Bear Creek Reservoir Technical Review Part 2: Phosphorus Loads

The amount of phosphorus delivered to a reservoir is referred to as the "load;" it is usually expressed as pounds or kilograms per year. Load is the product of flow and concentration, and it must be calculated separately for each source of flow to the reservoir. Accurate estimation of annual load depends on a thorough knowledge of water sources and on the ability to explain the variation in phosphorus concentrations associated with each flow source.

Hydrology and Water Budget

Development of a water budget precedes estimation of phosphorus loads. In general, flow sources can be classified as surface inflows, precipitation, or groundwater. Some of those sources are measured directly (major tributaries and precipitation), and some are usually inferred by calculation (ungaged surface inflows and any groundwater contribution). A solid understanding of reservoir hydrology also can aid in targeting future sampling efforts by showing which sources are likely to be most influential in annual phosphorus load calculations.

The water budget for Bear Creek Reservoir is built on the assumption that the computed inflow provided by the US Army Corps of Engineers (USACE) is accurate (except as noted later), and is equal to the sum of all component sources. The assumption makes it possible to use residuals[1] to estimate components, such as ungaged surface runoff, that are not measured directly. The objective of the water budget analysis is to provide a firm foundation for the estimation of phosphorus loads.

Data Sources for Surface Flows

The USACE provided daily records of reservoir operations from July 1977 through 2006. Water surface elevation is used to determine the volume of water in the reservoir. Daily net change in storage reflects the balance of inflow, outflow, and evaporation. Daily inflow is computed from the measured outflow, the net change in storage, and the estimated evaporation. Reservoir inflow includes contributions from tributaries, direct surface runoff, direct precipitation, and any groundwater flow. A comparison of USACE inflow and outflow data show almost perfect correlation (Figure 1), as expected because inflow is computed from outflow (with an adjustment for net precipitation). The slope is unity and the intercept (321 AF/y) is close to the annual value expected for evaporation (ca. 3 ft/y).

[1] Flow residuals are used in this document to isolate the portion of the total flow that was not measured. The total inflow to the reservoir is computed by the USACE, and some components of the total are measured directly (gaged inflows and precipitation). The difference between the total and the measured components is the residual (i.e., the remainder after accounting for the measured flows). The residual should be positive or zero if all flows are measured with perfect accuracy, but will occasionally be negative due to random errors in measured values.

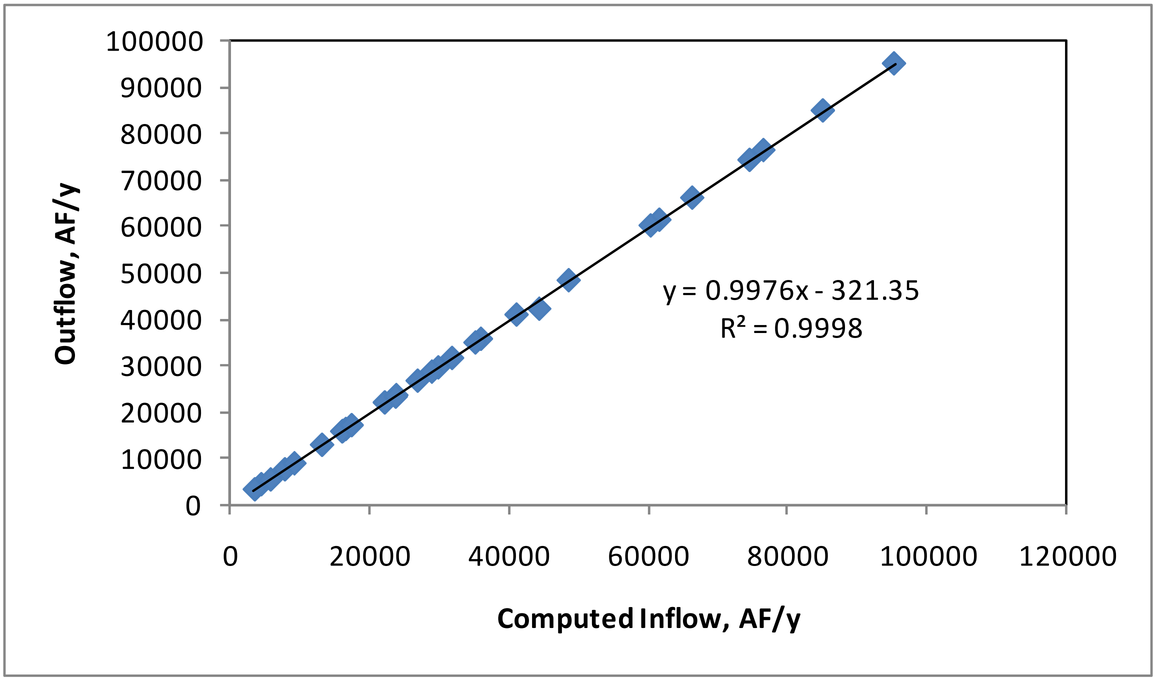

Figure 1. Comparison of outflow measured for Bear Creek Reservoir with USACE computed inflow to the reservoir. Perfect agreement is expected because the inflow is computed from the outflow (with adjustments for evaporation). Data from USACE, 1978-2005.

Two major tributaries – Bear Creek and Turkey Creek – account for virtually all of the watershed area drained by the reservoir (Table 1).[2] Consequently, the gaged flows from the two tributaries should account for almost all of the computed inflow. Any major departures from this expectation deserve careful review. Adjustments may be necessary to preserve internal consistency when developing the load estimates.

Name	Gage Number	Area, mi2	Period of Record Used
Bear Creek near Morrison	06710605	176.0	1987-2006
Turkey Creek near Morrison	06711040	50.6	1987-1989
Turkey Creek near Canyon Mouth	06710995	47.4	1998-2001
Turkey Creek near Indian Hills	06710992	45.9	2001-2006
Ungaged		9 to 14	
Reservoir at dam		236.0	1978-2006
Bear Creek at Sheridan	06711500	260.0	1978-2005

Table 1. Key hydrologic features for establishing the water budget of Bear Creek Reservoir. USGS gages are identified by station numbers. Period of record (POR) varies among the gages. The watershed area that is ungaged depends on the location of the Turkey Creek gage.

[2] The placement of existing stream flow gages is such that runoff is recorded for all but 4-6% of the watershed. The location of the gaging station on Turkey Creek has changed over time, but all locations represent very similar drainage areas. The principal difference among the three locations on Turkey Creek is that the two upstream sites do not measure releases from Soda Lakes, which may contribute a few hundred AF annually to the reservoir as part of exchanges executed by Denver Water Department (DWD).

The Bear Creek watershed comprises about 75% of the land that drains to the reservoir, and much of the watershed lies at high elevation. A plot of annual flows at the Bear Creek gage vs. the USACE computed inflows to the reservoir shows that Bear Creek contributed about 75% of the inflow in most years (Figure 2). There are two situations in which the Bear Creek contribution was sufficiently large to draw attention – 1996 and those few years when the computed inflow exceeded 40,000 AF/y. In these situations, Bear Creek alone, or in combination with Turkey Creek, would exceed the computed inflow (i.e., flows would be internally inconsistent with the computed inflow).

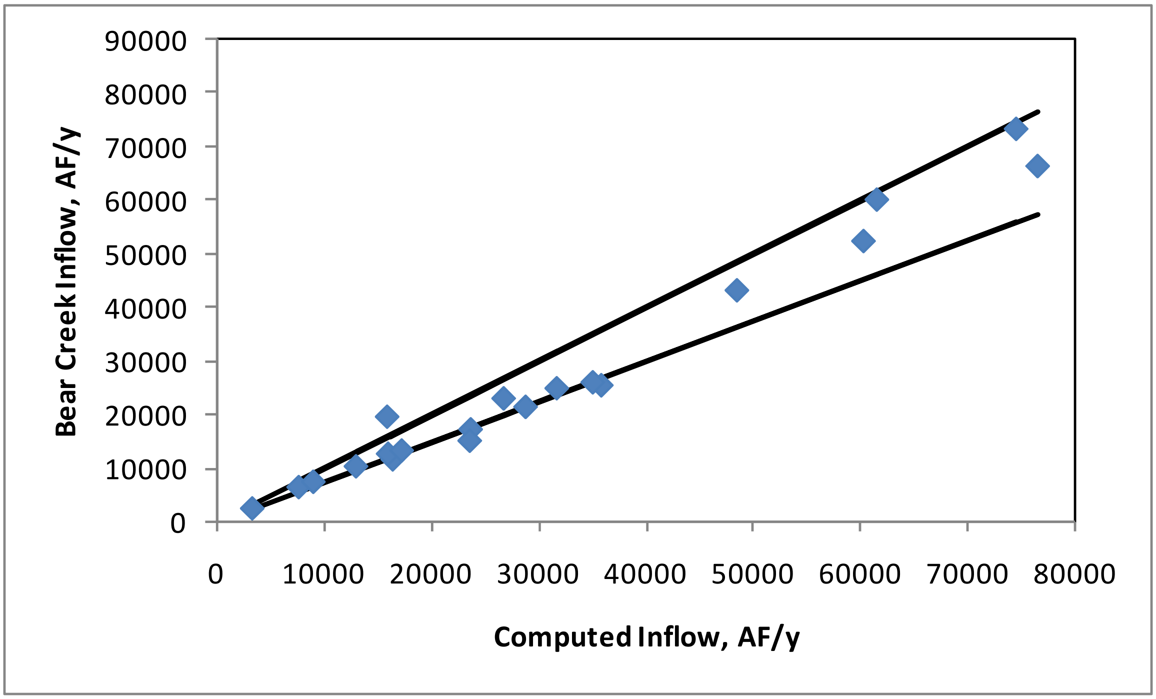

Figure 2. Annual inflows from Bear Creek (USGS gage near Morrison) plotted against the USACE computed inflow to the reservoir. The contributions expected if Bear Creek represented 75% of the computed inflow (lower line) or matched the computed inflow (upper line). One point (1996) lies above the 1:1 line; see text.

In 1996, the flow measured in Bear Creek was substantially larger than the total inflow computed by the USACE, suggesting that one of the numbers is incorrect. It would be difficult to validate the accuracy of the USGS gage upstream, but it is relatively simple to check the computed inflow against another gage downstream. The actual comparison is with the reservoir outflow, from which the reservoir inflow is computed (see above). The USGS gage at Sheridan is a few miles downstream of the reservoir, and watershed area is increased only 10% between the reservoir and the gage.

In most months, the Sheridan gage and the reservoir outflow agree well when reservoir releases exceed 1000 AF/month (ca. 17 cfs) (Figure 3). When reservoir releases fall below 17 cfs, flows at Sheridan appear to be sustained at a baseline level of about 250 AF/month. There are several outliers on the graph, the most extreme of which are from the fall of 1996 (mainly Sep-Nov) when the measured outflow was much smaller than the flow at Sheridan. In the fall of 1996, USGS gages above and below the reservoir recorded substantially higher flows than those reported by the USACE. We conclude that there was a measurement problem that resulted in a significant underestimate of reservoir releases.

Although the problem was restricted to a few months in 1996, the effect on the USACE computed inflow is large enough to require some adjustment. The USACE computed inflow for 1996 was replaced with an estimate set equal to the average of computed inflows in two other years (1990 and 2004) when the flows at the Sheridan gage were most similar to that recorded during 1996 (Table 2).

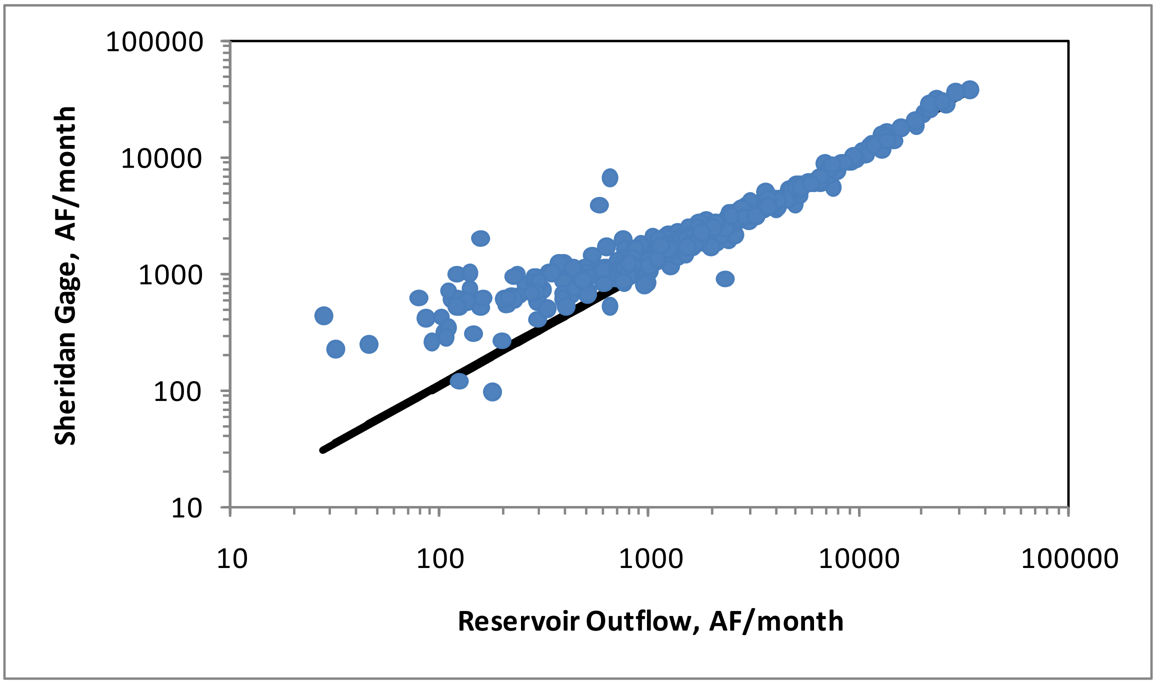

Figure 3. Monthly flows measured at the Sheridan gage as a function of releases from Bear Creek Reservoir for the period Jan-1978 through Dec-2005. The solid line is 1.1 times the outflow.

Year	USACE Computed Inflow	USACE Measured Outflow	Bear Creek at Sheridan	Adjusted Total Inflow	Adjusted Outflow
1987	61597	61216	73920	61597	61216
1988	35940	35589	39343	35940	35589
1989	7765	7496	13899	7765	7496
1990	***26850***	***26575***	***32672***	26850	26575
1991	31793	31474	37182	31793	31474
1992	23780	23466	29252	23780	23466
1993	16518	16179	21309	16518	16179
1994	16092	15759	19379	16092	15759
1995	74569	74106	93090	74569	74106
1996	16001	15671	31731	***27871***	***27550***
1997	48569	48198	53865	48569	48198
1998	76566	76225	87447	76566	76225
1999	60355	60002	66772	60355	60002
2000	13101	12778	16131	13101	12778
2001	17353	17008	20100	17353	17008
2002	3437	3199	4831	3437	3199

Year	USACE Computed Inflow	USACE Measured Outflow	Bear Creek at Sheridan	Adjusted Total Inflow	Adjusted Outflow
2003	23693	23141	26528	23693	23141
2004	***28891***	***28526***	***32847***	28891	28526
2005	35147	34796	39679	35147	34796
2006	9128	8793	10992	9128	8793

Table 2. USACE computed inflow and measured outflow (AF/y) with adjustment to 1996 values. The adjustment is based on locating two years when flows at the USGS Sheridan gage were most similar to the flow measured in 1996; these are 1990 and 2004 (shown in bold italics). The USACE flows from 1990 and 2004 were averaged and substituted for the values reported in 1996.

During wet years (computed inflow >40,000 AF/y), the gaged inflow from Bear Creek represents a larger proportion (>85% vs. 70-80% at flows <40,000 AF/y) of the computed inflow (Table 3). It is impotrant to determine if the increased proportion is real or the result of an error. One possibility is that Bear Creek makes a proportionately higher contribution in wet years because much of the watershed is at high elevation. However, adopting such an assumption would lead to the conclusion that Turkey Creek makes a disproportionately small (and unrealistic) contribution in those same years. The problem could be addressed directly if Turkey Creek had been gaged in all years, but this is not the case. However, there are two high-flow years (1987 and 1999) when gage records are available for both tributaries. In both years, the sum of the gaged inflows exceeded the computed inflow. In contrast, the sum of those flows in other years did not exceed 95% of the computed inflow.

Year	Bear Creek Measured Inflow	Turkey Creek Measured Inflow	Adjusted Total Inflow	Bear Creek as % of Inflow	Gaged as % of Inflow	Adjusted Bear Creek
1987	60238	14756	61597	98	122	***49277***
1988	25415	8772	35940	71	95	25415
1989	6310		7765	81		6310
1990	22955		26850	85		22955
1991	24850		31793	78		24850
1992	17146		23780	72		17146
1993	11514		16518	70		11514
1994	12572		16092	78		12572
1995	73513		74569	99		***59655***
1996	19514		27871	70		19514
1997	43232		48569	89		***38855***
1998	66536		76566	87		***61253***
1999	52466	8173	60355	87	100	***48284***
2000	10213	2226	13101	78	95	10213
2001	13185	2324	17353	76	89	13185
2002	2321	562	3437	68	84	2321
2003	15016	7401	23693	63	95	15016
2004	21365	4443	28891	74	89	21365
2005	25969	7146	35147	74	94	25969
2006	7307	1158	9128	80	93	7307

Table 3. Basis for adjusting annual inflows from Bear Creek. In high flow years (inflow >40,000 AF/y), the gaged flow in Bear Creek is an unusually large proportion of the total inflow. In those years, the Bear Creek inflow was capped at 80% of the computed inflow (shown in bold italics in the final column). See text for more details.

The problem with accepting a very high contribution from Bear Creek during high flow years is that it might bias the Turkey Creek contribution in those years when Turkey Creek flows were not measured. To minimize bias, Bear Creek flows were adjusted in wet years (total inflow >40,000 AF/y) by arbitrarily capping Bear Creek at 80% of the computed inflow (Table 3). The adjustment is made before parsing the other flow contributions, and it is carried through the phosphorus load calculations below.

Precipitation

Precipitation falling directly on the surface of Bear Creek Reservoir is assumed to be equal to precipitation recorded at the nearby National Weather Service Cooperative Network Station at Lakewood (054762).[3] The volumetric contribution of direct precipitation was calculated monthly as the product of total precipitation (inches/month) and reservoir surface area (at the monthly average water surface elevation). Surface area was estimated from the following relationship developed from data provided by the USACE; it applies to elevations encountered during the study (5550 – 5580 ft AMSL):

$Area = (4.035 \times 10^{-72}) e^{(0.03042 * Elevation)}$.

Direct precipitation accounts for a tiny fraction of total inflow to the reservoir. Given an average precipitation of about 16.6 inches per year, and an average surface area of about 110 acres, the expected contribution would be about 152 AF/y.

Parsing the Other Flow Sources

The remaining flow sources include Turkey Creek, runoff from ungaged portions of the watershed, and possibly groundwater. Flows in Turkey Creek were measured in about half of the years in the study period, and those measurements were made at three different locations, two of which do not account for water exchanges released from Soda Lakes. These inconsistencies in the data record hinder reconstruction of flows in the years when gages were not operating. Alternatively, Turkey Creek flows in all years can be derived from a flow residual calculated from the computed inflow, the Bear Creek inflow, and direct precipitation:

$Residual = Inflow_{USACE} - (Inflow_{Bear\ Cr.} + Precipitation)$.[4]

Two assumptions can facilitate interpretation of the residual: 1) groundwater is small enough to be ignored, and 2) runoff characteristics of the ungaged portion of the watershed are the same as those of the Turkey Creek watershed. Given those assumptions, a plot of the residual against flows measured in Turkey Creek should be linear, and the slope should be greater than one. The correspondence between the two values is quite good (Figure 4), strengthening the argument for estimating Turkey Creek flows

[3] Data available from Western Regional Climate Center (http://www.wrcc.dri.edu)
[4] Adjusted values for the computed inflow and the Bear Creek inflow are used in this calculation.

from the flow residual in all years. The slope of the relationship is very close to the expected value of 1.27, and the intercept is in the range of values observed for releases from Soda Lakes.[5]

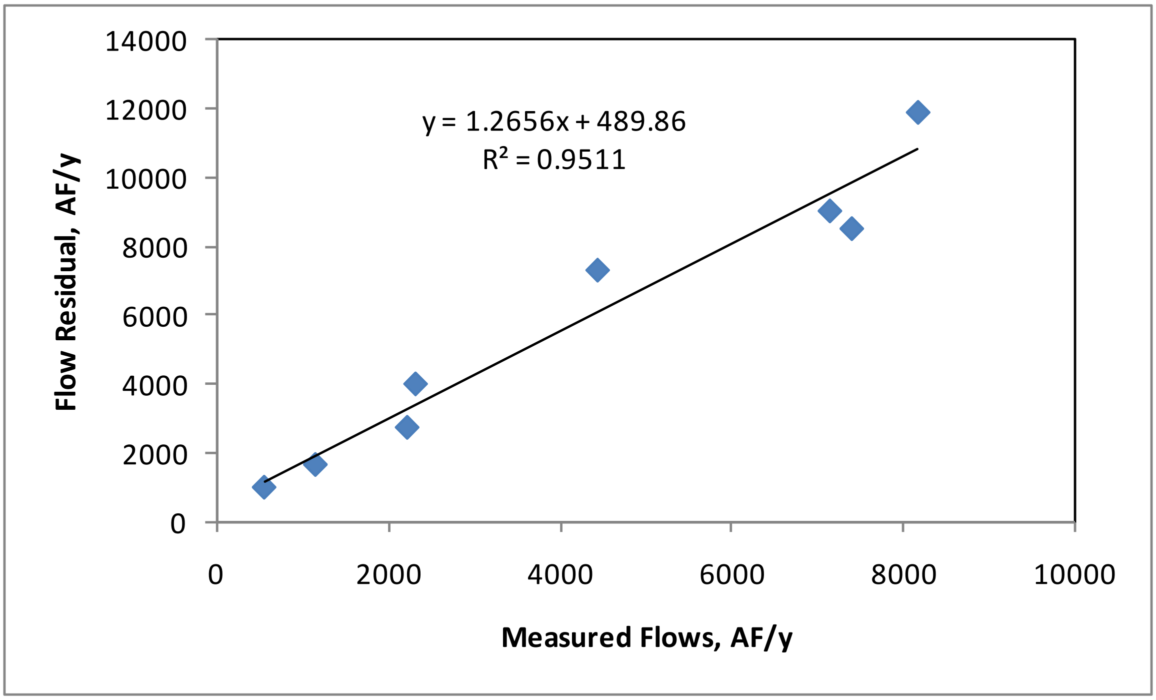

Figure 4. Comparison of the flow residual to flows measured in Turkey Creek, 1999-2006.

Parsing Inflows in Each Year

The broad aim of the water budget analysis is to support calculation of phosphorus loads in every year. There is considerable confidence now in the annual values for Bear Creek and direct precipitation components of the water budget. Interpretation of the flow residual yields reasonable estimates of flows in Turkey Creek and a practical approach to obtain flows from the ungaged portion of the watershed. The parsing of annual flows has proceeded as far as possible with the available hydrologic information (Table 4). At the same time, parsing has probably gone beyond what can be supported with phosphorus concentration data. For reasons to be explained later, the flow residual will not be partitioned for the purpose of estimating loads.

Year	Computed Inflow	Outflow	Bear Creek	Direct Precipitation	Flow Residual	Turkey Creek	Ungaged
1987	61597	61216	49277	226	12093	9522	2571
1988	35940	35589	25415	147	10379	8172	2207

[5] If runoff characteristics for the ungaged watershed match those of the Turkey Creek watershed, the flow residual would be about 30% larger than measured flow in Turkey Creek based on watershed areas (see Table 1). Releases from Soda Lakes are probably independent of flows from the Turkey Creek watershed, and they are not a constant contribution. In previous years, the Soda Lakes exchange has ranged from 0-920 AF (median 276); no data were available after 1998.

Year	Computed Inflow	Outflow	Bear Creek	Direct Precipitation	Flow Residual	Turkey Creek	Ungaged
1989	7765	7496	6310	152	1303	1026	277
1990	26850	26575	22955	164	3731	2938	793
1991	31793	31474	24850	178	6765	5327	1438
1992	23780	23466	17146	145	6489	5109	1379
1993	16518	16179	11514	132	4873	3837	1036
1994	16092	15759	12572	150	3371	2654	717
1995	74569	74106	59655	225	14689	11566	3123
1996	27871	27550	19514	137	8220	6472	1748
1997	48569	48198	38855	172	9541	7513	2028
1998	76566	76225	61253	190	15123	11908	3215
1999	60355	60002	48284	197	11874	9350	2524
2000	13101	12778	10213	123	2766	2178	588
2001	17353	17008	13185	147	4021	3166	855
2002	3437	3199	2321	84	1033	813	220
2003	23693	23141	15016	164	8512	6703	1810
2004	28891	28526	21365	215	7311	5757	1554
2005	35147	34796	25969	153	9025	7106	1919
2006	9128	8793	7307	131	1690	1331	359
Median	27360	27062	20439	153	7038	5542	1496
Average	31951	31604	24649	162	7140	5622	1518
% of Total			77%	1%	22%	18%	5%

Table 4. Parsing of flows (AF/y) for Bear Creek Reservoir. Adjustments were made to the computed inflow in 1996, and the Bear Creek flows in 1987, 1995, and 1997-99. The flow residual is calculated as the remainder after subtracting Bear Creek and direct precipitation from the computed inflow. The ungaged flow is a fixed proportion of the Turkey Creek inflow, and both components were derived directly from the flow residual. See text for further explanation.

Estimating Annual Phosphorus Load to Bear Creek Reservoir

Development of a Methodology for Bear Creek

The strategy for estimating annual loads from surface inflows is based on assigning a concentration to each daily flow and calculating every daily load, the sum of which yields the annual load. An estimation strategy is needed because concentrations are recorded much less frequently than are flows. For example, flow in the Bear Creek is reported daily, but phosphorus concentrations typically are measured only 14-17 times per year (i.e., less than 5% of the days). Concentrations must be assigned to the other 95% of flows in order to estimate annual phosphorus loads.

Because surface inflow is the most important component of the water budget (Bear Creek alone is almost 80% of the total inflow), considerable attention is devoted to understanding variability of phosphorus concentrations in each tributary. Stream flows often, but not always, exert a strong influence on phosphorus concentrations. Characterization of the relationship between flow and concentration is a necessary precursor to the estimation of the annual phosphorus load to the reservoir.

When total phosphorus concentrations for Bear Creek are plotted against gaged stream flow, no strong relationship is evident (Figure 5). However, there is the sharp reduction in concentrations by 1995 as indicated in Exhibit 2. Lack of a strong relationship between concentration and flow is not completely surprising because flows in Bear Creek are managed, and upstream diversions may obscure an underlying relationship between concentration and flow.

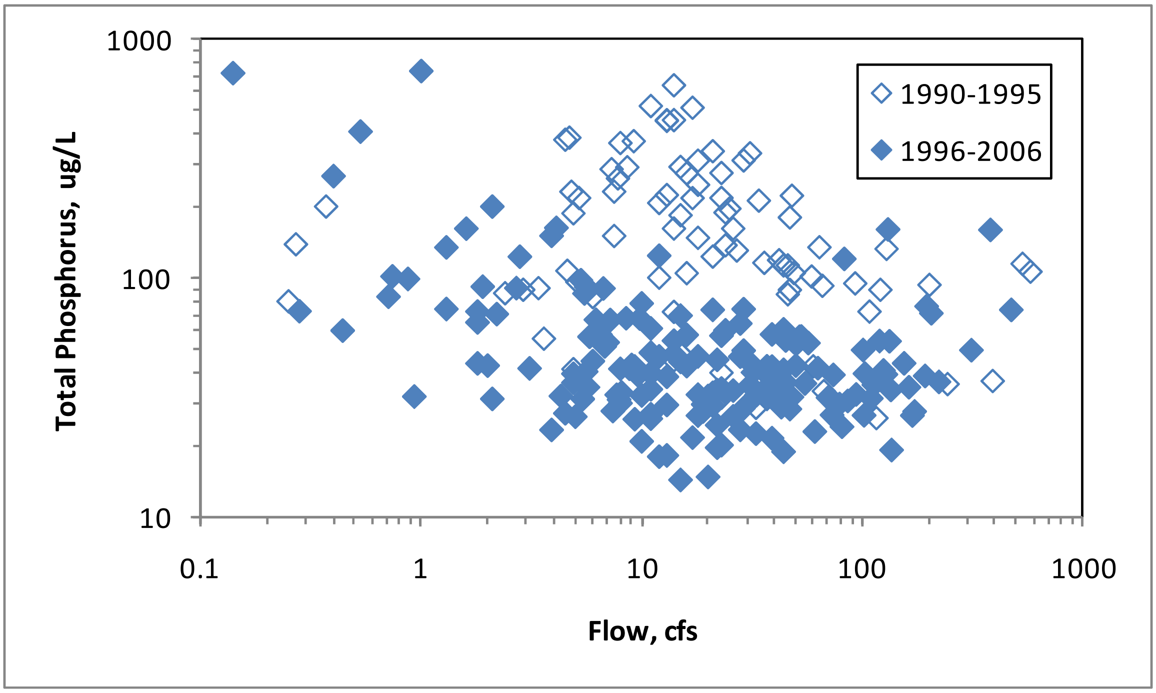

Figure 5. Relationship between total phosphorus concentration and stream flow (log scales) measured at the gage on Bear Creek just above the reservoir. The data are divided into two time periods to highlight a reduction in concentrations that occurred over the first few years of the study.

Phosphorus concentrations in Bear Creek vary by two orders of magnitude (from 7.6 – 729 µg/L) over the period of record, although the full range of concentrations may not occur in every year. Thus, even though there is no apparent relationship between flow and concentration when all years are lumped together, it may be prudent to allow for the possibility of a relationship within shorter time blocks.

The variability in phosphorus concentrations among years is displayed effectively with box-and-whisker plots showing the distribution of values observed in each year. The 16-y record of phosphorus concentrations for the Bear Creek reveals a conspicuous trend that affects loads (Figure 6). The reduction in concentrations beginning in 1994 probably reflects improved performance by POTWs. Concentrations rose during the drought of 2002 and 2003, suggesting some connection between flow and concentration. Direct comparison of concentrations among years therefore may be misleading unless some consideration is given to flow conditions in each year.

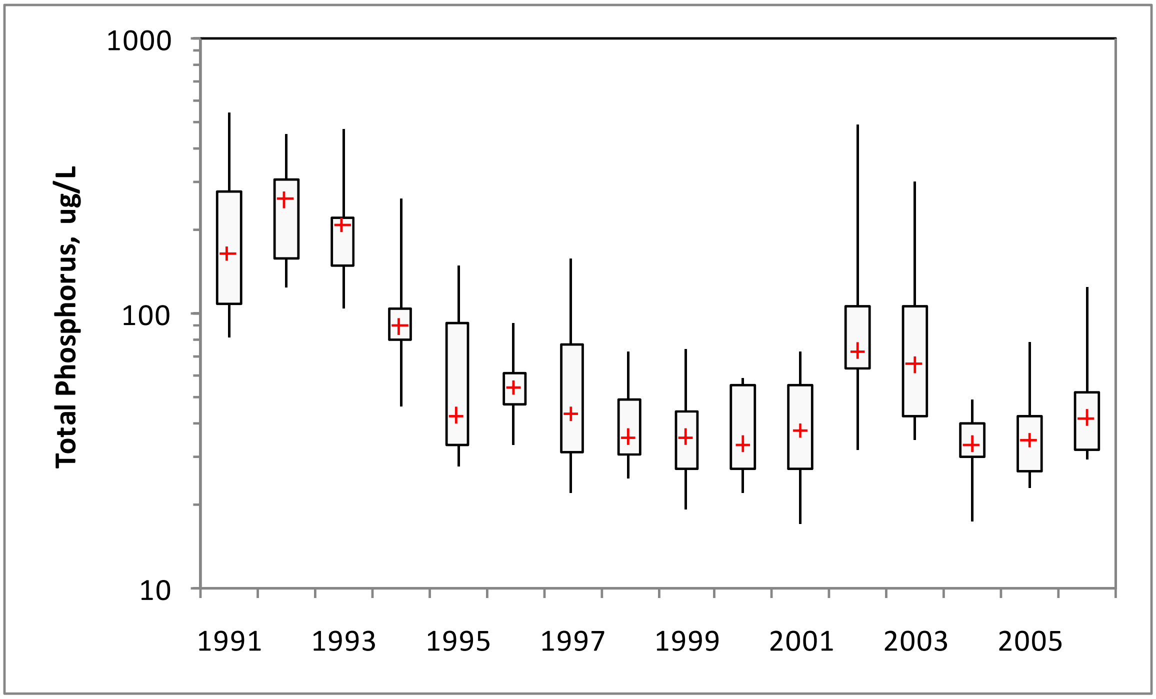

Figure 6. Annual distribution of phosphorus concentrations (log scale) in Bear Creek. The box-and-whisker plots delineate the 95th, 75th, 25th, and 5th percentiles of the measured concentrations. Taller boxes indicate more variability in phosphorus concentrations during that year. A "plus" symbol indicates the median concentration in each year.

To account for year-to-year variations in flow conditions, concentrations can be classified according to the daily flow when each sample was taken. In each year, some samples are taken when flows are low, and others are taken when flows are high. If there is a common frame of reference for flow magnitude, a subset of concentrations taken under comparable flow conditions can be compared across all years. A common frame of reference for flows can be established by defining percentiles for all daily flows recorded during the 16-y period of study.

Three flow categories (low, intermediate, and high) were defined by setting boundaries corresponding to the 20th and 80th percentiles of daily flows recorded from 1991-2006. Thus, the intermediate category included all flows between 6.1 and 42 cfs. The percentiles were chosen to optimize the number of concentration measurements within three flow categories in each year (Table 5). Not surprisingly, the intermediate category is well represented in almost all years, while either extreme shows considerable variation from year to year.

Year	Low Flow	Intermediate Flow	High Flow	Total	Time Block
1991	1	9	6	16	1
1992	1	12	4	17	
1993	3	11	2	16	
1994	7	6	3	16	
1995	4	5	8	17	2
1996	2	9	5	16	
1997	1	7	8	16	

Year	Low Flow	Intermediate Flow	High Flow	Total	Time Block
1998	0	6	10	16	
1999	2	5	10	17	3
2000	3	9	2	14	
2001	2	13	1	16	
2002	14	2	0	16	
2003	7	7	2	16	4
2004	0	9	7	16	
2005	3	9	5	17	
2006	7	10	0	17	

Table 5. Number of phosphorus concentration measurements per year within each of three flow categories established on the basis of the distribution of the 16-y record of flow in Bear Creek above the reservoir. Low-flow, intermediate-flow, and high-flow categories aggregate days when the gaged flow was less than or equal to the 20th percentile of the 16-y flow record (6.1 cfs), between the 20th and 80th percentiles of flow (between 6.1 – 42 cfs), or equal to or greater than the 80th percentile of the flow record (42 cfs), respectively. The study period is divided into consecutive 4-year time blocks.

The study period was divided into four consecutive four-year time blocks. Aggregation of sampling dates, each with a measured phosphorus concentration, into a time-and-flow framework improves the basis for statistical analyses and phosphorus load calculations by increasing sample size. However, aggregation can only be justified if phosphorus concentrations, measured under comparable flow conditions, do not differ among the years within each time block.

Phosphorus concentrations measured on days with intermediate flows were compared among years within each time four-year block on the basis of the Kruskal-Wallis test, a nonparametric analog of a standard analysis of variance (ANOVA). No significant differences were found (P=0.05). Similar comparisons are not feasible for the high or low flow categories due to the small sample sizes in several years; it was assumed that aggregation is justified for each flow category based on the results from the intermediate flow category.

Aggregation of phosphorus concentrations strengthens the basis for estimating loads in large part because concentration is not measured frequently in any one year. Because the association between flow and concentration is weak, it is reasonable to postulate that all concentrations within a given time-and-flow category are equally valid for calculating the phosphorus load for days falling within the same time-and-flow category. This assumption supports development of a methodology based on random sampling from each time-block and flow-category combination.

The random sampling concept can be explained using the intermediate-flow category from the first time block as an example. During the 1991-1994 sampling period, 990 days (68% of the four-year period) can be classified in the intermediate flow category (between the 20th and 80th percentiles of all flows included in the 16-y study). Phosphorus concentrations were measured on only 38 (4%) of those 990 days. It is assumed that each of the 38 measured concentrations is equally likely to have occurred on any of the 990 days in the intermediate flow category. Thus, the set of 38 measured phosphorus concentrations can be sampled at random to assign a concentration to each of the 990 days.

The same process is repeated to assign concentrations to each day classified in the low-flow category and in the high-flow category for the 1991-1994 time block. Then, the process is repeated in all three flow categories for each of the other three time blocks. Daily loads are calculated (product of measured flow and assigned concentration) and then summed over all days within each year to compute the annual phosphorus load. The random sampling procedure is repeated 100 times (each time randomly drawing a new concentration for each day of the flow record), yielding 100 estimates of annual loads.

The methodology takes a relatively thin data set and, by aggregation, creates a more complete representation of the likely distribution of phosphorus concentrations. By replication, it also provides a measure of the uncertainty associated with the computed annual load. The ability to produce a distribution characterizing loads in each year is especially useful for conveying uncertainty as it may relate to management decisions. Box-and-whisker plots show the distributions of annual phosphorus loads in Bear Creek determined from 100 replicates of the random sampling methodology (1991 – 2006; Figure 7). The “boxes” for individual years appear compressed because variation among years is large relative to variation among replicates within a year. Median values are given in Table 6.

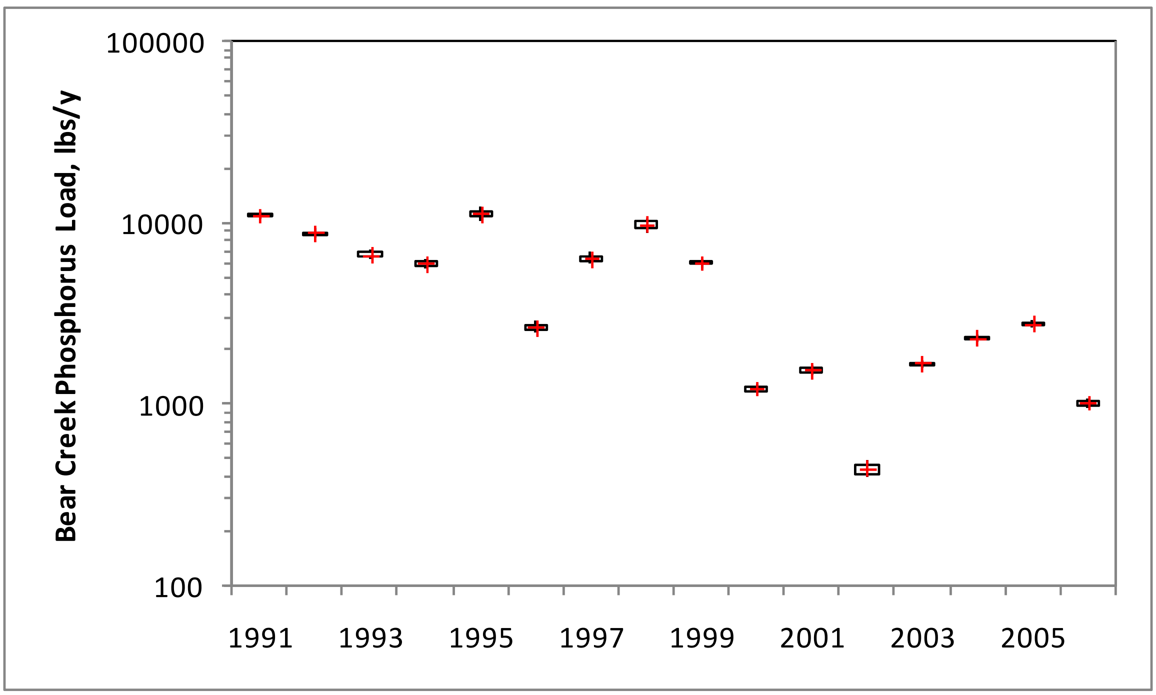

Figure 7. Annual phosphorus loads (lbs/y) for Bear Creek (1991 – 2006) calculated by random sampling of the data aggregated in a time-and-flow framework. The box-and-whisker plots delineate the 95th, 75th, 25th, and 5th percentiles of the measured concentrations, and the asterisk locates the median. Adjustments to annual flows have not been incorporated.

Year	Bear Creek	Turkey Creek	Ungaged	Precipitation	Total
1991	11050	5172	93	42	16358
1992	8838	4904	88	34	13865
1993	6694	3901	61	31	10188
1994	5997	2125	38	35	8195
1995	9168	928	251	53	10399

Year	Bear Creek	Turkey Creek	Ungaged	Precipitation	Total
1996	2663	442	119	32	3257
1997	5745	535	144	41	6465
1998	9154	963	260	45	10422
1999	5547	998	452	46	7044
2000	1216	154	37	29	1437
2001	1542	131	96	35	1804
2002	442	23	20	20	505
2003	1687	492	74	39	2291
2004	2318	152	98	51	2619
2005	2795	455	120	36	3405
2006	1016	37	17	31	1101

Table 6. Calculations of annual phosphorus load (lbs/y) from all sources to Bear Creek Reservoir (1991-2006). Adjustments to annual flows from Bear Creek were applied linearly to annual loads. Special calculations apply to Turkey Creek and ungaged sources; see text for explanation.

Load Estimation Methodology for Turkey Creek

Phosphorus concentrations in Turkey Creek are plotted against instantaneous stream flow, which was measured by velocity-weighted cross-section method at the time and place of sampling (Figure 8). Instantaneous flow is available on all sampling dates; nearby gages were operating for only about half of the study period. For samples taken after 1994, concentrations generally increase with increasing flow, although there is considerable "noise" in the relationship (Figure 9).

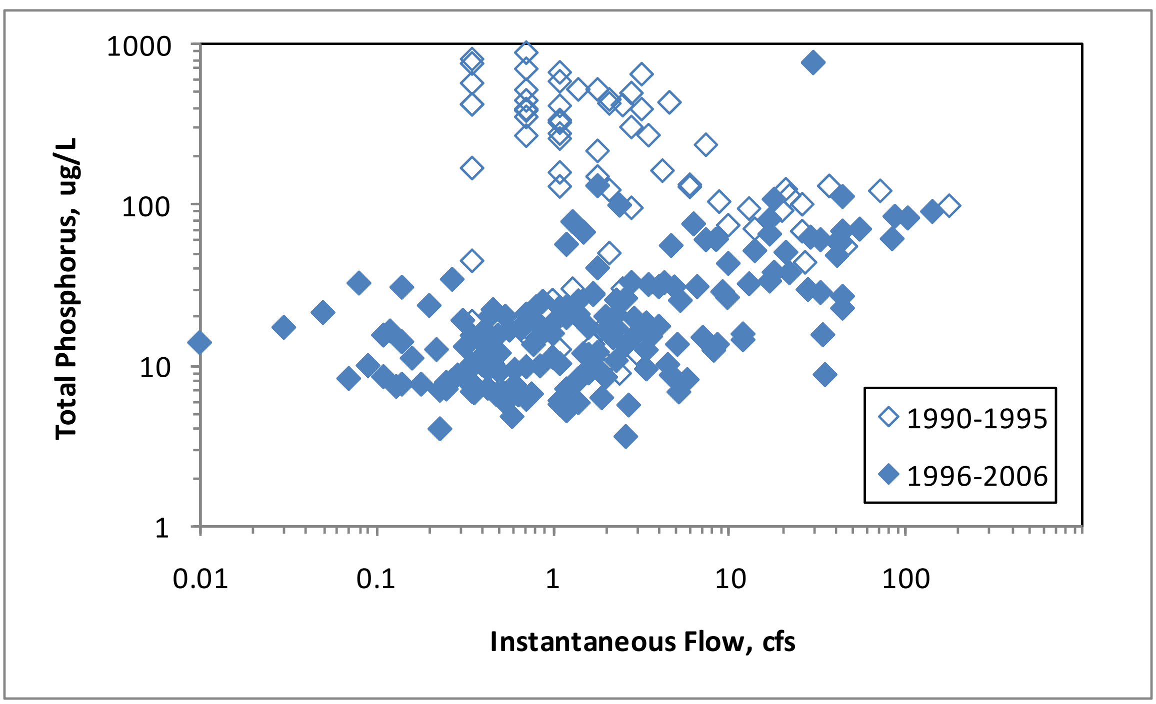

Figure 8. Relationship between total phosphorus concentration and instantaneous stream flow (log scales) measured in Turkey Creek.

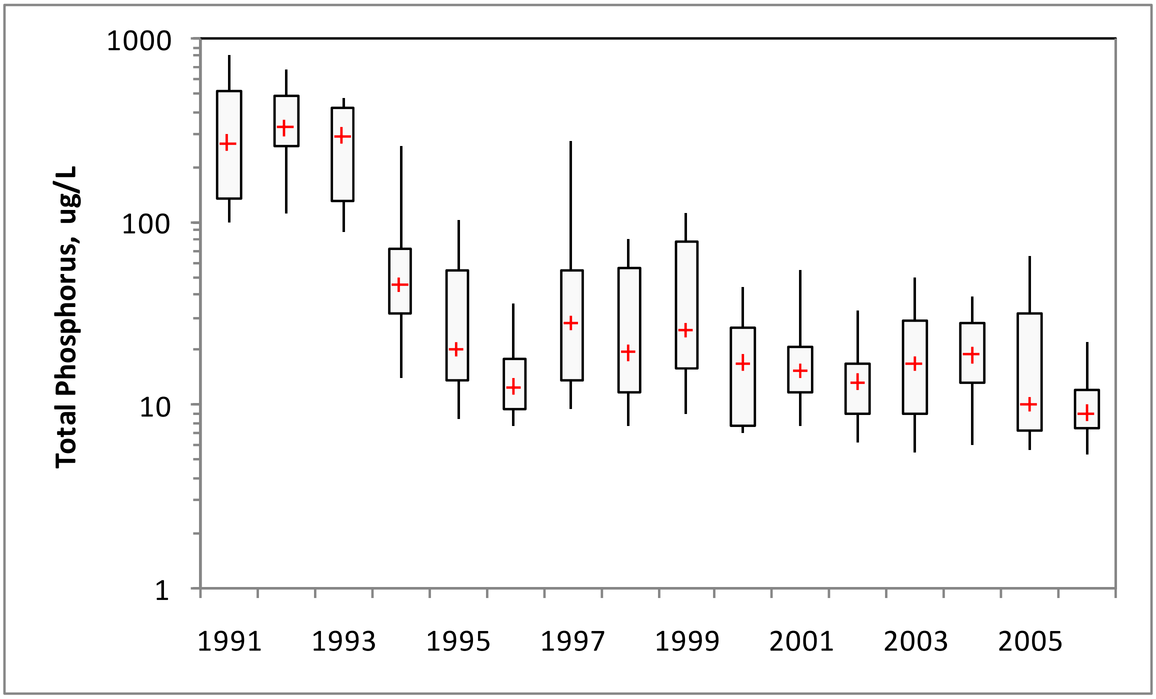

Figure 9. Annual distribution of phosphorus concentrations (log scale) in Turkey Creek. The box-and-whisker plots delineate the 95th, 75th, 25th, and 5th percentiles of the measured concentrations. Taller boxes indicate more variability in phosphorus concentrations during that year. A "plus" symbol indicates the median concentration in each year.

Instantaneous flows are normalized before evaluating temporal trends in phosphorus concentrations by time-and-flow aggregations. Daily flow percentiles were defined with the available gage records (1998-2006) and are applied to all sampling dates in the period of study. The low flow category is defined for those daily flows less than or equal to the 25th percentile (0.4 cfs), the intermediate category is for flows between 0.4 and 3.7 cfs, and the high flow category is defined as those daily flows greater than or equal to the 75th percentile (3.7 cfs). Each sampling date is classified according to the measured instantaneous flow, which was measured in all years. Implicitly, the distribution of instantaneous flows is assumed to match the distribution of gaged flows. An adequate number of samples was available each year in the intermediate flow category (Table 7).

Year	Low Flow	Intermediate Flow	High Flow	Total	Time Block
1991	4	9	3	16	1
1992	2	12	3	17	
1993	1	9	6	16	
1994	4	5	2	11	
1995	2	9	6	17	2
1996	7	6	3	16	
1997	2	6	8	16	
1998	2	7	7	16	
1999	0	12	5	17	3
2000	4	8	2	14	
2001	3	12	1	16	

Year	Low Flow	Intermediate Flow	High Flow	Total	Time Block
2002	9	7	0	16	
2003	5	5	6	16	4
2004	0	7	9	16	
2005	1	8	8	17	
2006	4	11	2	17	

Table 7. Number of phosphorus concentration measurements per year within each of three flow categories established on the basis of the distribution of a 9-y record of flow in Turkey Creek above the reservoir. Low-flow, intermediate-flow, and high-flow categories aggregate days when the gaged flow was less than or equal to the 25th percentile of the 9-y flow record (0.4 cfs), between the 25th and 75th percentiles of flow (between 0.4 – 3.7 cfs), or equal to or greater than the 75th percentile of the flow record (3.7 cfs), respectively. The study period is divided into consecutive 4-year time blocks.

Statistical evaluation based on the intermediate flow category supports aggregation of the Turkey Creek phosphorus data into the four time blocks described previously for the Bear Creek analysis. A slightly narrower range of percentiles (25th to 75th) is used to define the intermediate flow category, and the period of record is shorter (1998-2006) for establishing those percentiles. Within the intermediate-flow category, the Kruskal-Wallis test showed no significant differences among years in phosphorus concentrations. The random sampling methodology, described above for Bear Creek, is applied to produce annual estimates of phosphorus loads in Turkey Creek for those years with daily gage records (1999-2006). Distributions of estimated annual loads in Turkey Creek are shown in Figure 10.

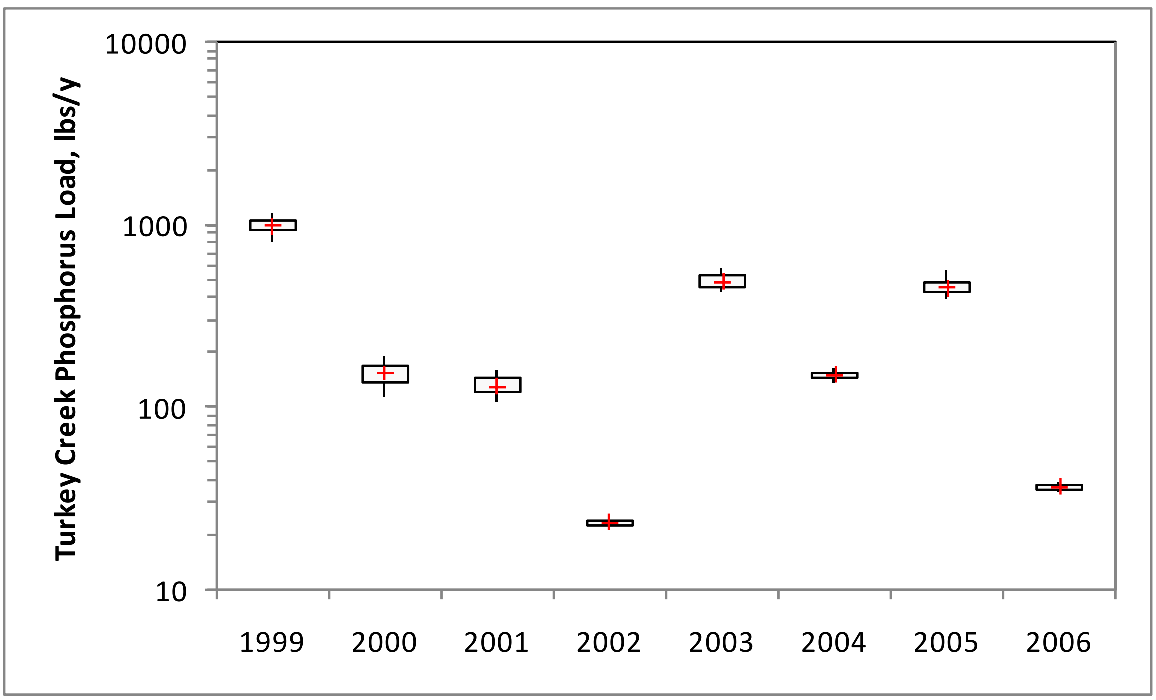

Figure 10. Annual phosphorus loads for Turkey Creek (1999 – 2006) calculated by the random sampling load methodology and adjusted to balance the annual inflow budget. The box-and-whisker plots delineate the 95th, 75th, 25th, and 5th percentiles of the measured concentrations, and the asterisk locates the median. Adjustments to annual flows have not been incorporated.

The annual loads generated by the random sampling methodology provide the best estimates for 1999-2006, but cannot be used in earlier years because daily flows are not available prior to April 1998. At first glance, it might seem feasible to estimate annual phosphorus loads for the missing years on the basis of estimated annual flows. As shown previously, the annual flow in Turkey Creek can be estimated from the residual inflow (computed inflow less Bear Creek and direct precipitation) with which it is highly correlated. There are two problems with this approach – 1) it leaves unresolved the problem of estimating loads for ungaged inflows, and 2) it does not include a mechanism to account for the very high phosphorus concentrations in Turkey Creek from 1991 through 1994.

Direct estimation of loads associated with the ungaged inflows is not possible because there are no concentration data and no daily flows. However, annual loads could be estimated by treating the ungaged flow as if it had the same phosphorus per unit volume as Turkey Creek. This is a reasonable assumption insofar as the watersheds are similar in location and runoff characteristics. Furthermore, the impact of errors in the assumption is not likely to be great because ungaged flows are only a few percent of the total annual inflow to the reservoir.

The ungaged component of inflow can be derived from the inflow residual by subtraction when Turkey Creek gage flows are available (1999-2006) or by proportion when they were not available (1991-1998; see Figure 4). The load delivered by the ungaged flow is estimated with the annual flow-weighted phosphorus concentration for Turkey Creek in the same year. This concentration is known for recent years (1999-2006) or can be derived for earlier years. A relationship between annual load and annual flow in Turkey was derived for the years with gage records (Figure 11), and it can be applied to estimate loads for the other years.

The sequence of steps for producing annual loads from Turkey Creek is sufficiently complex to justify a brief re-cap. For 1999-2006, annual loads were estimated directly from daily gaged flows and measured concentrations using the same random sampling methodology applied to Bear Creek. For all other years, the annual loads were calculated from an empirical relationship that predicts load as a function of annual flow, which was derived from the residual inflow to the reservoir (i.e., there are no daily gage records to use in probabilistic modeling). Up to this point, the phosphorus per unit volume from each year is applied directly to the ungaged flows to yield annual loads for the ungaged component. One more step is needed to produce annual loads for Turkey Creek: annual loads for 1991-1994 must be multiplied by a correction factor to account for the higher concentrations observed in those years.[6] The multiplication factor is derived from a load duration curve.

[6] The ungaged contribution does not receive the same adjustment. It was assumed that the reduction in phosphorus concentrations observed in Turkey Creek after 1994 was the result of controls implemented on POTWs. Such a mechanism would be unlikely to influence concentrations in ungaged parts of the watershed.

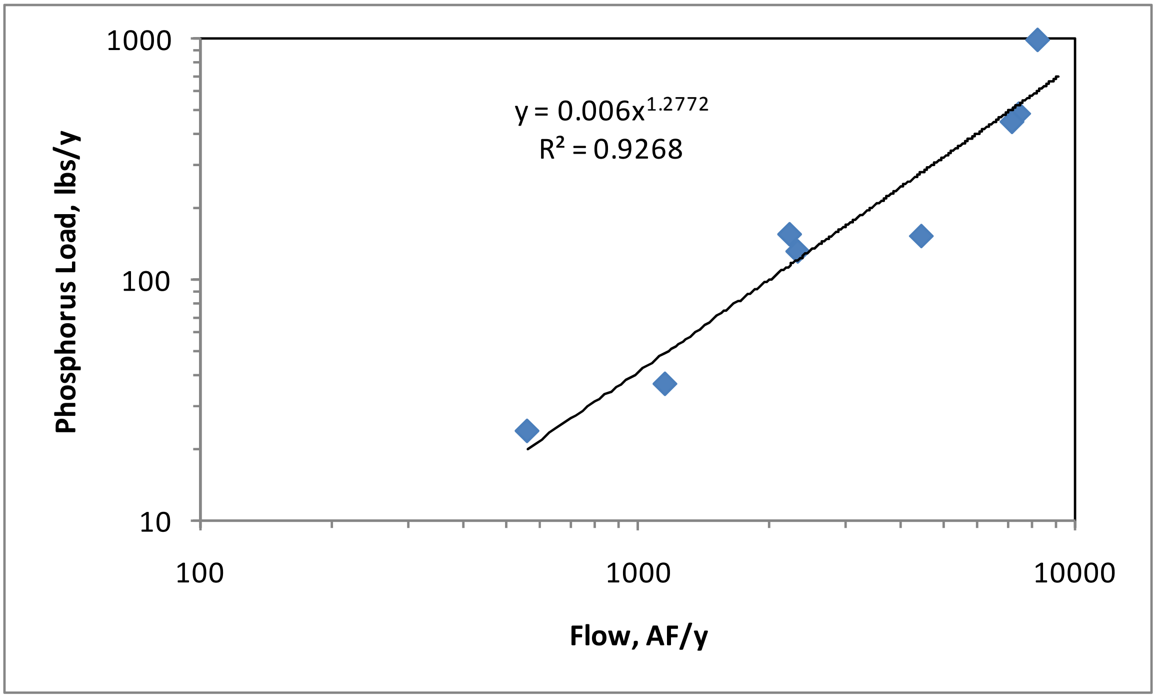

Figure 11. Phosphorus load as a function of annual flow (log scales) in Turkey Creek, 1999-2006. Loads were estimated by the random sampling methodology. Annual flows are based on gage records. See text for details.

Year	Turkey Creek Direct Estimation	Turkey Creek by Regression	Flow-wt Phosphorus, ug/L	Ungaged	Turkey Creek at Augmented Concentration
1991		345	357	93	5172
1992		327	353	88	4904
1993		227	326	61	3401
1994		142	294	38	2125
1995		928	30	251	
1996		442	25	119	
1997		535	26	144	
1998		963	30	260	
1999	998		45	452	
2000	154		25	37	
2001	131		21	96	
2002	23		15	20	
2003	492		24	74	
2004	152		13	98	
2005	455		23	120	
2006	37		12	17	

Table 8. Annual phosphorus loads (lbs/y) for Turkey Creek and from ungaged sources. Direct estimation was possible for years where daily flow records were available. An empirical relationship was used to estimate loads as a function of flow in other years. Loads for 1991-1994 were further augmented to account for the higher concentrations measured in those years. The contribution from ungaged sources is based on the flow-weighted phosphorus concentration in Turkey Creek (before augmenting the values in 1991-1994).

A load duration curve plots calculated daily loads against the percentile of the corresponding daily flow (Figure 12). It is apparent that daily loads from 1991-1994 are much higher than those obtained in more recent years when compared for all but the highest flows (left end of the percentile scale). Fortunately, 1991-1994 was not a time of especially high flows. Curves representing fixed concentration conditions (a surrogate for an annual flow-weighted concentration) can be fit by eye to the daily loads plotted for each time period. Attention was focused primarily on fitting the curves to loads in the middle of the flow percentile range. The ratio of these two concentrations (a correction factor of about 15) provides a reasonable basis for adjusting annual loads from 1991 through 1994. The ratio is needed for adjusting annual loads because daily loads can only be produced on the few days when samples were taken.

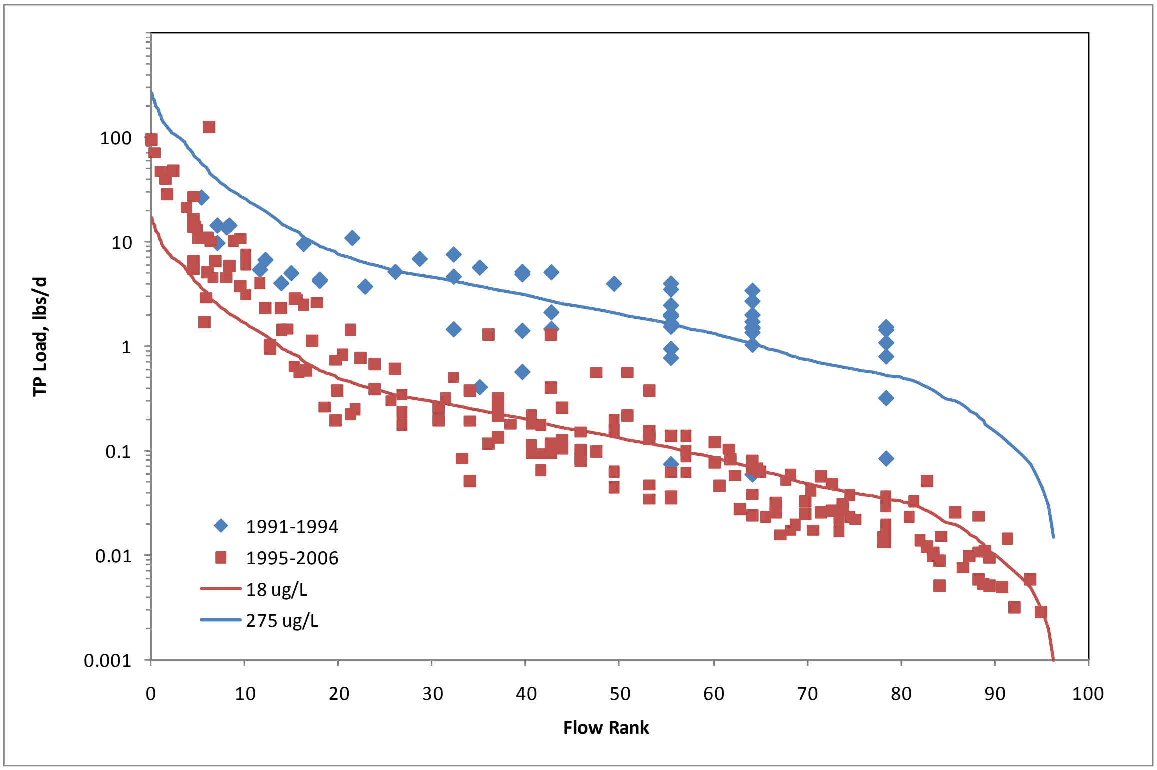

Figure 12. Load duration curves for phosphorus in Turkey Creek. Symbols represent daily loads calculated from measured flow and phosphorus. Loads are plotted against percentiles for the measured flow. Flow percentiles were derived from the set of daily gaged flows (1998-2006) and applied to instantaneous flow measured on sampling dates throughout the study period. The two curves were fit by eye to daily loads from the middle range of flows; each curve represents the set of daily loads expected if concentration were constant across all flows.

Phosphorus in Precipitation

Precipitation falling directly on water surface of the reservoir adds phosphorus to the lake, but the quantity is likely to be small because precipitation usually is less than 1% of the water budget. A constant phosphorus concentration of 87.5 ug/L is applied to the annual flow contributed from precipitation. The concentration is taken from the Chatfield Reservoir Clean Lakes study because no comparable data are available at Bear Creek Reservoir. In view of the small contribution (ca. 30-50 lbs/y; Table 6) to the total phosphorus load, use of a constant concentration is acceptable.

Internal Phosphorus Load

In many lakes, virtually all phosphorus load comes from external sources like tributaries or direct precipitation. Bear Creek Reservoir is likely also to have had internal release of phosphorus based on historical information about phosphorus concentrations and dissolved oxygen profiles. Prior to 1993, the reservoir was stratified. In the hypolimnion, dissolved oxygen was depleted rapidly (Figure 13) and phosphorus concentrations increased significantly. The chemical conditions associated with oxygen depletion also are likely to be associated with release of phosphorus from the sediments.

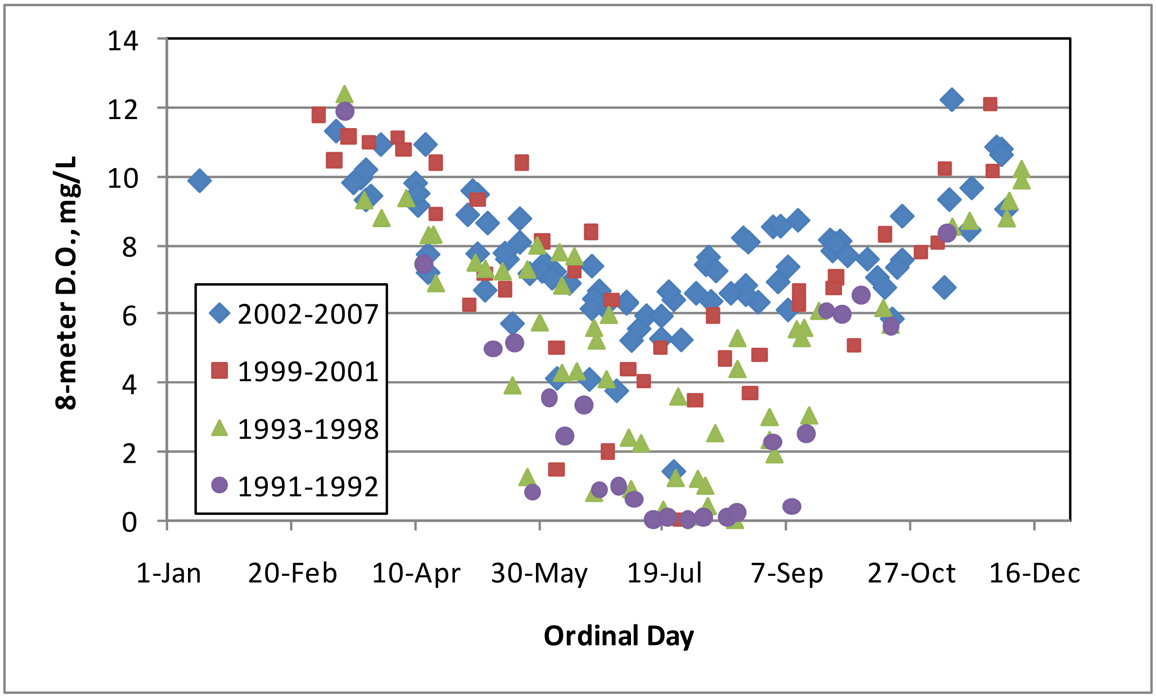

Figure 13. Deep water (8 meters below surface) dissolved oxygen concentrations in Bear Creek Reservoir, 1991-2007. The data are aggregated across years by plotting against ordinal day. Years are segregated according to aerator technology: 1991-1992 – no aeration; 1993-1998 – hypolimnetic aeration without disrupting stratification; 1999-2001 – full water column aeration with barrel aerators; 2002-2007 – full water column aeration with pan diffusers.

Beginning in 1993, hypolimnetic aeration was installed to benefit deep water oxygen concentrations without disrupting stratification. Performance of those aerators was erratic. Aerators installed in June 1999 disrupted stratification and were more effective in maintaining oxygen concentrations throughout the water column. Since 2002, performance of aerators has been consistent and aeration has been effective in maintaining oxygen throughout most of the water column. Despite aeration, internal release of phosphorus may continue for many years and may comprise an important source of phosphorus for algal production. This appears to be happening in Bear Creek Reservoir because, in late summer, phosphorus concentrations in the lake may exceed concentrations in the tributaries.

Estimating Phosphorus Content of the Reservoir

Internal release can be estimated by measuring the rate at which the phosphorus content of the reservoir changes, after accounting for other sources. The ideal situation for measuring the rate of change is a year in which there is little or no inflow or outflow and the water column is well-mixed.

Mixing minimizes vertical concentration gradients, making the calculation of whole-lake concentration less sensitive to inaccuracies in the estimation of water volumes associated with each sample.

Bear Creek Reservoir typically is operated with a relatively constant volume. When the reservoir is at multi-purpose pool elevation, it contains just over 1900 AF. Water surface elevations vary little in most years because the release is from the surface (most reservoirs release primarily from the bottom). Elevations may increase substantially in a high runoff year like 1995, or decline in a drought year like 2002. Nevertheless, the relatively narrow range of volumes in most years facilitates the calculation of phosphorus content on every sampling date.

The monitoring program provides phosphorus data from three depths within the water column. The top and bottom samples tend to be at the same depths on most dates, but the mid-water sample may vary more. Records of actual sampling depths are not available for all years. To make the analysis tractable, some assumptions have been made regarding the volume of water to which each of the three concentration values should be assigned. When the reservoir is divided into three regions of equal depth increments, from top to bottom, the regions contain 56%, 33%, and 11% of the total volume, which is normally about 1900 AF. The percentages are relatively insensitive to actual depth for the normal operating range.

On each sampling date, the volume-weighted phosphorus concentration for the whole lake is calculated from the three measured concentrations (top, mid, and bottom), each weighted by the appropriate volume percentage (56%, 33%, and 11%, respectively). Calculations are made on each sampling date, and the pattern over time is shown in Figure 14. Not surprisingly, the pattern looks much like that of the mixed layer phosphorus, which accounts for more than half of the weighted value.

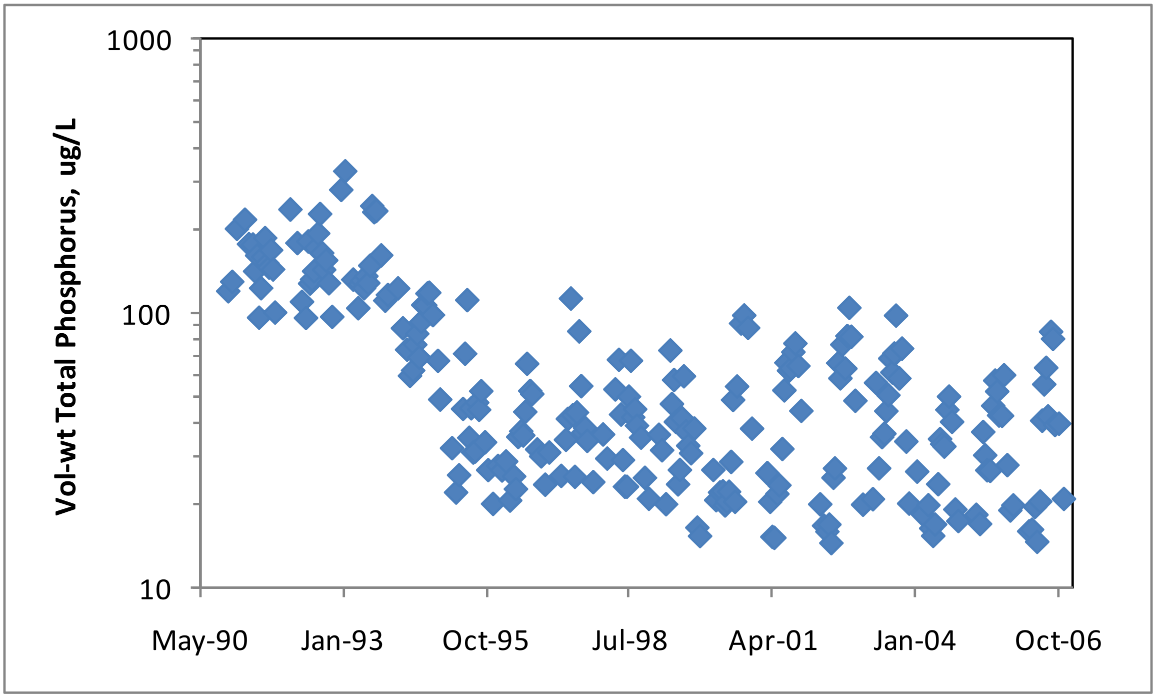

Figure 14. Volume-weighted phosphorus concentration in Bear Creek Reservoir on each sampling date. See text for description of calculation.

Estimating Internal Release of Phosphorus

Internal release may occur throughout the year, but, because the rates of biological processes are temperature-dependent, water temperature determines whether or not there will be any significant contribution of phosphorus to the water column. The observed pattern of internal release suggests that temperatures greater than 15°C are necessary for significant release. The seasonal pattern of temperature in the mixed layer is very consistent, showing that the surface waters first exceed 15°C sometime in May and fall below that threshold by the end of September (Figure 15). There is more variability for the timing of the initial temperature threshold than the final, and this makes sense given the variability in the volume of spring runoff. When aerators are operating efficiently, the bottom temperature should be approximately the same as that of the mixed layer; this is generally true after 1999. The variability in operation of aerators, as well as the variability in runoff conditions, makes it necessary to tailor the temporal boundaries separately for each year.

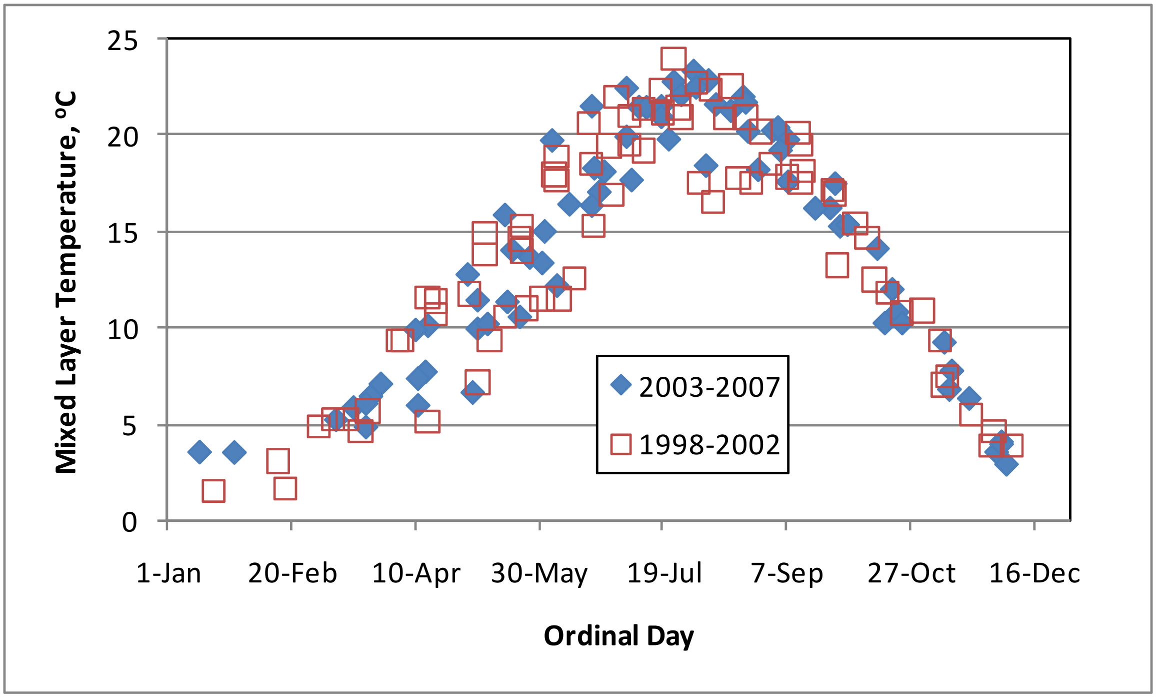

Figure 15. Average temperature in the mixed layer of Bear Creek Reservoir. Each point represents the average of values measured at 1, 2, and 3 meters in the vertical profile. Data are restricted to years when aerators have destratified the reservoir for most or all of the summer months.

The rate of internal release in each year can be estimated by regression analysis using the set of whole-lake phosphorus concentrations. All dates, beginning on the last date with temperature less than 15°C and ending on the last date with temperature greater than 15°C, are included to provide the best estimate of the average rate. When aerators are operating, the time window extends roughly from the end of May through the end of September. Logically, the best opportunity for seeing the "pure" effect of internal load is in the years with lowest inflow. Thus, the drought of 2002 provides a convenient laboratory for estimating internal phosphorus release. Bottom temperature exceeded 15°C by June 6 and remained above that threshold through September 26. There was very little inflow at any time during that year. For the interval from May 23 through September 26, whole-lake phosphorus concentrations increased from 17 to 83 ug/L (Figure 16). The slope of the regression line indicates that phosphorus was being added at a rate of about 0.6 ug/L/d.

The year with the second lowest inflow was 2006. Phosphorus concentrations increased from 15 to 86 ug/L during the summer months when there was very little inflow(Figure 17). The release rate was about 0.6 ug/L/d. Similar results were obtained for 2000 (Figure 18). The next year with relatively low flow was 2001, where there was considerable flow during the summer months and a lower apparent release rate (Figure 19).

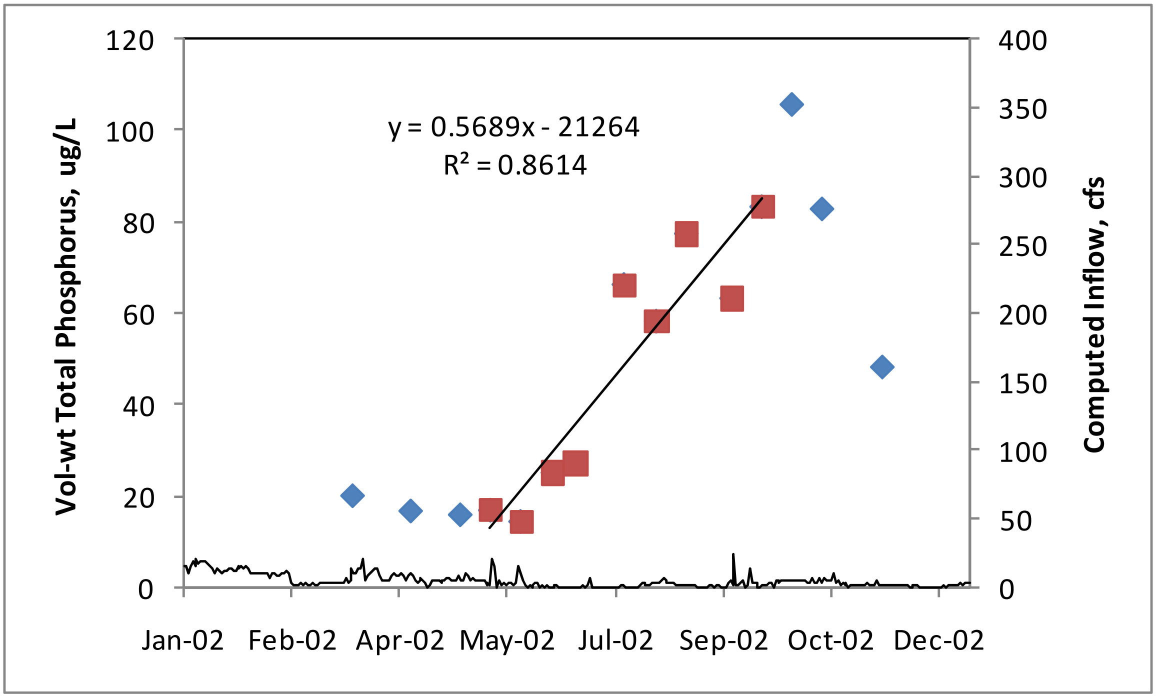

Figure 16. Trajectory of whole-lake phosphorus concentrations in Bear Creek Reservoir during the drought year of 2002. All sampling dates are shown, and those dates used to define the release rate are shown as solid squares. Computed inflow is shown as a solid line, scaled according to the right axis.

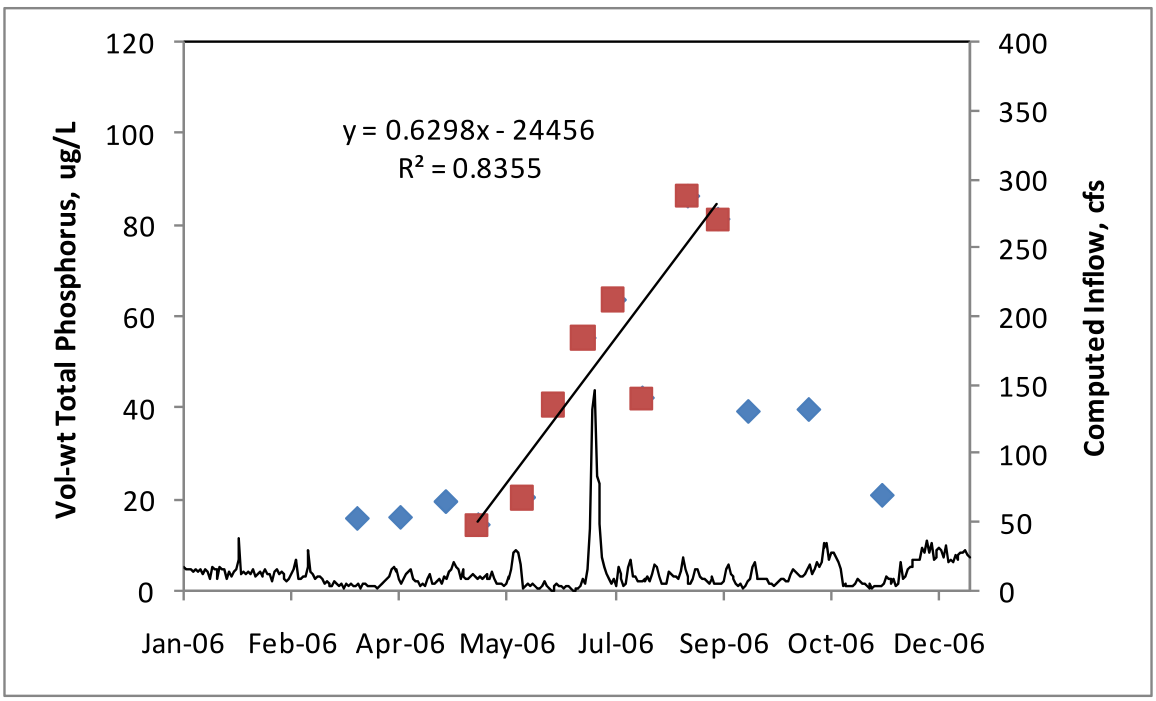

Figure 17. Trajectory of whole-lake phosphorus concentrations in Bear Creek Reservoir during 2006. All sampling dates are shown, and those dates used to define the release rate are shown as solid squares. Computed inflow is shown as a solid line, scaled according to the right axis.

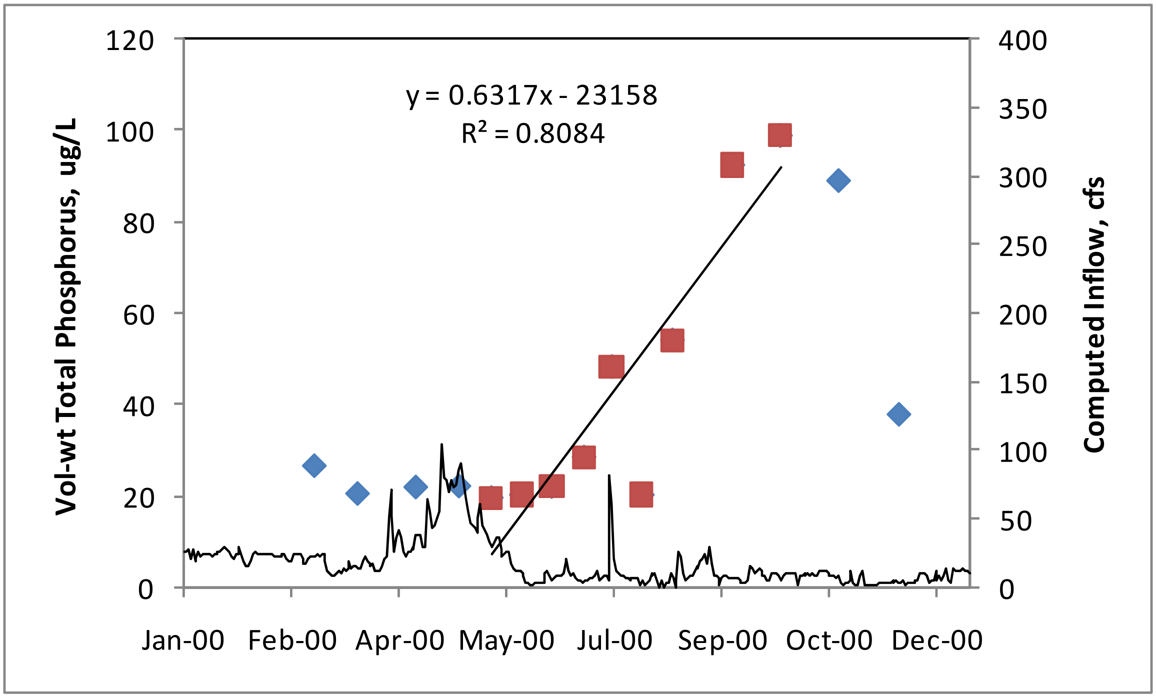

Figure 18. Trajectory of whole-lake phosphorus concentrations in Bear Creek Reservoir during 2000. All sampling dates are shown, and those dates used to define the release rate are shown as solid squares. Computed inflow is shown as a solid line, scaled according to the right axis.

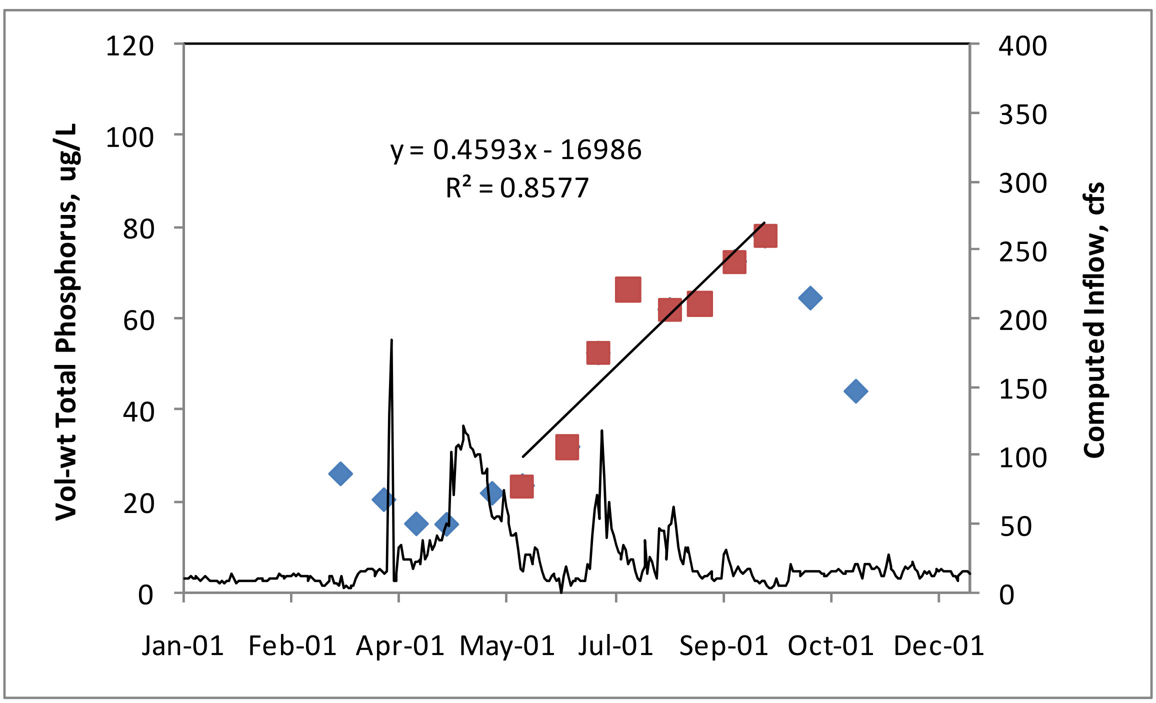

Figure 19. Trajectory of whole-lake phosphorus concentrations in Bear Creek Reservoir during 2001. All sampling dates are shown, and those dates used to define the release rate are shown as solid squares. Computed inflow is shown as a solid line, scaled according to the right axis.

The general pattern emerging from the analysis of internal release is that it exerts a potent effect on phosphorus concentrations in years when it is not overshadowed by large inflows (Table 9). In addition, the timing of the release concentrates the effect in the summer months when it can exert the greatest effect on algal abundance. The estimation procedure is based on those years with low flows that occurred during the operation of de-stratification (1999-2006). The data suggest a release rate that yields phosphorus increases of about 0.6 ug/L/d. Assuming that release occurs for about four months (120 days), and the volume of the reservoir is 1900 AF, internal load contributes about 400 lbs of phosphorus. The internal load is assumed to be constant in all years, even though the effect on whole-lake concentration may be obscured by dilution in high-runoff years.

Year	Inflow	Slope	Start	End	Interval Flow, DSF	Aerator Operation
2002	3437	0.5689	5/23/2002	9/26/2002	272	De-stratified
2006	9128	0.6298	5/17/2006	9/5/2006	1460	De-stratified
2000	13101	0.5718	5/23/2000	9/12/2000	1314	De-stratified
2001	17353	0.4593	6/7/2001	9/27/2001	2693	De-stratified
2003	23693	0.5807	5/27/2003	9/2/2003	3725	De-stratified
2004	28891	0.2318	6/1/2004	9/28/2004	6190	De-stratified
2005	35147	0.2204	6/1/2005	9/27/2005	4759	De-stratified
1999	60355	0.1829	6/29/1999	9/8/1999	8207	De-stratified, part season
1996	16001	0.2376	6/26/1996	9/11/1996	783	Hypolimnetic aeration
1994	16092	0.5063	6/15/1994	9/24/1994	880	Hypolimnetic aeration
1993	16518	1.6619	6/22/1993	9/15/1993	1574	Hypolimnetic aeration
1997	48569	0.0370	7/7/1997	9/17/1997	5595	Hypolimnetic aeration
1995	74569	0.1882	7/26/1995	9/20/1995	3513	Hypolimnetic aeration
1998	76566	<0	7/20/1998	9/14/1998	5592	Hypolimnetic aeration
1992	23780	<0	7/21/1992	9/29/1992	1234	Stratified
1991	31793	<0	7/30/1991	9/10/1991	3201	Stratified

Table 9. Internal phosphorus release rate as indicated by the slope of whole-lake concentration during the period when temperatures were in excess of 15°C. The years are divided into three groups according to operation of aerators (hypolimnetic aeration was installed in 1993 and replaced with a destratification system in June 1999) and ranked within each group according to computed annual inflow. The start and end dates indicate the period of time when bottom temperatures are in excess of 15°C. During the measurement interval, the total inflow (as day-second-feet) is shown. See text for more details.

Phosphorus Export

Not all phosphorus delivered from external sources becomes available for algae, because some portion of the load is retained in the reservoir. A good estimate of the proportion retained is crucial for linking the load that is allowable; i.e., the load that is consistent with attainment of nutrient criteria. In the absence of internal load, retention can be estimated as the difference between load and export.[7] When internal load is important, as it is for Bear Creek Reservoir, the difference between load and export is net retention, but the quantity of interest is gross retention.

[7] Phosphorus export is simply the mass of phosphorus that leaves via the reservoir outflow.

The amount of phosphorus leaving the reservoir is estimated from the outflow volume, which is measured daily, and the measured concentration, which is measured on sampling dates. As explained previously for load estimates, concentrations must be assigned to each day of the year. The basis for assigning concentrations to the outflow is different than the probabilistic approach applied to the inflows for reasons related to sources of variability.

Phosphorus concentrations in the outflow should be much less variable than those in the inflows because the large volume of the reservoir acts as a buffer against the kind of short-term variability that may affect concentrations in streams. In other words, outflow concentration should be largely independent of outflow volume. Consequently, the best estimate of concentration to apply to the outflow is the “typical” concentration of the water mass that is being released. For most of the time, the water released from Bear Creek Reservoir is close to the surface, which is unusual for reservoirs.

The concentration of phosphorus in the “top” sample from the lake is used to represent the export concentration. Selection of the surface sample is consistent with the assumption of the mass-balance models that outflow concentration matches surface concentration in the lake. On a few dates, chiefly in the winter when ice conditions were unsafe, the outflow concentration is used in place of the lake surface sample.

Temporal patterns appear on two time scales. There is a strong seasonal pattern in which concentrations are elevated progressively and substantially from May through September (Figure 20), suggesting a measurable role for internal loading. In addition there are trends over time that record the sharp decline in concentrations after 1994, as well as an increase in variability in recent years (Figure 21). It is not clear why variability should increase, although the increase might be related to operation or performance of aeration equipment.

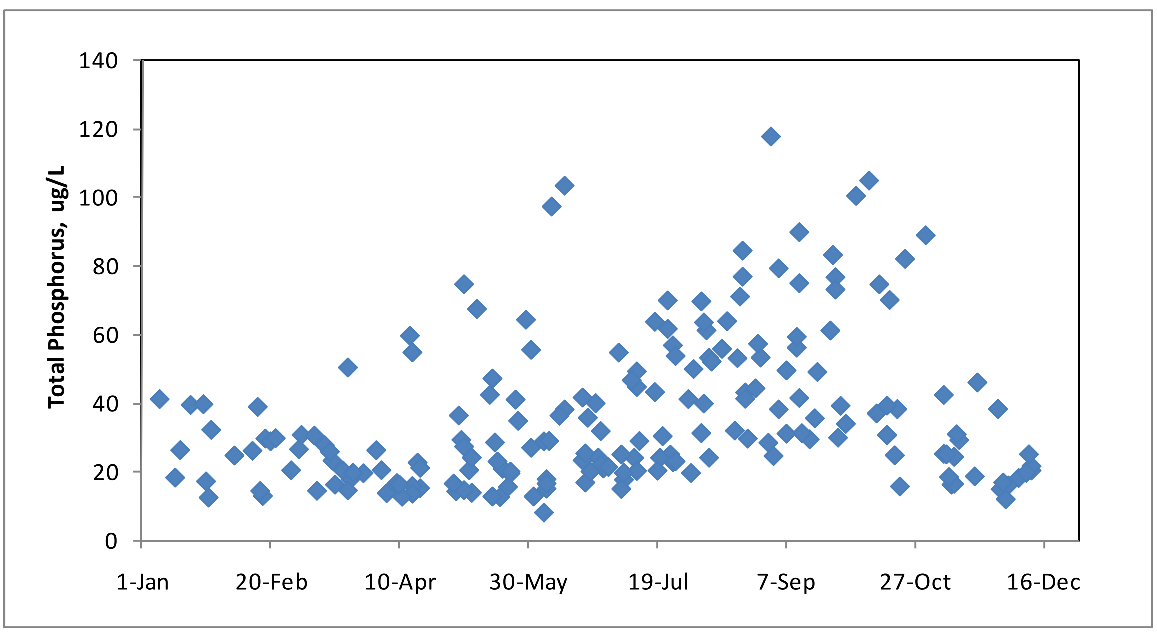

Figure 20. Seasonal pattern of phosphorus concentrations in the surface water of Bear Creek Reservoir, 1995-2006. Earlier years were omitted because the higher concentrations would have obscured the seasonal pattern.

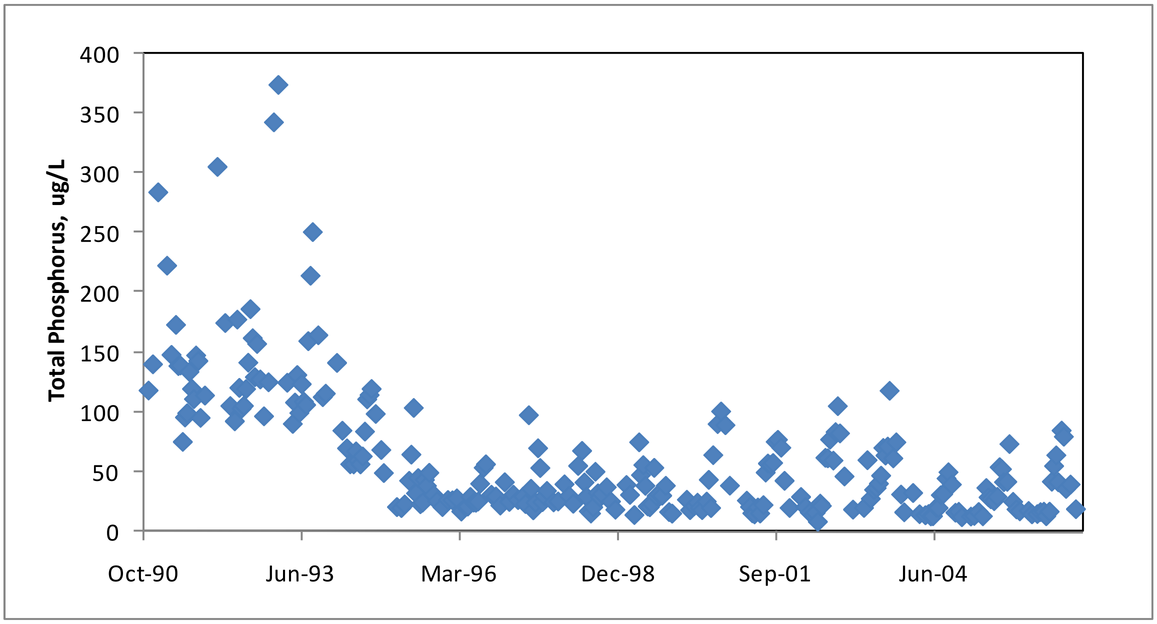

Figure 21. Total phosphorus concentrations in the surface water of Bear Creek Reservoir. On a few dates, chiefly in the winter months when ice conditions were unsafe, the outflow concentration was used.

Aggregation is applied to samples taken within seasons each year (Table 10). Stratification season medians were determined for each year in the period of record. Differences among years may be relatively large. The same strategy is applied to the other months, even though it crosses the calendar year boundary. The median concentration is shown with the final year of each non-stratification season (e.g., Oct 1998 through Mar 1999 is shown with the 1999 data).

Year	Outflow, AF/y	Total Phosphorus, ug/L			Phosphorus Mass, lbs/y		Net Retention, %
		Winter	Stratification	Input	Load	Export	
1991	31474	181	136	189	16358	11060	32
1992	23466	144	125	214	13865	7525	46
1993	16179	127	123	227	10188	4961	51
1994	15759	115	67	187	8195	2818	66
1995	74106	49	42	51	10399	7709	26
1996	27550	26	24	43	3257	1750	46
1997	48198	30	29	49	6465	3474	46
1998	76225	27	31	50	10422	5840	44
1999	60002	30	30	43	7044	4384	38
2000	12778	18	24	40	1437	823	43
2001	17008	64	36	38	1804	1587	12
2002	3199	29	23	54	505	227	55
2003	23141	46	60	36	2291	3346	negative
2004	28526	31	20	33	2619	1374	48
2005	34796	14	36	36	3405	2820	17
2006	8793	17	41	44	1101	525	52
2007		39					

Table 10. Phosphorus export and retention values for Bear Creek Reservoir. Export was derived from seasonal median phosphorus concentrations as explained in the text. The stratification season extends from April through September and the winter season extends from October through March. Annual average (flow-weighted) input concentrations are shown for perspective. Outflow, load, and export for 1996 are adjusted as explained in the text. Gross retention is estimated from load and export values shown in the table, but without adjusting for internal release.

Phosphorus Retention

A significant portion of the phosphorus load is retained in Bear Creek Reservoir, and this is common for most lakes. In most years, net retention is in the range of 30-50% (Table 10). Variability among years does not appear to be associated with residence time, which is often cited as a predictor of retention.[8]

Net retention is relatively easy to estimate, but it will underestimate gross retention where internal load is important. As long as internal load is relatively constant, the difference may not matter much. However, if there is an expectation that internal load will dissipate over time, as seems likely for Bear Creek Reservoir, gross retention is needed for predicting future conditions in the lake.

Although internal phosphorus release can have a very significant impact on summer concentrations in Bear Creek Reservoir, the actual number of pounds released is usually much smaller than the external load. In addition, it seems unlikely that all 400 pounds of internal load becomes part of the annual export. Thus, net retention may be adequate for developing the allowable load estimate; it may be preferable to gross retention in the sense that the net value will tend to overestimate in-lake phosphorus concentrations by underestimating the full extent to which external load is likely to be retained.

The typical annual value for net retention is about 45%, based on individual comparisons of load and export (Table 10). It is also possible to estimate net retention by regressing phosphorus export against phosphorus load (Figure 22). The slope of the relationship shows export as a fraction of load; that fraction is the complement of retention. The intercept could be interpreted as the amount of internal load that is exported, but the accuracy and precision of the intercept would have to be investigated before relying on the number. The intercept is smaller than the 400 lbs/y that has been estimated as the internal phosphorus load, but the slope is relatively insensitive to the larger number (if the intercept were set to 400, retention would be 41% instead of 39%).

[8] Studies comparing phosphorus retention among lakes have shown that higher flushing rates (shorter residence times) tend to result in less retention of phosphorus. However, there is little information to suggest that this factor controls variability in retention among years for the same lake.

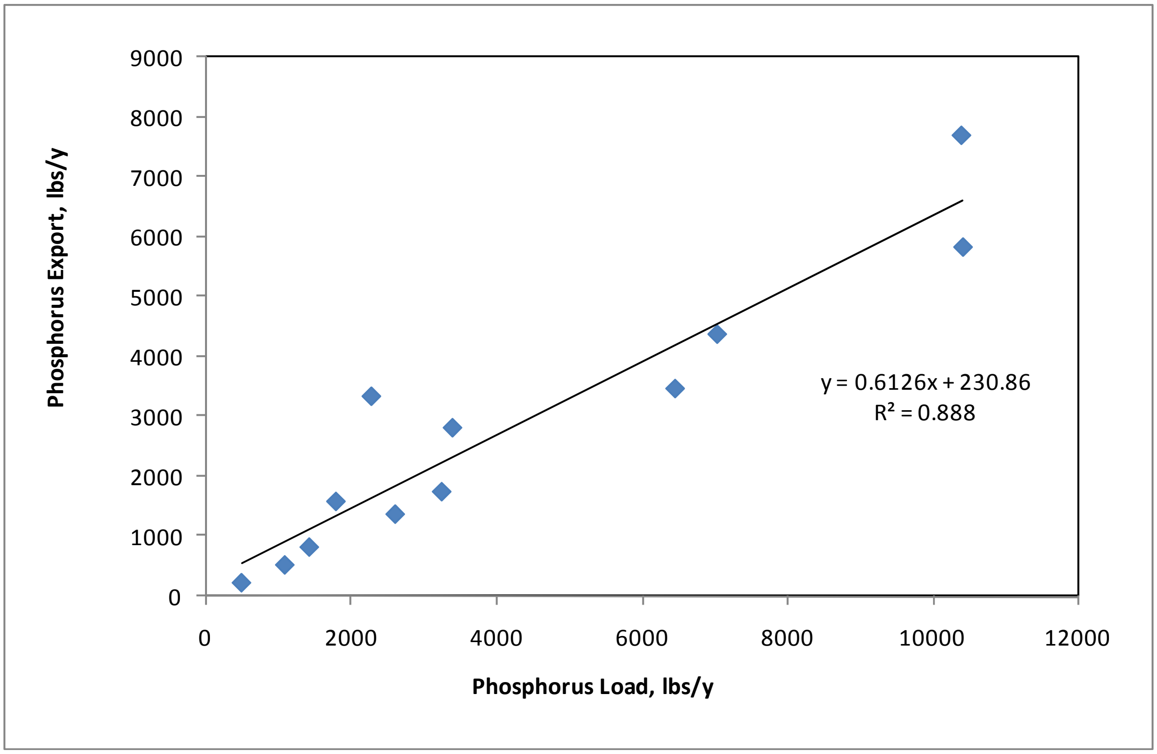

Figure 22. Phosphorus export as a function of external load to Bear Creek Reservoir, 1995-2006. Earlier years were excluded because phosphorus controls had not been completed. The intercept suggests that about 40% of the load is retained. See Table 10 for data.

Conclusions

Most of the phosphorus load to Bear Creek Reservoir comes from external sources, of which Bear Creek is the single largest source. Loads were reduced significantly after POTW controls were fully operational in 1994. Flow-weighted annual average phosphorus concentration (input concentration) appears to be relatively stable across a wide range of flows at about 0.127 lbs/AF (or 47 ug/L).

Although internal phosphorus load is small relative to external load in most years, it can be a potent driver of summer phosphorus concentrations in the lake. In low-flow years, internal release can increase volume-weighted phosphorus to 100 ug/L during the summer months. The increase is important for stimulating algal abundance and boosting summer average concentrations well above what would be expected in the absence of internal release.

About 40% of the external phosphorus load is retained annually in the reservoir. Retention varies somewhat from year to year, but the variation appears to have no pattern or connection to other measured variables. The retention value is relatively insensitive to internal load in the scale of values observed for Bear Creek Reservoir. Consequently, net retention can be used to predict in-lake concentrations expected in the absence of internal load.