Total Phosphorus Loads for Selected Tributaries to Sebago Lake, Maine

Water-Resources Investigations Report 01-4003

Prepared in cooperation with the Portland Water District

U.S. Department of the Interior
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Augusta, Maine
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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
inch (in.)	25.40	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile ($ft^3/s/mi^2$)	0.01093	cubic meter per second per square kilometer
pound per year (lb/yr)	0.4536	kilogram per year

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F = (1.8 × °C) + 32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C = (°F - 32) / 1.8

Altitude, as used in this report, refers to distance above or below sea level. In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

The streamflow and water-quality data-collection networks of the Portland Water District (PWD) and the U.S. Geological Survey (USGS) as of February 2000 were analyzed in terms of their applicability for estimating total phosphorus loads for selected tributaries to Sebago Lake in southern Maine.

The long-term unit-area mean annual flows for the Songo River and for small, ungaged tributaries are similar to the long-term unit-area mean annual flows for the Crooked River and other gaged tributaries to Sebago Lake, based on a regression equation that estimates mean annual streamflows in Maine. Unit-area peak streamflows of Sebago Lake tributaries can be quite different, based on a regression equation that estimates peak streamflows for Maine.

Crooked River had a statistically significant positive relation (Kendall's Tau test, $p=0.0004$) between streamflow and total phosphorus concentration. Panther Run had a statistically significant negative relation ($p=0.0015$). Significant positive relations may indicate contributions from nonpoint sources or sediment resuspension, whereas significant negative relations may indicate dilution of point sources.

Total phosphorus concentrations were significantly larger in the Crooked River than in the Songo River (Wilcoxon rank-sum test, $p<0.0001$). Evidence was insufficient, however, to indicate that phosphorus concentrations from medium-sized drainage basins, at a significance level of 0.05, were different from each other or that concentrations in small-sized drainage basins were different from each other (Kruskal-Wallis test, $p=$ 0.0980, 0.1265). All large- and medium-sized drainage basins were sampled for total phosphorus approximately monthly. Although not all small drainage basins were sampled, they may be well represented by the small drainage basins that were sampled.

If the tributaries gaged by PWD had adequate streamflow data, the current PWD tributary monitoring program would probably produce total phosphorus loading data that would represent all gaged and ungaged tributaries to Sebago Lake. Outside the PWD tributary-monitoring program, the largest ungaged tributary to Sebago Lake contains 1.5 percent of the area draining to the lake. In the absence of unique point or nonpoint sources of phosphorus, ungaged tributaries are unlikely to have total phosphorus concentrations that differ significantly from those in the small tributaries that have concentration data.

The regression method, also known as the rating-curve method, was used to estimate the annual total phosphorus load for Crooked River, Northwest River, and Rich Mill Pond Outlet for water years 1996-98. The MOVE.1 method was used to estimate daily streamflows for the regression method at Northwest River and Rich Mill Pond Outlet, where streamflows were not continuously monitored. An averaging method also was used to compute annual loads at the three sites. The difference between the regression estimate and the averaging estimate for each of the three tributaries was consistent with what was expected from previous studies.

INTRODUCTION

Sebago Lake is the second largest lake in Maine. The Portland Water District (PWD) monitors the lake for various chemical constituents, including total phosphorus. Phosphorus loads are calculated by the PWD each year by multiplying the annual mean phosphorus concentration by the mean annual streamflow for each tributary of the lake (Portland Water District, written commun., 1998). Phosphorus loads are essential when establishing mass balances for a lake, as well as for detecting trends in annual transport rates and assessing the effects of measures to reduce phosphorus loading from both point and nonpoint sources (Kronvang and Bruhn, 1996).

The U.S. Geological Survey (USGS) and the PWD have worked cooperatively for several years to assess the water resources of the Sebago Lake Basin. As part of this study, a project was begun to describe the streamflow and water-quality data-collection networks of the USGS and the PWD, and to determine whether the data collected in these networks are likely to produce reasonably accurate estimates of phosphorus loads into Sebago Lake. This report describes the adequacy of the data-collection networks, the methods used to compute phosphorus loads, and the total phosphorus loads for selected tributaries.

DESCRIPTION OF THE STUDY AREA

Sebago Lake in southern Maine is surrounded by the towns of Standish, Sebago, Naples, Casco, Raymond, and Windham (fig. 1). Portland, Maine's largest city, is about 15 mi southeast of the lake. Sebago Lake has a surface area of 45.0 mi^2, a mean depth of 101 ft, a maximum depth of 316 ft, and a mean hydraulic retention time of 5.4 years (Pacific Northwest Environmental Research Laboratory, 1974).

The drainage area of Sebago Lake Basin is 440 mi^2 (Cowing and McNelly, 1978), including the 45.0 mi^2 of lake surface area (fig. 1). The basin is predominately rural, hilly, and forested with some farmland and residential development. There are many lakes and ponds in the basin. The surficial geology of the basin consists primarily of glacial till (a mixture of sand, silt, clay, and stones), except near the Crooked River, where the materials are mostly sand and gravel glacial outwash deposits (Thompson and Borns, 1985).

The principal tributary to Sebago Lake is the Songo River, which drains an area of 275 mi^2. The Crooked River, which flows into the Songo River about 2 mi upstream from Sebago Lake, has a drainage area of 154 mi^2. 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 COLLECTION AND ANALYSIS

This section contains a description of the data-collection networks, an analysis of the adequacy of the networks to provide the necessary data, and the methods used to compute phosphorus loads.

Data-Collection Networks in the Sebago Lake Basin

Streamflow data are collected by the USGS and the PWD on tributaries to Sebago Lake (fig. 2). The USGS has collected streamflow data for different periods of record at several locations on three tributaries--continuous data at Crooked River near Naples (at State Highway 11, USGS gaging station number 01063100) since October 1995; continuous data at Stony Brook at East Sebago (at State Highway 114 and 11, USGS gaging station number 01063310) since October 1995; seasonal data at the Crooked River gaging station from 1975 to 1977; and continuous data at Standish Brook at mouth at Sebago Lake (01063452) since August 1999. Daily mean streamflows are published annually by the USGS (Nielsen and others, 1997; 1998; 1999). Streamflow data are collected using the techniques described in Rantz and others (1982). These techniques involve continuous collection of stream stage (height) data and periodic streamflow measurements. The relation between stage and streamflow on each tributary is used to calculate streamflow when stage measurements are made with no corresponding streamflow measurement.

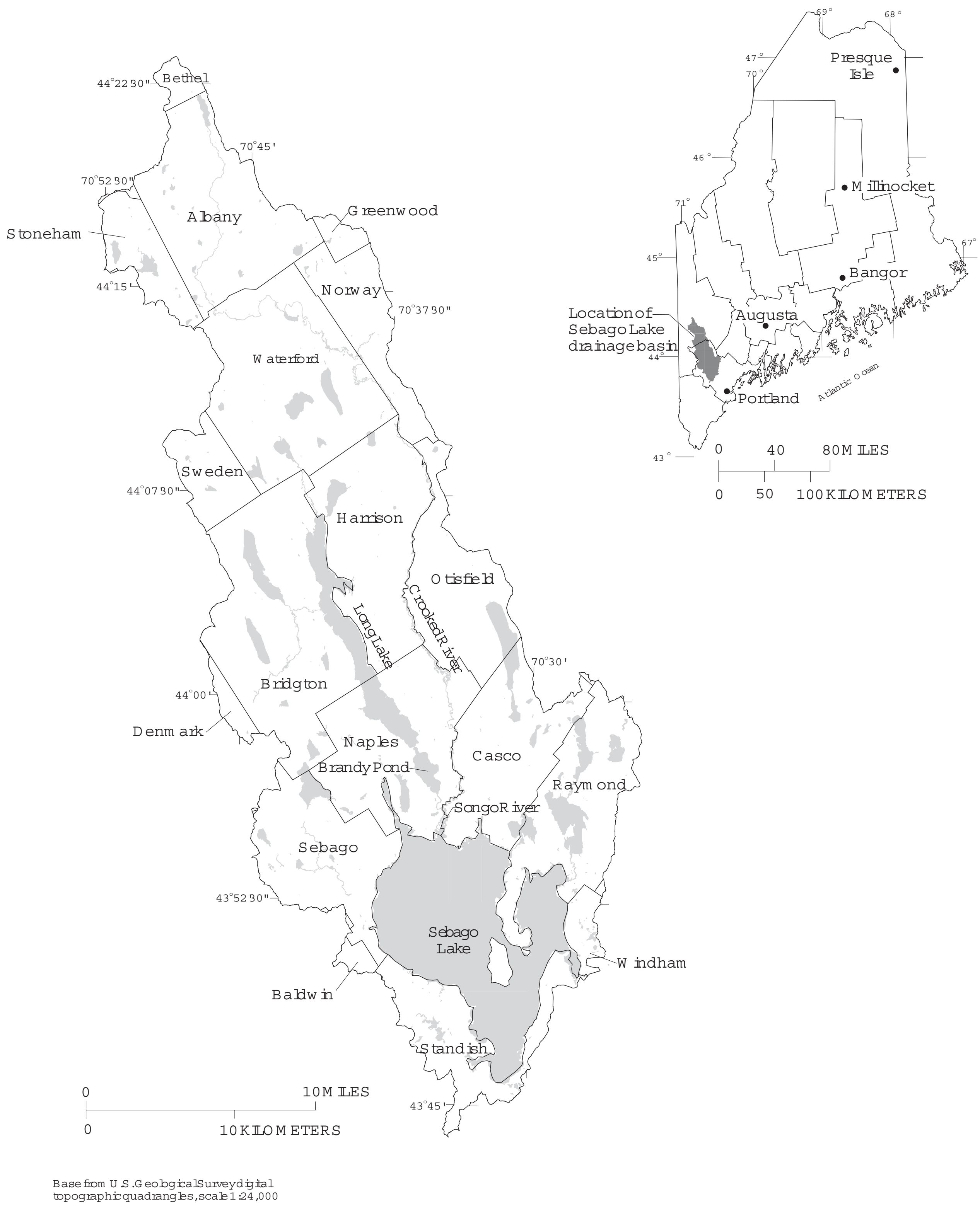

Figure 1. Sebago Lake drainage basin, Maine.

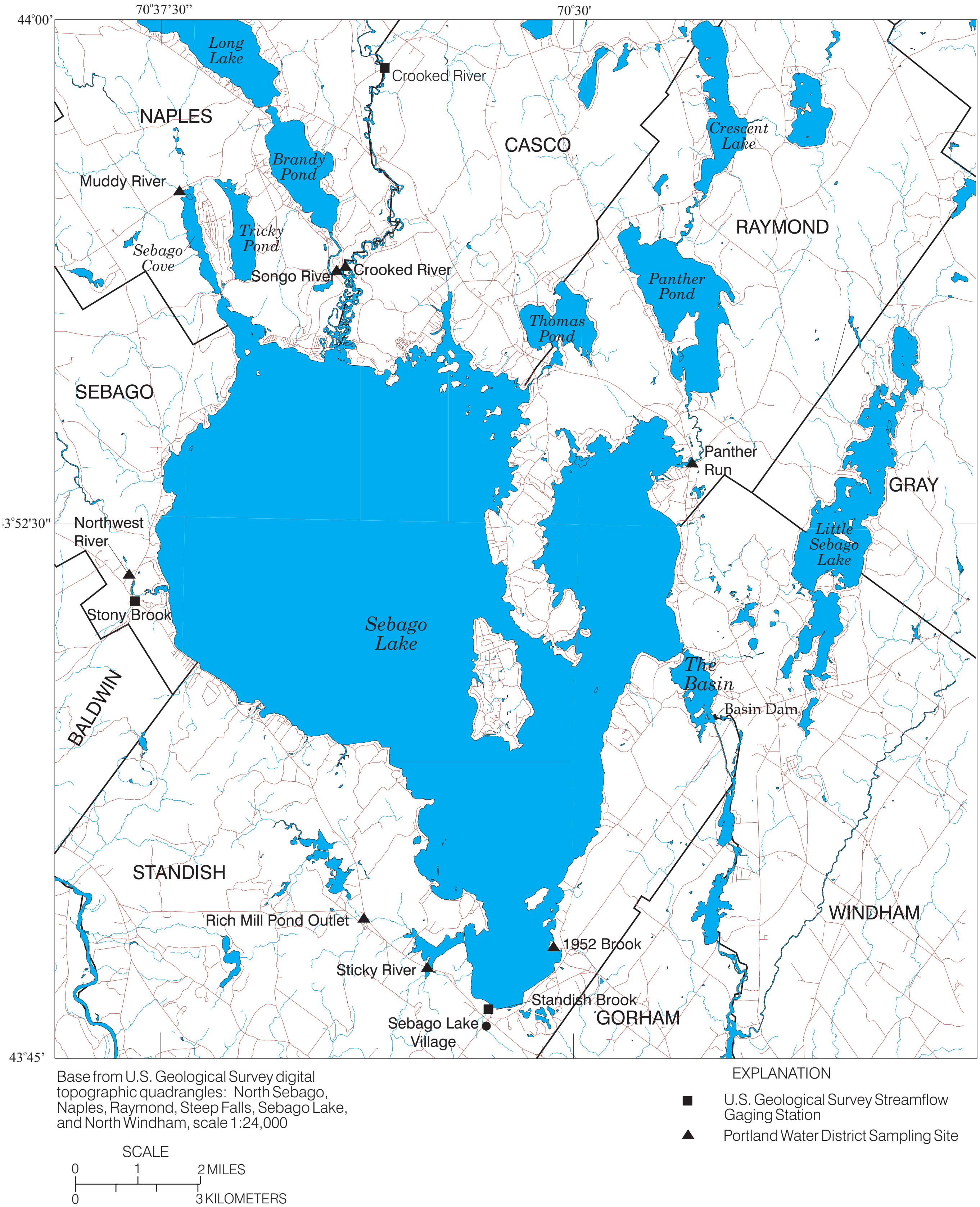

Figure 2. Data-collection locations on tributaries to Sebago Lake, Maine.

The PWD collects streamflow or stage-only data on seven tributaries to Sebago Lake, in addition to the three USGS sites. These tributaries are Songo River, Muddy River, Northwest River, Rich Mill Pond Outlet, Sticky River, 1952 Brook, and Panther Run. A few USGS streamflow measurements have also been made at these seven tributaries (Nichols and Silverman, 1998). The PWD records stream stage approximately monthly (when water quality samples are collected) and measures streamflow periodically (Portland Water District, written commun., 1998). The relation between stage and streamflow on each tributary is used to calculate streamflow when stage measurements are made with no corresponding streamflow measurement. Review of the quality of the PWD's streamflow and stage data was beyond the scope of this report.

Many errors are possible when collecting stage and streamflow data. Certain locations on streams are subject to variable backwater, which causes inaccuracies when determining streamflow from the relation between stage and streamflow. Variable backwater can be caused by a lake, a confluence with another stream, debris, ice, and aquatic growth. The relation between stage and streamflow also can be altered by changes in streambeds (erosion or fill). If streamflows have not been measured throughout the full range of stages (especially at very high and very low stages), significant errors in the stage-streamflow relation can result. Stage errors can be caused by settlement or uplift of stage gages. Streamflow measurement errors can be caused by inaccurately calibrated equipment, a measurement cross section with an inadequate number of velocity and depth measurements, and rapidly changing stage (Rantz and others, 1982).

The PWD collects water-quality data on nine tributaries to Sebago Lake (all streams shown in fig. 2, except Stony Brook). Samples are collected approximately monthly and are analyzed by PWD for various chemical constituents, including total phosphorus. Phosphorus loads are calculated by PWD each year by multiplying the annual mean phosphorus concentration by the annual mean streamflow for each tributary (Portland Water District, written commun., 1998). Review of the quality of PWD water-quality sampling and analyses was beyond the scope of this report.

Adequacy of Current Stream-Gaging Network

Total Tributary Input

The drainage areas of the tributaries in the PWD tributary-monitoring program were determined using USGS topographic maps and information in Cowing and McNelly (1978). The sum of the drainage areas of these sites is 344 mi^2. The amount of ungaged tributary drainage area and direct runoff to Sebago Lake is 51 mi^2 or 12.9 percent of the drainage basin area of Sebago Lake (excluding Sebago Lake surface area). The largest ungaged tributaries to Sebago Lake are the outlet of Sebago Cove, which has 6.1 mi^2 of ungaged area downstream from Muddy River at Kimball Corner Road in Naples, and Thomas Pond Outlet, which has a drainage area of 5.2 mi^2 on the Casco/Raymond town line.

A regression equation for estimating the mean annual streamflow (over many years) for ungaged drainage basins in Maine was described by Parker (1978). The equation used drainage basin area and mean annual precipitation as explanatory (independent) variables. The regression equation has a very low standard error of estimate (6.9 percent). This means that approximately 68 percent of the mean annual streamflows predicted by the regression equation were within 6.9 percent of the actual mean annual streamflows of the gaging stations used to create the equation.

The mean annual streamflow from the Parker regression equation varies with mean annual precipitation on a unit-area basis ($ft^3/s/mi^2$). Because the exponent in the regression equation for drainage area is 0.985, rather than 1.000, the unit-area mean annual streamflow also will vary slightly with drainage area. The mean annual precipitation in the Sebago Lake drainage basin has little variability and ranges from slightly less than 42 in. to slightly more than 44 in. (Knox and Nordenson, 1955). The mean annual streamflow based on the Parker equation will vary by about 6.5 percent with a 2-in. change in the mean annual precipitation. The mean annual streamflow will vary by about 10 percent with a 3-in. change in the mean annual precipitation. The mean annual streamflow will vary by only about 7 percent with a 100-fold change in drainage area. Therefore, mean annual streamflows for tributaries to Sebago Lake (on a unit-area basis) are similar.

Peak streamflows also are important to consider, because much of the phosphorus transport takes place during major flow events. Regression equations for estimating peak streamflows of given recurrence intervals for ungaged drainage basins in Maine were described by Hodgkins (1999). The recurrence interval is the average period of time between peak streamflows that are equal to or greater than a specified peak streamflow. For example, the 2-year peak streamflow is the streamflow that would be equaled or exceeded, on long-term average, once in 2 years. The regression equations use drainage basin area and percentage of basin wetlands as explanatory variables. Larger drainage areas and smaller amounts of basin wetlands will generate larger peak streamflow estimates. The basin wetlands variable is computed using National Wetland Inventory Maps that include lakes and ponds as wetlands.

The estimated peak streamflows vary with the amount of basin wetlands and by drainage area on a unit-area basis. The percentage of basin wetlands in a drainage basin can vary considerably between adjacent drainage basins. For example, the 154-mi^2 Crooked River Basin (immediately upstream from the confluence with the Songo River) is 10.3 percent wetlands. The 119-mi^2 Songo River Basin (immediately upstream from the confluence with the Crooked River) is 17.3 percent wetlands. The percentage of wetlands in both basins was computed using the grid-sampling method described in Hodgkins (1999). The difference in basin wetland area results in higher estimated peak streamflows (on a unit-area basis) for the Crooked River than for the Songo River. The estimated 2-year peak streamflow for the Crooked River is 3,240 ft^3/s, and the unit-area peak streamflow is 21.0 $ft^3/s/mi^2$. We are 68 percent confident that the true peak flow lies between 15.0 $ft^3/s/mi^2$ and 29.4 $ft^3/s/mi^2$. The estimated 2-year peak streamflow for the Songo River is 1,690 ft^3/s, and the unit-area peak streamflow is 14.2 $ft^3/s/mi^2$. We are 68 percent confident that the true peak flow lies between 10.2 $ft^3/s/mi^2$ and 19.9 $ft^3/s/mi^2$. The estimated unit-area 2-year peak streamflow is 48 percent higher for the Crooked River than for the Songo River.

It is unlikely that the flow in the Songo River can be measured accurately using conventional stage/flow relations, as described in Rantz and others (1982). This is because of the small elevation change between Brandy Pond and Sebago Lake and the presence of Songo Locks (which controls the elevation change). If accurate streamflows are not computed, an additional 119 mi^2 of the drainage area can be considered ungaged. This would leave 170 mi^2 of ungaged drainage area or 43.0 percent of the drainage area of Sebago Lake (excluding Sebago Lake surface area). The stage/flow relations on Panther Run, Northwest River, Muddy River, Rich Mill Pond Outlet, Sticky River, and 1952 Brook are assumed to be adequate but review of the quality of those records was beyond the scope of this report.

The size of a tributary's drainage basin is by far the most important variable in determining the mean annual streamflows to Sebago Lake. Most large tributaries to Sebago Lake have the potential to be adequately gaged for streamflow using stage/flow relations. The notable exception is the Songo River (upstream from the confluence with the Crooked River) with a drainage area of 119 mi^2. Other than the Songo River drainage area, only 51 mi^2 out of 395 mi^2 of tributary drainage area to Sebago Lake are not gaged. Of these 51 mi^2, the largest single ungaged area is 6.1 mi^2. Adding a streamflow gage to this site would increase the gaged tributary area by 1.5 percent. The (long-term) mean annual streamflow for the Songo River and the small ungaged tributaries to Sebago Lake are similar (on a unit-area basis) to the streamflow for the Crooked River and other gaged tributaries to Sebago Lake; however, it is unknown how similar the annual mean streamflows for Sebago Lake tributaries are for any single given year.

The size of a tributary's drainage basin is the most important variable in determining the magnitude of peak streamflows entering Sebago Lake; however, other basin and climatic characteristics, such as the amount of wetlands, also are important. The Songo River (upstream from the Crooked River) likely produces lower peak streamflows (on a unit-area basis) than the Crooked River; however, the uncertainty of the peak streamflow estimates makes definitive conclusions about peak-flow similarities impossible. This also would be the case if the Songo River was compared to the Northwest River, Panther Run, or other tributaries. It is important to adequately gage peak streamflows on the Songo River (upstream from the Crooked River) because the Songo River drains

119 mi^2 or 30.1 percent of the Sebago Lake drainage area (exclusive of Sebago Lake surface area).

Of the 12.9 percent remaining ungaged drainage basin area, the next largest ungaged tributary drains 1.5 percent of the Sebago Lake drainage area. Thomas Pond Outlet and Batchelder Brook are typical of the small, ungaged drainage basins. Peak streamflows for these sites (table 1) were calculated using methods described in Hodgkins (1999). The 2-year peak streamflows for Thomas Pond Outlet and Batchelder Brook are 3.1 percent and 4.3 percent, respectively, of the estimated 2-year peak streamflow for the Crooked River. Thomas Pond Outlet and Batchelder Brook drainage areas are 3.4 percent and 1.5 percent of the Crooked River drainage area. Peak streamflows from small, ungaged drainage basins are generally small but can be larger than their drainage areas would indicate, as seen in the Batchelder Brook streamflows.

Range of Streamflow

The full range of streamflow is recorded at the USGS streamflow-gaging stations in the Sebago Lake Basin because stage is continuously recorded. The full range of streamflow at PWD gages is not likely to be recorded in any given year, because the stage at these gages is recorded approximately monthly when water-quality samples are collected.

Table 1. Estimated 2-year peak streamflows for selected tributaries to Sebago Lake

Tributary	Drainage area (square miles)	Percent wetlands	Estimated 2-year peak streamflow (cubic feet per second)
Thomas Pond Outlet	5.18	20.0	101
Batchelder Brook	2.36	3.7	140
Crooked River	154	10.3	3,240

The USGS has published daily mean streamflows for Crooked River at Route 11 (150 mi^2 drainage area) for the 1996-98 water years[1] (Nielsen and others, 1997; 1998; 1999). The PWD sampled the Crooked River at its confluence with the Songo River (154 mi^2) 12 to 15 times per year in the 1996-98 water years (Portland Water District, written commun., 1999). The maximum and minimum daily mean streamflows on the days that PWD sampled were compared to the maximum and minimum daily mean streamflows for each water year (table 2).

[1]A water year runs from October 1 of the previous calendar year to September 30 of the current calendar year. For example, the 1996 water year runs from October 1, 1995 to September 30, 1996.

Table 2. Selected daily mean streamflows for U.S. Geological Survey gaging station on Crooked River

Water year	Highest daily mean streamflow on a sampling day (cubic feet per second)	Maximum daily streamflow for year (cubic feet per second)	Lowest daily mean streamflow on a sampling day (cubic feet per second)	Minimum daily streamflow for year (cubic feet per second)
1996	2,290	2,700	51	25
1997	1,380	2,670	55	48
1998	1,720	3,020	43	41

For the 1996 water year, the highest daily mean streamflow on a sampling day was 85 percent of the maximum daily mean streamflow, and the lowest streamflow on a sampling day was 204 percent of the lowest streamflow for the year. For the 1997 water year, the highest streamflow on a sampling day was 52 percent of the highest streamflow for the year, and the lowest streamflow on a sampling day was 115 percent of the lowest streamflow for the year. For the 1998 water year, the highest streamflow on a sampling day was 57 percent of the highest streamflow, and the lowest streamflow on a sampling day was 105 percent of the lowest streamflow for the year. As this shows, monthly sampling at tributaries can miss a significant part of the full range of streamflows. Monthly sampling at smaller, flashier tributaries may miss even more of the full range of streamflow.

The Maintenance of Variance Extension, Type I ("MOVE.1") (Hirsch, 1982; Helsel and Hirsch, 1992) is a method used to estimate streamflow on days when no data are collected. The explanatory (independent) variable, as applicable to this report, is daily streamflow from a continuous-record (USGS) streamflow-gaging station. The response (dependent) variable is streamflow from a stream without continuous streamflow records. 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 (Helsel and Hirsch, 1992).

MOVE.1 was analyzed for its applicability at six PWD gages (Panther Run, Northwest River, Muddy River, Rich Mill Pond Outlet, Sticky River, and 1952 Brook) for water years 1996-98. MOVE.1 assumes that a linear relation exists between the concurrent streamflows at the continuous-record gaging stations and the noncontinuous ones. Logarithms of the streamflows are commonly used to linearize the data. If ice was noted at a PWD site during a measurement, the measurement was not used because of the possibility of variable backwater at the noncontinuous gage. Variable backwater was possible because flow typically was based on gage-height readings. Zero streamflows also were not used because the logarithm of zero cannot be computed.

The logarithms of streamflows at the six PWD sites were plotted against the logarithms of streamflows for Crooked River and for Stony Brook. The plots were analyzed for curvature, for outliers that may have a large influence on the relation between the variables, and for non-constant variance (Helsel and Hirsch, 1992). The plots for Panther Run, Muddy River, Sticky River, and 1952 Brook showed unacceptable curvature patterns, outliers, or non-constant variance. MOVE.1 equations at these sites were judged to be inadequate to compute daily streamflows for later use as input to a tributary load estimator. The plots for Northwest River against Crooked River and for Rich Mill Pond Outlet against Stony Brook were judged to be acceptable.

The MOVE.1 equation for Northwest River was computed as:

$$Y_i = 1.0461X_i - 1.0562 \qquad (1)$$

where

Y_i are the logarithms (base 10) of the estimated daily mean streamflows on Northwest River, and

X_i are the logarithms of the daily mean streamflows on Crooked River.

The MOVE.1 equation for Rich Mill Pond Outlet was computed as:

$$Y_i = 0.5136X_i + 0.8571 \qquad (2)$$

where

Y_i are the logarithms of the estimated daily mean streamflows on Rich Mill Pond Outlet, and

X_i are the logarithms of the daily mean streamflows on Stony Brook.

The daily mean streamflows for Northwest River and Rich Mill Pond Outlet were computed using these two equations for water years 1996-98. These daily streamflows are used later in the report as input to a tributary phosphorus load estimator.

Adequacy of the Water-Quality Network

The concentration data for total phosphorus collected by the PWD and the corresponding PWD or USGS streamflow data for water years 1996-98 were analyzed for streamflow-related trends in total phosphorus concentration. The streams analyzed were Crooked River, Panther Run, Northwest River, Muddy River, Rich Mill Pond Outlet, Sticky River, Standish Brook, and 1952 Brook. Water samples for phosphorus were collected approximately monthly (Portland Water

District, written commun., 1998) just upstream from the confluence of the Crooked River with the Songo River (drainage area of 154 mi^2). The streamflow data used for Crooked River were daily mean streamflows from USGS gaging station number 01063100 at State Highway 11 (drainage area of 150 mi^2). No correction for the difference in drainage areas was made to the streamflows. Streamflows for the remaining tributaries were determined based on gage-height readings made by the PWD when samples were collected. If ice was noted when the gage height was read, the reading was not used because of the possibility of backwater at the noncontinuous gage. Zero streamflows also were not used. Kendall's tau was used to measure the strength of the monotonic relation between streamflow and total phosphorus concentration (Helsel and Hirsch, 1992). The relation between streamflow and concentration with this test does not have to be linear to indicate a significant relation. The attained significance level (p-value) of Kendall's tau (table 3) indicates the probability of obtaining the Kendall's tau value for each stream when there is no relation between streamflow and total phosphorus concentration. For example, the probability is 11 percent that the apparent negative relation between streamflow and total phosphorus concentration for the Northwest River is in fact due to chance.

Based on the data in table 3, the Crooked River shows a highly significant positive relation between streamflow and total phosphorus concentration. Concentrations of phosphorus tended to increase as streamflow increased. Panther Run shows a highly significant negative relation between streamflow and total phosphorus concentration. The data analyzed in table 3 are limited, because many sites had less than 20 concurrent measurements of streamflow and total phosphorus concentration. As more data are collected, different patterns in the data may emerge. Significant positive or negative relations in the streamflow and total phosphorus data may indicate the source of the phosphorus. A decrease in total phosphorus with increasing streamflows may indicate point source dilution (Young and others, 1988), whereas an increase in total phosphorus with increasing streamflows may indicate sediment resuspension or contributions by nonpoint sources (Preston and others, 1989).

All total phosphorus data collected by the PWD approximately monthly from 1995-99 (Portland Water District, written commun., 1999) were used to look for differences in concentration between tributaries. The tributaries were divided into groups consisting of large, medium, and small drainage basins.

The tributaries with large-sized drainage basins are Crooked River (57 measurements of total phosphorus) and Songo River (just upstream from its confluence with Crooked River; 46 measurements). The Wilcoxon rank-sum test (Helsel and Hirsch, 1992) was used to test whether one group of measurements tended to produce larger or smaller observations than the second group. This test does not require an assumption of normality of the data. Total phosphorus concentrations in the Crooked River were significantly larger than the total phosphorus concentrations in the Songo River at a p-value of <0.0001.

Table 3. Values and attained significance level of Kendall's tau for eight Sebago Lake tributaries for streamflow and total phosphorus concentration

Tributary	Kendall's tau	Kendall's tau attained significance level (p-value)	Number of concurrent streamflow and total phosphorus concentration measurements
Crooked River	+0.374	0.0004	42
Panther Run	-0.536	0.0015	18
Northwest River	-0.305	0.1102	15
Muddy River	-0.424	0.0526	12
Rich Mill Pond Outlet	-0.131	0.3302	27
Sticky River	-0.304	0.0671	19
Standish Brook	-0.320	0.0598	18
1952 Brook	-0.257	0.1783	15

The tributaries with medium-sized drainage basins are Panther Run (48 measurements of total phosphorus), Northwest River (46 measurements), and Muddy River (41 measurements). The Kruskal-Wallis test (Helsel and Hirsch, 1992) was used to test whether at least one group tended to produce larger or smaller observations than the other groups. This test does not require an assumption of normality of the data. The p-value for this test was 0.0980. For a commonly used significance level of 0.05, the data did not prove that a statistically significant difference in total phosphorus concentrations was present between tributaries with medium-sized drainage basins.

The tributaries with small-sized drainage basins are Rich Mill Pond Outlet (47 measurements of total phosphorus), Sticky River (41 measurements), Standish Brook (37 measurements), and 1952 Brook (31 measurements). The p-value using the Kruskal-Wallis test was 0.1265. For a commonly used significance level of 0.05, the data did not prove that a statistically significant difference in total phosphorus concentrations was present between the tributaries with small-sized drainage basins.

All tributaries to Sebago Lake that drain large- and medium-sized drainage basins were sampled approximately monthly for total phosphorus. Several small tributaries were sampled. No significant difference in the total phosphorus concentrations was proven (at a significance level of 0.05) for the small tributaries, possibly indicating that all the small tributaries to Sebago Lake were well-represented by the ones that were sampled; however, point and nonpoint sources of total phosphorus may be present in unmeasured basins that are not present in the four measured small-sized basins.

Methods of Computing Loads

Loads (mass/time) of chemical constituents, such as total phosphorus, are computed as the product of streamflow (volume/time) and concentration (mass/volume). The best method to compute annual loads—the summation of loads over time—would require continuous records of streamflow and concentration, or a close approximation of continuous records. Daily (or more frequent) sample collection for concentration can be very expensive, and high-frequency records of concentration are rare (Preston and others, 1992). Previous studies have used high-frequency records from five large agricultural basins in Michigan and Ohio (Preston and others, 1992; 1989; Young and others, 1988; Richards and Holloway, 1987; Dolan and others, 1981); from four small agricultural basins in northern Europe (Kronvang and Bruhn, 1996; Rekolainen and others, 1991); and from eight small agricultural basins in the southern half of Wisconsin (Robertson and Roerish, 1999). Because of the rarity of high-frequency concentration data, load estimation methods are often used with semi-monthly or monthly concentration data.

Load-estimation methods can be divided into three broad classes: averaging, ratio, and regression. Averaging methods are the simplest approach. Annual load estimates are made by using averages as representative measures of streamflow, concentration, or load for a given time interval and summing over the year (Preston and others, 1989). The most commonly used ratio method has been Beale's ratio estimator. In this method, loads are calculated as the product of the total annual streamflow and the ratio of mean daily load and mean daily streamflow, with a correction for statistical bias (Preston and others, 1992). The regression method (also called the rating-curve method) generally uses the relation between the log of sampled load (the response variable) and the log of sampled streamflow (along with other explanatory variables) to estimate loads. Annual load estimates are generally made by entering daily streamflows (and values of other explanatory variables) into the regression equation, calculating daily loads, and summing over the year.

Preston and others (1989) found that no class of load-estimation methods is superior for all test cases considered. Inconsistencies appear to be related to the strength of the relation between streamflow and concentration and the nature of the annual hydrograph. Kronvang and Bruhn (1996) found an increasing number of studies that show that no individual estimation method is superior and that poor accuracy can be obtained for a specific stream for a given constituent and year. The best method in their study was site and time dependent. Preston and others (1992) found the performance of load-estimation methods to be substantially different among tributaries.

For sampling programs with infrequent sampling (less than about 50 samples per year), averaging methods tend to underestimate annual loads when constituent concentrations are positively related to streamflow and overestimate loads when concentrations are negatively related to streamflow (Richards and Holloway, 1987). This is because infrequent sampling will miss many high streamflows that heavily influence the annual load. Based on findings in the previous section of this report, total phosphorus loads computed by averaging methods for Crooked River will tend to underestimate true loads. Total phosphorus loads computed by averaging methods for Panther Run will tend to overestimate true loads.

Ratio methods assume that concentrations do not vary between measurements; therefore, if streamflow and concentrations increase between measurements, such as during a peak streamflow that is not sampled, the load estimates will be severely underestimated (Robertson and Roerish, 1999). Many previous studies that compare load-estimation methods fail to account for the appropriateness of the assumptions inherent to the method being evaluated when drawing conclusions about which methods work best. Regression methods generally provide better estimates of mean constituent loads than do ratio methods if the assumptions of the regression equations are met (Crawford, 1996).

No comparative studies of phosphorus load-estimation methods are known for forested basins in the northeastern United States. Based on the small number of studies that have been performed elsewhere, it appears that, given a limited data-collection budget, the best phosphorus load-estimation method is the regression method, if the assumptions inherent to regression analyses are met for individual streams. This method, however, has significant error associated with it for small flashy streams. Robertson and Roerish (1999) found that the regression method with the most effective sampling strategy for their study was imprecise. Median errors were about 30 percent and errors for some individual sites were much greater.

The tributary drainage areas to Sebago Lake generally are similar in size to those studied by Robertson and Roerish (1999). Because of this, it is assumed that Sebago Lake tributaries having 3 years of continuous streamflow data and monthly phosphorus concentration data (currently only Crooked River) will produce total phosphorus load estimates that have errors similar to those in Robertson and Roerish. Tributaries with noncontinuous streamflow gages where continuous streamflows can be estimated using the MOVE.1 method (Northwest River and Rich Mill Pond Outlet) have additional error that was not quantified for this report. The load estimates for these tributaries are not expected to be biased. Loads for the remainder of the gaged tributaries to Sebago Lake cannot be estimated with confidence because the MOVE.1 method is not applicable (lack of data or a violation of the method assumptions). Phosphorus load-estimation methods for these sites will probably not provide accurate loads without a continuous streamflow gage.

If the tributaries gaged by PWD had adequate streamflow data, the current PWD monitoring program for total phosphorus would probably produce tributary load data that would represent all gaged and ungaged tributaries to Sebago Lake. Outside the PWD tributary monitoring program, the largest ungaged tributary to Sebago Lake contains 1.5 percent of the area draining to the lake. In the absence of unique point or nonpoint sources of phosphorus, these ungaged tributaries are unlikely to have total phosphorus concentrations that significantly differ from the small tributaries that have concentration data. As discussed earlier in the report, a statistically significant difference in total phosphorus concentration between four small tributaries to Sebago Lake was not proven.

In terms of sampling strategies for concentration data, Preston and others (1992) found that some allocation of samples to high streamflows can provide substantial benefits, especially in streams with high streamflow variability. Among the benefits was an overall increase in accuracy for all three classes of estimators and a reduction in the bias of the averaging and regression estimators. One of the streams discussed in Preston and others (1992) had a drainage area of 149 mi^2, however, four of the five streams had drainage areas between 1,250 mi^2 to 6,400 mi^2.

Robertson and Roerish (1999) analyzed different total phosphorus sampling strategies (some of them included high-flow sampling in addition to regular sampling) on eight streams with drainage areas of 5.4 mi^2 to 42 mi^2. This is the largest known study that compares sampling strategies on small streams. For a sampling period of 3 years, yields (loads per unit area) computed by regression methods from the different sampling strategies were compared to true yields. Robertson and Roerish found that additional high-flow sampling does reduce errors associated with regression methods, but can introduce significant biases into the load estimations. Semi-monthly sampling with no additional high-flow sampling produced the lowest or very close to the lowest error for the two different measures of overall error in their study. The yield estimates from semi-monthly and monthly sampling, with no additional high-flow sampling, had very low bias when compared to the true yields. With more than 3 years of data, it is expected that monthly and semi-monthly sampling should result in similar errors (Robertson and Roerish, 1999).

PHOSPHORUS LOADS IN SELECTED TRIBUTARIES TO SEBAGO LAKE

The regression method, also known as the rating-curve method (Cohn and others, 1989; Crawford, 1991), was used to estimate the total phosphorus load for Crooked River, Northwest River, and Rich Mill Pond Outlet for water years 1996-98. For Crooked River, 42 measurements of total phosphorus concentration were available for this time period. The concentration data were collected by PWD just upstream from the confluence with the Songo River. Daily mean streamflow data for these same days came from USGS streamflow-gaging station 01063100 at Route 11. For Northwest River and Rich Mill Pond Outlet, 15 and 27 measurements, respectively, of total phosphorus concentration were available for the 1996-98 water years. Concentration and streamflow measurements were collected by PWD as part of their tributary monitoring program.

To create the regression equations, loads were computed for each set of concentration and streamflow measurements at the three sites and then transformed by taking the natural log of the loads. The natural log of load was the response (dependent) variable. Various combinations of the natural log of streamflow, (natural log of streamflow)^2, time, and sine (time) and cosine (time) were tested to determine the best regression equation. The sine and cosine term was used to describe seasonality in the data.

Ordinary least-squares regression techniques (Helsel and Hirsch, 1992) were used to compute regression parameters. The best combination of variables was based on the Aikaike Information Criteria (Helsel and Hirsch, 1992). An estimate of the uncertainty in the estimated load was obtained using the method described by Likes (1980) and Gilroy and others (1990). A detailed description of these methods can be found in Crawford (1996).

The best combination of variables for Crooked River was natural log of streamflow, (natural log of streamflow)^2, and sine (time) and cosine (time). The best combination for Northwest River was natural log of streamflow and sine (time) and cosine (time). For Rich Mill Pond Outlet, the best combination of variables was the single variable natural log of streamflow. All variables in the three regressions were significant at a significance level (alpha value) of 0.01. Various regression diagnostics were performed to test regression assumptions, including looking for high-influence points with Cook’s D statistic, multi-collinearity problems with the Variance Inflation Factor (VIF) statistic (Helsel and Hirsch, 1992), and non-normality of the residuals with the Turnbull-Weiss Likelihood Ratio Normality Test statistic (Turnbull and Weiss, 1978). Various types of residual plots were analyzed (Helsel and Hirsch, 1992). All regression diagnostics indicated good regression models for the three streams.

Estimates of total phosphorus load for Crooked River, Northwest River, and Rich Mill Pond Outlet for each day in water years 1996-98 were made using the regression equations. Daily mean streamflows from the USGS Crooked River gaging station were used as input to the Crooked River regression equation. Daily mean streamflows for Northwest River and Rich Mill Pond Outlet for all days in the 1996-98 water years were computed using the MOVE.1 method described earlier in the report. The loads were retransformed to original units using the method derived by Bradu and Mundlak (1970), based on work by Finney (1941). This method is described in Cohn and others (1989).

The average loads for water years 1996-98 for the three streams are shown in table 4. The standard deviation of the load for Crooked River (2,200 lb/yr) indicates that the probability that the true average load is between 14,600 lb/yr and 19,000 lb/yr is approximately 68 percent. The probability that the true average load is between 12,400 lb/yr and 21,200 lb/yr is approximately 95 percent. As explained in Robertson and Roerish (1999), however, the standard deviation of regression models may underestimate the true error. The standard deviation of the load for Northwest River and Rich Mill Pond Outlet were not computed for this report due to their complexity.

Estimations of total phosphorus load for the three streams for water years 1996-98 were also made using an averaging method (table 4). The total phosphorus concentrations in these years were averaged, and streamflows on these days also were averaged. The total phosphorus load was computed as the product of the average concentration and the average streamflow.

Table 4. Average annual total phosphorus load estimates for three Sebago Lake tributaries for the 1996-98 water years

Tributary	Drainage area (square miles)	Load estimate from regression method (pounds per year)	Standard deviation of regression method (pounds per year)	Load estimate from averaging method (pounds per year)
Crooked River	150	16,790	2,190	14,500
Northwest River	22.3	766.5	Not computed	966.5
Rich Mill Pond Outlet	4.86	306.6	Not computed	295.9

As expected, the load computed for Crooked River using the averaging method is smaller than the load computed by the regression method. This is consistent with the strong evidence of a positive relation (p=0.0004) between streamflow and total phosphorus concentration for Crooked River. As discussed earlier, the averaging method, with limited sampling, will tend to underestimate loads when concentrations are positively related to streamflow. The load computed for Northwest River by the averaging method is larger than the load from the regression method. This is consistent with the weak evidence of a negative relation (p=0.1102) in the streamflow/concentration data for Northwest River. The loads computed for Rich Mill Pond Outlet are approximately the same using both methods. This is consistent with the lack of evidence of relation (p=0.3302) in the streamflow/concentration data for Rich Mill Pond Outlet.

SUMMARY AND CONCLUSIONS

The streamflow and water-quality networks of the PWD and the USGS as of February 2000 were analyzed in terms of their applicability for estimating total phosphorus loads for tributaries of Sebago Lake in southern Maine. The streamflow networks were analyzed for their ability to describe total tributary input to Sebago Lake and their ability to describe the total range of streamflow at gaged sites.

The long-term unit-area mean annual flows for Songo River and small ungaged tributaries are similar to the long-term unit-area mean annual flow for Crooked River and other gaged tributaries to Sebago Lake, based on a regression equation that estimates mean annual streamflows in Maine.

Unit-area peak flows for Sebago Lake tributaries can be quite different, based on a regression equation that estimates peak streamflows for Maine. It is unlikely that streamflow in the Songo River can be measured accurately by conventional techniques. It is important to adequately gage peak flows on Songo River (upstream from its confluence with Crooked River) because it drains 30.1 percent of the Sebago Lake drainage area (excluding Sebago Lake surface area). Estimated 2-year peak flows for two typical small, ungaged tributaries are about 3 to 4 percent of the estimated 2-year peak flow for Crooked River.

Monthly determination of flows for Sebago Lake tributaries can miss a significant part of the full range of flows during a year. For 3 recent years of monthly sampling on Crooked River by PWD, the highest daily mean flow on a sampling day was 52 percent to 85 percent of the highest daily flow for the year.

The MOVE.1 method can be used to estimate streamflows at tributaries that are not continuously monitored, if assumptions of the method are met. The MOVE.1 method was judged to be inadequate to estimate flows at Panther Run, Muddy River, Sticky River, and 1952 Brook; however, it was judged to be adequate and was used to estimate continuous daily flows for Northwest River and Rich Mill Pond Outlet.

A Kendall's tau test was used to determine the relation between streamflow and total phosphorus concentration. Crooked River had a statistically significant (p=0.0004) positive relation. Panther Run had a statistically significant (p=0.0015) negative relation. Positive relations indicate contributions from nonpoint sources or sediment resuspension, whereas negative relations indicate dilution of point sources.

Concentrations of total phosphorus in the Crooked River were significantly larger than those in the Songo River (Wilcoxon rank-sum test, p<0.0001). The evidence was insufficient, at a significance level of 0.05, to indicate that concentrations from medium-sized drainage basins were different from each other or that concentrations from small-sized drainage basins were different from each other (Kruskal-Wallis test, p= 0.098, 0.1265). All large- and medium-sized drainage basins were sampled for total phosphorus approximately monthly. Although not all small-sized drainage basins were sampled, they may be well represented by the small-sized drainage basins that were sampled.

If the tributaries gaged by PWD had adequate streamflow data, the current PWD tributary monitoring program would probably produce total phosphorus load data that would represent all gaged and ungaged tributaries to Sebago Lake. Outside the PWD tributary monitoring program, the largest ungaged tributary to Sebago Lake contains 1.5 percent of the area draining to the lake. In the absence of unique point or nonpoint sources of phosphorus, ungaged tributaries are unlikely to have total phosphorus concentrations that differ significantly from the small tributaries for which concentration data are available.

The largest known study for comparison of sampling strategies on small streams found that for a sampling period of 3 years, high-flow sampling in addition to regular sampling does reduce the errors associated with regression methods, but can introduce significant biases into the load estimations. Semi-monthly sampling with no additional high-flow sampling produced the lowest or very close to the lowest error for the two different measures of overall error in the study. With more than 3 years of data, it is expected that monthly and semi-monthly sampling should result in similar errors.

On the basis of results from a small number of studies that have been performed elsewhere, it appears that when intensive sampling is precluded by a limited budget, the best method for estimating phosphorus load is the regression method, if the assumptions inherent to regression analyses are met for individual streams. This method, however, has inherent error when applied to small, flashy streams. The regression method in the largest study of small streams had median errors of about 30 percent, although the error for some individual streams was much greater. It is assumed that if 3 years of continuous streamflow and monthly phosphorus concentration data were available for all Sebago Lake tributaries, as they are for Crooked River, estimates of total phosphorus load would have similar errors. Tributaries with noncontinuous streamflow gages, but where continuous streamflows can be estimated using the MOVE.1 method (Northwest River and Rich Mill Pond Outlet), have additional error that was not quantified for this report. Streamflows for the remainder of the gaged tributaries to Sebago Lake cannot be estimated with confidence because the MOVE.1 method is not applicable, and phosphorus load-estimation methods for these sites will probably not provide accurate loads without a continuous streamflow gage.

The regression method, also known as the rating-curve method, was used to estimate the annual total phosphorus load for Crooked River, Northwest River, and Rich Mill Pond Outlet for water years 1996-98. An averaging method also was used to compute annual loads at the three sites. The difference between the regression estimate and the averaging estimate for each of the three tributaries was consistent with what was expected from previous studies.

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