In cooperation with the
Maine Department of Human Services Drinking Water Program and
Lake Auburn Watershed Protection Commission

Water Budget for Lake Auburn, Maine, May 1, 2000 through April 30, 2003

Scientific Investigations Report 2004-5106

U.S. Department of the Interior
U.S. Geological Survey

Cover Photograph: The Basin outlet dam, April 2003. (Photography by Gregory Stewart, U.S. Geological Survey)

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U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

Volume in million cubic feet (Mcf) may be converted to million gallons (Mgal) as follows:

$$\text{Mgal} = (\text{Mcf})*7.48$$

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

$$°C = (°F - 32) / 1.8$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Water Budget for Lake Auburn, Maine, May 1, 2000 through April 30, 2003

By Robert W. Dudley

Abstract

Annual water budgets were developed for Lake Auburn in southwestern Maine for three water-budget years, May 1, 2000 through April 30, 2003. The measured inflow components of the water budget are direct precipitation to the surface of the lake and surface-water inflow. Mean annual inflow (precipitation and surface water) to Lake Auburn during water-budget years 2001-03 was 816 million cubic feet. The measured outflow components of the water budget are evaporation from the surface of the lake, municipal water-supply withdrawals by the Auburn and Lewiston Water Districts, and surface-water outflow. Mean annual outflow (evaporation, withdrawals, and surface water) during water-budget years 2001-03 was 834 million cubic feet. The two largest components of the water budget are the surface-water inflow and municipal withdrawals. Surface-water inflow was about 62 percent of the mean annual inflow budget and municipal withdrawals were about 47 percent of the mean annual outflow budget. Changes in lake storage also were included in the water budget.

Dry conditions were present in Maine from 1999 to 2002, with a severe drought occurring in 2001 and 2002. On February 20, 2002, Auburn Water District recorded Lake Auburn's lowest recorded water level, 256.7 ft, during the period of record from April 1, 1940 to June 20, 2003.

The total inflow and outflow volumes, adjusted for changes in lake storage, nearly balance for each water year. Any non-zero remainder volume for a given water-budget year is the residual. The mean annual residual for the three water-budget years is -1.06 million cubic feet (-7.93 million gallons). The changing sign of the computed residual from water-budget year to water-budget year during the 3-year study period indicates that no systematic errors were made in estimating inflows to or outflows from Lake Auburn. Because ground-water flow is unaccounted for in this water budget, any net ground-water flow is assumed to be contained in the residual term.

Introduction

The Maine Drinking Water Program began a Source Water Assessment Program in 1998 to evaluate all public water supplies to determine the potential for future contamination of drinking-water sources and avenues to protect those sources. Water-supply evaluation includes delineation of source-water protection areas, inventories of potential sources of contamination, and assessments of the susceptibility of the drinking-water source to contamination (Maine Department of Human Services, 2000). Because contaminants may be transported to a water-supply reservoir by surface-water runoff, direct precipitation, or ground-water infiltration and discharge, the determination of a water budget is an important component of a source-water assessment.

A study was done by Camp Dresser and McKee from 1985 to 1987 to characterize water quality in the Lake Auburn watershed. Objectives of the study were to identify and investigate existing water-quality issues in the lake and watershed, estimate possible effects of rezoning on water quality, and develop recommendations for a long-term water-quality monitoring program (Camp Dresser and McKee, 1987). The investigators concluded that the water quality of Lake Auburn was good and recommended various erosion, storm-water, and land-use controls for future management of water-quality in the watershed (Camp Dresser and McKee, 1987).

The Auburn Water District (AWD) and Lewiston Water Division (LWD) are responsible for maintaining an adequate water supply for the cities of Auburn and Lewiston; Lake Auburn is the sole source for both communities (Normand Lamie, Auburn Water District, oral commun., 2003). A quantitative analysis of the water budget for Lake Auburn will provide information to the AWD and LWD that is integral to managing the water supply as well as protecting the water quality. The U.S. Geological Survey (USGS), in cooperation with the Maine Department of Human Services Drinking Water Program, and the Lake

Auburn Watershed Protection Commission, began a study in 2000 to compute a water budget for Lake Auburn for a 3-year period.

Purpose and Scope

This report presents annual water budgets for Lake Auburn for water-budget years 2001-03. For this report, a water-budget year is defined as a year beginning May 1 and ending April 30 and is denoted as the year in which it ends—thus, the year from May 1, 2000 to April 30, 2001 is called water-budget year 2001. This 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. Amounts of direct ground-water flow into and out of the lake bed were not quantified in this investigation.

Description of the Study Area

Lake Auburn, in southwestern Maine (fig. 1), is the principal water supply for about 45,000 people. In 2002, the AWD and LWD treated and delivered a daily average of about 1.03 million ft^3 (cubic feet) (7.7 Mgal (million gallons)) of water to residents of Lewiston and Auburn (Auburn Water District and the Lewiston Water Division, 2002). The cities of Lewiston and Auburn are about 25 mi (miles) southwest of Augusta (fig. 1) with 2001-02 populations of 35,690 and 23,203, respectively (Maine Register, 2002). Combined, Lewiston and Auburn are the second-most populous urban area in Maine, second only to the city of Portland (2001 population of 64,249) (Maine Register, 2002). Lake Auburn is north of the city of Auburn on the western side of the Androscoggin River (fig. 1).

Lake Auburn, completely confined within the corporate limits of Auburn, has a mean surface area of 3.53 mi^2 (square miles), a mean depth of 40 ft (feet), a maximum depth of 120 ft, and an approximate volume of 3,920 million ft^3 (Auburn Water District and the Lewiston Water Division, 2002; Maine Department of Environmental Protection, October 1, 2003). Based on the mean annual flow of 825 million ft^3 through the lake (computed as the average of the mean annual inflow and mean annual outflow for the water-budget study described in this report), the lake had a mean hydraulic retention time of 4.75 years.

The water level of Lake Auburn is controlled at the East Auburn Dam on Bobbin Mill Brook (fig. 1). The dam was originally a timber-crib structure constructed in the late 1800's for sawmill operations, and later was acquired by AWD from the Union Power Company in the early 1920's. The current (2004) dam structure was built in 1946, when the original structure was replaced with a concrete, earth-fill, and stone-wall structure; this was followed by a comprehensive upgrade in 1967. Repairs were made in April 2002, during this water-budget study, to eliminate leakage (approximately 4 Mgal/d) through the spillway stoplogs and sluice gate (Normand Lamie, Auburn Water District, written commun., 2004). The present dam is 16 ft high and has a 90-ft long concrete spillway (Normand Lamie, Auburn Water District, written and oral commun., 2003).

The Lake Auburn Watershed Protection Commission owns about 1,700 acres of land in the Lake Auburn watershed and about 70 percent of the Lake Auburn shoreline to help protect the quality of the water supply (Normand Lamie, Auburn Water District, oral commun., 2003). The AWD and LWD collect lake and stream water-quality data during ice-free months. The water-quality samples are analyzed for constituents including dissolved oxygen, bacteria, volatile organic chemicals, metals, radionuclides, organic carbon, nutrients, temperature, and water clarity (Auburn Water District and the Lewiston Water Division, 2002).

Physiography and Geology

The topography of the Lake Auburn watershed and surrounding area is hilly with elevations ranging from 235 ft at the Bobbin Mill Brook gaging station (USGS streamflow-gaging station number 01056505) to 770 ft on Hersey Hill, about 1.5 mi west of The Basin (fig. 1). The watershed is rural and is predominantly forested with some farmland, hayfields, gravel mining pits, and residential development.

During a period from about 1.5 million to as recent as 10,000 years ago, continental glaciers intermittently covered Maine. As the glaciers slowly moved across the land, they altered the landscape by eroding and transporting rock and sediment debris for miles. The rock and sediment debris was deposited by meltwater streams and at the ice margins as the glaciers melted. As a result, the surficial geology of present-day Maine is largely composed of sand, gravel, and other unconsolidated sediments (Marvinney and Thompson, 2000; Johnson, 1925). The surficial geology of the Lake Auburn watershed is predominantly glacial till (a heterogeneous, unsorted mix

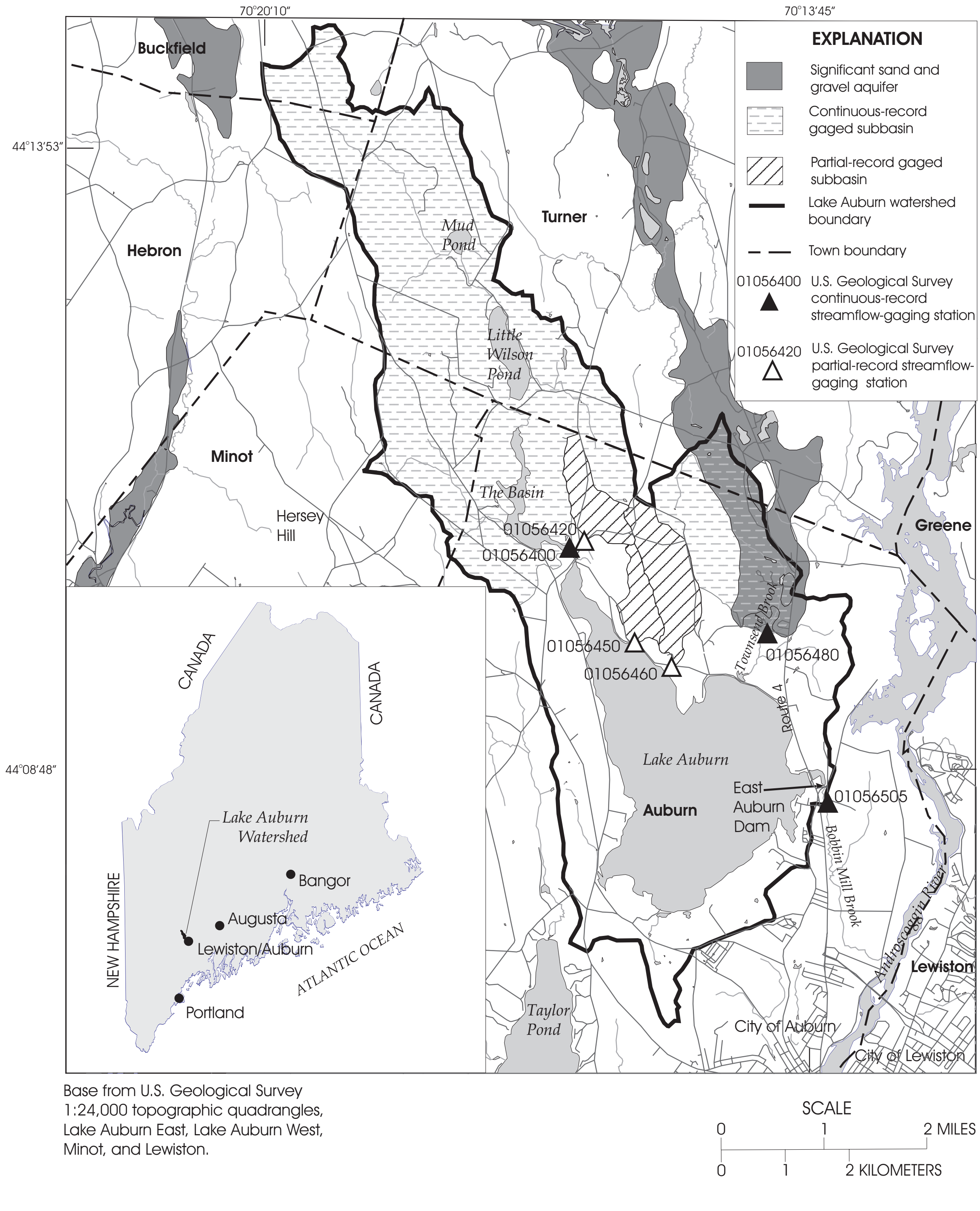

Figure 1. Location of the Lake Auburn study area.

of material ranging in size from fine sand to boulders) and ice-contact glaciofluvial deposits of sand, gravel, and silt (Thompson and Borns, 1985). The ice-contact glaciofluvial deposits were deposited by meltwater streams adjacent to stagnant glacial ice in the northwestern arm of the watershed forming the hilly topography bordering The Basin, Little Wilson Pond, and Mud Pond. The northern and western shores of Lake Auburn, as well as the shoreline of Little Wilson Pond, roughly demarcate the inland limit of late glacial marine submergence (Thompson and Borns, 1985).

Throughout the State of Maine, fractured bedrock and scattered sand and gravel deposits serve as ground-water aquifers. In the Lake Auburn watershed, the Townsend Brook watershed is underlain by a significant sand and gravel aquifer (Neil, 1998a, 1998b). A significant sand and gravel aquifer is defined as an aquifer capable of yielding 10 or more gallons per minute to a typical private well. The aquifer in the Townsend Brook watershed is a source of water to the brook during low-flow periods and may be hydraulically connected with sand and gravel deposits extending northward outside of the surface-water drainage for Lake Auburn (fig. 1).

Climate

The temperate climate in the Lake Auburn watershed is typified by mild summers and cold winters. Based on records from the National Weather Service (NWS) station at Lewiston, the mean annual temperature (1971-2000) is 46.7 ^{o}F, and mean monthly temperatures range from 20.5 ^{o}F in January to 71.4 ^{o}F in July. The mean annual precipitation (1971-2000) at the Lewiston station is 45.8 in. and is fairly evenly distributed throughout the year (National Oceanic and Atmospheric Administration, 2002).

Dry conditions were present in Maine from 1999 to 2002, with a severe drought occurring in 2001 and 2002. During this period, most USGS ground-water wells were at record-low levels, more than 2,000 private water-supply wells went dry, and water levels declined in all major surface-water reservoirs to below regulatory and (or) previous record-low levels (Lombard, 2004). On February 20, 2002, AWD recorded Lake Auburn's lowest recorded water level, 256.7 ft, during the period of record from April 1, 1940 to June 20, 2003. The mean lake level during the same period of record was 259.8 ft.

Surface-Water Hydrology

The USGS, using techniques described by Rantz and others (1982), collected streamflow data for five inflow streams to and one outflow stream from Lake Auburn from 1999 to 2003 (table 1). Continuous streamflow data were recorded for two inflow tributaries, The Basin Outlet (USGS gaging station number 01056400) and Townsend Brook (station 01056480), and one outflow stream, Bobbin Mill Brook (station 01056505) (fig. 1). Non-continuous streamflow data (partial-record stations) were collected for three small, unnamed inflow streams (stations 01056420, 01056450, and 01056460) (fig. 1). Streamflow data for these surface-water stations are published in annual USGS data reports (Stewart and others, 2001, 2002, 2003, 2004).

The total watershed area contributing runoff to Lake Auburn is 14.77 mi^2 (Fontaine, 1978). The principal tributary to Lake Auburn, on the basis of drainage-area size, is The Basin Outlet, which drains 8.01 mi^2. The Basin Outlet drains a chain of ponds in the northwestern half of the Lake Auburn watershed including The Basin, Little Wilson Pond, and Mud Pond (fig. 1). After The Basin Outlet, the inflow tributaries to Lake Auburn, listed

Table 1. U.S. Geological Survey streamflow-gaging stations in the Lake Auburn watershed used for computing the water budget.
[Feb, February; Apr, April; Jun, June; Aug, August]

U.S. Geological Survey streamflow-gaging station			
Number	Name	Period of record	Type of record
01056400	The Basin Outlet at North Auburn	Feb 2000-Apr 2003	Continuous
01056420	Unnamed Brook at Johnson Road at North Auburn	Jun 2000-Apr 2003	Partial
01056450	West Unnamed Brook at Lakeshore Drive near Auburn	Jun 2000-Apr 2003	Partial
01056460	East Unnamed Brook at Lakeshore Drive near Auburn	Jun 2000-Apr 2003	Partial
01056480	Townsend Brook near Auburn	Apr 2000-Apr 2003	Continuous
01056505	Bobbin Mill Brook near Auburn	Aug 1999-Apr 2003	Continuous

from largest to smallest by drainage area size, are Townsend Brook (1.88 mi^2), East Unnamed Brook at Lakeshore Drive (0.56 mi^2), Unnamed Brook at Johnson Road (0.34 mi^2), and West Unnamed Brook at Lakeshore Drive (0.23 mi^2) (fig. 1, table 1). The two continuous-record USGS stations on The Basin Outlet and Townsend Brook were used to measure streamflow runoff from 67 percent (9.89 mi^2) of the Lake Auburn watershed area. The three partial-record stations on East Unnamed Brook at Lakeshore Drive, Unnamed Brook at Johnson Road, and West Unnamed Brook at Lakeshore Drive were used to gage streamflow runoff from 7.7 percent of the watershed area (1.13 mi^2) (table 1). Runoff from the remaining 3.75 mi^2 of the Lake Auburn watershed area was ungaged.

Bobbin Mill Brook is the sole surface-water outflow from Lake Auburn. The continuous-record USGS station on Bobbin Mill Brook gaged 100 percent of the surface-water outflow from the watershed during the study. The surface area of Lake Auburn is 3.53 mi^2; thus, the drainage area represented by the Bobbin Mill Brook streamflow-gaging station is 18.3 mi^2.

Data Used in this Study

Annual water budgets for Lake Auburn were computed for water-budget years 2001-03. The major water-budget components used to compute the annual water budgets for Lake Auburn include direct precipitation to the lake surface, evaporation from the lake surface, surface-water inflows, surface-water outflows, municipal water-supply withdrawals by AWD and LWD, and changes in lake storage.

Precipitation

Precipitation data obtained from the NWS station at Lewiston were used to estimate direct precipitation to the surface of Lake Auburn. The mean annual precipitation for the Lewiston station during the 2001-03 period of the study was 37.6 in. (table 2)—17.9 percent lower than the 30-year (1971-2000) mean (normal) of 45.8 in. for this station. Precipitation was 4.6 in. below normal in water-budget year 2001, 11.0 in. below normal in water-budget year 2002, and 8.9 in. below normal in water-budget year 2003. The mean monthly precipitation for the station during the 3-year period of the study was 3.1 in. March 2001 had the largest amount of monthly precipitation (7.4 in.); and August 2001 had the smallest amount of monthly precipitation (0.22 in.).

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 obtained from the NWS stations at Lewiston were used to estimate air temperatures at Lake Auburn. The monthly hours of daylight were interpolated from data presented by Dunne and Leopold (1978) that relate duration of daylight to latitude.

The Hamon equation was used to compute daily evaporation from Lake Auburn (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 2).

Surface-Water Inflows and Outflows

Surface-water inflows to and outflows from Lake Auburn were calculated using several different techniques because of the variety of streamflow data available. Inflows from The Basin Outlet and Townsend Brook to Lake Auburn and outflows from Lake Auburn at Bobbin Mill Brook (table 3) were computed using continuous-stage recorders and standard USGS streamflow-gaging techniques (Rantz and others, 1982). Streamflow data collected at USGS streamflow-gaging stations are published annually in water-resources data reports (Stewart and others, 2001, 2002, 2003, 2004).

Inflows to Lake Auburn from three tributaries with partial streamflow records— East Unnamed Brook at Lakeshore Drive, West Unnamed Brook at Lakeshore Drive, and Unnamed Brook at Johnson Road, (table 3)—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

Table 2. Annual precipitation and evaporation for Lake Auburn, water-budget years 2001-03.
[All values given in inches; Lake Auburn precipitation estimated using precipitation data from the National Weather Service climate station at Lewiston, Maine (Natural Resources Conservation Service, 2002; U.S. Geological Survey, October 1, 2003; National Oceanic and Atmospheric Administration, October 1, 2003); Lake Auburn evaporation estimated using air-temperature data from the National Weather Service climate station at Lewiston, Maine (National Oceanic and Atmospheric Administration, September 1, 2003); water-budget year is defined as a year beginning May 1 and ending April 30 and denoted as the year in which it ends—thus, water-budget year 2001 is the year spanning from May 1, 2000 to April 30, 2001]

Water-budget year (May 1 to April 30)	Lake Auburn precipitation	Precipitation difference from 1971-2000 mean	Lake Auburn evaporation
2001	41.2	-4.6	21.6
2002	34.8	-11.0	24.1
2003	36.9	-8.9	22.7
Mean	37.6	-8.2	22.8

explanatory (independent) variable, as used here, is daily streamflow from a (usually nearby) continuous-record USGS streamflow-gaging station. The response (dependent) variable is streamflow data from a partial-record gage. 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 assumes a linear relation between the concurrent logarithms of measured streamflows at the continuous-record gaging sites and the partial-record gaging sites.

MOVE.1 was analyzed for its applicability to the three partial-record streamflow gages for water-budget years 2001-03. The logarithms of streamflow values for the three partial-record streamflow-gaging stations were plotted in relation to the logarithms of flow values for nearby continuous-record streamflow-gaging stations including The Basin Outlet, Townsend Brook, and Little Androscoggin River near South Paris (station number 01057000; fig. 1). Relation plots for each station were analyzed for linearity, outliers that may have a large effect on the relation between the variables, and constant variance. The plots in relation to streamflow values for

Table 3. Annual surface-water inflow to and outflow from Lake Auburn for gaged and ungaged tributaries, water-budget years 2001-03.
[Inflows and outflows are given in millions of cubic feet; water-budget year is defined as a year beginning May 1 and ending April 30 and denoted as the year in which it ends—thus, water-budget year 2001 is the year spanning from May 1, 2000 to April 30, 2001; mi^2, square miles]

U.S. Geological Survey streamflow-gaging station		Drainage area (mi^2)	2001	2002	2003	Mean
Number	Name					
01056400	The Basin Outlet at North Auburn	8.01	392	215	266	291
01056420	Unnamed Brook at Johnson Road at North Auburn	0.34	15.7	12.4	12.9	13.7
01056450	West Unnamed Brook at Lakeshore Drive near Auburn	0.23	8.78	6.66	6.65	7.36
01056460	East Unnamed Brook at Lakeshore Drive near Auburn	0.56	21.2	16.4	15.3	17.6
01056480	Townsend Brook near Auburn	1.88	62.9	40.7	45.4	49.7
	All other ungaged inflow	3.75	152	118	116	129
Total surface-water inflow and outflow budget:						
	Total surface-water inflow	14.8	652	408	463	508
01056505	Total surface-water outflow, Bobbin Mill Brook near Auburn*	18.3	446	154	160	253

* Drainage area of Bobbin Mill Brook outflow includes the surface area of Lake Auburn (3.53 mi^2)

the Little Androscoggin River near South Paris were judged to be the best for all three partial-record gages.

Although the relations for streamflow between the three partial-record gages and Little Androscoggin River continuous-record gage were the best, the plots indicated sparse data for extending the relation to high flows. Due to this questionable relation for high flows, the MOVE.1 relation was not used for the months with the highest flows. Instead, the cubic feet per square mile (CFSM) method was used to estimate April flows for the three partial-record gages. The mean April flow for each water-budget year for each of the three gages was computed as the product of the ratio of their respective drainage areas with that of the Little Androscoggin River, multiplied by the mean April flow at the Little Androscoggin River gage.

Inflow to Lake Auburn from ungaged drainage areas was estimated by use of the CFSM method. The total monthly inflow volume per square mile from East Unnamed Brook at Lakeshore Drive, West Unnamed Brook at Lakeshore Drive, and Unnamed Brook at Johnson Road was multiplied by the remaining ungaged drainage area (3.75 mi^2) to calculate mean monthly flows from this ungaged drainage area to Lake Auburn.

During periods of low flow (summer and early fall), the sand and gravel aquifer in the Townsend Brook watershed provides Townsend Brook with substantial base flow. For example, during August, September, and October of the drought in 2001, Townsend Brook (12.7 percent of the Lake Auburn watershed) provided 96 percent of the 7.13 million ft^3 (53.3 Mgal) that flowed into Lake Auburn during that time. By comparison, The Basin Outlet, draining 54.2 percent of the Lake Auburn watershed, provided 0.08 million ft^3 (0.60 Mgal) during August and zero during September and October of 2001. For August, September, and October of the following drought year (2002), Townsend Brook contributed 80 percent and The Basin Outlet provided 17 percent of the total surface-water inflow—a 3-month total inflow volume of 8.92 million ft^3 (66.7 Mgal).

Although streamflow runoff volume from Townsend Brook was substantial during low-streamflow periods, the total streamflow runoff volume per square mile from Townsend Brook during the 3-year study period was 25.7 percent less than the volume from the rest of the watershed. The lower runoff volume per square mile from Townsend Brook could be a result of infiltration of water into the sand and gravel aquifer during ground-water recharge periods where the water was later evapotranspirated by vegetation from the root zone, and (or) transported through the aquifer to discharge outside of the Lake Auburn surface-water drainage area.

Withdrawals and Lake Storage

Total monthly municipal withdrawals from Lake Auburn, in millions of gallons, were provided to the USGS by the AWD. These data were converted to millions of cubic feet for the water-budget calculations. During the three water-budget years examined, the AWD and LWD withdrew a mean of 392 million ft^3 (2,930 Mgal) of water from the lake per year (table 4). Annual withdrawals during the 3 years showed little variation, with values ranging from 379 to 402 million ft^3 (2,840 to 3,010 Mgal). Monthly withdrawals varied seasonally with larger withdrawals during the summer and smaller withdrawals during the winter and spring. The mean monthly withdrawal over the three-year period was 32.7 million ft^3 (245 Mgal) with a maximum of 40.7 million ft^3 (304 Mgal) in July, 2000 and a minimum of 25.8 million ft^3 (193 Mgal) in October, 2001.

The AWD controls the level of the lake at the East Auburn Dam on the eastern side of Lake Auburn (fig. 1). Changes in lake storage were computed with an equation that relates lake-water level to storage volume. Lake Auburn water-level data, measured on the 1st, 10th, and

Table 4. Annual municipal withdrawals from Lake Auburn and changes in lake storage, water-budget years 2001-03.

[All values given in millions of cubic feet; water-budget year is defined as a year beginning May 1 and ending April 30 and denoted as the year in which it ends—thus, water-budget year 2001 is the year spanning from May 1, 2000 to April 30, 2001]

Water-budget year	Withdrawal	Net change in storage
2001	402	0.00
2002	379	-139
2003	396	89.0
Mean	392	-16.7

20th day of each month since April 1, 1940, were provided to the USGS by the AWD. The water levels that corresponded to the first day 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 quadratic storage-rating equation. Summing all the monthly changes in storage for all the months in a water-budget year yielded an annual net change in storage for that water-budget year (table 4). The largest monthly gain in storage was between March 1 and April 1, 2003 with a net gain of 139 million ft^3 (1,040 Mgal) of water, and the largest monthly loss from storage was between July 1 and August 1, 2001 with a net loss of 108 million ft^3 (808 Mgal) of water. During the 3-year period of study, there was a net loss of 49.9 million ft^3 (373 Mgal) of water from storage—consistent with the fact that the lake level was lower on May 1, 2003 (260.5 ft) than it was on May 1, 2000 (261.0 ft).

Water levels during the 2001-03 water-budget years were measured by AWD personnel and periodically calibrated using a surveyor's level, back-sighting on a benchmark tablet constructed on the Route 4 bridge on the eastern side of Lake Auburn (Mary Jane Dillingham, Auburn Water District, oral commun., 2004). The median water level recorded during the period of study was 259.6 ft. The lowest water level recorded during the period of study was 256.7 ft on February 20, 2002, which also is the record-low water level for the period of record since April 1, 1940. The highest water level recorded during the period of study was 261.2 ft on June 20 and July 1, 2002—only 0.4 ft lower than the maximum control elevation of East Auburn Dam (261.6 ft) (Normand Lamie, Auburn Water District, written commun., 2003). The record-high water level for the period of record for Lake Auburn is 262.4 ft, recorded on April 1, 1953 as a result of a flood in southwestern Maine that occurred during March 27-30, 1953.

Water Budget for Lake Auburn, May 1, 2000 through April 30, 2003

The water budget equation used for this investigation of Lake Auburn is summarized as follows: Water into the lake (inflows) is equal to water out of the lake (outflows) plus net change in storage in the lake itself, shown as:

$$ppt + SW_{in} + GW_{in} = E + SW_{out} + GW_{out} + WD + \Delta S \qquad (1)$$

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

ΔS is net change in storage.

Monthly volumes were computed for all components of the water budget except ground-water flow in and out of the lake bed (figs. 2 and 3). The annual water budgets for water-budget years 2001-03 for Lake Auburn are illustrated in figure 4. The largest component of the inflow water budget is the surface-water component (fig. 5), making up, on average, about 62 percent of the total mean annual inflow. The largest component of the outflow water budget is the municipal withdrawals by AWD and LWD (fig. 6), making up, on average, about 47 percent of the total mean annual outflow.

The total mean annual inflow to Lake Auburn during water-budget years 2001-03 was 816 million ft^3 (6,100 Mgal). The total mean annual outflow from Lake Auburn for the same period was 834 million ft^3 (6,240 Mgal).

The annual water budgets for Lake Auburn for water-budget years 2001-03 are shown in table 5. The total inflow and outflow volumes, adjusted for changes in lake storage, nearly balance for the 3-year water-budget. Any non-zero remainder volume for a given water-budget year is the residual. The mean annual residual for the three water-budget years is -1.06 million ft^3 (-7.93 Mgal). The changing sign of the residual from water-budget year to water-budget year (table 5) indicates that no systematic errors were made with regard to estimating inflows to or outflows from Lake Auburn. Because ground-water flow is unquantified in this water budget, any net ground-water flow through the lake bed is assumed to be contained in the residual term.

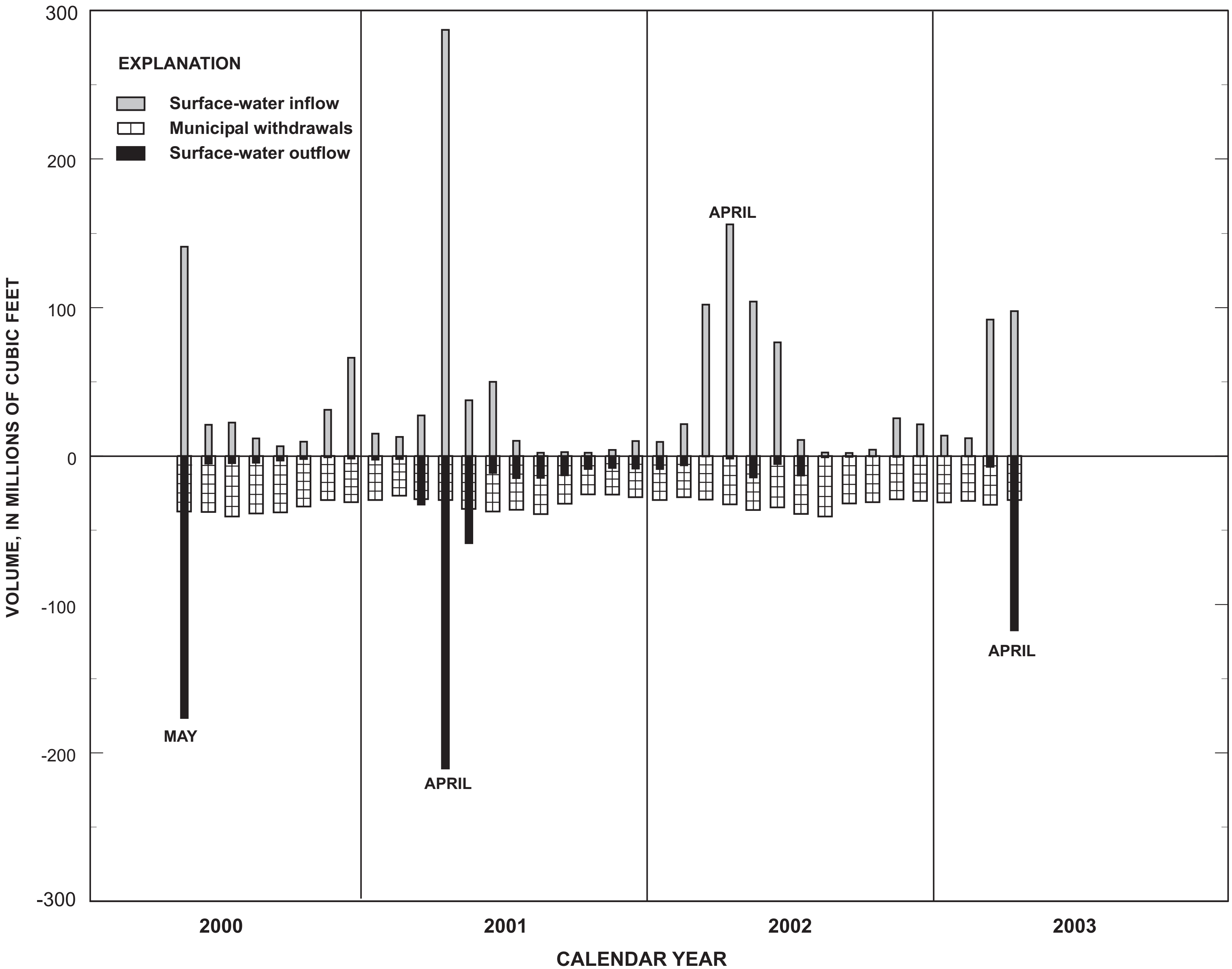

Figure 2. Monthly surface-water inflow, surface-water outflow, and municipal withdrawal volumes for the Lake Auburn water budget, water-budget years 2001-03.

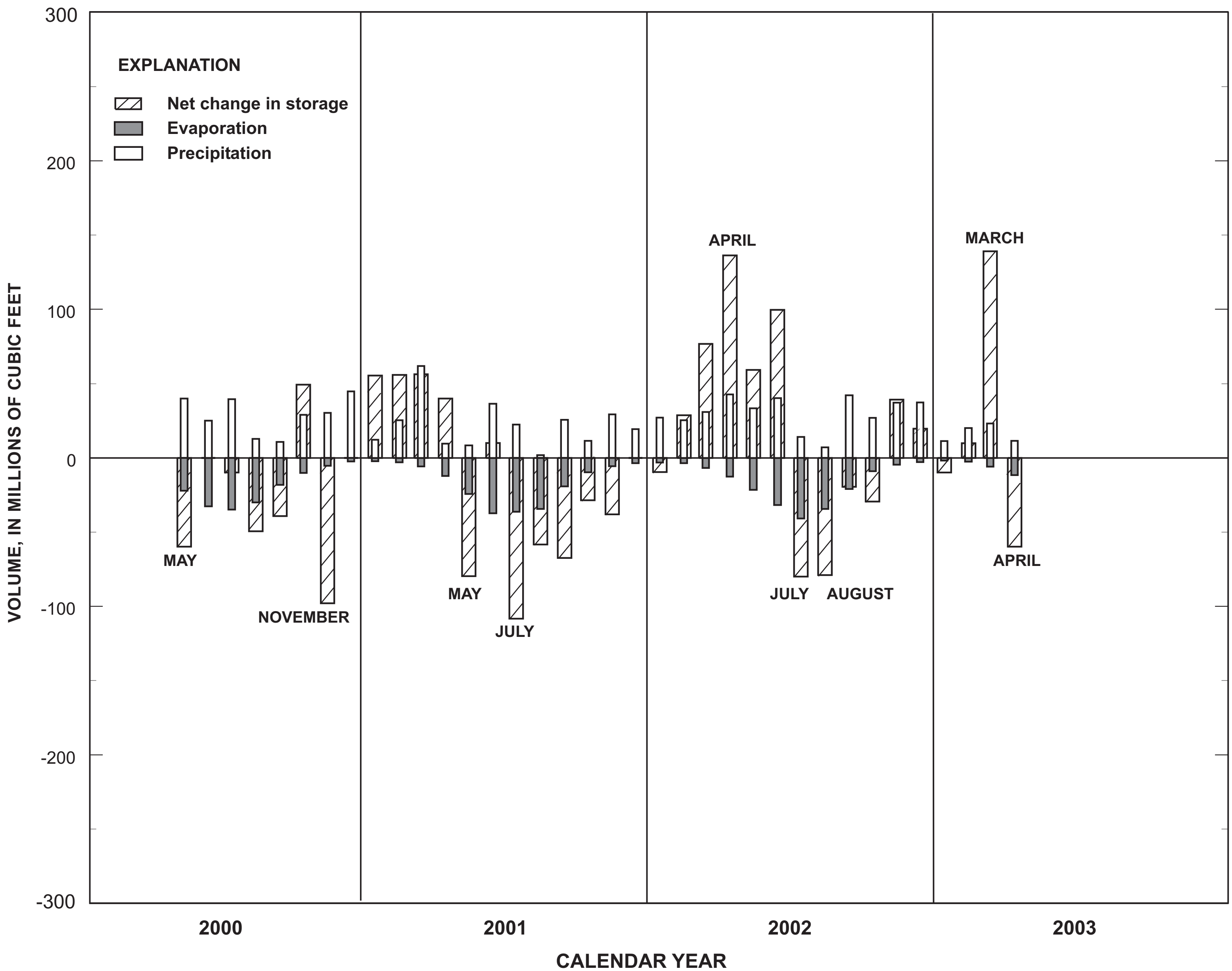

Figure 3. Monthly precipitation, evaporation, and net changes in storage for the Lake Auburn water budget, water-budget years 2001-03.

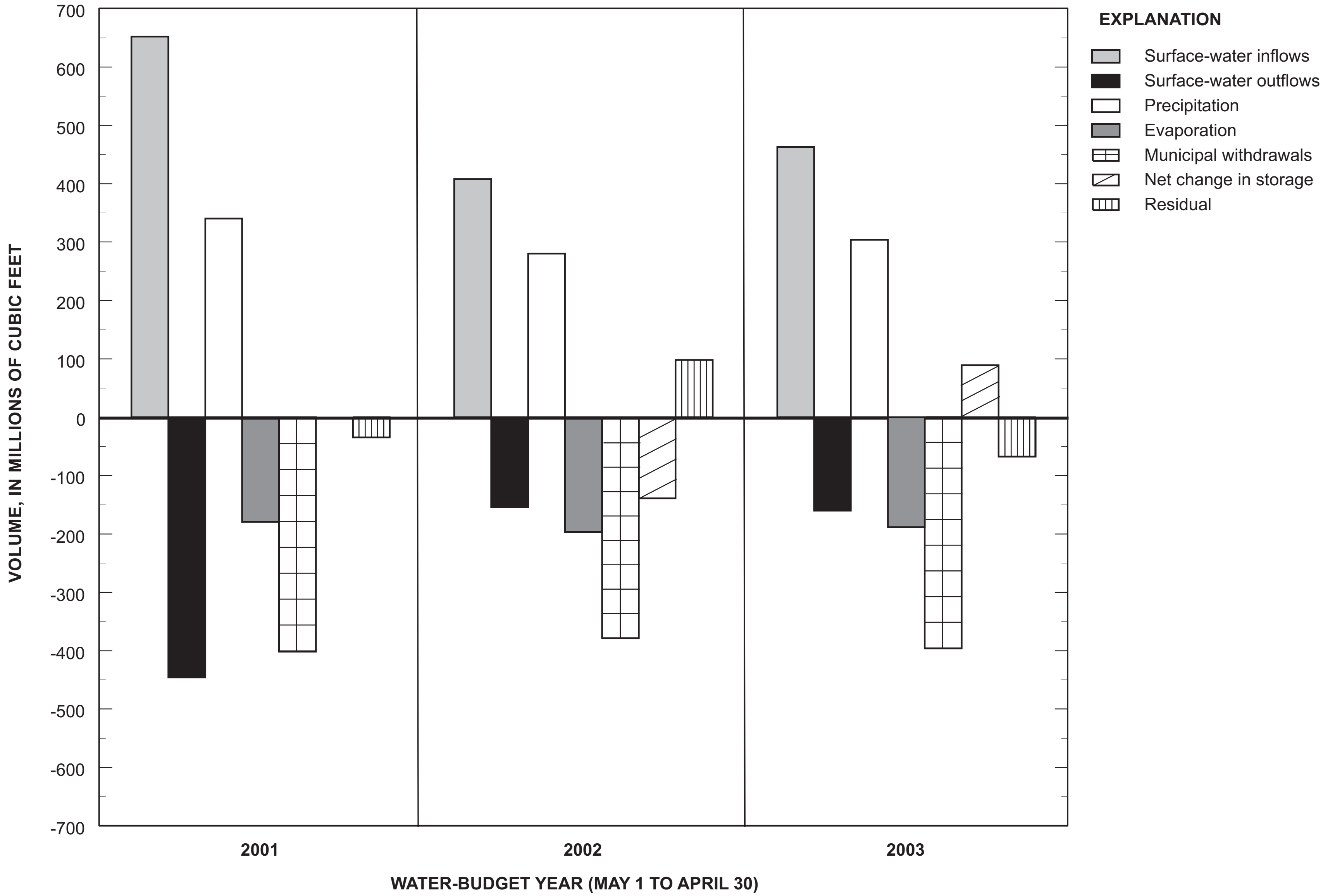

Figure 4. Annual surface-water inflows and outflows, precipitation, evaporation, municipal withdrawals, net changes in storage, and residuals for the Lake Auburn water budget, water-budget years 2001-03.

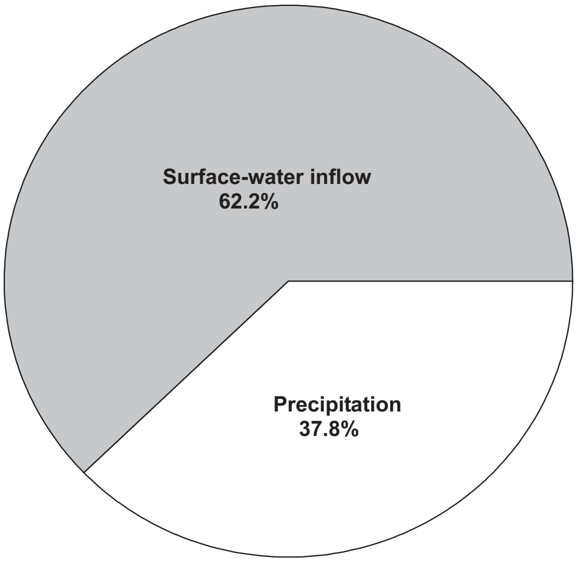

Figure 5. Mean annual inflow water budget for Lake Auburn, water-budget years 2001-03.

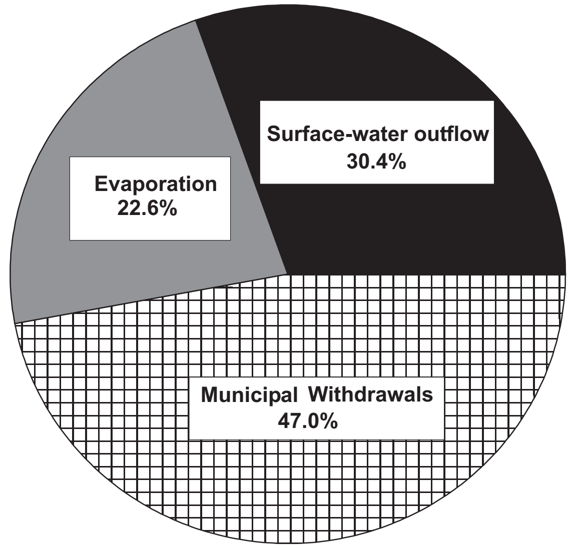

Figure 6. Mean annual outflow water budget for Lake Auburn, water-budget years 2001-03.

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 Lake Auburn was counted as precipitation input; precipitation falling elsewhere in the Lake Auburn watershed, 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 NWS climate station in Lewiston served as the estimate for precipitation directly on the lake. The NWS climate station in Lewiston is about 3.5 mi from the centroid of the lake.

Winter (1981) evaluated errors associated with the collection and interpretation of precipitation data and related its importance to water-balance studies of lakes. As precipitation data are averaged over longer time

Table 5. Annual water budgets for Lake Auburn, water-budget years 2001-03.

[All values given in millions of cubic feet; water-budget year is defined as a year beginning May 1 and ending April 30 and denoted as the year in which it ends—thus, water-budget year 2001 is the year spanning from May 1, 2000 to April 30, 2001]

Water-budget year	Preciptiation	Evaporation	Surface-water inflow	Surface-water outflow	Municipal withdrawals	Net change in storage	Residual
2001	340	179	652	446	402	0.00	-34.5
2002	280	197	408	154	379	-139	98.3
2003	304	188	463	160	396	89.0	-67.0
Mean	308	188	508	253	392	-16.7	-1.06

periods, errors are smaller than errors associated with precipitation data averaged over shorter time periods. Errors can be in the range of 10 to 20 percent for monthly estimates, and about 5 percent for seasonal time-period estimates, based on studies in relatively flat terrain with a sparse precipitation-gage density (200-250 mi^2/gage) (Winter, 1981). The mean annual precipitation in the Lake Auburn watershed shows little areal variability, ranging from 44 to 46 in., based on regional precipitation data for the northeastern United States from 1950-81 (Randall, 1996). Given the proximity of the NWS precipitation station to the lake and the low spatial variability in precipitation for the watershed, annual precipitation estimates from the NWS Lewiston station are assumed to be within 5 percent of the actual precipitation falling on the surface of the lake.

Evaporation

Hamon (1961) evaluated his evaporation equation against year-round data for valleys covering a wide variation in 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 from May through September. 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 21.6 in. in water-budget year 2001 to 24.1 in. in water-budget year 2002 with a 3-year mean of 22.8 in. By comparison, a 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 23.5 in. for the Lake Auburn area. Another map of annual lake evaporation based on climatological data from 1930-49 shows a value of 22 in. for the Lake Auburn area (Knox and Nordenson,1955). The congruence of these evaporation estimates lends a measure of confidence to using the Hamon equation for this water budget. Due to this 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 greater.

Surface-Water Inflows

Surface-water inflows to the lake include channelized and non-channelized flow. All gaged, channelized flow into Lake Auburn is estimated using USGS streamflow-gaging station data (67 percent of the total contributing watershed area to the lake). USGS streamflow records that are rated as excellent (good, fair) are estimated to be within 5, (10, 15) percent of the true daily streamflow 95 percent of the time (Stewart and others, 2001). Most records for the 3-year study period are rated good or fair.

All other surface-water inflows are estimated using MOVE.1 or the CFSM methods. The surface-water inflow from East Unnamed Brook at Lakeshore Drive, West Unnamed Brook at Lakeshore Drive, and Unnamed Brook at Johnson Road (7.7 percent of the total contributing watershed area to the lake) was estimated using MOVE.1. Errors associated with the MOVE.1 method were not computed. The data at these sites indicated questionable relations at high flows so the CFSM method was used to estimate mean April inflows for these drainage areas—the MOVE.1 relation was used to estimate inflows for all other months. The CFSM method also was used to estimate flow contribution from the remaining, ungaged parts of the watershed (25 percent of the total contributing watershed area to the lake). Error associated with this method is not known. Because the CFSM estimates are based on flows for East Unnamed Brook at Lakeshore Drive, West Unnamed Brook at Lakeshore Drive, and Unnamed Brook at Johnson Road, errors in MOVE.1 estimates for these streams will contribute to errors in the CFSM estimates.

Surface-Water Outflows

All surface-water outflow from Lake Auburn is estimated using USGS streamflow-gaging station data. USGS streamflow records that are rated as excellent (good, fair) are estimated to be within 5, (10, 15) percent of the true daily streamflow 95 percent of the time (Stewart and others, 2001). Most records for the 3-year study period are rated good or fair.

Withdrawals

Data for municipal water-supply withdrawals from Lake Auburn by AWD and LWD were provided to the USGS courtesy of the AWD and LWD. The monthly withdrawal volumes are measured using Venturi-type flow meters with a mean estimated error of about 5 percent (Daniel Rodrigue, Auburn Water District, oral commun., 2003).

Lake Storage

Storage was computed using a quadratic function that relates lake elevation with storage volume. It is assumed that the surface area of the lake used in this equation is within 5 percent (0.18 mi^2) of its true surface area (3.53 mi^2). AWD is able to report the water level with an accuracy of 0.05 ft (Mary Jane Dillingham, Auburn Water District, oral commun., 2003). 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 about 3.0 percent at the median lake level (259.6 ft).

Ground Water

Ground water flow into and out of Lake Auburn through the lake bed is unquantified in this water budget. Any net ground-water flow through the lake bed is assumed to be contained in the residual term. Because ground water can affect the chemical composition of a lake's water, even when it is a small component of a lake's total water budget, quantifying the exchange of ground water with Lake Auburn is an important prerequisite to managing the water quality. Solutes that originate in the shallow ground water, occurring either naturally from geologic sources or atmospheric deposition or from anthropogenic sources such as septic tank leach fields or farmland, can flow into the lake through ground water, eventually affecting the water quality of the lake. To understand a lake's nutrient or chemical budget, ground-water inputs and losses must be quantified (Sacks and others, 1998).

Residual

Under ideal conditions, the residual for a thorough water budget conducted over a long period of time (many years) should be equal to zero. For a water-budget that does not directly quantify ground-water flow through the lake bed, the residual term is assumed to be composed of unquantified net ground-water flow and uncertainties associated with the estimates of all other water-budget components. Monthly residuals for the water budget calculated in this report are well-distributed about zero and show no correlation with time or any other water-budget component.

Errors associated with budgeting precipitation, net changes in storage, and municipal withdrawals are relatively small. Assuming an uncertainty of about 5 percent for precipitation estimates, the error in computing annual water volume input to Lake Auburn from precipitation would be 1.9 percent of the mean annual inflow budget (816 million ft^3). Error associated with uncertainties in the calculation of storage volume, although variable with volume, is assumed to be about 3.0 percent for computing storage at median lake level (259.6 ft). Although municipal withdrawals are the largest component of the mean annual outflow water budget, the mean error in estimating withdrawals (5 percent uncertainty) would be about 2.4 percent of the mean annual outflow budget (834 million ft^3).

Errors associated with budgeting evaporation and ungaged surface-water inflows are the largest contributions of uncertainty to the water budget. If the uncertainty in estimating annual evaporation is assumed to be about 20 percent, the error in computing water volume removed from Lake Auburn due to evaporation would be 4.5 percent of the mean annual outflow budget. The error associated with surface-water inflow from the ungaged areas of the watershed cannot be reasonably quantified.

Summary

The U.S. Geological Survey (USGS), in cooperation with the Maine Department of Human Services Drinking Water Program, and the Lake Auburn Watershed Protection Commission, began a study in 2000 to compute a water budget for Lake Auburn for a 3-year period (May 1, 2000 through April 30, 2003). Computation and associated uncertainty of the following major water-budget components were included: (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 Lake Auburn during water-budget years 2001-03 is 816 million ft^3 (cubic feet) (6,100 Mgal (million gallons)). The total mean annual outflow from Lake Auburn for the same period is 834 million ft^3 (6,240 Mgal). The largest component of the inflow water budget is surface-water inflow, making up, on average, about 62 percent of the total mean annual inflow. The largest component of the outflow water budget is the municipal withdrawals by Auburn Water District and Lewiston Water Division, making up, on average, about 47 percent of the total mean annual outflow.

The significant sand and gravel aquifer in the Townsend Brook watershed provides Townsend Brook with substantial base streamflow during low-streamflow periods. During August, September, and October of the drought years 2001 and 2002, Townsend Brook (12.7 percent of the Lake Auburn watershed) provided 96 and 80 percent, respectively, of the total surface-water inflow to Lake Auburn. Although streamflow runoff volume from Townsend Brook was relatively substantial during low-streamflow periods in 2001 and 2002, the total streamflow runoff volume per square mile from Townsend Brook over the 3-year study period was 25.7 percent less than the volume from the rest of the watershed. This diminished runoff could be a result of infiltration of water into the sand and gravel aquifer during ground-water recharge periods where the water was later evapotranspirated by vegetation from the root zone, and (or) transported through the sand and gravel aquifer to discharge outside of the Lake Auburn surface-water drainage area.

The total inflow and outflow volumes, adjusted for changes in lake storage, nearly balance for each water year. The remainder of the sum of inflow minus outflow volumes is the residual. The mean annual residual for the three water-budget years is -1.06 million ft^3 (-7.91 Mgal). The residual term is assumed to be composed of unquantified net ground-water flow and uncertainties associated with all other measured and estimated water-budget components.

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