Review and Analysis of Hydrologic Information

on Cherry Creek Watershed and Cherry Creek Reservoir

Prepared by: William M. Lewis, Jr.
James F. Saunders, III

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Introduction

The transport of nutrients to Cherry Creek Reservoir can be estimated from the flows of surface water and groundwater into the reservoir and the discharge-weighted mean concentrations for each of these flows on an annual basis. There are substantial uncertainties in estimates of surface flows into the reservoir, however, and the alluvial flows into the reservoir must be approximated on the basis of transmissivity, slope, and alluvial cross sections. Because the estimation methods may be subject to considerable error, the Cherry Creek Basin Authority has adjusted its estimates to make them consistent with computed inflow to the reservoir as obtained by the U.S. Army Corps of Engineers through its measurements of measured outflow, evaporation, precipitation, and changes in lake volume. Thus the current estimates of hydrology for Cherry Creek Reservoir and its watershed are dependent on measurements of gaged surface flows, estimates of alluvial flow, and all of the information used by the U.S. Army Corps of Engineers in computing total inflow to Cherry Creek Reservoir.

The purpose of this report is to review and analyze the basis for estimating total flow and flow components into and through Cherry Creek Reservoir, and to identify any inconsistencies or possible errors that might have a significant effect on the estimation of nutrient transport. It is expected that all empirically-based estimates are subject to some unavoidable measurement error. Therefore, attention is focused on conceptual errors or omissions that could cause significant bias in the estimates.

Runoff from Undeveloped Lands

Given that 85% of the land surface for the watershed of Cherry Creek Reservoir is still undeveloped, runoff from undeveloped lands remains a very important component of the water budget. The most reliable source of information on runoff from undeveloped lands is the record of stream discharges for the Franktown gage (Figure 1). The gage, which is still in service, was installed in November of 1939, and therefore offers a very long period of record. In addition, because of the proximity of bedrock to the streambed at the point of gaging, this gage probably reflects total water yield from the basin above, i.e., no significant alluvial flow bypasses the gage. In contrast, gages below Franktown (e.g., Parker and Melvin) are underlain by thick alluvium, which is likely to convey a significant amount of water not detectable by a gage.

Total flow past the Franktown gage has extended from a low of 2090 acre feet in the drought year of 1954 to a high of 23,141 acre feet in 1984 (all annual values given here are based on water years). The annual flow across years is close to 7000 acre feet as an average and 5000 acre feet as a median. The watershed area above the gage is 169 mi^2. Thus the water yield is 0.78 inches per year as an average and 0.56 inches per year as a median. The median precipitation, as judged by the gage at Castle Rock (which is most relevant to the Franktown gage), is approximately 15 inches per year. Thus the median ratio of annual runoff to annual precipitation is 3.7% (1941-1999). This estimate of runoff for the Franktown gage is close to the value projected by Denver Urban Drainage (4 to 5%) for undeveloped land in the Denver region. The median is emphasized here over the mean because modelling or projection of nutrient loads is conducted primarily in the context of representative years; years of extreme wetness strongly affect the mean but not the median.

The Cherry Creek Basin Authority currently estimates, for modelling purposes, that the runoff from undeveloped land is equal to approximately 1% of the annual precipitation. The discrepancy between estimates from the Franktown gage (3.7%) and the estimate apparently intended for use in modelling by the Cherry Creek Basin Authority (stated as 1.1%: Appendix I, Cherry Creek Reservoir Watershed Model, 1 May 2000, Figure 5) for runoff is probably explained by differences in the treatment of surface runoff and alluvial flow fed by precipitation. The Cherry Creek Basin Authority's approach is to estimate surface runoff corresponding to storms surpassing specific thresholds of intensity that are expected to generate significant surface runoff. Recharge to the alluvium is not counted as runoff because it does not appear at the surface, but it is important to remember that precipitation partly becomes alluvial water that may enter Cherry Creek Reservoir. Because alluvial flow has the capacity to move nutrients into the reservoir, nutrient loading at the reservoir cannot be estimated from surface flow alone. The data for the Franktown gage suggest that the difference between the 1% of annual precipitation appearing as surface flow to the reservoir and the 3.7% estimated empirically at Franktown could be all or partly accounted for by alluvial flow from the watershed to the reservoir.

Estimates of Alluvial Flow by Use of the Melvin and Franktown Gages

A gage formerly located near the old town site of Melvin is useful, in conjunction with the Franktown gage, for estimating alluvial flows prior to the time of watershed development at points below Franktown. The record for the Melvin gage extends from October 1939 through September 1969 (there are also some additional measurements for 1984). The drainage area above the Melvin gage is 360 mi^2. Information for the Franktown gage can be used in estimating the expected total movement of water (including surface and alluvial components) past the Melvin gage prior to development.[1] The median runoff observed at the Franktown gage, when corrected for area (360 mi^2 at the Melvin gage versus 169 mi^2 at Franktown gage), is the estimate of expected flow (including both surface and alluvial components) at the Melvin gage.

The expected flow at the Melvin gage can be compared on an annual basis over the period of record to the observed surface runoff (Figure 2). The difference between expected total flow and observed surface flow is an estimate of the alluvial flow (Figure 3). The median expected total flow at Melvin is 10,680 acre feet per year, of which a median of 4560 acre feet per year[2] passes through the alluvium and the balance (6120 acre feet per year) passes across the surface. An additional 700 acre feet/yr can be added to account for drainage area outside the reach of the Melvin gage (estimate from relative areas), for a total of 11,400 acre feet per year. The alluvial flow thus corresponds to

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[1] Precipitation for the portion of the watershed between the gages is assumed to be the same as that for the watershed above the Franktown gage. This assumption is probably in error, but not by a sufficiently large amount to have much effect on the general conclusions of this analysis.

[2] Median difference is 4560; difference of medians is 5530.

about 6.3 cfs. There is no strong association between the alluvial flow and flow observed at the Franktown gage (Figure 4).

Flow through the alluvium, as calculated by the method described above, does not show any significant trend over time. Construction of the reservoir, which began to accumulate water in 1959, appears not to have affected this component of the water budget. Recent pumping of large volumes of water and present consumptive use of water are not taken into account in this analysis, however (see below), nor is any hydrologic effect of change in land use.

A study by Leonard Rice Engineers (1989)[3] estimated, on the basis of a different approach than the one used here, that alluvial flow under the dam equaled approximately 4400 acre feet per year. Thus the Rice study and the Melvin gage analysis produce very similar results (4400 versus 4560 acre feet per year), if alluvial flow at the dam and at the upper end of the reservoir are of similar magnitude, as they appear to be on the basis of the alluvial water flows calculated as explained above from gage data.

The data for the Melvin gage, which is located very close to the reservoir, indicates that a median of almost half of the total flow to the reservoir's upper edge passes through the alluvium. Furthermore, the analysis suggests that the amount of water passing through the alluvium to the edge of the reservoir is independent of or weakly dependent on amount of runoff, i.e., that the alluvial contribution is more or less constant and the variation in total water flow to the reservoir among years is expressed as variation in surface flow, at least as close to the reservoir as the Melvin gage.

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[3] The Leonard Rice report (1989) estimates flow under the dam as 4400 acre feet per year and concludes that 2400 acre feet comes from alluvium and 2000 acre feet comes from the lake.

Alluvial pumping is substantial in the Cherry Creek Basin at present, but some of the pumped water is returned as treated wastewater either through surface discharge or infiltration.[4] There is no evidence of progressive decline in alluvial water table levels caused by pumping, although the record is not very long (Figure 5).

Estimates of alluvial flow have been made by Halapaska from hydraulic transmissivity, as estimated from well pumping, the difference between static and dynamic level in the well at MW9, and slope. According to the Halapaska data, the flow rate at MW9 would be about 5 cfs (about 3600 acre feet per year), but the estimate may be too high because the assumed slope (0.006) is higher than actual (0.0040 – 0.0045).[5] A revised estimated based on a more realistic slope is 3.5 cfs or ~ 2500 acre feet/yr, which is lower than the estimate based on the Melvin gage (4600 acre feet/yr), but the estimate of cross-section and transmissivity for MW9 is subject to error, which may or may not be significant. Estimates based on transmissivity may be affected (depending on the depth of the wells) by the fact that the alluvium does not have uniform transmissivity (coarser material is found at the bottom, as indicated by USGS studies cited in the Leonard Rice report).

The significance of alluvial flow for phosphorus loading of the reservoir depends on the fate of this flow once it reaches the reservoir margin; some or all of the alluvial flow may pass completely under the reservoir (see below).

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[4] Aurora pumps water from the basin (3600 to 5000 acre feet per year 1989-1993; 1000 – 2200 acre feet per year more recently). Other alluvial pumped water (~ 2500 acre feet per year) is not removed, but some is consumed within the basin. Present loss through pumping very roughly would be 3000 acre feet/yr (export plus consumption).

Flow Rates and Residence Time for Water in the Alluvium

The size of the alluvium can be estimated from alluvial cross sections obtained by Halapaska for each of the well sites. On the basis of linear interpolation from one well site to another and estimates of pore volume from hydraulic transmissivity data, the water holding capacity of the alluvium appears to be approximately 124,000 acre feet, which is about 10 times the lake volume.

Flow velocities in the alluvium are low. According to the estimates mentioned above, the flow velocities would be 1.5 to 2.0 feet per day, or 7 to 10 years per mile of flow. On a volumetric basis (volume over flow rate), the hydraulic residence time of the alluvium is about 34 years. The estimates of flow rate are composites, i.e., they do not take into account differential flow in various parts of the alluvium, as might occur through vertical differences in hydraulic transmissivity, local mounding or cratering of the alluvium caused by discharge or withdrawal of water, etc.

The information on alluvial volume and alluvial flow rates is significant in several respects for nutrient loading of Cherry Creek Lake. First, the slow rate of movement of water in the alluvium is consistent with the concept that nutrients entering the alluvium at points close to the reservoir are more significant to current loading of the reservoir than nutrients entering the alluvium at points more distant from the reservoir. Contrary to some current assumptions in modelling, however, it is also evident that all nutrients entering the alluvium are potentially significant to future nutrient loading of the reservoir, given that all waters of the alluvium are moving steadily, albeit slowly, toward the reservoir. Thus nutrient loading of the alluvium at any point more than a few hundred

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[5] This slope was obtained from absolute alluvial water surface elevations at MW9 and lake elevations.

yards from the reservoir might be essentially irrelevant to the nutrient loading of the reservoir in a particular year, but certainly could be significant to the nutrient loading of the reservoir in future years, unless a case can be made that all alluvial water passes completely under the reservoir (see below). Similarly, use of pumped water in constructing annual loading budgets for specific years is unrealistic because of the slow movement of alluvial water.

Flow of Alluvial Water Beneath Cherry Creek Reservoir

Cherry Creek Dam includes a cutoff trench that does not extend to bedrock at all points, although at one point it does contact the Denver formation below the alluvium. The designers of the dam left a substantial cross section of alluvium beneath the cutoff trench. According to the Leonard Rice report (1989), the thickness of the alluvium below the cutoff trench at one point reaches 50 feet. Direct evidence of connection between the alluvium below the dam and the water stored behind the dam is available through observation of water levels in the wells near the toe of the dam. The water levels in these wells respond to changes in reservoir water levels.

Estimates of Outflow

The median measured release from the reservoir is 2640 acre feet (WY 1961 – 1999; as measured by USACE at the gates that allow water to exit the dam; Figure 6). There is a USGS gage just below the dam, but it obviously does not incorporate water flowing beneath the dam. The Leonard Rice study estimated the underflow at 4400 acre feet, suggesting total outflow of approximately 7000 acre feet per year.

Additional losses include evaporation, which must be offset by precipitation. Assuming precipitation of approximately 16 inches per year, and evaporation of approximately 37 inches per year, the net loss via the atmosphere is 1400 acre feet per year. This leads to a total loss estimate of 8400 acre feet per year.

Reconciliation of Gains and Losses

The median flow to the upper edge of the lake estimated as outlined above would be approximately 11,400 acre feet per year (including surface and subsurface flows). The total annual outflow is estimated as 8400 acre feet per year, or 3000 acre feet per year less. The inflow estimate is based upon predevelopment conditions. The difference between inflow and outflow therefore may be accounted for by changes in water use that accompanied development. The withdrawal and use of water do in fact account for 3000 acre feet per year of losses superimposed on the background condition.

Alluvial Flow Pathways

Although 7000 acre feet per year seems a reasonable estimate for total flow past the dam, the pathways for water through and beneath the reservoir are subject to considerable uncertainty. According to the Leonard Rice study, no water from the alluvium above the dam actually enters the reservoir. Instead, according their analysis, water derived from surface flows to the reservoir exits through the bottom of the reservoir at a rate of approximately 2000 acre feet per year. There is, however, no direct evidence for this conclusion. Observation of significant dry weather flows at the toe of the deltaic deposits where Cherry Creek enters the reservoir suggest that alluvial water does enter the reservoir (Lewis 1995). Thus the pathway for movement of water from points above the reservoir to points below the reservoir is still unresolved, and may vary seasonally.

If all of the alluvial water passes beneath the reservoir, then its quality would be irrelevant to nutrient loading of the reservoir. If a significant amount of this water enters the reservoir and mixes with the surface waters of the reservoir, then it contributes to the total nutrient load of the reservoir. The resolution of this issue obviously has important implications for nutrient management of the reservoir.

Use of Calculated Inflow to Correct Measured Inflows

The USACE calculates an estimated inflow as a residual sufficient to balance the difference between change in storage, measured outflow, and net precipitation (precipitation minus evaporation). This approach fails to take into account underflow. If underflow originates in part from the lake itself, then the USACE calculation will be biased by that portion of the outflow that originates in the lake and passes through the alluvium below the dam, thus bypassing the outflow gates. In other words, use of this approach will result in a systematic underestimate of inflow to the reservoir, and therefore of nutrient input to the reservoir. It is not possible to tell at present whether the bias is a significant one or not.[6]

Conclusions

The main issue yet to be resolved for Cherry Creek hydrology is the extent to which alluvial water reaching the edge of the reservoir passes into the reservoir as opposed to passing further through the alluvium and underneath the reservoir without entering the reservoir itself. This issue obviously has a potential bearing on the total nutrient loading of the reservoir.

The present analysis suggests that the practice of computing specific annual credits for reduction of phosphorus load to the reservoir due to pumping of alluvial water from the watershed is unrealistic in that the passage of alluvial water from the site of pumping to the reservoir occurs over very long intervals of time (e.g., 10 – 20 years, depending on location).

The analysis described here raises questions about the influence of greater amounts of pumping in the future. Increased pumping may change the balance between alluvial and surface flows. The significance of such a change would depend on the amount of alluvial flow that is actually entering the reservoir.

The practice of using USACE calculated inflow to adjust inflow estimates based on gage data may be misleading in that the USACE calculations do not take into account underflow.

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[6] Presence of negative residual calculated inflows would be a clue, but the USACE calculations are based on an algorithm that does not allow residuals to be less than or equal to zero.

Inflow	
Natural surface flow at Melvin	6,120
Natural subsurface flow at Melvin	4,560
Natural flow not measured at Melvin	700
Natural total flow at lake margin	11,380
Pumping withdrawals	3,000
Current Total Flow at Lake Margin	8,380
Outflow	
Measured outflow (at gates)	2,640
Subsurface outflow	4,400
Net atmospheric loss	1,400
Current Total Outflow	8,440

Table 1. Summary of water balance for Cherry Creek Reservoir based on data and assumptions given in the text (acre feet per year; median across years).

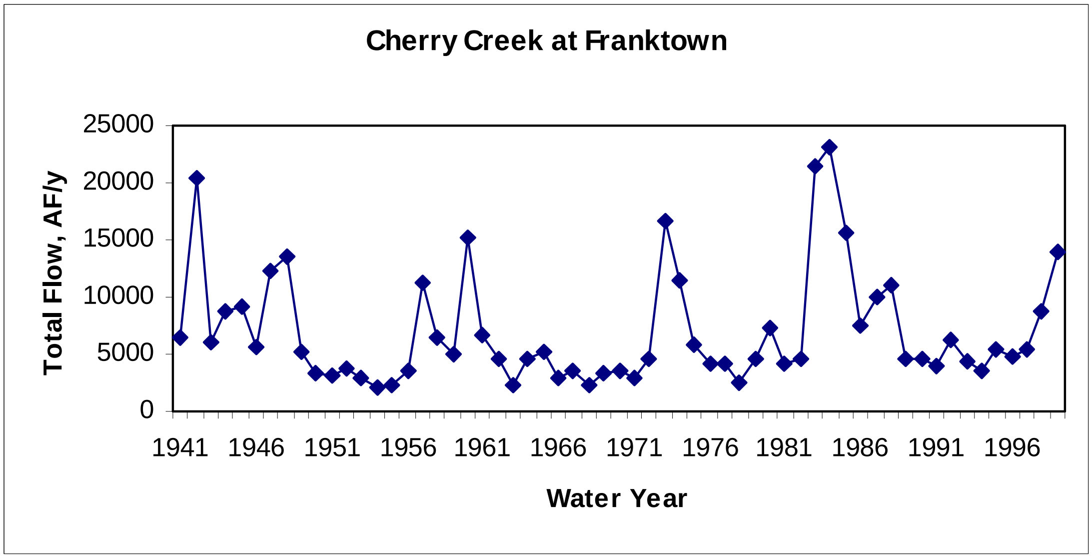

Figure 1. Franktown gage: annual flow versus time.

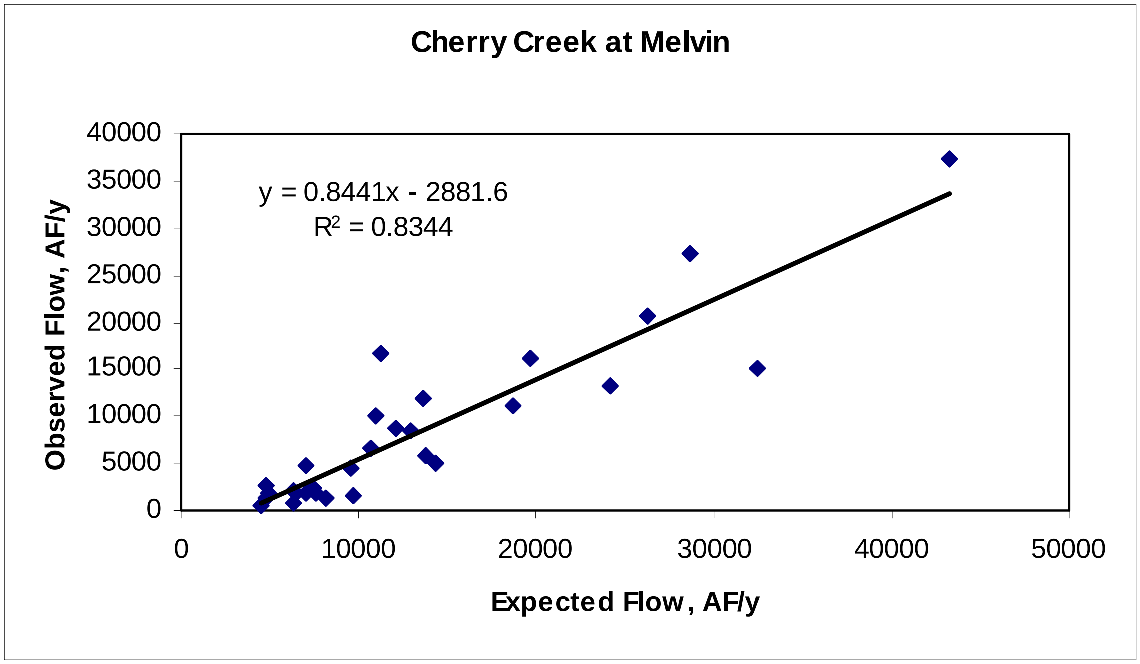

Figure 2. Expected and observed flow at the Melvin gage.

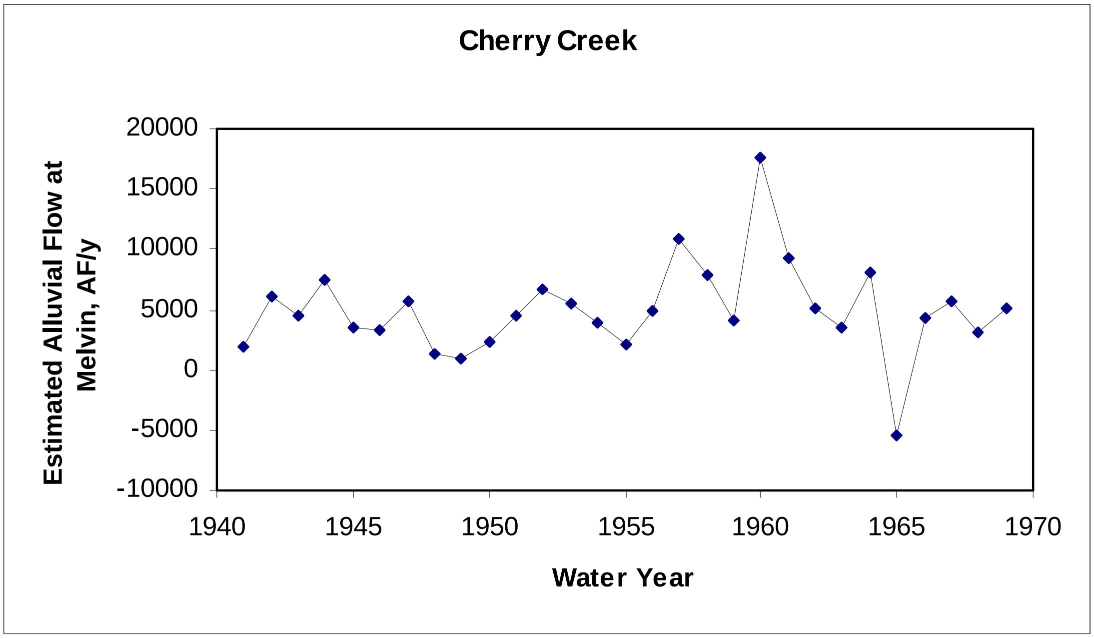

Figure 3. Flow through the alluvium over time, as estimated from Melvin gage data.

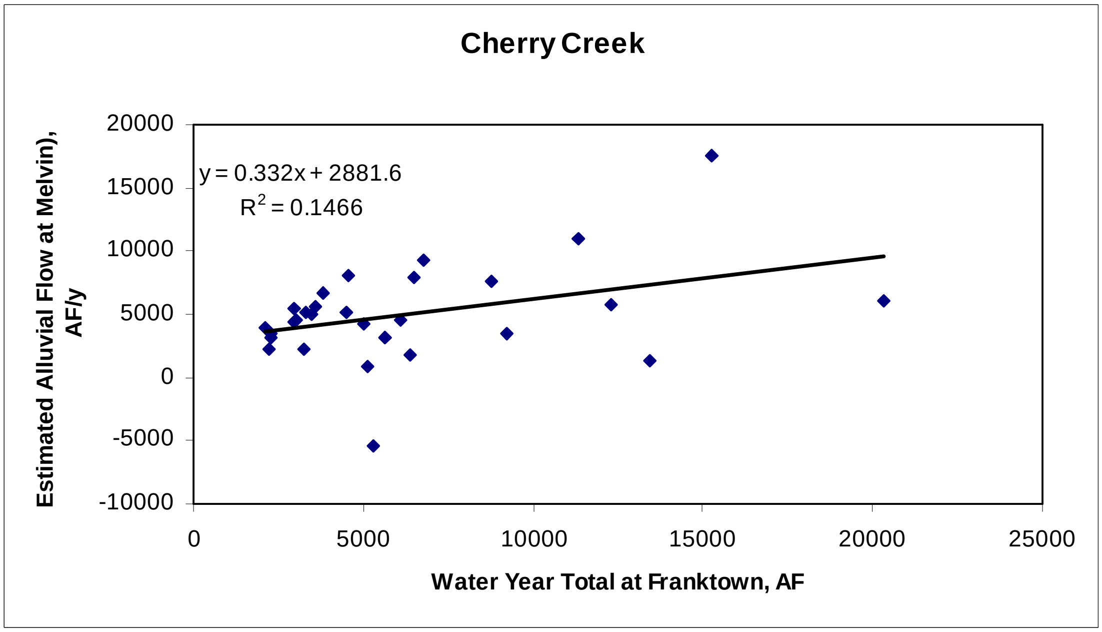

Figure 4. Alluvial versus observed flow at Franktown over time.

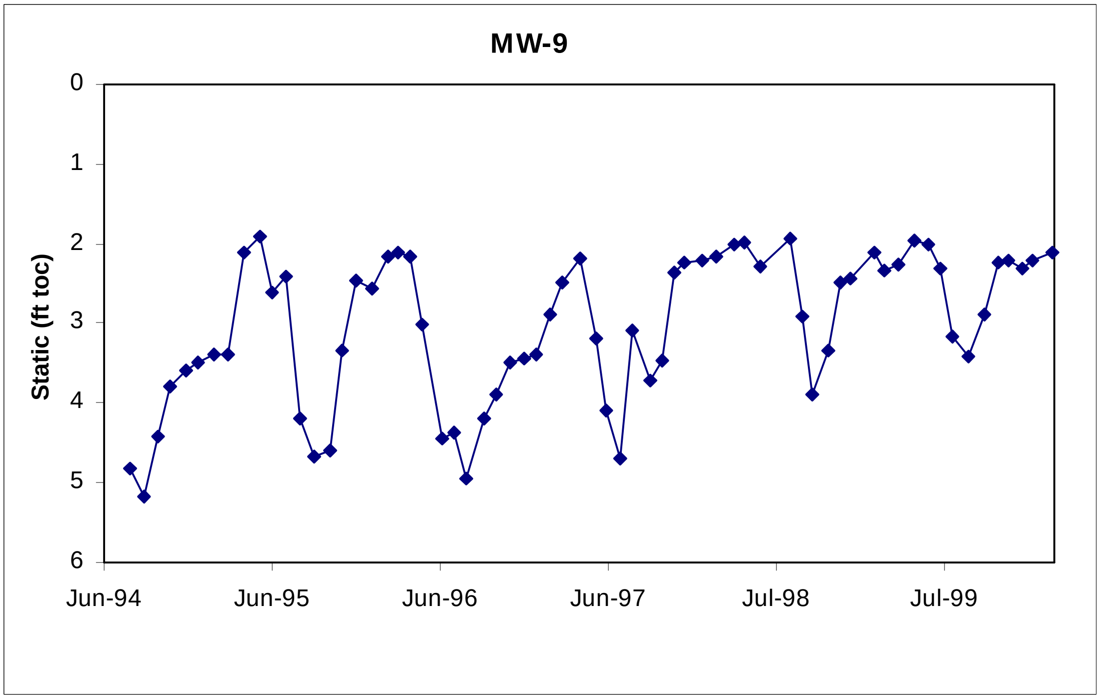

Figure 5. Alluvial water levels over the period of record (ft toc = feet from top of casing).

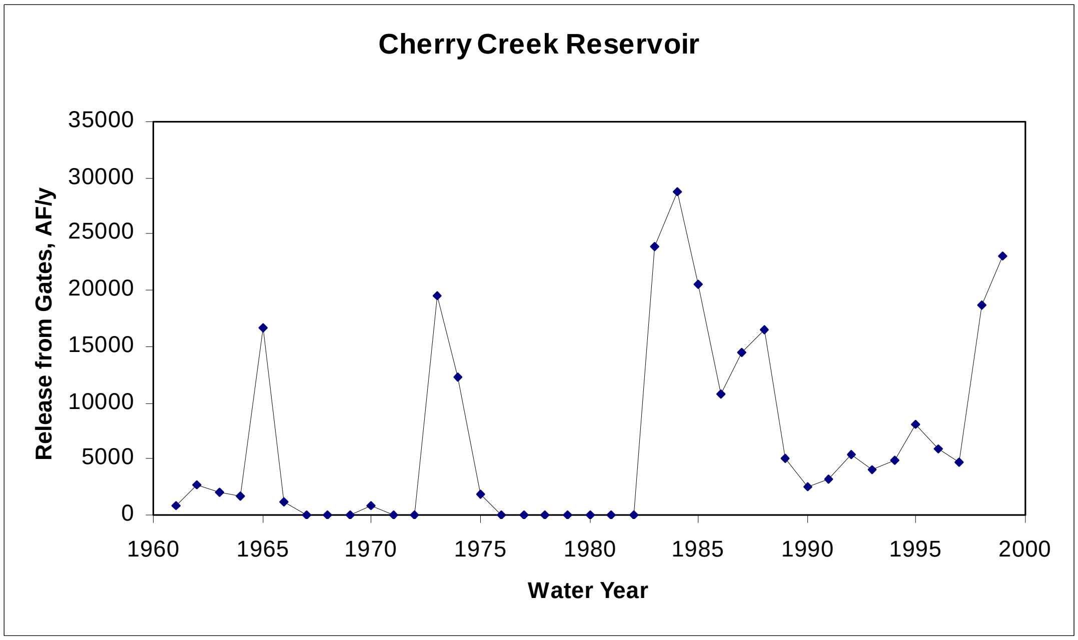

Figure 6. Reservoir releases over time.