Bear Creek Reservoir Annual Water Budget

Overview

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

The water balance for Bear Creek Reservoir is built on the assumption that the USACE computed inflow is accurate, and that the sum of all component sources must equal the computed inflow exactly. The assumption makes it possible to use residuals to estimate components, such as ungaged surface runoff, that are not measured directly. It is important throughout the development of the water budget to keep in mind that the objective is to use the hydrologic data to provide a solid foundation for the estimation of phosphorus loads, and not to develop the "perfect" water budget.

Data Sources for Surface Flows

The USACE has maintained records on reservoir operations since July 1977, although the reservoir was not brought to multi-purpose pool level until 1979. The elevation and outflow are measured on a daily basis, making it possible to calculate change in storage and the computed inflow (with assumptions about evaporation). The computed inflow represents the sum of contributions from tributaries, direct surface runoff, direct precipitation, and any groundwater flow. Daily operations records were provided by the USACE.

There are two major tributaries to the reservoir – Bear Creek and Turkey Creek, which account for most of the watershed drained by the reservoir. Depending on gage location, only 4-6% of the watershed is ungaged (Table 1). The three gages on Turkey Creek represent very similar drainage areas, but the two upstream locations do not measure releases from Soda Lakes that may send a few hundred AF annually to the reservoir as part of exchanges executed by Denver Water Department.

Name	Gage Number	Area, mi2	POR 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.

Flows in Bear Creek have been measured at the Sheridan gage for many years, and those records can be compared with reservoir outflows as a check on internal consistency. A gage just above the reservoir was added in 1986, and it provides information of central importance to the water budget. 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 computed inflows shows that it contributed about 75% of the inflow in most years (Figure 1). It appears to comprise a larger percentage in the few years when flows were very high (>30,000 AF/y in Bear Creek), and these high flow years deserve more attention because of the implications for flow residuals as explained below. In addition, one year (1996) is very unusual in that the flow measured in Bear Creek is substantially larger than the computed inflow; it too deserves further comment.

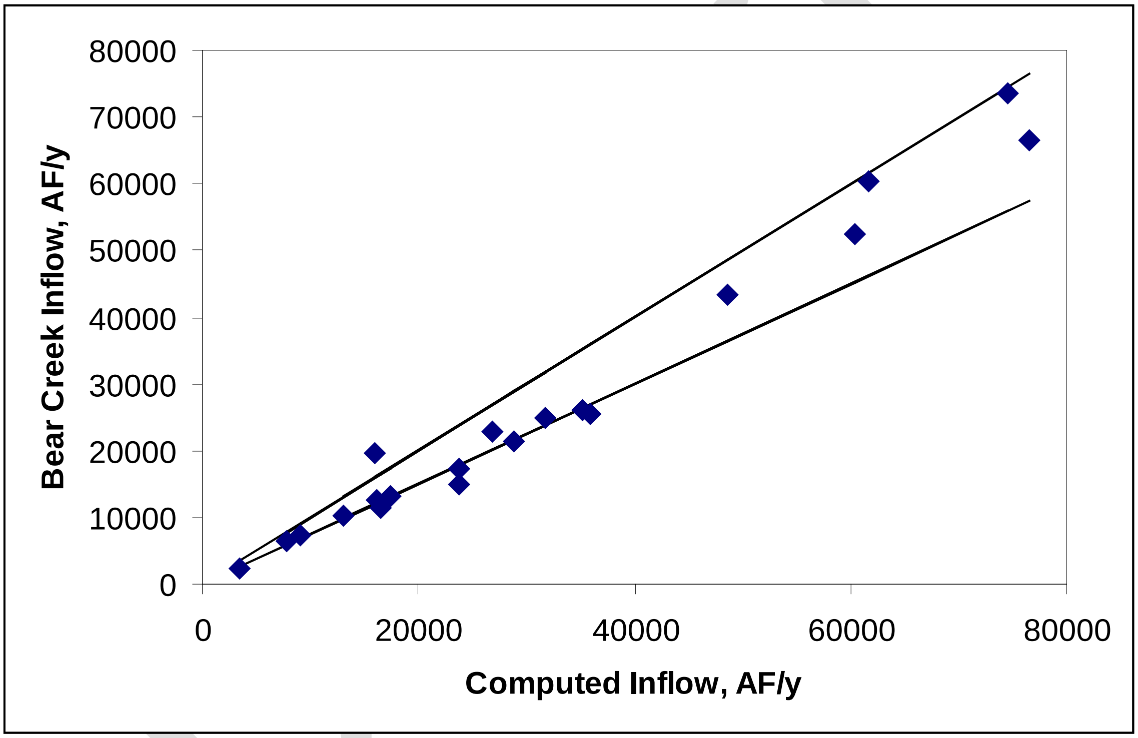

Figure 1. Annual inflows from Bear Creek plotted against the computed inflow to the reservoir. The two lines represent the contribution expected if Bear Creek represented exactly 75% of the computed inflow (lower line) or matched the computed inflow (upper line).

One way to diagnose potential problems in the high-flow years is to examine consistency among data sources. For example, the computed inflow should be perfectly correlated with the outflow because they are linked through calculation, and the data show the expected relationship (Figure 2). The slope is unity and the intercept (322 AF/y) is small enough to be close to the value expected for evaporation. The internal consistency is reassuring.

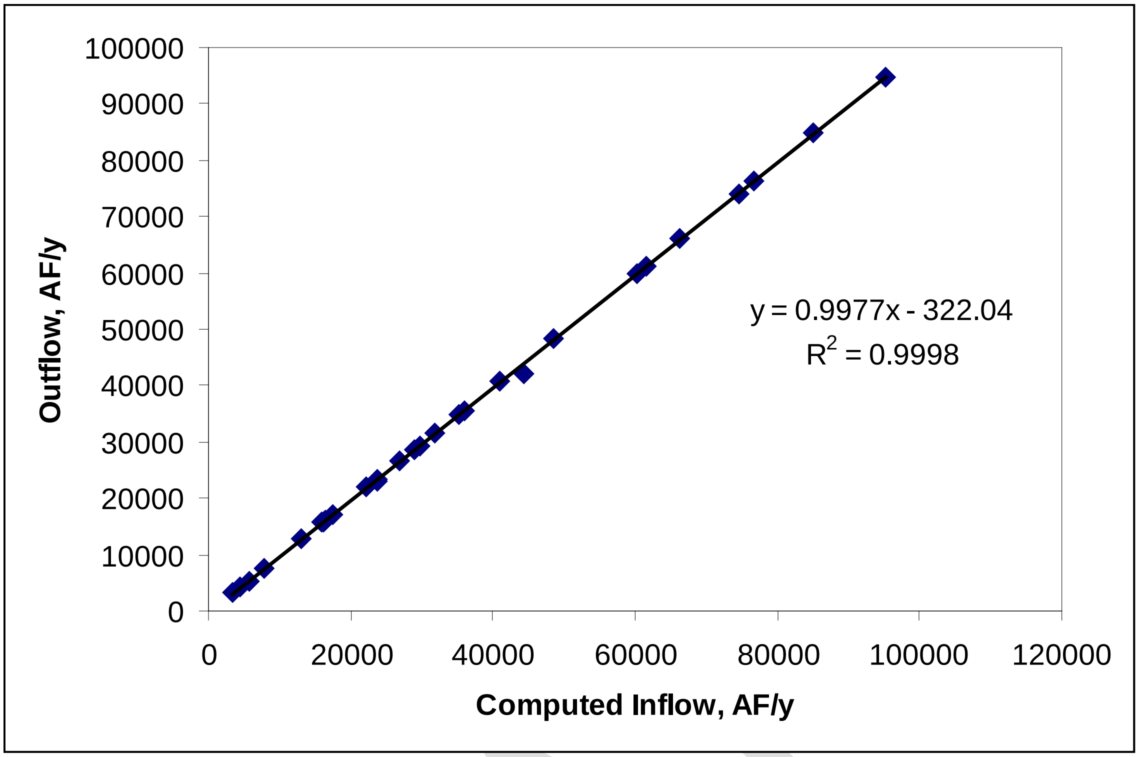

Figure 2. Comparison of measured outflow with computed inflow to Bear Creek Reservoir. Perfect agreement is expected because the inflow is computed from the outflow (with adjustments for evaporation, precipitation, and change in storage). Data from USACE, 1978-2005.

A second check on consistency is based on a comparison of the USACE outflow with flows measured at the Sheridan gage downstream. The two should agree well because there are no major sources in between, and the watershed area is increased by only about 10%. This comparison is based on monthly flows (Figure 3). The Sheridan gage records flows tend to be at least 10% higher than the reservoir outflow. When releases fall below 1000 AF/month (ca. 17 cfs), flows at Sheridan appear to be sustained by other sources, showing a baseline level in the vicinity of 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 unrealistically small – only 10-15% of the flow at Sheridan. Clearly, there was a measurement problem of some kind in 1996 that will require special handling for estimating phosphorus loads.

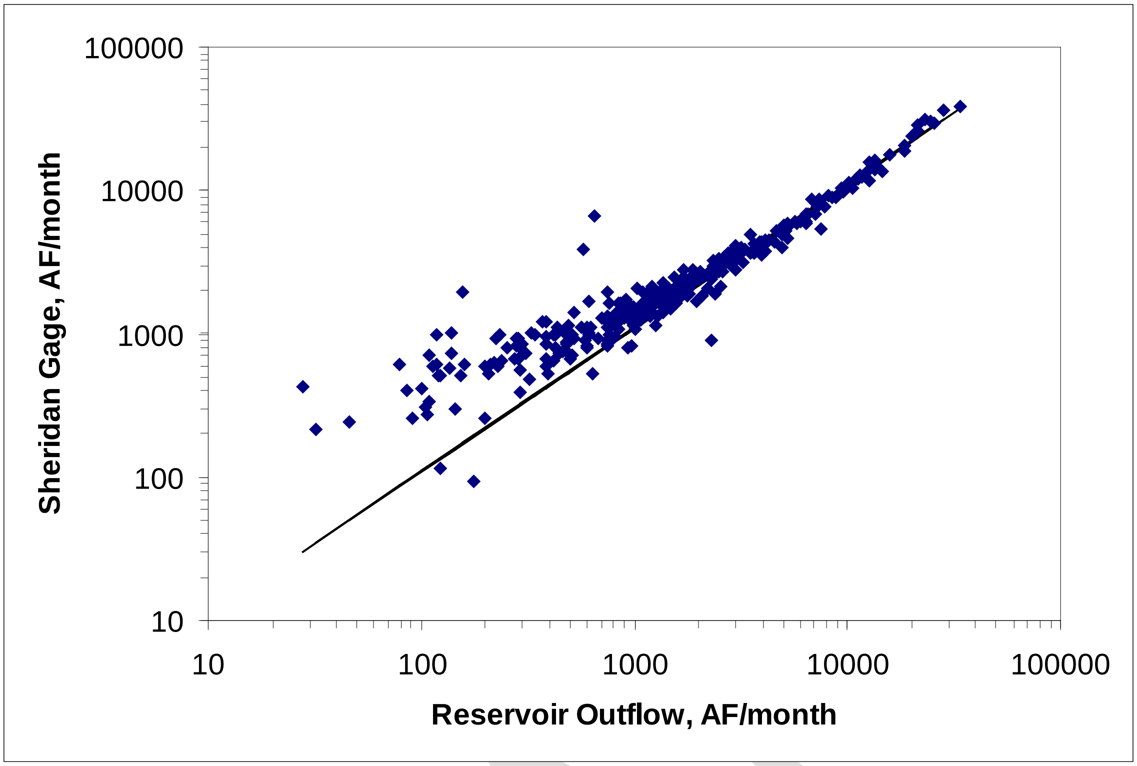

Figure 3. Monthly flows measured at the Sheridan gage as a function of releases from Bear Creek Reservoir for the period Jan-1978 through Dec-2005. The line is 1.1 times the outflow.

Precipitation

Precipitation falling directly on the surface of Bear Creek Reservoir calculated based on monthly records for the National Weather Service Cooperative Network Station at Lakewood (054762), as reported through the Western Regional Climate Center (http://www.wrcc.dri.edu). The volumetric contribution of direct precipitation was estimated in each month as the product of the total precipitation (inches/month) and the surface area of the reservoir at the average elevation for the month. An exponential relationship was fit to elevation and surface area based on data provided by the USACE for the elevation range of interest (5550 – 5580 ft AMSL):

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

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

Parsing the Other Flow Sources

Records spanning the full period of water quality sampling exist for two flow sources – Bear Creek and precipitation – and for the total inflow as computed by the USACE (with the possible exception of 1996). A residual, including flows from Turkey Creek, ungaged portions of the watershed, and any groundwater inflow, can be calculated for each year as follows:

$$Residual = Inflow_{USACE} – (Inflow_{Bear\ Cr.} + Precipitation).$$

Variation among years is expected, but the residual shows some unusual features (Figure 4). It is immediately apparent that 1996 is unusual because the residual is negative; as indicated previously, there is reason to question the flows reported in the fall of 1996, and thus to exclude that year from calculation of loads and other analyses related to the water budget. In general, the residuals tend to increase with increasing inflow, but a few years (1987 and 1995 in particular) do not show this expected pattern.

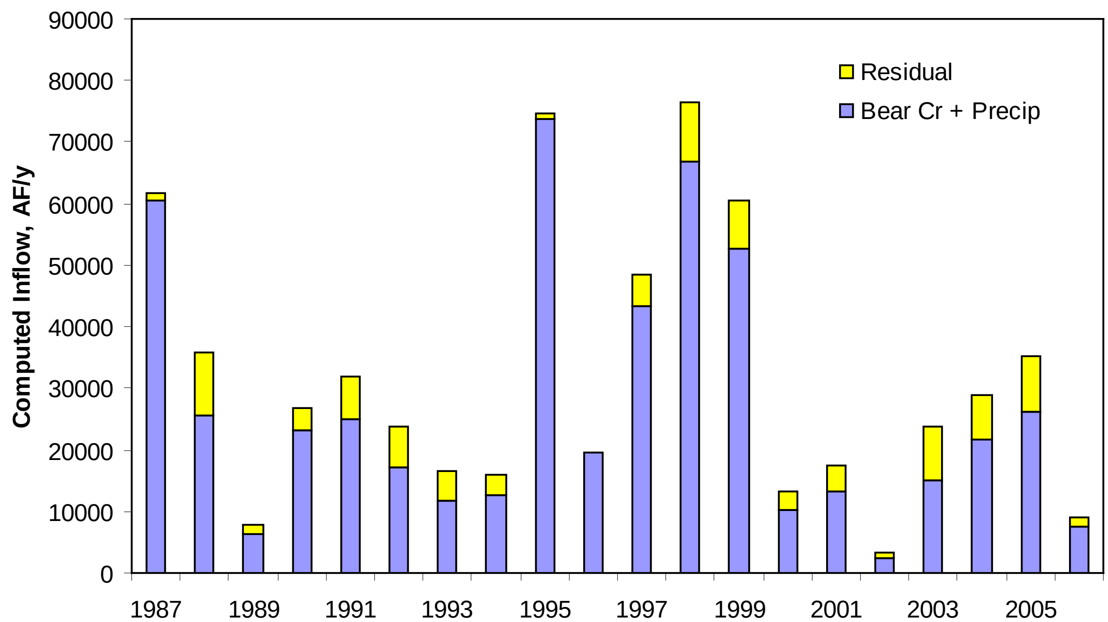

Figure 4. Computed inflow separated into measured and residual components. Contributions from Bear Creek and precipitation were measured in all years. The residual includes Turkey Creek, ungaged portions of the watershed, and any groundwater inflow. Note that the residual is negative in 1996 (see text).

The residual tends to be about 30% of the flow in Bear Creek, as long as the Bear Creek flow is less than about 30,000 AF/y (Figure 5). In the five years (1987, 1995, 1997-99) when Bear Creek flows were higher than 30,000 AF/y, the residual is unpredictable. For some years, another step can be taken to parse the residual. Flows in Turkey Creek were gaged in some, but not all, years in the period of record. The gage has been operated at three different locations, and this is important mainly with respect to the operation of Soda Lakes for exchanges. Records of the exchanges were made available by DWD through 1998, and these data help determine the amount and timing of those releases that entered the stream below the gages that have been operated since 1999.

If the residual were attributable entirely to Turkey Creek and the ungaged surface flows (i.e., there was no groundwater contribution), it would be logical to expect a strong correlation between the residual and flows measured in Turkey Creek, which are available for 10 of the 20 years being analyzed (1987-88, 1999-2006). If the two years with very high flow in Bear Creek are excluded (for reasons explained above), there is a very strong relationship between the residual and the measured Turkey Creek flow

(Figure 6). The slope suggests that the residual is due mainly to ungaged areas, which are about 20% of the area above the Turkey Creek gage. That the slope is 1.13 instead of 1.20 may be the result of the ungaged areas being at lower elevation. The intercept of 700 AF is within the range, but somewhat larger than, the flow expected for exchanges from Soda Lakes (median 276; range 0-920 AF). The presence of a small alluvial contribution also is a possibility, as suggested in the Clean Lakes Study, but it is not possible to parse the residual any further with the data presently available.

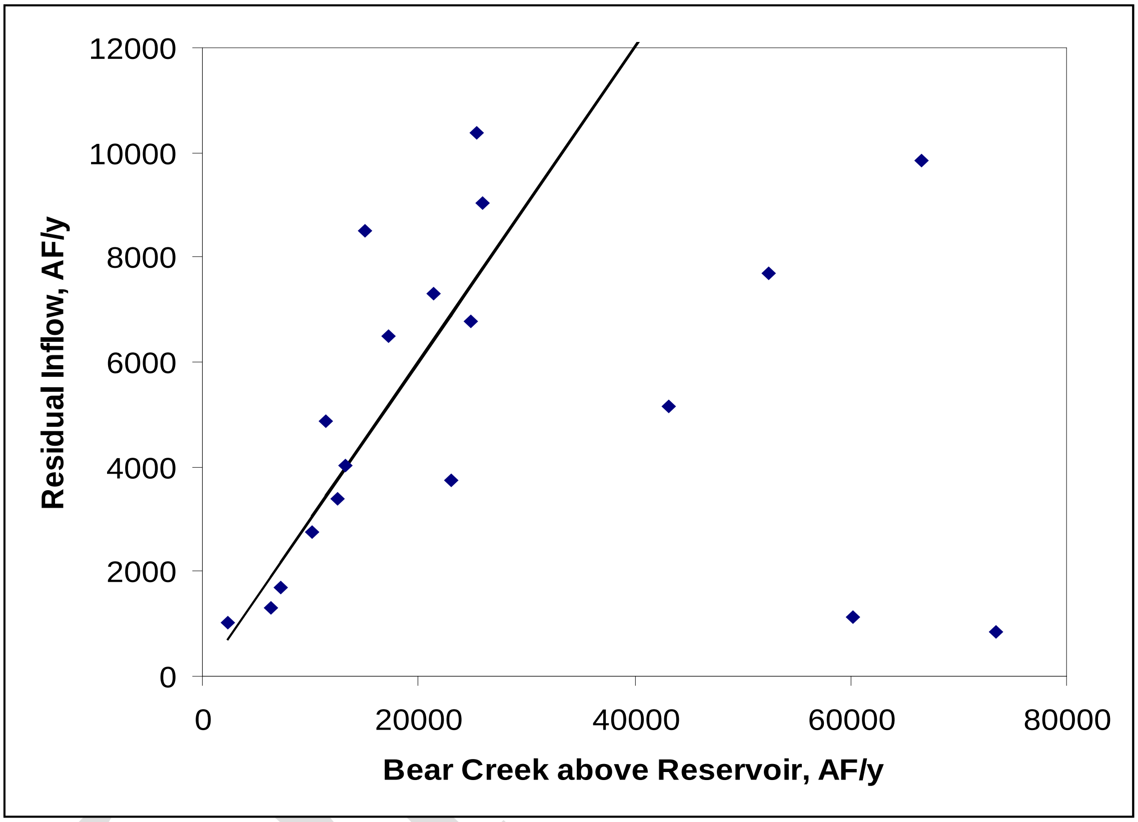

Figure 5. Residual inflows (computed minus Bear Creek and precipitation) as a function of flows measured in Bear Creek. The line represents 1.3 times the Bear Creek inflow (see text).

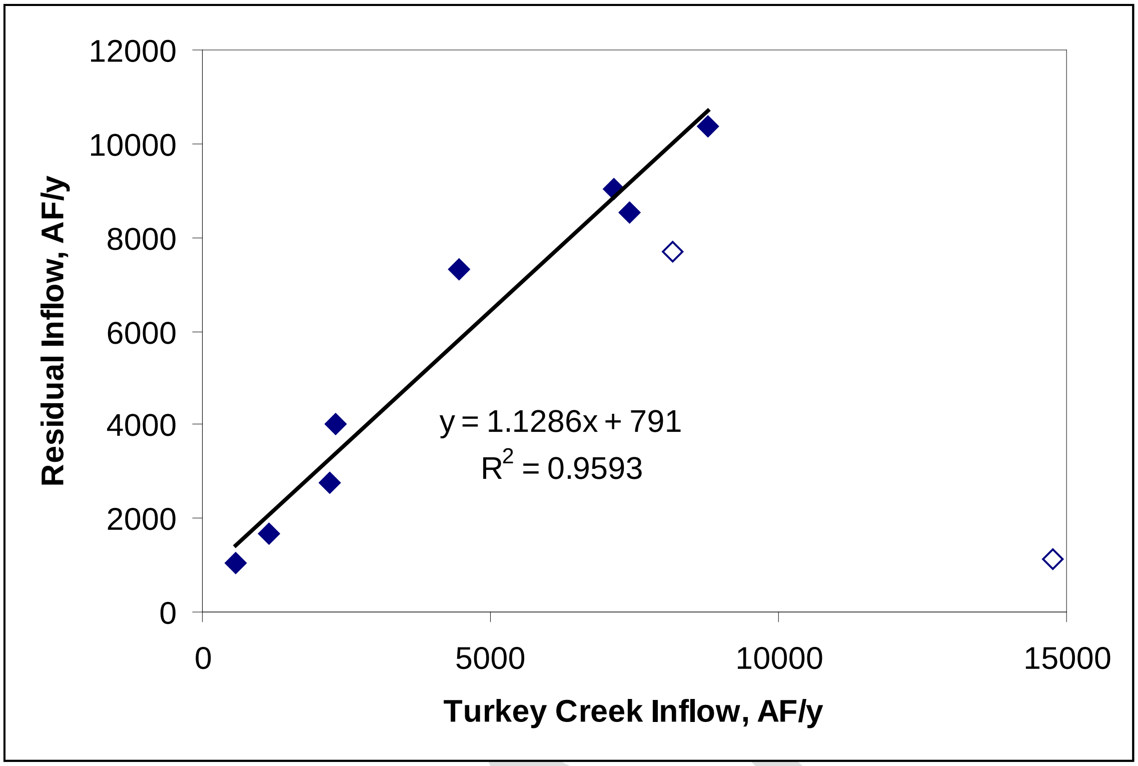

Figure 6. Relationship between inflow residuals and flows measured in Turkey Creek. Data are available from 1987-88 and 1999-2006, but data from 1987 and 1999 (shown as open symbols) have been excluded from the line for reasons explained in the text.

Constructing the Water Budget

The foundation of the water budget is the computed inflow, for which the median was 25,315 AF/y. The median contribution from Bear Creek (20,439 AF/y) represents about 80% of the computed inflow, and the median contribution from precipitation (153 AF/y) represents only 1% (Figure 7). Medians are used to circumvent as much as possible the aforementioned problems associated with certain years (1987, 1995-1999). The residual is parsed on two assumptions: 1) it consists entirely of surface inflows from Turkey Creek and ungaged areas, and 2) the ungaged component is 13% of the Turkey Creek component (as explained previously). The typical contribution from Turkey Creek is 17% (4180 AF/y), leaving 2% (543 AF/y) from ungaged sources. It is reassuring that only 2% of the water budget is associated with flows for which no phosphorus concentrations were measured.

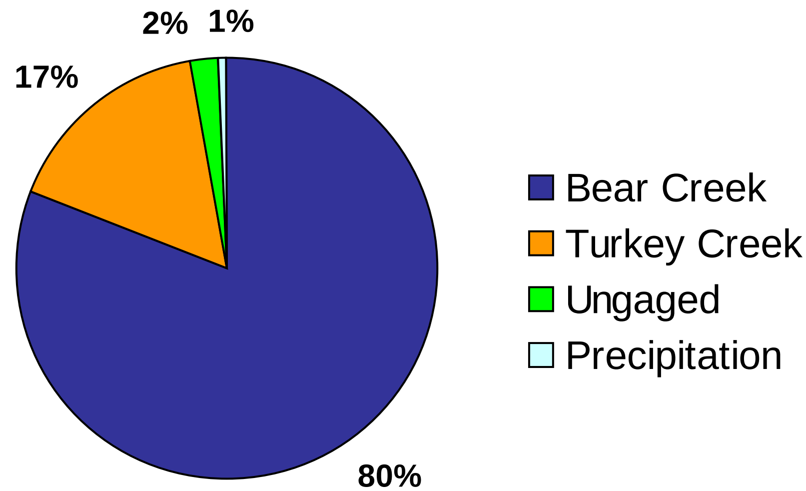

Figure 7. Major components of the water budget for Bear Creek Reservoir. See text for explanation.

The broader aim of the water budget analysis is to produce a set of parsed flows in every year to support calculation of phosphorus loads. Several assumptions are necessary in order to account for problems identified in some years. The first assumption is that precipitation data are acceptable as measured in all years.

The second assumption is that the USACE computed inflow is accurate except in 1996 (as discussed previously). In 1996, the computed inflow was too low to account for even the measured flow sources. An adjustment to the computed inflow is proposed on the basis of the strong relationship between the outflow and the Sheridan gage. In 1996, the flow measured at the Sheridan gage was 31,731 AF/y. There are two years with very similar flows – 1990 (32,672 AF) and 2004 (32,847 AF); the corresponding outflows were 26,575 AF and 28,526 AF, and the corresponding computed inflows were 26,850 AF and 28,891 AF. Clearly these are much higher than the USACE computed inflow of 16,000 AF as reported in the original data. For the purpose of developing phosphorus loads, the average of values from 1990 and 2004 will be substituted for the computed inflow reported in 1996 (Table 2).

A third assumption is needed regarding the very high inflows (>30,000 AF/y) reported for Bear Creek for 1987, 1995, and 1997-99. They are atypically high with respect to the computed inflow, and a comparison of the outflow with the Sheridan gage shows nothing unusual. An adjustment is proposed for those years whereby the Bear Creek inflow is restricted to 80% of the computed inflow to be more consistent with conditions observed in other years.

A fourth assumption is used to estimate Turkey Creek inflows in all years. Although gage records exist for half of the years, almost all of these were measured at locations some distance from the reservoir. The distance is important not so much for differences in watershed area, but for the possibility that water management actions (e.g., Soda Lakes exchange) could alter the amount of water actually reaching the reservoir. The proposal is to parse the revised residual (after applying adjustments described under assumptions two and three above) between Turkey Creek and ungaged watershed areas. Parsing is based on the assumption that the ungaged component is 13% of Turkey Creek flows and that there is no alluvial component.

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 2. Parsing of flows (AF/y) for Bear Creek Reservoir in preparation for estimation of phosphorus loads. Significant adjustments were made to the computed inflow in 1996, and the Bear Creek flows in 1987, 1995, and 1997-99. See text for explanation.