Estimating Annual Phosphorus Load to Bear Creek Reservoir

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

The flow sources for Bear Creek Reservoir include two major surface inflows (Bear Creek and Turkey Creek), ungaged surface runoff, and direct precipitation (Table 1). An alluvial source is a possibility, as suggested during the Clean Lakes Study, but it cannot be large and will be ignored for the purpose of phosphorus load estimates. Measured records were used as much as possible, but some adjustments and estimation procedures were necessary to achieve internal consistency among data sources. For example, when flows in Bear Creek were unusually high (4 of 16 years), some downward adjustment was necessary to match the computed inflow. In addition, all inflows from Turkey Creek were estimated from residuals because the gage record was short and gage locations were not ideal. Finally, all ungaged flows were estimated as a fixed proportion of the flow residuals, making the ungaged contribution a fixed percentage of the Turkey Creek flow. Justifications for the special handling and the full details on flow sources and the water budget are presented in a separate document.

Year	Computed Inflow	Outflow	Bear Creek	Turkey Creek	Ungaged	Precipitation
1987	61597	61216	49277	10702	1391	226
1988	35940	35589	25415	9185	1194	147
1989	7765	7496	6310	1153	150	152
1990	26850	26575	22955	3302	429	164
1991	31793	31474	24850	5987	778	178
1992	23780	23466	17146	5742	746	145
1993	16518	16179	11514	4312	561	132
1994	16092	15759	12572	2983	388	150
1995	74569	74106	59655	12999	1690	225
1996	27871	27550	19514	7274	946	137
1997	48569	48198	38855	8444	1098	172
1998	76566	76225	61253	13383	1740	190
1999	60355	60002	48284	10508	1366	197
2000	13101	12778	10213	2447	318	123
2001	17353	17008	13185	3559	463	147
2002	3437	3199	2321	914	119	84
2003	23693	23141	15016	7533	979	164
2004	28891	28526	21365	6470	841	215
2005	35147	34796	25969	7986	1038	153
2006	9128	8793	7307	1496	194	131

Table 1. Inflows (AF/y) to Bear Creek Reservoir in preparation for estimation of phosphorus loads. Significant adjustments were made to the outflow and computed inflow in 1996, and to the Bear Creek flows in 1987, 1995, and 1997-99. Turkey Creek inflows and ungaged flows were estimated in all years. The alluvial component is assumed to be negligible.

Development of a Load Estimation Methodology for Bear Creek

The strategy proposed for estimating loads from surface inflows is based on assigning a concentration to each daily flow and calculating the daily loads, the sum of which yields the annual load. The strategy is needed because concentrations are measured 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 time). Concentrations must be assigned to the other 95% of flows in order to compute the annual phosphorus load.

Because surface inflow is the most important component of the water budget, considerable attention is devoted to understanding variability of phosphorus concentrations in each tributary. Stream flows often 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 1). Perhaps the most important feature of the graph is the sharp reduction in concentrations by 1995. 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.

Although it is possible that there truly is no association between flow and concentration in Bear Creek, that is not a comfortable conclusion. Phosphorus concentration varies by nearly two orders of magnitude over the period of record (from 7.6 – 729 µg/L), and the full range of concentrations may not occur in all years. In other words, even though there is no apparent relationship between flow and concentration, it does not make sense to assume that any concentration could apply to all years. Clearly, most of the high concentrations observed across much of the flow range were restricted to the years prior to 1995.

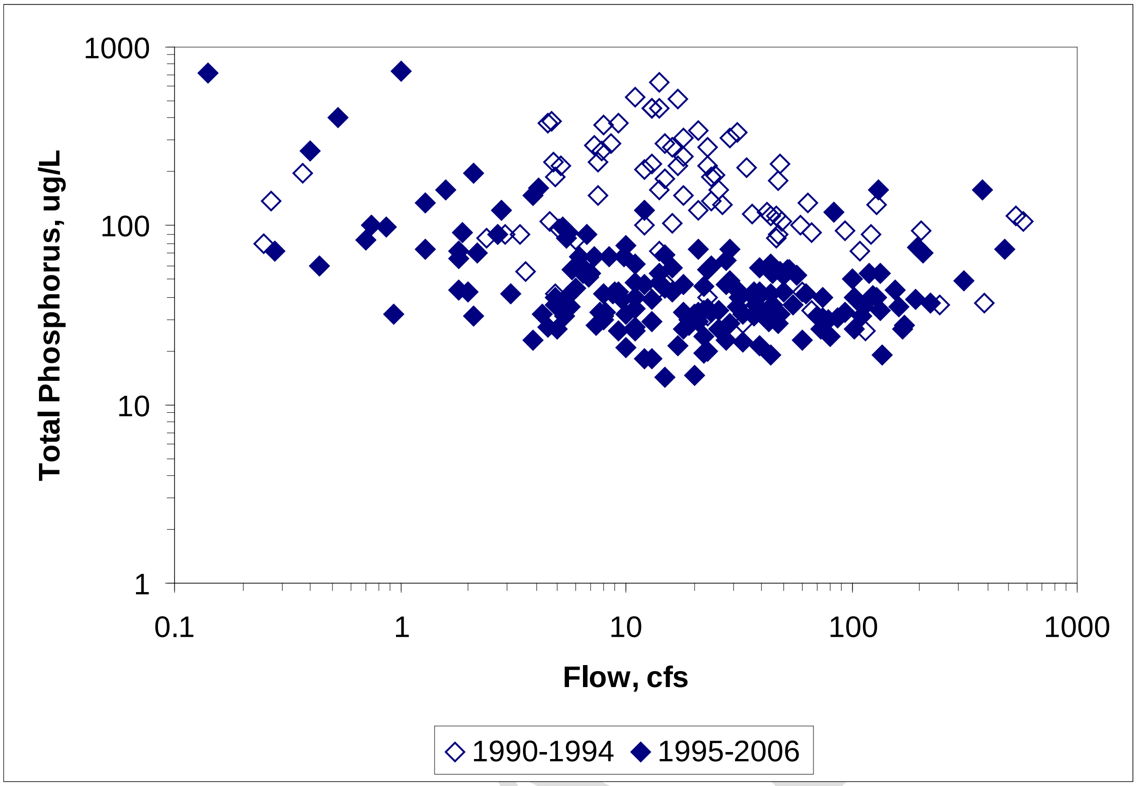

Figure 1. Relationship between total phosphorus concentration and stream flow (log scales) measured at the gage on Bear Creek just above the reservoir. The data are divided into two time periods to highlight a reduction in concentrations that occurred over the first few years of the study.

The variability in phosphorus concentrations among years can be visualized 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 2). The reduction in concentrations prior to 1995 may reflect improved performance by point sources. Higher concentrations during 2002 and 2003 may show the influence of drought. However, direct comparison of concentrations among years may be misleading unless some consideration is given to flow conditions in each year.

In order to facilitate comparisons of concentrations among years, “normalization” for flow is necessary. Even though there is no apparent relationship between flow and concentration when all data from the period of record are lumped, there may be underlying relationships that apply to shorter time periods. Moreover, there is a need to accommodate the logical expectation that concentrations associated with the very lowest flows are not going to be the same as those associated with the very highest flows.

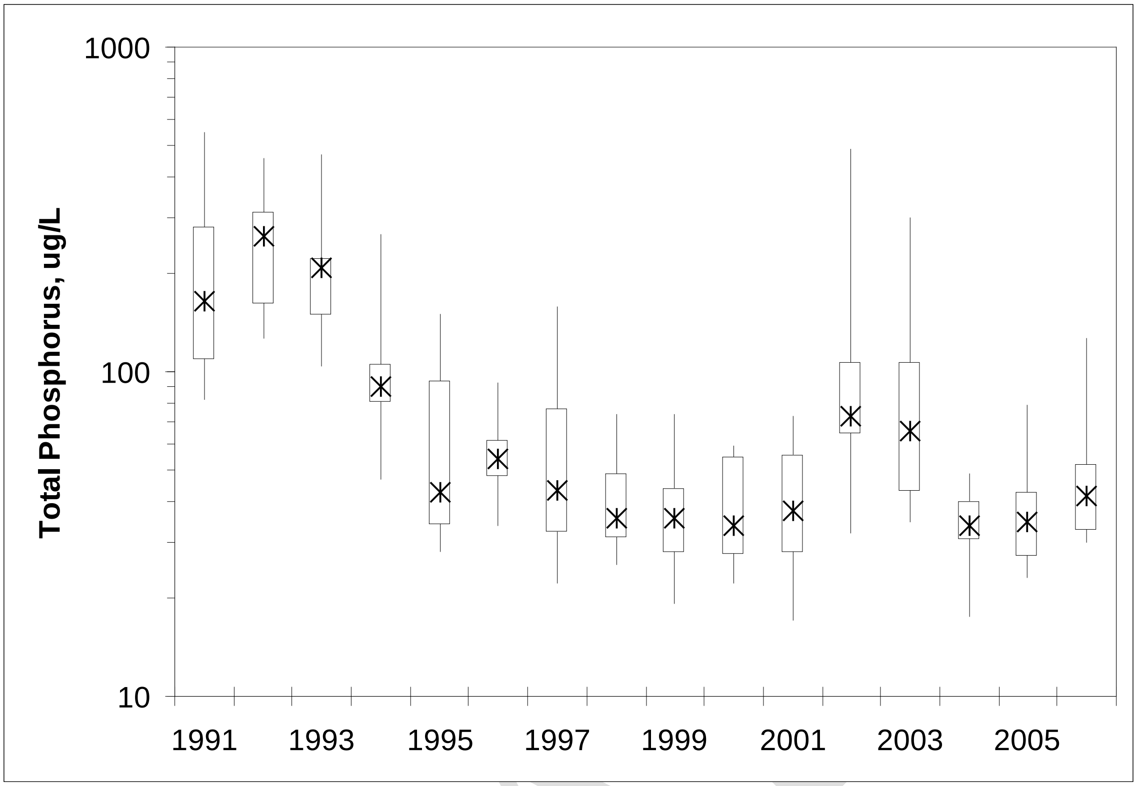

Figure 2. Annual distribution of phosphorus concentrations (log scale) in Bear Creek. The box-and-whisker plots delineate the 95th, 75th, 25th, and 5th percentiles of the measured concentrations. Taller boxes indicate more variability in phosphorus concentrations during that year. An asterisk indicates the median concentration in each year.

The normalization procedure classifies each measured phosphorus concentration according to the stream flow recorded on the sampling date. Flow categories are based on percentiles derived from all daily flows from the 16-y period of study. Basing the flow percentiles on the period of study rather than individual years is important because it establishes a fixed frame of reference for normalizing prior to comparing concentrations among years. Three flow categories (low, intermediate, and high) were established with boundaries that are largely arbitrary. Quartiles were used first, with the intermediate flow category containing the two middle quartiles, but sample size was too small in some years. Widening the interval slightly to extend from the 20th to the 80th percentiles yields a sample size of 6 or more in most years (Table 2).

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	
1998	0	6	10	16	

Year	Low Flow	Intermediate Flow	High Flow	Total	Time Block
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 2. 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.

Aggregation of phosphorus data into a time-and-flow framework can improve the basis for statistical analyses and phosphorus load calculations by increasing sample size. As a first cut, the data are split into consecutive 4-year blocks. In part, this division builds on existing knowledge that the first four years were characterized by very high phosphorus concentrations. Aggregation can only be justified if years within blocks are similar in terms of phosphorus concentrations. Therefore, phosphorus concentrations measured on days with intermediate flows were compared among years within each time block on the basis of the Kruskal-Wallis test, a nonparametric analog of ANOVA. No significant differences were found. Similar comparisons are not feasible for the high and low flow categories due to the small sample sizes in several years; it is 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. [NB: The monitoring program for Bear Creek Reservoir is not deficient compared to other reservoir monitoring programs.] 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 leads directly to 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 (1991-1994) as an example. During that 4-y period, about 68% of the daily flows were between the 20^{th} and 80^{th} percentiles of all flows included in the 16-y study (i.e., slightly more than the 60% expected from the full period of record). Phosphorus concentrations were measured on 38 (4%) of the 990 days in that intermediate-flow category. Assuming that each of the 38 concentrations is an equally valid estimate of the true concentration for any of the days in the intermediate flow category, any one of those concentrations can be chosen at random to represent concentration on each of those days. The same process is applied separately to the other two flow categories (low and high) for the 1991-1994 time block, and to all three flow categories for the other three time blocks. Daily loads are then summed within each year to compute the annual phosphorus load.

The sampling procedure can be repeated many times, each time randomly drawing a new concentration for each day of the flow record, yielding as many estimates of annual loads as one has the patience to produce. The value of the methodology is that it takes a relatively thin data set and, by aggregation, creates a more complete representation of the 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 3). The boxes for each year are compressed because of the large range of loads among years. In most cases, the interquartile range (25th to 75th percentiles) is less than 10% of the median. Median values are given in Table 3.

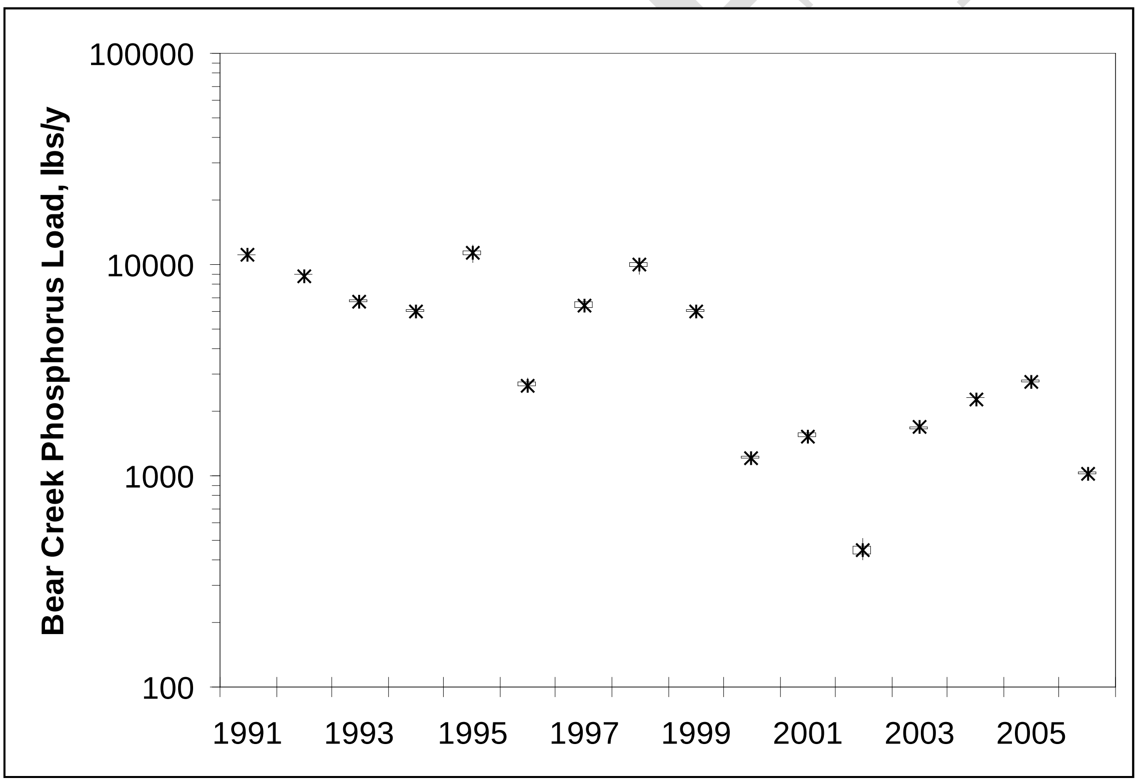

Figure 3. Annual phosphorus loads for Bear Creek (1991 – 2006) calculated by random sampling of the data aggregated in a time-and-flow framework. The box-and-whisker plots delineate the 95th, 75th, 25th, and 5th percentiles of the measured concentrations, and the asterisk locates the median.

Year	Bear Creek	Turkey Creek	Ungaged	Precipitation	Total
1991	11050	340	44	42	11477
1992	8838	319	41	34	9233
1993	6694	205	27	31	6957
1994	5997	116	15	35	6163
1995	9168	1126	146	53	10493
1996	2663	460	60	32	3215
1997	5745	579	75	41	6439
1998	9154	1178	153	45	10530
1999	5547	811	105	46	6510
2000	1216	85	11	29	1342
2001	1542	152	20	35	1749
2002	442	19	2	20	483
2003	1687	485	63	39	2273
2004	2318	384	50	51	2802
2005	2795	531	69	36	3431
2006	1016	40	5	31	1092

Table 3. Calculations of annual phosphorus load from all sources to Bear Creek Reservoir (1991-2006). Special calculations apply for several sources; see text for explanation.

Application of Load Estimation Methodology to Turkey Creek

Phosphorus concentrations in Turkey Creek are plotted against the instantaneous stream flow measured at the time and place of sampling (Figure 4). Instantaneous flow is used because gage records are not available at the sampling site, and nearby gages were operating for only about half of the study period. For samples taken after 1994, concentrations generally increase with increasing flow, although the variables are not tightly coupled (Figure 5).

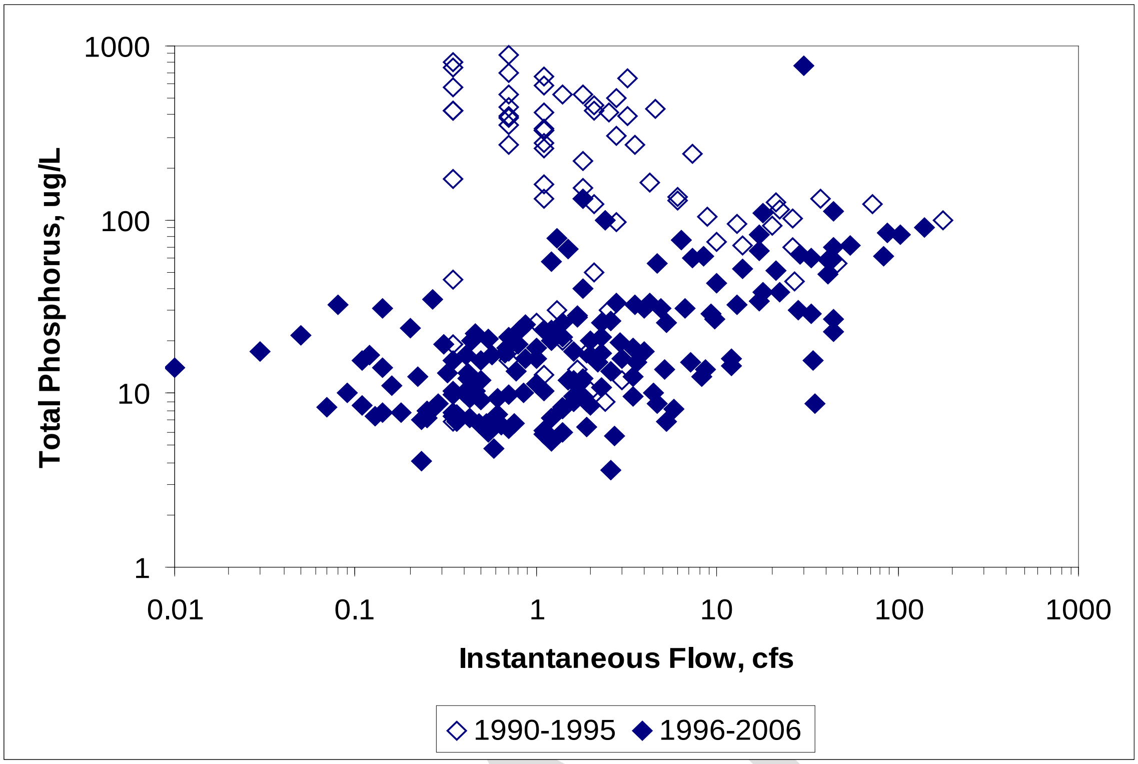

Figure 4. Relationship between total phosphorus concentration and instantaneous stream flow (log scales) measured in Turkey Creek.

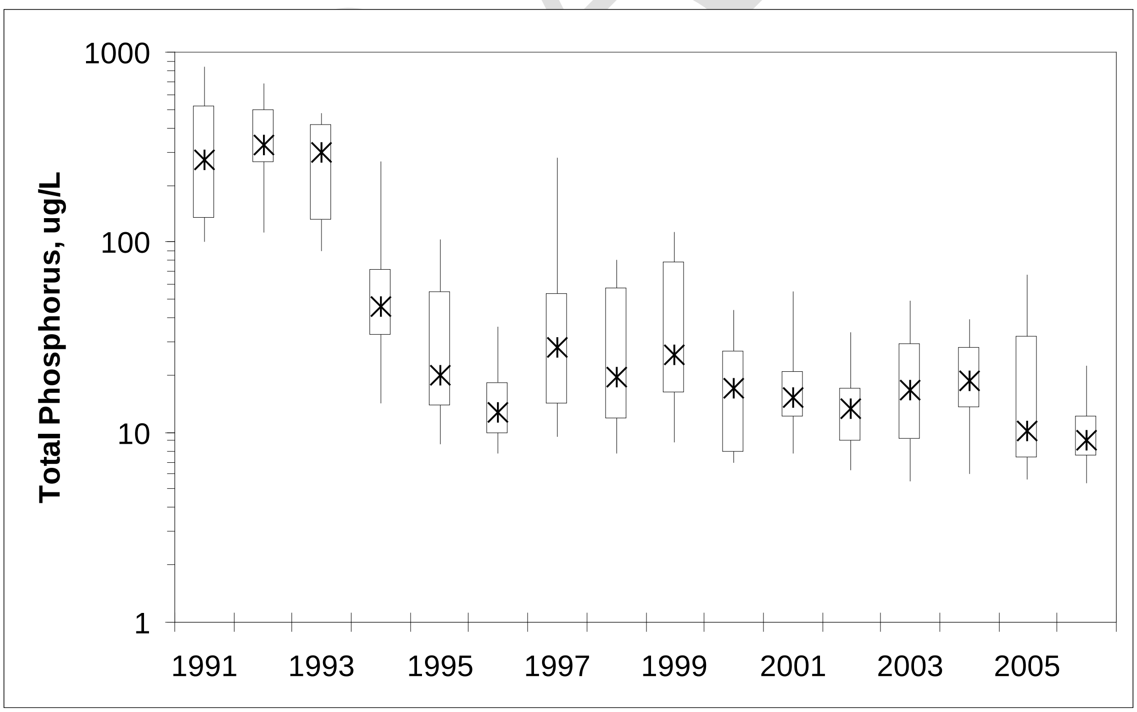

Figure 5. Annual distribution of phosphorus concentrations (log scale) in Turkey Creek. The box-and-whisker plots delineate the 95th, 75th, 25th, and 5th percentiles of the measured concentrations. Taller boxes indicate more variability in phosphorus concentrations during that year. An asterisk indicates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

Given even a weak relationship between concentration and flow (Figure 4), it is important to normalize flows before evaluating temporal trends in phosphorus concentrations by time-and-flow aggregations. Flow percentiles are defined with the available gage records (1998-2006) even though that record is shorter than the period of study. The low flow category is defined for those daily flows less than or equal to the 25^{th} 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 75^{th} percentile (3.7 cfs). Sampling dates are classified according to the instantaneous flows, which were measured in all years. An adequate number of samples was available each year in the intermediate flow category (Table 4).

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	
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 4. 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 for the Bear Creek analysis. A slightly narrower range of percentiles (25^{th} to 75^{th}) 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 load methodology, described above for Bear Creek, is applied to the estimation of annual phosphorus loads in Turkey Creek. The random-sampling method was applied 100 times to those years with daily gage records (1998-2006). Box-and-whisker plots show distributions of annual phosphorus loads in Turkey Creek (Figure 6).

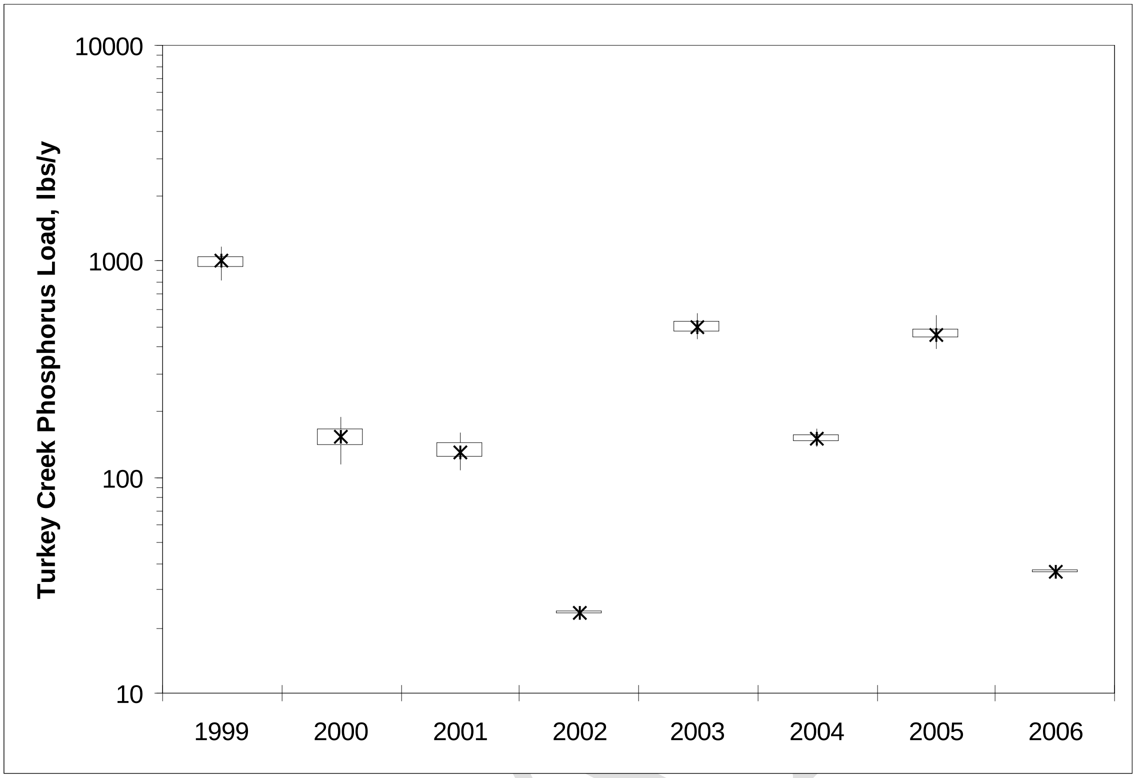

Figure 6. Annual phosphorus loads for Turkey Creek (1998 – 2006) calculated by the random sampling load methodology and adjusted to balance the annual inflow budget. The box-and-whisker plots delineate the 95th, 75th, 25th, and 5th percentiles of the measured concentrations, and the asterisk locates the median.

During the period of study, there are no daily flow records for Turkey Creek prior to April 1998. Nevertheless, it is desirable to estimate of phosphorus loads in all years on the basis of the best available information. The approach for estimating Turkey Creek loads in 1991-1998 relies on a relationship between flow and load for the years when both were measured (Figure 7). The flow used in the regression analysis was determined by the method of residuals (as outlined in the hydrology document) because it is available in all years. The regression relationship derived from those years when gage records were available (1999-2006) is used to estimate the load from Turkey Creek in all years (Table 3).

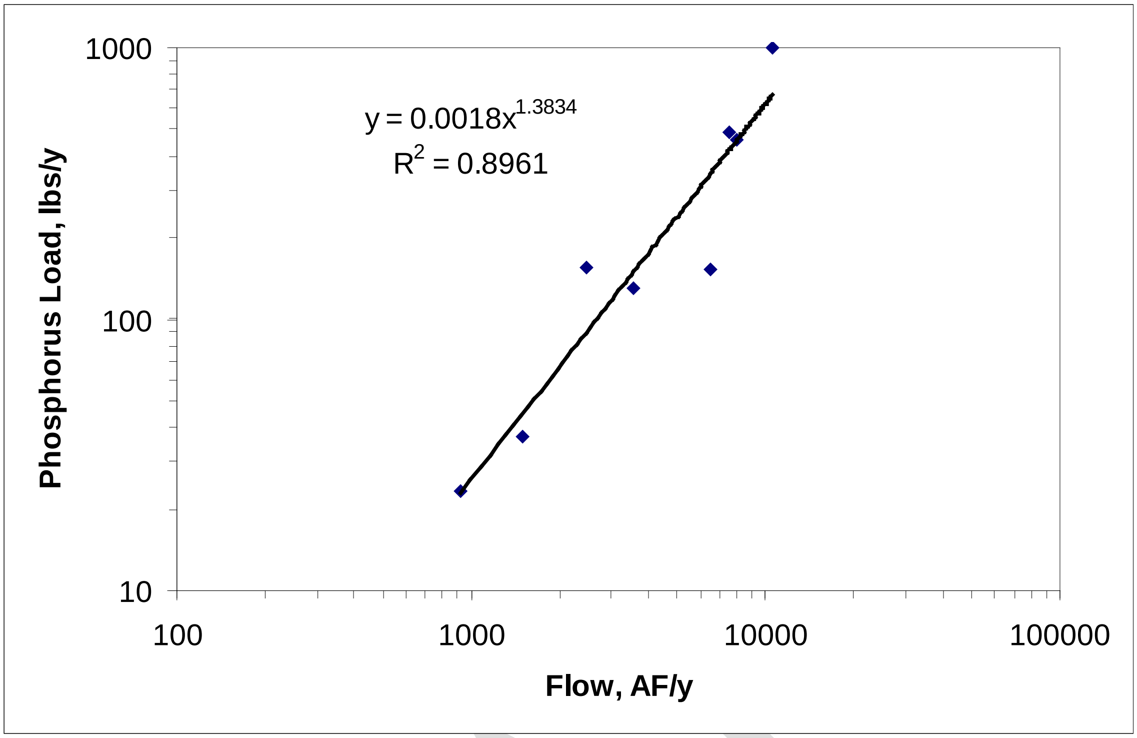

Figure 7. Phosphorus load as a function of annual flow (log scales) in Turkey Creek, 1999-2006. Loads were estimated by the random sampling methodology. Flows were determined from residuals. See text for details.

Phosphorus from Other Sources

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 3) to the total phosphorus load, use of a constant is acceptable.

There is also a small contribution of phosphorus from surface runoff that is not measured at gages. This component of the water budget was determined as part of the residual, which also included Turkey Creek. In those years when gage records were available for Turkey Creek, the ungaged flow was about 13% of the flow measured in Turkey Creek (or about 2% of the total inflow). The ungaged flow may come from small tributaries or from direct surface runoff, neither of which is sampled regularly. Fortunately, because the contribution to flow is so small, there is little penalty for ignorance of the actual phosphorus concentration. For simplicity, the phosphorus load from ungaged sources is treated as a fixed proportion (13%) of the load delivered by Turkey Creek in each year (i.e., it is assumed to have the same phosphorus concentration as that observed in Turkey Creek).

Distribution of Phosphorus Sources to Bear Creek Reservoir

The relative importance of the four flow sources to the total annual phosphorus load is shown in Table 5. Bear Creek is the primary source of phosphorus load, contributing almost 90% of the median annual load. Turkey Creek contributes less than 10% of the median annual load, and the other two components make very small contributions. Partitioning of sources makes it easier to see where control efforts, if needed, are likely to be most influential.

Source	Median Annual Phosphorus Load (lbs/y)
Bear Creek	4171 (87%)
Turkey Creek	362 (8%)
Ungaged	47 (1%)
Direct Precipitation	36 (1%)
Total	4797 (100%)

Table 5. Median annual phosphorus budget for Bear Creek Reservoir (1991 – 2006). Load estimates for each year are shown in Table 3.