Estimating Annual Phosphorus Load to Chatfield Reservoir

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

The flow sources for Chatfield Reservoir include two gaged surface inflows (South Platte River and Plum Creek), two small ungaged tributaries (Deer Creek and Massey Draw), direct surface runoff, direct precipitation, and alluvial inflow (Table 1). More detail on flow sources and the water budget is presented in the accompanying document. The flow sources differ considerably in relative importance and temporal patterns of variability, both of which influence the assessment of variability in phosphorus concentrations.

Source	Mean Annual Inflow (AF)	Percent of Total
South Platte River	118,988	75.6
Plum Creek	26,764	17.0
Ungaged Runoff	5,924	3.8
Plum Creek Alluvium	3,787	2.4
Direct Precipitation	1,918	1.2
Total	157,381	100.0

Table 1. Mean annual inflow budget for Chatfield Reservoir (1976 – 2006).

Development of a Load Estimation Methodology for the South Platte River

Because gaged surface inflows are the most important component of the water budget, appropriate attention should be devoted to understanding variability in the associated phosphorus concentrations. In many streams, phosphorus concentrations are strongly influenced by variations in flow, and stream flows may vary substantially over time. Where such a relationship exists between flow and concentration, its characterization becomes a practical necessity for load estimation because concentrations typically are measured much less frequently than are flows. Flow in the South Platte at Waterton, for example, is reported daily, but phosphorus concentrations typically are measured only 15-20 times per year (i.e., about 5% of the time). What concentration is appropriate for the other 345-350 days?

The strategy proposed for estimating loads from surface inflows is based on assigning a concentration to each daily flow. The basis for assignment is optimized through a detailed characterization of variation in concentration. Once a concentration value is associated with each flow, daily loads are calculated and summed to yield the annual loads.

The influence of flow on total phosphorus concentration is a logical starting point for the characterization of variation. A plot of total phosphorus concentration against flow in the South Platte shows no apparent relationship (Figure 1), despite expectations to the contrary. In retrospect, this is not completely surprising because flows in the South Platte are managed intensively. The large volume and long residence time of water in upstream reservoirs buffers concentration compared to the daily variations seen in tributary streams. Additionally, much of the water is diverted for municipal use before reaching the Waterton gage, further obscuring any underlying relationship between phosphorus concentration and flow.

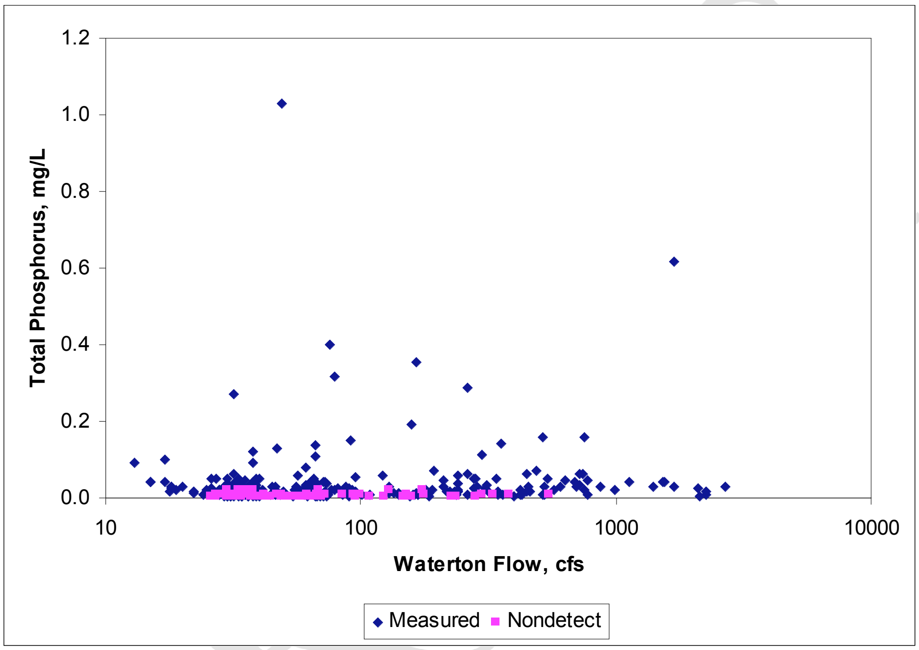

Figure 1. Relationship between total phosphorus concentration and stream flow (log scale) measured at the Waterton gage on the South Platte River. Nondetects are separated from other data points.

It is possible that there truly is no association between flow and concentration in the South Platte, but that is not a comfortable conclusion. Phosphorus concentration varies substantially over the period of record (from nondetects to more than 1 mg/L). At the same time, some caution should be exercised insofar as the full range of concentrations may not occur in all years.

The variability in phosphorus concentrations among years can be visualized effectively with box-and-whisker plots that show the distribution of values observed in each year. The 20-y record for the South Platte at Waterton reveals no obvious trends, but it does show that there have been oscillations in concentration – notably in the late 1990s and since 2002 – that are likely to affect loads (Figure 2). To acknowledge the possibility of subtle trends over time, data were aggregated into four blocks of five years each, beginning with the first complete year of sampling (1987). Aggregating phosphorus concentrations is advantageous because it increases the sample size from which to evaluate temporal patterns, and it segregates oscillations in phosphorus concentrations relatively well.

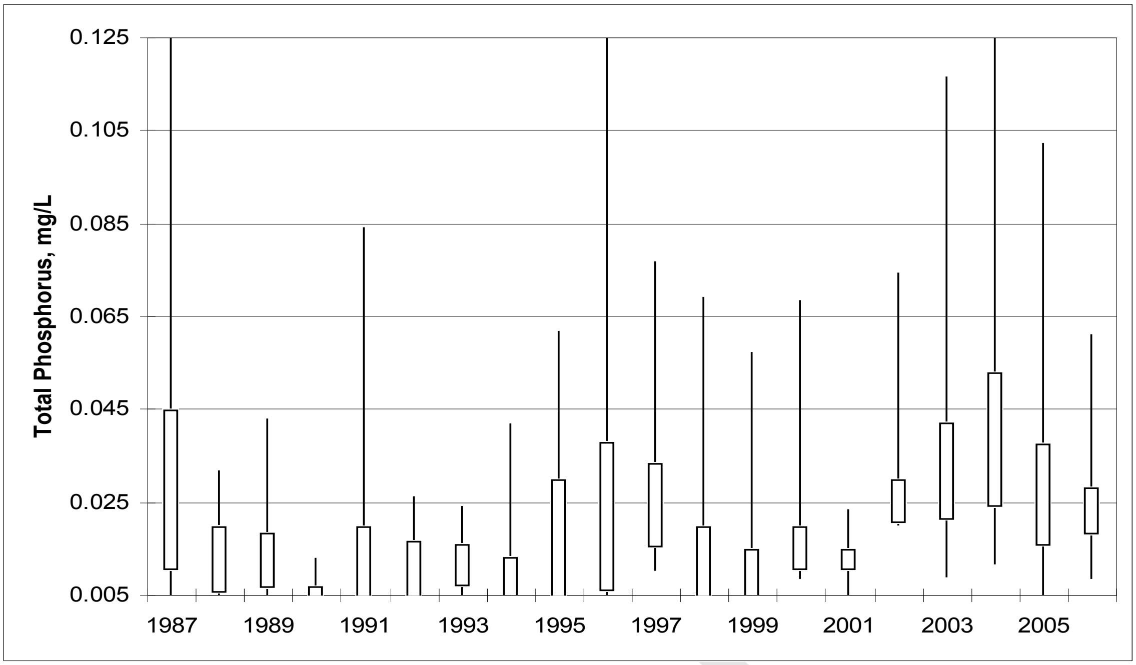

Figure 2. Inter-annual variability in phosphorus concentrations in the South Platte River at Waterton. The box-and-whisker plots delineate the 95th, 75th, 25th, and 5th percentiles of the measured concentrations. The abscissa is truncated at the upper end to reduce compression of the boxes and at the lower end (0.005 mg/L) to indicate the detection limit that applied in most years.

Within each block, the five individual years can be compared on the basis of phosphorus concentration. In order to facilitate comparisons of concentrations among years, some "normalization" for flow is desirable. 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 may not be the same as those associated with the very highest flows.

A coarse approach is proposed for the normalization procedure whereby all daily flows from the 20-y period of record are ranked and assigned to one of four quartiles (e.g., 0-25%, 25-50%, etc). The low-flow category includes all days with average flow in the lowest quartile, which means flows less than or equal to the 25th percentile flow (32 cfs for 1987-2006). The intermediate-flow category includes the middle two quartiles of flows (between 32 and 72 cfs). The high-flow category includes the highest quartile of flows, meaning those that are greater than or equal to the 75th percentile flow (72 cfs). Basing the quartiles on the period of record rather than individual years is important because it establishes a fixed frame of reference for normalizing prior to comparing concentrations among years.

Every day in the 20-y period of record can be classified according to time (four consecutive 5-y blocks) and flow (high, intermediate, and low flow categories). In anticipation of statistical comparisons, phosphorus concentrations are placed within this time-and-flow framework on the basis of sampling date (Table 2). Segregation of the data on the basis of time and flow distribution is a conservative approach because it admits the possibility of temporal changes in phosphorus concentrations as well as a relationship between concentration and flow that may be obscured by water management.

Year	< 25th Percentile (n)	>25th , < 75th Percentile (n)	> 75th Percentile (n)
1987	3†	3†	13
1988	2†	10	5
1989	4	4	8
1990*	3†	7	6
1991	7	11	7
1992	5	10	6
1993	1†	15	7
1994	7	8	7
1995	2†	9	11
1996	2†	11	9
1997	5	8	11
1998*	2†	5	8
1999*	1†	8	6
2000	1†	10	4
2001	3†	8	4
2002	5	10	0
2003	5	9	2
2004	6	7	6
2005	6	8	4
2006	5	3†	7
Total	**75**	**164**	**131**

† Data excluded from statistical analyses because of small sample sizes (n < 4)

Table 2. Distribution of phosphorus concentrations among years within flow groupings. Three flow groupings were established based on the distribution of the 20-y record of flow in the South Platte River at Waterton. Low-flow, intermediate-flow, and high-flow groupings consisted of phosphorus concentrations measured when the daily gaged flow was less than or equal to the lowest quartile of the 20-y flow record (32 cfs), between the upper and lower quartiles of flow (between 32 – 72 cfs), or equal to or higher than the highest quartile of the flow record (72 cfs), respectively.

The distribution of phosphorus measurements among the flow percentiles varies quite a bit from year to year (Table 2), and this is to be expected. In a high flow year like 1995, few of the daily flows (<10%) are in the low-flow quartile, making it less likely that water quality samples would be taken. Conversely, in the drought year of 2002, the high-flow quartile was poorly represented (3% of daily flows) and no water quality samples were taken under those flow conditions. The intermediate-flow category, on the other hand, is well-represented in terms of phosphorus measurements in most years.

Aggregation of phosphorus data into a 5-y time-and-flow framework improves the basis for statistical analyses and phosphorus load calculations only if years within blocks are similar in terms of phosphorus concentrations. Therefore, phosphorus concentrations measured during intermediate and high flows were compared among years within each 5-

y block on the basis of the Kruskal-Wallis statistical test. This nonparametric test was used to avoid assumptions about the underlying statistical distribution and to facilitate handling of nondetects. Three years (1990, 1998, and 1999) were excluded from statistical analyses because annual median phosphorus concentrations were less than the detection limit. Within each flow category (low, intermediate, high) some additional years were excluded from due to low sample sizes ($n < 4$; Table 2). Statistical comparisons among years within time-blocks also were not made for the low-flow group of measurements because individual years were frequently represented by very few measurements ($n < 4$) during the lowest quartile of flow (Table 2).

At both intermediate and high flows, the Kruskal-Wallis test revealed no significant differences among five years within any block. This supports the aggregation of phosphorus concentrations into 5-y blocks within each flow category. Although small sample size precluded a similar statistical comparison of concentrations measured at low flows, it is reasonable to assume that there are no differences among years within 5-year blocks because no such differences were observed during intermediate or high flows and because variability in phosphorus concentrations assigned to the lowest quartile of flows is unlikely to significantly skew annual load estimates.

When phosphorus concentrations are grouped by flow categories, temporal patterns emerge (Figure 3). Phosphorus concentrations appear to increase through time, particularly during the last ten years. The increases are most apparent at low and intermediate flows; the trend is less conspicuous at high flows.

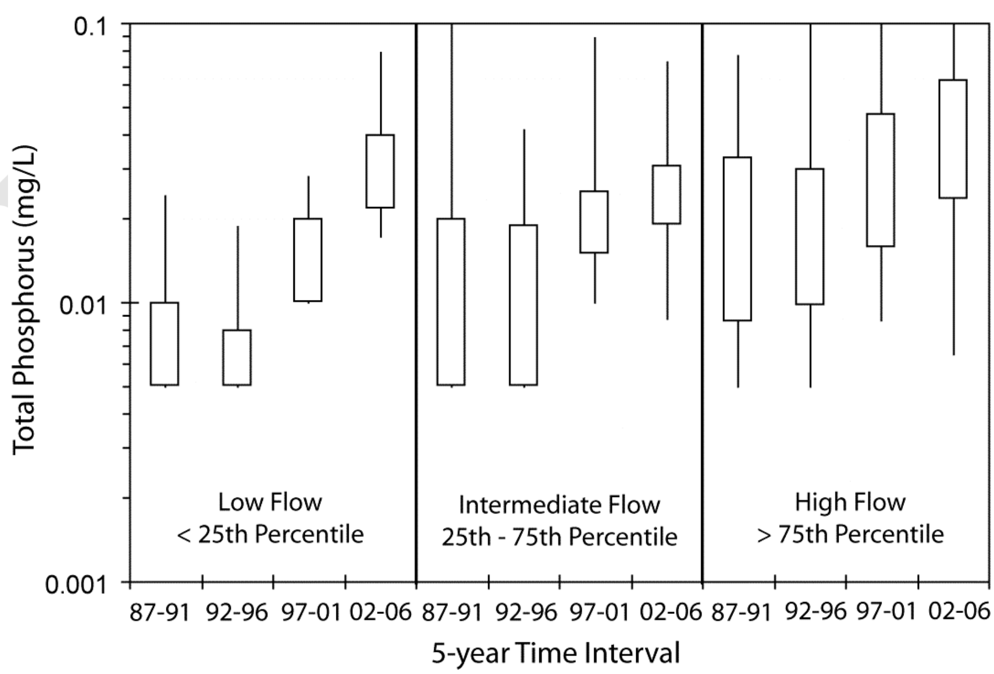

Figure 3. Five-year distributions of total phosphorus concentrations measured at low, intermediate and high flows in the South Platte River (Waterton) during each of four consecutive 5-y blocks. The box-and-whisker plots delineate the 95th, 75th, 25th, and 5th percentiles of the measured concentrations. The abscissa is truncated at the upper end (0.1 mg/L).

The proposed strategy for estimating annual loads from the South Platte is shaped by a desire to account for temporal patterns with flow quartiles. There is clear evidence for increasing concentration over time, but the effect is not equally prominent in all flow categories. In a relative sense, concentrations have increased most conspicuously in the low-flow category and least noticeably in the high-flow category. The trend over time and the association with flow must be incorporated into load calculations.

The entanglement of time and flow as factors affecting phosphorus concentration creates difficulties for estimating loads in large part because concentration is not measured frequently in any year. The monitoring program for Chatfield Reservoir is not deficient compared to other reservoir monitoring programs, but the overlay of a temporal trend on a system where flow and concentration are only weakly coupled is an unanticipated complication. The optimal approach in this case is to assume that all phosphorus concentrations from one flow category within one 5-y block are equally valid for calculating daily loads. This assumption leads directly to a methodology based on random sampling from each block-category combination.

The random sampling concept can be described using the low-flow category from the most recent time block (2002-2006). During that 5-y period, about one-third of the daily flows were less than the 25th percentile flow for the period of record. On days when flows were low, phosphorus concentrations were measured 27 times (i.e., about 4% of the relevant days). Assuming that each of the 27 measurements is equally valid as an estimate of the true concentration on any of these days, a concentration can be chosen at random for each day in the low flow category. The same process is applied to the other two flow categories for the 2002-2006 block, and to all three flow categories for the other three time blocks. Daily loads are then summed within each year. The entire sequence is repeated 100 times to establish a distribution of load estimates for each year.

The beauty of the methodology is that the sampling procedure can be repeated many times, yielding as many estimates of annual loads as one has the patience to produce. The value of the methodology is that it makes the best use of a relatively thin data set. Furthermore, the ability to produce a distribution characterizing loads in each year is especially useful for conveying uncertainty, which may influence management decisions.

Box-and-whisker plots show the distribution of annual phosphorus loads in the South Platte determined from 100 runs of the random sampling procedure (Figure 4). The methodology performs well in terms of hydrologic expectations; years characterized by a large range in flow (e.g., 1995) show higher variability in the load calculation while years with only small fluctuations in flow (e.g., 2002) show much lower variability in the load calculation. Median values for annual loads are given in Table 3.

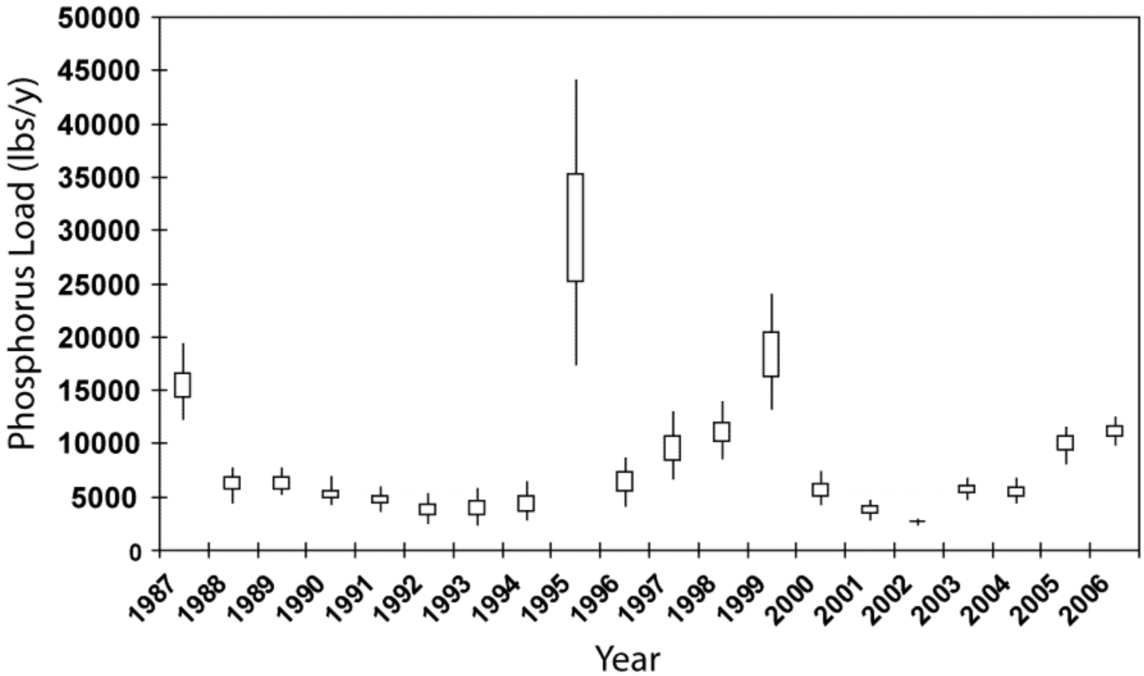

Figure 4. Annual phosphorus loads for the South Platte River (1987 – 2006) calculated by random sampling of the data aggregated in a time-and-flow framework. The box-and-whisker plots delineate the 95th, 75th, 25th, and 5th percentiles of the measured concentrations.

Application of Load Methodology to Plum Creek

Phosphorus concentrations and flow are not tightly coupled in Plum Creek, but the relationship between concentration and flow is stronger than in the South Platte (Figure 5). Uncertainty in the concentration-flow relationship makes the random sampling methodology attractive for computing annual phosphorus loads in Plum Creek, also.

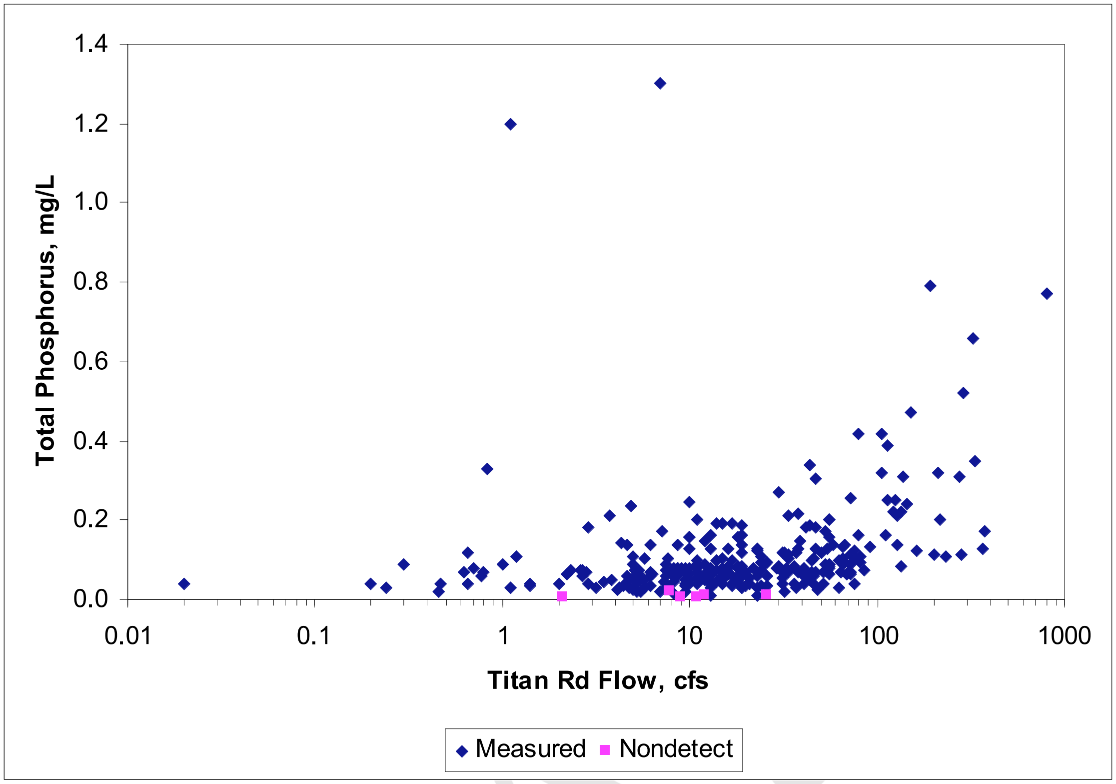

Figure 5. Relationship between total phosphorus concentration and stream flow (log scale) measured at the Titan Rd gage on Plum Creek. Nondetects are separated from other data points.

Phosphorus concentrations in Plum Creek do not show strong temporal trends, although concentrations are relatively high early in the record (1987, 1988; Figure 6). Years of relatively high phosphorus concentrations (e.g., 1987, 1988, 1998) tend to be years of relatively high flows (Figure 7), and thus may reflect the concentration-flow relationship rather than a temporal trend in phosphorus concentrations.

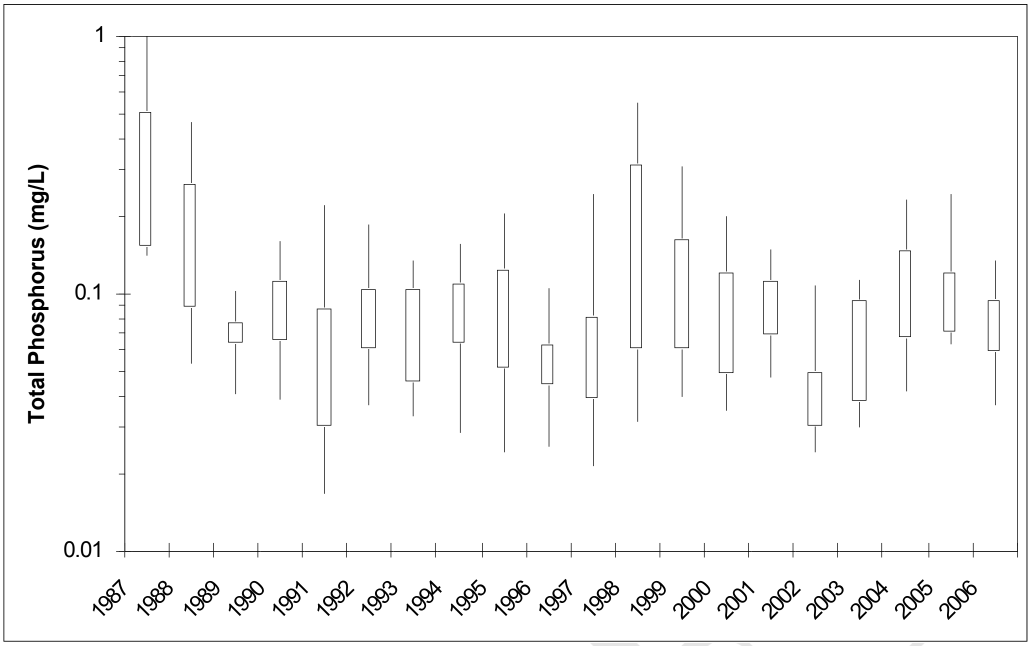

Figure 6. Inter-annual variability in phosphorus concentrations in Plum Creek at Titan Rd. The box-and-whisker plots delineate the 95th, 75th, 25th, and 5th percentiles of all phosphorus concentrations measured in each year.

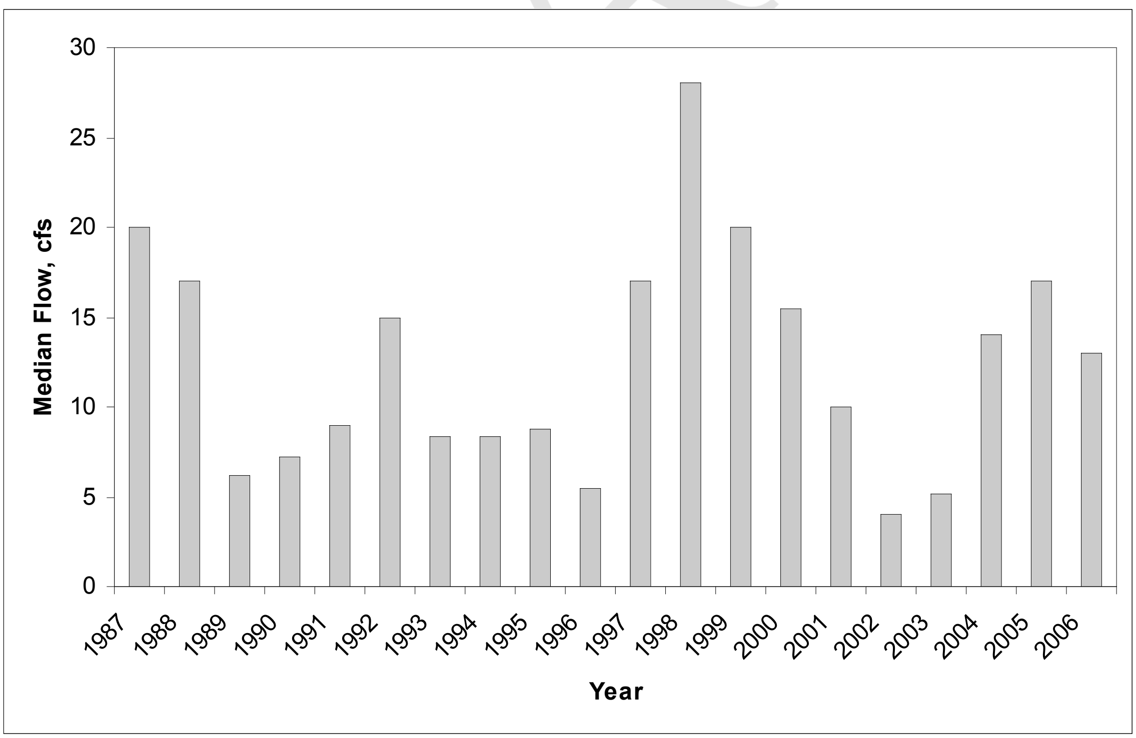

Figure 7. Annual median flows in Plum Creek, 1987-2006.

Given the variability of phosphorus concentrations at annual time-steps (Figure 6) and the relationship between concentration and flow (Figure 5), it is useful to evaluate temporal trends in phosphorus concentrations by the time-and-flow "normalization" procedure applied to the South Platte data. Phosphorus concentrations were aggregated into four blocks of five years each, beginning with the first complete year of record (1987). Within each block, phosphorus data were further segregated into groups of low (≤ 25th percentile, ≤ 4.4 cfs), intermediate (25th – 75th percentile, 4.4 – 24 cfs), and high flows (≥ 75th percentile, ≥ 24 cfs) based on the 20-y record of flows gaged at Titan Rd (1987 – 2006).

In Plum Creek, unlike the South Platte, there are no strong temporal trends in phosphorus concentrations in any flow category (Figure 8). High phosphorus concentrations early in the record (1987,1988) may skew phosphorus distributions upward in the first time block (1987-1991). The lack of a significant temporal trend in Plum Creek phosphorus concentrations is also supported by nonparametric Mann-Whitney tests (single comparison analogs to the Kruskal-Wallis test), which showed no significant differences between the first and last time blocks in any flow category. While there does not appear to be a temporal trend associated with phosphorus concentrations in Plum Creek, the relationship between phosphorus concentrations and flow is apparent especially in the high flow category.

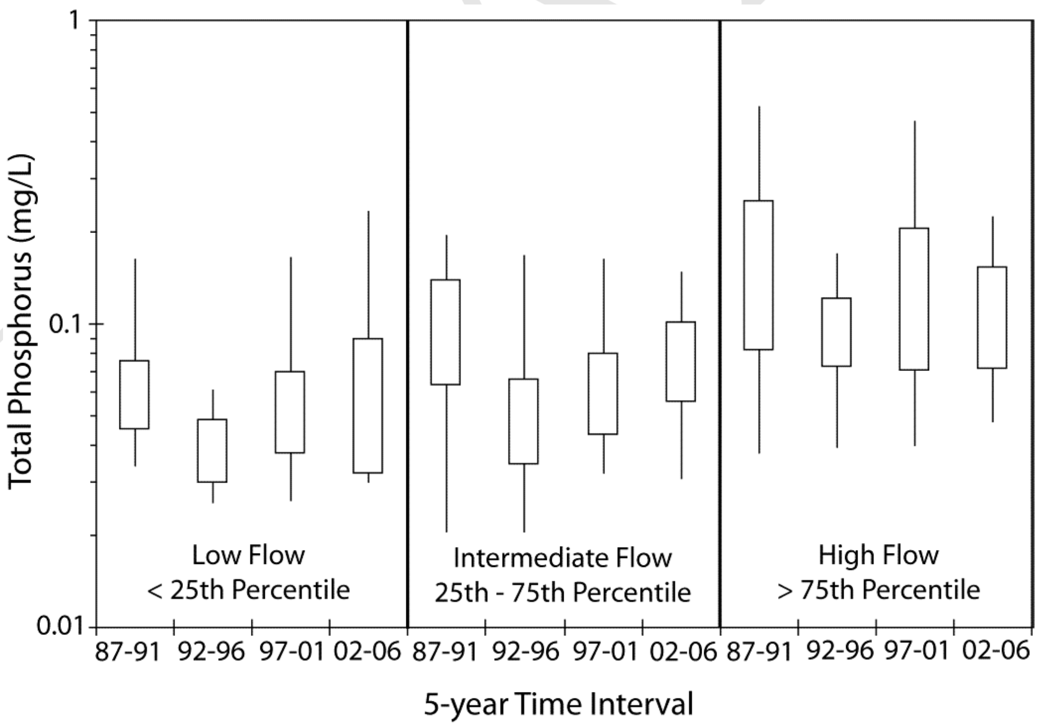

Figure 8. Five-year distributions of total phosphorus concentrations measured in Plum Creek (Titan Rd.) during low, intermediate, and high flows. The box-and-whisker plots delineate the 95th, 75th, 25th, and 5th percentiles of the measured concentrations. Nondetects were few (n = 8) and were excluded from analyses.

In Plum Creek, the relationship between flow and concentration is stronger than that in the South Platte, but the temporal trend in phosphorus concentration is weaker. The random sampling methodology developed for the South Platte, where variation related flow and time was addressed, can be adapted for application to Plum Creek by focusing solely on the role of flow. Phosphorus data from the entire period of record (1987-2006) were assigned to ten categories according to deciles of daily flows. Box-and-whisker plots show the distribution of annual phosphorus loads in the Plum Creek determined from 100 calculations made for each day of the flow record (1987 – 2006; Figure 9). Median values are shown in Table 5.

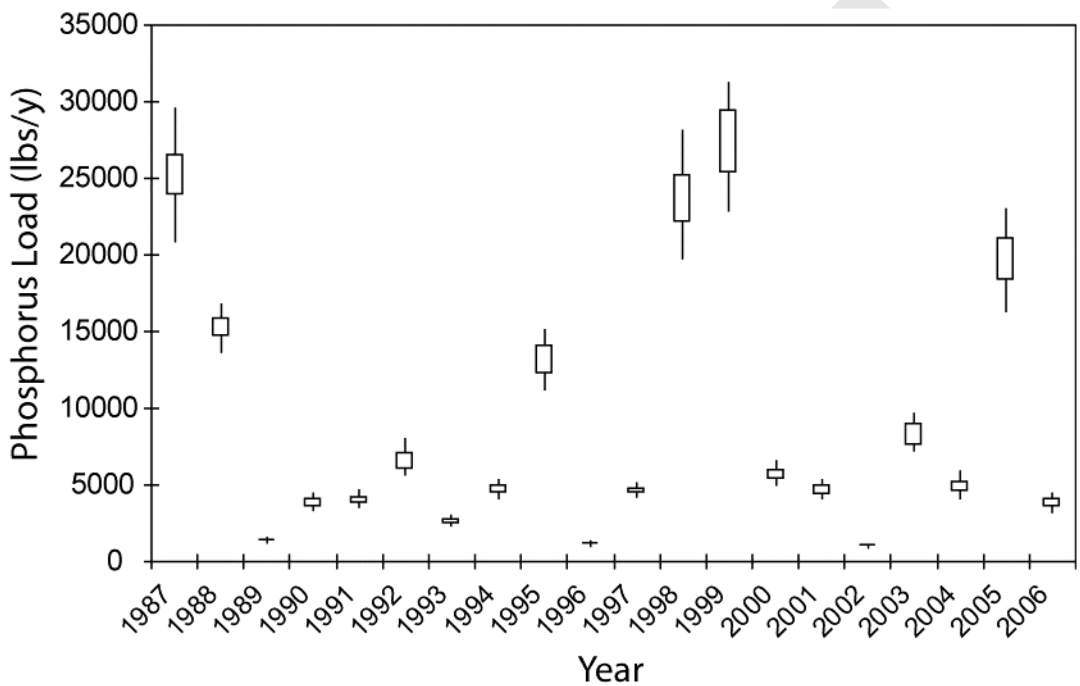

Figure 9. Annual phosphorus loads for Plum Creek (1987 – 2006) calculated by the random sampling methodology. The box-and-whisker plots delineate the 95th, 75th, 25th, and 5th percentiles of the measured concentrations.

Phosphorus from Precipitation

Bulk precipitation falling directly on the surface of the reservoir contributes a small amount of phosphorus. As described previously, the contribution of direct precipitation to total inflow is calculated as the product of the monthly precipitation and the computed mean monthly surface area for the reservoir. A monthly phosphorus load was computed by applying a phosphorus concentration for precipitation (0.087 mg/L; 1982 Clean Lakes Study) to the monthly inflow from direct precipitation. The sum of monthly loads provides the estimate of annual phosphorus load from direct precipitation (Table 3). Computed annual phosphorus loads from direct precipitation falling generally are small (317 – 634 lbs/y) relative to tributary sources (Table 3), diminishing potential concerns about the use of a single concentration value for all years. Sensitivity of the load estimate to different phosphorus concentrations could be evaluated by selecting different concentrations to use in the calculation (e.g., 0.155 mg/L applied previously to Cherry Creek Reservoir), but the small contribution of precipitation to the total annual inflow (Table 1) makes it unlikely that different concentrations will seriously influence the calculated distribution of phosphorus loads to Chatfield Reservoir.

Chatfield Alluvial Phosphorus

There is a substantial alluvium in the Plum Creek basin, and alluvial inflow makes a measurable contribution to the water budget of the reservoir (Table 1). Consequently, it is important to assign a phosphorus concentration for the purpose of calculating annual loads. Chemistry has been monitored in six alluvial wells along Plum Creek (Table 3). Samples were collected on 28 dates from 1990-2000. Not all sites were sampled on every date, and samples were not taken in every year. A summary of the total phosphorus data is given in Table 4.

Well	Location
1W	At Plum Creek WWTP
2W	Town of Sedalia cistern
3W	Town of Castle Rock well at Douglas County fairgrounds
4W	Residential well on Airport Rd SW of Louviers – Flying C Ranch
5W	Residential well west of Louviers
6W	Plum Creek stables on Titan Rd

Table 3. Monitoring wells located along the Plum Creek alluvium.

Date	1W	2W	3W	4W	5W	6W
6-Jul-90	0.105	0.061	0.061			
30-Aug-90	0.102	0.066				
28-Sep-90	0.115	0.067	0.071	0.012	0.051	*0.005*
13-Nov-90	0.037	0.067	0.171	*0.005*	*0.005*	*0.005*
18-Dec-90	0.123	0.067	0.019	0.052	*0.005*	*0.005*
4-Apr-91	0.060	0.100	0.090	0.010	0.010	*0.005*
12-Jun-91	0.040	0.140	0.080			0.030
4-Sep-91	0.084	0.059	0.046	0.051	0.028	0.028
6-Dec-91	0.108	0.059	0.011	0.029	0.060	0.007
19-Feb-92	0.092	0.121	0.074	*0.005*	0.029	*0.005*
27-May-92	0.114	0.071	0.036	*0.005*	0.023	*0.005*
26-Aug-92	0.120	0.067	0.028	0.020	*0.005*	0.041
16-Nov-92	0.750	0.109	0.059	0.010	0.024	*0.005*
17-Feb-93	0.053	0.126	0.074		0.032	*0.005*
1-Nov-93	0.124	0.076		*0.005*	0.025	*0.005*
15-Jun-95	0.016	0.137	0.059		0.003	
8-Apr-98	0.130	0.050	0.230	*0.010*	0.020	
23-Apr-98	0.100	0.040	0.160	*0.010*	*0.010*	
13-May-98	0.100	0.050	0.280	*0.010*	0.010	

Date	1W	2W	3W	4W	5W	6W
27-May-98	0.100	0.040	0.340	*0.010*	0.010	
10-Jun-98	0.080	0.020	0.250	*0.010*	0.010	
24-Jun-98	0.090	0.070	0.500	0.050	0.060	
5-Apr-00	0.200	0.040	0.330	0.010	0.020	
25-Apr-00	0.200	0.040	0.310	0.010	0.020	
3-May-00	0.140	0.060	0.320		0.020	
24-May-00	0.130	0.140	0.380		0.030	
7-Jun-00	0.110	0.050	0.340	0.020	0.020	
21-Jun-00	0.150	0.060	0.220		0.010	
Median	**0.107**	**0.067**	**0.125**	**0.010**	**0.020**	**0.005**

Table 4. Summary of total phosphorus concentrations (mg/L) measured in alluvial monitoring wells along Plum Creek. Values less than the MDL are shown in italics.

There is considerable spatial variation among the sites (Figure 10). In general, the sites more distant from the reservoir (1W, 2W, and 3W) have higher phosphorus concentrations than those that are closer to the reservoir (4W, 5W, and 6W). Although the basis for the pattern is not understood at this time, it may be related to the fact that the more distant sites are really in the alluvium of East Plum Creek. It is assumed that the chemistry of the sites closer to the reservoir is more likely to be representative of the alluvial inflow.

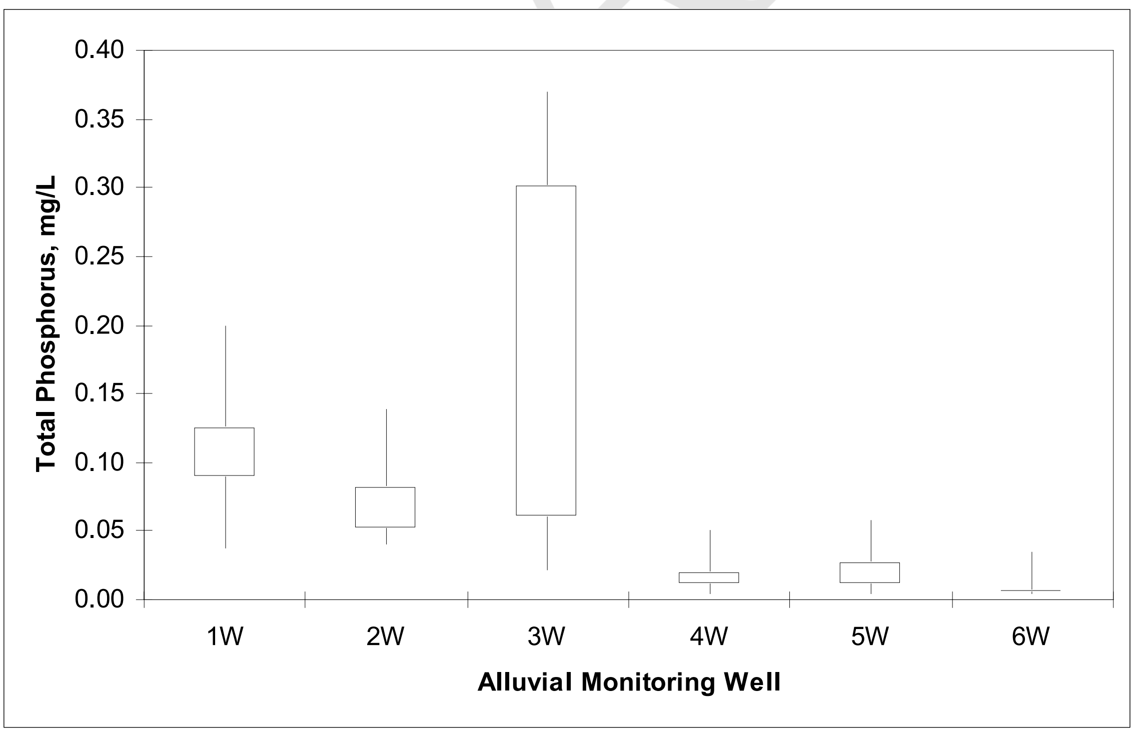

Figure 10. Box-and-whisker plots summarizing total phosphorus concentrations measured in alluvial monitoring wells along Plum Creek. Each box shows the range for the central 50% of the data (i.e., between the 25th and 75th percentiles). The tips of the whiskers indicate the 5th and 95th percentile concentrations.

Phosphorus concentrations in the alluvium should be relatively stable, based on extensive experience with the nearby Cherry Creek alluvium. Thus, a median concentration is likely to provide the best for estimating loads. Ordinarily, one would select the median from the well that is closest to the reservoir, but the very short record for site 6W diminishes its suitability. Sites 4W and 5W, both of which are near Louviers, are close enough to be suitable. The data from these two sites were aggregated, and the median concentration of the combined set is 0.010 mg/L.

The Clean Lakes study provides some perspective on the concentration of phosphorus in groundwater. In 1982, the estimated contribution of phosphorus to annual load for Chatfield was given as 1170 lbs, and the associated flow was 12370 AF. The flow-weighted concentration derived from the load data is 0.034 mg/L. According to the report, the load estimate is based on measured concentrations, but the raw data have not been located. While 0.034 mg/L is higher than the median of sites 4W and 5W, it is within the range of the measured values (ca. 90th percentile).

The concentration proposed for use in the present technical review is the 0.010 mg/L value derived from recent data. It is based on a large number of measurements taken from known locations. If the alluvial component proves to be a significant concern, the appropriate choice for concentration can be revisited through sensitivity analysis or collection of additional data.

Alluvial inflow generally is relatively constant from year to year, and calculation of alluvial inflow at time-steps shorter than five years is unlikely to contribute much resolution to estimates of P load from alluvial sources. When the value for phosphorus concentration derived above (0.010 mg/L) is applied to annual calculations of alluvial inflow to Chatfield Reservoir, the resultant estimate of the annual phosphorus load (127 – 185 lbs/y) from alluvial sources is small relative to tributary sources. Once again, other concentrations could be used to evaluate the effect on load calculations.

Phosphorus from Ungaged Sources

The “ungaged” component is intended to represent contributions from small tributaries and direct surface runoff, but this is not strictly true as explained in the document describing the water budget. For convenience in balancing the water budget, this component also absorbs any unexplained flow residual. Nevertheless, it will be viewed as the ungaged surface contribution in terms of setting the phosphorus concentration.

There are a few measurements of phosphorus concentrations in the ungaged tributaries (e.g., Massey Draw, Deer Creek), but not enough to support annual load calculations. An alternative approach is proposed whereby this component simply augments the contribution from Plum Creek. The ungaged contribution to the water budget is assumed to have a flow-weighted phosphorus concentration matching that of Plum Creek. For example, if the computed annual inflow from ungaged areas is 20% of the gaged annual inflow from Plum Creek, the annual phosphorus load from ungaged areas is calculated as 20% of the computed annual phosphorus load for Plum Creek. The phosphorus load attributed to ungaged areas could be further segregated based on proportion of the total ungaged area comprised by each ungaged watershed (e.g., Massey Draw, Deer Creek), but this would not improve the resolution of the phosphorus load unless a basis is established for ascribing different phosphorus concentrations to each ungaged area.

Annual Loads and Partitioning of Phosphorus Sources to Chatfield Reservoir

The contributions of the various flow sources to the annual phosphorus load are summarized in Table 5. The construction of the table follows the pattern of components established in the water budget analysis. It is surprising how often the contribution from Plum Creek exceeds that from the South Platte (10 of 20 years). The explanation is plain from the discharge-weighted concentrations, which are about four times greater in Plum Creek than in the South Platte.

	Annual Phosphorus Load (lbs/y)						
Year	**South Platte**	**Plum Creek (Gaged)**	**Plum Creek (Adjusted)**	**Alluvium**	**Precipitation**	**"Ungaged"**	**Total**
1987	15,255	25,039	25,039	127	608	5,236	46,265
1988	6,143	15,348	15,348	127	397	5,119	27,134
1989	6,081	1,374	1,374	127	418	1,008	9,008
1990	5,076	3,818	3,331	127	404	0	8,938
1991	4,791	3,981	3,981	127	494	644	10,037
1992	3,800	6,542	6,542	170	410	2,186	13,108
1993	3,882	2,600	2,600	170	460	1,102	8,214
1994	4,278	4,716	4,716	170	398	526	10,088
1995	29,558	13,076	13,076	170	619	4,858	48,281
1996	6,344	1,132	1,132	170	423	693	8,762
1997	9,223	4,583	3,884	169	634	0	13,910
1998	11,019	23,868	23,868	169	442	3,935	39,433
1999	18,316	27,716	25,402	169	565	0	44,452
2000	5,487	5,711	5,711	169	466	265	12,097
2001	3,585	4,692	4,692	169	396	573	9,415
2002	2,639	1,006	404	185	317	0	3,545
2003	5,599	8,373	7,336	185	453	0	13,573
2004	5,362	4,864	4,864	185	550	718	11,679
2005	9,962	19,441	13,900	185	471	0	24,518
2006	11,018	3,841	1,279	185	431	0	12,913

Table 5. Annual phosphorus loads from all sources of inflow to Chatfield Reservoir. The ungaged component is affected by adjustments to flow made to balance the water budget (see text). Plum Creek phosphorus loads are calculated first for gaged inflows, but may be adjusted downward as required to reconcile the reservoir water balance. The annual phosphorus load to the reservoir is the total of the South Platte, Adjusted Plum Creek, Alluvium, Precipitation, and Ungaged contributions.

The relative importance of phosphorus sources can be gaged from averages over the period of record (Table 6 and Figure 11). The total annual phosphorus load to Chatfield Reservoir is dominated by the South Platte River and Plum Creek, with only a small portion coming from ungaged areas, alluvial sources, and direct precipitation.

Source	**Average Annual Phosphorus Load (lbs/y)**
South Platte River	8,371
Plum Creek	8,424
Ungaged Runoff	163
Plum Creek Alluvium	1,307
Direct Precipitation	468
Total	18,769

Table 6. Average annual phosphorus budget for Chatfield Reservoir (1987 – 2006).

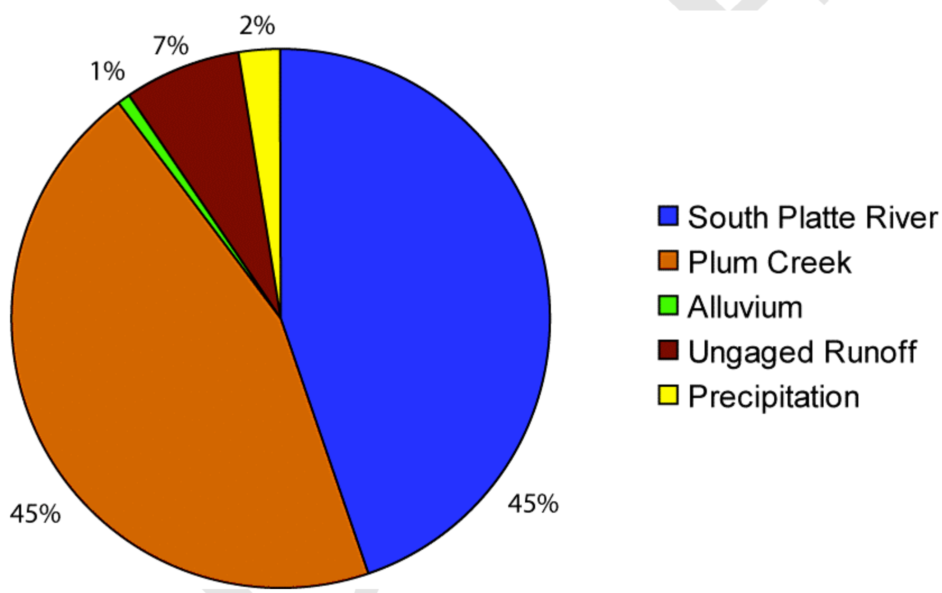

Figure 11. Average annual phosphorus inflow budget for Chatfield Reservoir (1987 – 2006).

Comparison of New Phosphorus Loads with Previous Load Estimates

Because a new methodology has been employed for calculating loads to Chatfield Reservoir, it invites comparison with previous estimates (as recorded on the 'Loading Trends' tab of the 'Chatfield Master Data 2006.xls' file on the Authority's web site). Although some differences are expected because the computational approaches are not the same, the same general patterns are expected because the same flows and concentrations have been used.

In general, the random sampling method provides higher estimates of annual load for the South Platte (Figure 12), but generally similar results for Plum Creek (Figure 13). Estimates of total load show considerable scatter, but no obvious bias (Figure 14); the scatter is expected since the total load is little more than the sum of the two main tributaries.

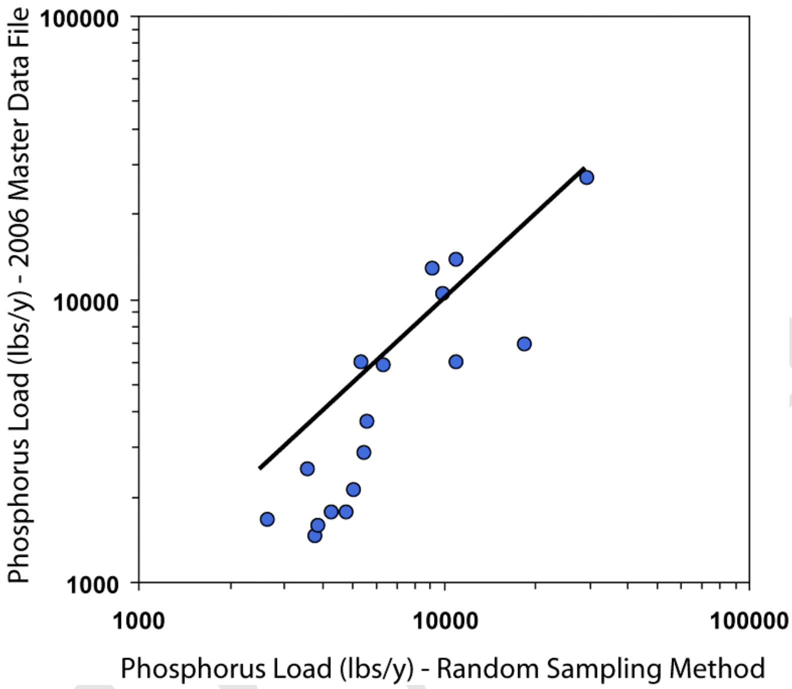

Figure 12. Annual phosphorus loads for the South Platte River (1990 – 2006) obtained from the 2006 Master Data File, Chatfield Watershed Authority website, and from the random sampling protocol applied to a 5-y time-and-flow data aggregation framework. The solid line represents the line of equivalency.

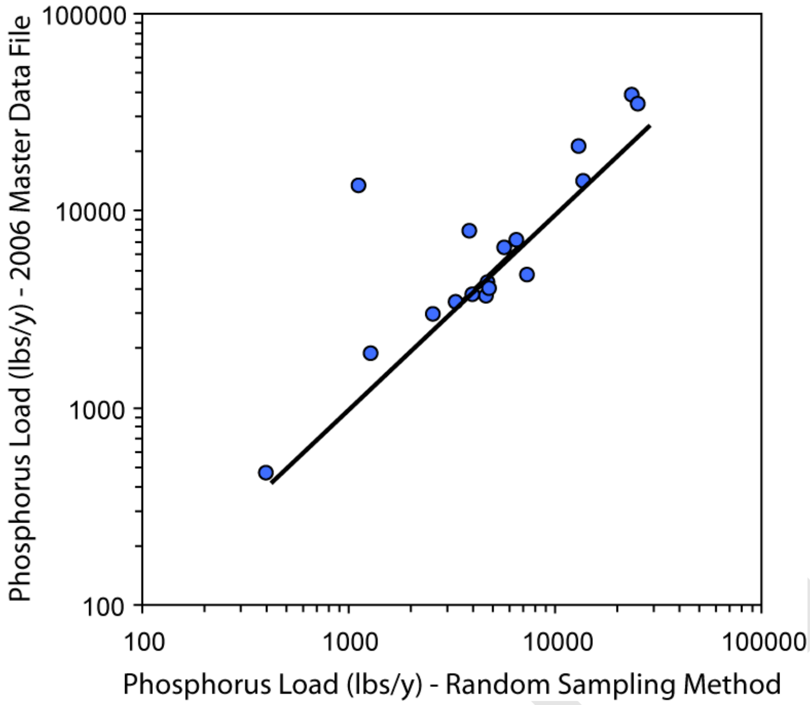

Figure 13. Annual phosphorus loads for Plum Creek (1990 – 2006) obtained from the 2006 Master Data File, Chatfield Watershed Authority website, and from the random sampling load methodology. The solid line represents the line of equivalency.

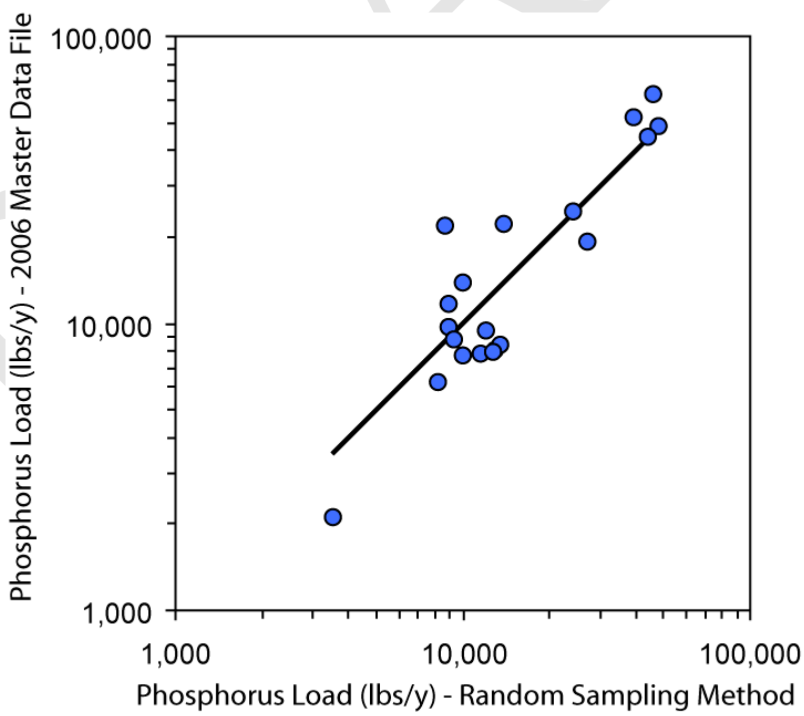

Figure 14. Annual phosphorus loads to Chatfield Reservoir (1987 – 2006) obtained from the 2006 Master Data File, Chatfield Watershed Authority website, and from the random sampling load methodology. The solid line represents the line of equivalency.

The random sampling methodology is a relatively robust approach in that it incorporates variability in concentration without making assumptions about the underlying distribution (as would be required with a regression-based approach). Additionally, the method provides a distribution of probable loads, which is useful in a management context, but which has not been available previously. Moreover, the new methodology is more complete in terms of incorporating all likely sources of phosphorus including ungaged areas, precipitation, and the alluvium.