271	353
Stony Brook inflow	2.02	2.31	2.30	2.38	2.25
Panther Run inflow	97.5	90.6	90.2	57.2	83.9
Northwest River inflow	47.3	43.8	42.4	31.3	41.2
Rich Mill Pond inflow	9.42	9.99	10.0	10.2	9.90
Sticky River inflow	4.26	6.00	5.97	6.42	5.66
Muddy River inflow	16.5	21.2	21.0	22.2	20.2
Songo River inflow	342	262	268	197	267
Ungaged inflow	128	158	158	166	152
Sebago Lake:					
Total inflow	1,050	968	960	764	935
Total outflow	853	801	846	619	780

Inflows from the ungaged drainage area of the Songo River (121 mi^2) were computed for 1996-99 by use of regression equations. An ordinary least-squares regression equation was developed to estimate mean monthly flow for each of the 48 months. The explanatory variable in each regression equation was the logarithm of drainage area from 21 rural, unregulated streams in Maine, New Hampshire, and Massachusetts (fig. 3, table 3). The response variable was the logarithm of mean monthly flow for each month from 1996 to 1999. Mean monthly inflow for the Songo River was estimated by entering the drainage area for the Songo River into each equation.

Several regression diagnostics were performed on all of the regression equations using methods of Helsel and Hirsch (1992). Coefficients in the equations were checked for reasonability in sign and magnitude. The explanatory variable in each of the regression equations was checked for statistical significance. In all cases, the explanatory variable was highly significant ($p<0.0001$). Residuals plots were checked for curvature, constant variance, normality, and for presence of outliers. The 10 largest residuals were checked for geographical biases. Cook's D statistic was computed to look for high influence points. All regression diagnostics were consistent with a reasonable regression model for each of the monthly regressions.

The remaining inflow to Sebago Lake, from channelized and unchannelized areas, that was not estimated by previous methods in this section was estimated by use of the cubic feet per square mile (cfsm) method. The 56.5 mi^2 of remaining drainage area is the sum of many small basins, each having areas less than about 6 mi^2. Data are inadequate in the region to compute regression equations for these small drainage areas. The mean monthly inflows per square mile for each month at Rich Mill Pond Outlet, Sticky River, Muddy River, and Stony Brook were arithmetically averaged. This average value was multiplied by the remaining drainage area (56.5 mi^2) to calculate a mean monthly flow of this drainage area to Sebago Lake.

Data on surface-water outflow from Sebago Lake were supplied by SAPPI. These data include flows from the lake into the SAPPI power canal (Eel Weir Project canal) as well as outflows into the natural channel of the Presumpscot River. Leakage from the Eel Weir Project dam at the outlet of Sebago Lake into the natural channel of the Presumpscot River was not included in the data provided by SAPPI. This leakage was measured by the USGS as 28 ft^3/s and is constant regardless of lake level or regulated releases into the river. This leakage flow was added to the amount of outflow provided by SAPPI to compute total surface-water outflow from Sebago Lake (table 2).

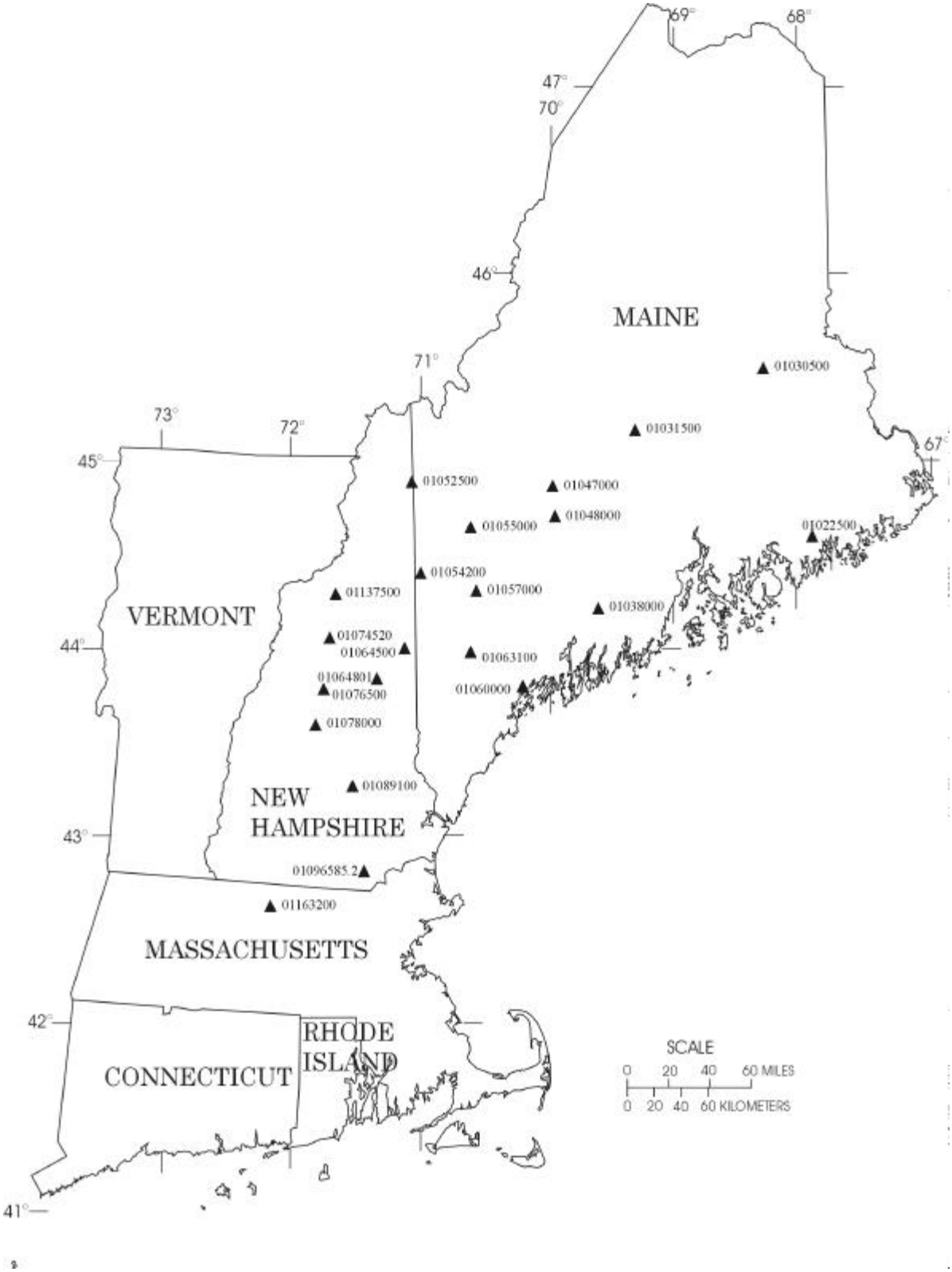

Figure 3. Surface-water sites used in regression analysis.

Table 3. Streamflow-gaging stations used for mean monthly inflow regression equations for the Songo River

Streamflow-gaging station number	Streamflow-gaging station name	Drainage area (square miles)
01022500	Narraguagus River at Cherryfield, Maine	227
01030500	Mattawamkeag River near Mattawamkeag, Maine	1418
01031500	Piscataquis River near Dover-Foxcroft, Maine	298
01038000	Sheepscot River at North Whitefield, Maine	145
01047000	Carrabassett River near North Anson, Maine	353
01048000	Sandy River near Mercer, Maine	516
01052500	Diamond River near Wentworth Location, New Hampshire	152
01054200	Wild River at Gilead, Maine	69.6
01055000	Swift River near Roxbury, Maine	96.9
01057000	Little Androscoggin River near South Paris, Maine	73.5
01060000	Royal River at Yarmouth, Maine	141
01063100	Crooked River near Naples, Maine	150
01064500	Saco River near Conway, New Hampshire	385
01064801	Bearcamp River at South Tamworth, New Hampshire	67.6
01074520	East Branch Pemigewasset River at Lincoln, New Hampshire	115
01076500	Pemigewasset River at Plymouth, New Hampshire	622
01078000	Smith River near Bristol, New Hampshire	85.8
01089100	Soucook River at Pembroke Road near Concord, New Hampshire	81.9
01096585.2	Beaver Brook at North Pelham, New Hampshire	47.8
01137500	Ammonoosuc River at Bethlehem Junction, New Hampshire	87.6
01163200	Otter River at Otter River, Massachusetts	34.1

Withdrawals and Lake Storage

Total monthly withdrawals, in millions of gallons, from Sebago Lake were provided to the USGS by PWD. These data were converted to cubic feet for the water-budget calculations. During the 4 water years examined for this water budget, the PWD withdrew a mean of 1,130 million ft^3 (or about 8,460 Mgal) of water from the lake per year. Annual withdrawals during the 4 years showed relatively little variation with values ranging from 1,110 to 1,150 million ft^3 (table 4). Monthly withdrawals varied seasonally with larger withdrawals during the summer and smaller withdrawals during the winter and spring. The mean monthly withdrawal over the 4-year period of record was 94.3 million ft^3 with a maximum of 123 million ft^3 and a minimum of 67.9 million ft^3.

Table 4. Annual withdrawals from Sebago Lake and changes in lake storage, 1996-99

[Values in millions of cubic feet]

Water year	Withdrawal	Net change in storage
1996	1,110	1,260
1997	1,150	775
1998	1,130	-140
1999	1,140	1,980
Mean	1,130	969

Changes in lake storage were computed with an equation that relates lake-water level to storage volume. Sebago Lake water levels were provided to the USGS by SAPPI. SAPPI controls the level of the lake at The Basin Dam (fig. 2) on the east side of Sebago Lake. Water levels during the 1996 to 1999 water years

were measured using a staff gage and tape-down point constructed at a concrete stilling well in The Basin near the Eel Weir project. During calm conditions, water levels were read from the staff gage located on the exterior of the concrete stilling well. During conditions that rendered the use of the staff gage impractical (such as wavy and windy conditions), water levels were measured from a tape down point inside the stilling well. The water-level data used for this water budget were weekly water levels in Sebago Lake provided by SAPPI. The weekly water levels that most closely corresponded to the first of each month were used to calculate monthly changes in storage in the lake. The water-level data were converted to a storage value, in millions of cubic feet, using a storage rating equation. Summing all the monthly changes in storage for all the months in a water year yielded an annual net change in storage for that water year (table 4).

WATER BUDGET FOR SEBAGO LAKE

The water budget equation used for this investigation of Sebago Lake is a straightforward equation, and can be summarized as water in (inflows) is equal to water out (outflows) plus net change in storage:

$$ppt + SW_{in} + GW_{in} = E + SW_{out} + GW_{out} + WD + \Delta St \quad ,$$

where ppt is precipitation,
SW_{in} is surface-water flow in,
GW_{in} is ground-water flow in,
E is evaporation,
SW_{out} is surface-water flow out,
GW_{out} is ground-water flow out,
WD is withdrawals, and
ΔSt is net change in storage.

Monthly volumes were computed for all components of the water budget. Plots of monthly surface-water inflow, outflow, precipitation, evaporation, withdrawals, and change in storage volumes are shown in figures 4 and 5. The total mean annual water budget and the yearly water budgets for water years 1996-99 for Sebago Lake are given in table 5. Annual inflows, outflows, and net changes in storage are illustrated in figure 6. The total mean annual inflow to Sebago Lake during water years 1996-99 is 35,100 million ft^3 (or about 262,000 Mgal). The total mean annual outflow from Sebago Lake for the same period is 28,200 million ft^3 (or about 211,000 Mgal). The two largest components of the inflow and outflow water budgets are the surface-water components, making up, on average, 84.0 and 87.3 percent of the total mean annual inflow and outflow water budgets, respectively.

The total inflow and outflow volumes, adjusted for changes in lake storage, do not balance for each water year. The remainder volume is the residual. The mean annual residual for the 4 water years is 5,860 million ft^3 (43,900 Mgal). The relatively consistent magnitude and sign (positive) of the residual from water year to water year (table 5) indicates either a systematic overestimation of inflows or underestimation of outflows from Sebago Lake. The residual also could be partially composed of unaccounted ground-water flow. The geologic features controlling the storage and flow of ground water around Sebago Lake are complex and non-uniformly distributed. No effort has been made to quantify ground-water flow into or out of Sebago Lake for this water budget because a ground-water-level network with high-quality systematic data adequate to compute these budget items is not in place. Any net ground-water flow is assumed to be contained within the residual term.

Table 5. Annual water budget for Sebago Lake, 1996-99

[All volumes are in millions of cubic feet]

Water year	Precipitation	Evaporation	Surface-water inflow	Surface-water outflow	Withdrawals	Net change in storage	Residual
1996	5,490	2,390	33,100	27,100	1,110	1,260	6,740
1997	5,820	2,340	30,600	25,300	1,150	775	6,870
1998	5,500	2,510	30,200	26,700	1,130	-140	5,480
1999	5,580	2,610	24,100	19,500	1,140	1,980	4,360
Mean	5,600	2,460	29,500	24,700	1,130	969	5,860

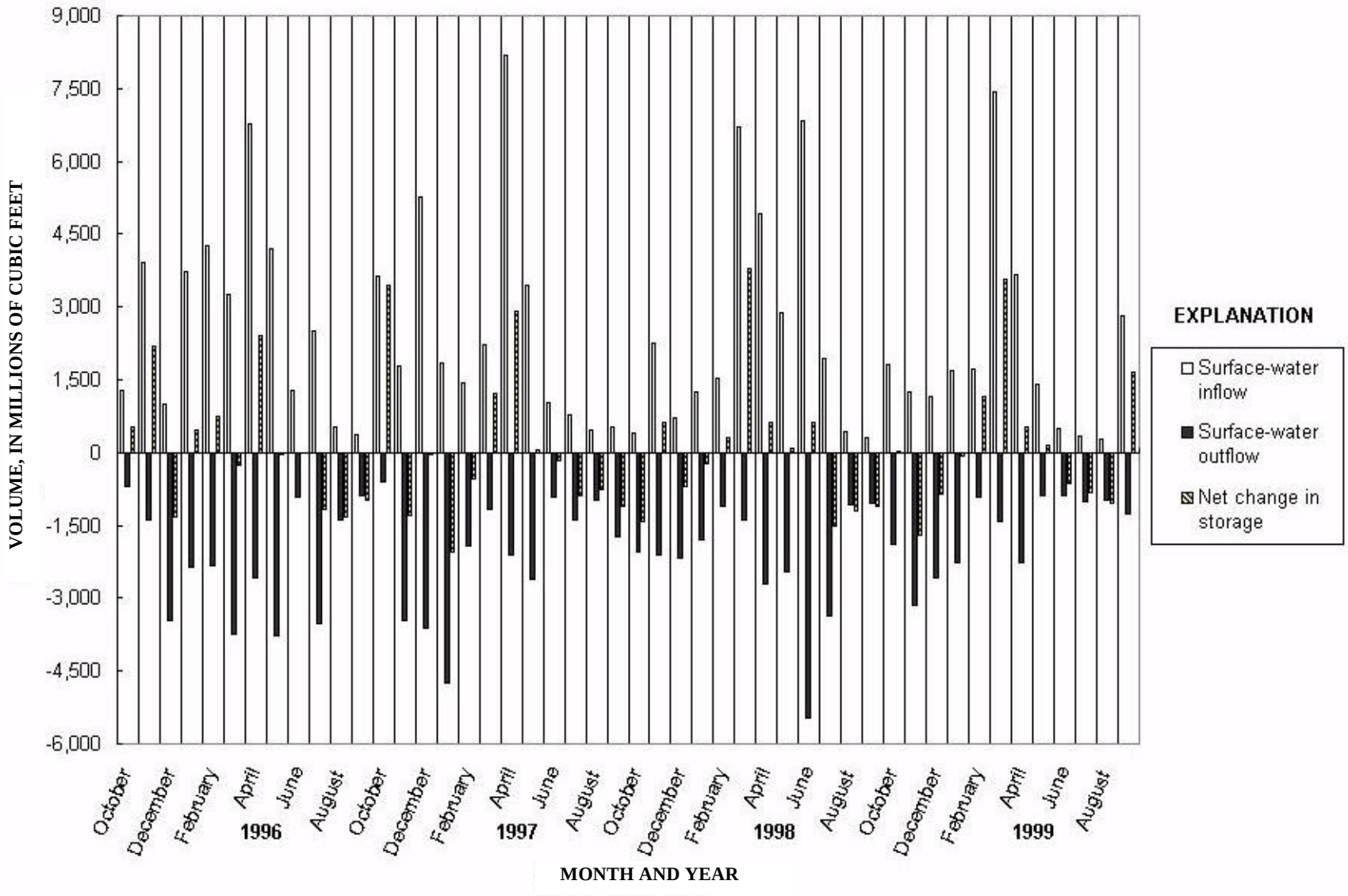

Figure 4. Monthly surface-water inflow, outflow, and net change in storage volumes for the Sebago Lake water budget, 1996-99.

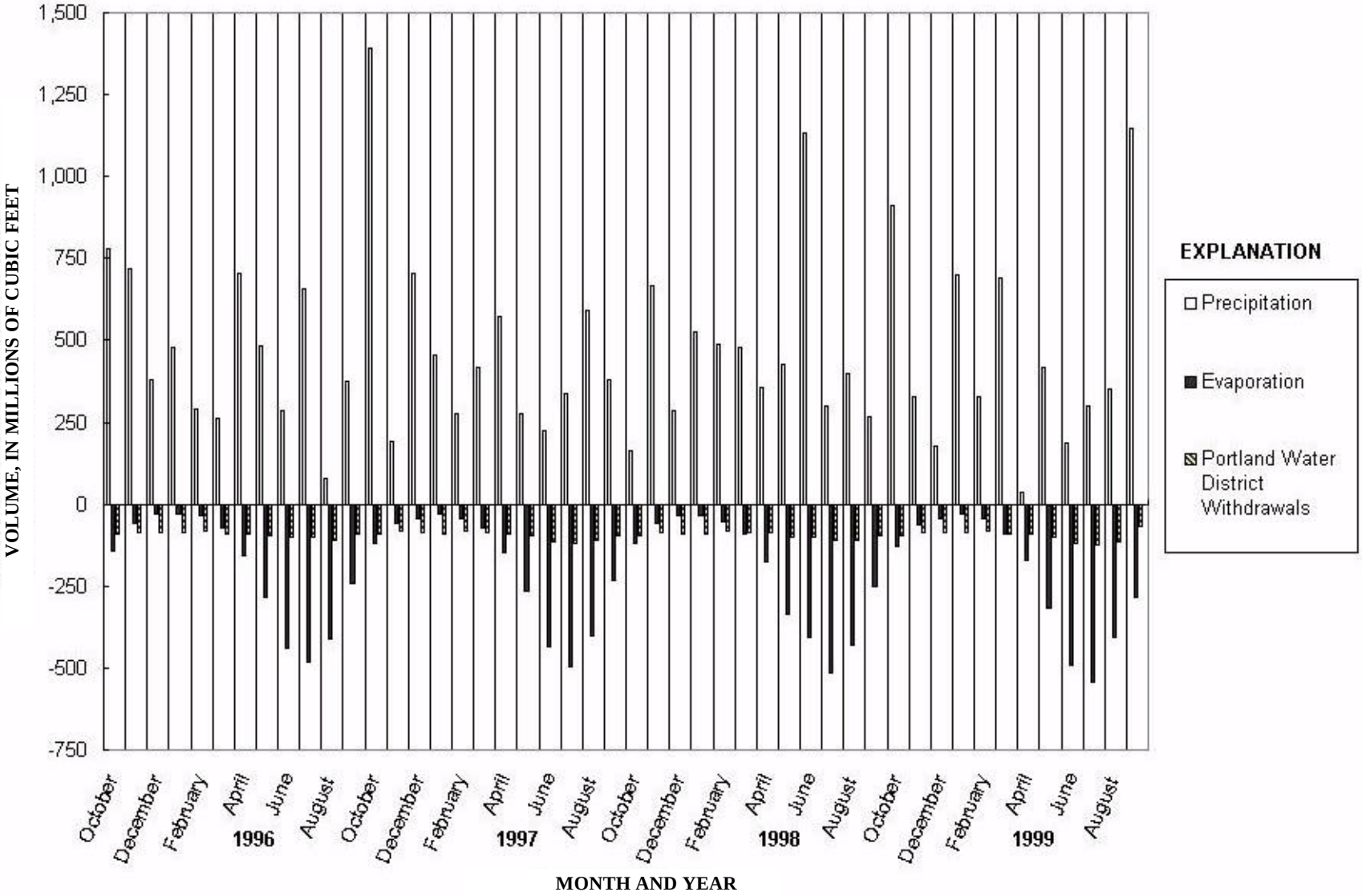

Figure 5. Monthly precipitation, evaporation, and withdrawal volumes for the Sebago Lake water budget, 1996-99.

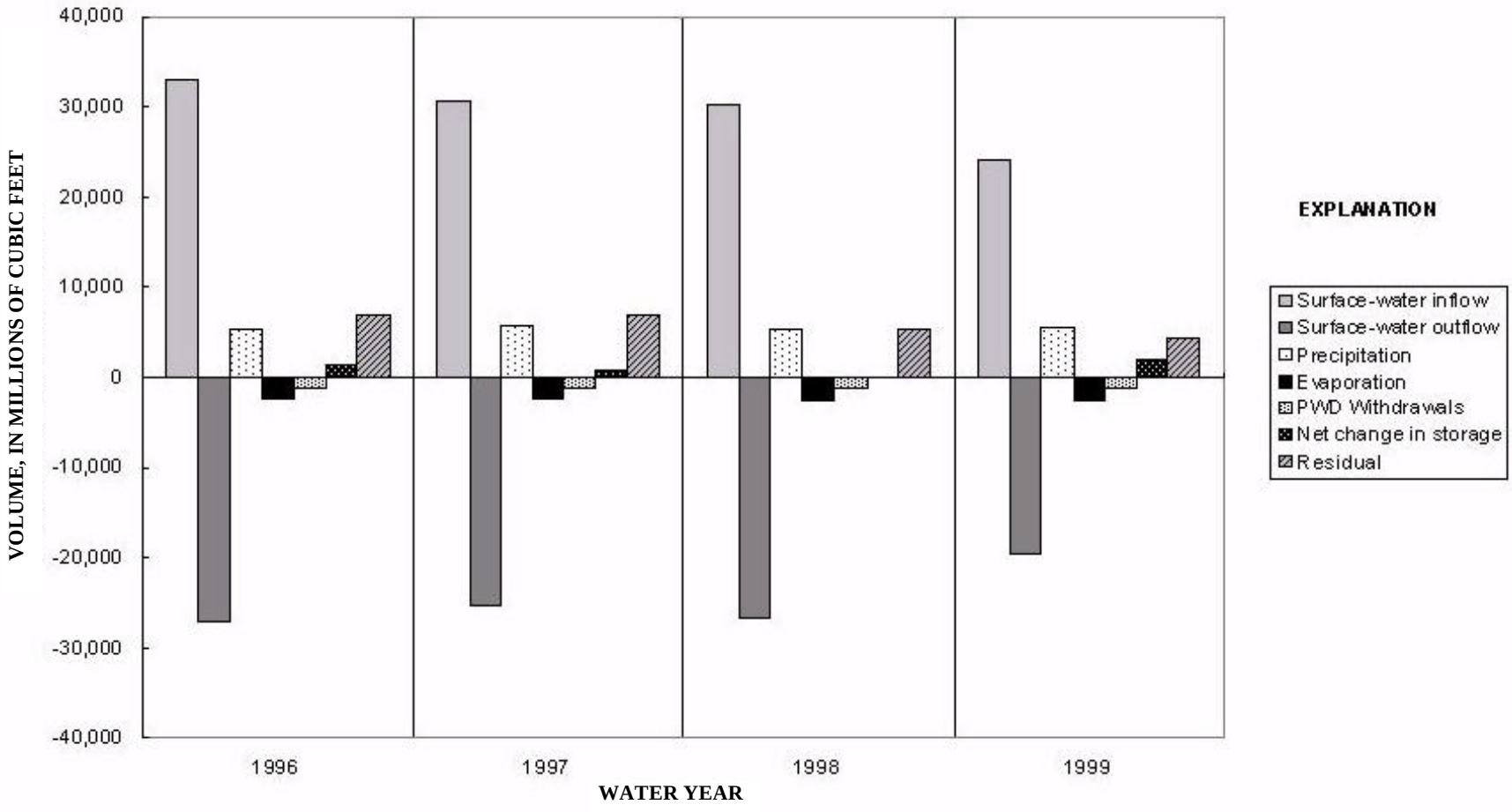

Figure 6. Annual surface-water inflows and outflows, precipitation, evaporation, withdrawals, net changes in storage, and residuals for annual Sebago Lake water budget, 1996-99.

UNCERTAINTIES OF WATER-BUDGET COMPONENTS

Although the water budget can be summarized in a straightforward manner, accurately quantifying each of the individual terms used in the budget is more difficult. This discussion of uncertainties and limitations of data is intended to aid in evaluating the accuracy of each term in the water budget equation and to help identify the major components of the budget residual. The potential errors associated with the following hydrologic components are estimated on an annual basis. It is expected that errors associated with short-term (monthly) hydrologic estimates are larger than long-term (annual) estimates.

Precipitation

Precipitation that falls directly on the surface area of Sebago Lake was counted as precipitation input; precipitation falling elsewhere in the Sebago Lake drainage basin, for budget purposes, was accounted for with the surface-water inflow budget term. Because no precipitation stations are located directly on the lake itself, the values from the four NWS climate stations around Sebago Lake were combined in an unweighted mean to serve as the estimate for precipitation directly on the lake. The four NWS climate stations have a density coverage of about 200 mi^2/station.

Winter (1981) evaluated errors associated with areal averaging of point NWS precipitation data and related its importance to water-balance studies of lakes. For a NWS station density of 250 mi^2/station, errors for estimating individual storms can be greater than 60 percent. As the data are arithmetically averaged over longer time periods, errors decrease. Errors can be on the order of 5 percent for seasonal time-scale estimates, based on studies in relatively flat terrain. The mean annual precipitation in the Sebago Lake drainage basin exhibits little areal variability, normally ranging from 42 to 44 in. (Knox and Nordenson, 1955). All four NWS stations are in a region of low topography, and orographic effects are likely not a concern. For this study, annual precipitation estimates are assumed to be within 5 percent of the actual precipitation on the lake.

Surface-Water Inflows

Surface-water inflows to the lake include channelized and non-channelized flow. All gaged, channelized flow into Sebago Lake is estimated using USGS streamflow-gaging station data (38.2 percent of the total contributing drainage area to the lake). USGS streamflow records that are rated as good (fair) are estimated to be within 10 (15) percent of the true daily streamflow 95 percent of the time (Nielsen and others, 2000).

All other (or ungaged) surface-water inflows are estimated using regression equations, MOVE.1, or the cfsm method. The surface-water inflow from Songo River, which drains 30.1 percent of the total contributing drainage area to the lake, was estimated using regression equations. The smallest standard error of estimate for the 48 monthly regression equations was +17 percent to –15 percent, and the largest was +149 percent to –60 percent. The median standard error was +58 percent to –37 percent. The standard errors were usually high in summer and fall and low in winter and spring. Annual errors were not computed.

The surface-water inflow from 17.4 percent of the total contributing drainage area to the lake was estimated using MOVE.1. Errors associated with the MOVE.1 method were not computed, but may be large, particularly for Panther Run, Sticky River, and Muddy River. The data at these sites indicated some problems with curvature, outliers, or non-constant variance; however, the MOVE.1 method was assumed to be the best method of flow estimation for these sites. The cfsm method was used to estimate flow contribution from 14.3 percent of the total drainage area. Error associated with this method is not known, however, errors in MOVE.1 estimates for the Sticky and Muddy Rivers will contribute to errors in the cfsm estimates.

Evaporation

Hamon (1961) evaluated his evaporation equation against year-round data for valleys covering a wide variation and climate, including sites in Wisconsin and Maine. He also evaluated the equation against an extensive year-round study of monthly lake evaporation in New England and New York and found close correspondence (Hamon, 1961).

The Hamon equation was one of 11 equations compared with evaporation determined by a rigorous

energy-budget method (Winter and others, 1995; Sturrock, 1992). Winter and others (1995) found that although evaporation estimated by the Hamon equation compared reasonably well with values computed by the energy-budget method, it showed some seasonal bias during the May through September time period. Specifically, the Hamon equation overestimated evaporation early in the summer season, and underestimated evaporation later in the summer season.

Annual evaporation values computed for this water budget using the Hamon equation ranged from 22.10 in. in water year 1997 to 24.68 in. in water year 1999 with a 4-year annual mean of 23.24 in. By comparison, an NWS contour map of annual lake evaporation for the United States, for the period 1946-55, (Bedient and Huber, 1988) shows a value of about 24 in. for the Sebago Lake area. Another map of annual lake evaporation, by Knox and Nordenson (1955), and based on climatological data from 1930-49, indicates 23 in. for the Sebago Lake area. The congruence of the three evaporation estimates lends a measure of confidence to using the Hamon equation for this water budget. Due to the close correspondence to other studies, computed annual evaporation for this study is assumed to be within 20 percent of the actual evaporation. Error associated with monthly evaporation estimates is expected to be considerably greater.

Surface-Water Outflows

The error in streamflow data for Sebago Lake provided by SAPPI was not quantified, but check-flow measurements in the Eel Weir Project canal by the USGS over several years are consistently about 100 ft^3/s higher than the values measured by SAPPI.

Withdrawals

Data for municipal water-supply withdrawals from Sebago Lake by PWD were provided to the USGS courtesy of the PWD. The monthly PWD withdrawal volumes are measured using a flow meter with a reported error of less than 1 percent (Phillip Boissonneault, written commun., 2001).

Lake Storage

Storage was computed using a linear function that relates lake elevation with storage volume. The linear relation between water level and storage volume assumes that any change in lake surface area due to changes in water level is negligible. This is a valid assumption for Sebago Lake, which has no significant floodplains or bordering wetlands. It is assumed that the surface area of the lake used in this equation is within 5 percent (2.3 mi^2) of its true surface area (45.6 mi^2).

Using the staff gage and tape-down point at the concrete stilling well, SAPPI was able to measure the water level with an accuracy of 0.05 ft (Thomas Howard, South African Pulp and Paper Inc., oral commun., 2001). The combined uncertainty of accurately delineating the area of the lake and accurately measuring the water level of the lake for the purpose of computing storage is 5.1 percent at the median lake level (264.16 ft).

Residual

Errors associated with budgeting precipitation, evaporation, and net changes in storage are relatively small. Assuming an uncertainty of about 5 percent for precipitation estimates, the error in computing annual water volume input to Sebago Lake from precipitation would be 0.8 percent of the mean annual inflow budget. Error associated with uncertainties in the calculation of storage volume, although variable with volume, is about 5.1 percent for computing storage at median lake level (264.16 ft). If the uncertainty in estimating annual evaporation is assumed to be about 20 percent, the error in computing water volume removed from Sebago Lake due to evaporation would be 1.7 percent of the mean annual outflow budget. Even if the uncertainty in evaporation estimates were assumed to be as high as 50 percent, it would still amount to an insignificant part (4.4 percent) of the mean annual outflow budget.

The greatest potential contributions to error in the calculation of the water budget for Sebago Lake are errors associated with estimating surface-water inflow and outflow, because they are the two largest elements of the budget, and net ground-water flow because it was not computed for this budget. The consistently positive value of the residual during the 1996-99 water years is likely to be the product of a systematic error with the estimation of inflows, outflows, and (or) unaccounted net ground-water flow out.

A statistically significant relation (Mann-Kendall test, $p<0.0001$) between monthly surface-water inflows and the corresponding computed

monthly budget residuals is shown in figure 7. At lower inflow volumes, the residuals appear to be well distributed, with an equal number of points above and below zero. As inflow volumes become greater, however, the residuals become predominantly positive and increase in value with increasing inflow volume. This could indicate an overestimation of total inflows, an underestimation of total outflows, error associated with unaccounted for net ground-water outflow, or a combination of all three. It is interesting to note that there is not a similar relation between surface-water outflows and the residuals or lake level and the residuals.

Though there are no observable correlations between outflows and the residuals or lake levels and the residuals, errors associated with these budget components are still possible. A constant error over time would not show up in plots of residuals versus these components. If the consistent underestimation of 100 ft^3/s in the Eel Weir Project canal outflow is correct, it would account for more than half of the mean annual residual volume. Thus, the water budget residual is probably composed of error in the estimated surface-water inflows at high flows for the ungaged drainage areas, a constant error in surface-water outflow, and unaccounted net ground-water flow.

SUMMARY AND CONCLUSIONS

This report presents an annual water budget for Sebago Lake for water years 1996-99, with the computation and associated uncertainty of the following major water-budget components: (1) inflows, including direct precipitation on the lake and all major surface-water tributary inflows; (2) outflows, including evaporation, surface-water outflow, and municipal water-supply withdrawals; and (3) changes in lake storage.

The total mean annual inflow to Sebago Lake during water years 1996-99 is 35,100 million ft^3 (or about 262,000 Mgal). The total mean annual outflow from Sebago Lake for the same period is 28,200 million ft^3 (or about 211,000 Mgal). The two largest components of the inflow and outflow water budgets are the surface-water components, making up, on average, 84.0 and 87.3 percent of the total mean annual inflow and outflow water budgets respectively.

The remainder of the sum of inflow minus outflow volumes, adjusted for changes in lake storage, is the residual. The mean annual residual for the 4 years is 5,860 million ft^3 and is relatively consistent in magnitude and sign (positive) each water year. This could indicate an overestimation of total inflows, an underestimation of total outflows, error associated with unaccounted for net ground-water flow out, or a combination of all three.

Errors associated with budgeting precipitation, evaporation, and net changes in storage are relatively small. The largest potential errors in calculating the water budget for Sebago Lake are those associated with surface-water inflow and outflow, because they are the two largest elements of the budget, and ground-water flow (net in or out) because it was not computed.

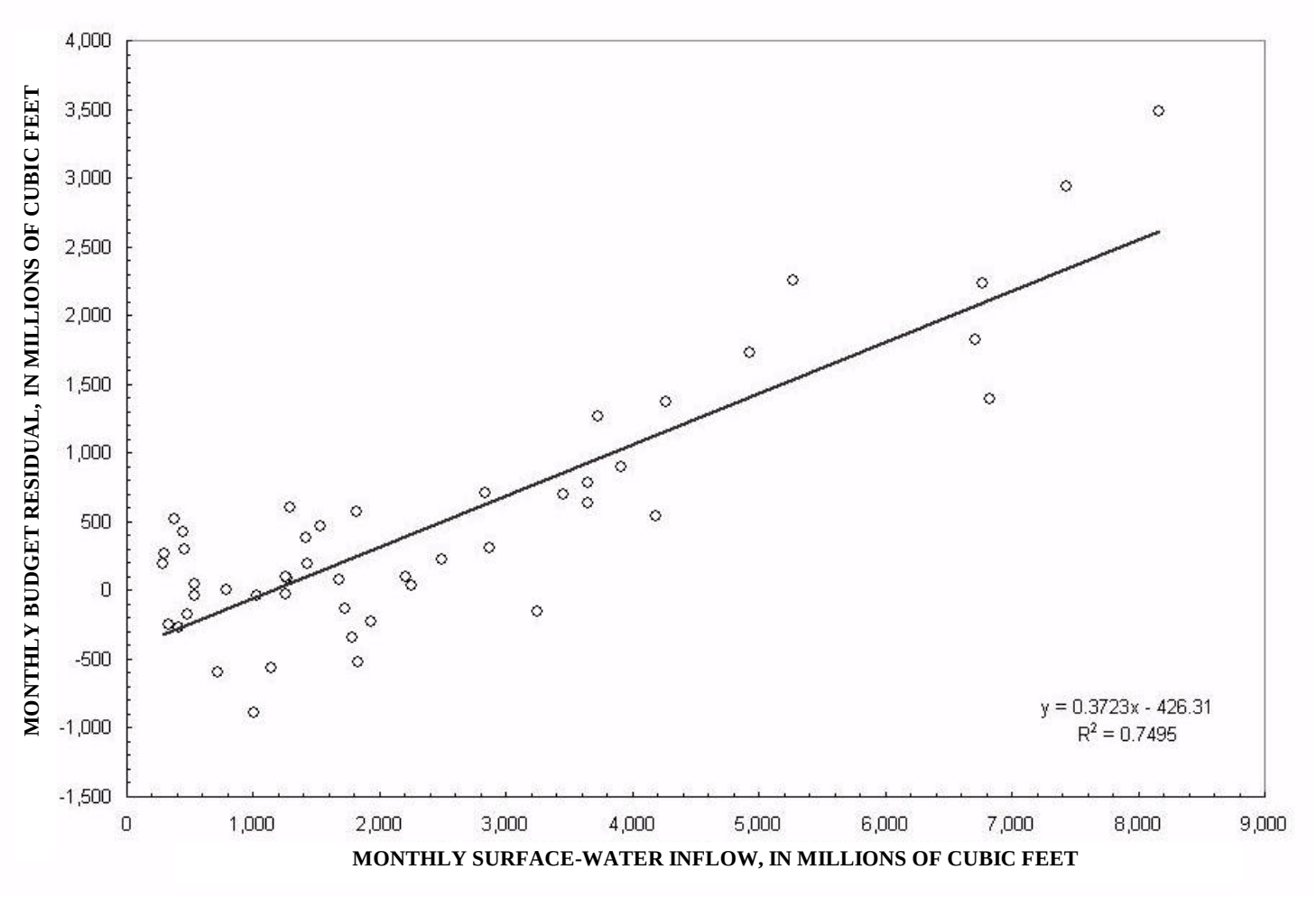

Figure 7. Statistically significant relation of monthly budget residuals to monthly surface-water inflows. [Higher inflows correlate with greater residual values.]

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