Applications of the CE-QUAL-W2 Model For Lake Murray Relicensing Issues

Prepared for SCE&G

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1. Introduction

Background on Development of the Model: A CE-QUAL-W2 model was developed on Lake Murray (Sawyer and Ruane, 2006) to address several water quality issues associated with Lake Murray that are being considered for the relicensing process:

- low DO and temperature in the releases from Saluda Hydro,
- restrictions for operating Unit 5 due to impact to coolwater fisheries,
- reduced striped bass habitat in the lake due to low DO in the regions of the lake where their temperature preferences occur, and
- the effects of revising the pool level management policy.

The CE-QUAL-W2 model is a two-dimensional water quality model that simulates the effects of inflow water quality and reservoir operations on in-lake water quality as well as the releases from the lake. This model was developed using all available water quality data collected by SCDHEC and SCE&G on Lake Murray and its inflows, as well as using external comparisons of water quality at other projects similar to Lake Murray.

The objectives of the modeling effort were the following:

- To assess the benefits of reduction in nutrient loading from the watershed to DO levels in the releases from Saluda Hydro – determine how much DO would increase in the releases from Saluda Hydro after nutrient controls are implemented in the watershed.
- To assess the benefits of reduction in nutrient loading from the watershed to DO levels in Lake Murray – determine how much DO would increase in the metalimnion of the lake so that habitat would increase for coolwater fish species, including blue-back herring and striped bass.
- To assess the effects of operations of Unit 5 on habitat for fish in Lake Murray and releases from Saluda Hydro.
- To investigate the causes of fish kills that might be related to operations of Saluda Hydro

The model calibration approach involved an intensive reconciliation process to develop a robust model that considered:

- The objectives and scope of the model;
- All available data;
- Model settings, rates, and coefficients recommended in model manuals and other literature sources;
- Approaches recommended in the user manuals for the model used;
- Ensuring model integrity for representing the Lake Murray ecosystem. Model integrity with the ecosystem was accomplished by ensuring that the model was representative of data and other information on organic matter (dissolved and particulate, labile and refractory) in the system, phosphorus and nitrogen concentrations, algal levels, pH, and alkalinity.

The model was calibrated and tested using several simulation scenarios and the following provides a summary:

- The model is well-calibrated for temperature and DO, especially for the main body of the lake, i.e., the first 20-25 km upstream from the dam.
- Phosphorus and Chlorophyll *a* concentrations are well-calibrated throughout the main body of the lake.
- The model is well-suited for addressing the following objectives: DO and temperature in the releases from Saluda Hydro; DO and temperature in the metalimnion which is the habitat for blue-back herring and striped bass; and algal levels in the upper regions of the lake.
- The Lake Murray W2 model is limited in scope to the calibrated water quality constituents in the lake and the effects of its direct inflows from the Saluda River, Little Saluda River, Bush River, and other smaller tributaries. It simulates the effects of temperature, DO, nutrients, organic matter, and other constituents discussed above in these inflows. It was specifically calibrated for the objectives stated above.

The model was used to predict water quality in Lake Murray and its releases assuming that phosphorus was reduced so that inflows had the maximum phosphorus concentrations that complied with SCDHEC lake criteria (Sawyer and Ruane, 2006). If TP in the inflowing rivers and creeks to Lake Murray were reduced to the criteria set for lakes by SCDHEC, they would be among the cleanest 30% of the hydropower reservoirs reported in a recent EPA study.

The results of the model runs using the assumed nutrient reductions showed that DO would improve significantly in the releases from Saluda Hydro—especially if special pool level draw downs can be shifted to other times of the year beyond the low DO period. The results also showed restrictions for operating Unit 5 due to current concerns about striped bass habitat and entrainment of blueback herring would be eliminated. In addition, the model results showed that trophic status in Lake Murray would improve significantly. By inference, the problem with low DO in the inflow regions of the lake and the issue regarding low pH in the releases from Saluda Hydro would be significantly improved or eliminated.

Relicensing Issues Identified by the Water Quality Technical Working Committee (TWC): The TWC identified the following issues to be addressed using the CE-QUAL-W2 model:

- The causes of striped bass fish kills reported in previous years, especially factors related to Saluda Hydro operations, i.e., pool level management for Lake Murray, Unit 5 operations versus operations of Units 1-4.
- Determination of operational changes that might increase habitat in Lake Murray for striped bass and blue-back herring
- In evaluating these issues and exploring potential operational changes, track any potential impacts that could occur to the tailwater cold-water fishery

The following factors were considered in addressing these issues:

- Annual flow regimes
- Pool level management
- Unit 5 operations
- Lake Murray and Saluda Hydro release water quality data

- Lake Murray habitat for striped bass and blue-back herring
- Water quality, meteorological, and operations data over the period 1990-2005
- Emphasis was placed on Lake Murray from Blacks Bridge to Saluda Dam

Several committee members hypothesized that there may be a correlation between fish kills and lower than normal DO levels in Lake Murray that may be attributed to higher than normal inflows from the Saluda River. This hypothesis as well as the effects of Saluda Hydro operations on fish habitat were investigated by analyzing available data as well as using the CE-QUAL-W2 model to investigate the causes of impacts to fisheries.

SCDNR requested that the following operating strategy be considered: preferentially operate Unit 5 during high DO months to preserve cold water in the bottom layers of the lake and perhaps keep DO higher in the metalimnion to maintain DO in the water column, but track potential increases of temperature in the releases to avoid impacting the coldwater fishery.

<u>Plan for Using CE-QUAL-W2 to Address the Water Quality TWC Relicensing Issues</u>: The following subtasks were conducted to address the above issues.

1. Summarized and analyzed water quality, meteorological, flow, and operations data for the period of study, 1990-2005, to detect patterns that indicate correlation between these factors. Prepare graphs detailing Lake Murray surface elevation, average annual flow, cumulative inflow/outflow, forebay temperature and DO profiles.
2. Set up CE-QUAL-W2 for the years when major striped bass fish kills occurred. The model had already been calibrated 1992, 1996, and 1997. To address the causes of the major fish kills, the model was also set up for 1991, 1998, 2000, 2001, and 2005).
3. To address the causes for the major fish kills, selected model years were run to identify the causes that apparently contributed to the fish kills, i.e., antecedent conditions that might have led up to the fish kills occurring. All these runs were

made using existing nutrient conditions. A range of habitat criteria were considered, i.e., for temperature and DO conditions, to account for the uncertainty in these ranges. After apparent causes are identified for each fish kill, they were examined/evaluated using the models and data for other years to verify that these causes were logical, sensible, and valid. This process was intended to provide confidence in the results of the diagnosis of the cause(s) of the fish kills.

4. For the determined causes, the models for selected years were used to explore ways to avoid such fish kills in the future. The potential solutions included changes in Saluda Hydro operations (i.e., pool level management, operations of Unit 5 compared to the other units) and nutrient reductions.

Plan to address the effects on water quality and fish habitat of holding pool levels more level each year, e.g., minimum pool raised to elevation 354 ft above MSL: As part of the relicensing process, SCE&G is considering raising the minimum pool elevation. This could affect water quality and fish habitat. Over the period of study (1990-2005), fish kills have occurred more frequently (i.e., two-thirds of the years with major fish kills) in years when the minimum pool elevation was at or near elevation 354 msl.

The CE-QUAL-W2 model was used to evaluate dropping the winter minimum pool elevation to 350 and 354 ft msl to determine the effects on release water quality and fish habitat. The model was setup for wet years, normal years, and low flow years to see how water quality was affected by setting the minimum pool elevation to that being evaluated by SCE&G. The evaluation assessed striped bass habitat and temperature and DO in the releases. The evaluation also determined how much longer it would take for the lake to mix at the end of the stratification period. Concern was expressed that the lake might not mix until December or January and low DO in the release would occur for this extended period.

One factor that also was assessed was the potential impact of SOD (sediment oxygen demand) increasing up to levels seen at other projects in the SE USA. This was supported by seasonal SOD dynamics measured at Douglas Reservoir (TVA).

Another impact on water quality that was expected to occur due to changing the minimum winter pool level was in the Little Saluda River embayment, especially upstream from the bridge on SC Hwy 391. This is a relatively large embayment with a small watershed; therefore, the residence time of water in this embayment is relatively long. If minimum pool elevation is raised, there might be less water exchange between this embayment and the main body of Lake Murray. This would lead to increased “internal cycling” of nutrients in this embayment to the point that it may become insensitive to nutrient loads from the watershed because the release of nutrients in the sediments of the embayment could be sufficient to support eutrophic conditions in the embayment. In some cases this condition can lead to the formation of algal mats on the water, and these mats of algae are known to significantly affect water quality and water uses. To assess this potential water quality problem, the model was used to assess the changes that might occur in the embayment.

2. Causes of Fish Kills

To better understand why fish kills occurred in some years and not others, the following parameters were analyzed: hydrology (inflow and outflow), lake levels, and meteorology. The reported fish kills are presented in Table 2-1, which is a summary of information provided by Reed Bull, Midlands Striper Club. This complete summary as well as a summary written by Ron Ahle, SCDNR are in Appendix 1 and 2, respectively.

Figures 2-1 through 2-3 show the pool elevations for the years 1990 through 2005. Figures 2-2 and 2-3 show the same data but the years in which fish kills occurred indicated by the red lines and the other years are indicated by blue lines. There were no apparent correlations between those years with fish kills and the main considerations for pool levels: winter minimum pool elevation, summer pool level, and special drawdown conditions.

Figures 2-4 through 2-9 show the cumulative outflows from Lake Murray for individual years. These results indicate that outflows vary significantly from year to year.

Figures 2-5, -7, and -9 show that fish kills occurred when cumulative flows were high, especially for the months March through June.

Temperature and DO profiles of data from the forebay of Lake Murray and longitudinal plots of temperature and DO in the reservoir (see Figures 2-10 through 2-23) show that these variables are correlated with flows through the reservoir, i.e., in years with higher flows the temperature increases more rapidly and DO decreases more rapidly at the depths where striped bass habitat occurs. Striper habitat is generally confined to those areas where temperature is less than about 27 ^{o}C and the DO is greater than about 2 mg/L.

Met data were also analyzed, but there were no apparent correlation with fish kills (see Figure 2-24 through 2-28).

Based on this analysis of the data, the following preliminary findings were developed:

- High inflows and associated outflows, especially during March-June, are the primary cause for fish kills
- Higher outflows cause the bottom of the lake to warm, and lower DO levels are associated with this warmer water
- As a result, striped bass habitat is reduced more significantly during years with high inflows and outflows for Lake Murray, especially over the period March-June.

PERIOD	DATES	FISH KILL COUNTS	SIZE	REPORTED CAUSE	COMMENTS
1971* – 1977	N/A	N/A	N/A	N/A	See SCDNR Annual Report Sec. – Fish Kill Investigations See Item 1
Summer 1990	8/17/1990	1157	12" – 37"	DO Depletion Thermal Stress	Lake Down During Period, See Item 2
Summer 1991	7/19/91 -8/16/91	3139	12" – 41"	DO Depletion Thermal Stress	Lake Down During Period, See Item 3
Summer 1993	9/9/93 – 9/16/93	592	15" – 23"	DO Depletion Thermal Stress	See Item 4
Summer 1994	8/15/94 – 9/14/94	64	N/A	DO Depletion Thermal Stress	See Item 5
Summer 1998	7/30/98 – 8/10/98	456	N/A	DO Depletion Thermal Stress	See Item 6
Summer 2005	Several Weeks Aug. 2005	742	17" – 38"	DO Depletion Thermal Stress	See Item 7 Lake Drawn Down 3 Year Prior to Kill

Table 2-1. Summary of Striped Bass Die-off Events, 1971-2005

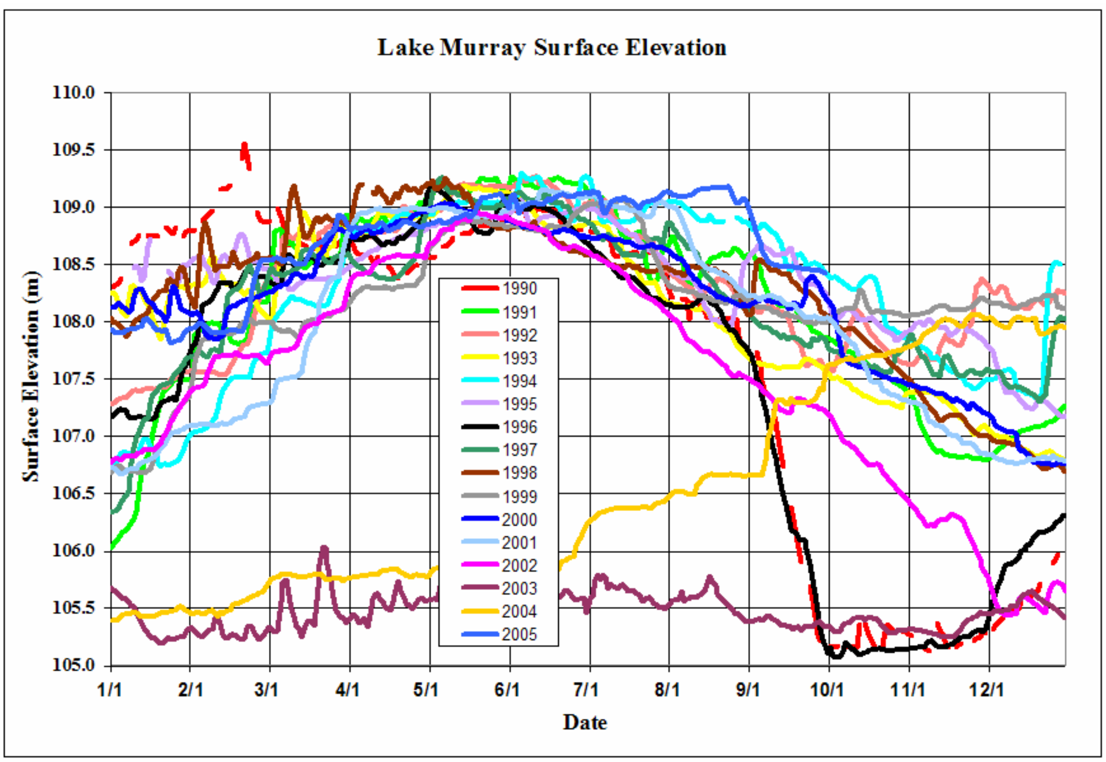

Figure 2-1. 1990-2005 Lake Murray Surface Elevation-Plotted by Julian Day

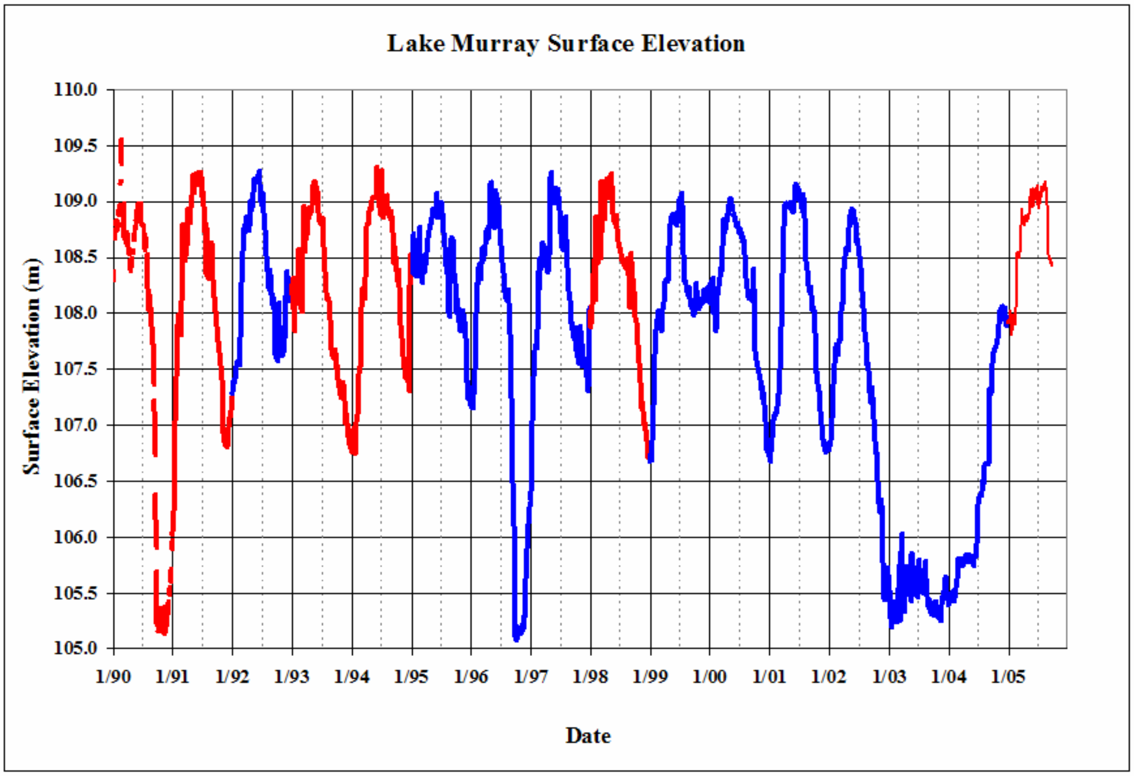

Figure 2-2. 1990-2005 Lake Murray Surface Elevation-Plotted by Date

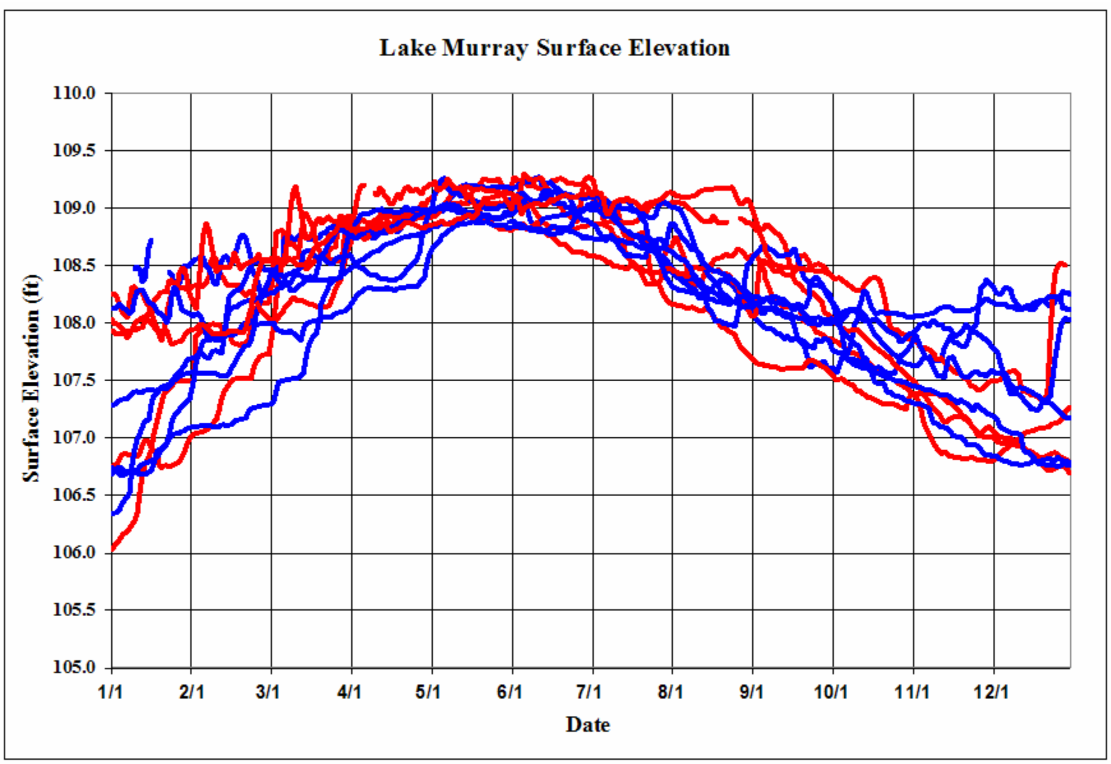

Figure 2-3. 1990-2005 Lake Murray Surface Elevation with Fish Kill Years in Red

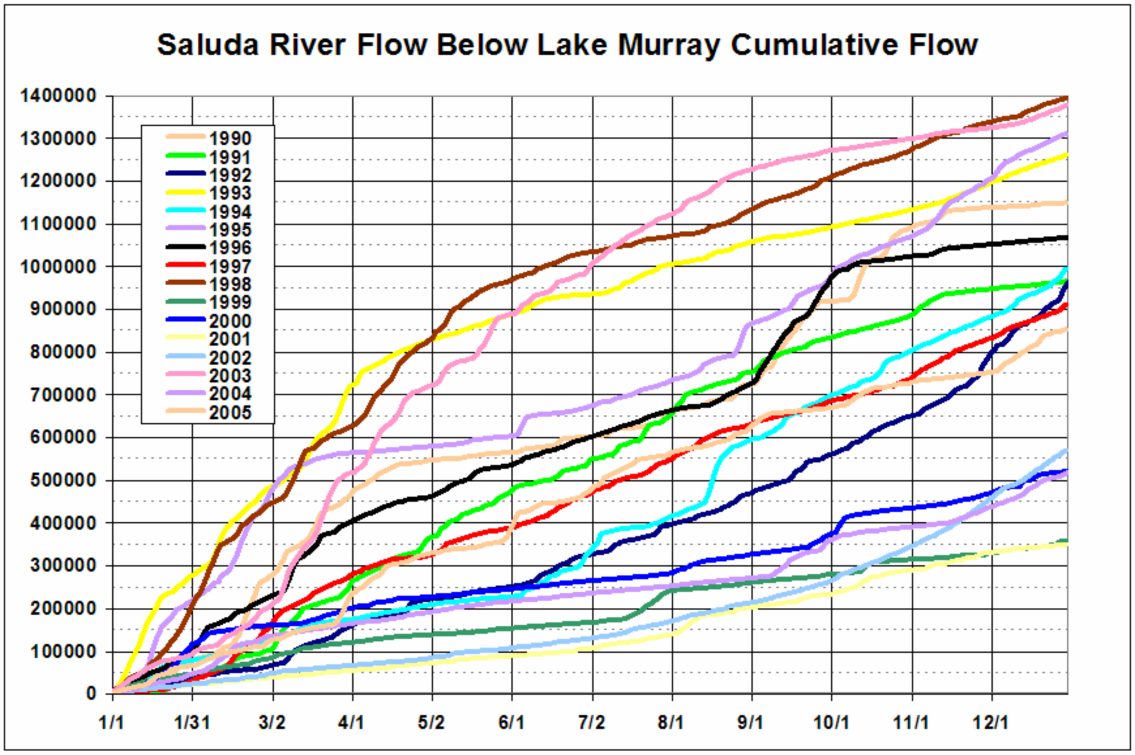

Figure 2-4. Lake Murray Cumulative Outflow – January-December

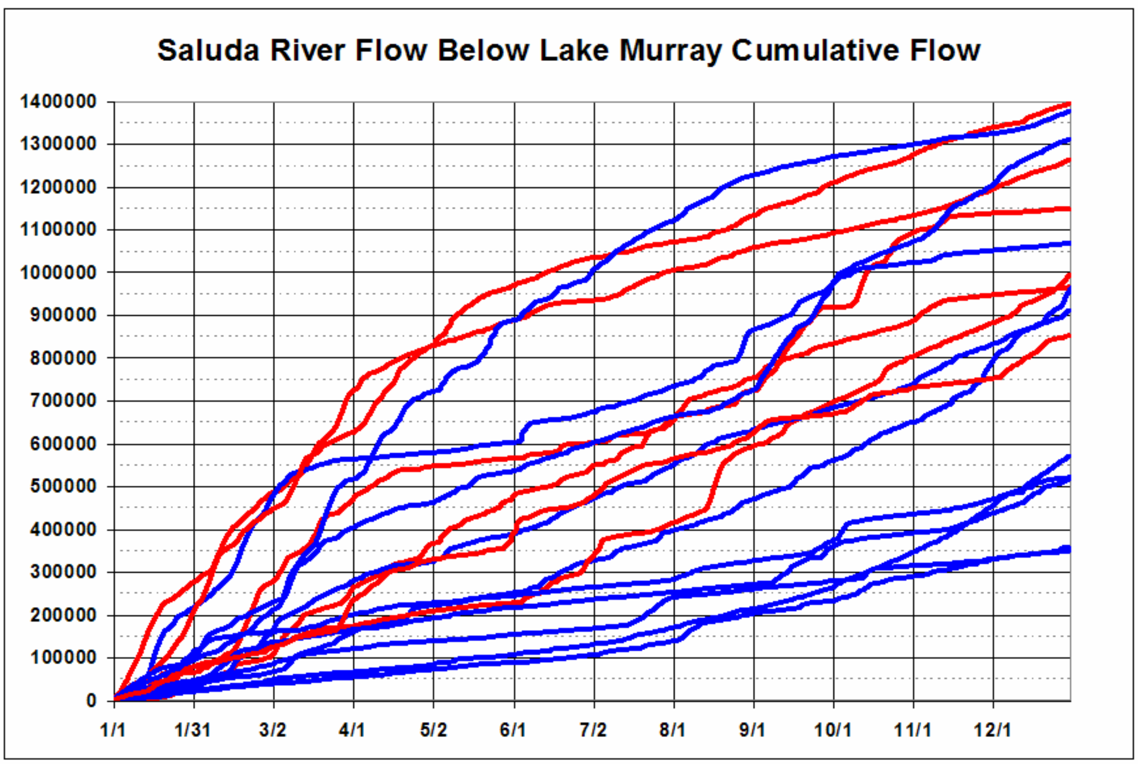

Figure 2-5. Lake Murray Cumulative Outflow – January-December with Fish Kill Years in Red

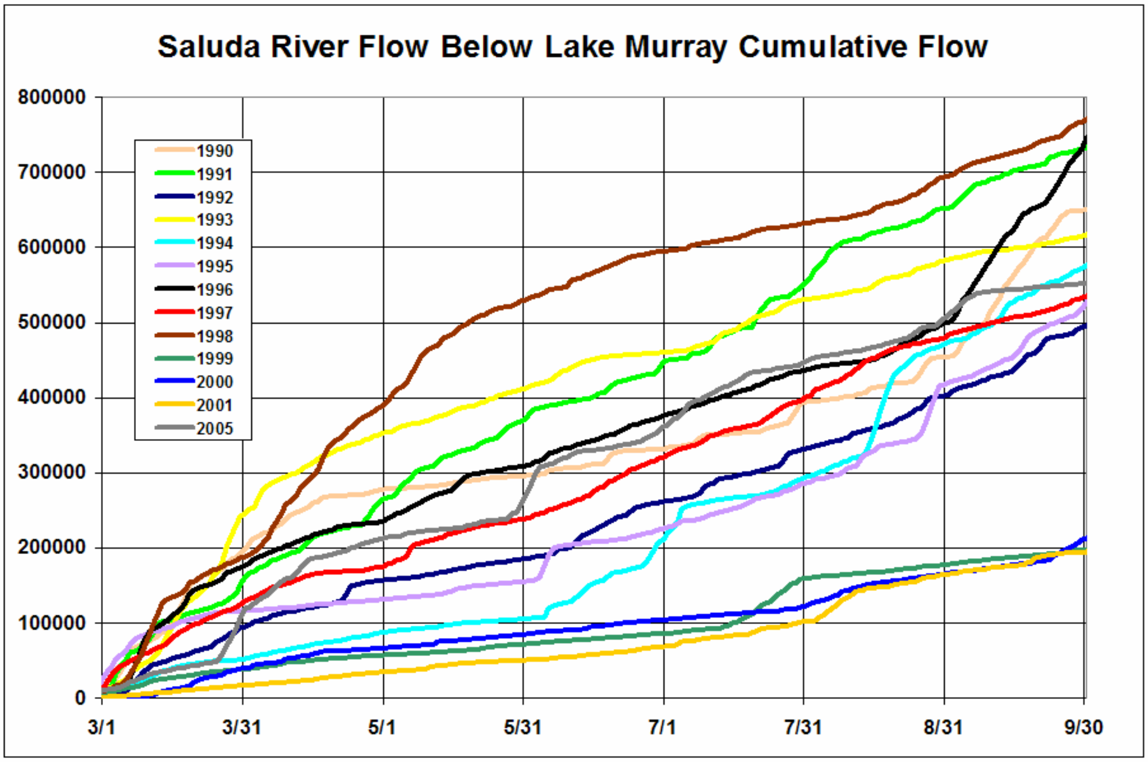

Figure 2-6. Figure 2-4. Lake Murray Cumulative Outflow – March - September

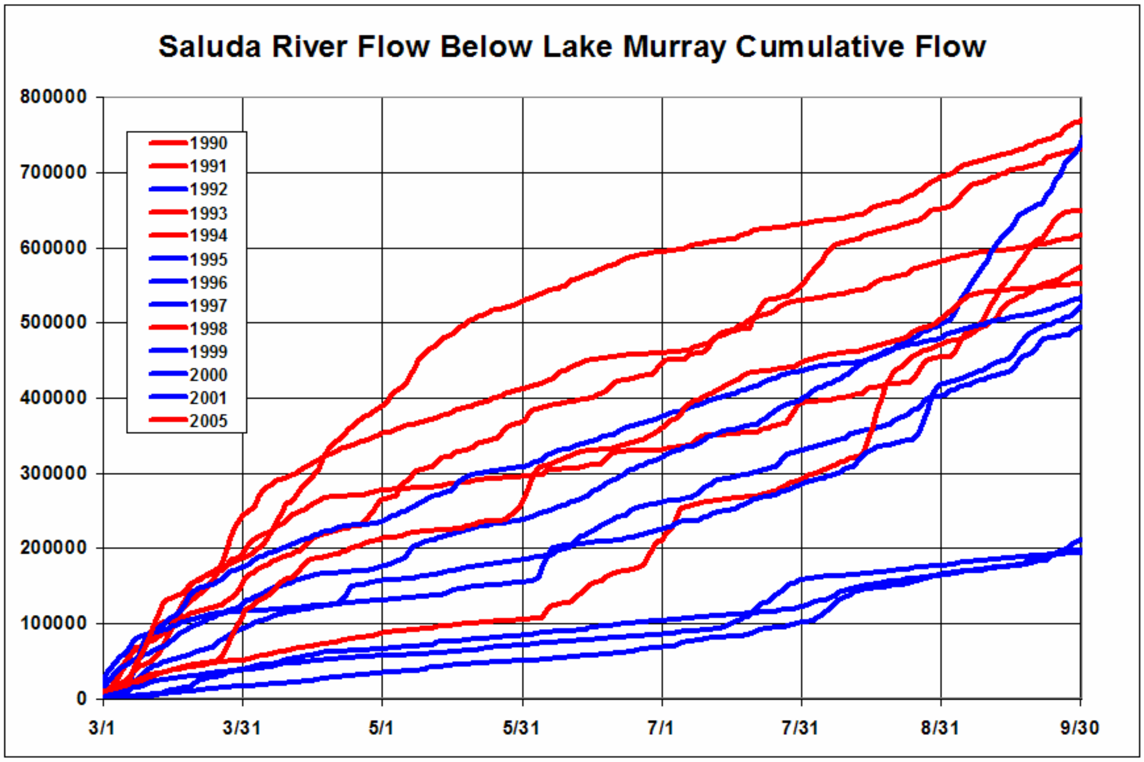

Figure 2-7. Lake Murray Cumulative Outflow – March-September with Fish Kill Years in Red

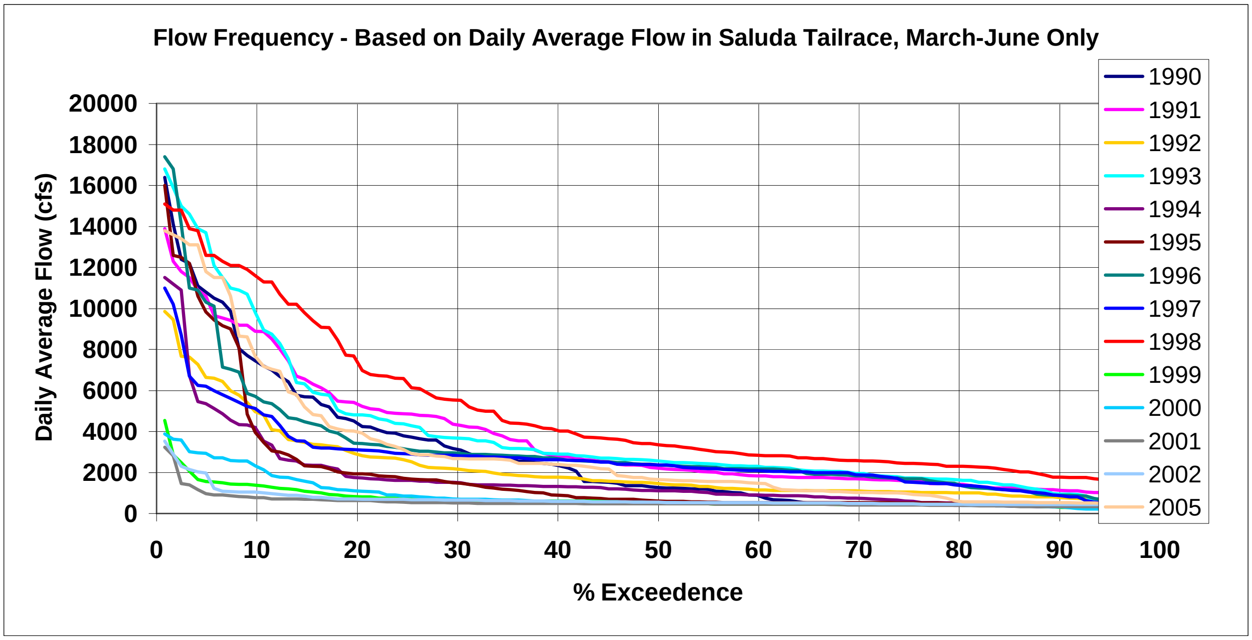

Figure 2-8. Lake Murray Outflow Frequency – March - June

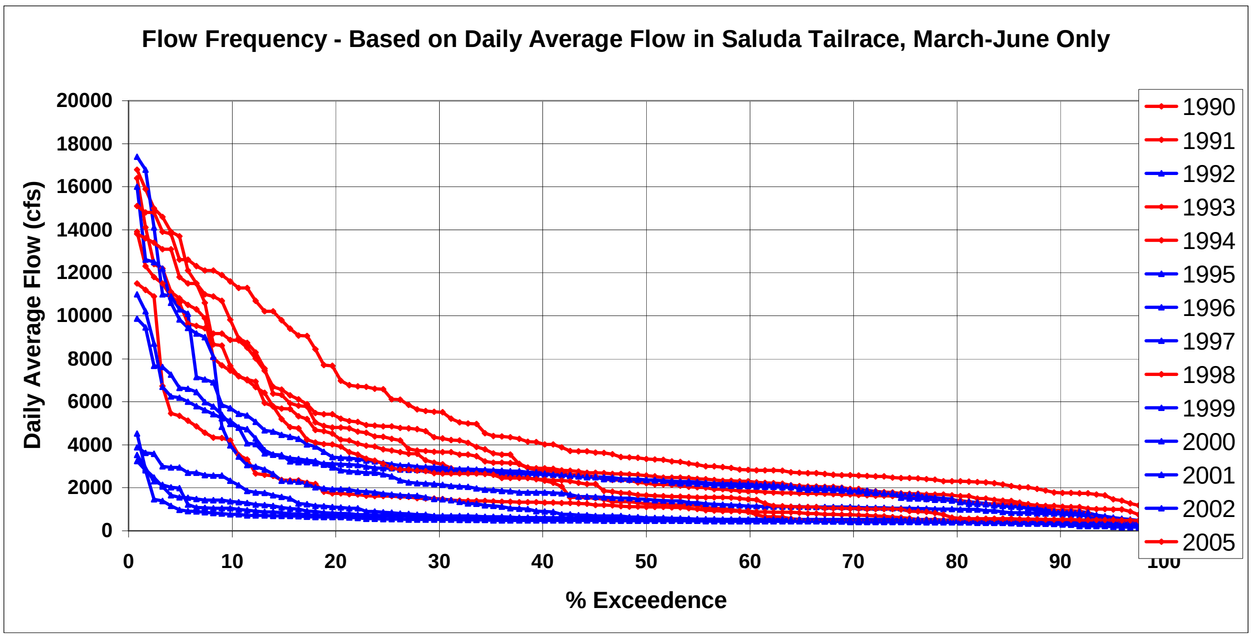

Figure 2-9. Lake Murray Outflow Frequency – March – June with Fish Kill Years in Red

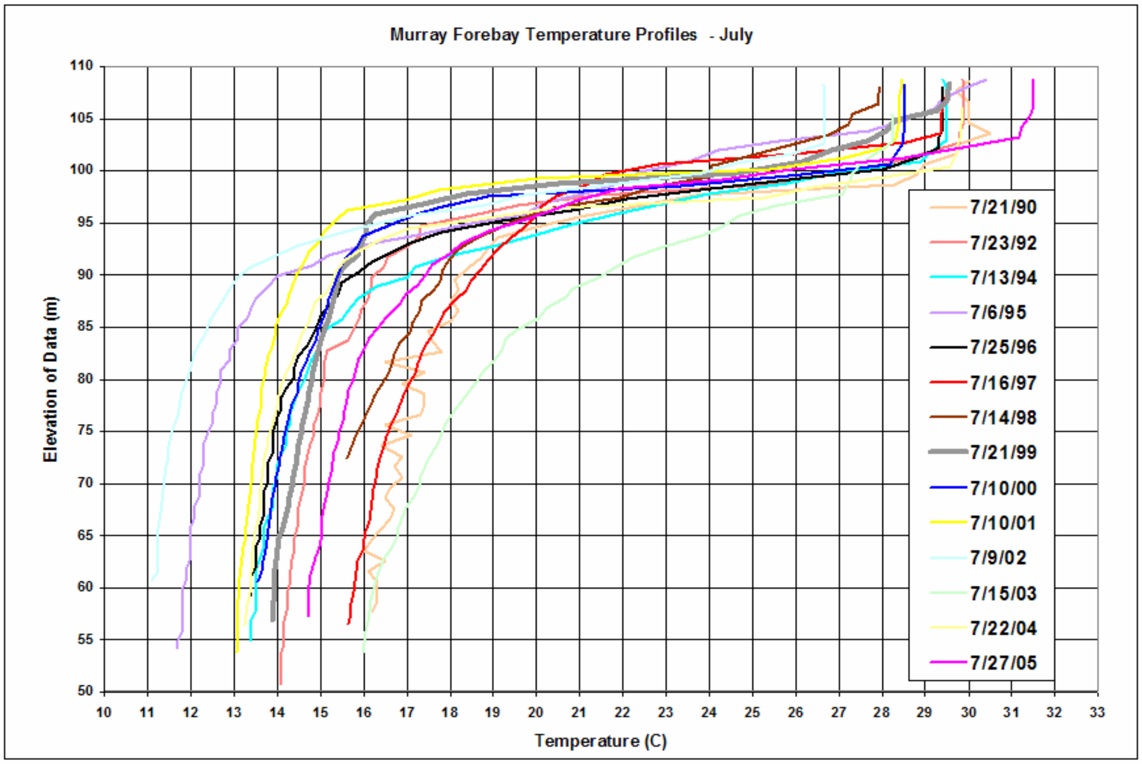

Figure 2-10. Lake Murray July Temperature Profiles, 1990-2005

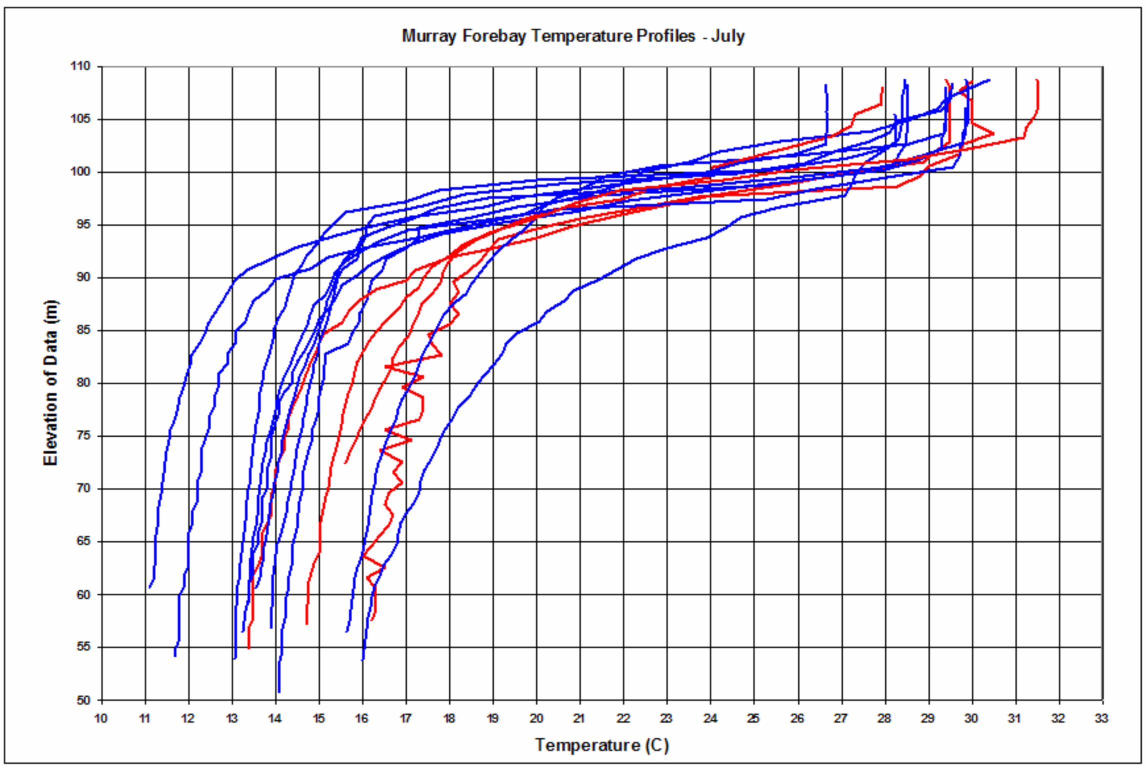

Figure 2-11. Lake Murray July Temperature Profiles, 1990-2005 - with Fish Kill Years in Red

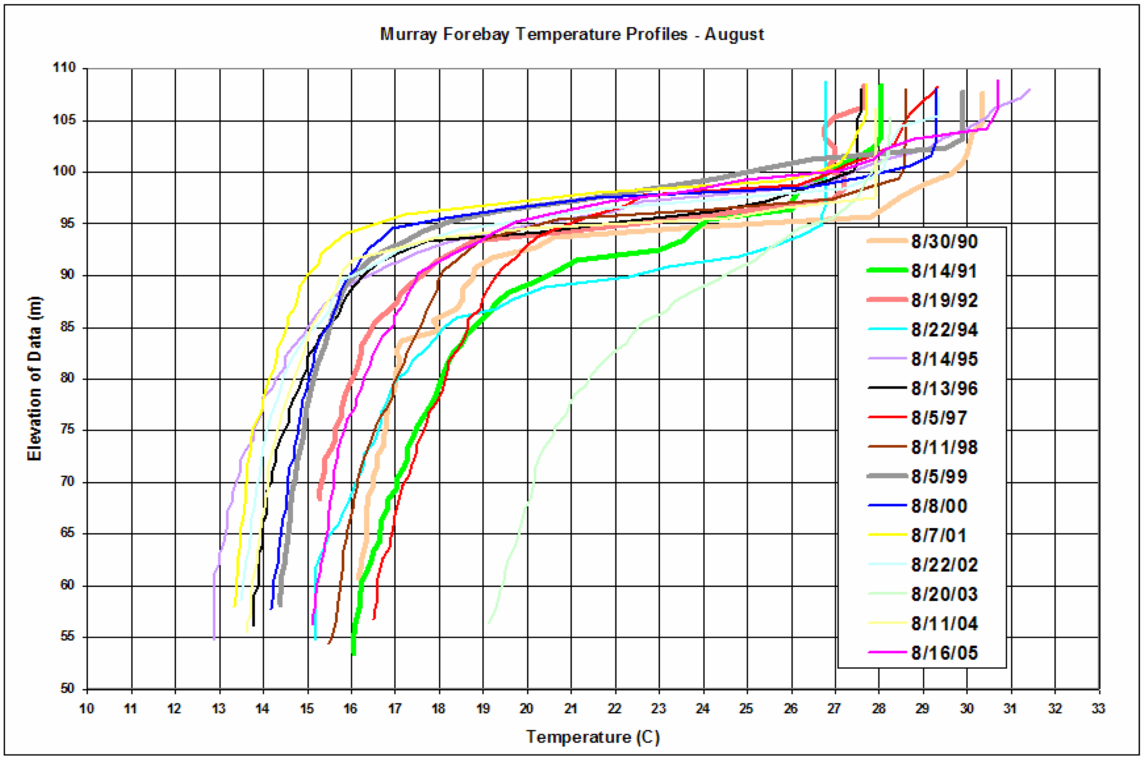

Figure 2-12. Lake Murray August Temperature Profiles, 1990-2005

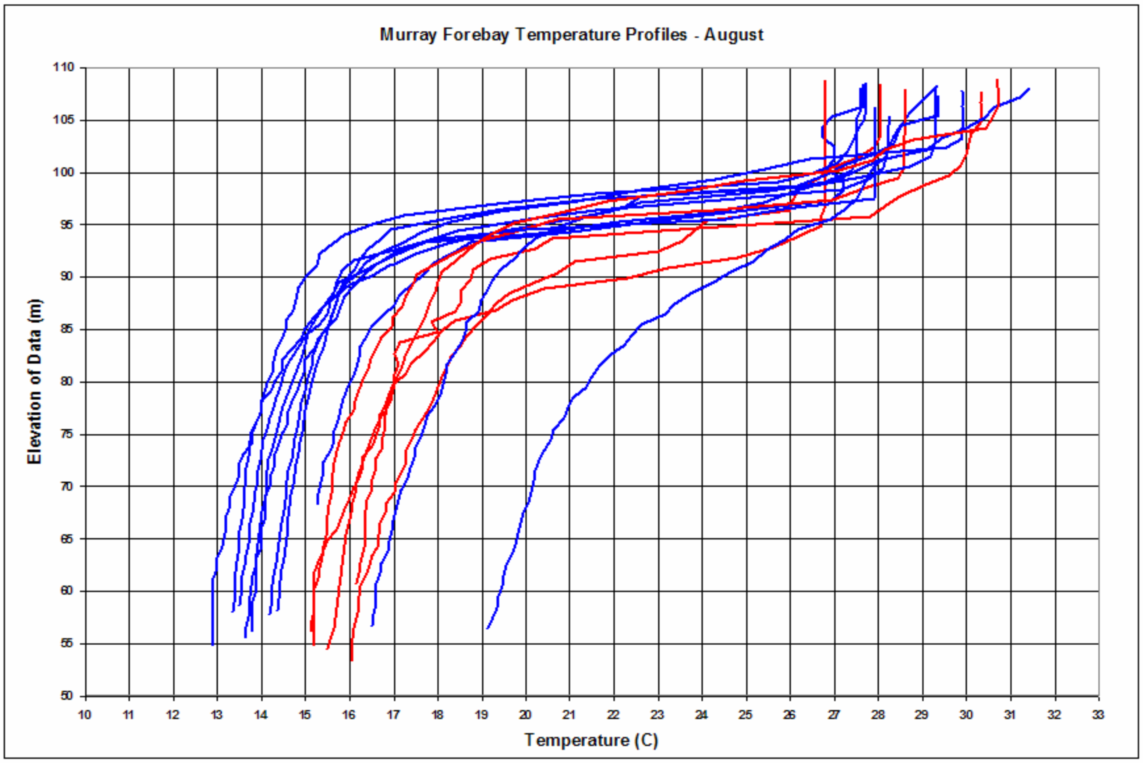

Figure 2-13. Lake Murray August Temperature Profiles, 1990-2005 - with Fish Kill Years in Red

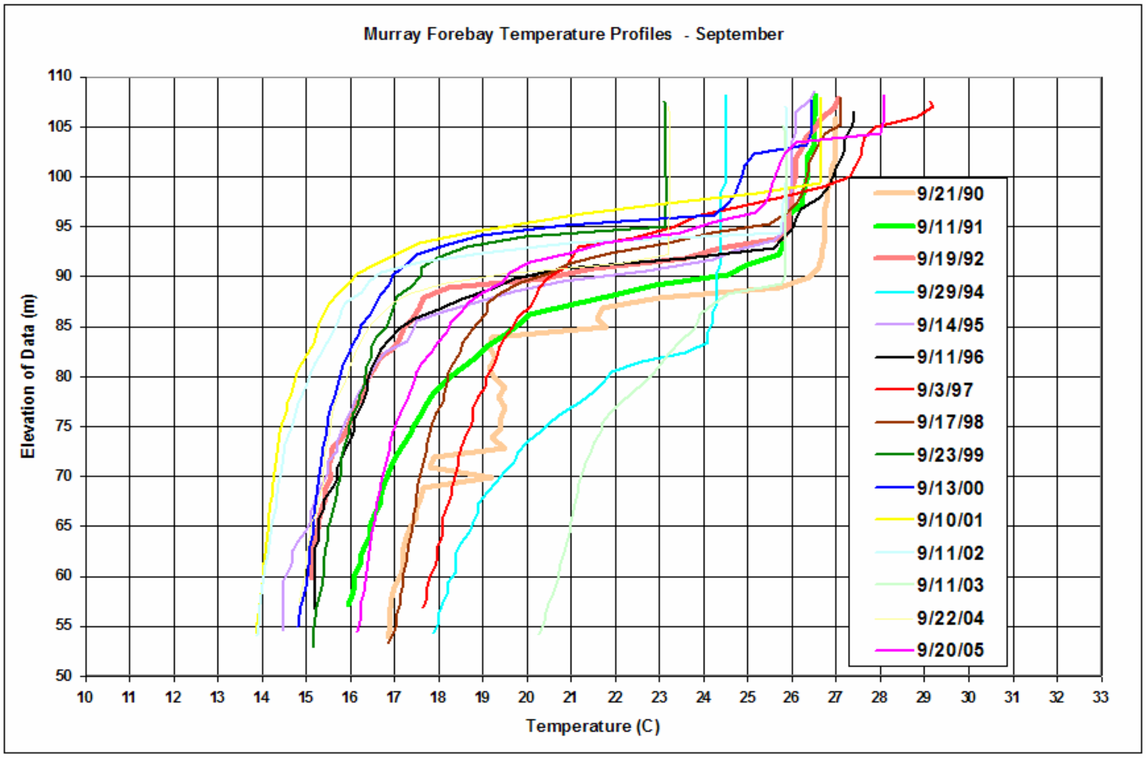

Figure 2-14. Lake Murray September Temperature Profiles, 1990-2005

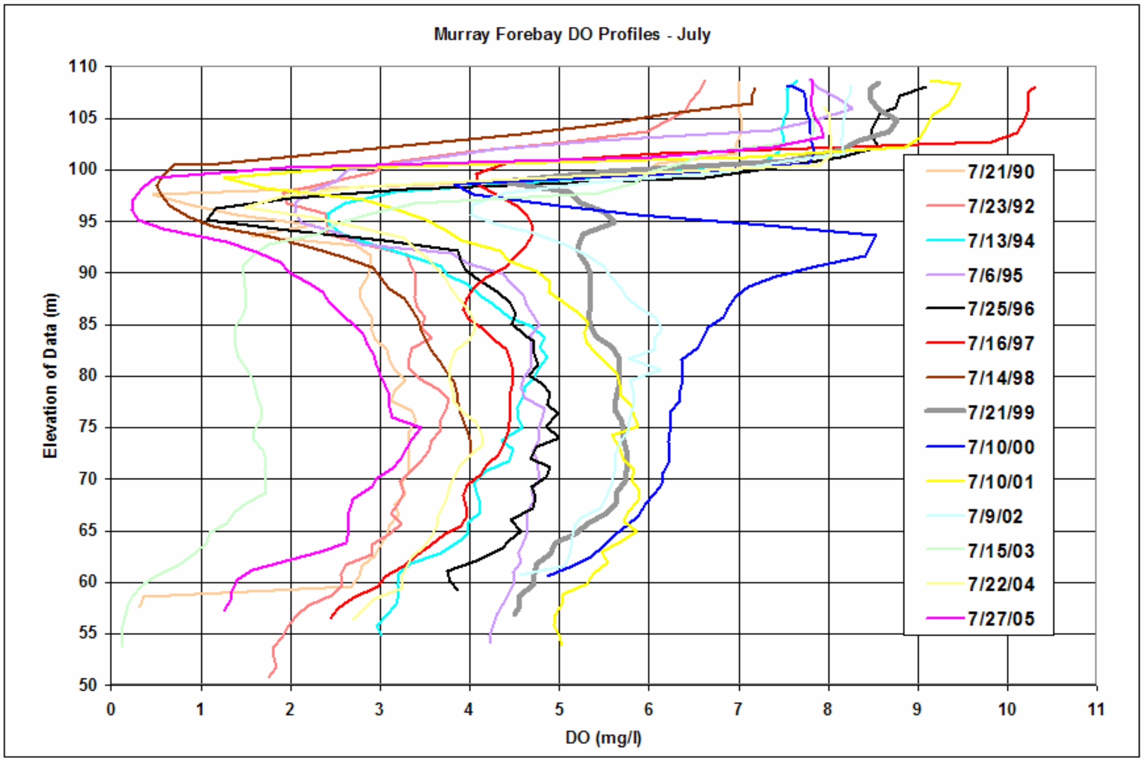

Figure 2-15. Lake Murray July DO Profiles, 1990-2005

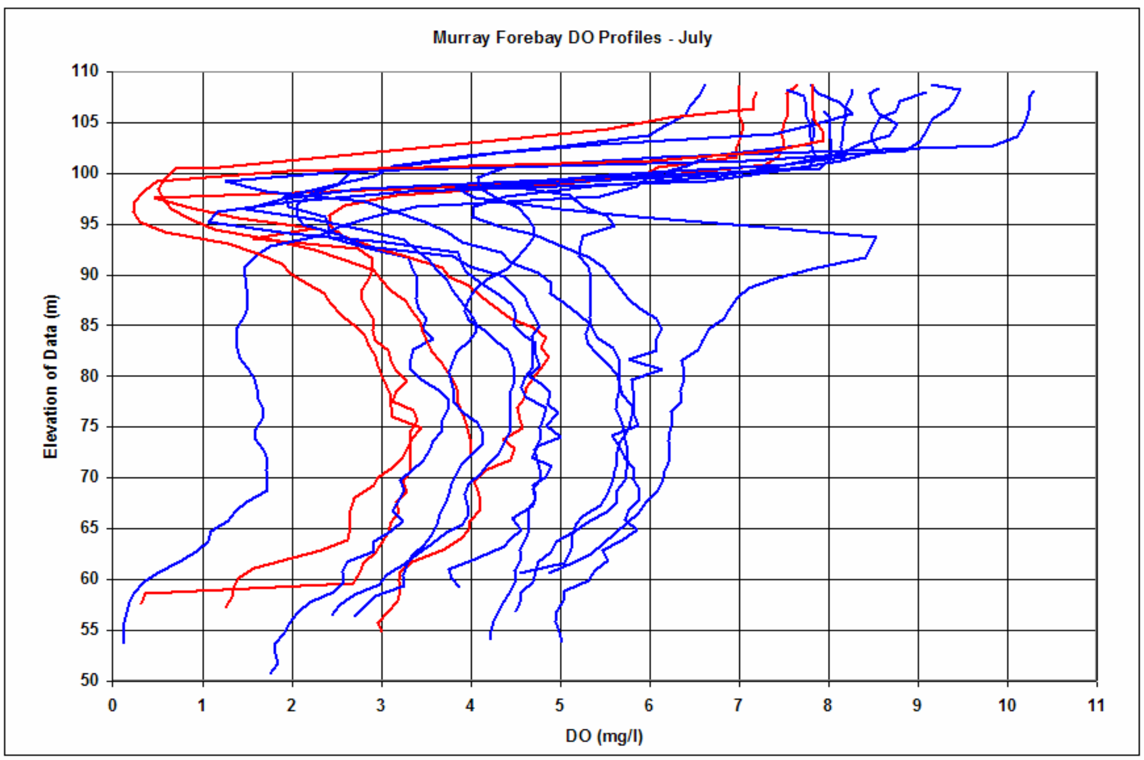

Figure 2-16. Lake Murray July DO Profiles, 1990-2005 - with Fish Kill Years in Red

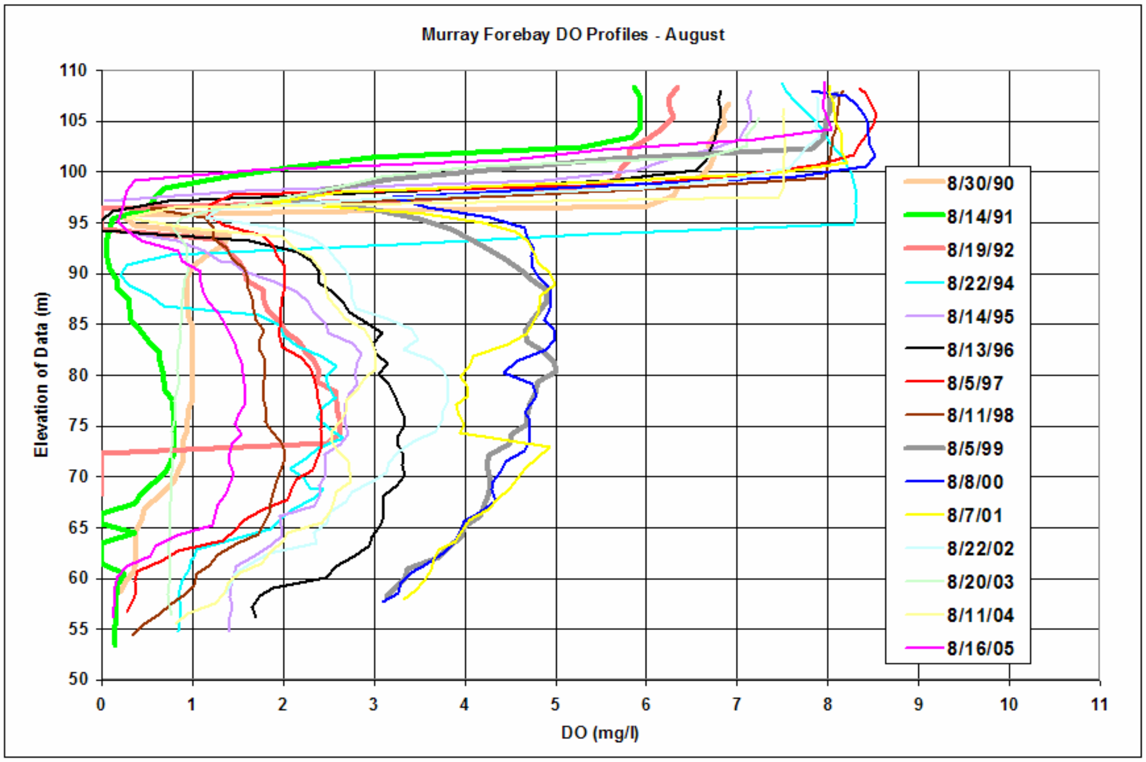

Figure 2-17. Lake Murray August DO Profiles, 1990-2005

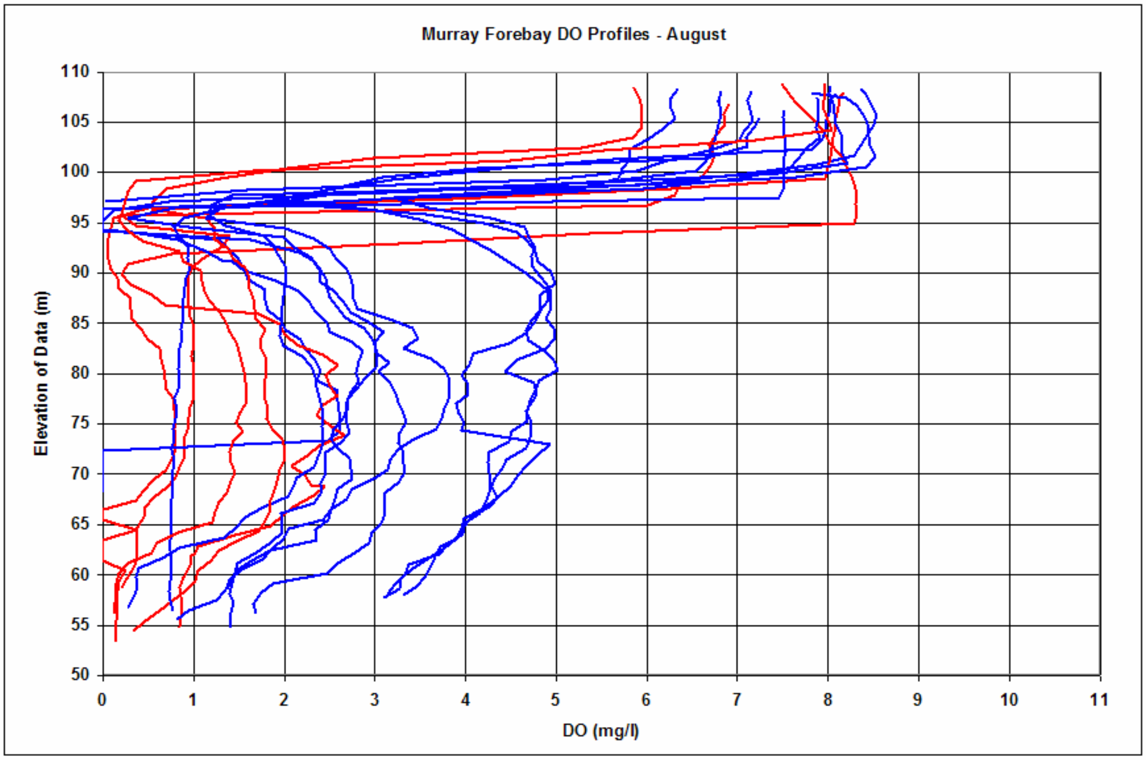

Figure 2-18. Lake Murray August DO Profiles, 1990-2005 - with Fish Kill Years in Red

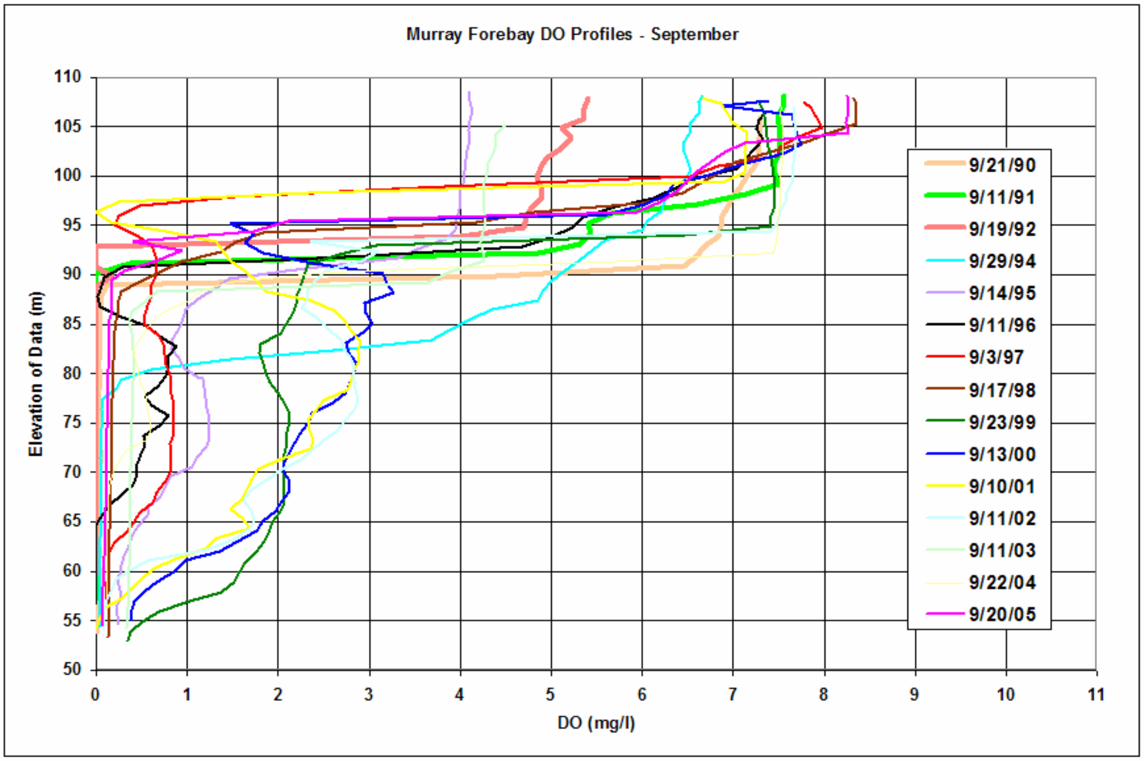

Figure 2-19. Lake Murray September DO Profiles, 1990-2005

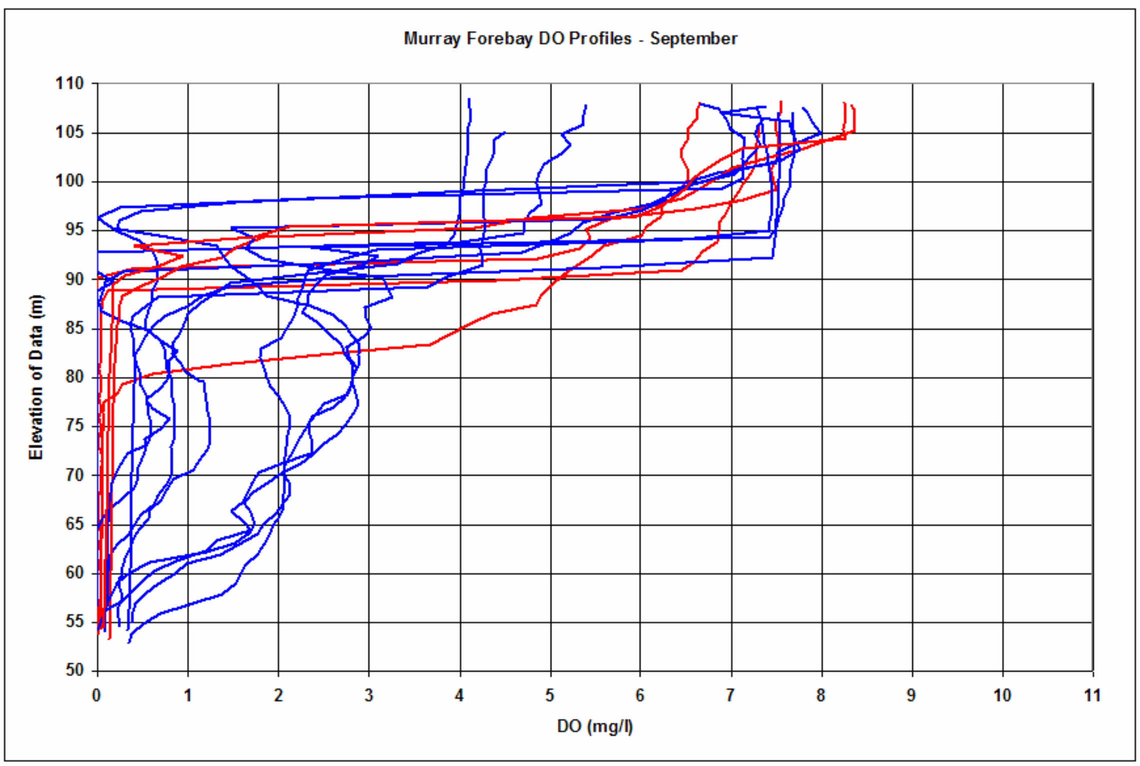

Figure 2-20. Lake Murray September DO Profiles, 1990-2005 - with Fish Kill Years in Red

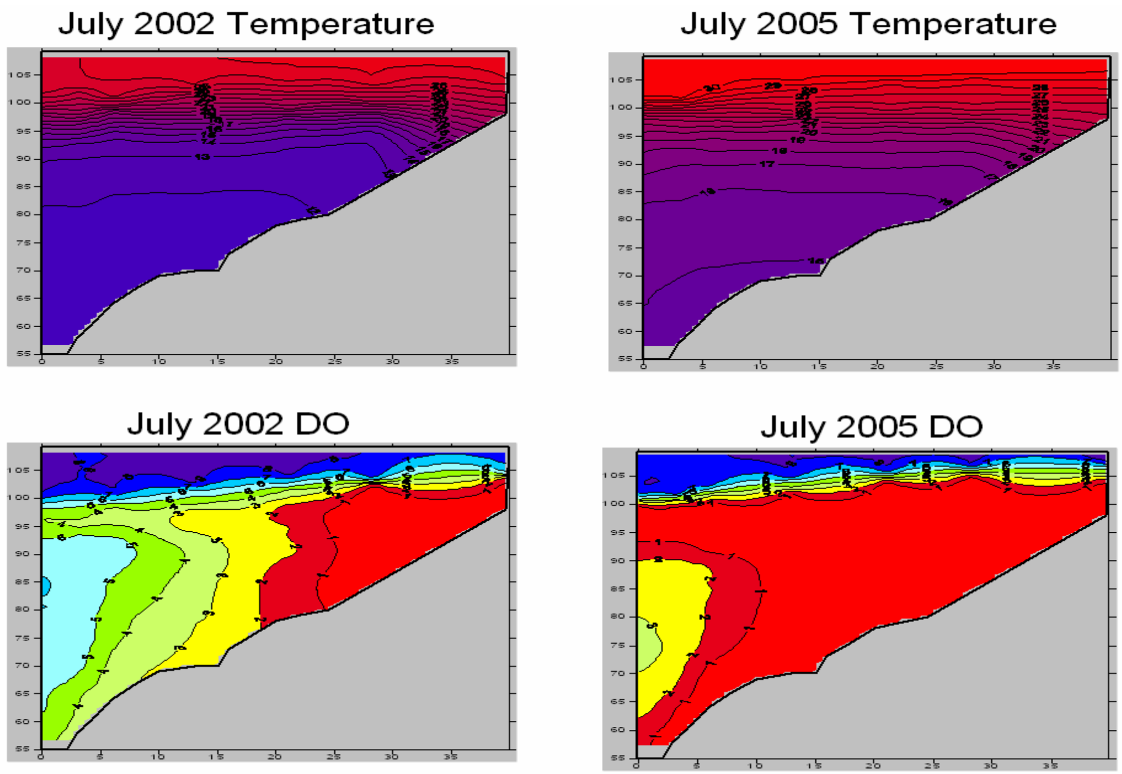

Figure 2-21. Lake Murray July Longitudinal Contour Plots

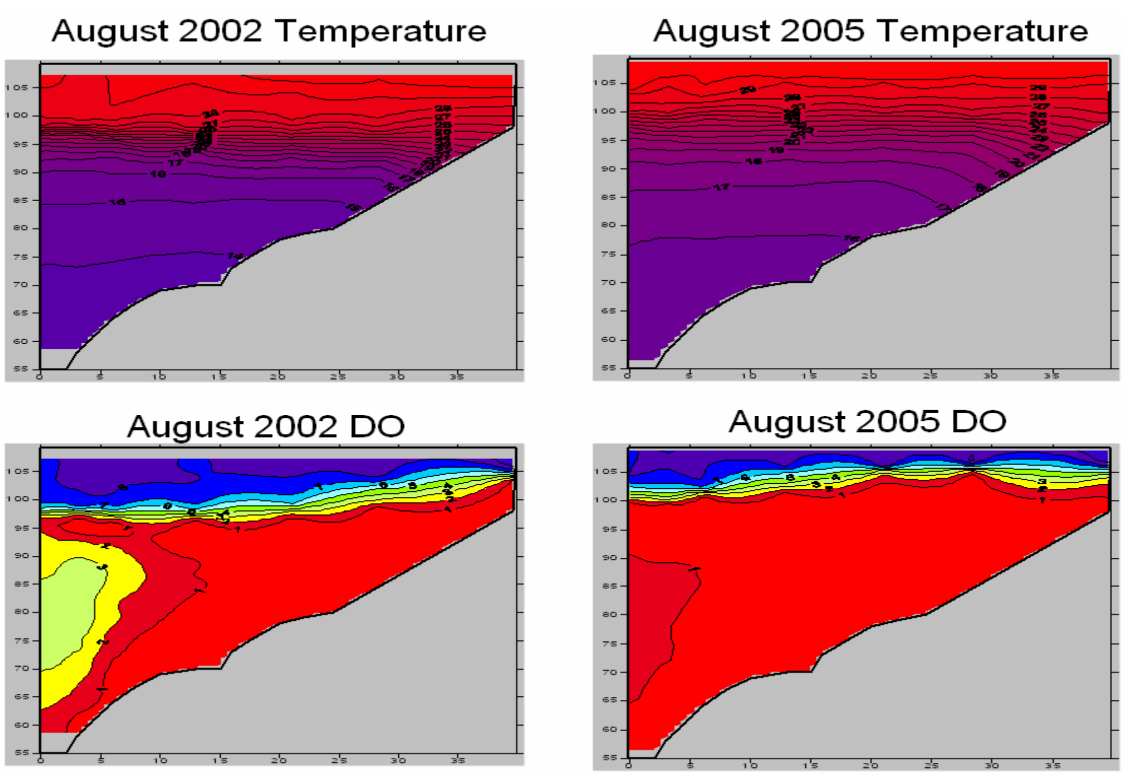

Figure 2-22. Lake Murray August Longitudinal Contour Plots

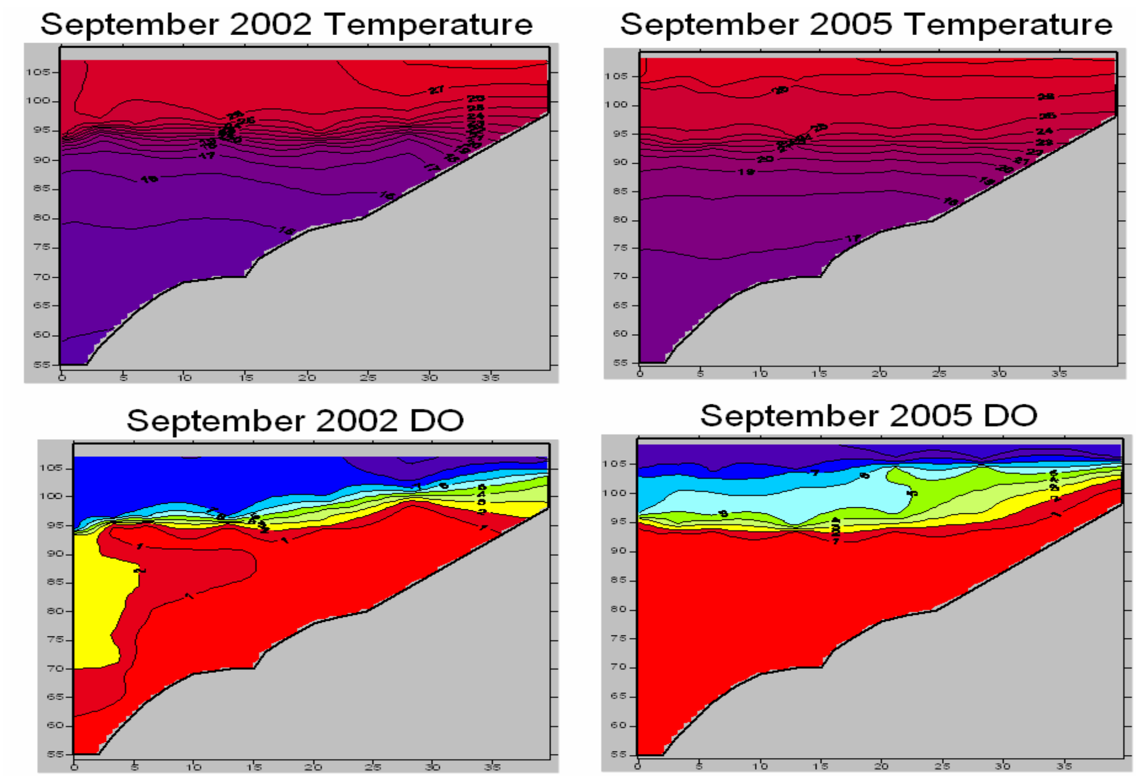

Figure 2-23. Lake Murray September Longitudinal Contour Plots

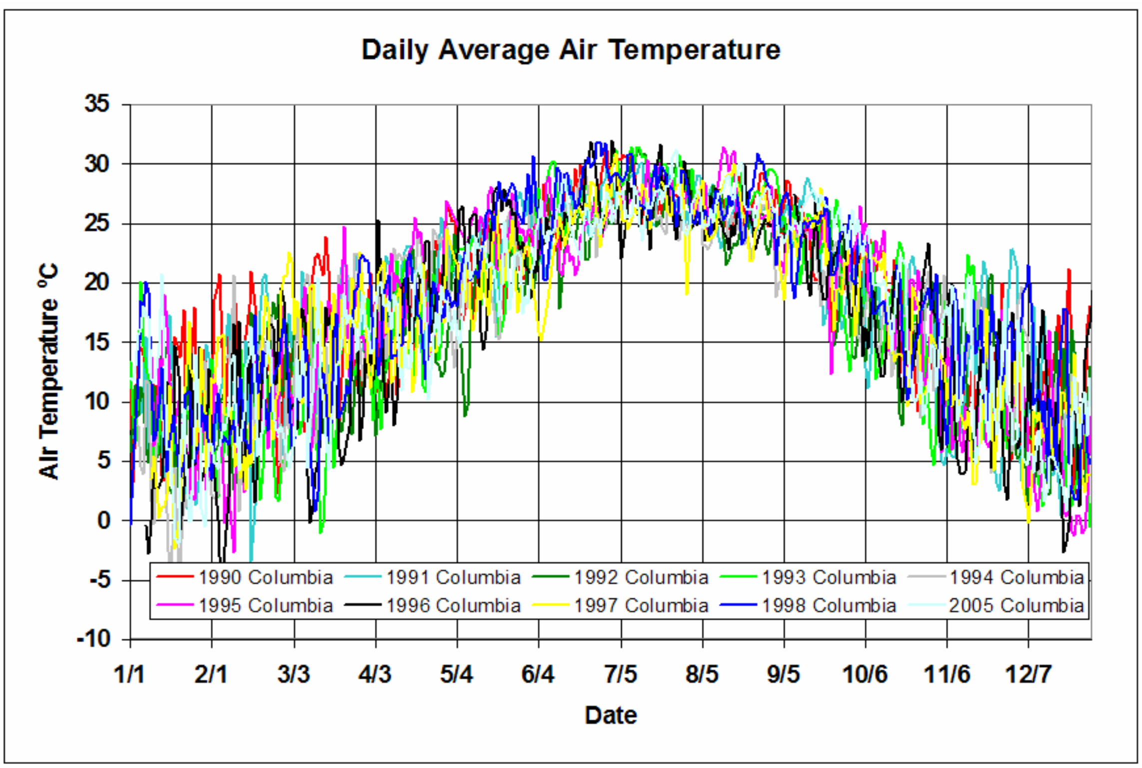

Figure 2-24. Columbia Air Temperature, 1990-2005

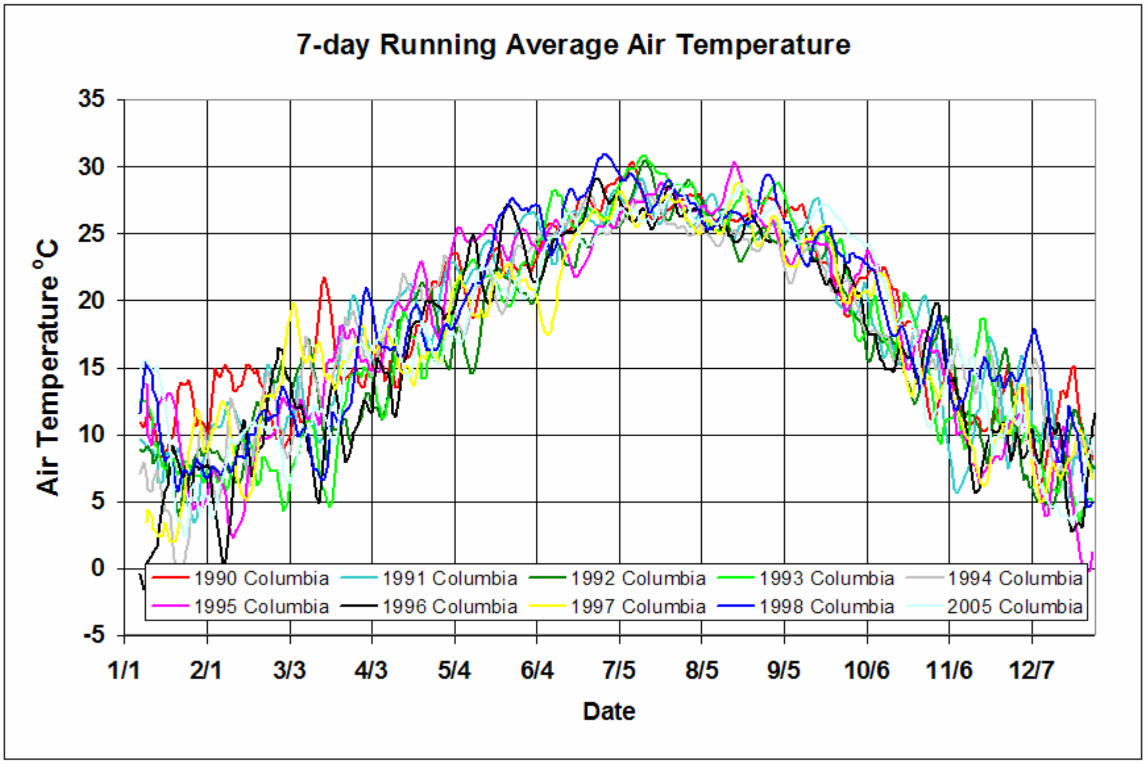

Figure 2-25. Columbia 7-day Average Air Temperature, 1990-2005

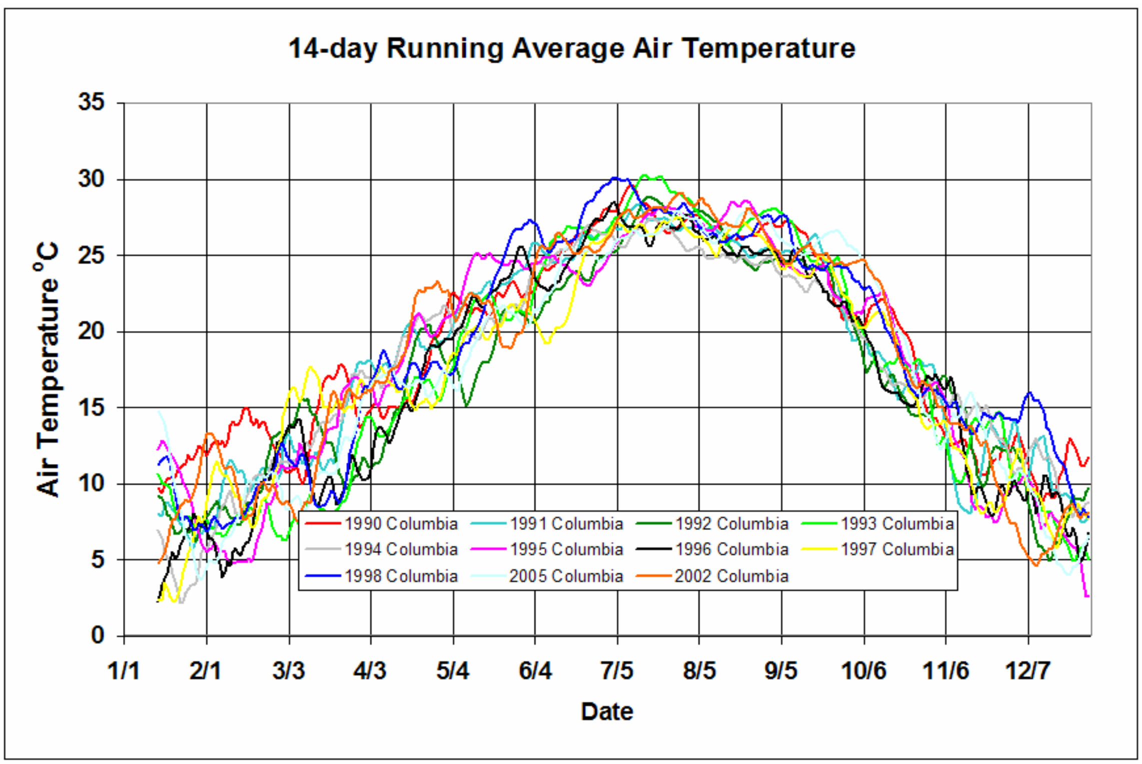

Figure 2-26. Columbia 14-day Average Air Temperature, 1990-2005

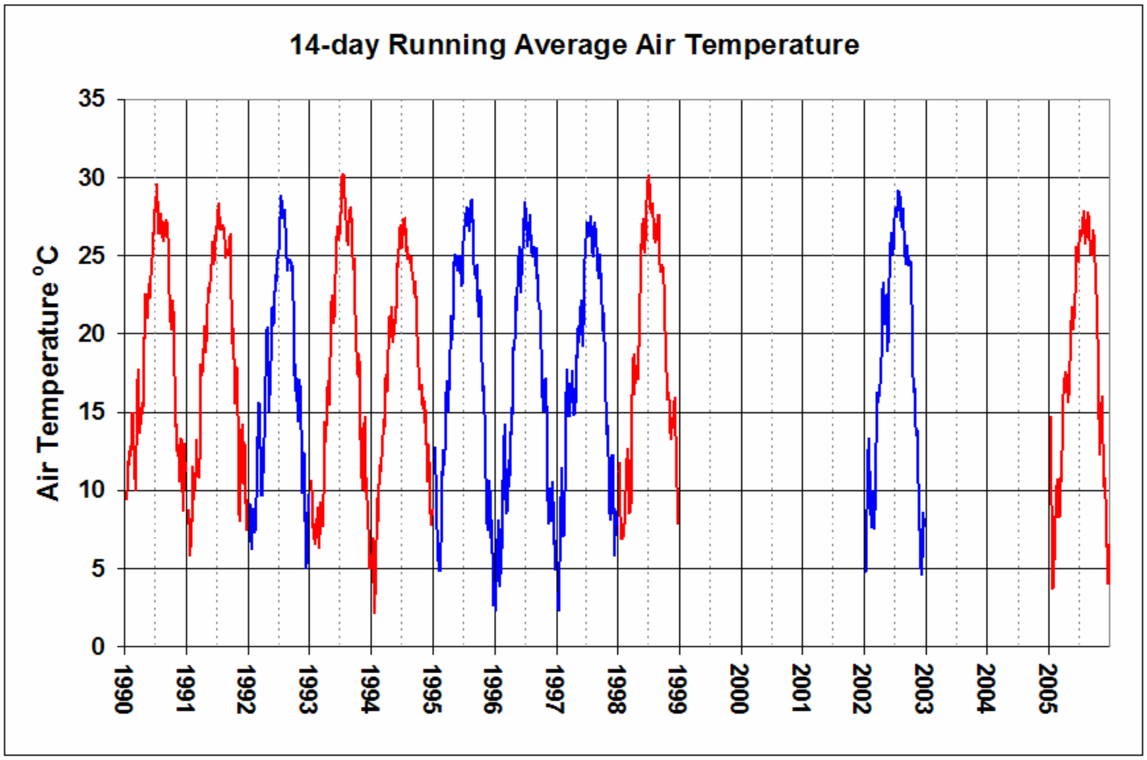

Figure 2-27. Columbia 14-day Average Air Temperature, 1990-2005

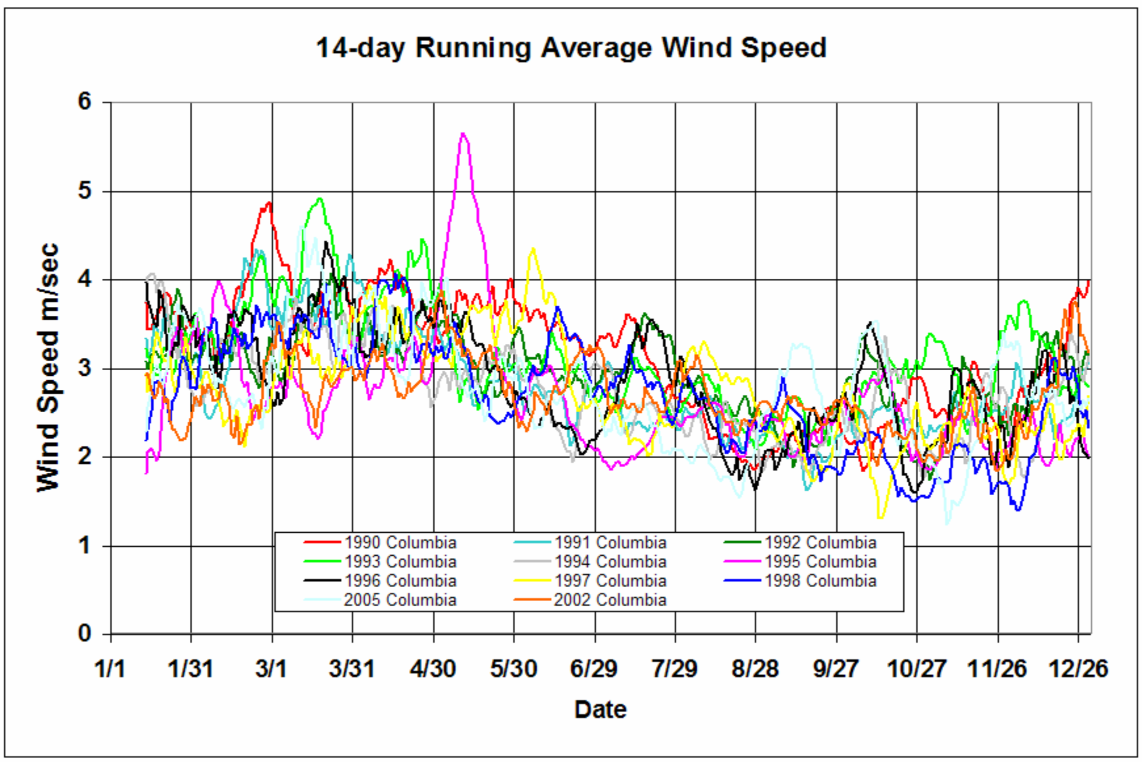

Figure 2-28. Columbia Wind Speed Data, 1990-2005

3. Model Calibrations for Each Year

The model was originally calibrated for 1992, 1996 and 1997. These calibrations were discussed and summarized in a 2006 report (Sawyer and Ruane, 2006). When it was decided to use the model to assess factors that might impact striper habitat, the model calibrated to additional years. The additional years for which the model was calibrated included 1991, 1998, 2000, 2001 and 2005. Of these years, there were documented fish kills in 1991, 1998 and 2005. The calibrations for these additional years are presented in Appendix 3.

During the original calibration process (1992, 1996 and 1997) many of the model inputs, including the coefficients, were adjusted to improve the calibrations for each year, resulting in different coefficients for different years. However, as the reconciliation process continued the differences in model settings for the different years converged and in the end were reconciled such that zero-order SOD and wind sheltering coefficient were the only variables that needed to be varied each year. Another adjustment that was made was in the winter-time dew-point temperature.

To evaluate how well the model simulated the observed temperature and DO profiles, two descriptive statistics were used. One statistic used was the absolute mean error (AME) which is the sum of the differences between the observed and predicted values divided by the number of pairs compared. The AME indicates how far, on the average, computed values are from observed values (Cole and Tillman, 2001). The second statistic used was the root mean square error (RMS). The RMS indicates that 67% of the model results versus observed data are within the value of the RMS.

4. Model Applications

Striped Bass Habitat Criteria

Striped bass habitat suitability has been defined by using three types of habitat: optimal, suboptimal and unsuitable (Crance, 1984, as referenced by Schaffler, Isely and Hayes, 2002). Optimal habitat is defined as temperatures between 18.0 and 24.0 ^{o}C and DO concentrations exceeding 5.0 mg/L. Suboptimal habitat is defined as temperatures between 12.0 and 18.0 ^{o}C or between 24.0 and 30.0 ^{o}C and DO concentrations of 2.5 to 5.0 mg/L. Unsuitable habitat is defined as water having temperatures warmer than 30 ^{o}C or DO concentrations less than 2.5 mg/L.

These criteria were considered for all modeled years using current conditions (i.e., pool elevations, nutrient loads, and unit operations); and as shown in Figure 4-1, optimal habitat as defined by Crance is not available in Lake Murray generally during the months July through September. Figure 4-2 shows available habitat for temperature less than 27 ^{o}C and DO greater than 2.5 mg/L. These criteria were developed for Lake Murray using a reconciliation process considering fish kills listed in Table 2-1 and the model results for each year. Figure 4-3 shows available habitat for temperature less 30 ^{o}C and DO greater than 2.5 mg/L, indicating considerably greater habitat than would be consistent with the observed fish kills. Therefore the criteria used for the rest of the modeling applications for Lake Murray were temperature less than 27 ^{o}C and DO greater than 2.5 mg/L.

Pool Level Management

The first consideration for modeling was the effects of changing the pool level operations for Lake Murray. The pool levels considered for model evaluations were 358' during the months May through August with minimum winter pools at 350' and 354'. The following scenarios were modeled:

- 354' (Jan1) to 358(May1⇨Sept1) to 354 (Dec 31)
- 350' (Jan1) to 358(May1⇨Sept1) to 350 (Dec 31)

Assumptions:

- Assumed 500 cfs for minimum release
- Assumed reserve generation averaged 3hr every two weeks at 18,000 cfs
- Balance of releases were assumed to be used to supplement system demand.

Approach:

- The above scenarios were developed by KA using daily average flows using HEC-ResSim.
- CE-QUAL-W2 was run using daily average flows and release flows were adjusted so that target pool levels were attained.
- Using the daily average flows that were adjusted using the CE-QUAL-W2 model, the hourly flows for each day were developed using the assumptions above.

The results of the model runs for the pool level alternatives are presented as follows:

- for the pool level elevations, Figures 4-4 through 4-11,
- for the zone volume plots for striped bass habitat, Figures 4-12 through 4-19,
- for temperature in the releases, Figures 4-20 through 4-27, and
- for DO in the releases, Figures 4-28 through 4-35.

These results showed the following:

- Pool level elevations attained during the summer months were affected by the minimum winter pool elevation being at 350' in the two low flow years (2000 and 2001), but this was caused by water releases at Saluda Hydro being in excess of that needed for minimum releases and reserve generation for the two cases for winter pool elevations. If the releases from the lake had been reduced to minimum flows and reserve generation, the pool level would have been raised to 358'±. [Note: in 2001, about 47,000 ac-ft of excess water was released in January; in 2000, about 92,000 ac-ft of excess water was released in January. Each foot of water between elevation 354' and 358' contains about 47,000 ac-ft of water.]
- The volume of striped bass habitat was increased for the years 1992, 1996, and 1998. The volume increased marginally between the winter minimum pool levels

for 2000, but this increase would not have occurred if the releases from the lake had been reduced to minimum flows to allow the pool level to rise to 358'.

- The temperature of the releases was cooler for the years 1991, 1992, 1996, 1997, and 1998. Temperature was not cooler for the low flow years. It was not cooler for 2005 because the base case for 2005 already involved maintaining a higher pool level during the summer.
- The DO in the releases was similar for all the years modeled except the occurrence of the low DO lagged in time for the years 1991 through 1998.

Unit 5 Operations

The second consideration for modeling was the effects of changing the unit preference for operations from the current operating procedure to one where Unit 5 is the preferred first unit for operation. The current procedure and the alternative procedure were modeled as follows:

- Unit operations for the current procedure for all modeled years:
    - Units 1, 3 and 4 – Q < 9,600 cfs
    - Unit 5 – 9,600 < Q < 15,600 cfs
    - Unit 2 – Q > 15,600 cfs
- For the case where Unit 5 is operated first (for Q < 6,000 cfs), water is not released from Units 1-4 until release flow from Saluda Hydro exceeds 6000 cfs.

When Unit 5 is operated first, cooler water on the bottom of the lake is conserved leading to the availability of striper habitat improving in some years, and temperature in the releases being cooler in most years except low flow years.

The benefits to striped bass habitat by operating Unit 5 preferentially are shown in Figures 4-36 through 4-43. These figures show that habitat increased in 1997 (about 18 days of improvement to avoid near-zero model-derived striped bass habitat) and 1998 (about 10 days of improvement to avoid near-zero model-derived striped bass habitat), and did not decrease in any of the other years. It should be noted that striped bass habitat was depleted in 2005 even though the pool level was near 358' most of the summer and Unit 5 was used much of this year. The probable explanation for this occurring in 2005 is that March through June flows through the reservoir were high, in fact the June flows were twice the normal flow recorded over the period 1989 through 2005. Also, the DO in the hypolimnion in July was the lowest recorded by SEC&G (see figures 2-14).

Tailwater Temperature Considerations

Concern was expressed by the TWC that operation of Unit 5 preferentially would impact the temperature of the tailwater. There was considerable discussion about balancing the use of Unit 5 preferentially versus Units 1-4 preferentially considering the benefits to striped bass habitat in the lake and coolwater for the tailwater fishery, especially considering the warming of the tailwater as the river flows downstream. Also, the group raised the question as to whether it would be best to use temperature criteria to trigger preferential unit operations or a set date each year.

REMI was asked to develop a proposed unit operations protocol that accounted for the balancing of these considerations. To develop these recommendations, the following information was considered:

- The increase in temperature in the tailwater under the range of unit flow conditions as well as the month of the year, i.e., temperature increases during May thru Sept versus in October and versus in November.
- The release temperature and it's variation between U5 and U1-4 over the course of the year as well as between years
- Balancing the timing of the Unit 5 shift to Units 1-4 for minimum flows in May-July with the increased temperatures in the releases in September due to the consumption of the coolwater over the course of the summer
- Striper habitat benefiting from preserving cool bottom waters by releasing water through Unit 5
- The range of hydrologic conditions: wet years, dry years, normal years
- DO in the releases from U5 in late October and November. DO increases in the releases from Unit 5 about one month before DO increases in Units 1-4, so it's

advantageous to use Unit 5 to the extent practical during this last month of the low DO period.

The temperature increase in the tailwater was determined by using the USGS monitors in the tailrace and the river downstream near the mouth (i.e., gage numbers 02168504 and 02169000). Table 4-1 summarizes the determinations of the temperature increases at different operating levels at Saluda Hydro for the specified months. Temperature increases in November were insignificant.

Table 4-1. Temperature increases in the tailwater between Saluda Hydro and the USGS monitor at Columbia.

Generation levels and months of operation	Mean temperature increase, ^oC	Mean temperature increase + 2*Std Deviation, ^oC
Less than 1000 cfs, May-Sept	3.2	6.4
2500-3000 cfs, May-Sept	1.3	2.9
5000-6000 cfs, May-Sept	1.0	2.0
2500-6000 cfs, Oct	0.7	1.5

Release temperatures were reviewed for current conditions as well as the modeled conditions discussed in the previous two sections dealing with the effects of maintaining pool levels near 358’ over the months May through August and giving preference to Unit 5 operations to preserve coolwater on the bottom of the lake. This review combined with the analysis of the temperature increase in the tailwater indicated that the desired maximum temperature for the releases from Saluda Hydro would be about 14 ^oC. However, when this level was considered for a trigger for switching from Unit 5 preference to a Unit 1-4 preference, the model results on the release temperatures indicated that in several years the trigger dates would be in May (1991, 1997) or early June (1998, 2005) and cause the temperatures of the releases to be warmer than desired in late summer, i.e., 16 to 17 ^oC in mid-September. Therefore, a trigger of 15 ^oC was considered to attain cooler water in late August and September. Unfortunately, in some years the 15 ^oC level did not occur until late summer (1992, 1996, and 2000) and temperature of the minimum releases in these years was between 14 and 15 ^oC for about two months. After attempting to balance these trigger temperatures over the eight modeled years, it became evident that it was best to select a date that would attain the best balance of all factors considered, including considering meteorology combined with minimum flows. Beyond these factors two additional considerations entered the reasoning for selecting a date rather than a target temperature: 1) minimum flow maintenance in the future will result in minimum flows occurring a higher frequency of time; and 2) aeration of minimum flows sometimes starts in mid-June and Units 1, 3, and 4 are used for aerating the releases of minimum flows. Therefore, the date June 15 was selected for model exploration for all eight of the modeled years.

The following unit operations protocol was selected and evaluated using the model runs:

> ***For minimum flows***, use units 1, 3, or 4 June 15 thru Dec 1 (because they aerate at 500 cfs, and this provides the coolest water for the period when the tailwater heats the flow in the river down to the mouth) and U5 for Dec 1 to June 15 (this conserves the cool water in the bottom of the lake for releases to the tailwater during the summer and increases Striper habitat, too.) Using the units 1, 3, or 4 starting June 15 was recommended because starting earlier resulted in warmer releases in Sept and starting later caused warmer water in the releases. Triggers at 14 C and 15 C were considered, but neither worked well over the range of hydrologic conditions at Saluda. During the warmest months of the year (mainly June thru September), the temperature of the tailwater can increase over 6 ^{o}C by the time it reaches the USGS gage at Columbia. The average increase in temperature at minimum flow is 3.2 C. While these conditions will result in temperature > 20 for brief periods of time, this protocol will improve temperature over current conditions. Also, data collected in recent years in coldwater fish rivers in Northern states like MI and PA as well as in the natural trout streams and rivers in the Smoky Mountains all show temperature conditions exceeding 20 ^{o}C for brief periods.
>
> ***For generation flows (i.e., flows > minimum flow)***, use Unit 5 preferentially for 11 months of the year: November 1 until October 1 of the following year, and use units 1-4 preferentially in October. Using Unit 5 preferentially for generation conserves cool water in the bottom of the lake for minimum flows during the warmest months and for striper habitat. Release temperatures during generation do not warm as much as minimum flows. Releases at 2500-3000 cfs normally increase in temperature by 1.3 ^{o}C and can increase by 3 ^{o}C on rare occasions. Releases at 5000-6000 cfs normally increase in temp by 1.0 ^{o}C and can increase by 2 ^{o}C on rare occasions. October is consistently the month each year when the releases from Saluda are the warmest, so it's best to release water from one of the units drawing water from the bottom of the lake.

The results of the model runs using this protocol for unit operations are presented in Figures 4-44 through 4-74, and included in these figures are the following:

- for time-series of temperature and frequency plots, Figures 4-44 through 4-59,
- for DO in the releases, Figures 4-60 through 4-67, and
- for the zone volume plots for striped bass habitat, Figures 4-68 through 4-75.

These results of using the proposed unit operations protocol showed the following:

- Temperature in the releases was improved for all years, compared to other unit operational procedures. The temperature at the 5 to 20% levels of exceedence frequency was usually cooler, and at the 80% levels of exceedence frequency was usually warmer. This characteristic for temperature exposure for fish is best for trout fish growth rates. The maximum temperatures for the proposed protocol were usually about the same as the next-best alternatives for this consideration, but temperature results for near-maximum levels was much better for the proposed protocol.
- The proposed protocol for unit operations for minimum flows and generation flows had very little or no effect on striped bass habitat enhancements achieved previously by increasing summer pool levels and using Unit 5 preferentially for 1991, 1992, 1996, 2000, 2001, and 2005. For 1997 and 1998, striped bass habitat was marginally impacted by the proposed protocol for unit operations for minimum flows and generation flows, and the impacts were considerably less than the improvements provided by the higher target summer pool level and Unit 5 preferential operations in the months preceding June 15.

Considerations for Meteorology

The TWC raised a number of questions about the influence of meteorology on striped bass habitat in Lake Murray. As mentioned in section 2 of this report, meteorology data were analyzed to see if there was a relationship between meteorology and striped bass habitat, but no relationship was found. However in sensitivity runs, it was found that in some cases, when meteorology from a year in which a fish-kill did not occur is applied to the flow from a fish-kill year, the striped bass habitat may increase. An example of this is shown in Figure 4-76. In this case the 1992 meteorology was applied to the 2005 flows. With 2005 flow and meteorology the striped bass habitat is depleted around August 10, and does not return until around September 5. However, when the 1992 meteorology is applied to these same flow conditions, some striped bass habitat remains throughout the summer.

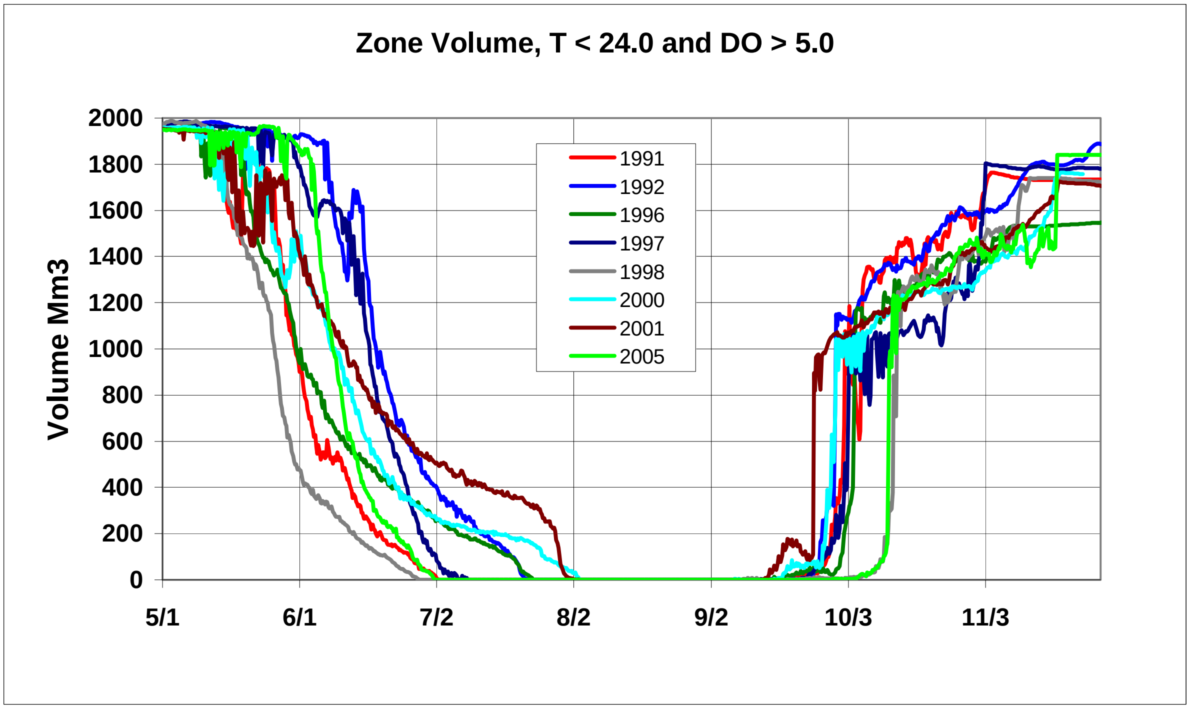

Figure 4-1. Model Predicted Habitat Volume, T < 24 and DO > 5

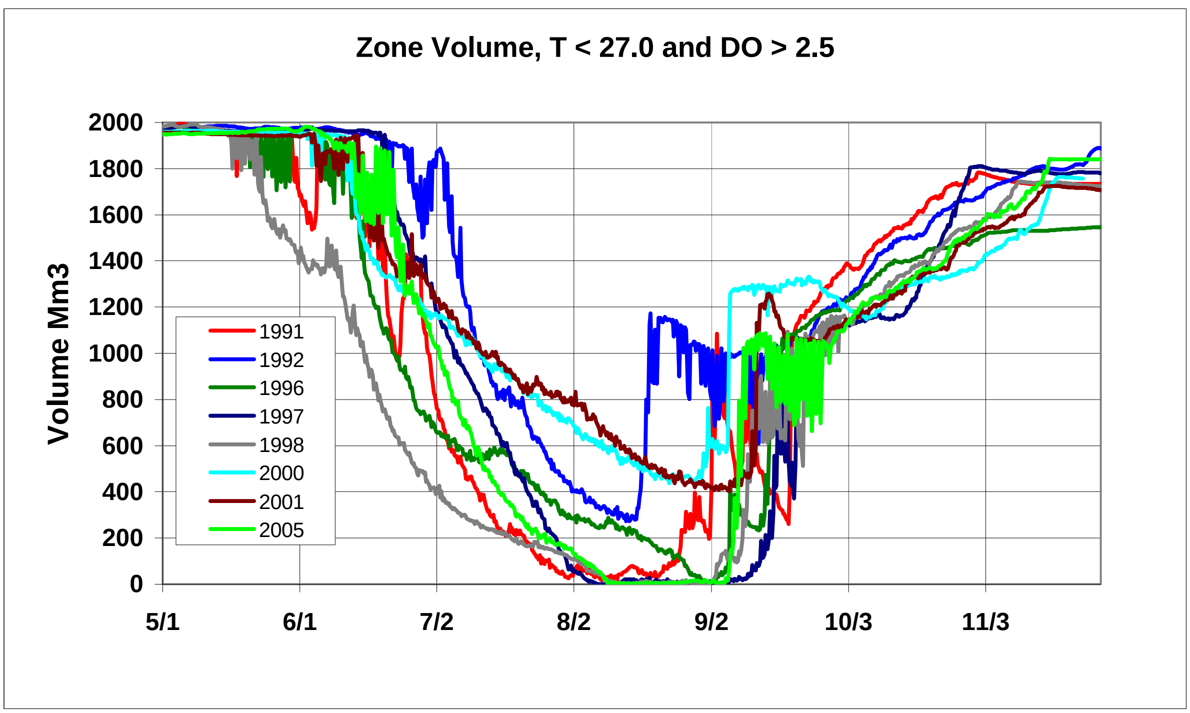

Figure 4-2. Model Predicted Habitat Volume, T < 27 and DO > 2.5

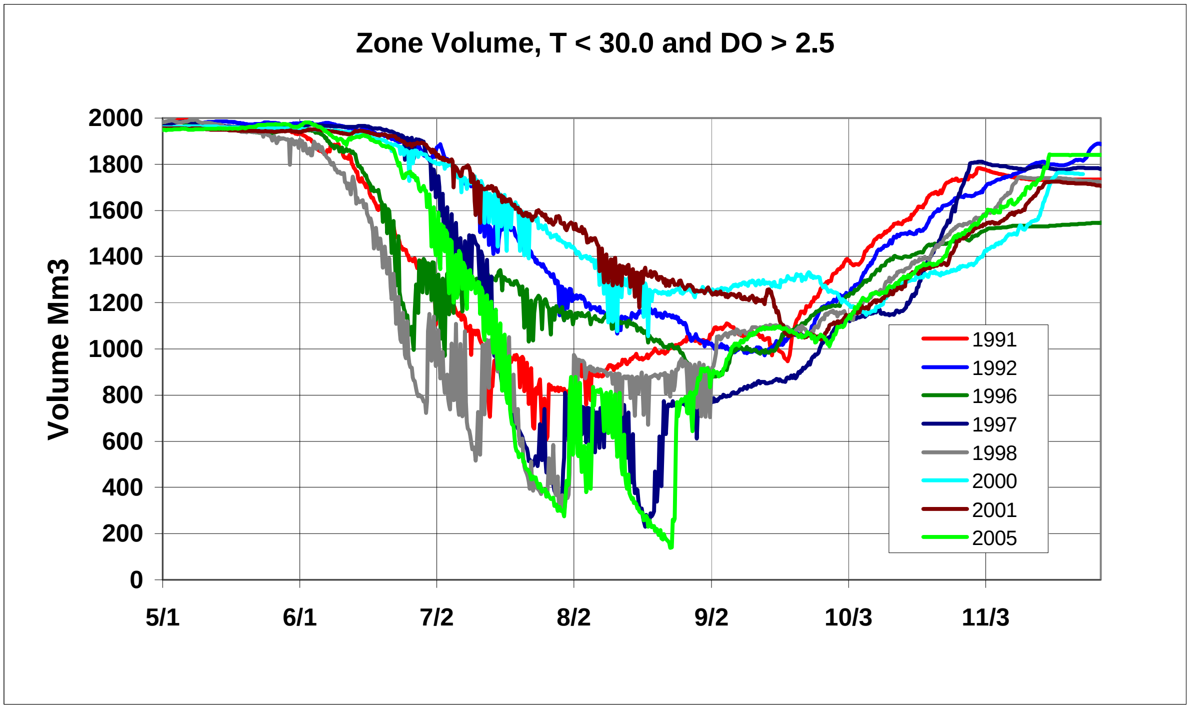

Figure 4-3. Model Predicted Habitat Volume, T < 30 and DO > 2.5

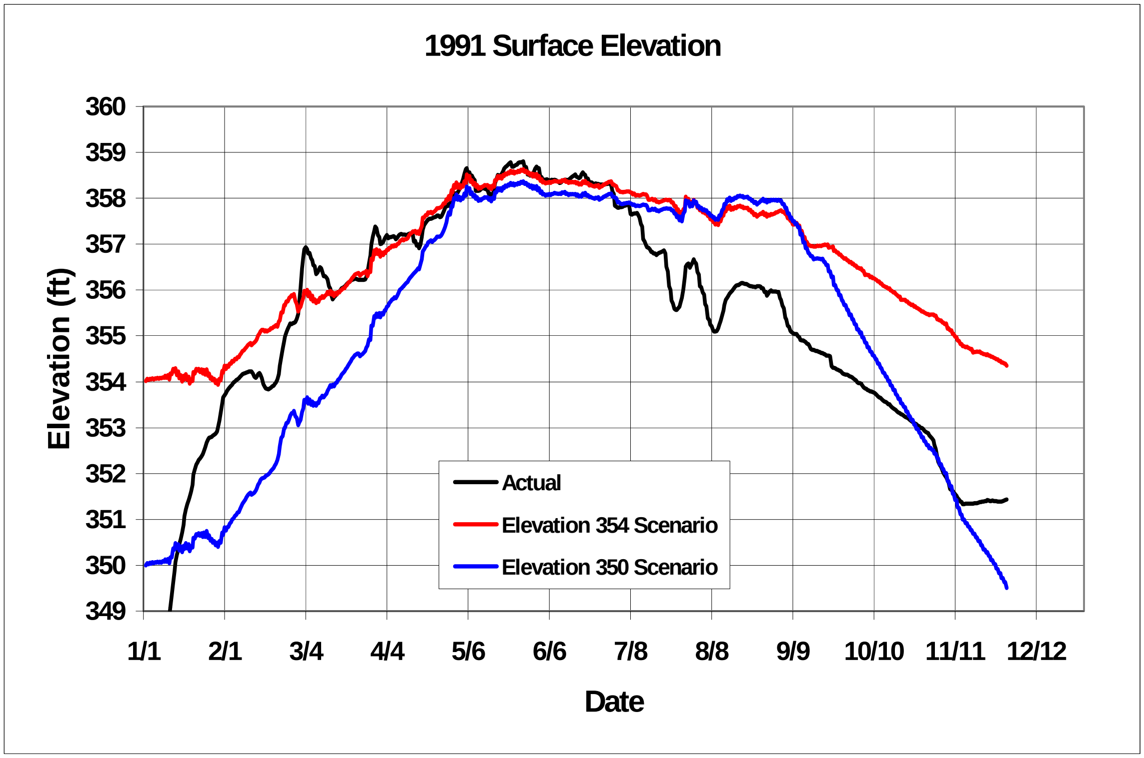

Figure 4-4. 1991 Lake Murray Surface Elevation

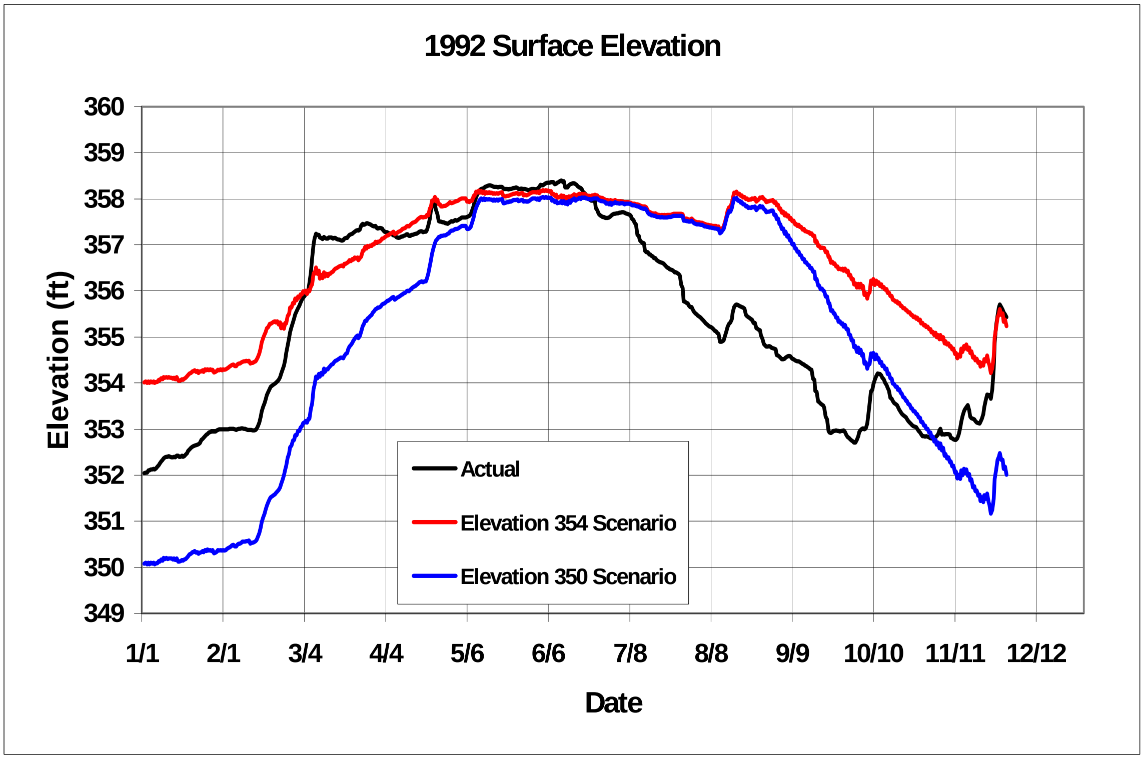

Figure 4-5. 1992 Lake Murray Surface Elevation

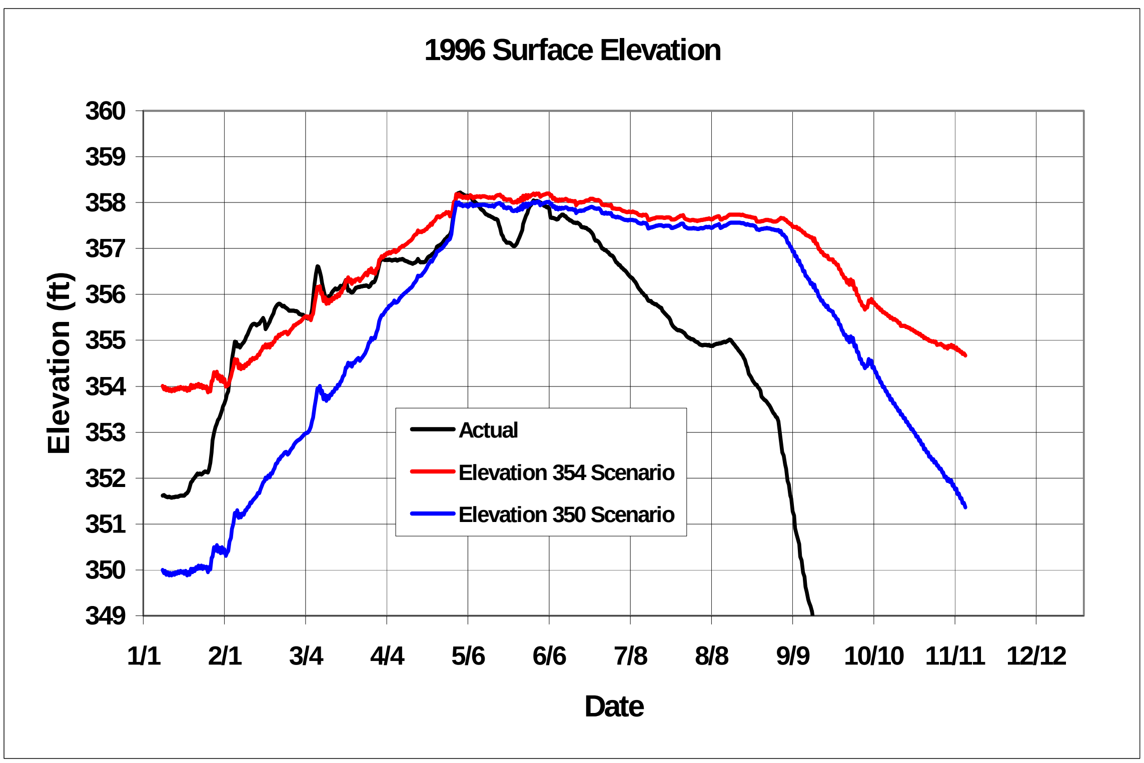

Figure 4-6. 1996 Lake Murray Surface Elevation

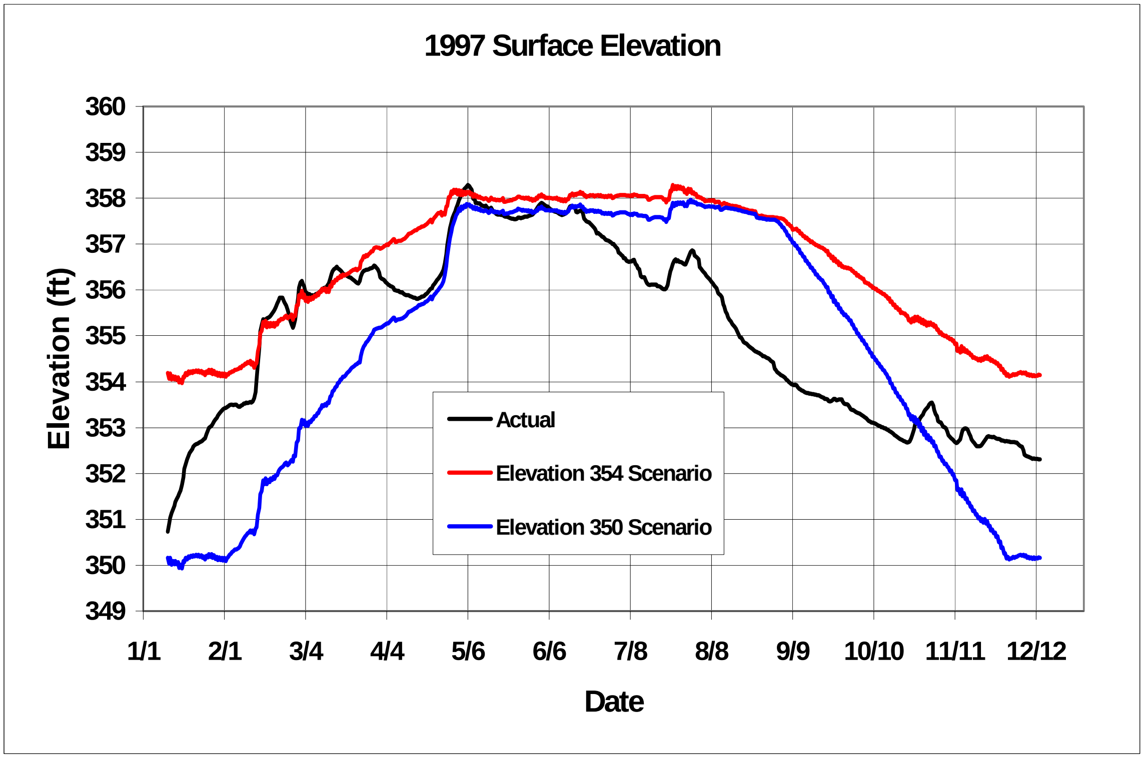

Figure 4-7. 1997 Lake Murray Surface Elevation

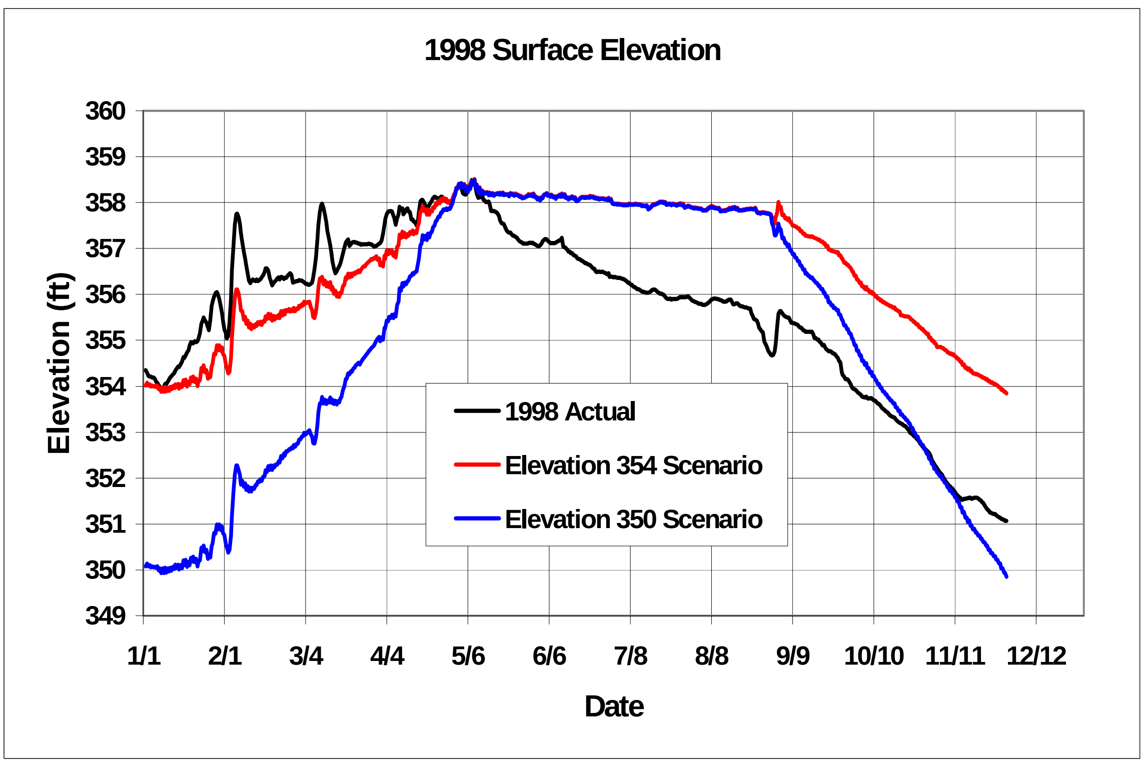

Figure 4-8. 1998 Lake Murray Surface Elevation

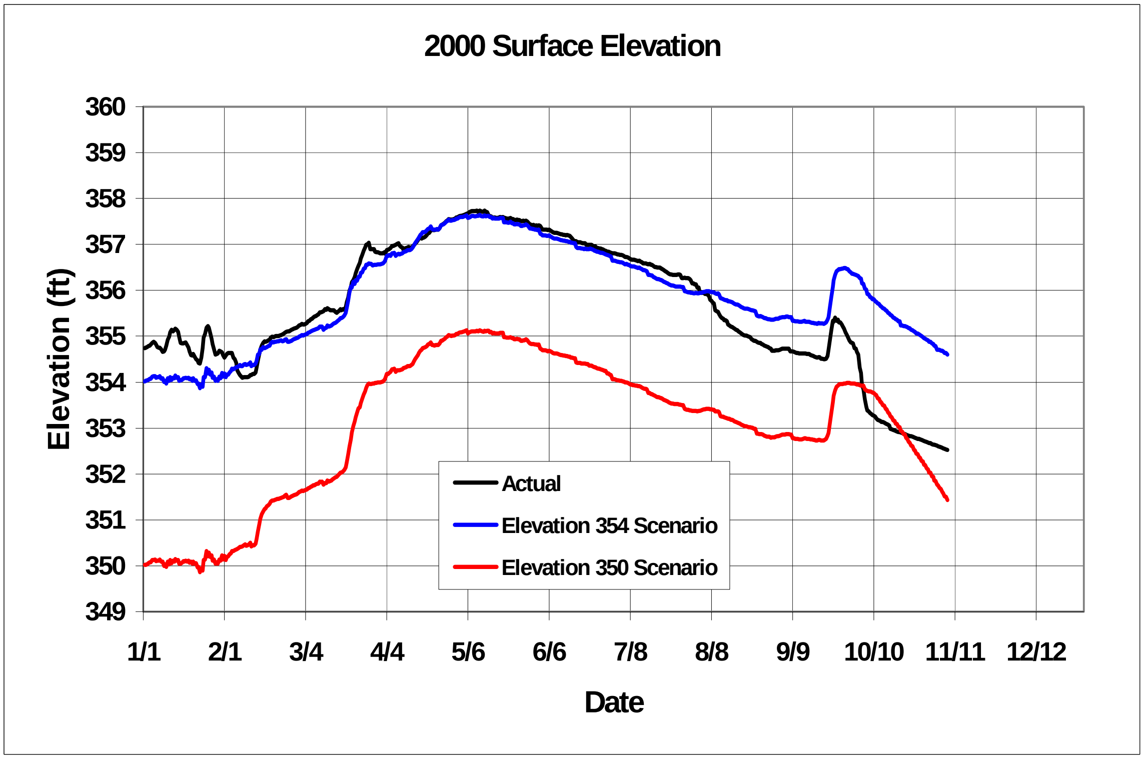

Figure 4-9. 2000 Lake Murray Surface Elevation

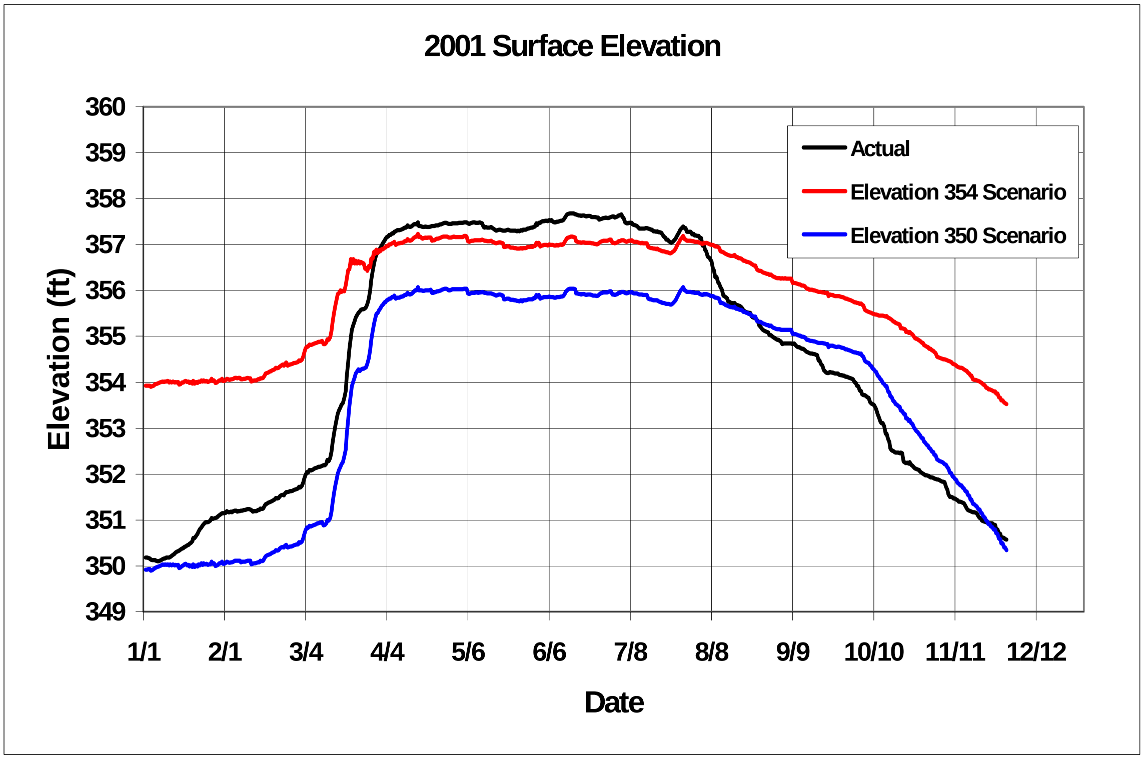

Figure 4-10. 2001 Lake Murray Surface Elevation

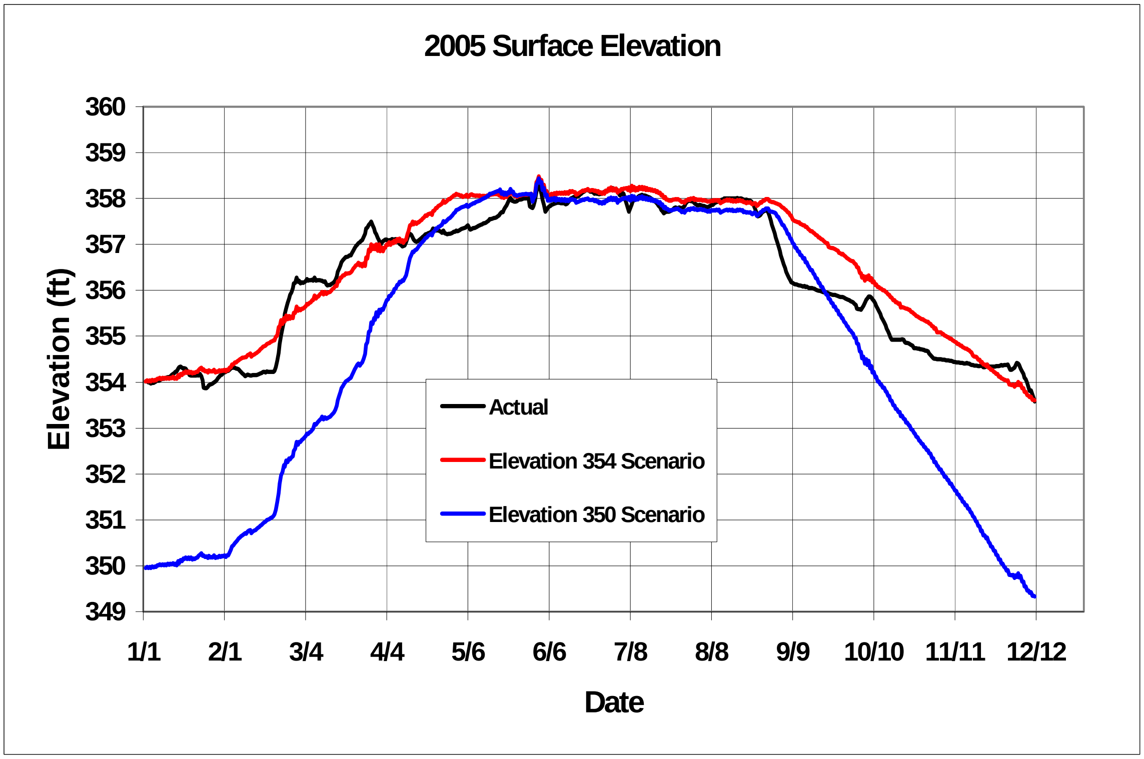

Figure 4-11. 2005 Lake Murray Surface Elevation

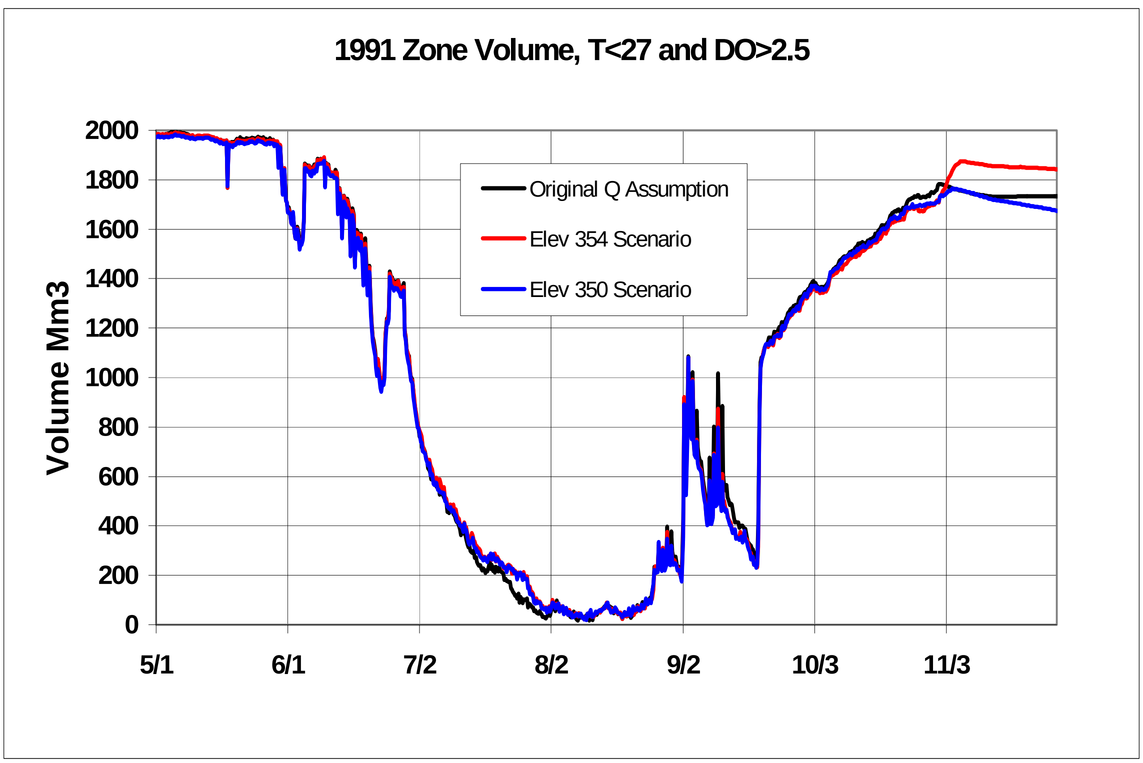

Figure 4-12. 1991 Lake Murray Volume of Striped Bass Habitat

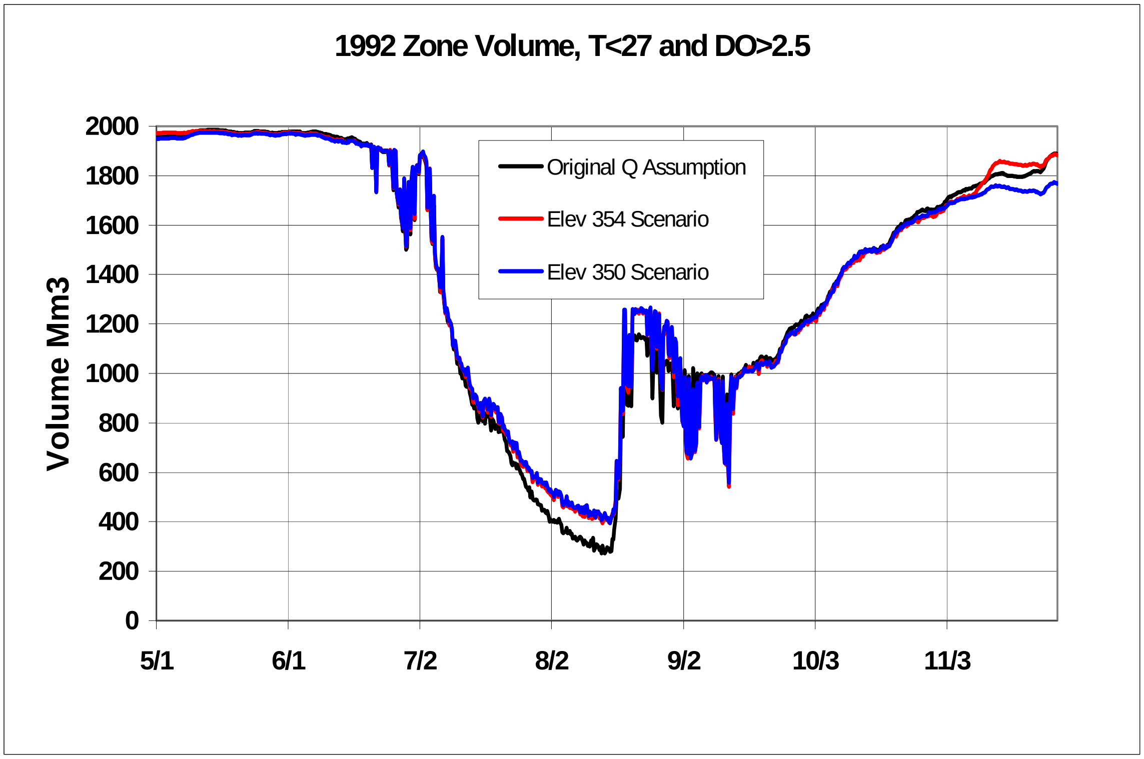

Figure 4-13. 1992 Lake Murray Volume of Striped Bass Habitat

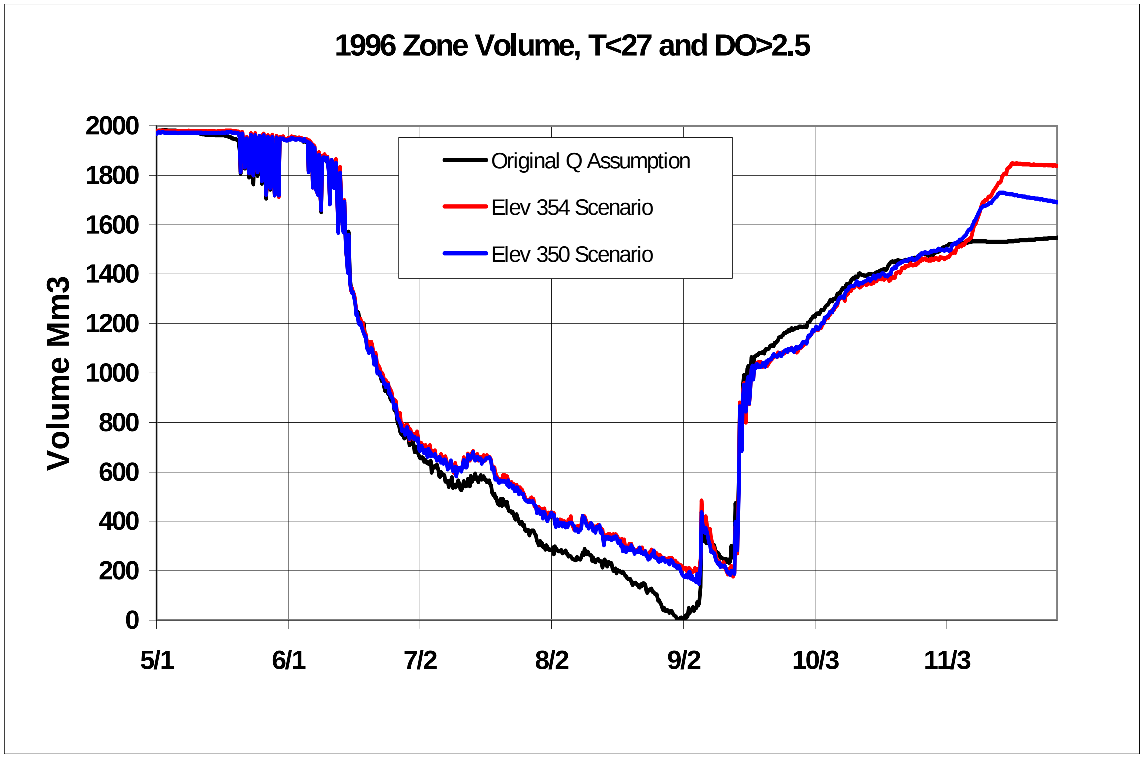

Figure 4-14. 1996 Lake Murray Volume of Striped Bass Habitat

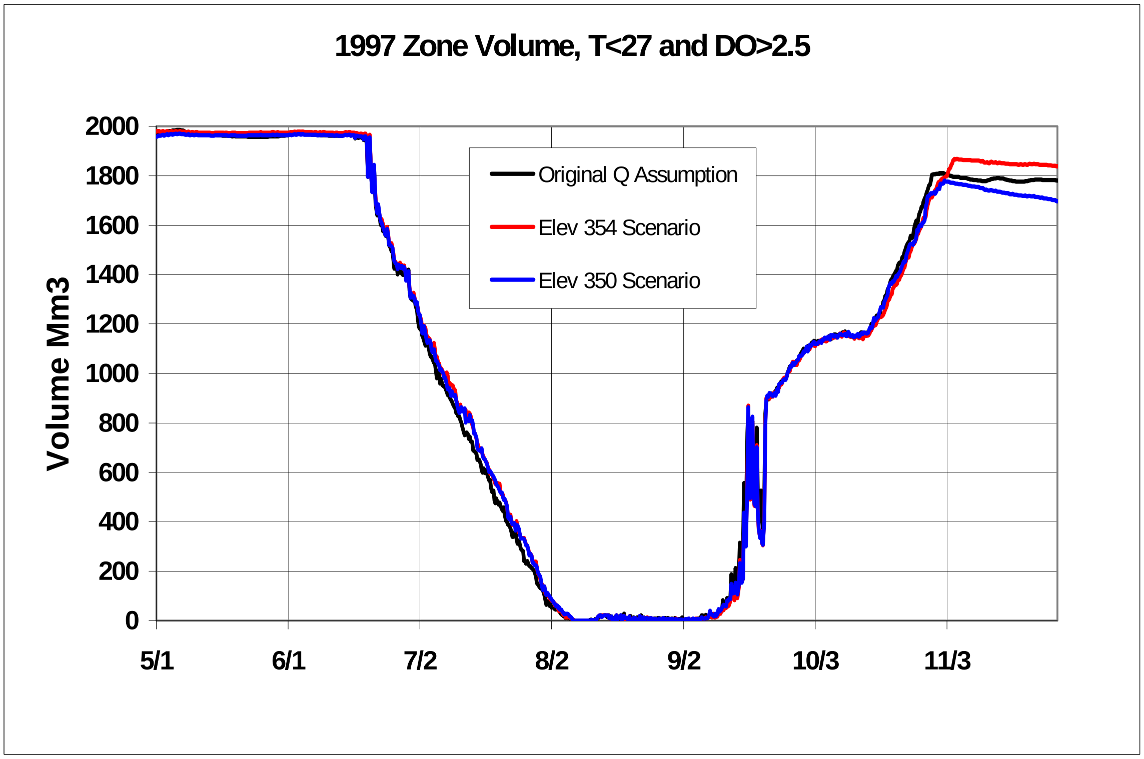

Figure 4-15. 1997 Lake Murray Volume of Striped Bass Habitat

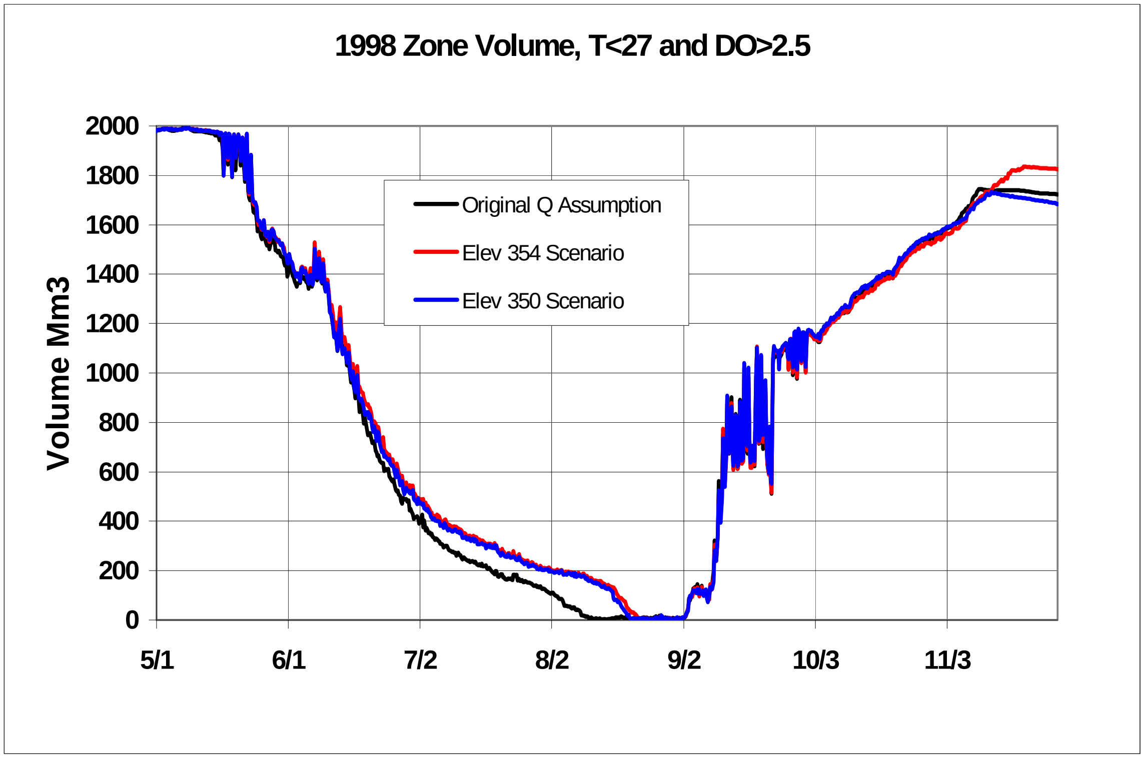

Figure 4-16. 1998 Lake Murray Volume of Striped Bass Habitat

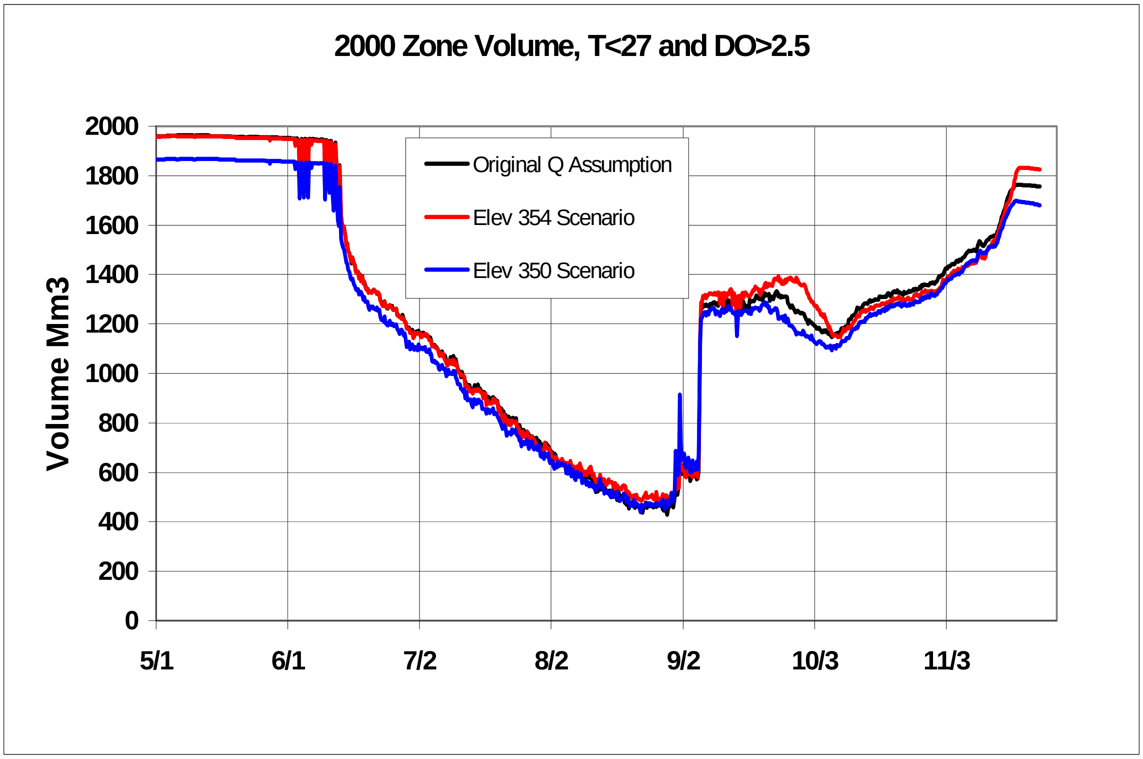

Figure 4-17. 2000 Lake Murray Volume of Striped Bass Habitat

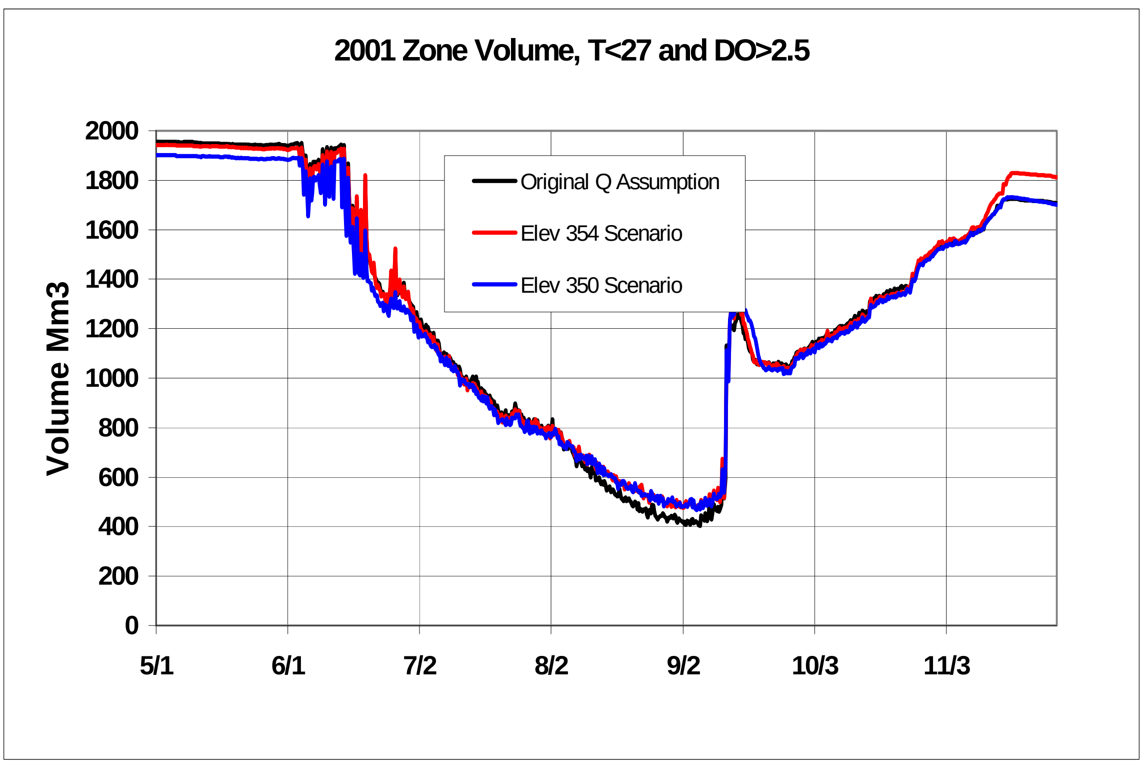

Figure 4-18. 2001 Lake Murray Volume of Striped Bass Habitat

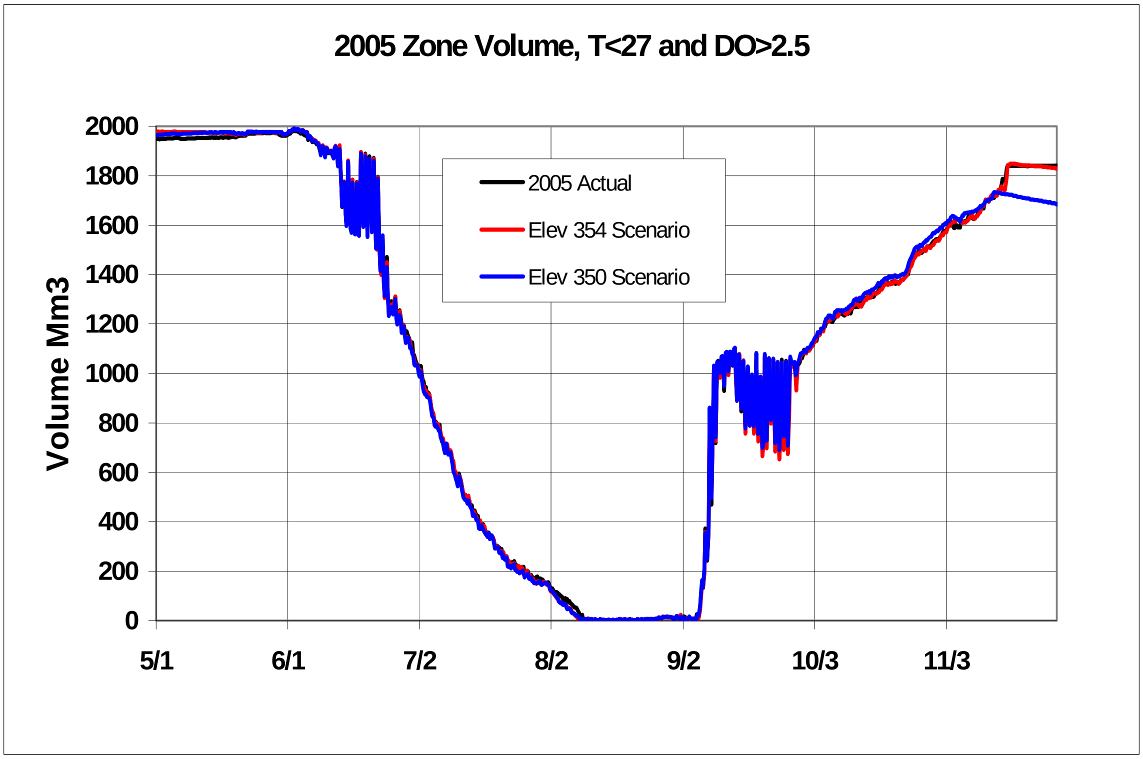

Figure 4-19. 2005 Lake Murray Volume of Striped Bass Habitat

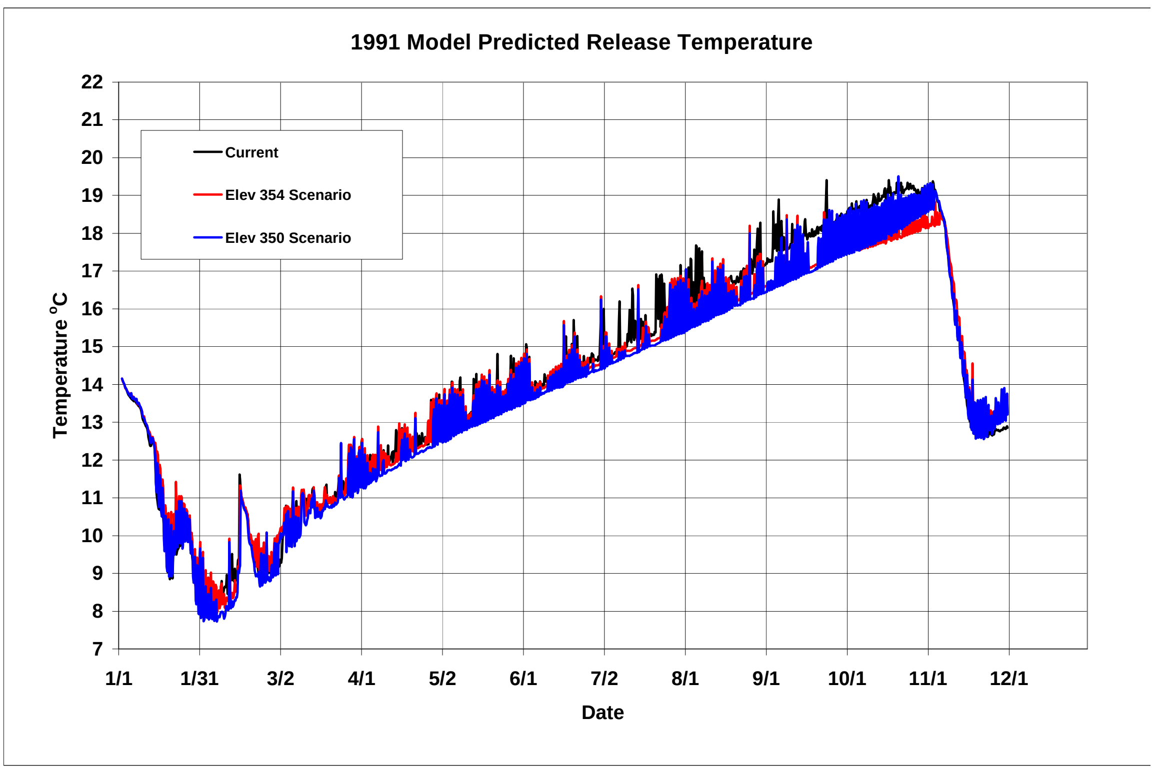

Figure 4-20. 1991 Lake Murray Discharge Temperature

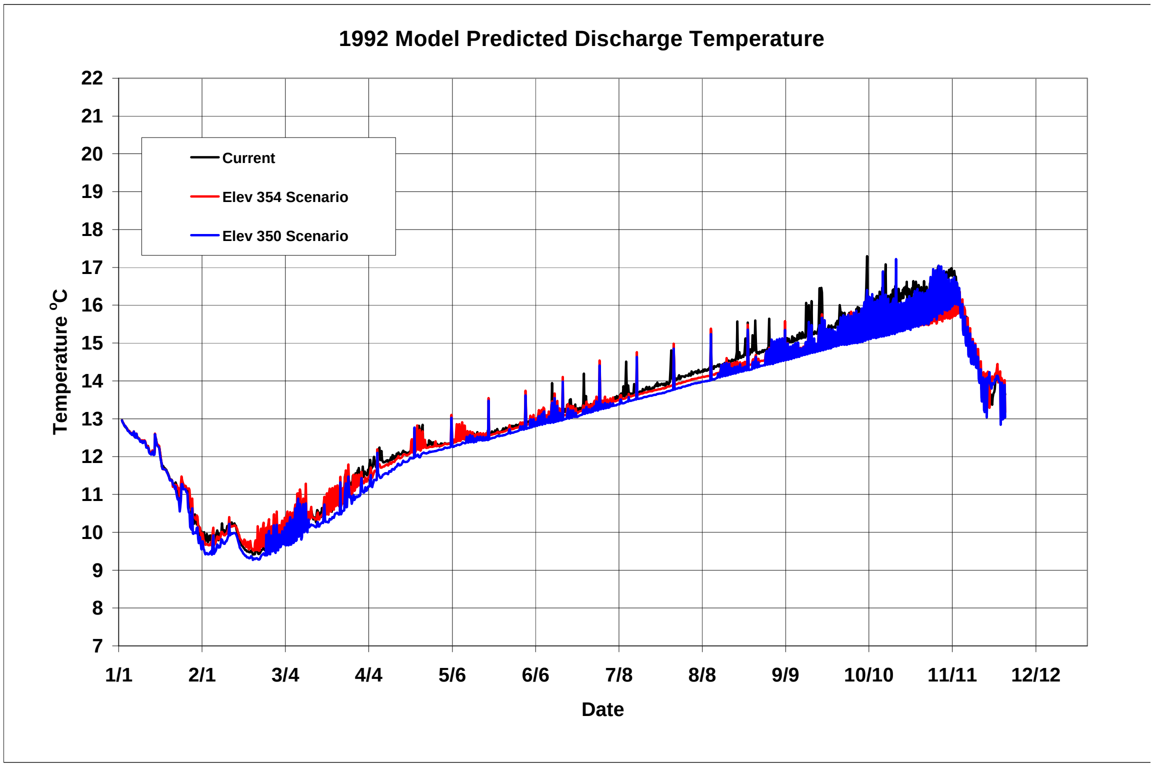

Figure 4-21. 1992 Lake Murray Discharge Temperature

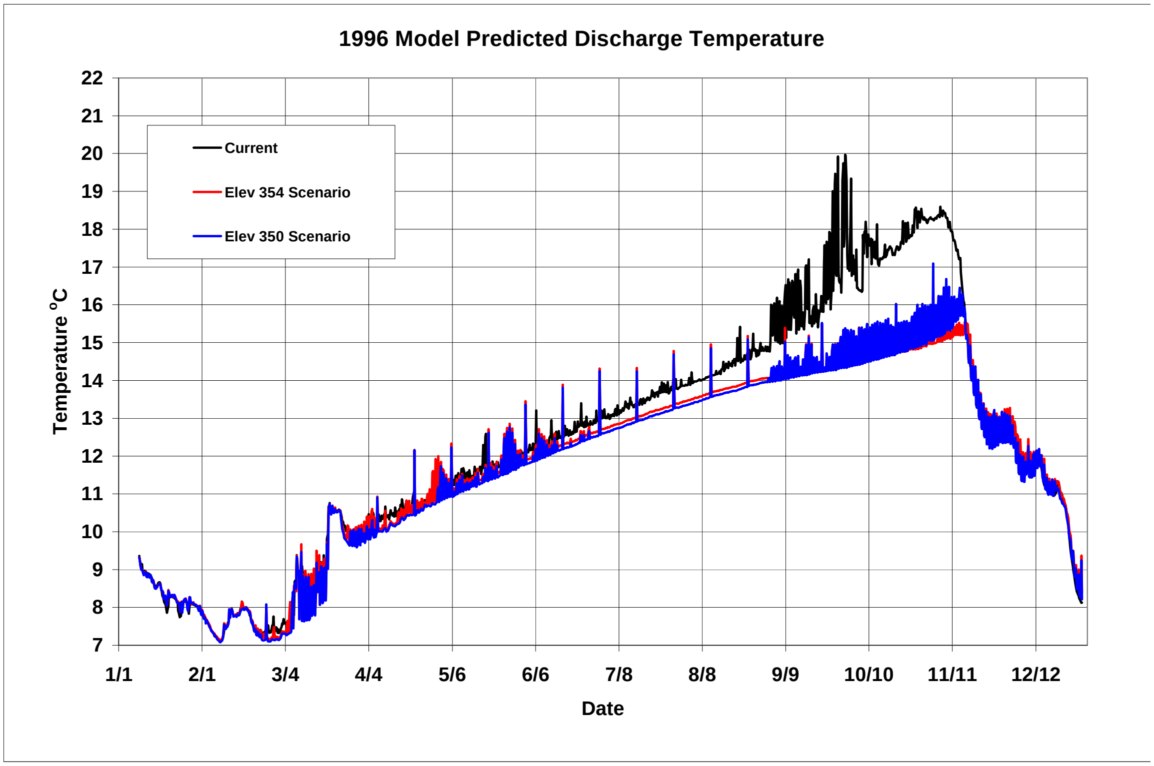

Figure 4-22. 1996 Lake Murray Discharge Temperature

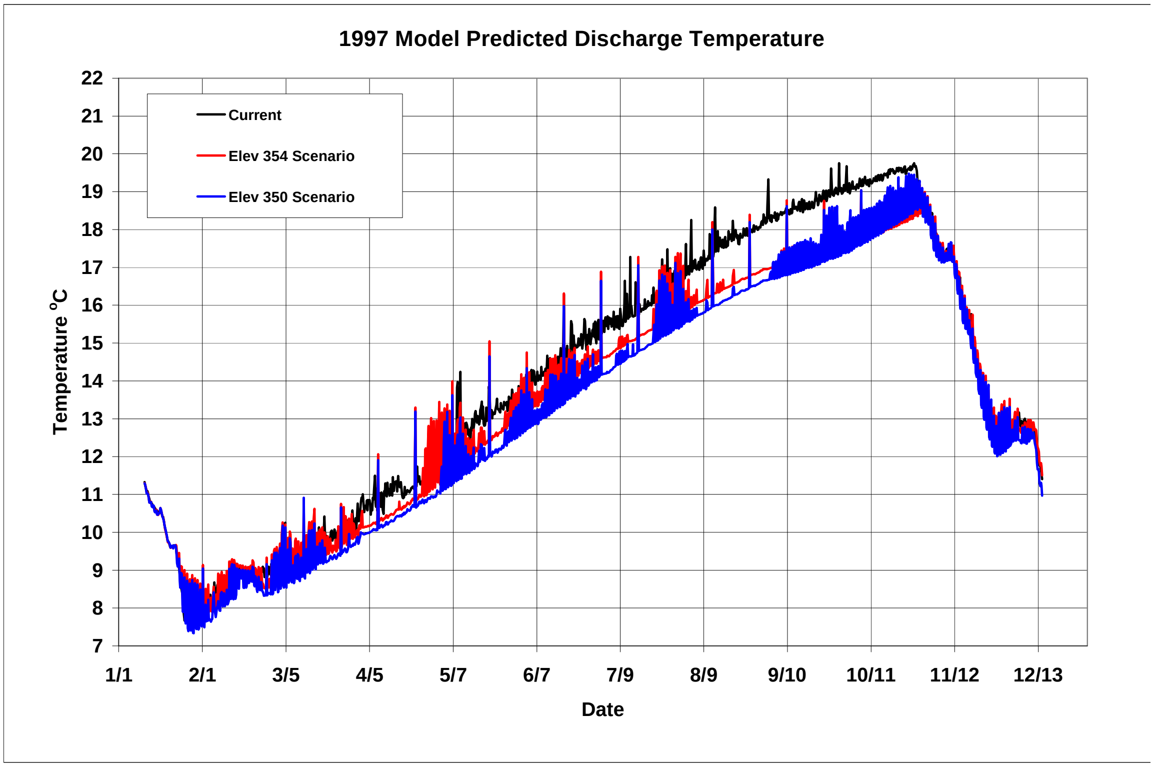

Figure 4-23. 1997 Lake Murray Discharge Temperature

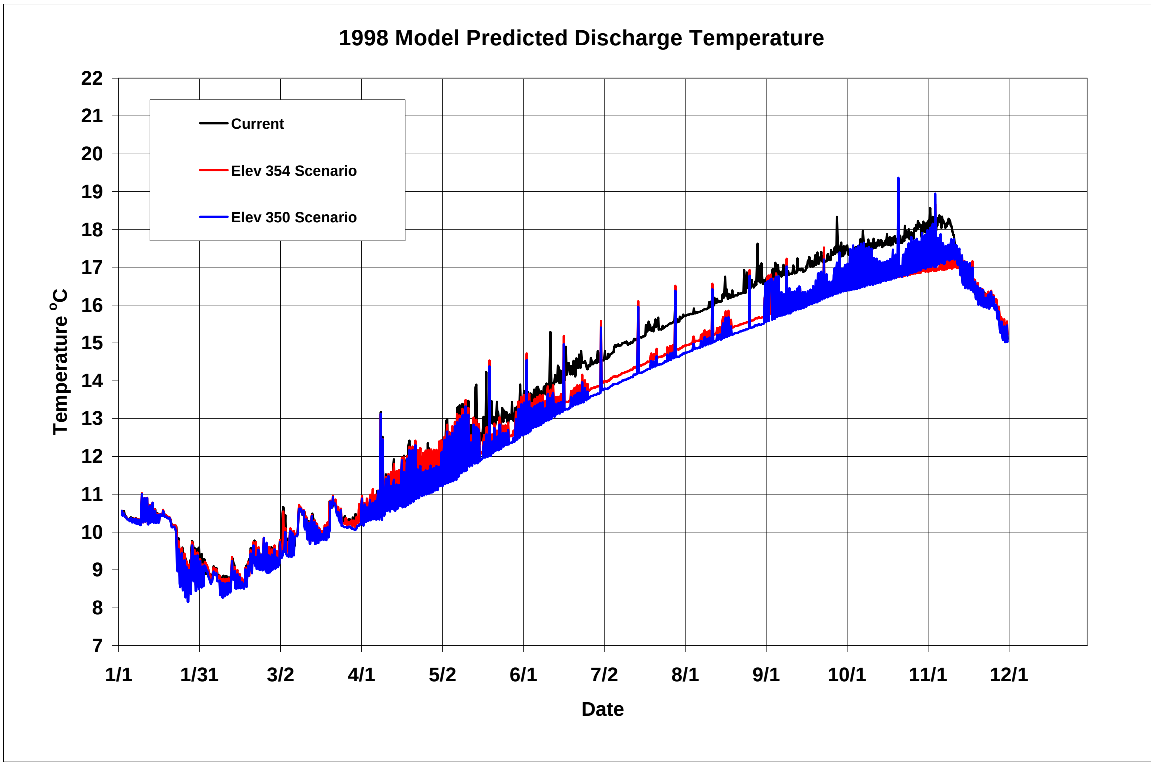

Figure 4-24. 1998 Lake Murray Discharge Temperature

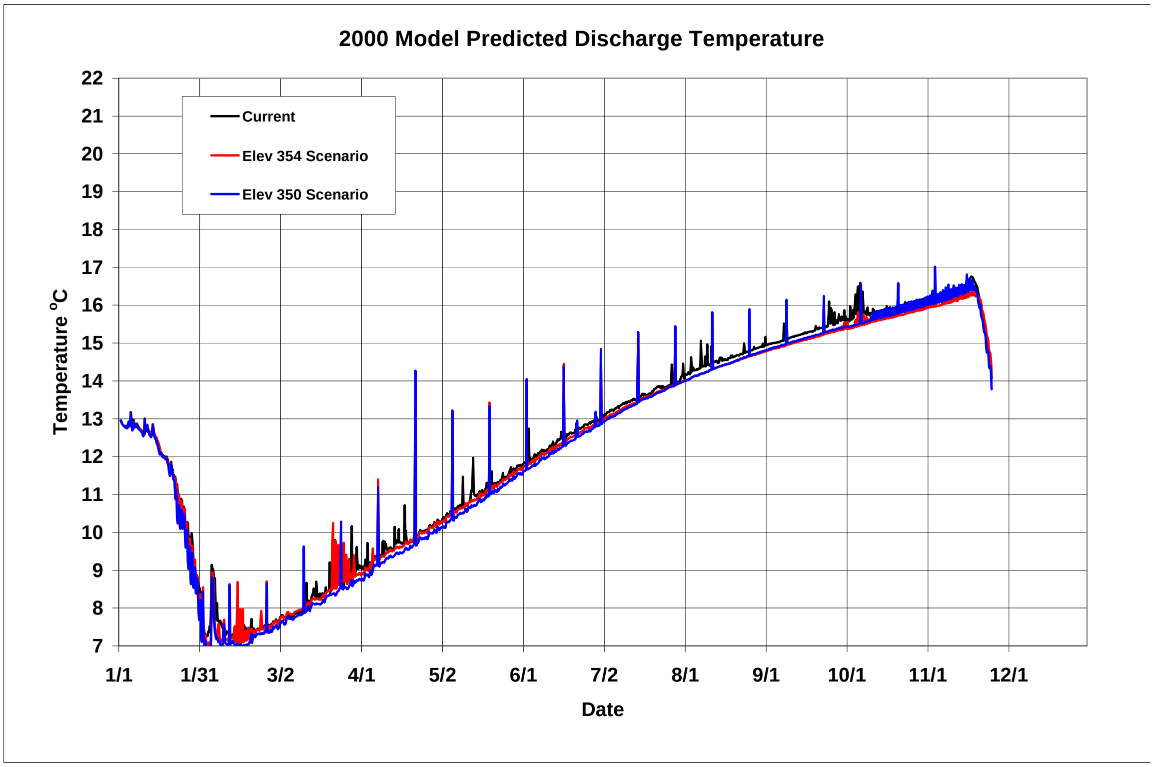

Figure 4-25. 2000 Lake Murray Discharge Temperature

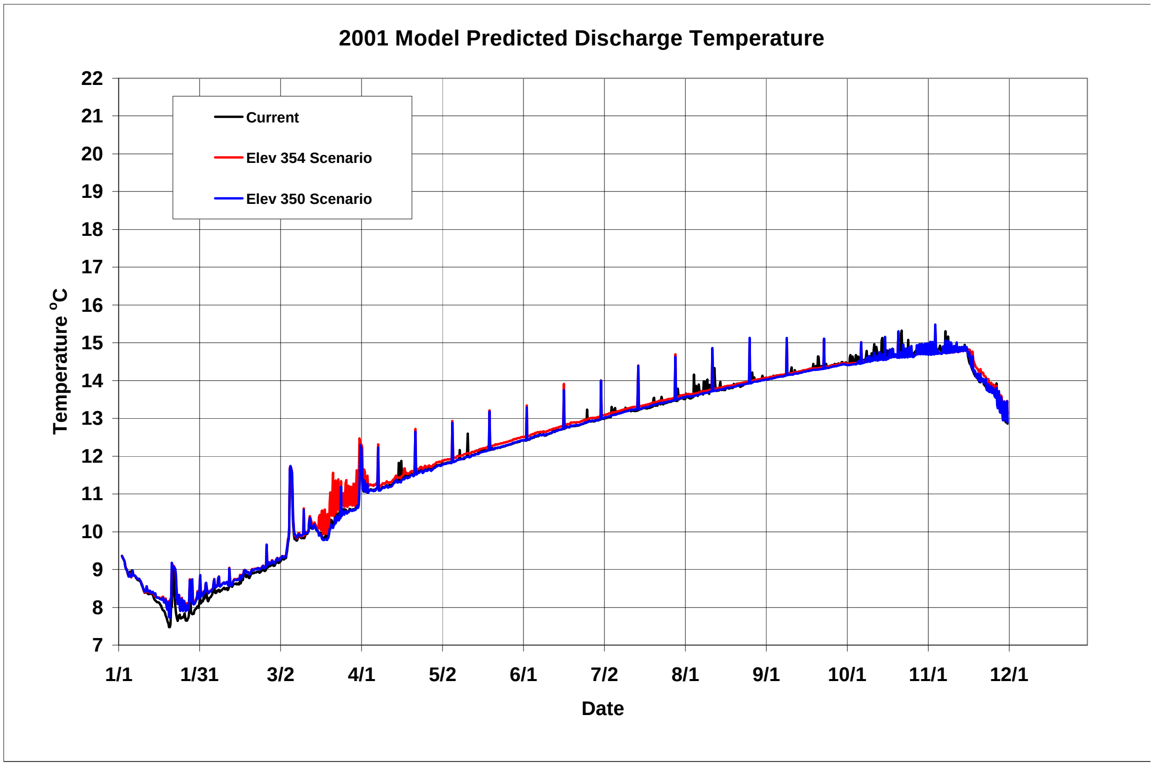

Figure 4-26. 2001 Lake Murray Discharge Temperature

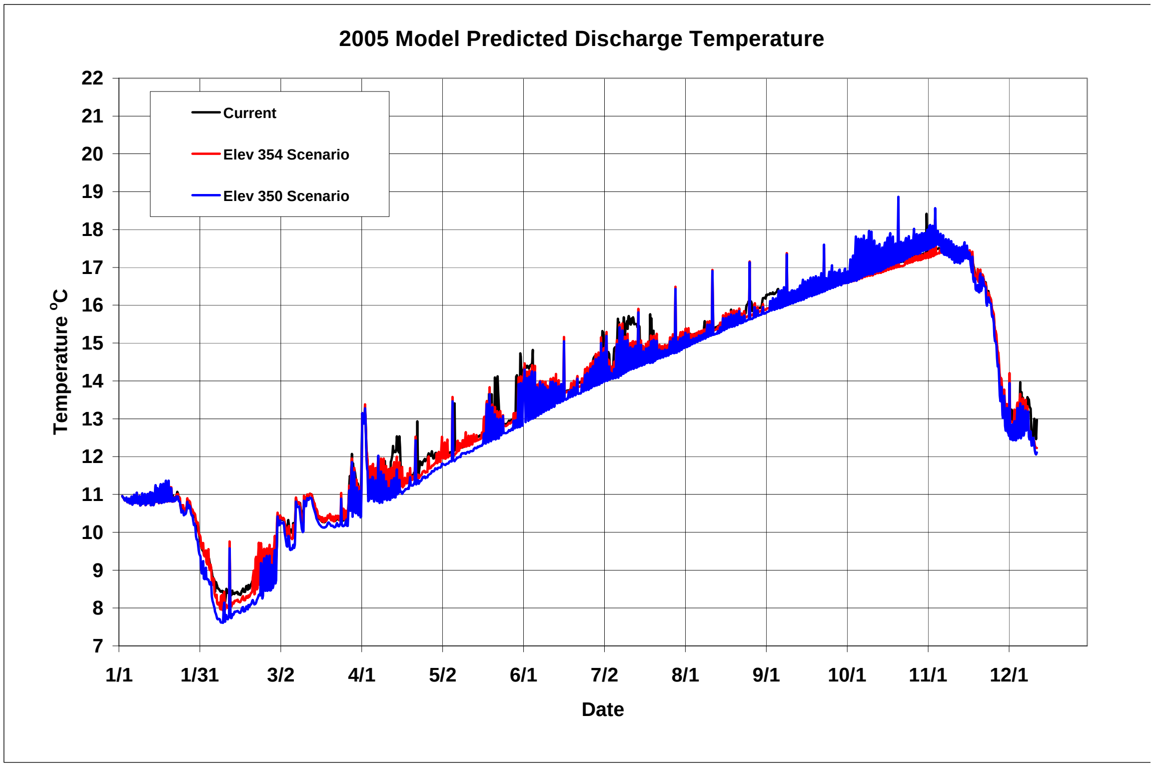

Figure 4-27. 2005 Lake Murray Discharge Temperature

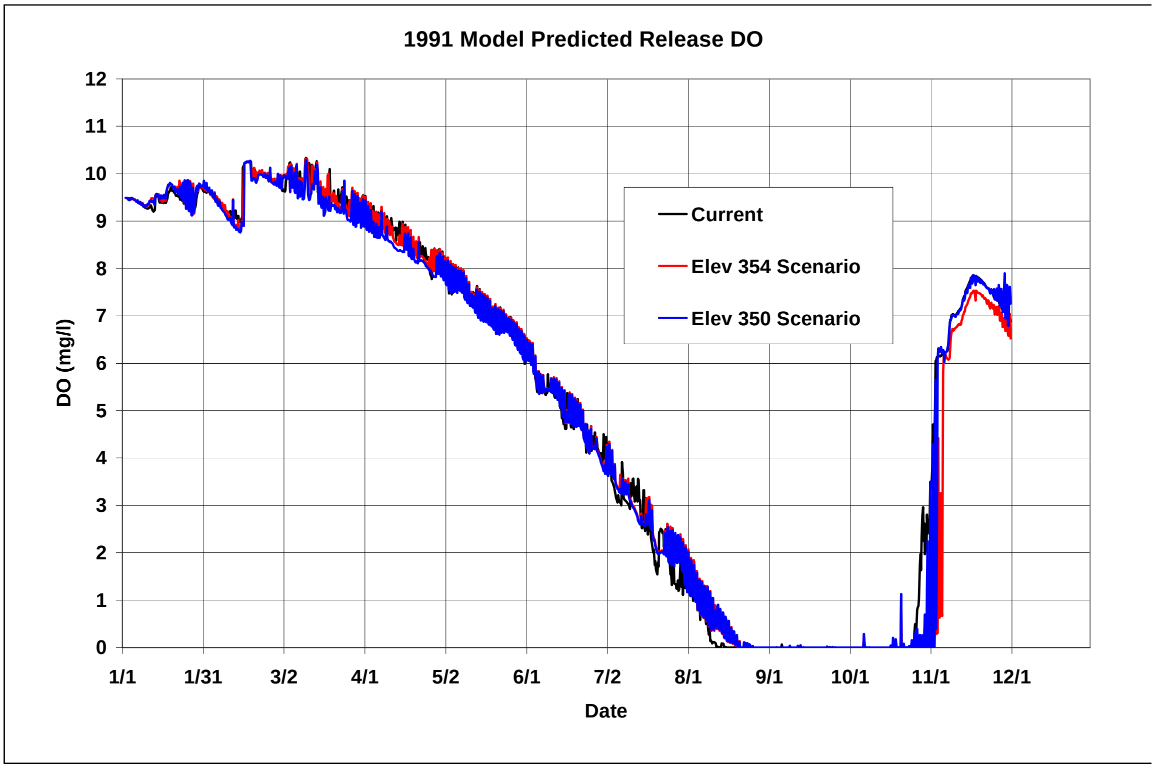

Figure 4-28. 1991 Lake Murray Discharge DO

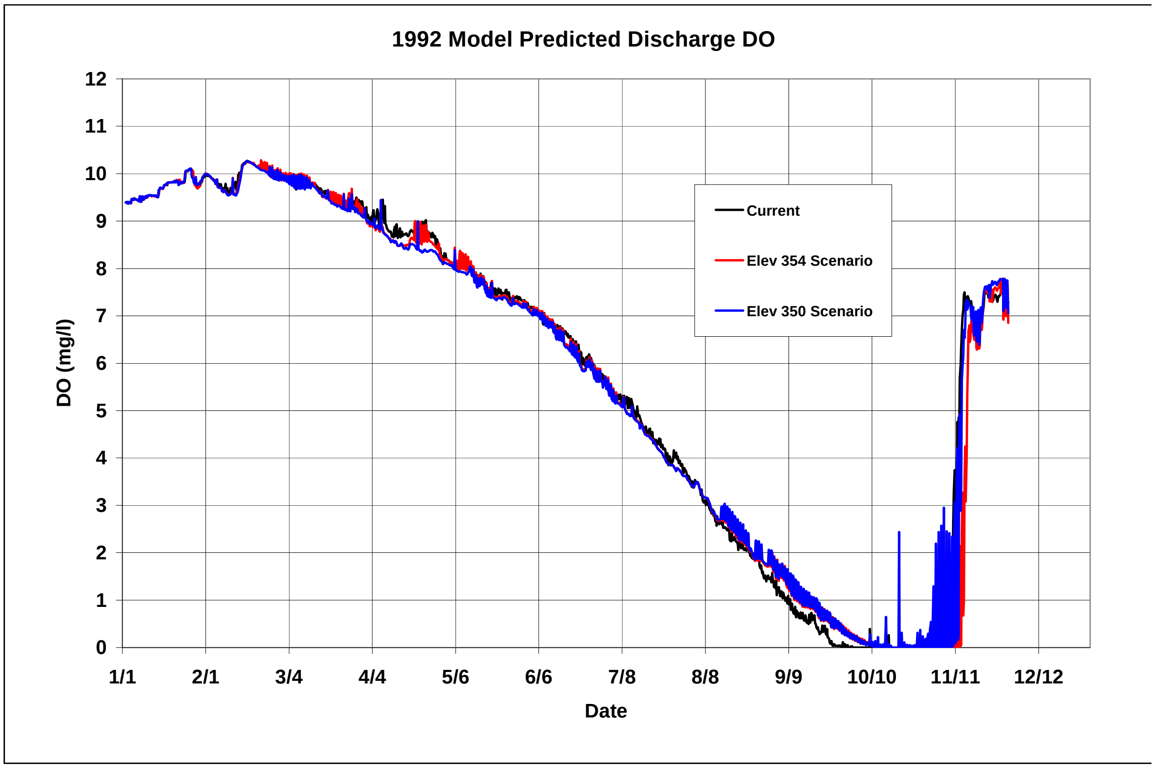

Figure 4-29. 1992 Lake Murray Discharge DO

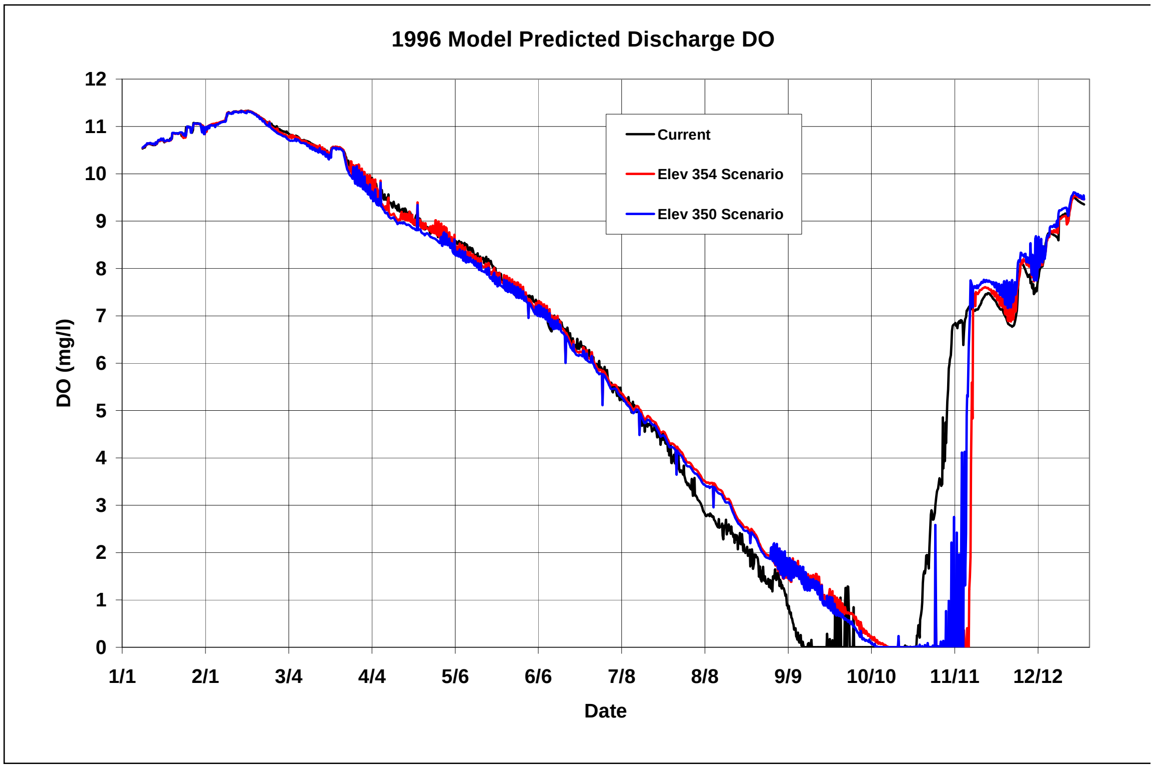

Figure 4-30. 1996 Lake Murray Discharge DO

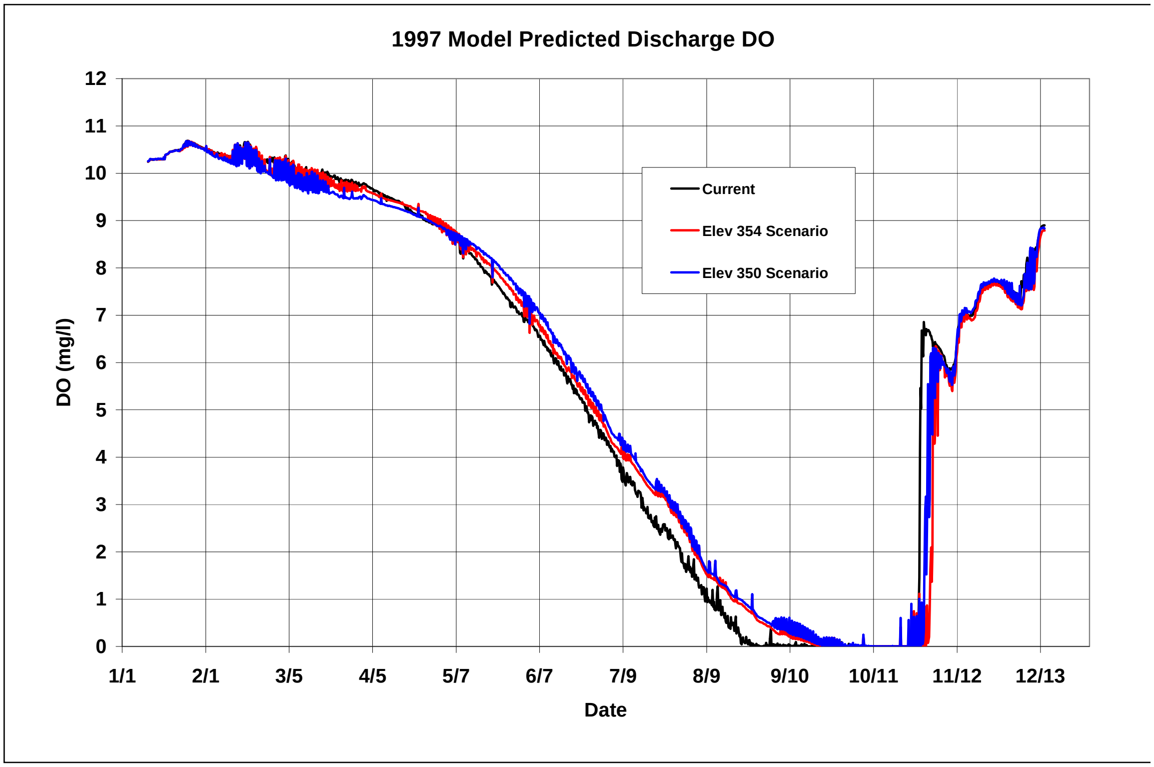

Figure 4-31. 1997 Lake Murray Discharge DO

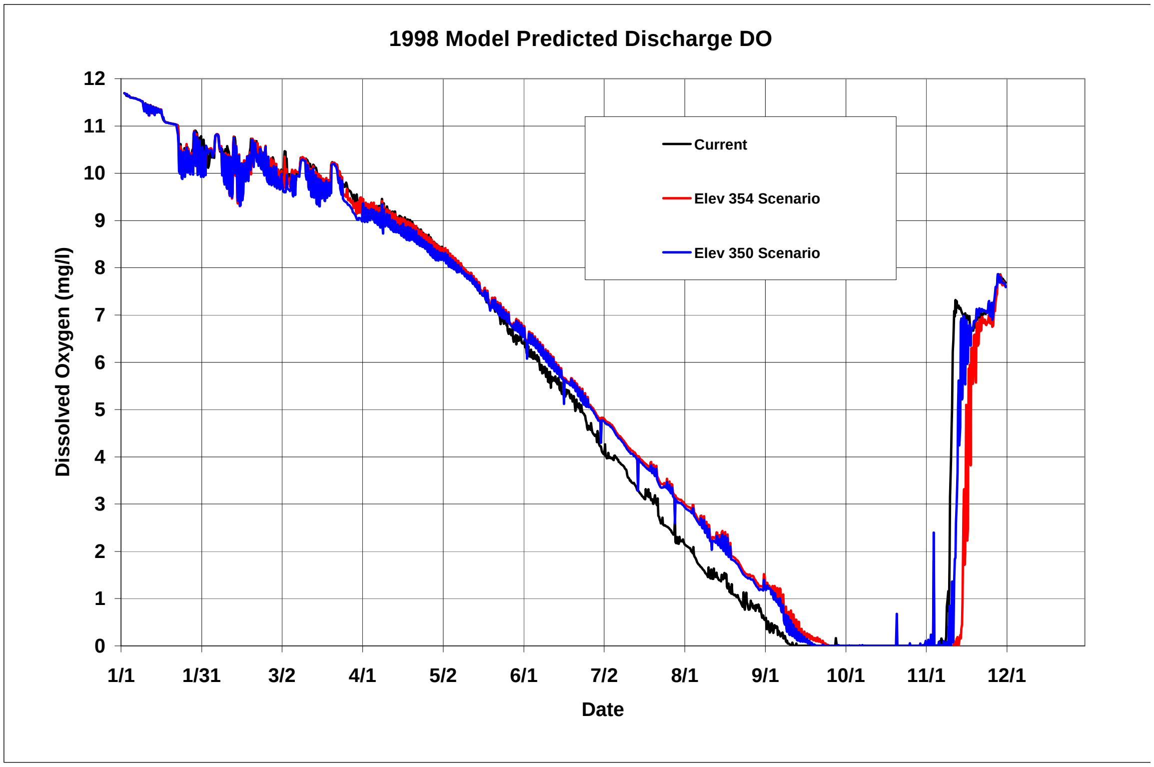

Figure 4-32. 1998 Lake Murray Discharge DO

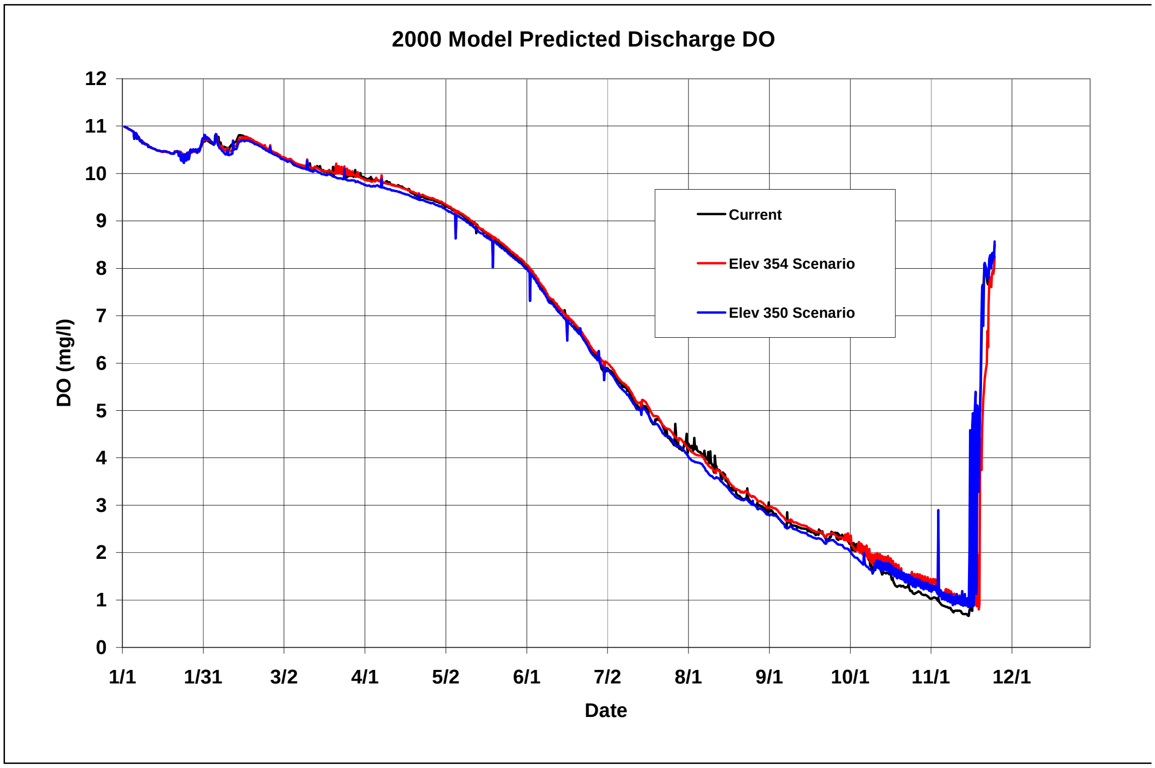

Figure 4-33. 2000 Lake Murray Discharge DO

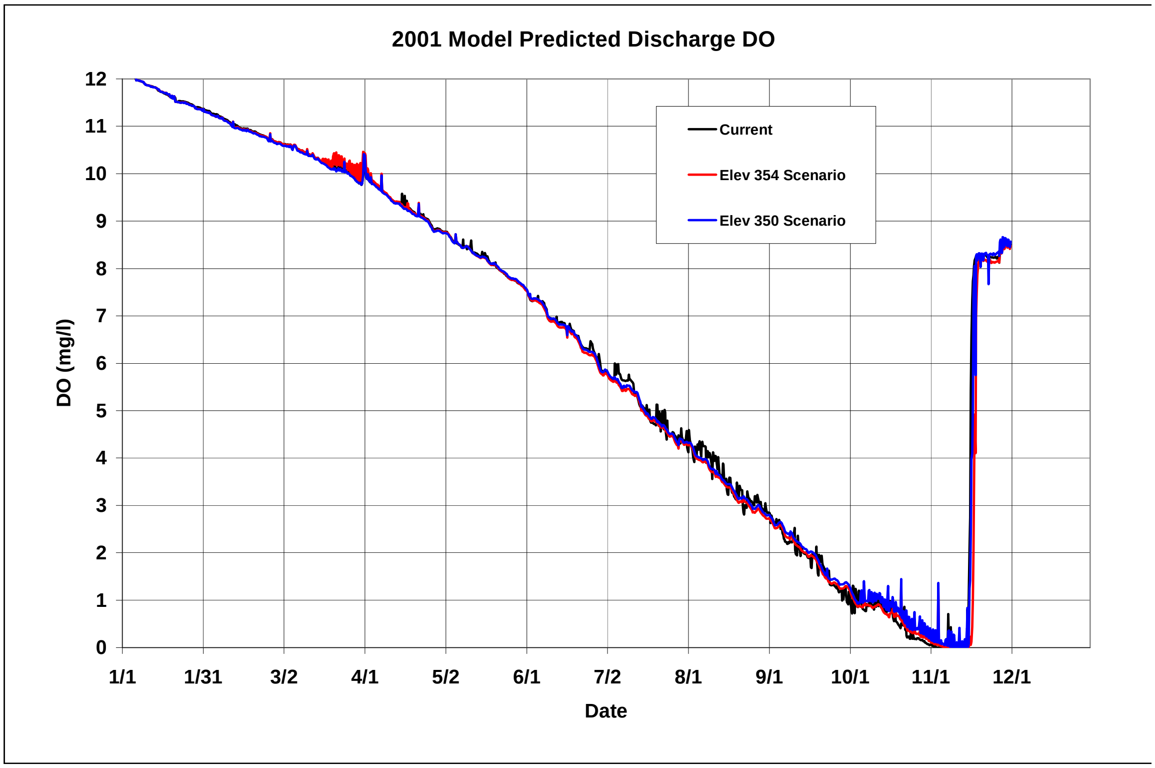

Figure 4-34. 2001 Lake Murray Discharge DO

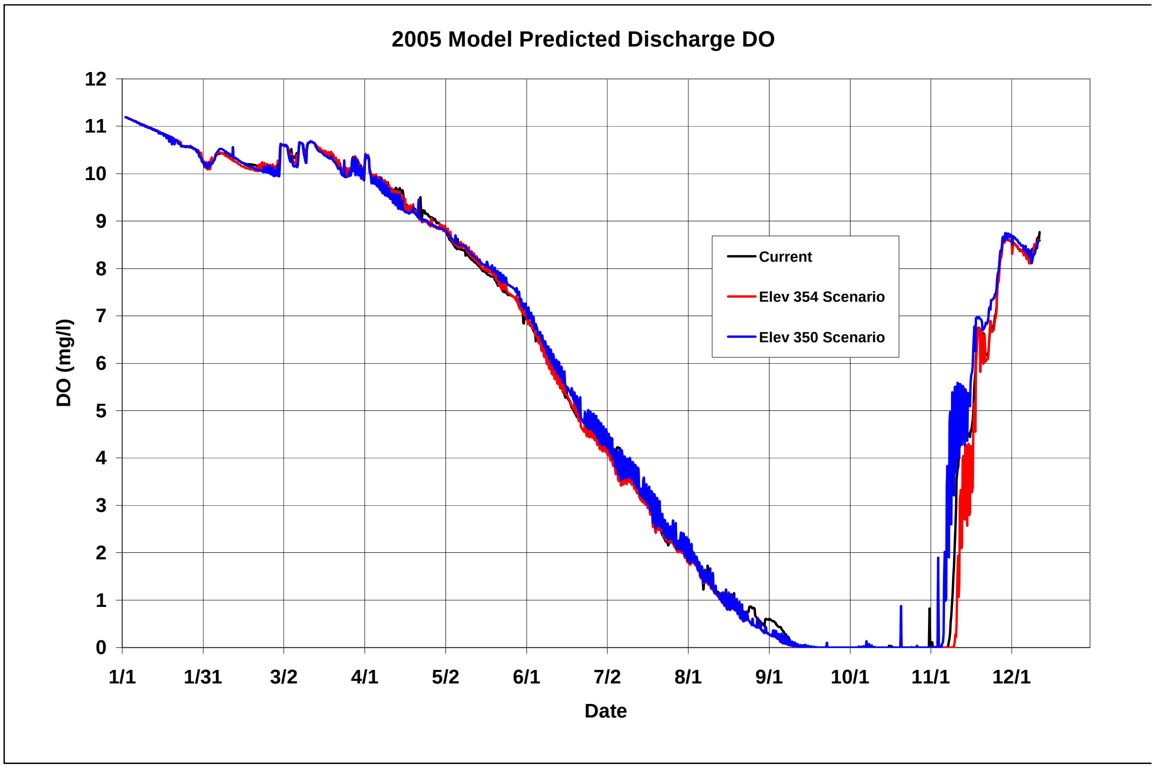

Figure 4-35. 2005 Lake Murray Discharge DO

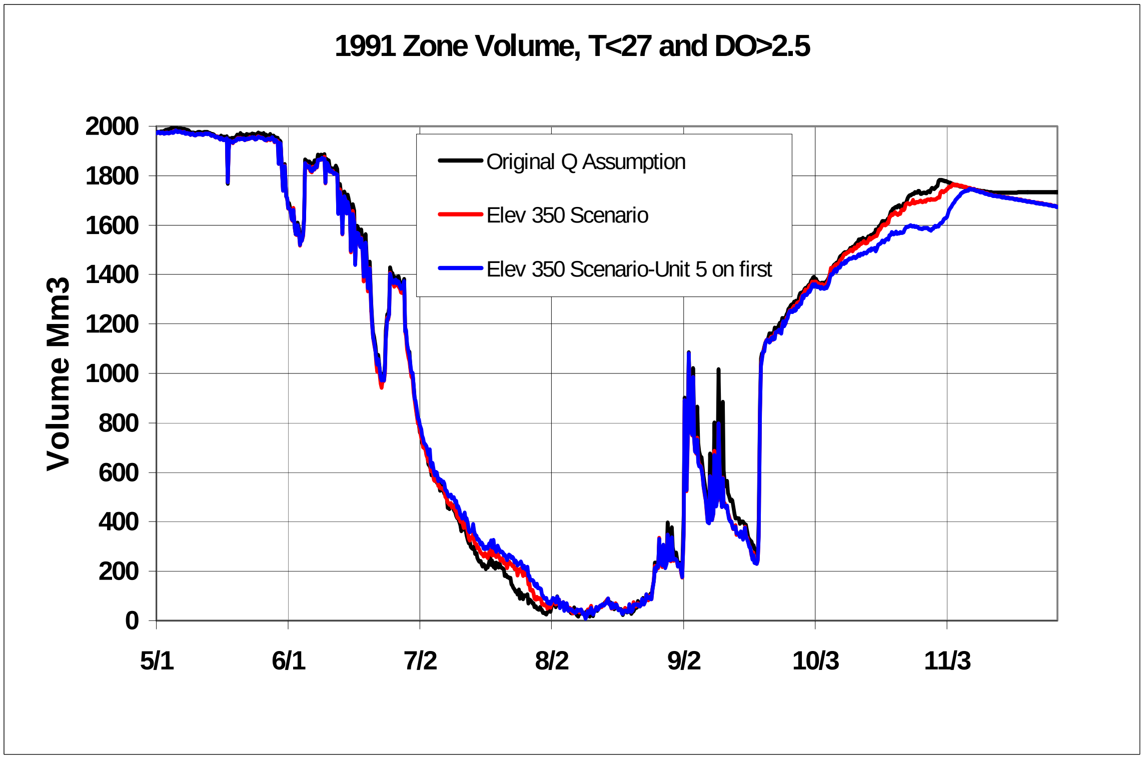

Figure 4-36. 1991 Lake Murray Striped Bass Habitat

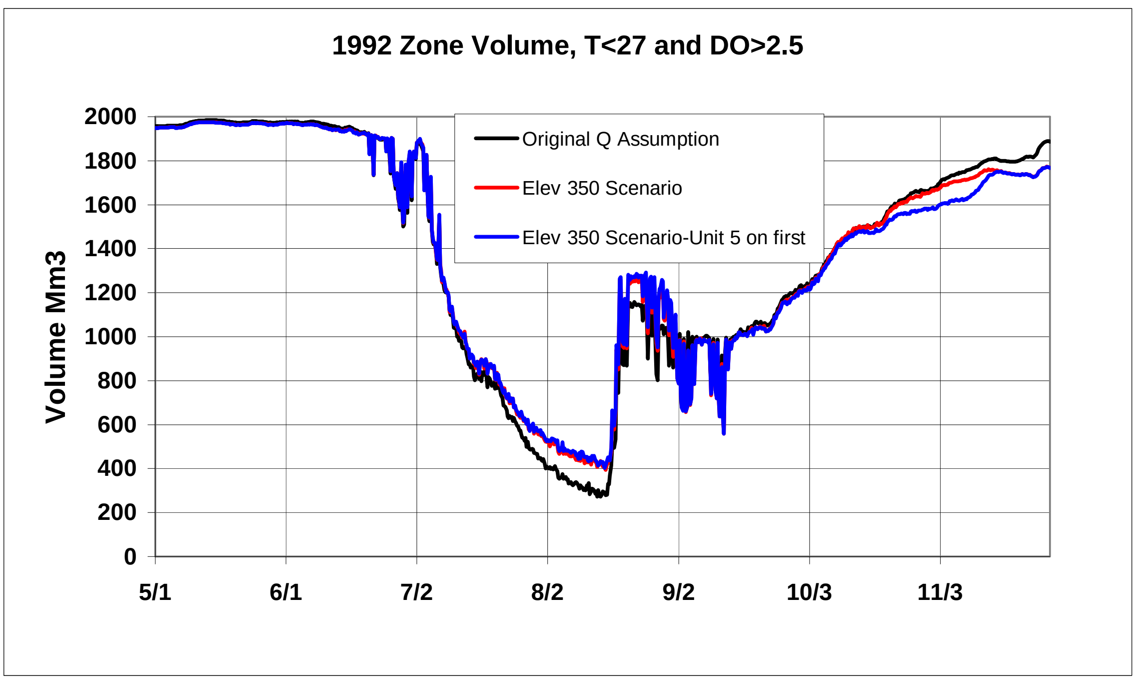

Figure 4-37. 1992 Lake Murray Striped Bass Habitat

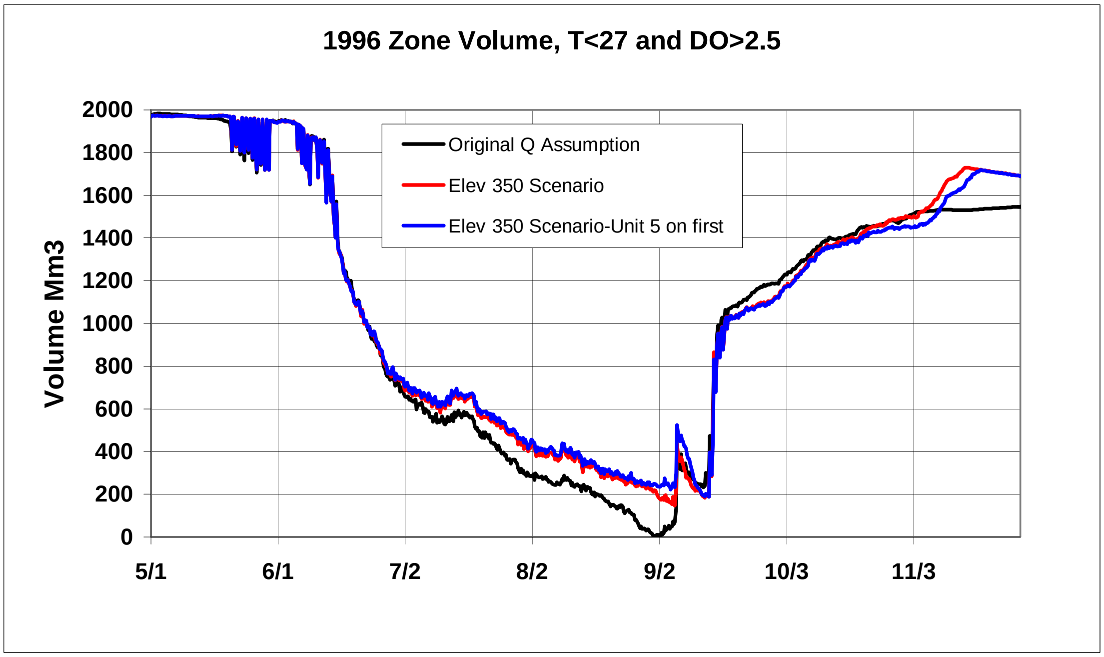

Figure 4-38. 1996 Lake Murray Striped Bass Habitat

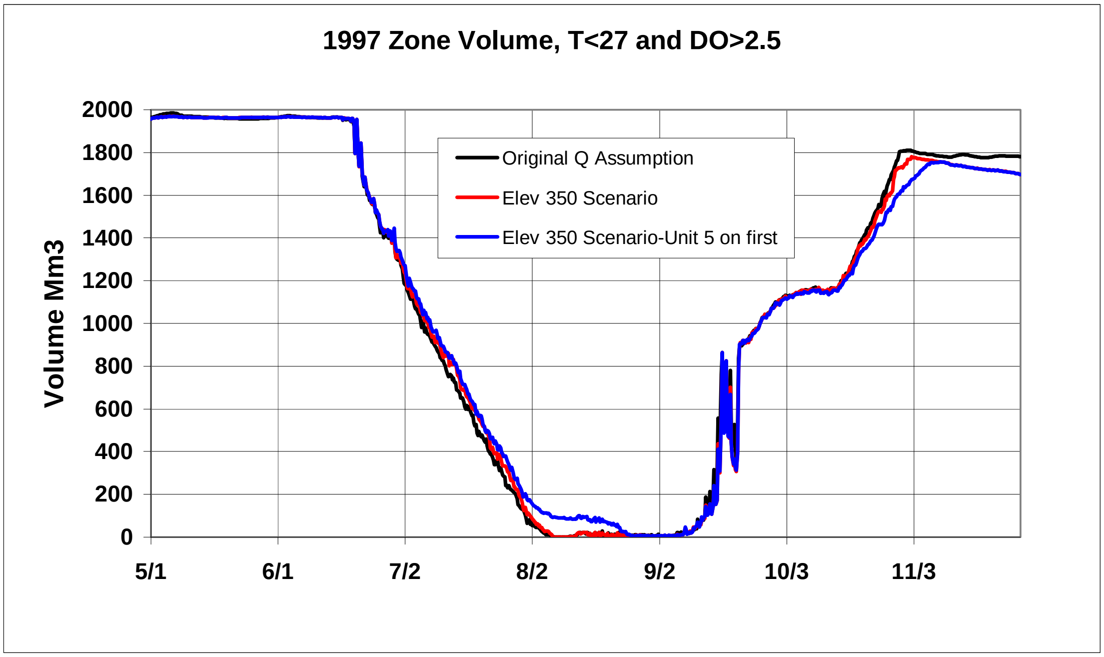

Figure 4-39. 1997 Lake Murray Striped Bass Habitat

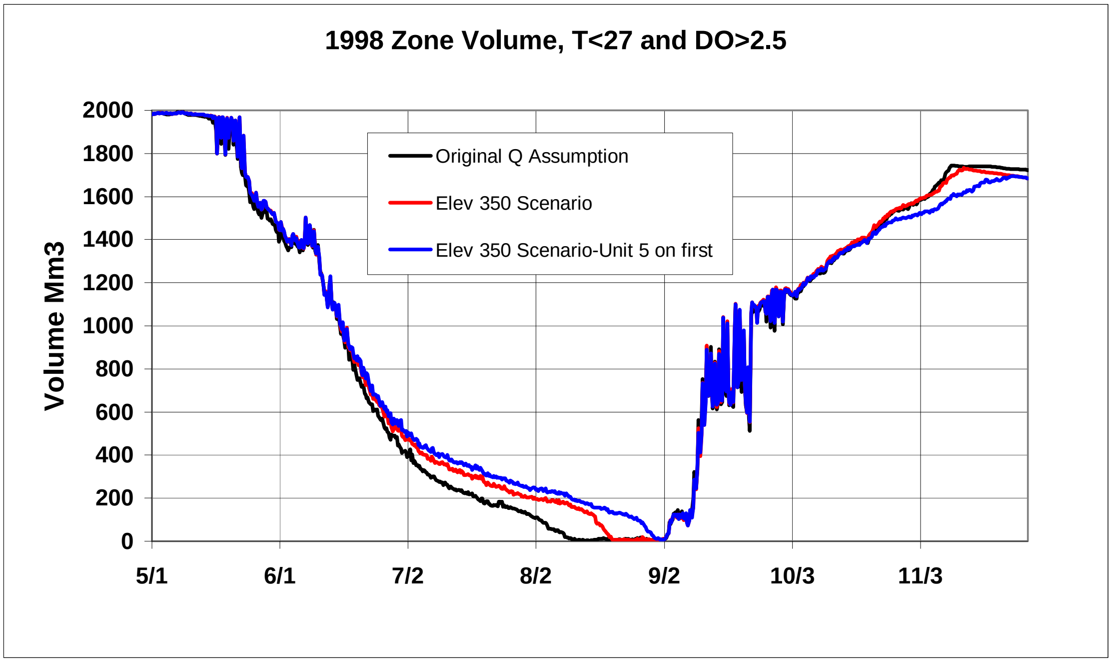

Figure 4-40. 1998 Lake Murray Striped Bass Habitat

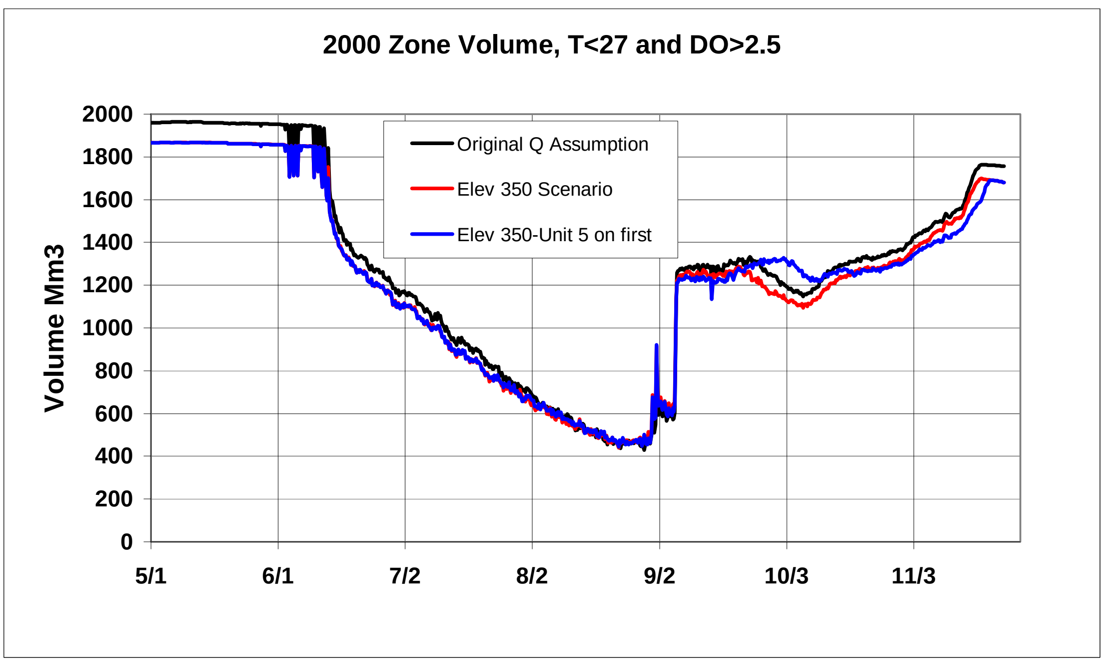

Figure 4-41. 2000 Lake Murray Striped Bass Habitat

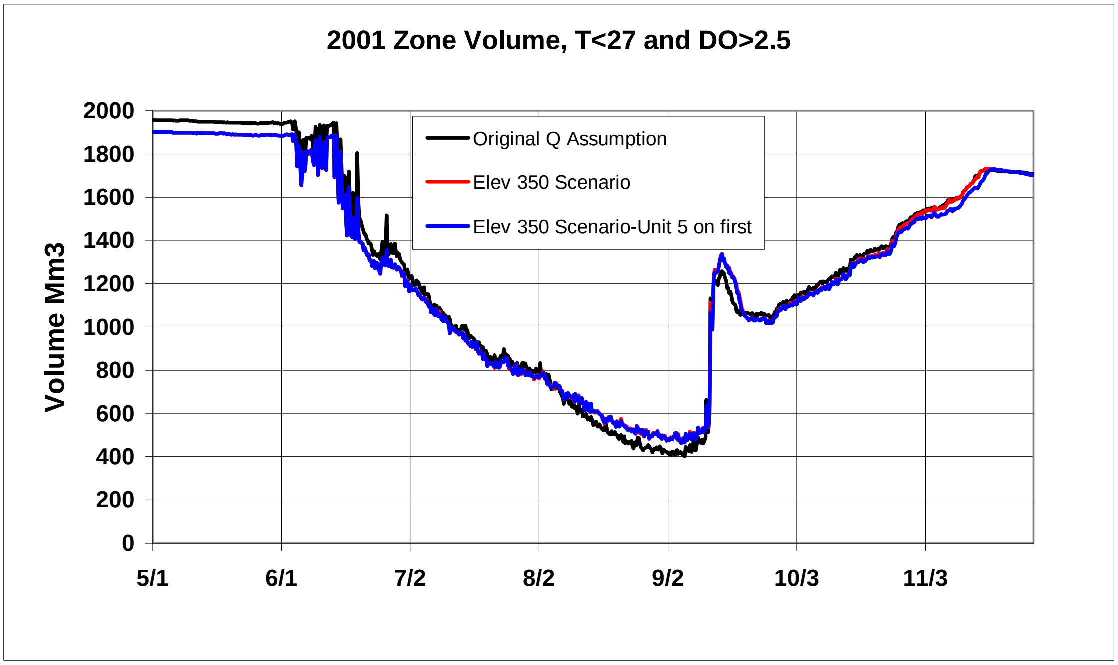

Figure 4-42. 2001 Lake Murray Striped Bass Habitat

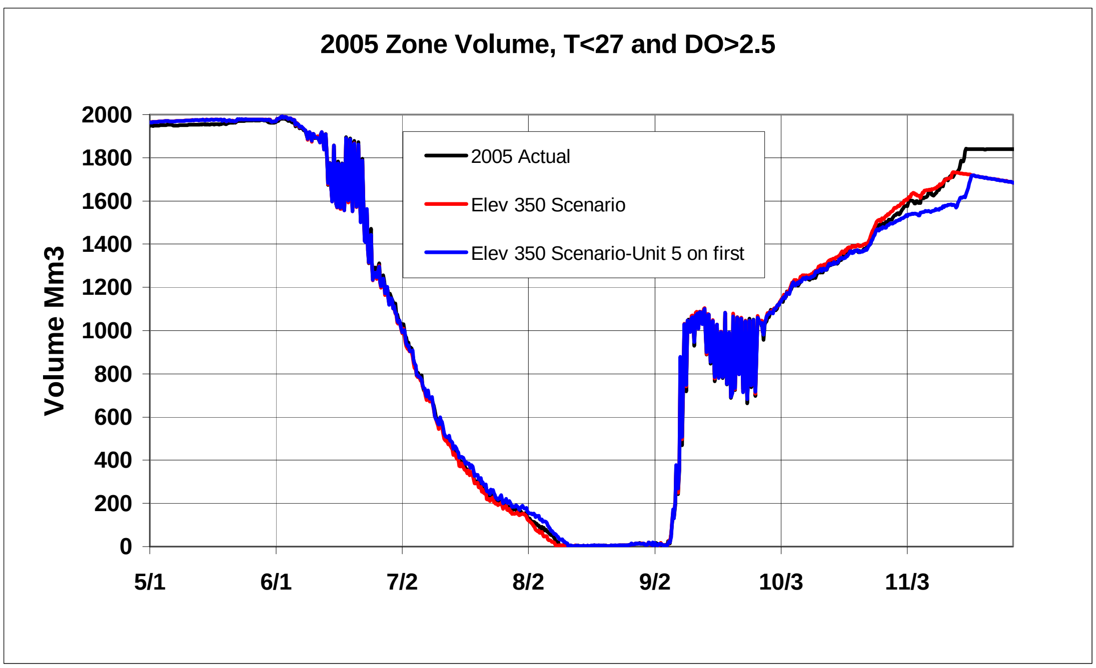

Figure 4-43. 2005 Lake Murray Striped Bass Habitat

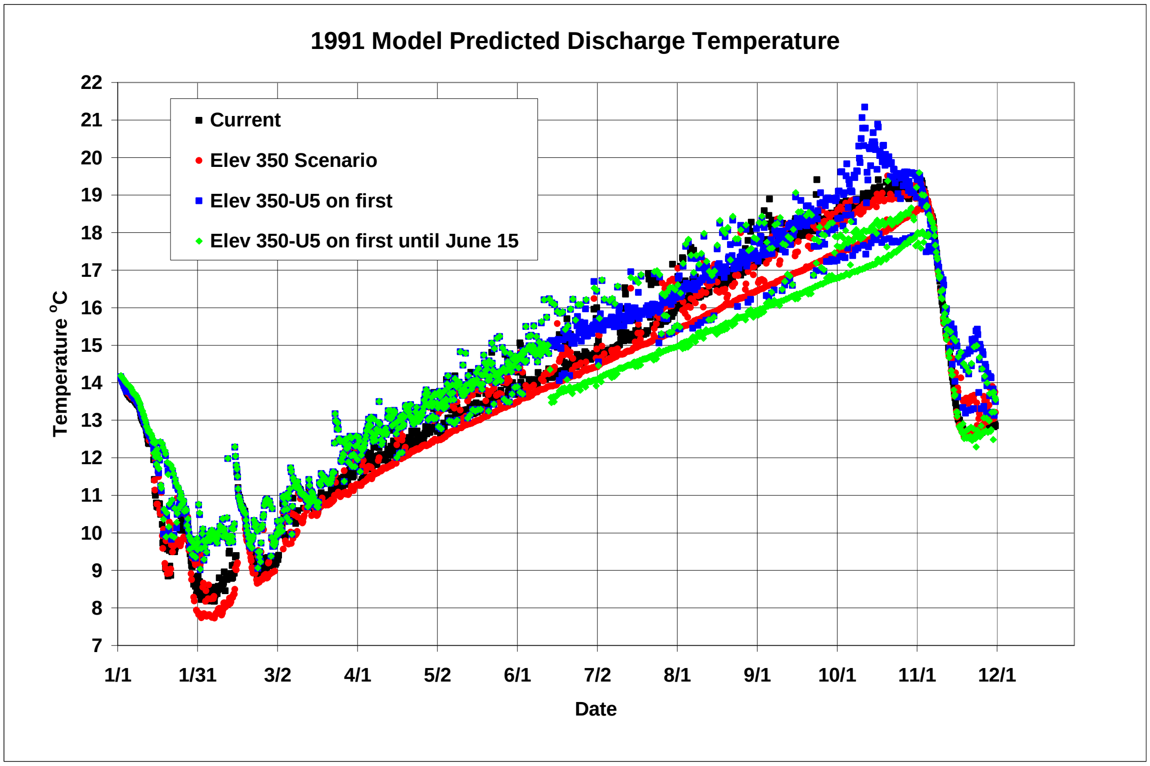

Figure 4-44. 1991 Release Temperature

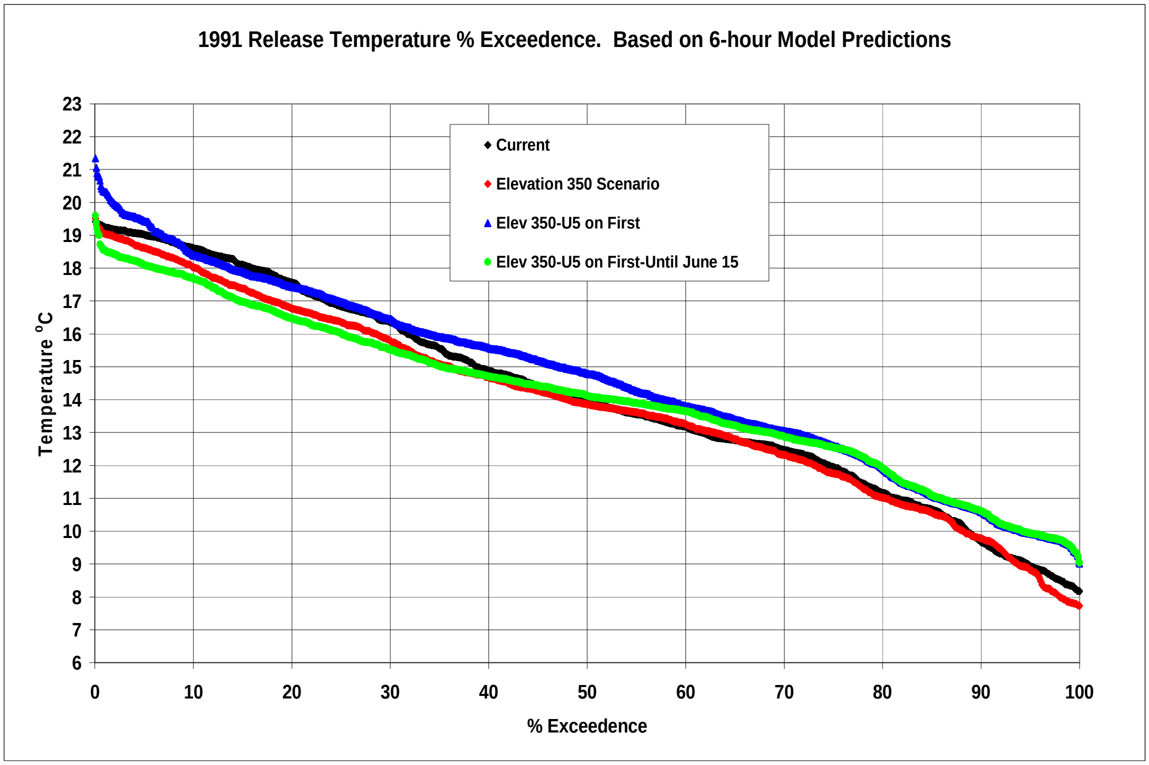

Figure 4-45. 1991 Release Temperature Exceedence

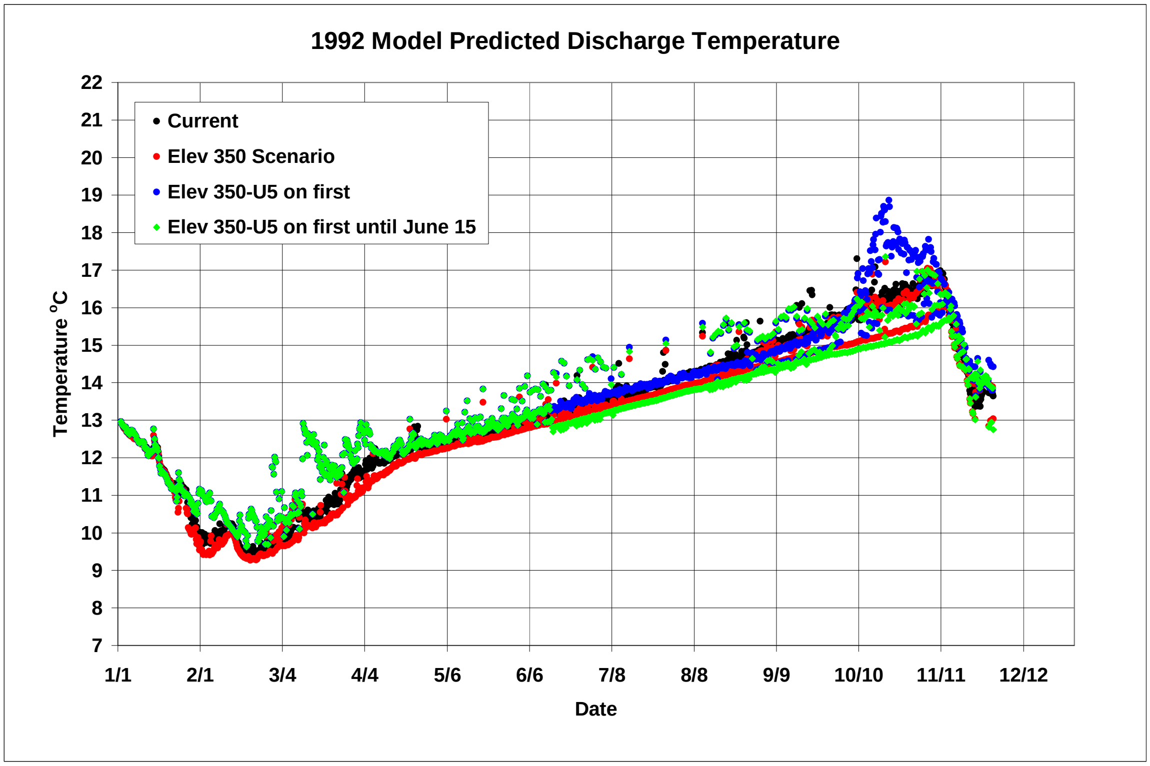

Figure 4-46. 1992 Release Temperature

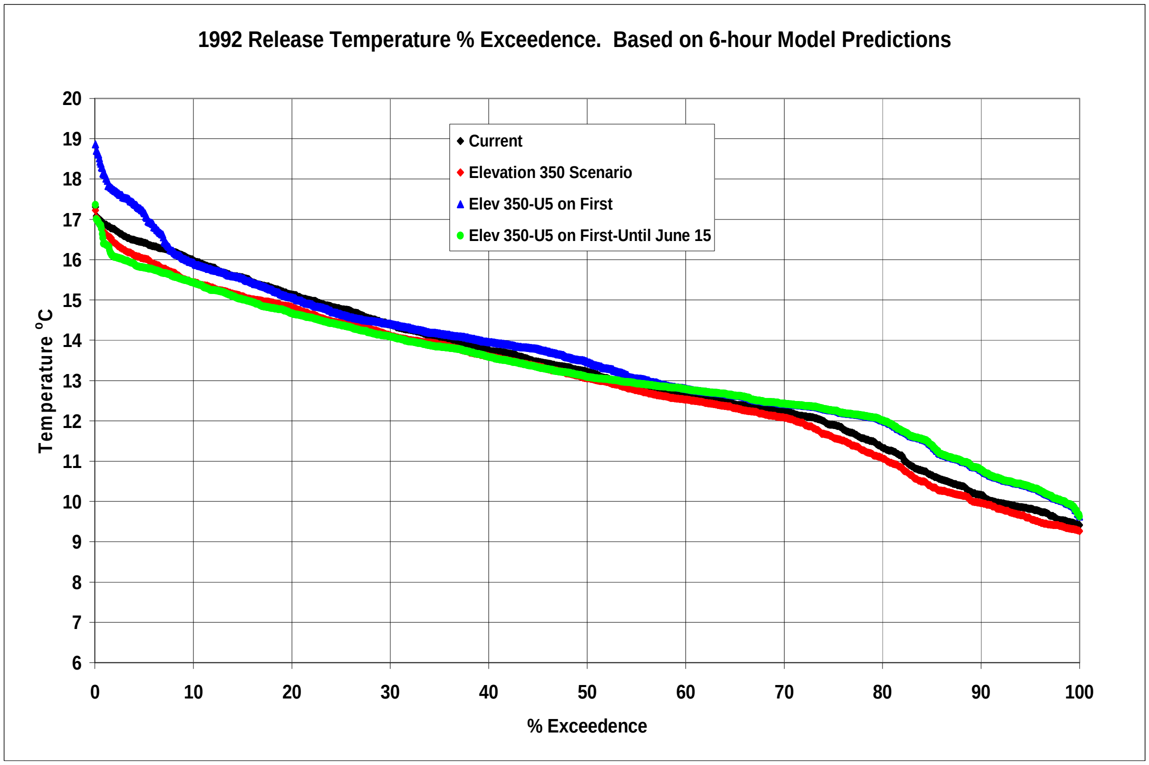

Figure 4-47. 1992 Release Temperature Exceedence

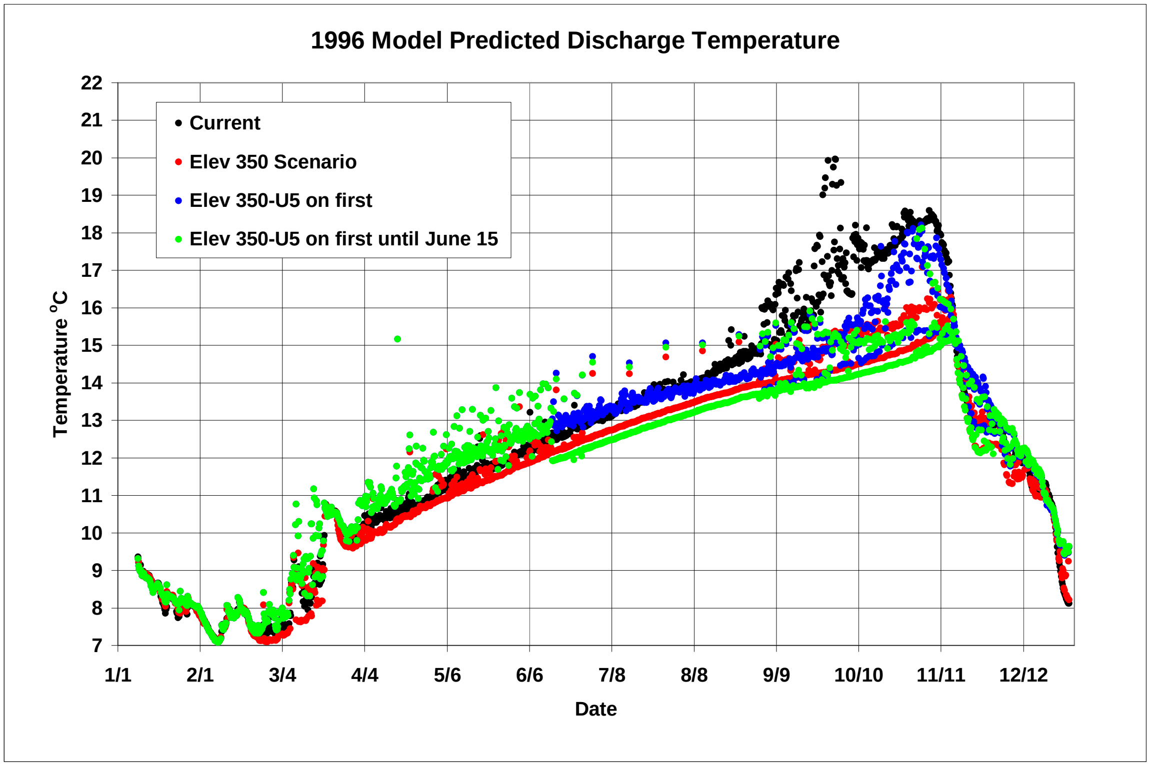

Figure 4-48. 1996 Release Temperature

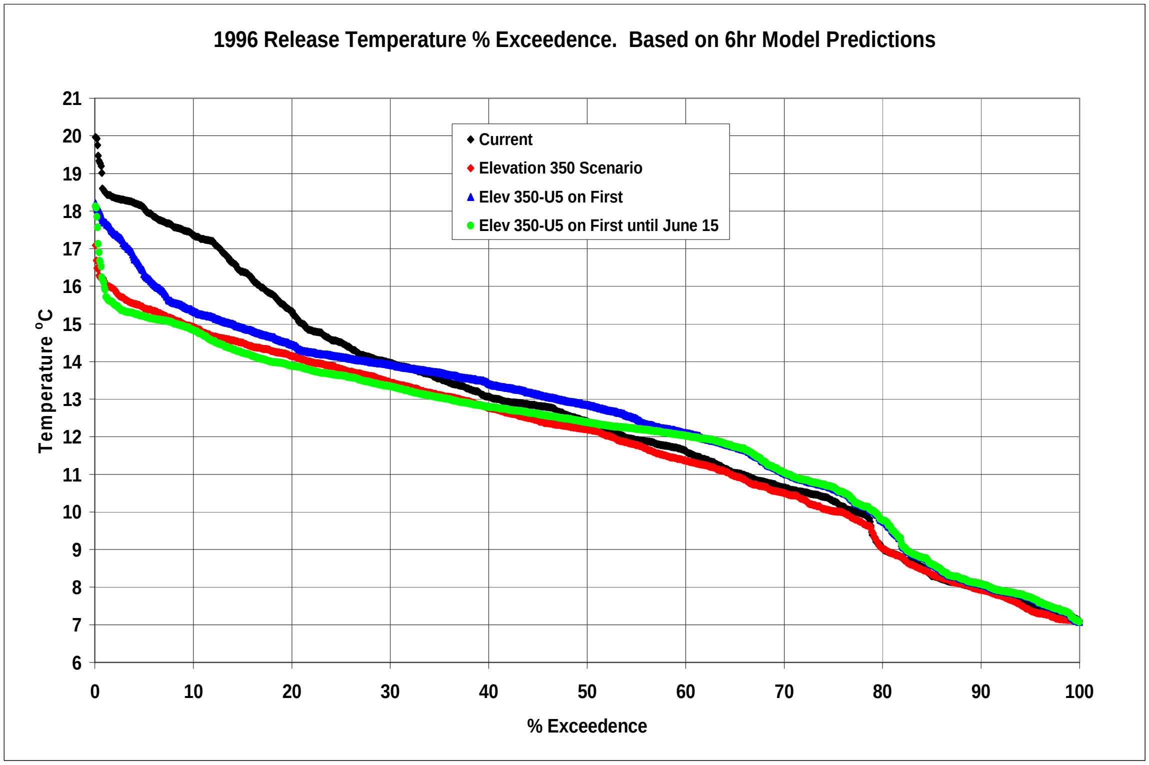

Figure 4-49. 1996 Release Temperature Exceedence

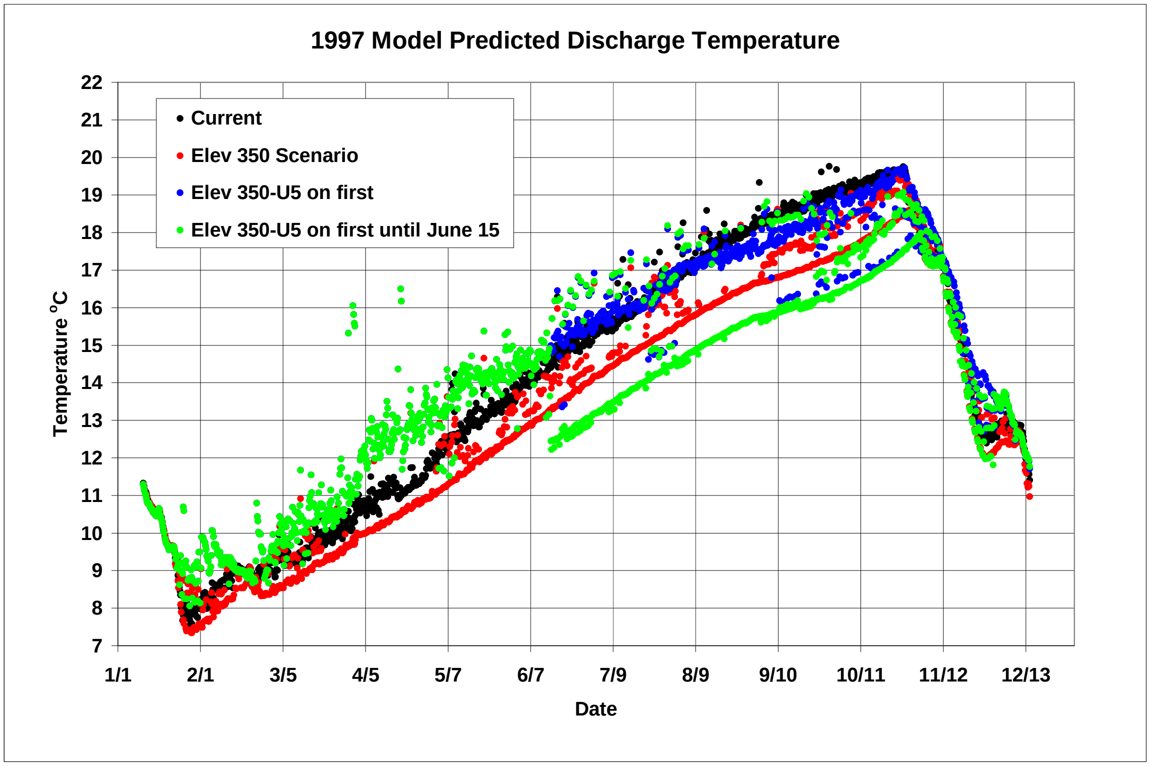

Figure 4-50. 1997 Release Temperature

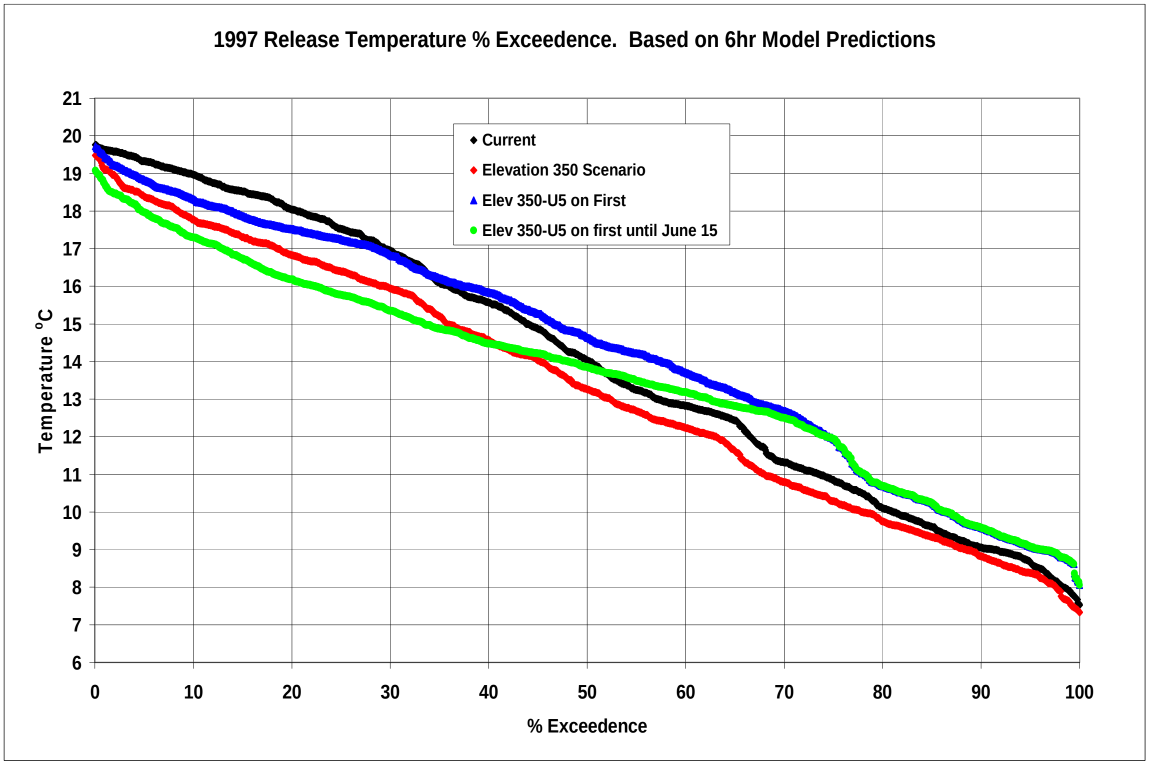

Figure 4-51. 1997 Release Temperature Exceedence

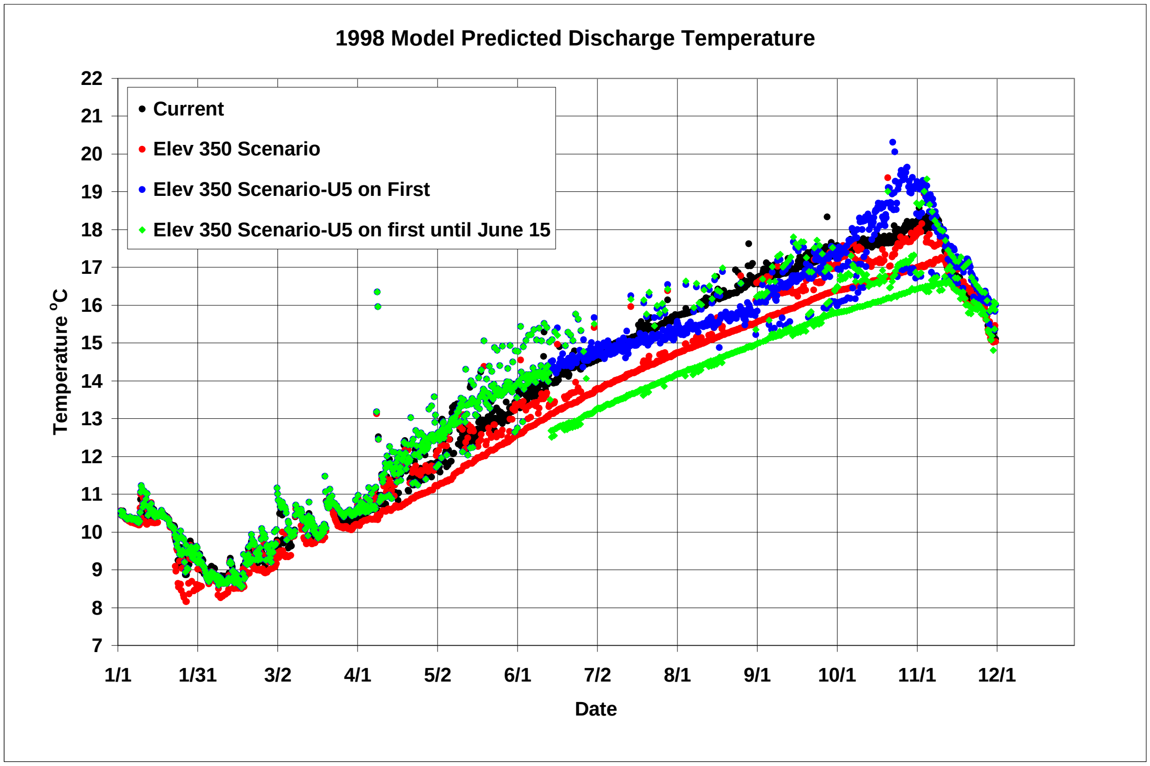

Figure 4-52. 1998 Release Temperature

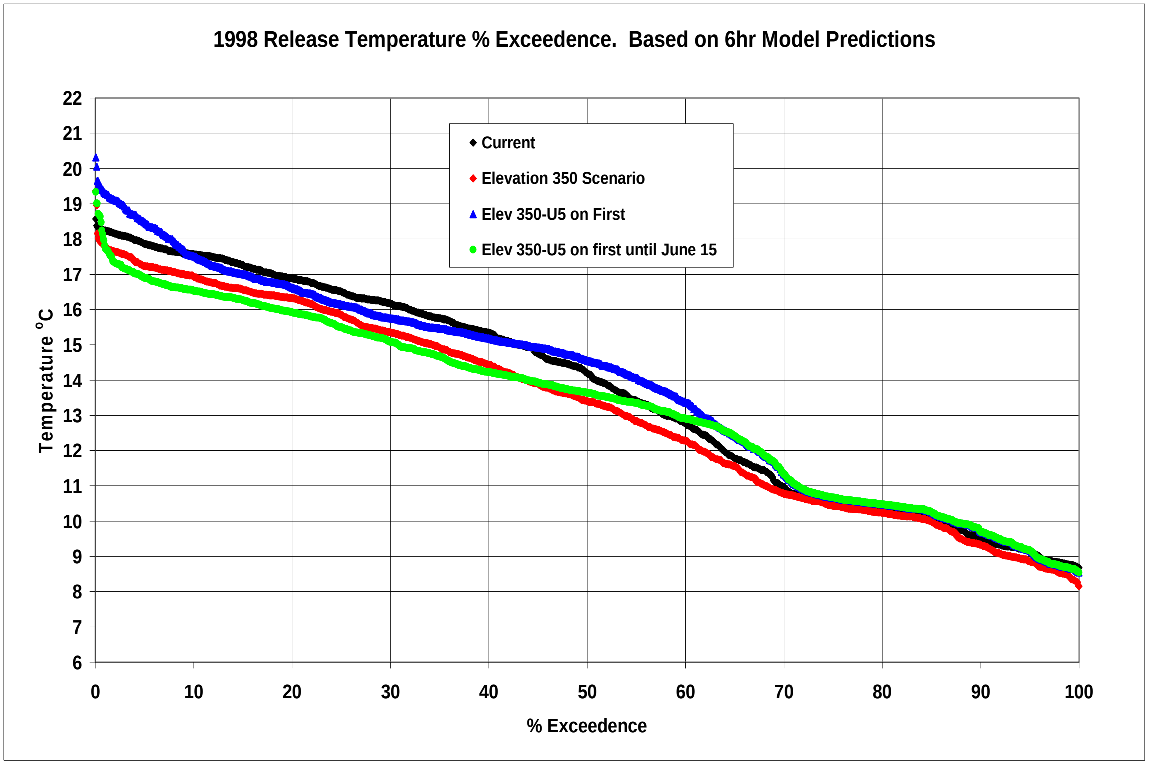

Figure 4-53. 1998 Release Temperature Exceedence

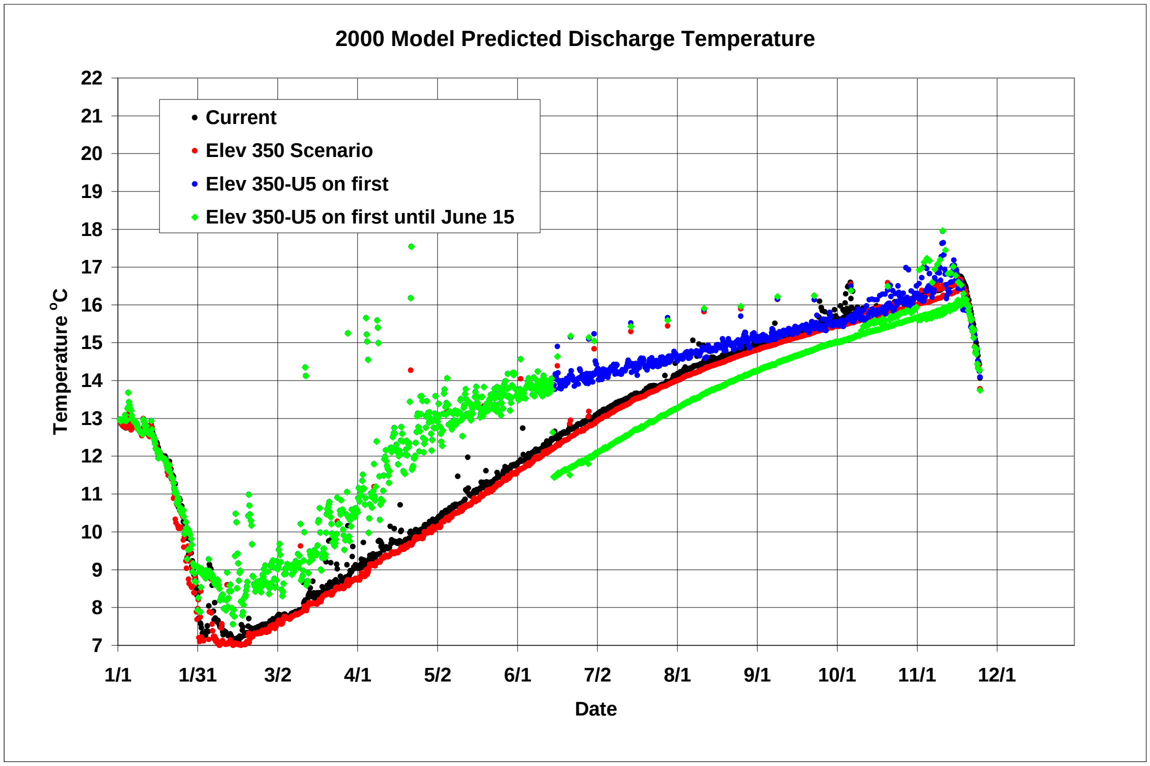

Figure 4-54. 2000 Release Temperature

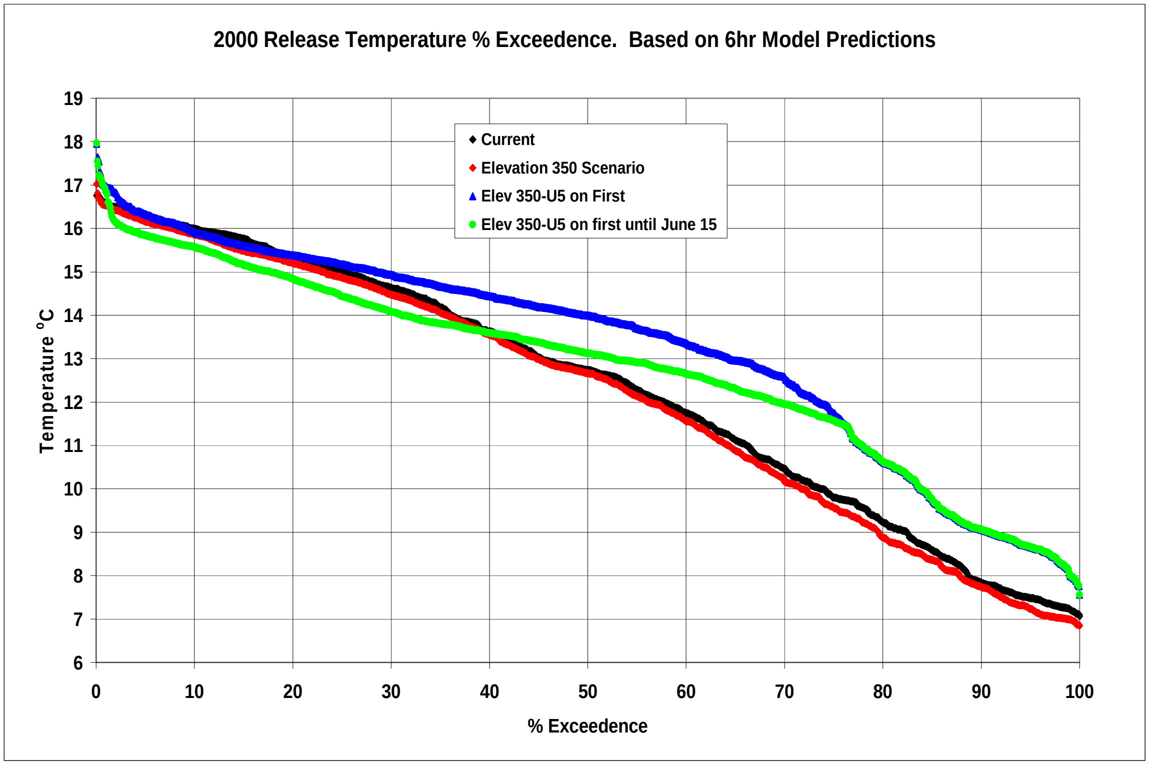

Figure 4-55. 2000 Release Temperature Exceedence

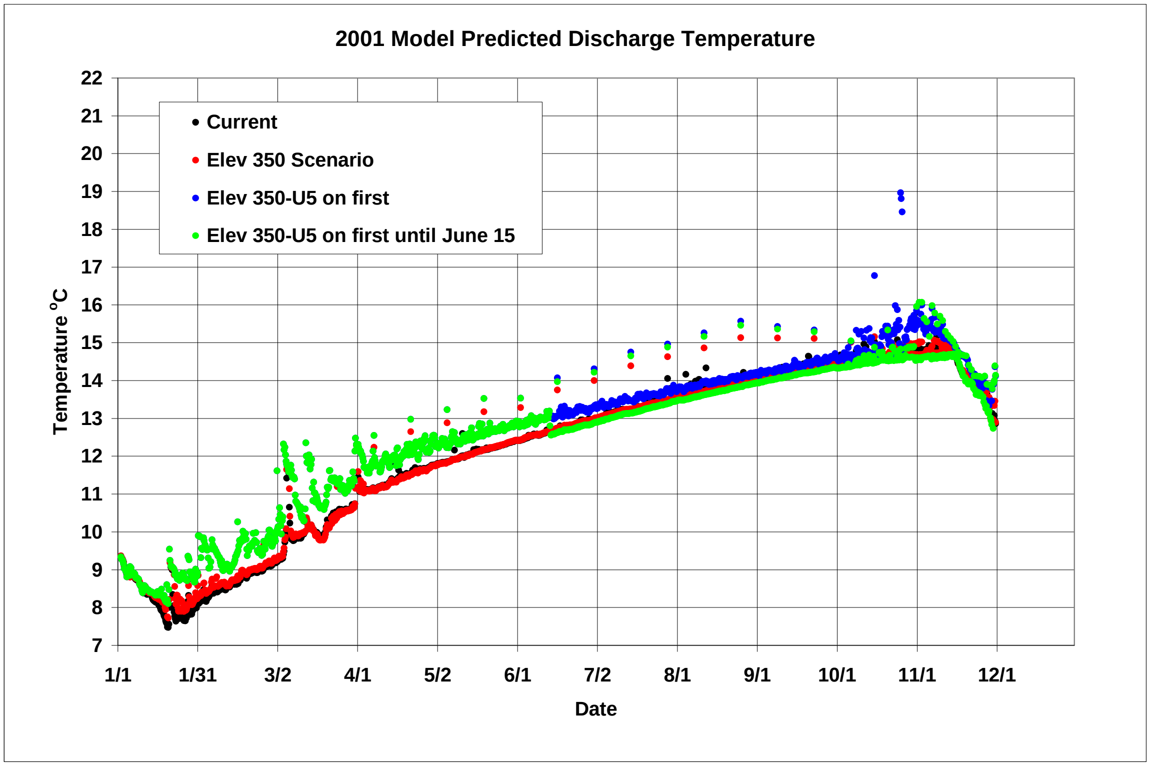

Figure 4-56. 2001 Release Temperature

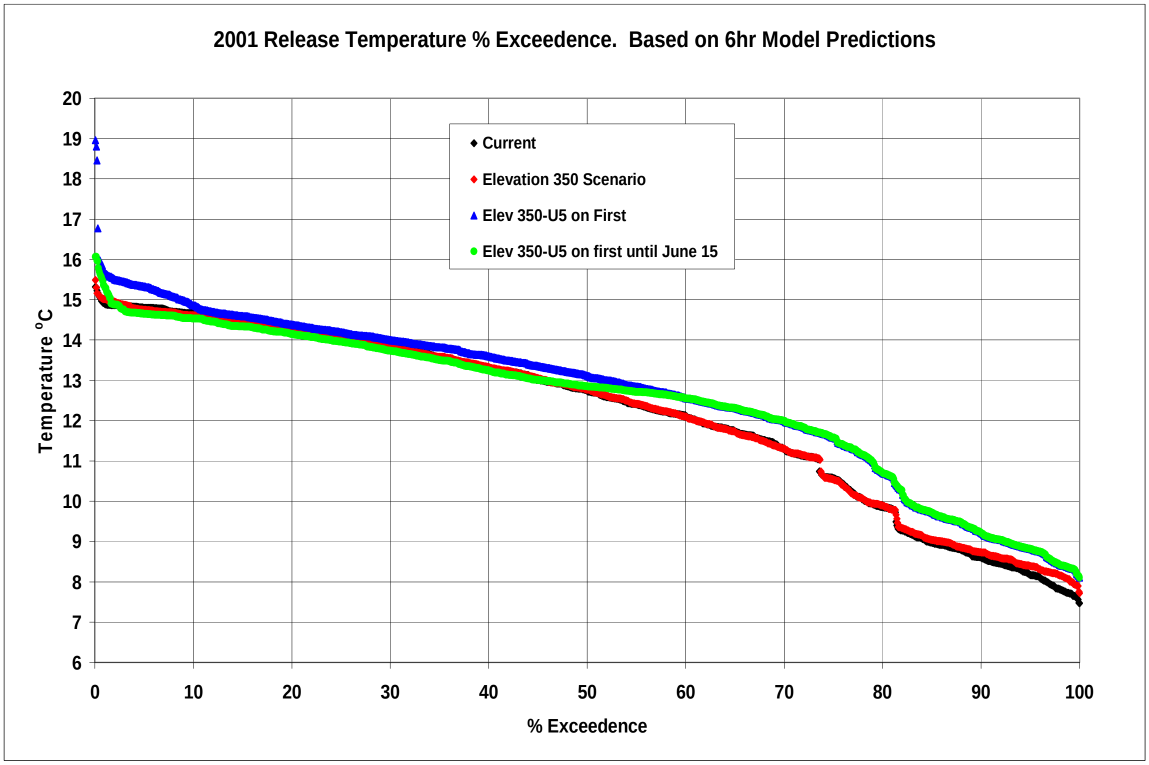

Figure 4-57. 2001 Release Temperature Exceedence

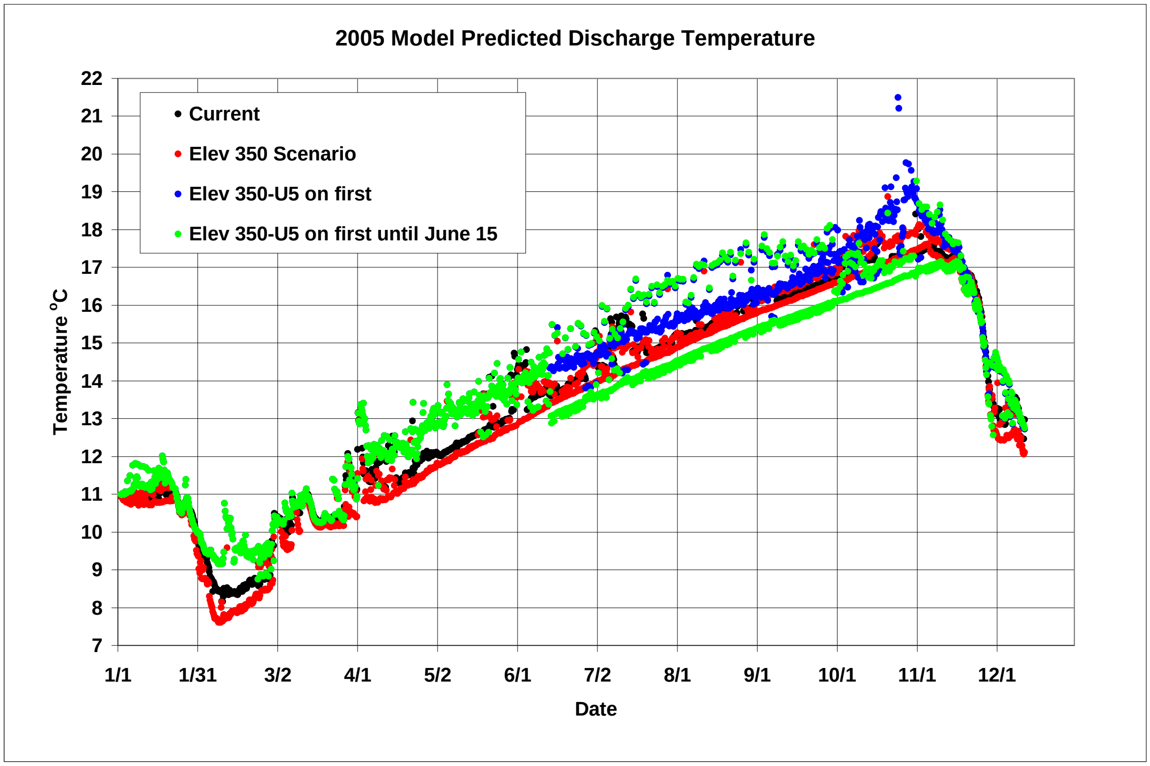

Figure 4-58. 2005 Release Temperature

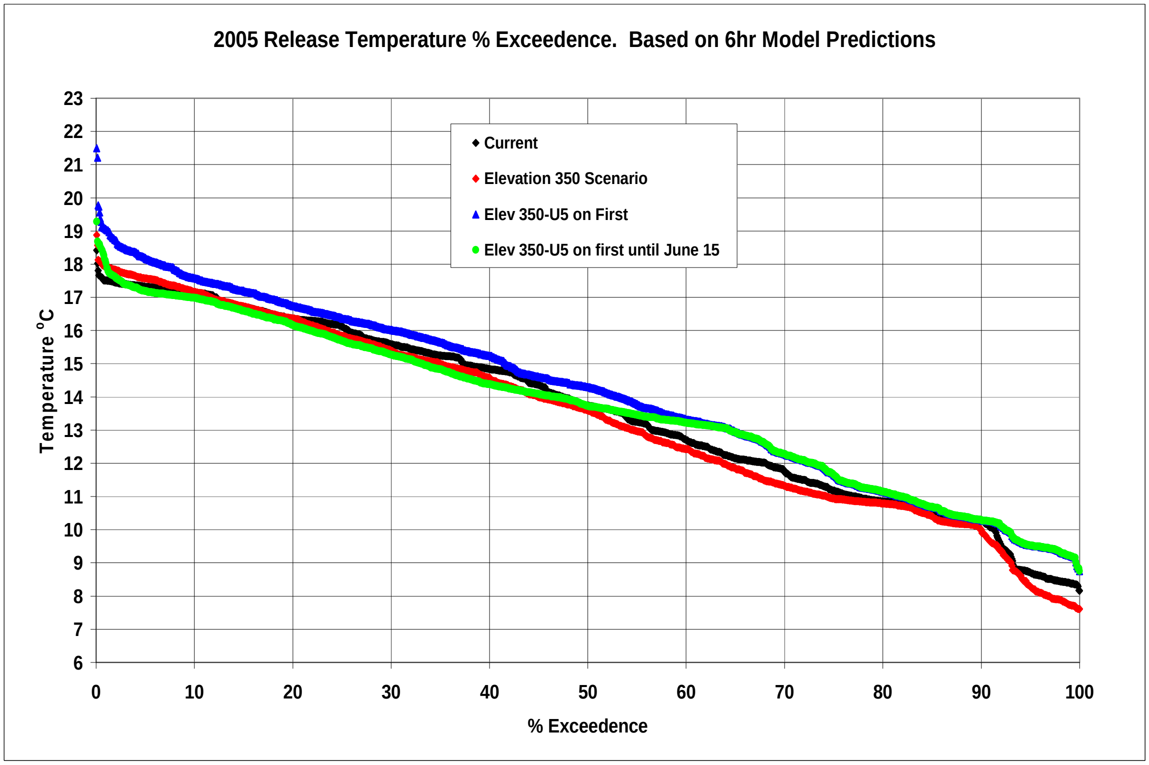

Figure 4-59. 2005 Release Temperature Exceedence

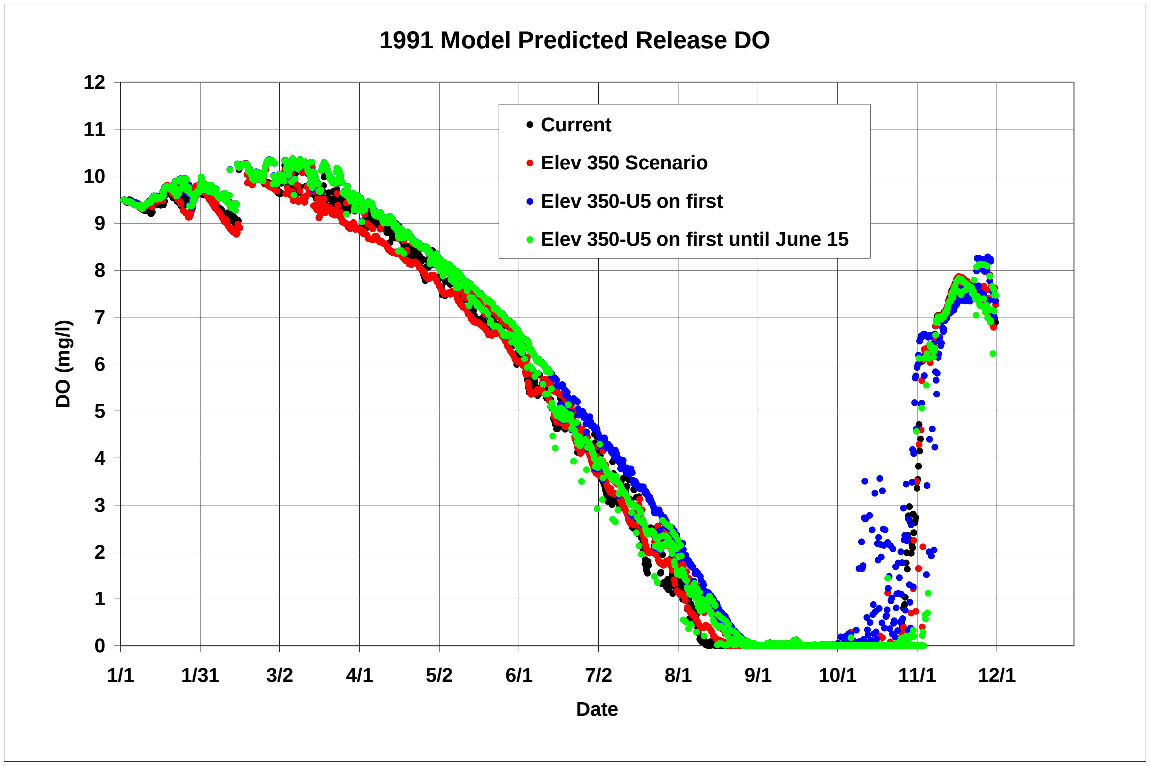

Figure 4-60. 1991 Release DO

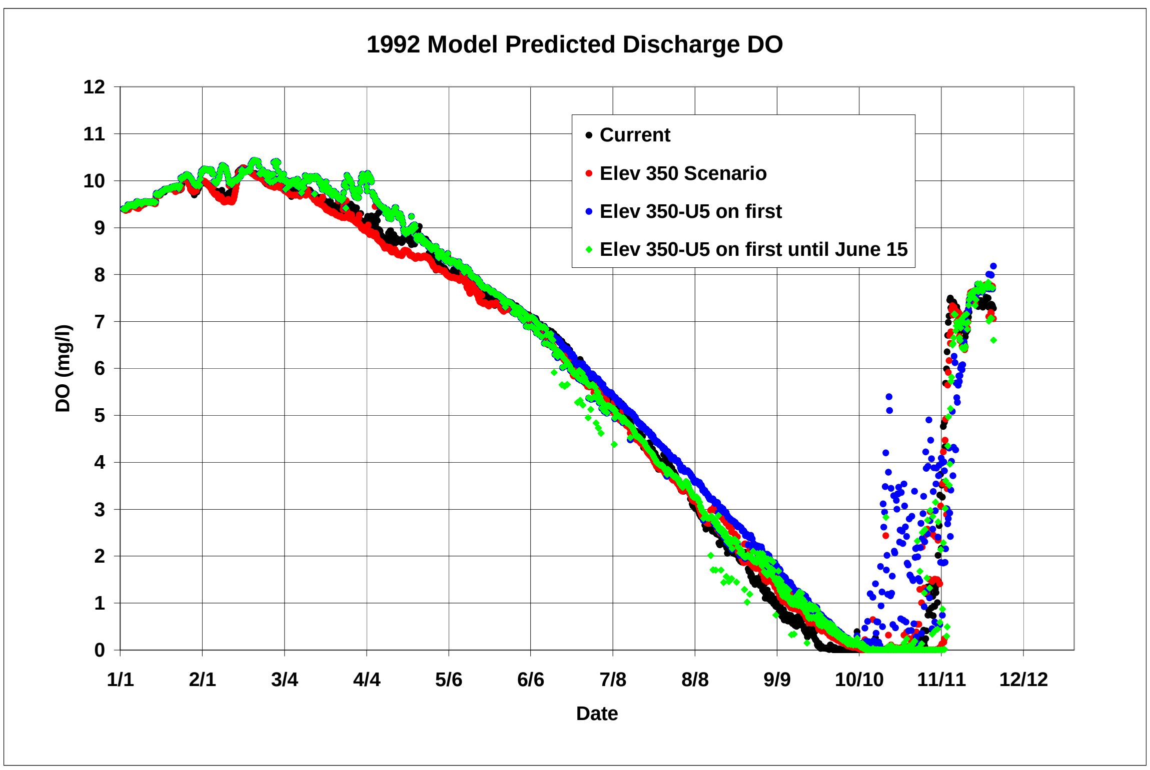

Figure 4-61. 1992 Release DO

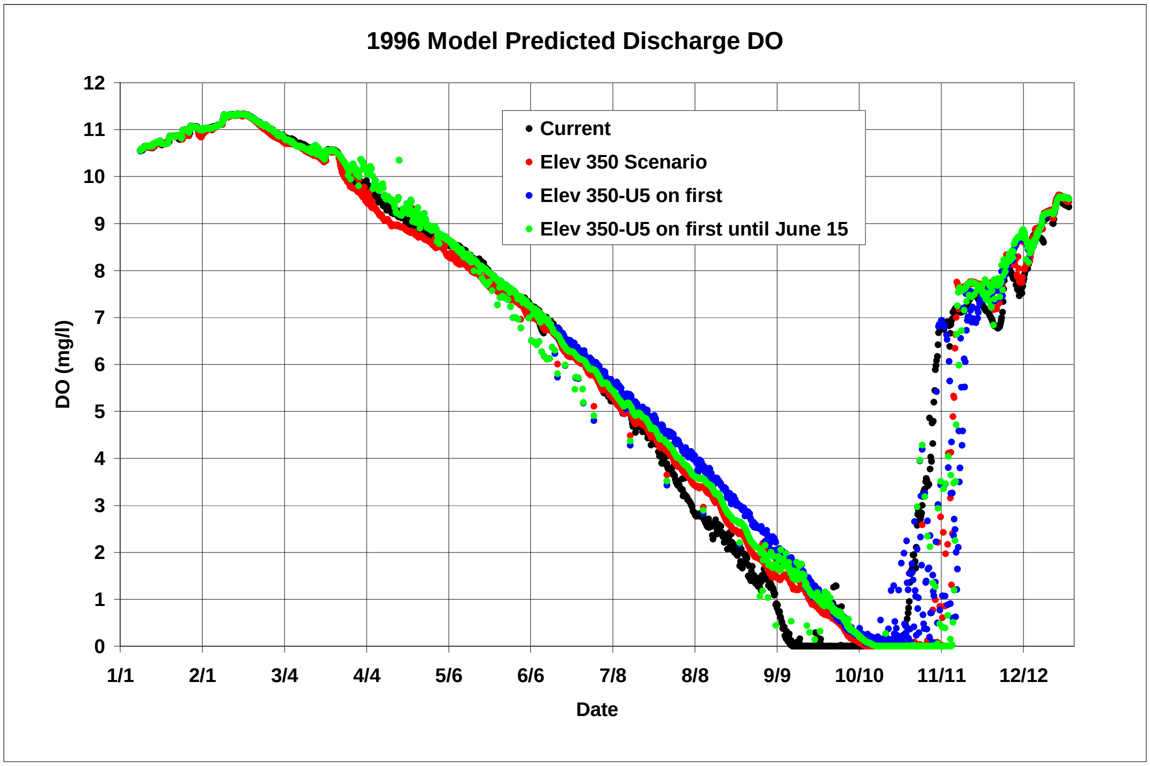

Figure 4-62. 1996 Release DO

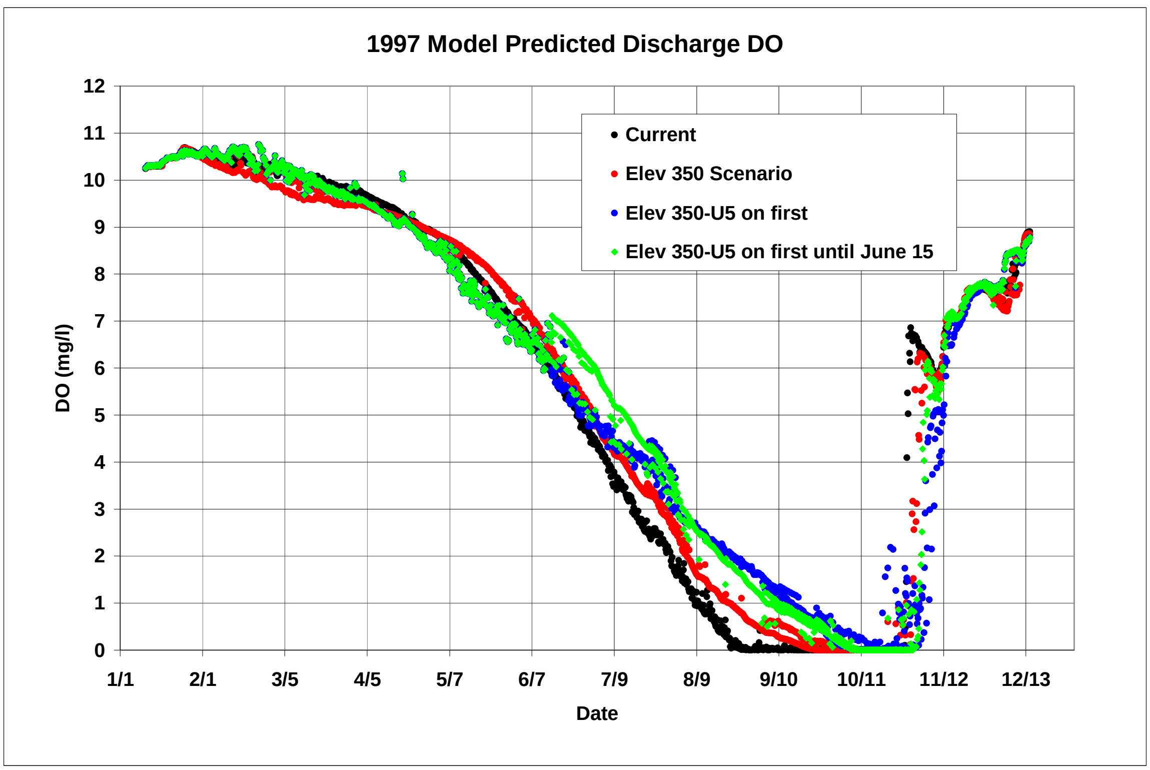

Figure 4-63. 1997 Release DO

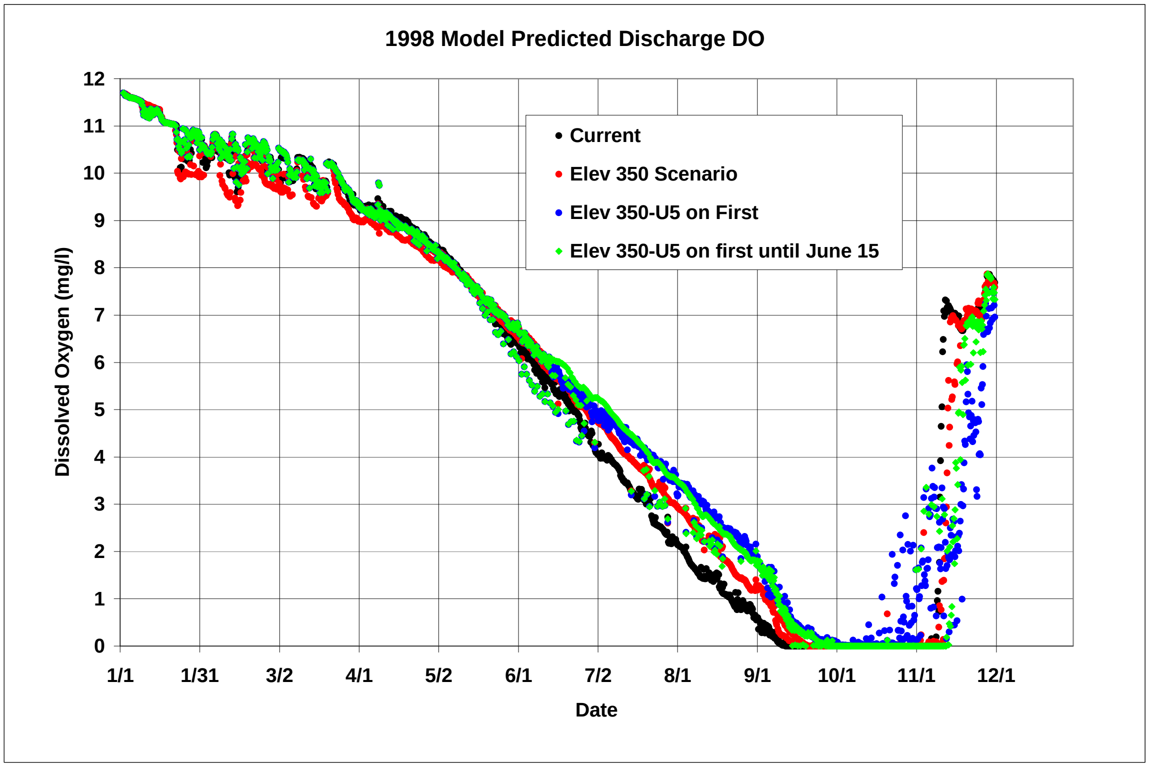

Figure 4-64. 1998 Release DO

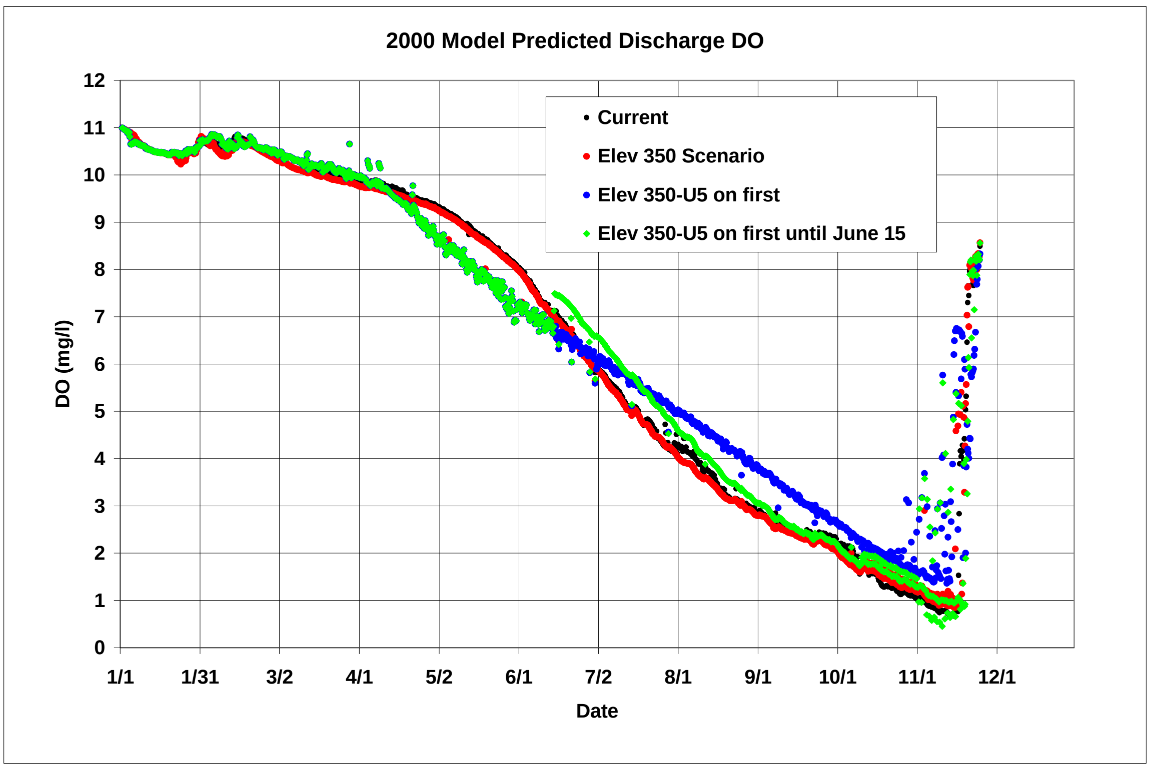

Figure 4-65. 2000 Release DO

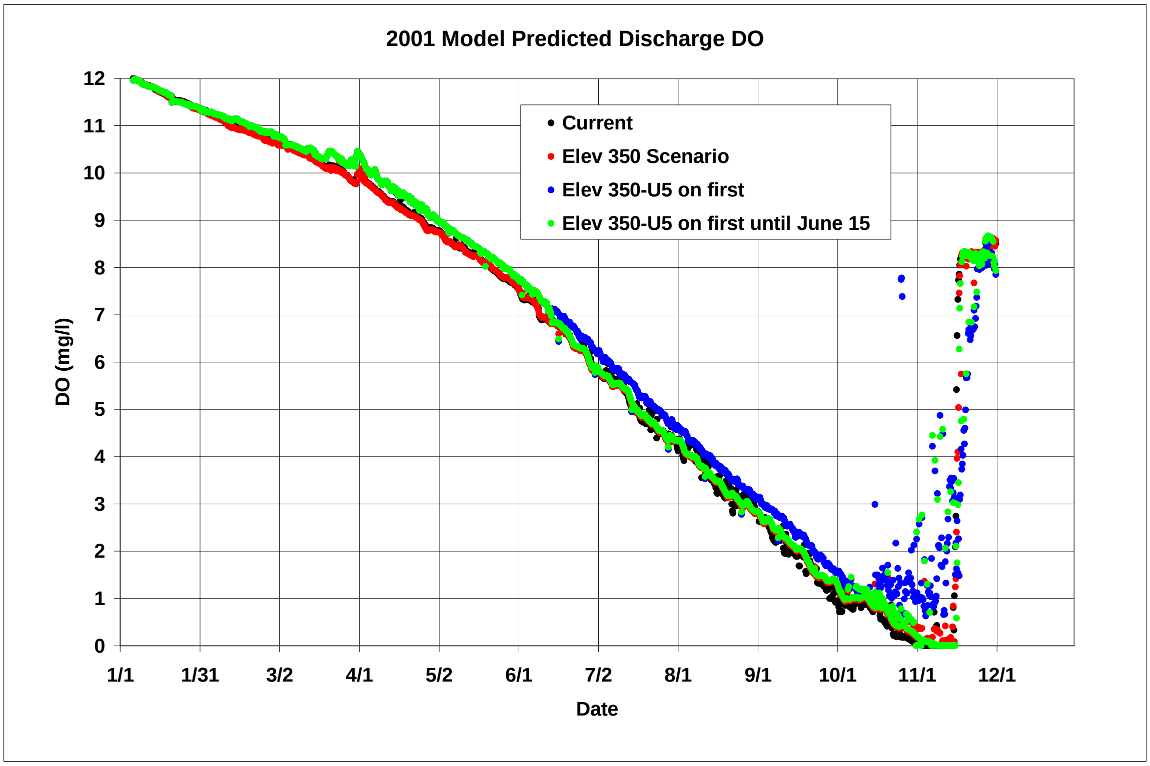

Figure 4-66. 2001 Release DO

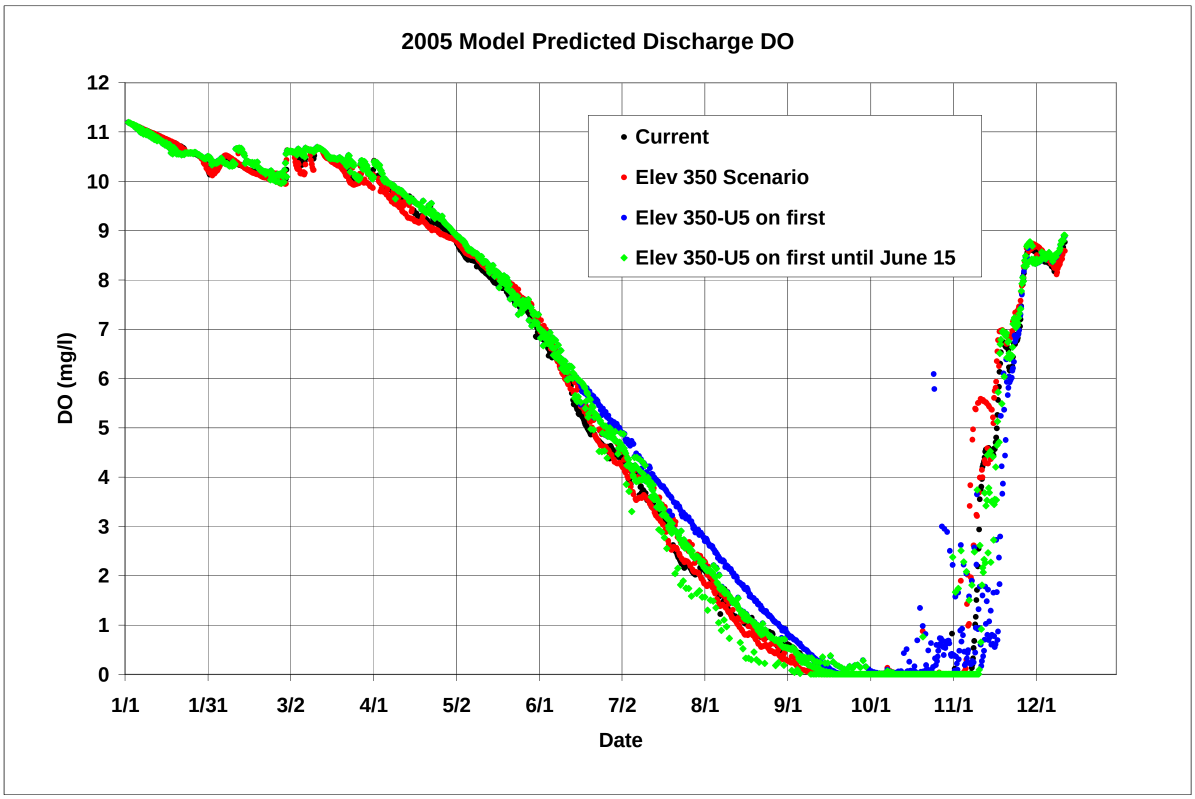

Figure 4-67. 2005 Release DO

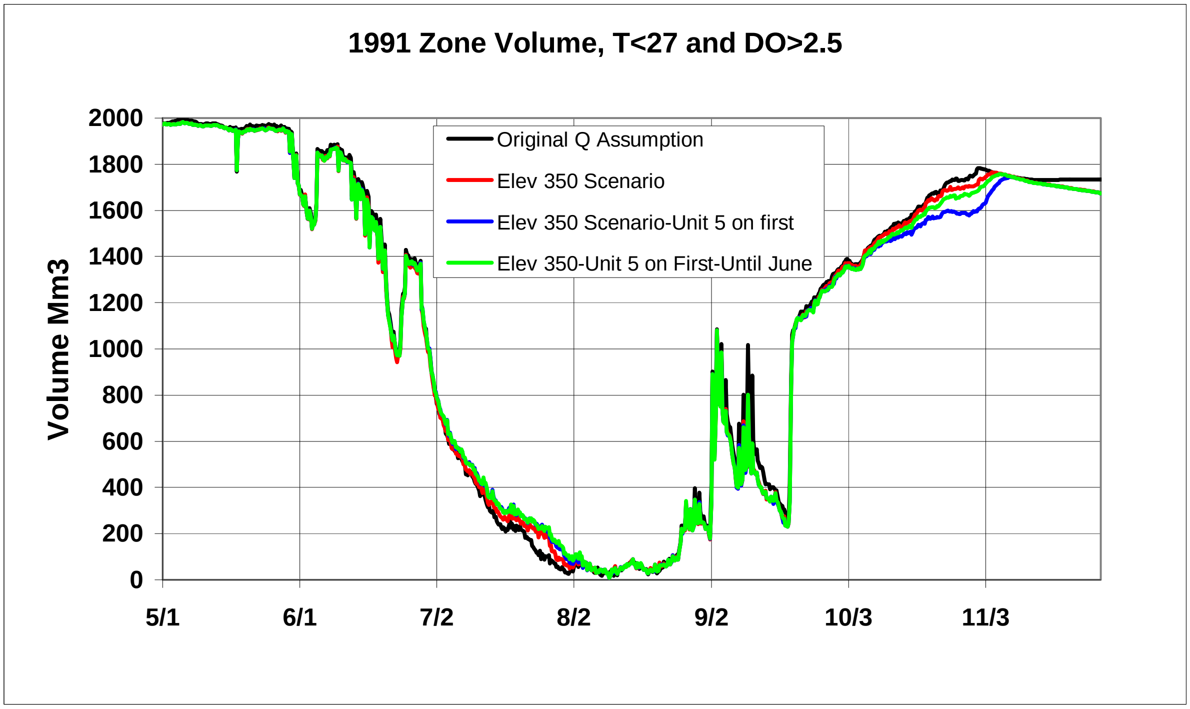

Figure 4-68. 1991 Lake Murray Striped Bass Habitat

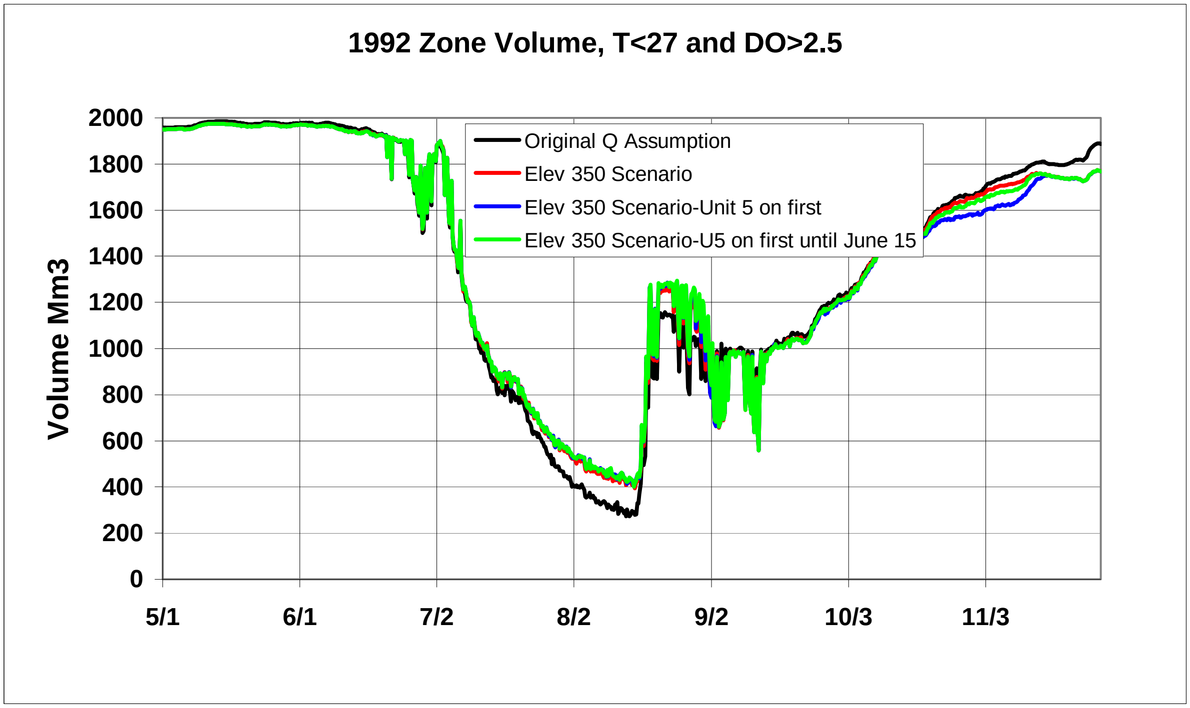

Figure 4-69. 1992 Lake Murray Striped Bass Habitat

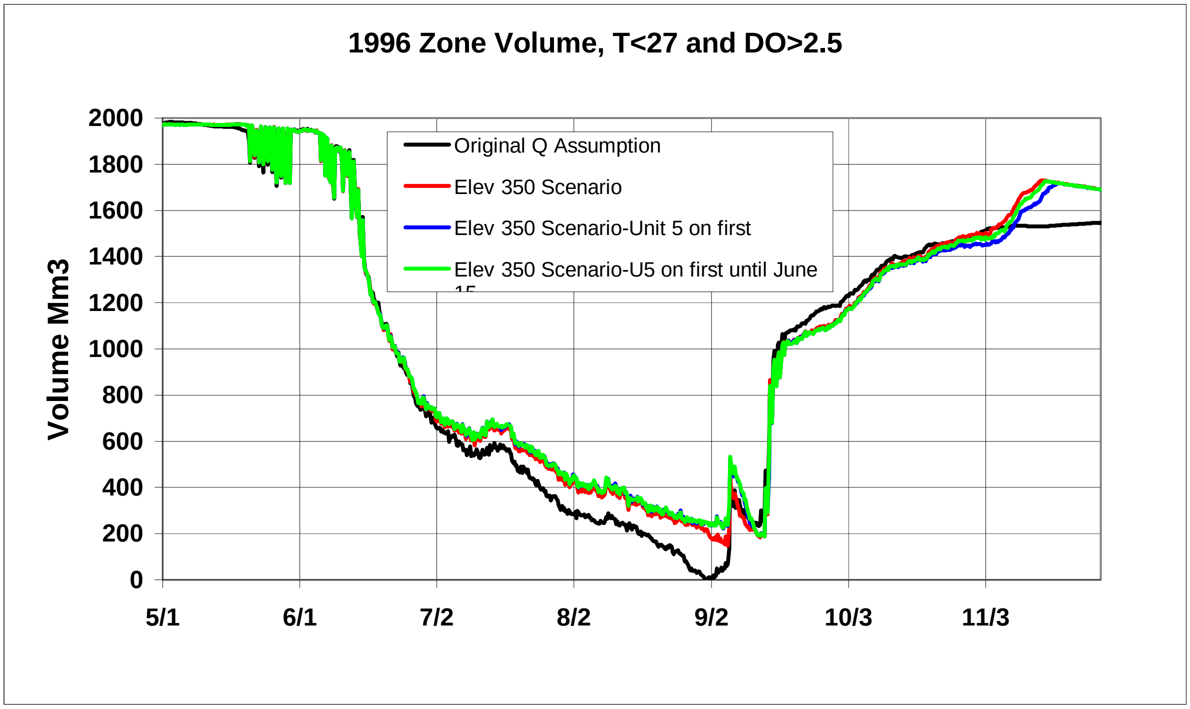

Figure 4-70. 1996 Lake Murray Striped Bass Habitat

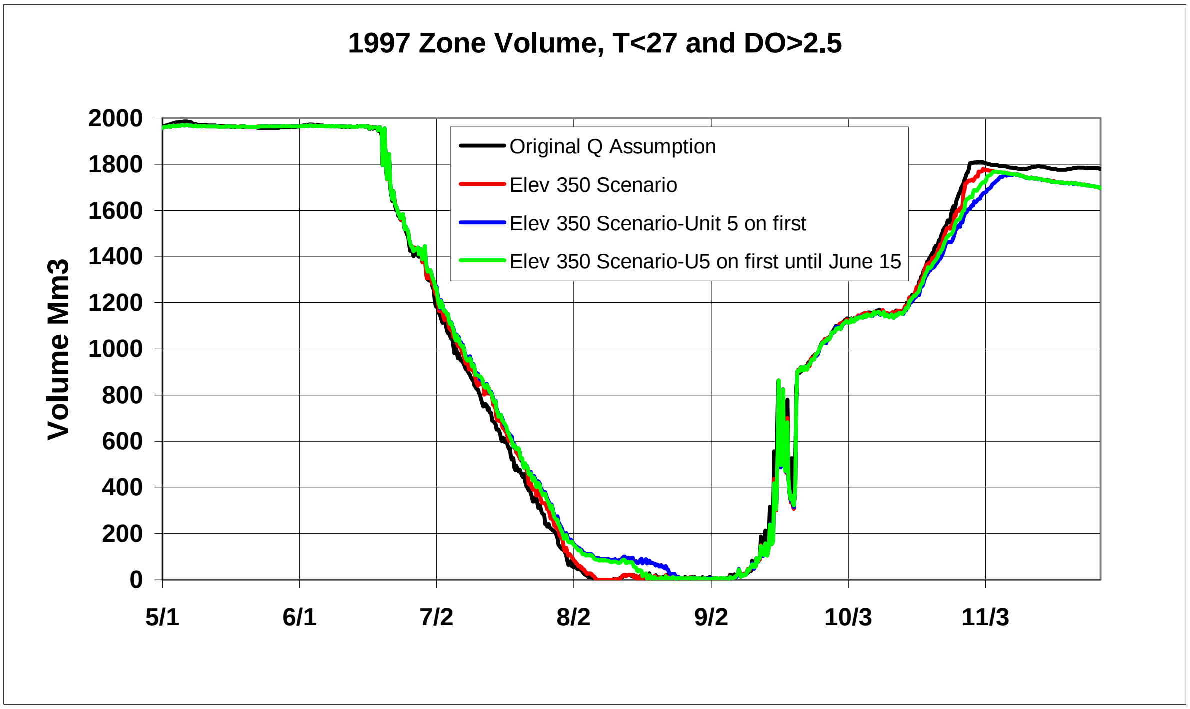

Figure 4-71. 1997 Lake Murray Striped Bass Habitat

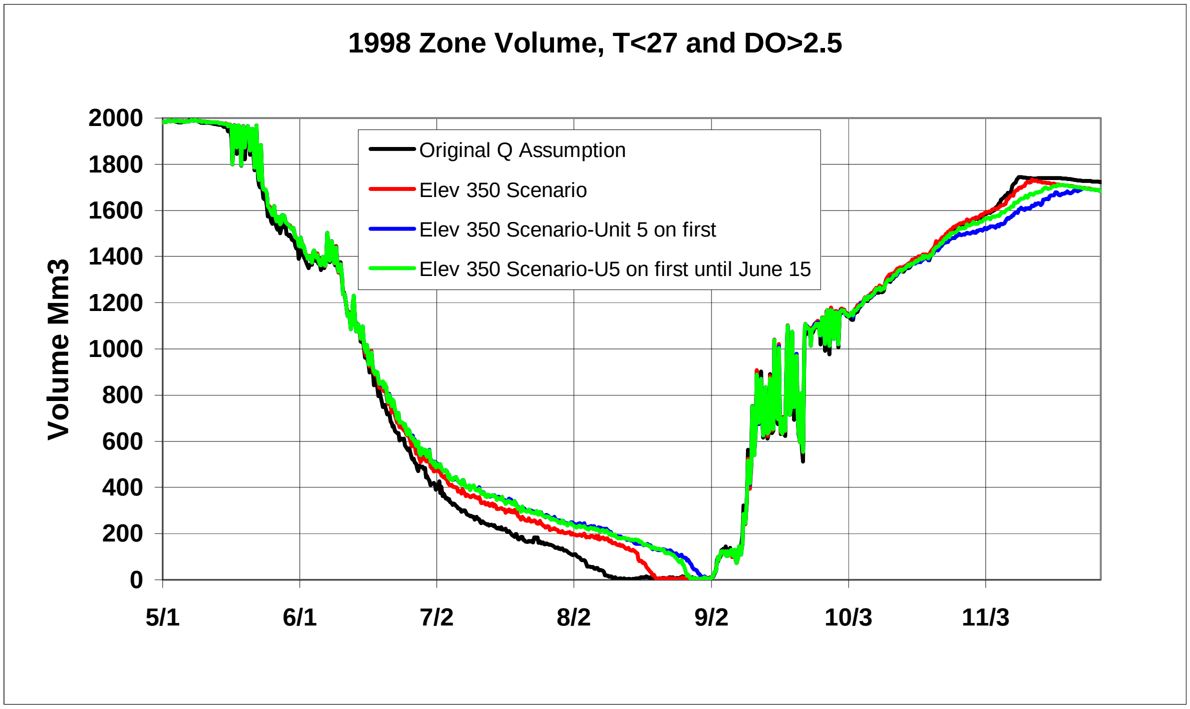

Figure 4-72. 1998 Lake Murray Striped Bass Habitat

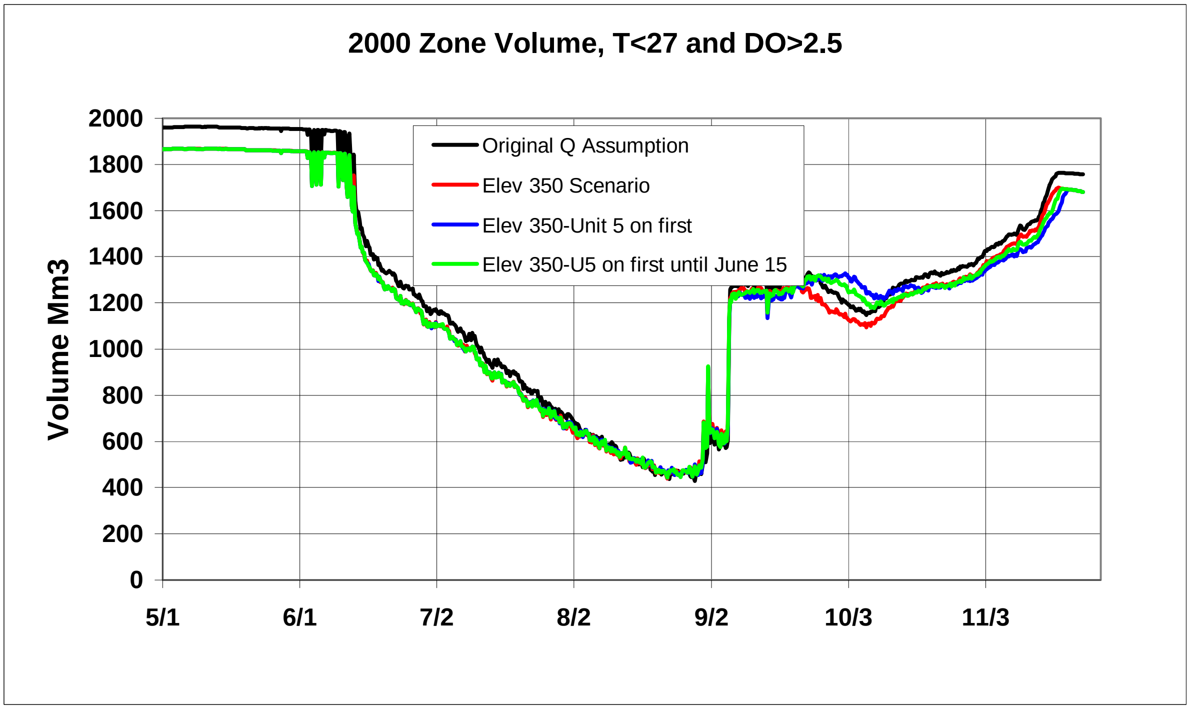

Figure 4-73. 2000 Lake Murray Striped Bass Habitat

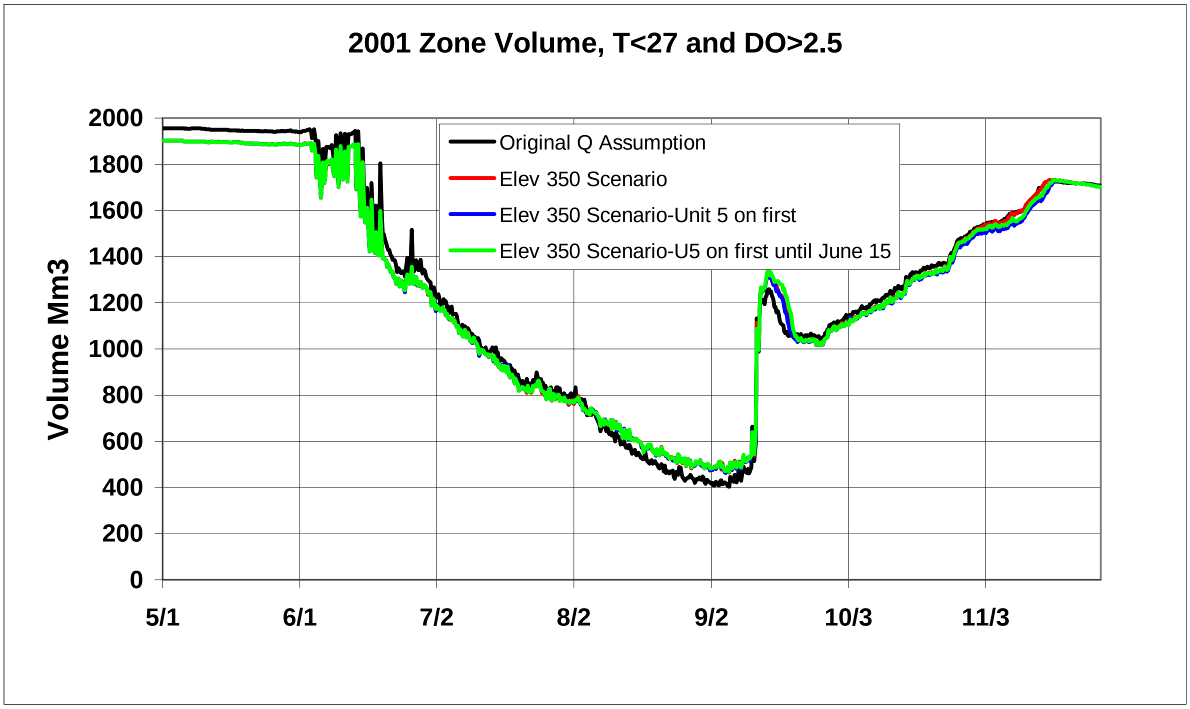

Figure 4-74. 2001 Lake Murray Striped Bass Habitat

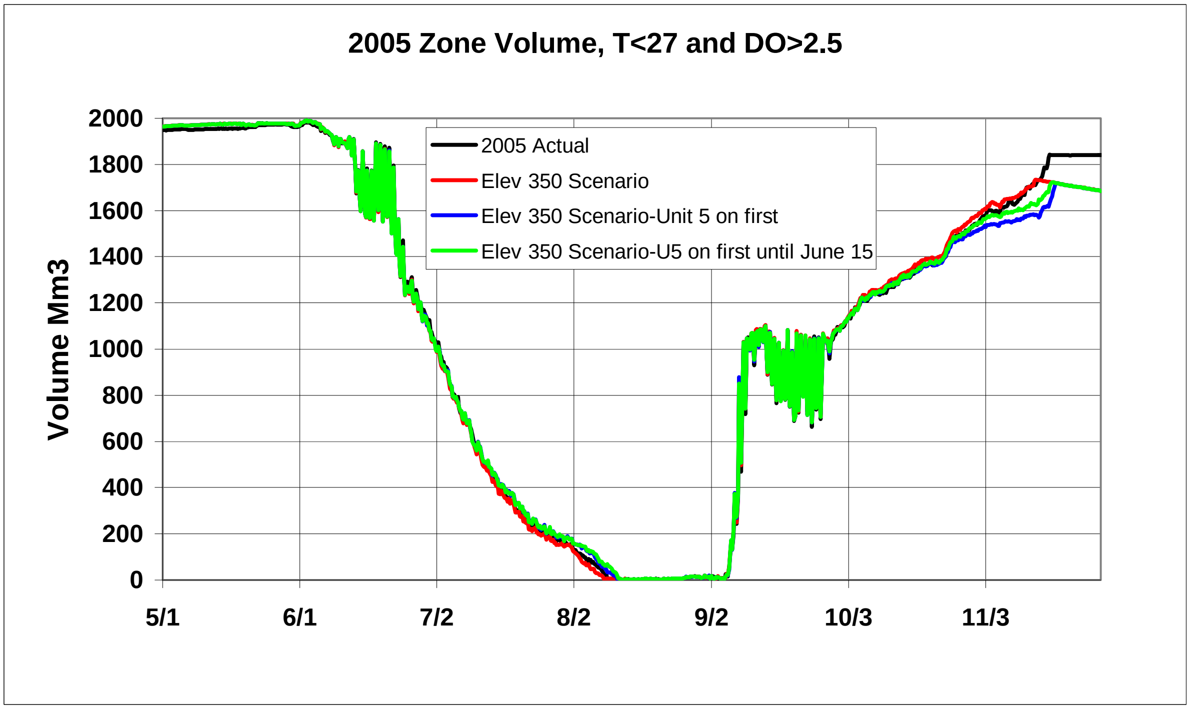

Figure 4-75. 2005 Lake Murray Striped Bass Habitat

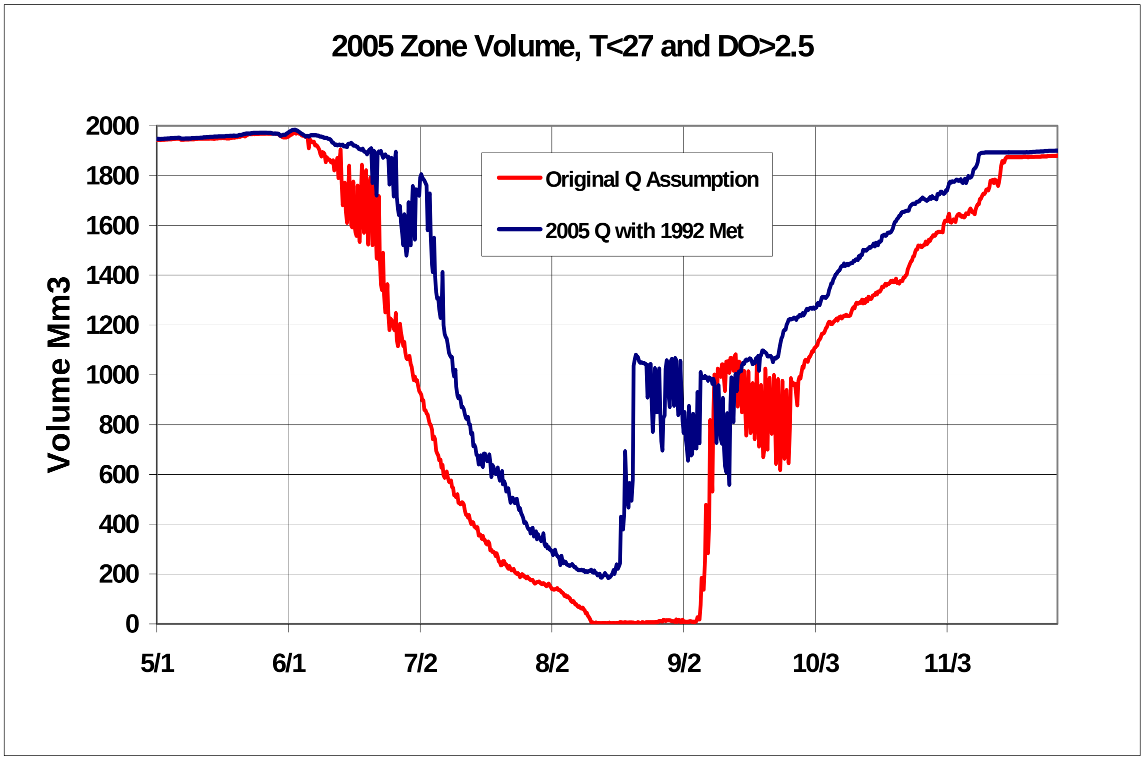

Figure 4-76. Comparison of Striped Bass Habitat Showing Sensitivity to Meteorology. The red line is 2005 Actual (2005 flow and meteorology) and the blue line is 2005 flows with 1992 Meteorology.

5. Minimum Winter Pool Level Considerations

As part of the relicensing process, SCE&G is considering raising the winter minimum pool elevation. This could affect water quality and fish habitat. Also, it is likely not needed to attain the target summer pool level of 358'.

Water quality considerations. The CE-QUAL-W2 model was used in the previous section to evaluate dropping the winter minimum pool elevation to 350 and 354 ft msl to determine the effects on release water quality and fish habitat. The model was setup using existing water quality settings for wet years, normal years, and low flow years to see how water quality was affected by setting the minimum pool elevation to that being evaluated by SCE&G. The evaluation assessed striped bass habitat and temperature and DO in the releases. The evaluation showed that there was no apparent impact of either minimum pool level to the issues on the main body of the lake.

Another impact on water quality that was expected to occur due to changing the minimum winter pool level to 354' was in the Little Saluda River embayment, especially upstream from the bridge on SC Hwy 391. This is a relatively large embayment with a small watershed; therefore, the residence time of water in this embayment is relatively long. If minimum pool elevation is raised, there would be less water exchange between this embayment and the main body of Lake Murray, especially in low flow years. This would lead to increased "internal cycling" of nutrients in this embayment to the point that it may become insensitive to nutrient loads from the watershed because the release of nutrients from the sediments of the embayment could be sufficient to support eutrophic conditions in the embayment. One factor that also was assessed was the potential impact of SOD (sediment oxygen demand) increasing up to levels seen at other projects in the SE USA. This was supported by seasonal SOD dynamics measured at Douglas Reservoir (TVA). In some cases this condition can lead to the formation of algal mats on the water, and these mats of algae are known to significantly affect water quality and water uses. To assess this potential water quality problem, the model was used to assess the changes that might occur in the embayment.

The results of modeling water quality in the Little Saluda embayment are presented in Figures 5-1 through 5-10. Figure 5-1 shows the model segments along the length of the embayment. Figures 5-2 through 5-5 show the phosphorus and chlorophyll a levels at two locations in the embayment for four cases: current conditions with the minimum pool at 350' and 354', one case with the SOD doubled to account for an anticipated increase in organic matter if minimum pool level is set to 354', and one case with the inflow phosphorus reduced to zero. The plots show that phosphorus was reduced when the inflow phosphorus is reduced to zero, but this action did not dramatically reduce phosphorus in the embayment especially under summer conditions. Under summer conditions it appears that two-thirds of the phosphorus was caused by internal phosphorus cycling. This finding indicates that the phosphorus cycling in Little Saluda embayment is sensitive to organic matter that is formed and settles to the bottom sediments in the embayment. It is also interesting to note for the case where phosphorus loads are reduced to zero that chlorophyll a is reduced for the early part of the summer but not for the latter part of the summer. [Note: it should be mentioned that data were insufficient to calibrate the CE-QUAL-W2 model for the Little Saluda embayment, so these model results are useful only for sensitivity analyses.]

Figures 5-6 through 5-9 show the potential effects of increased organic matter in the Little Saluda embayment on DO in the water column. These model runs were made by increasing the SOD in the embayment as well as reducing the phosphorus inputs to zero from the local tributaries to the Little Saluda embayment. The results indicate the DO in the embayment would be reduced primarily by the increased SOD. Figure 5-10 shows the DO in the main body of Lake Murray at Rocky Creek and indicates that DO would be marginally impacted by the increased SOD scenario.

There is a potential for the internal cycling of phosphorus in the Little Saluda embayment to impact SCDHEC's TMDL considerations on the Little Saluda River embayment.

Other parts of the lake are likely to be impacted by raising the minimum pool level to elevation 354:

1. Sediments and suspended solids that enter the lake from tributaries settle and accumulate near the inflow region to the lake. Dropping the pool level periodically on a regular basis causes these sediments to be resuspended and redeposited to deeper locations in the lake where they do little harm.
2. Dropping the pool level also causes aquatic plants to be killed or "die back" by freezing conditions. Exposure of plants to dry and freezing conditions causes plants to be reduced. This process is likely controlling weeds in Lake Murray to some extent, especially in the Little Saluda embayment.
3. Raising the pool level causes sediments to accumulate where aquatic weeds can grow and take root. After they establish roots, the plants cause even more sediment to accumulate. Once such sediment complexes get established, normal periodic scouring action (i.e., scouring flows every few years like every other year or annually) is not sufficient to re-suspend these sediments. So in some ways this is practically an irreversible impact.
4. The phenomena of sediment accumulation in reservoirs at their inflow areas is a complex process dependent on many factors: watershed size, land uses in watershed, hydrology of watershed, types of soil, frequency of high runoff, location within/without channel (velocity, erosion is important), and minimum pool level. The frequency/duration of minimum pool level occurring increases opportunity for sediment to be moved to lower depths of the lake and avoid build up that is difficult to be moved.

Hydrologic and Reservoir Operations Assessment to develop recommended minimum pool operations policy. Available inflow data and reservoir operations data were evaluated to determine current practices and hydrologic characteristics. Table 5-1 summarizes inflow data for the period 1927 through 2007 and reservoir operations data for the period 1980 through 2007. To protect water quality concerning the operating policy for the minimum winter pool level, it is recommended that the current practices be reviewed so that the frequency of dropping the pool level down to 350’ can be continued without impacting the objectives of those who wish to set the minimum winter pool level at 354’.

Following are the results of the assessment and recommendations for the winter minimum pool level policy:

1. Based on data for 1980 through 2007 (excluding 2003 and 2004), the winter pool level was down to about 350 ± 2’ about half the time (i.e., 13 of 26 years as shown in Table 5-1). It would be best to maintain this frequency of drawing the lake down to this level each year or risk poorer water quality (sediment accumulation, weeds, increased nutrient cycling from the sediments especially in embayments, and greater potential TMDL designation by DHEC that could lead to very expensive sediment treatments) compared to current conditions.
2. The data in Table 5-1 indicate that maintaining this frequency of drawing the lake down to this level for an average of every two years should not be difficult based on historical inflows and pool level data as well as taking advantage of using November flows to predict the years when Jan-Apr flows would likely be sufficient.
3. One interesting observation is that it appears that the minimum winter pool level has very little to do with attaining and maintaining a target summer pool level at elevation 358 ± 1’. Over the period 1980-2007 (26 years when 2003 and 2004 are excluded), 358 ± 1’ was attained in 24 years during the months of April-June. It appears that it is the lack of sufficient inflows during the summer period that causes the pool elevation to drop like it did in 2007 as well as in other years with low flows.
4. The months with highest average flows are Jan-April (i.e., the flow for these four months averages 77% greater flow than for the other months of the year), and based on data from 1927-2007 (81 years), only 9 years had what appeared to be “challenging” low flows that might prevent the lake from being filled to 358’; however, for the years where pool level data were available (1980-2007) there was only 1 year when the 358 ± 1’ was not attained: 2006. During 1980-2007, there were 8 years with “challenging” low flows available to fill the pool to 358 ± 1’, but 2006 was the only year that this goal was not attained.

5. Based on data from 1927-2007, when Nov mean flows were 1200 cfs or greater at Chappells (see Figure 5-11), the Jan-Apr flows were sufficient to safely attain the 358 ± 1' goal. The Nov mean flow of 1200 cfs was equaled or exceeded for 41 of the 81 years of record. Using this approach, the pool level in the winter could be dropped to 350' on an average frequency of every 2 years. Considering these 41 years, 3 of the years had "challenging" low flows that might prevent the lake from being filled to 358 but 2 of these years occurred during the period 1980-2007 when pool level data were available and in both of these years the 358 ± 1' goal was attained.
6. Although there is more likelihood of having greater flows for the period Jan-Apr when flows are high for the previous Nov, the consequence of dropping the winter pool elevation to 350 every year and not attaining the 358 ± 1' goal is not great: the estimated maximum number of years when the goal would not be attained is about 1 in 10 years, but based on experience between 1980 and 2007 it would likely be closer to 1 in 25-50 years. Again, when the summer pool drops after the 358 ± 1' goal is attained, it is because of low summer inflows, minimum flow provision, and high evaporation.

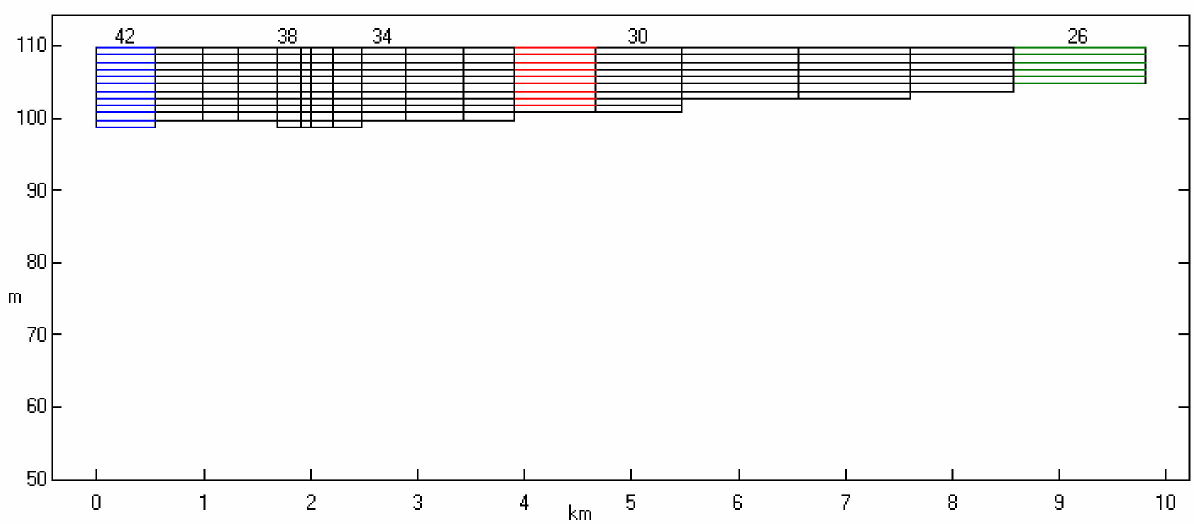

Figure 5-1. Model Segmentation for the Little Saluda River Arm of Lake Murray

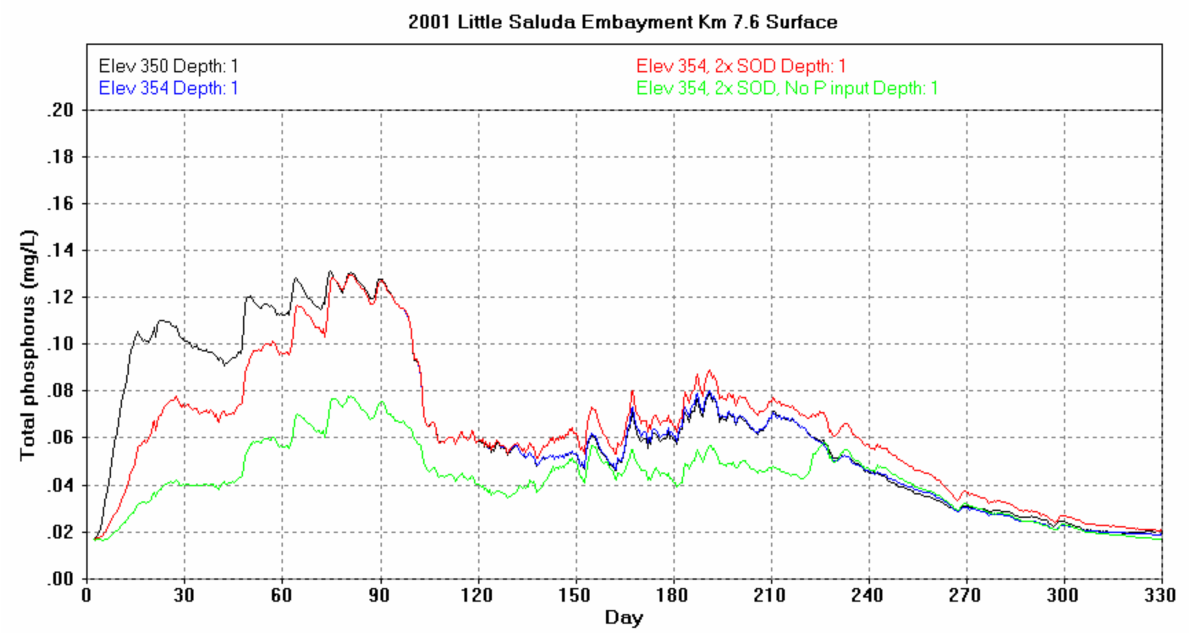

Figure 5-2. Little Saluda Embayment Km 7.6, Total Phosphorus at the Surface

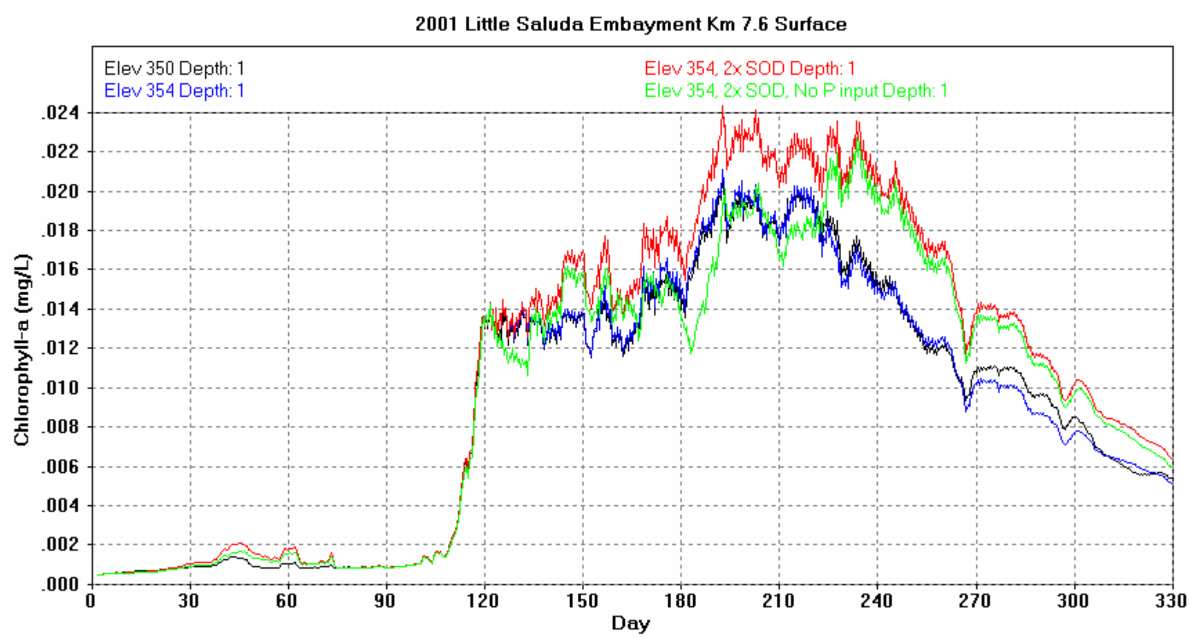

Figure 5-3. Little Saluda Embayment Km 7.6, Chlorophyll *a* at the Surface

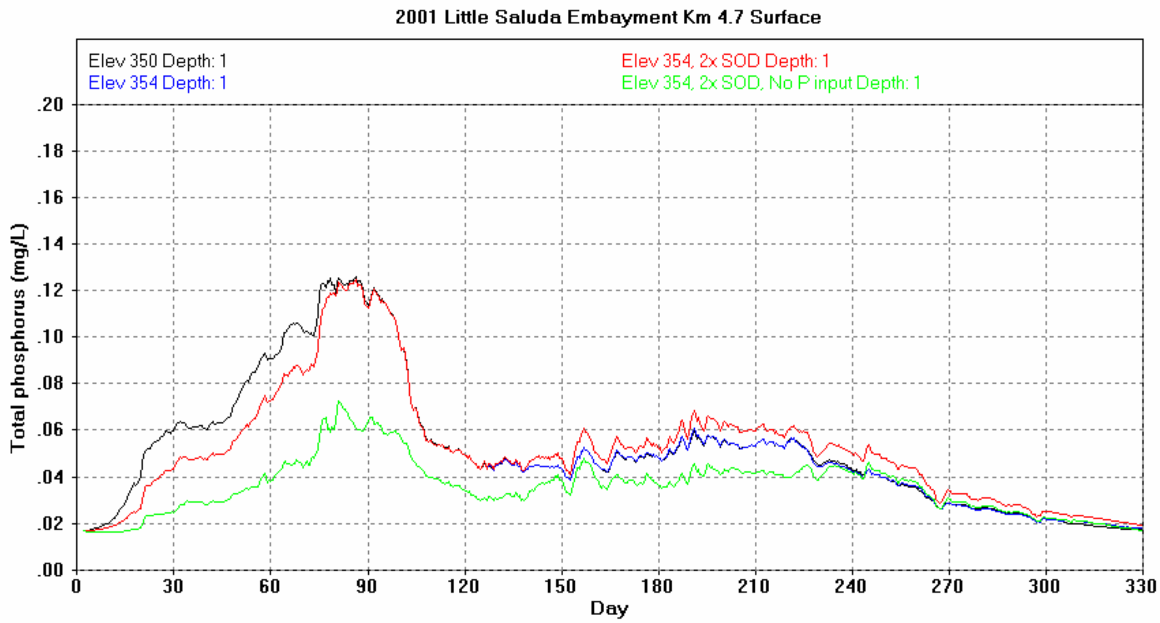

Figure 5-4. Little Saluda Embayment Km 4.7, Total Phosphorus at the Surface

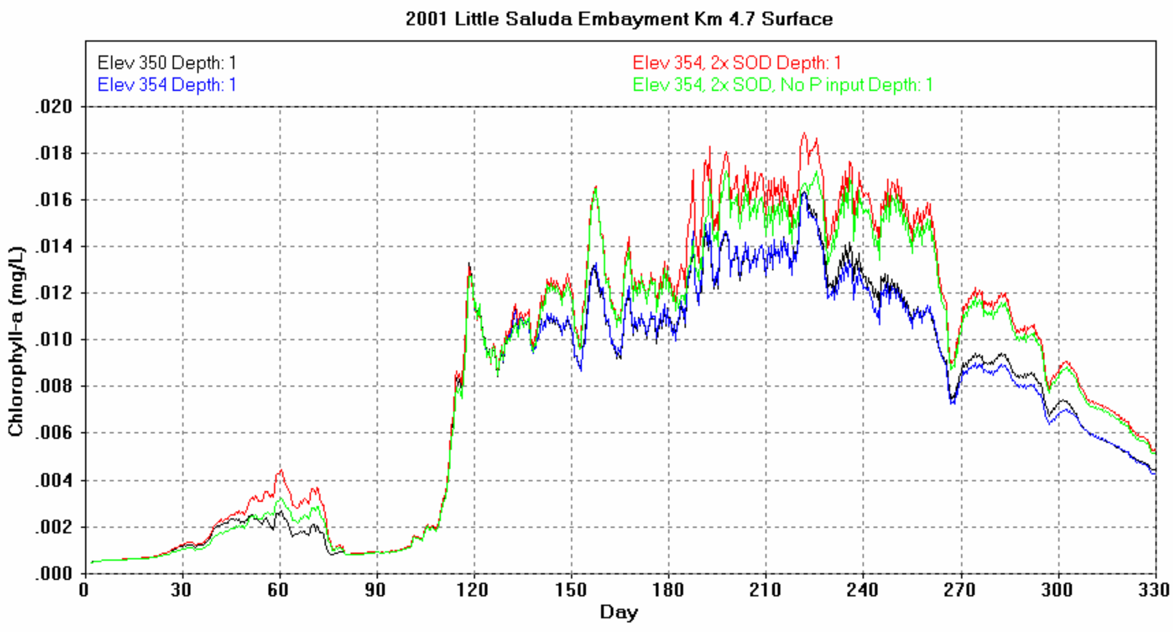

Figure 5-5. Little Saluda Embayment Km 4.7, Chlorophyll *a* at the Surface

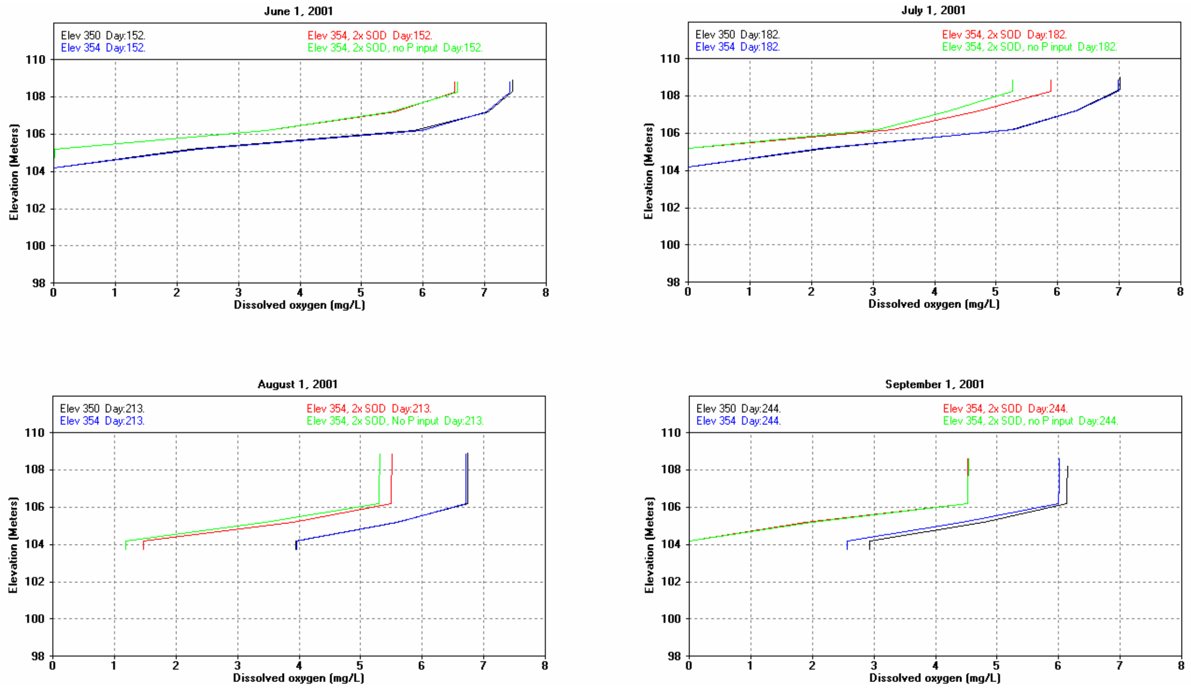

Figure 5-6. DO profiles from the Little Saluda Embayment Km 7.6

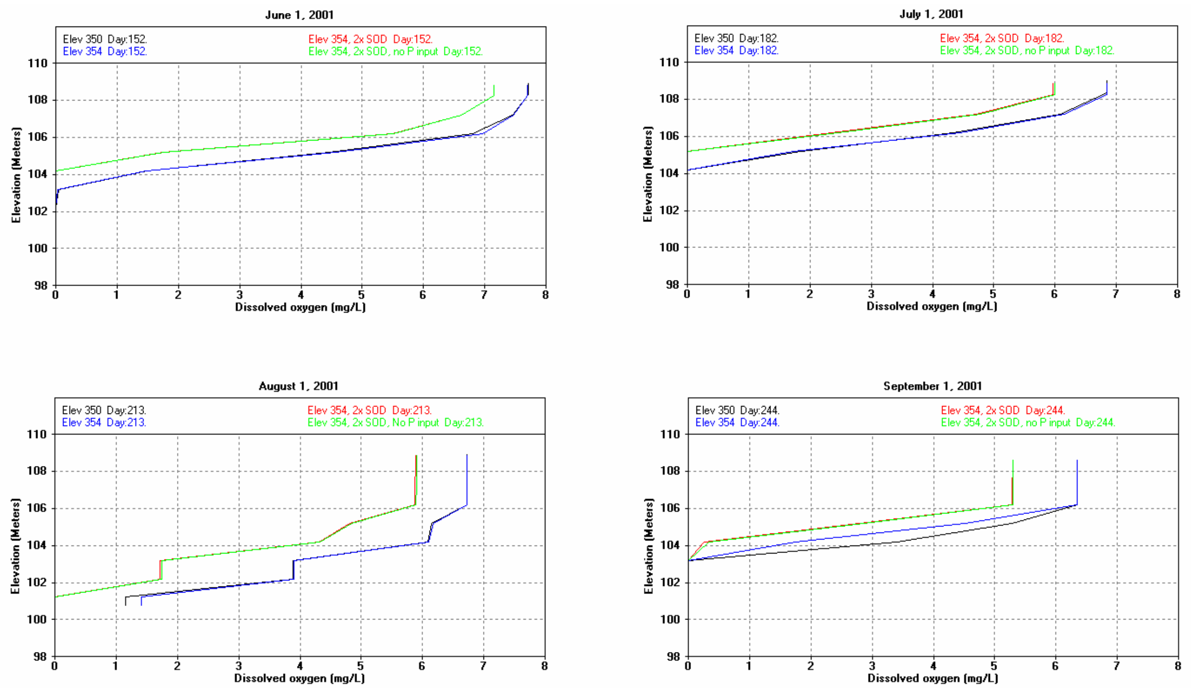

Figure 5-7. DO profiles from the Little Saluda Embayment Km 4.7

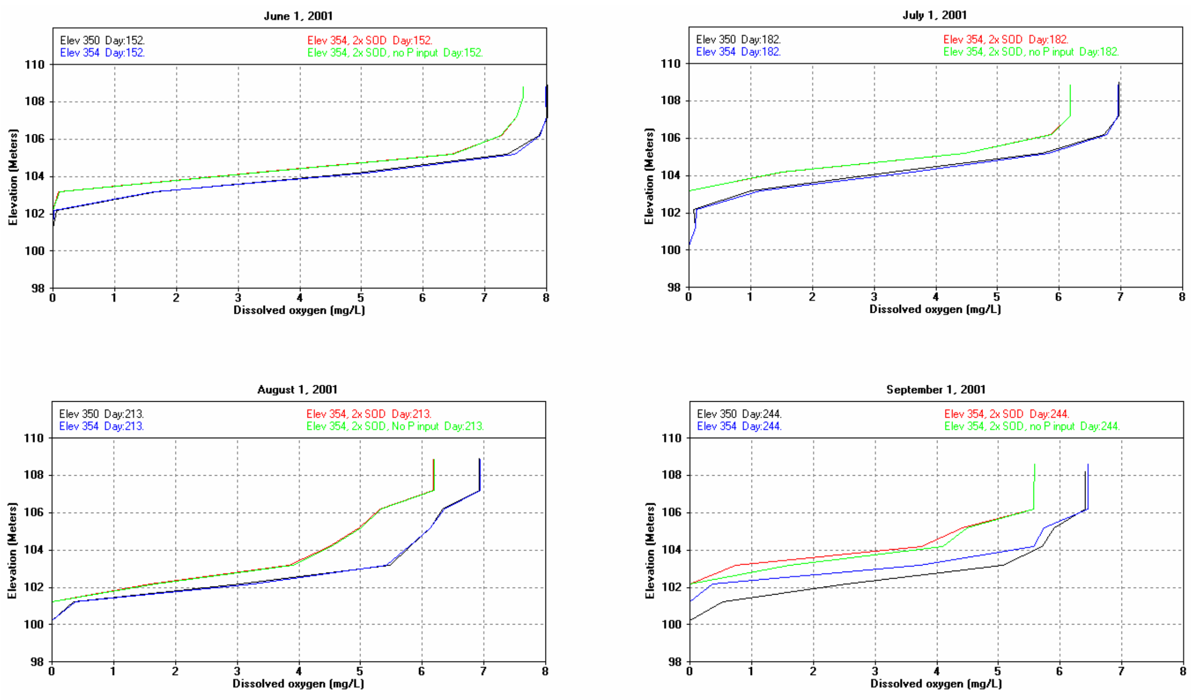

Figure 5-8. DO Profiles from the Little Saluda Embayment Km 2

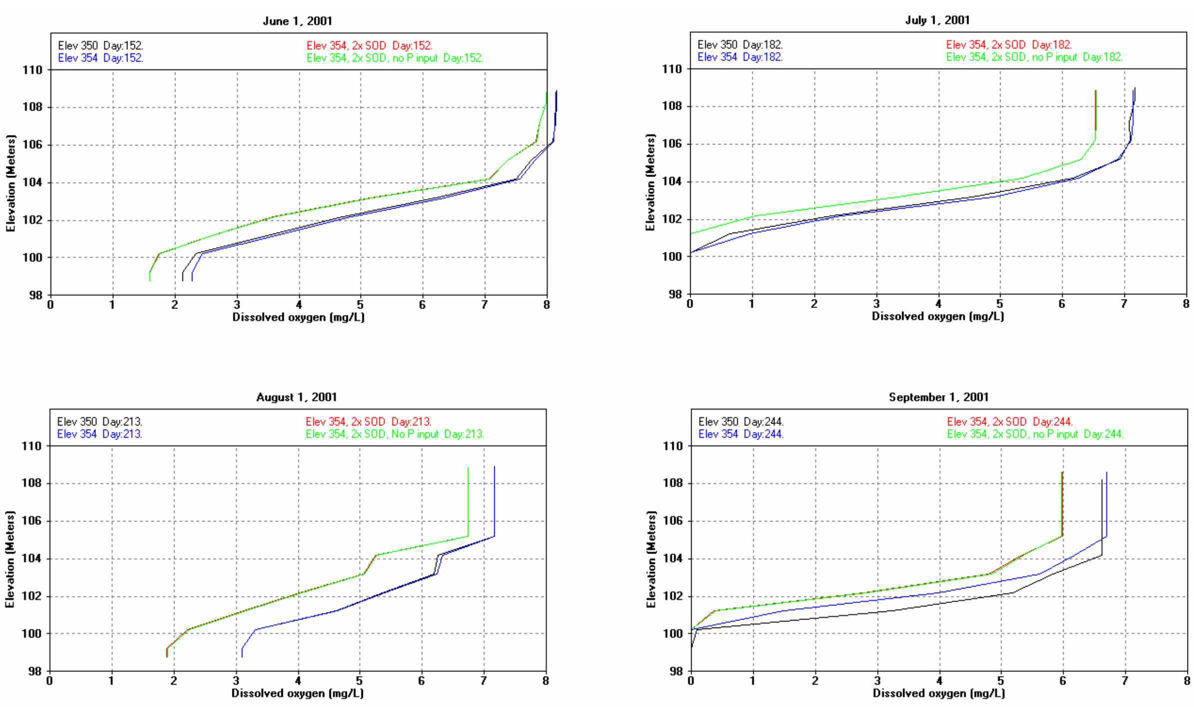

Figure 5-9. DO Profiles from the Little Saluda Embayment Km 0

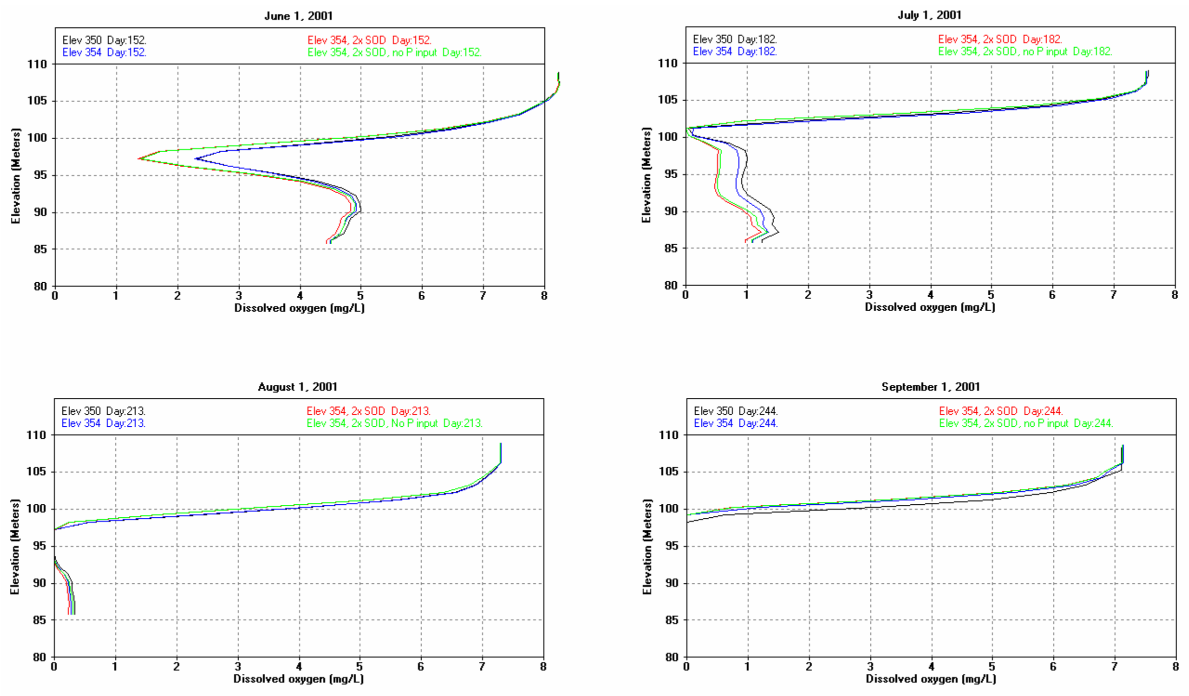

Figure 5-10. DO profiles on main branch, 26 km upstream of dam (near Rocky Creek)

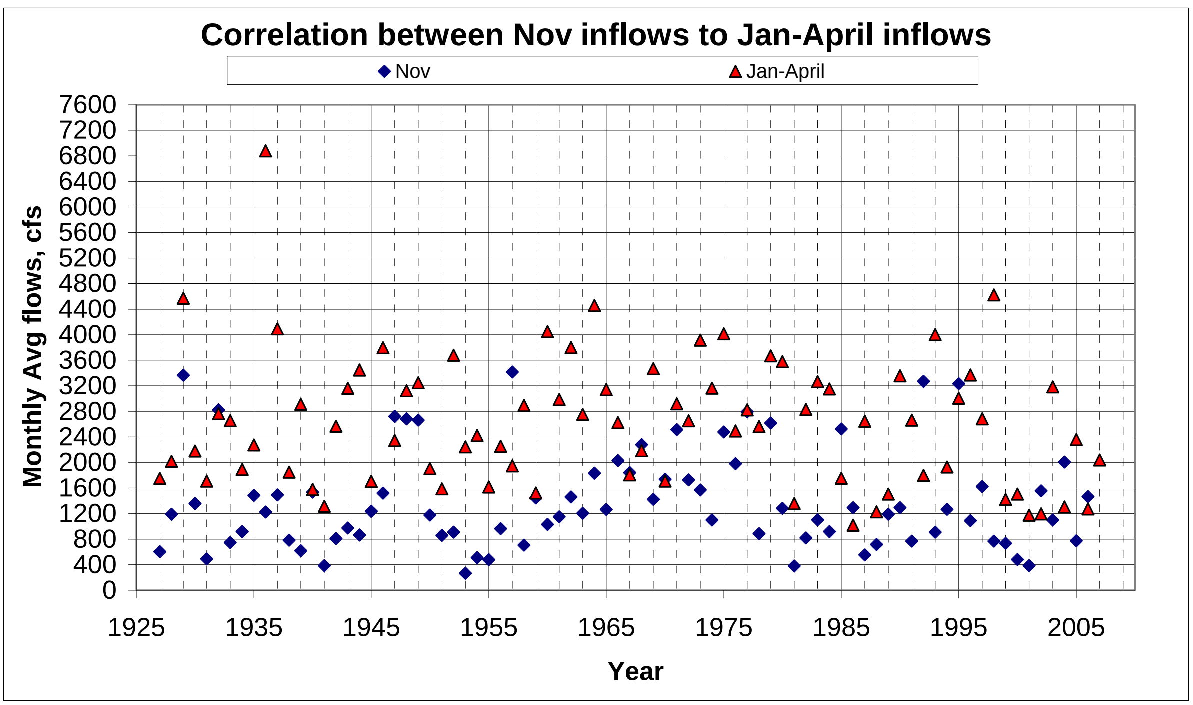

Figure 5-11. Comparison between November and Jan-April inflows to Lake Murray from Chappells. When November inflows are greater than 1200 cfs, the Jan-April inflows are sufficient to fill Lake Murray from elevation 350 to 358 93% of the time.

Table 5-1. Data used to develop recommended policy for winter pool level operations

	avg daily flow for Previous Nov, cfs	Winter min. pool, ft	Summer max pool, ft	avg daily flow Jan-April, cfs	Jan-April, ac-ft less min Q and reserve generation, multiplied by DA/evap multiplier	
1927	1,145			1,750	448,600	
1928	602			2,018	540,492	
1929	1,189			4,572	1,417,025	
1930	3,367			2,176	594,889	
1931	1,356			1,708	434,186	
1932	491			2,763	796,347	
1933	2,824			2,654	758,681	
1934	745			1,891	496,820	
1935	918			2,274	628,351	
1936	1,486			6,878	2,208,530	
1937	1,223			4,095	1,253,318	
1938	1,492			1,846	481,547	
1939	782			2,911	847,141	
1940	617			1,580	390,084	
1941	1,534			1,313	**298,536**	short, but 80, 01, and 02 filled with ~ this much flow
1942	385			2,567	729,080	
1943	809			3,160	932,426	
1944	973			3,448	1,031,439	
1945	864			1,702	432,126	
1946	1,234			3,796	1,150,787	
1947	1,519			2,345	652,632	
1948	2,721			3,124	920,157	
1949	2,684			3,249	963,057	
1950	2,661			1,902	500,852	
1951	1,175			1,590	393,516	
1952	859			3,678	1,110,375	
1953	909			2,243	617,712	
1954	265			2,422	679,316	
1955	509			1,617	403,040	
1956	477			2,251	620,543	
1957	965			1,947	516,296	
1958	3,417			2,892	840,534	
1959	706			1,522	370,179	
1960	1,443			4,050	1,237,788	
1961	1,028			2,985	872,538	
1962	1,148			3,801	1,152,503	
1963	1,459			2,753	792,830	
1964	1,203			4,458	1,378,071	
1965	1,831			3,142	926,163	
1966	1,262			2,624	748,557	
1967	2,027			1,808	468,334	
1968	1,840			2,185	597,720	
1969	2,277			3,468	1,038,132	
1970	1,424			1,706	433,585	
1971	1,739			2,917	849,029	
1972	2,516			2,652	758,252	
1973	1,727			3,917	1,192,229	
1974	1,570			3,162	933,284	
1975	1,097			4,014	1,225,519	
1976	2,478			2,492	703,169	
1977	1,981			2,824	817,283	
1978	2,792			2,561	726,849	
1979	886			3,670	1,107,372	
1980	2,617	351	359	3,578	1,075,884	filled
1981	1,282	350	357	1,358	**314,151**	**filled**
1982	380	354	359	2,830	819,084	
1983	818	354	359	3,268	969,406	
1984	1,100	353	359	3,153	929,938	
1985	917	353	357	1,754	449,801	
1986	2,523	352	357	1,017	**196,949**	**filled**
1987	1,293	354	358	2,647	756,450	
1988	551	351	357	1,227	**269,192**	**filled**
1989	715	353	359	1,505	364,344	filled
1990	1,190	355	358	3,357	1,000,208	special drawdown
1991	1,293	345	358	2,662	761,598	filled
1992	768	350	358	1,797	464,559	filled
1993	3,269	354	358	4,002	1,221,315	
1994	907	350	358	1,929	509,947	filled
1995	1,267	355	358	3,003	878,715	
1996	3,232	352	358	3,369	1,004,241	filled
1997	1,090	348	358	2,683	768,634	filled
1998	1,621	354	358	4,623	1,434,442	
1999	768	350	358	1,423	**336,288**	**filled**
2000	732	354	358	1,504	364,259	
2001	481	350	358	1,174	**251,003**	**filled**
2002	385	350	357.4	1,196	**258,296**	**filled**
2003	1,555	xx	xx	3,182	939,977	did not fill due to operations
2004	1,099	xx	xx	1,304	**295,670**	did not fill due to operations
2005	2,006	354	358	2,358	657,351	
2006	773	348	352	1,272	**284,593**	06 did not get filled from 348
2007	1,462	356	357	2,039	547,699	07 at 356 did not attain 358
	41	13 at 350	24 at 357-359	3	747,430	mean
	41+10		2 < 357	3+1		70 years > 364,000 ac-ft; 9 years < 364,000 ac-ft
	81 years total	looks like it's not winter pool that affects summer pool, but summer hydrology				364,000 ac-ft of inflow is estimated inflow needed to raise pool from 350 to 358
	note Jan-Apr flow is 77% greater than the avg of the rest of the months					

6. Conclusions

- Nutrients loads to Lake Murray are the dominant factor, the relative quantities and/or control of which can and do have the greatest impact on striped bass habitat.
- High inflow and outflows, especially during March-June, are a primary cause for fish kills.
- Higher outflows cause the bottom of the lake to warm, and low DO levels are associated with this warmer water.
- While flow is a dominant factor, it cannot be controlled in a manner effectively to avoid fish kills
- Meteorological conditions can affect striper habitat, but cannot be used to drive operating policies
- Model results indicate that the temperature and DO ranges of tolerable striper habitat in Lake Murray are approximately: $T < 27\ ^{o}C$ and $DO > 2.5$ mg/l
- Model results show that a preferential use of Unit 5 would help to preserve cooler bottom water, resulting in improved DO and increased striper habitat in some years
- Maintaining the target summer (May – August) pool level at 358 either increases or has no effect on striped bass habitat. Of the eight years modeled, there was noticeable improvement in the volume of striped bass habitat in four years. The other four years showed either slight improvement or no change. One of the years that showed no change was 2005, which stands to reason since in 2005 the pool level was held up until September 1.
- The combination of Unit 5 preferential operations and maintaining the target summer (May – August) pool level at 358 can further increase striped bass habitat. Of the eight years modeled, there was noticeable improvement in the volume of striped bass habitat in three years. The other five years showed either slight improvement or no change.
- The combination of Unit 5 preferential operations and maintaining the target summer (May – August) pool level at 358 can improve water quality in the releases.

- Unit 5 operations after August or September do not affect striped bass habitat.
- The following protocol for unit operations was developed: for minimum flows, use units 1, 3, or 4 June 15 thru Dec 1 and U5 for Dec 1 to June 15. For generation flows (i.e., flows > minimum flow)**,** use Unit 5 preferentially for 11 months of the year: November 1 until October 1 of the following year, and use Units 1-4 preferentially in October.

- These results of using the proposed unit operations protocol showed the following:
  1. Temperature in the releases was improved for all years, compared to other unit operational procedures. The temperature at the 5 to 20% levels of exceedence frequency was usually cooler, and at the 80% levels of exceedence frequency was usually warmer. This characteristic for temperature exposure for fish is best for trout fish growth rates. The maximum temperatures for the proposed protocol were usually about the same as the next-best alternatives for this consideration, but temperature results for near-maximum levels was much better for the proposed protocol.
  2. The proposed protocol for turbine unit operations for minimum flows and generation flows had very little or no effect on striped bass habitat enhancements achieved previously by increasing summer pool levels and using Unit 5 preferentially for 1991, 1992, 1996, 2000, 2001, and 2005. For 1997 and 1998, striped bass habitat was marginally impacted by the proposed protocol for turbine unit operations and the impacts were considerably less than the improvements provided by the higher summer pool level and Unit 5 preferential operations in the months preceding June 15.
- Regarding the assessment of setting the minimum winter pool level at elevation 354’, under summer conditions it appears that two-thirds of the phosphorus in the water column was caused by internal phosphorus cycling. This finding indicates

that the phosphorus cycling in Little Saluda embayment is sensitive to organic matter that is formed and settles to the bottom sediments in the embayment. It is also interesting to note for the case where phosphorus loads are reduced to zero that chlorophyll a is reduced for the early part of the summer but not for the latter part of the summer.

- There is a potential for the internal cycling of phosphorus in the Little Saluda embayment to impact SCDHEC's TMDL considerations on the Little Saluda River embayment.
- Other parts of the lake are likely to be impacted by raising the minimum pool level to elevation 354:
    1. Sediments and suspended solids that enter the lake from tributaries, and they settle and accumulate near the inflow region to the lake. Dropping the pool level periodically on a regular basis causes these sediments to be resuspended and redeposited to deeper locations in the lake where they do little harm.
    2. Dropping the pool level also causes aquatic plants to be killed or "die back" by freezing conditions. Exposure of plants to dry and freezing conditions causes plants to be reduced. This process is likely controlling weeds in Lake Murray to some extent, especially in the Little Saluda embayment.
    3. Raising the pool level causes sediments to accumulate where aquatic weeds can grow and take root. After they establish roots, the plants cause even more sediment to accumulate. Once such sediment complexes get established, normal periodic scouring action (i.e., scouring flows every few years like every other year or annually) is not sufficient to re-suspend these sediments. So in some ways this is practically an irreversible impact.
    4. The phenomena of sediment accumulation in reservoirs at their inflow areas is a complex process dependent on many factors: watershed size, land uses in watershed, hydrology of watershed, types of soil, frequency of high runoff, location within/without channel (velocity,

erosion is important), and minimum pool level. The frequency/duration of minimum pool level occurring increases opportunity for sediment to be moved to lower depths of the lake and avoid build up that is difficult to be moved.

- Regarding considerations for developing a policy for winter minimum pool levels, based on data for 1980 through 2007, the winter pool level was down to about 350 ± 2' about half the time. It would be best to maintain this frequency of drawing the lake down to this level each year or risk poorer water quality (sediment accumulation, weeds, increased nutrient cycling from the sediments especially in embayments, and greater potential TMDL designation by DHEC that could lead to very expensive sediment treatments) compared to current conditions.
- Maintaining the frequency of drawing the lake down to 350' for an average of every two years should not be difficult based on historical inflows and pool level data as well as taking advantage of using November flows to predict the years when Jan-Apr flows would likely be sufficient.
- One interesting observation is that it appears that the minimum winter pool level has very little to do with attaining and maintaining a target summer pool level at elevation 358 ± 1'. It appears that it is the lack of sufficient inflows during the summer period that causes the pool elevation to drop like it did in 2007 as well as in other years with low flows.
- The months with highest average flows are Jan-April (i.e., the flow for these four months averages 77% greater flow than for the other months of the year), and based on data from 1927-2007 (81 years), only 9 years had what appeared to be "challenging" low flows that might prevent the lake from being filled to 358'; however, for the years where pool level data were available (1980-2007) there was only 1 year when the 358 ± 1' was not attained: 2006. During 1980-2007, there were 8 years with "challenging" low flows available to fill the pool to 358 ± 1', but 2006 was the only year that this goal was not attained.
- Based on data from 1927-2007, when Nov mean flows were 1200 cfs or greater at Chappells (see Figure 5-11), the Jan-Apr flows were sufficient to safely attain the 358 ± 1' goal. The Nov mean flow of 1200 cfs was equaled or exceeded for 41 of

the 81 years of record. Using this approach, the pool level in the winter could be dropped to 350’ on an average frequency of every 2 years. Considering these 41 years, 3 of the years had “challenging” low flows that might prevent the lake from being filled to 358 but 2 of these years occurred during the period 1980-2007 when pool level data were available and in both of these years the 358 ± 1’ goal was attained.

- Although there is more likelihood of having greater flows for the period Jan-Apr when flows are high for the previous Nov, the consequence of dropping the winter pool elevation to 350 every year and not attaining the 358 ± 1’ goal is not great: the estimated maximum number of years when the goal would not be attained is about 1 in 10 years, but based on experience between 1980 and 2007 it would likely be closer to 1 in 25-50 years. Again, when the summer pool drops after the 358 ± 1’ goal is attained, it is because of low summer inflows, minimum flow provision, and high evaporation.

7. References

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