Calibration of the CE-QUAL-W2 Model For Lake Murray

Prepared for SCE&G

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Acknowledgments

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List of Acronyms

AGPM	Animation and Graphics Portfolio Manager (for CE-QUAL-W2)
AME	Absolute Mean Error
BOD_5	5-day Biological Oxygen Demand
DO	Dissolved Oxygen
EPA	Environmental Protection Agency
ISWO	International Surface Weather Observations
LDOM	Labile Dissolved Organic Matter
LPOM	Labile Particulate Organic Matter
LSR	Lower Saluda River
MDA	Minimum Detectable Amount
NCDC	National Climatic Data Center
O-PO4	Orthophosphate
POM	Particulate Organic Matter
RDOM	Refractory Dissolved Organic Matter
RMS	Root Mean Square
RPOM	Refractory Particulate Organic Matter
SCDHEC	South Carolina Department of Health and Environmental Control
SCE&G	South Carolina Electric & Gas
SOD	Sediment Oxygen Demand
TISS	Total Inorganic Suspended Solids
TKN	Total Kjeldahl Nitrogen
TMDL	Total Maximum Daily Load
TOC	Total Organic Carbon
TP	Total Phosphorus
USGS	United States Geological Survey
WSC	Wind Sheltering Coefficient

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Executive Summary

The following water quality issues regarding Lake Murray have been identified:

- Low dissolved oxygen (DO) in the Releases from Saluda Hydro,
- Restrictions for operating Unit 5 due to entrainment of blueback herring,
- Eutrophication in the upper regions of Lake Murray,
- DO less than the State standard in the inflow regions of the lake,
- Reduced striped bass habitat in the lake due to low DO in the regions of the lake where their temperature preferences occur, and
- Low pH in Lower Saluda River (LSR).

South Carolina Electric & Gas (SCE&G) decided to address these issues using a two-dimensional water quality model, CE-QUAL-W2, that simulates the effects of inflow water quality on in-lake water quality as well as the releases from the lake. This modeling effort was based on considering all available water quality data on Lake Murray and its inflows, as well as using external comparisons of results at other projects similar to Lake Murray.

First, the available data were analyzed to better understand the main water use issues on Lake Murray and to identify the most likely causes for the water quality problems in Lake Murray. Phosphorus was identified as the major probable cause, primarily because the phosphorus concentrations in the inflows were elevated and the primary sources of this phosphorus were a few point sources. Another observation about phosphorus in the watershed of Lake Murray was that the release from Lake Greenwood was relatively low in phosphorus due to reductions by wastewater treatment plants upstream from Lake Greenwood, as well as precipitation processes likely due to clay sorption and settling. It was estimated that about 60% of the phosphorus entering Lake Murray comes from point sources. If all sources of phosphorus were reduced so that rivers and creeks had phosphorus concentrations that complied with South Carolina Department of Health and Environmental Control (SCDHEC) lake criteria, phosphorus entering Lake Murray would be reduced by about 60%. A review of other reservoirs similar to Lake Murray indicated that lower phosphorus levels should improve DO in the releases from Saluda Hydro.

Using available data collected by SCDHEC, United States Geological Survey (USGS), and SCE&G, the CE-QUAL-W2 model was calibrated for the years 1992, 1996, and 1997, primarily for temperature, DO, algal levels, and phosphorus. Graphical and statistical analyses showed that the model was well calibrated for these water quality parameters.

The model was then tested using the calibration years for predicting water quality in Lake Murray and its releases assuming that phosphorus was reduced so that inflowing creeks and rivers had the maximum phosphorus concentrations that complied with SCDHEC lake criteria. The results of the model runs indicated that DO concentrations in the releases from Saluda Hydro were sensitive to phosphorus inputs, probably reducing the amount of aeration that might otherwise be applied —especially if special pool level drawdowns were shifted to other times of the year. The results also indicated that restrictions for operating Unit 5 due to current concerns about fish entrainment could be eliminated or alleviated. In addition, the model results indicated that trophic status and striped bass habitat in Lake Murray would improve. 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.

Finally, the test runs using the model indicated that five of the six water quality issues identified above could only be addressed reasonably by using phosphorus reduction in the watershed. Phosphorus reductions are likely the only practical approach considering that cost for other alternatives would be high, and there are no proven technologies for addressing these issues on the scale of Lake Murray. Also, point source discharges to some of the inflows, especially Ninety-Six Creek and the Bush River, are so high that there is no alternative but to reduce phosphorus in their discharges.

1. Introduction

Several water quality issues associated with Lake Murray need consideration for water quality management:

- low DO in the releases from Saluda Hydro,
- restrictions for operating Unit 5 due to entrainment of blueback herring,
- eutrophication in the upper regions of Lake Murray,
- DO less than the State standard in the inflow regions of the lake,
- reduced striped bass habitat in the lake due to low DO in the regions of the lake where their temperature preferences occur, and
- low pH in LSR.

SCE&G implemented a turbine venting program in 1997 to increase the DO in the releases from Saluda Hydro to the extent practical and is continuing this program to increase the amount of aeration by the turbine units. Water quality downstream from Saluda Hydro has significantly improved since 1998, and SCE&G continues to study and implement ways to increase DO in the LSR. The blueback herring and the striped bass habitat probably cannot be increased significantly or consistently each year without improving water quality in Lake Murray. Eutrophication in the upper regions of Lake Murray, low DO in the inflow regions of Lake Murray, and low pH in the LSR also cannot be corrected unless water quality in Lake Murray is improved.

In preparation for relicensing, SCE&G prepared a water quality database using all available data on Lake Murray, its watershed, and the LSR. SCE&G also decided to model water quality conditions in Lake Murray to better understand the effects of water quality in the inflows to Lake Murray on the six issues identified above. Specifically, SCE&G decided to develop a water quality model to determine the effectiveness of phosphorous reductions in Lake Murray on improving DO in the main body of the lake and its releases. The CE-QUAL-W2 model was selected for simulating the water quality in Lake Murray and predicting the effects of phosphorus reductions in the inflows.

The following sections provide additional background information on these water quality issues, as well as water quality conditions in the inflows and in Lake Murray. It will be shown that reservoirs like Lake Murray are sensitive to phosphorus loads. Then, the CE-QUAL-W2 model developed for Lake Murray will be presented along with predicted water quality conditions under reduced phosphorus loads and for some reservoir operational changes that are expected to increase DO in the turbine releases after phosphorus load reductions.

The results show that the six water quality problems identified above can be significantly alleviated by reducing phosphorus in the inflows to Lake Murray and that the most significant phosphorus loads are from wastewater discharges from communities located immediately upstream from the lake. The results also show that significant lake drawdowns in September and October can contribute to lower DO conditions in the releases from Saluda Hydro, especially if phosphorus was reduced in the inflows to the lake. Finally, a reduction in phosphorus in the lake would reduce the production of organic matter that is probably causing low pH levels in the LSR.

2. Description of Lake Murray and Saluda Dam

Figure 2-1 shows the entire Lake Murray watershed downstream from Buzzard's Roost Dam with primary reference points labeled.

Pertinent characteristics of Lake Murray are presented in Table 2-1. The reservoir has a maximum depth of 175 feet. The lake is approximately 41 miles long and has a maximum width of 14 miles. The shoreline length is 524 miles, with 330 miles developed for residential use. The shoreline development ratio is 17.7, which means that the lake has 17.7 times the shoreline length that would exist if the lake were circular. Therefore, processes related to the lake margin (e.g., shoreline development, recreational development, and housing development) could be significant.

Saluda Hydro has five turbines. Units 1-4 have a maximum discharge of about 3150 cfs each, and Unit 5 has a maximum discharge of about 5700 cfs. The intakes for Units 1-4 are near the bottom of the lake, and the intake for Unit 5 is about 80 feet deep. The average annual flow at Saluda Hydro is 2683 cfs, and the maximum turbine discharge is about 18,000 cfs. The normal operating procedure at Saluda Hydro for the years calibrated was to operate Units 1, 2, and 4 until the project flow reached about 9000 cfs; bring on Unit 5 in addition to these units until the project flow reached about 15,000 cfs; and then bring on Unit 3. Starting in 2004, preference for Unit 3 instead of Unit 2 was implemented. The primary use of the Saluda Project is for reserve, so it is not unusual for all the turbines to start generating on short notice.

McMeekin Steam Plant is located immediately downstream from the dam, and its condenser cooling water system was linked to the penstocks for Units 1 and 3 during the years studied (note: recent work at the dam changed this configuration, and the thermal discharge from McMeekin now goes to the Unit 2 penstock).

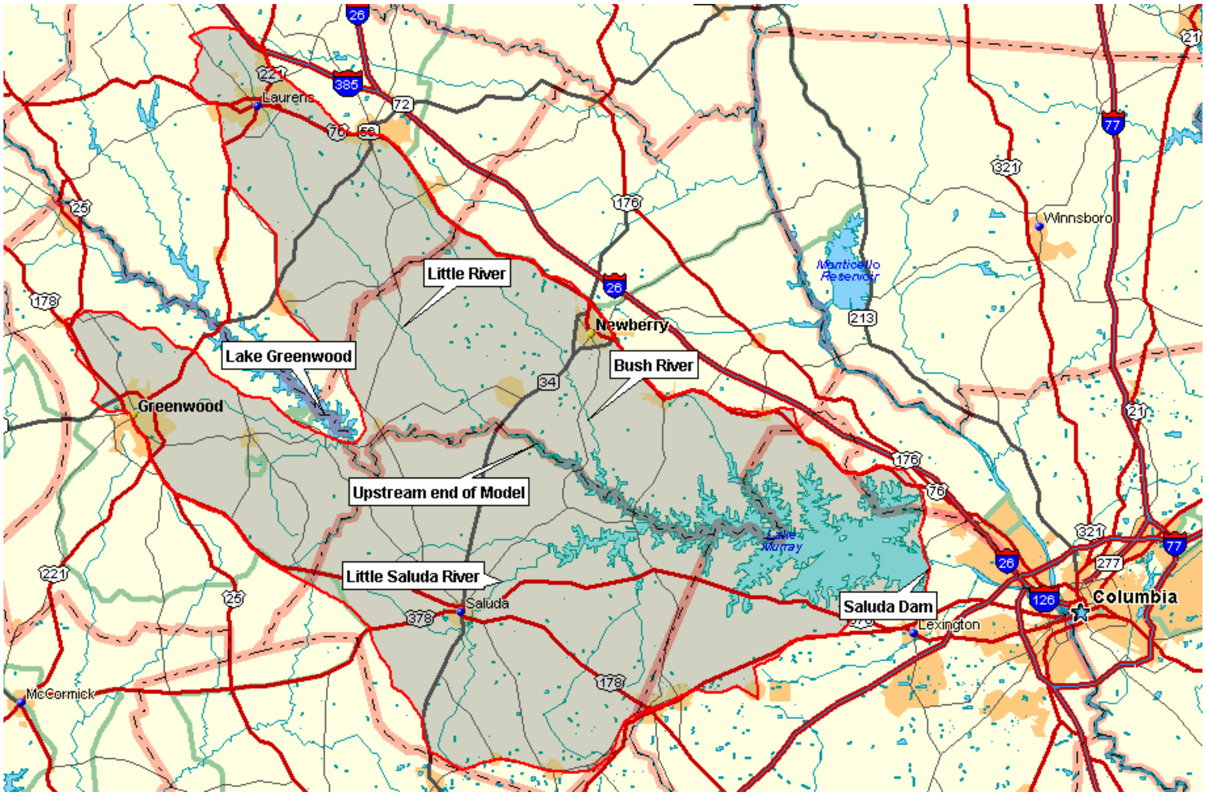


Figure 2-1. Lake Murray Watershed Downstream from Lake Greenwood

Table 2-1. Physical Characteristics of Lake Murray

	U.S. Customary System	Metric System
Maximum depth	175 feet	53.3 m
Mean Depth	46 feet	14 m
Drainage area	2260 square miles	5860 km^2
Area of Lake surface	70 square miles	182 km^2
Ratio of DA : lake area	32.2	32.2
Shoreline Length	524 miles	844 km
Shoreline Development Ratio	17.7	17.7
Total lake volume	2,118,000 ac-ft	2,613 hm^3
Useful lake volume	1,654,000 ac-ft	2,041 hm^3
Average Annual Flow	2683 cfs	76 cms
Nominal Residence Time	400 days	400 days
Depth of outlets, Units 1-4	175 feet	53 m
Depth of outlets, Unit 5	80 feet	24.4 m
Power Capacity per Unit, Units 1-4	32.5 MW	32.5 MW
Flow Capacity per Unit, Units 1-4	~3200 cfs	~90.6 cms
Power Capacity, Unit 5	72 MW	72 MW
Flow Capacity, Unit 5	5700 cfs	161 cms

3. Water Quality Characteristics of Lake Murray and Releases from Saluda Hydro

A considerable amount of water quality information has been collected on Lake Murray over the last six decades. The first data were collected in 1947, and these early efforts continued up to the early 1970s by the South Carolina Pollution Control Authority, SCDHEC, and the USGS. As part of the relicensing process for the current FERC license for operating the Saluda Project, SCE&G contracted with ERC, Inc., to conduct a comprehensive assessment of Lake Murray in 1974 and 1975. The SCDHEC has monitored the lake and its inflowing waters monthly since about 1973 and continued until recently when the monitoring strategy was revised. SCE&G, in cooperation with USGS, has collected data on Lake Murray since 1990.

One interesting finding by ERC was that most of the sedimentation in the lake took place in the reach from about Rocky Creek to Blacks Bridge. They found that these sediments were comprised of a greater percentage of small particles in comparison to other parts of the lake, with the exception of the lower part of the Little Saluda embayment. The lower deepwater stations had exhibited very little sediment deposition since completion of Saluda Dam.

Data collected by the SCDHEC, USGS, and SCE&G were used to perform this analysis. The primary monitoring stations used for this water quality assessment and development of the CE-QUAL-W2 model inputs are shown in Figure 3-1.

SCDHEC reported the following regarding water quality and water uses in Lake Murray (SCDHEC Assessment Reports in 1995 and 1998):

> The locations at Rocky Creek and in the Bush River arm of Lake Murray were reported to be among the most eutrophic sites on large lakes in South Carolina. All the locations between Rocky Creek and the dam, including the embayment locations, were reported to be among the least eutrophic in South Carolina. Their finding was based on data for the following parameters: water clarity, total phosphorus (TP), total inorganic nitrogen, chlorophyll *a*, and DO.

Watershed management was recommended to reduce phosphorus loading to a number of areas of the lake:

- Rocky Creek area of Lake Murray (S-279)
- Bush River arm of Lake Murray (S-309)

SCDHEC also listed pH as a concern below Saluda Dam. Low pH in reservoir releases is usually caused by decomposition of organic matter in the lake, and this commonly occurs in lake waters that have low alkalinity like Lake Murray. Organic matter in lakes comes from algal growths and aquatic plants, wastewater discharges in the watershed, and natural organic sources in watersheds. Low pH is caused by the formation of carbon dioxide as organic matter is decomposed—carbon dioxide in water forms carbonic acid that causes the pH to decrease. The low pH excursions (in magnitude as well as frequency) cannot be remedied practically except through watershed reductions of man-made sources of nutrients and organic loads.

It should be noted that phosphorus and pH was listed as the cause for several sites on Lake Murray (especially the Bush River arm, Black's Bridge, Little Saluda River arm) in the 303(d) lists for 2002, 2004, and 2006. These sites are not listed as near-term potential Total Maximum Daily Loads (TMDLs).

Nutrients, Algae, and Water Clarity

Inflow Stations

Considerable amounts of data are available for assessing the sources and trends of nutrients that enter Lake Murray, as well as the nutrient concentrations, algal productivity and water clarity in Lake Murray.

Figure 3-2 shows the TP concentrations over the period 1974 to 1998 in the tailwater of Buzzard's Roost Dam. There was an upward trend in concentrations until 1985 when the concentrations were substantially reduced and a downward trend began. This dramatic change is primarily attributable to the implementation of tertiary wastewater treatment for wastewater discharges to the Reedy River (tributary to Lake Greenwood) from the City of Greenville, SC. The median concentration of TP measured at this station between 1989 and

1998 is 0.020 mg/L. However, of the 117 observation used to calculate this mean, 39 (33%) were below the minimum detectable amount (MDA) of 0.02 mg/L. Biological Oxygen Demand (BOD_5) also decreased, dropping from a mean of about 2.5 mg/L during the period 1969 through 1986 to a mean of about 1.3 mg/L for the period 1987 through 1998. The decrease in BOD_5 lagged the decrease in TP perhaps due to the release of methane and other decomposition products from the sediments of Lake Greenwood sometime after the drop of TP in the water column. Total Kjeldahl nitrogen (TKN, a measure of the organic nitrogen and ammonia nitrogen) followed a pattern similar to that for TP, probably attributable to the TKN associated with algal growths. Nitrate+nitrite concentrations appeared to decrease over the period 1985 through 1987. In addition, nitrate+nitrite concentrations drop to near zero every year during the summer and autumn months. This drop in nitrate+nitrite indicates that conditions favor blue-green algae during this time in the upper end of Lake Murray since they can use dissolved N_2 as their source of nitrogen. Blue-green algae are often more troublesome than other algal species such as diatoms and green algae.

Figure 3-3 presents TP data collected at S-295 (Chappells) for the period 1988 through 1998. TP increased significantly between Buzzard's Roost Dam and station S-295, from about 0.02 mg/L at S-186 (just below Greenwood Dam) to about 0.05 mg/L at S-295 (approximately 3.5 miles downstream). This increase in TP is highly significant because phosphorus can cause organic matter (i.e., algal growths and aquatic plants) that is about 188 times its weight—this amount of organic matter can cause DO demands that are about 262 times the weight of phosphorus.

Water quality in hydropower reservoirs can be sensitive to the concentration of TP in their inflows. Figure 3-4 presents the results of a study conducted for the Environmental Protection Agency (EPA) to determine the TP concentrations in the inflows to hydropower reservoirs (Crossman, 2001). This figure shows that Lake Murray could be among the cleanest 25% of the reservoirs included in the study if the TP concentration was in the range of 0.03 mg/L. However, with the TP concentration found at S-295, Lake Murray receives TP concentrations that are near the 55 percentile ranking for reservoirs that are not considered to be TMDL sites.

The 1989-1998 TP data in Ninety-Six Creek (S-093) had a median concentration of 0.44 mg/L (Figure 3-5), about 22 times the concentration of TP in the Saluda River below Greenwood Dam. Using the median concentrations of TP in the Saluda River below Lake Greenwood and in Ninety-Six Creek in combination with their mean annual flows, the respective TP loads exerted on Lake Murray were estimated. This analysis showed that Ninety-Six Creek had a TP load of 270 lbs/day and the Saluda River had a load of 183 lbs/day. The station at S-295 had a load of about 494 lbs/day, so Ninety-Six Creek accounted for essentially all of the increase in TP between Greenwood Dam and Chappells.

The Bush River near its inflow point to Lake Murray also contained high concentrations of TP (Figure 3-6): about 0.6 mg/L. Using the same approach for estimating its TP load to Lake Murray, the Bush River had an estimated load of 294 lbs/day. After the Bush River enters the Saluda River at the upper end of Lake Murray, the estimated concentration of TP in the Saluda River was about 0.07 mg/L. However, since these data were collected, TP was reduced about 20-25% in the Bush River by TP reductions from a point source in the watershed.

The Little Saluda River near the inflow to the Little Saluda River arm of Lake Murray (station S-123) has been monitored by SCDHEC since 1974 (Figure 3-7). Their data show a significant decreasing trend over the years, with a significant drop in 1989. The current concentration of TP is about 0.14 mg/L, which leads to an estimated daily load of about 134 lbs/day.

Clouds Creek near the inflow to the Little Saluda River arm of Lake Murray (station S-255) has been monitored by SCDHEC since 1979 (Figure 3-8). Their data show a significant increasing trend over the years. The current concentration of TP is about 0.16 mg/L, which leads to an estimated daily load of about 76 lbs/day.

After all of the inflows entered the upper end of Lake Murray, the total estimated average concentration of TP was about 0.08 mg/L prior to the reduction in TP in the Bush River.

Annual average phosphorus concentrations in the inflows to Lake Murray are summarized in Figure 3-9 for the years 1989-1998. Figure 3-10 and

Table 3-1 summarize the distribution of flow and TP loadings between the major waterways that enter the upper end of Lake Murray. It is obvious from these charts and table that several smaller waterways contribute much greater TP loads than would be expected for the amount of water that they contribute. Four of the tributaries (i.e., Ninety-Six Creek, Bush River, Little Saluda River, and Clouds Creek) contributed 71 percent of the TP to Lake Murray, while their streamflow contributions totaled about 18 percent. The contributions from Ninety-Six Creek and Bush River were especially high. As discussed above, the TP concentrations in these smaller waterways were caused by point source discharges and development in the watershed. If these TP loads were reduced, especially the point sources, the upper areas of Lake Murray would have less algae and greater water clarity; and, the DO in the reservoir and in the releases from the Saluda Project likely would increase (Matthews et al., 2001; Williams, 2001).

Significant aquatic plant communities at the upper end of Lake Murray could contribute to high organic and nutrient loads in the upper area of the lake due to their die-off each year and settling in areas of the upper end of the lake (SCDHEC, 1998). This contribution to organic and nutrient loads to Lake Murray has not been assessed.

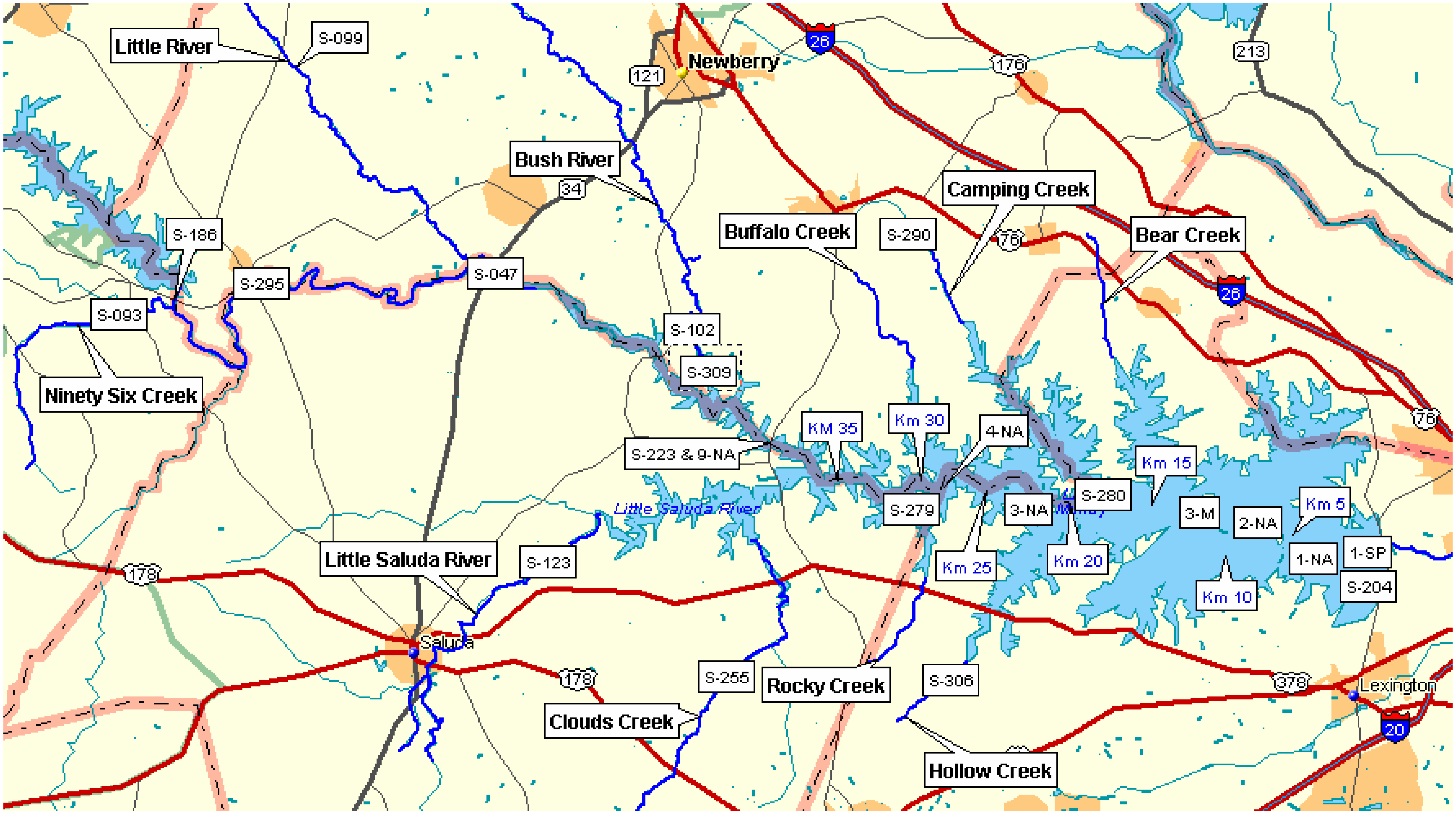


Figure 3-1. Primary SCDHEC and SCE&G Monitoring Stations used for Lake Murray Water Quality Analyses

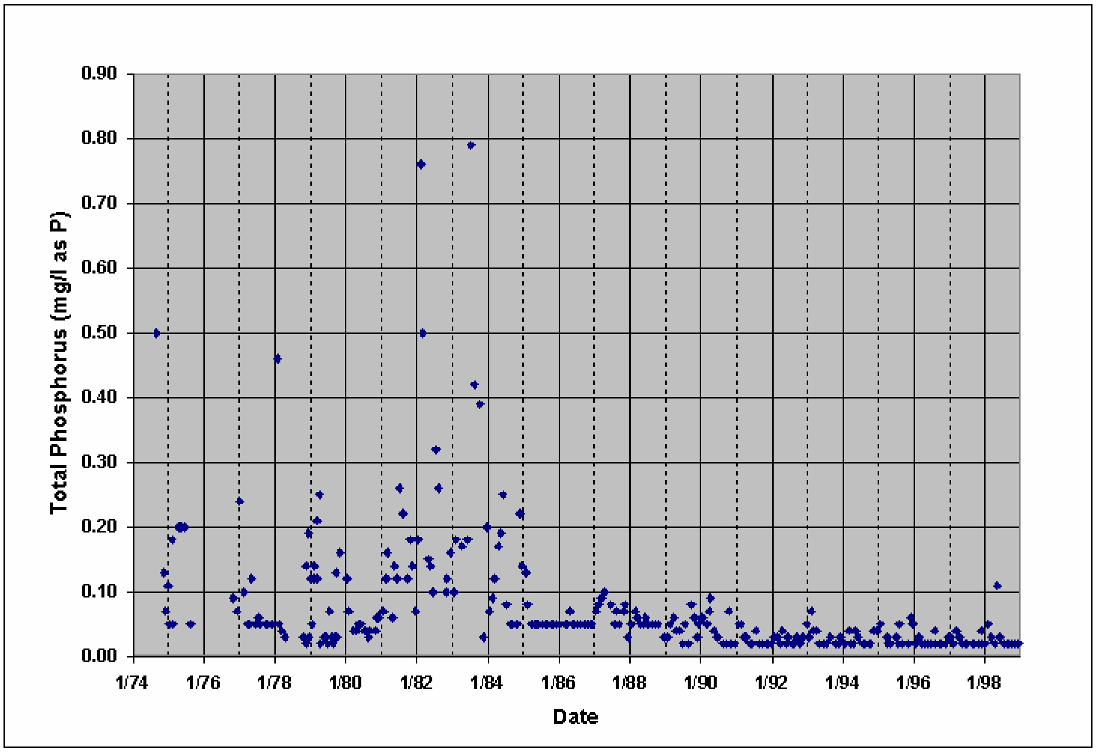


Figure 3-2. Total Phosphorus Measured at SCDHEC Station S-186 Located Downstream of Buzzard's Roost Dam (Lake Greenwood)

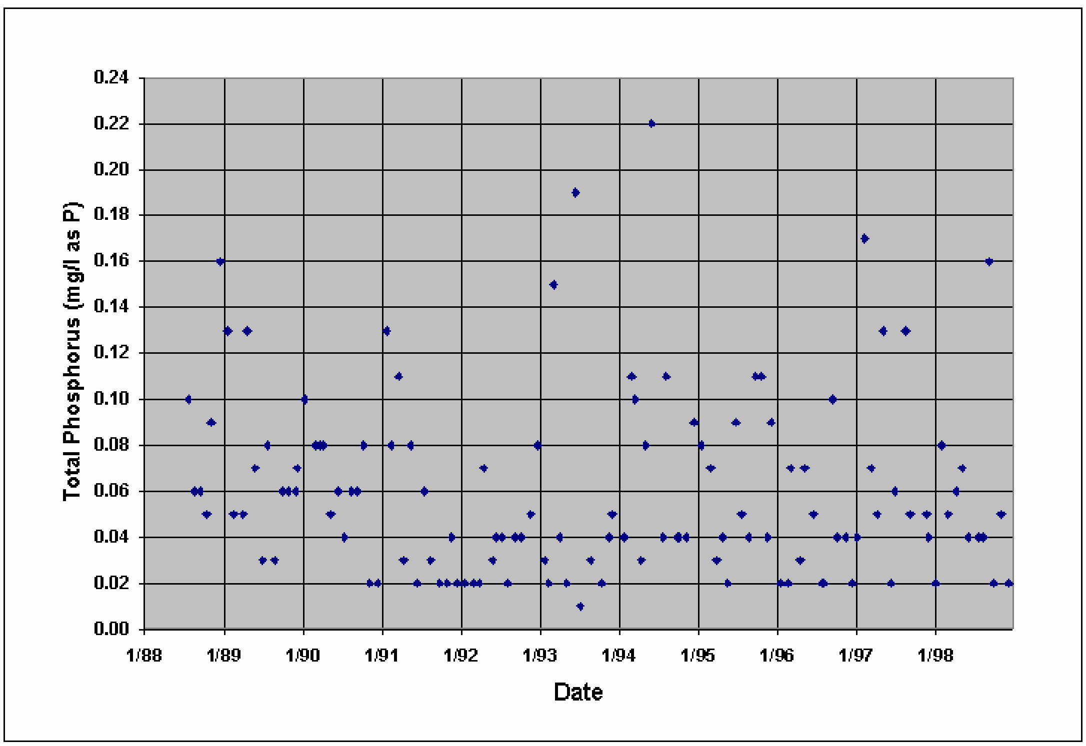


Figure 3-3. Total Phosphorus Measured at SCDHEC Station S-295, Chappells

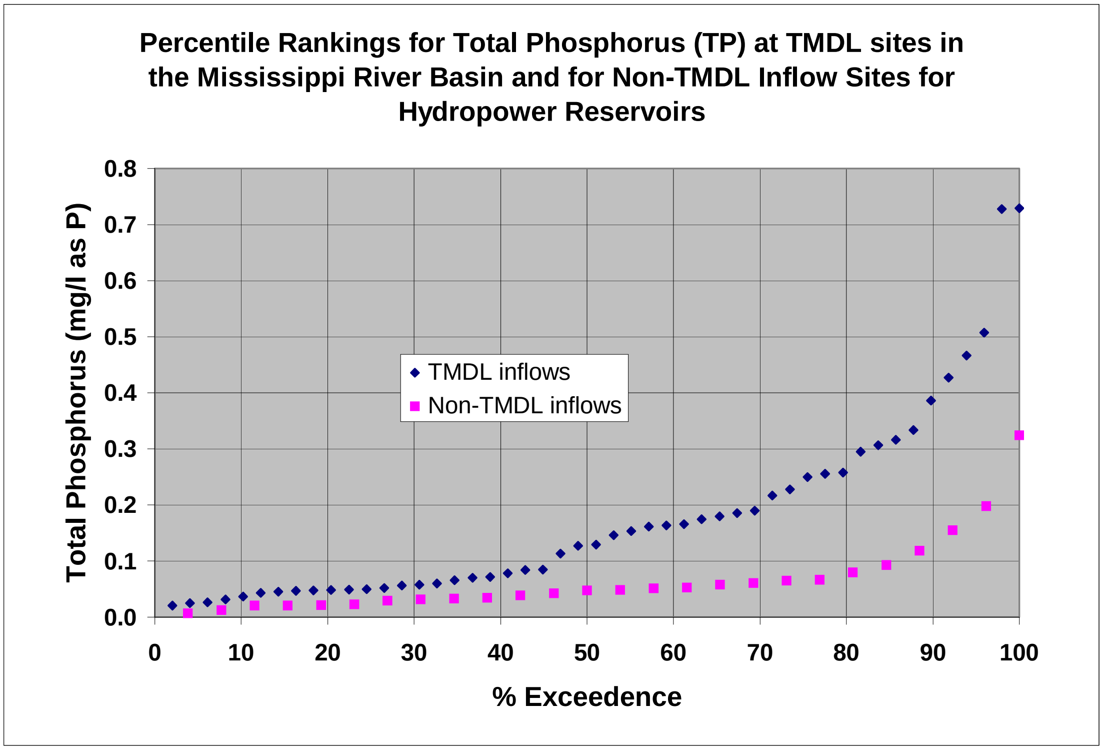


Figure 3-4. TP Frequency Plot for Inflows to Hydropower Projects (Crossman, 2001)

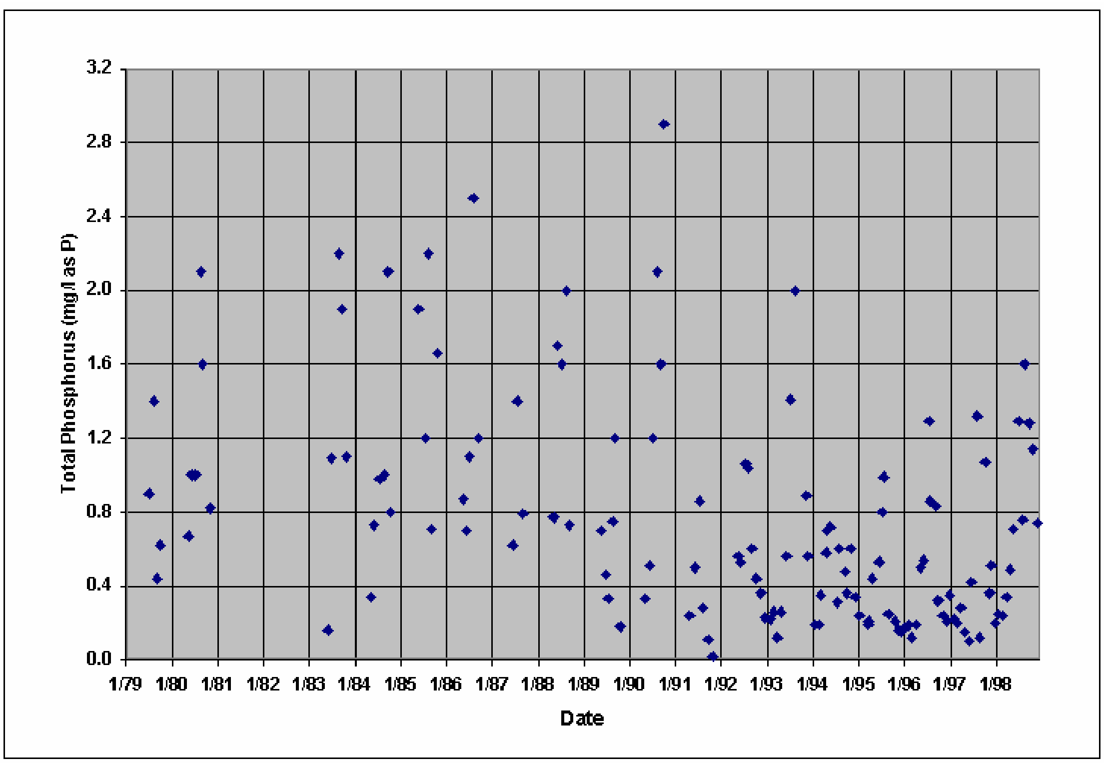


Figure 3-5. Total Phosphorus Measured at SCDHEC Station S-093 Located on Ninety-Six Creek, Approximately 2 Miles Upstream of the Saluda River

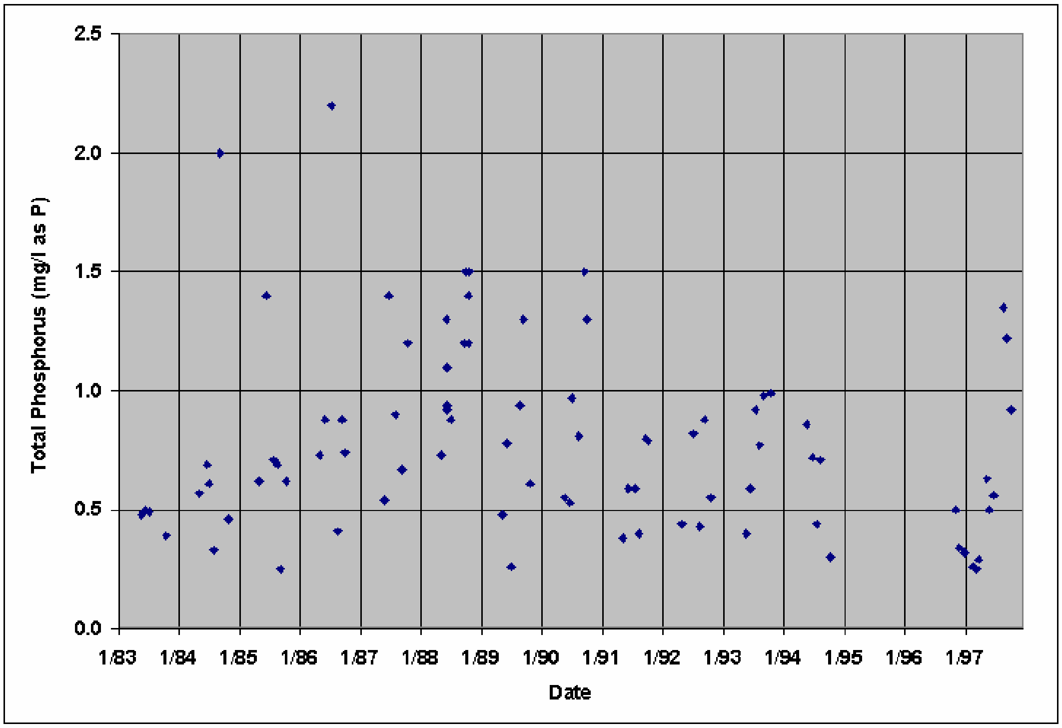


Figure 3-6. Total Phosphorus Collected at SCDHEC Station S-102 Located on the Bush River, Approximately 3.5 Miles Upstream of the Saluda River

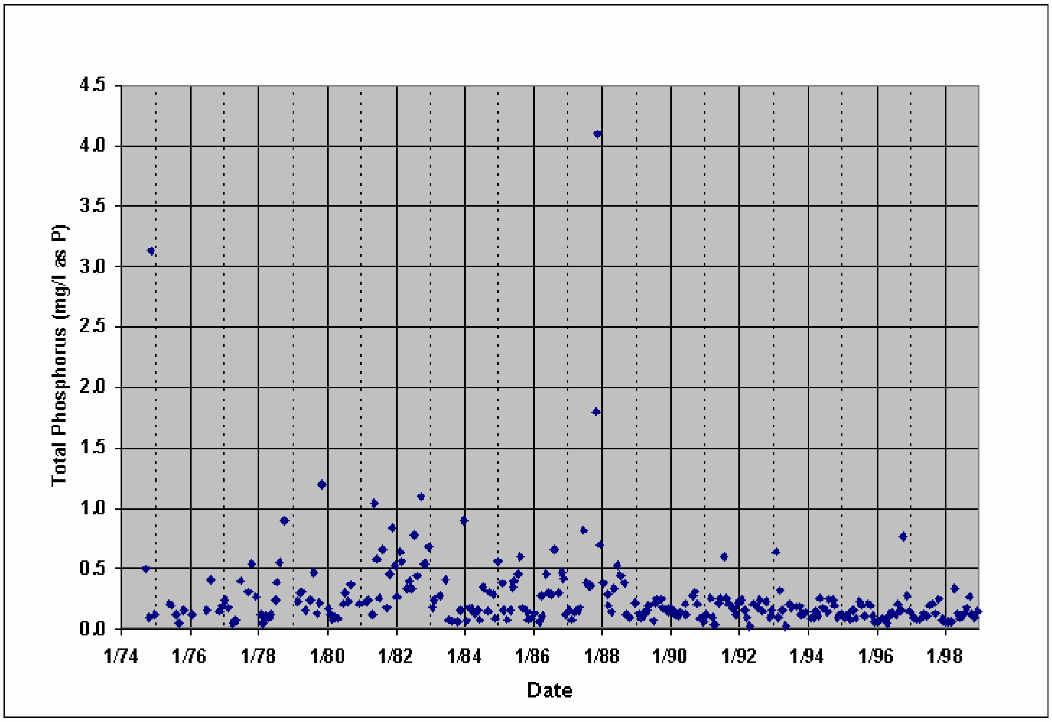


Figure 3-7. Total Phosphorus Collected at SCDHEC Station S-123 Located on the Little Saluda River, Approximately 13.9 Miles Upstream of the Saluda River

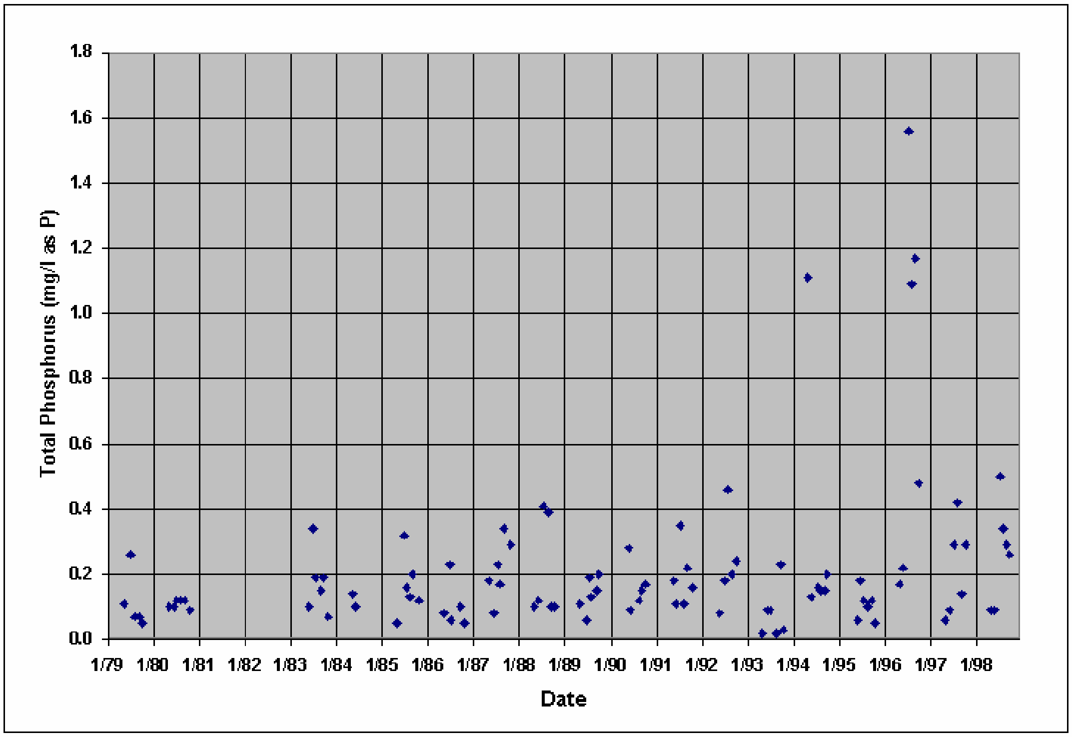


Figure 3-8. Total Phosphorus Collected at SCDHEC Station S-255 Located on Clouds Creek, Approximately 8.5 Miles Upstream of the Little Saluda River

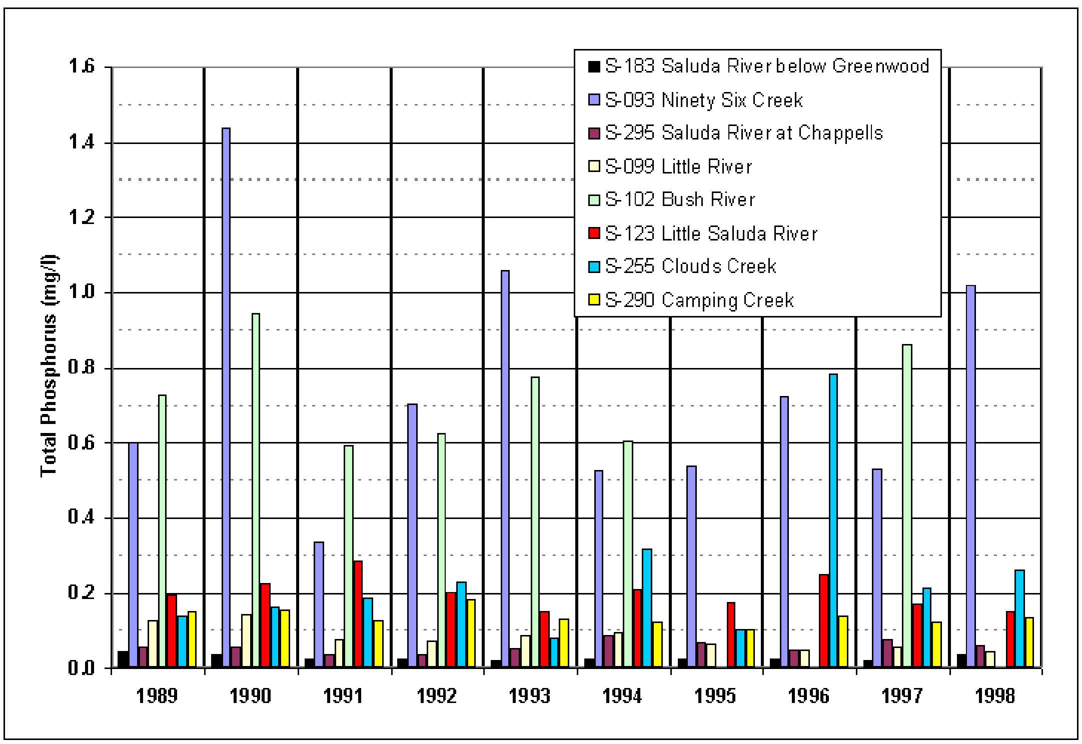
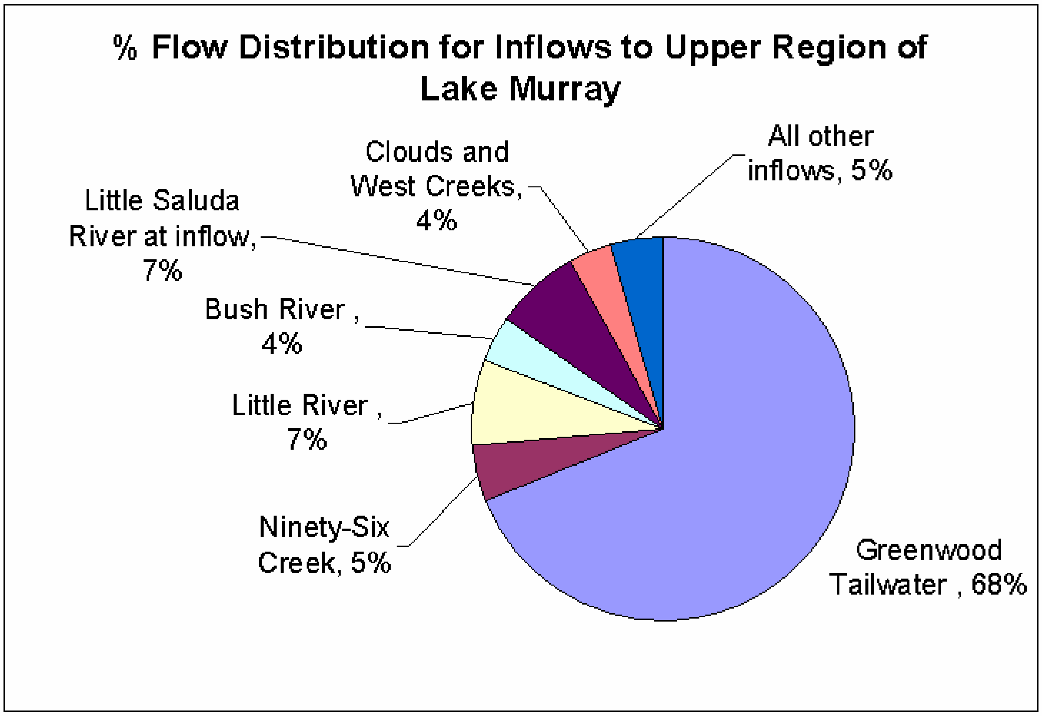


Figure 3-9. May-October Means of Total Phosphorus Measured at SCDHEC Stations Located in the Inflows to Lake Murray



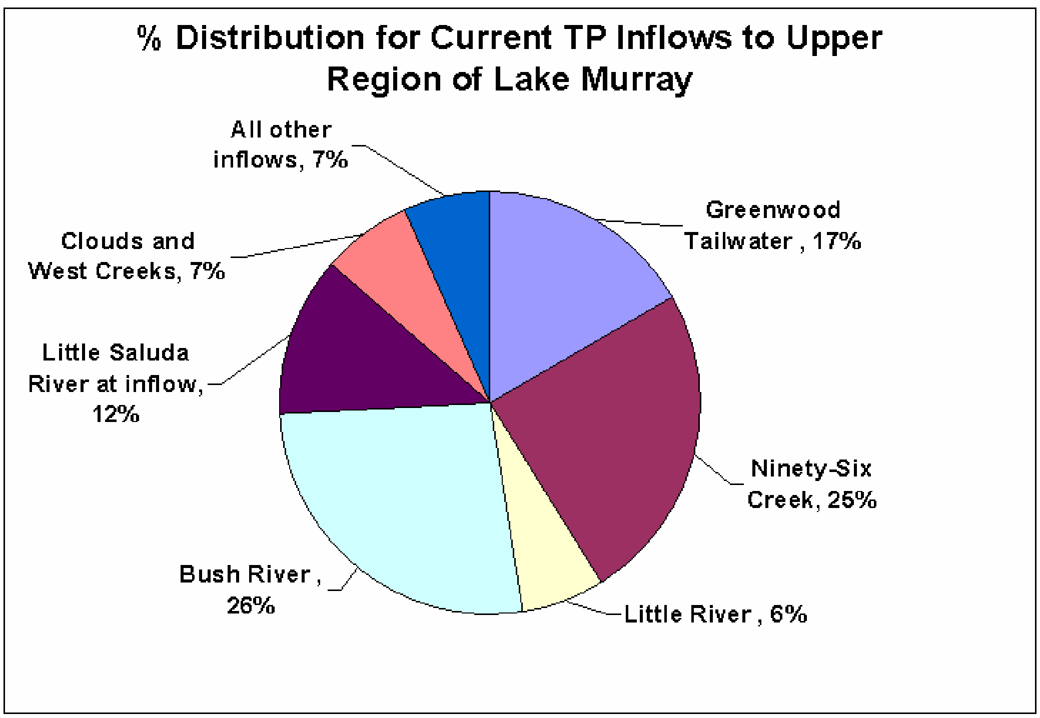


Figure 3-10. Pie Charts of Inflow and Phosphorus Loads to Upper Regions of Lake Murray

Table 3-1. Percent Contributions to the Upper Regions of Lake Murray of Total Phosphorous Loadings and Mean Stream Flows

Lake Murray Tributary	Mean Streamflow, percent	Phosphorus Load, percent	Ratio of Phosphorus Load to Flow
Bush River	3.4	26.8	7.9
Little Saluda River	6.7	12.2	1.8
Clouds and West Creeks	3.3	6.9	2.1
Ninety-Six Creek	4.3	24.6	5.7
Little River	6.8	6.2	0.9
Saluda River	63.8	16.7	0.3
All other flows	11.7	6.6	0.6

Upper End of Lake Murray, Including Embayments

The Bush River arm of Lake Murray (S-309) was reported in both the 1995 and 1998 reports to be among the most eutrophic sites on large lakes in South Carolina. The TP for this station is plotted in Figure 3-11, and the median TP was about 0.10, indicative of eutrophic-hypereutrophic conditions (Heiskary and Walker, 1987).

Figure 3-12 presents the TP data collected at Blacks Bridge since 1974 and shows that the current median TP concentration is 0.05 mg/L. This concentration corresponded to about the same as the median concentration observed at the upstream Saluda River station at Chappells (S-295), but was less than the estimated concentration 0.07 mg/L that entered the upstream end of Lake Murray due to the added TP load from the Bush River. This decrease in TP that occurred between the upstream end of the lake and Black's Bridge was attributed to precipitation of TP to the sediments, probably in the form of organic suspended solids, i.e., algae (Wetzel and Likens, 2000), and phosphorus adsorbed by clay particles that settled to the sediments.

At Lake Murray in the Rocky Creek area (S-279), SCDHEC commented in their 1998 report that this was among the most eutrophic sites on large lakes in South Carolina; but, in their 1995 report, they reported this site to be intermediate trophic status—in essence the opposite of their 1995 and 1998 ratings for the Blacks Bridge site, probably indicating that conditions at both locations were actually about the same for both periods. Figure 3-13 presents the TP data collected at this site for the period 1989-1998, where the median TP concentration was about 0.04 mg/L, only a slight decrease from the mean concentration observed at Blacks Bridge. This marginal decrease in TP shows that this station was still strongly influenced by inflow water quality and processes that are characteristic of what limnologists consider the transition zone of the reservoir. This observation is consistent with the two SCDHEC reports as well as the ERC report.

The Lower End of Lake Murray, Including The Embayments

For the forebay of Lake Murray (S-204), SCDHEC commented in their 1998 report that this was among the least eutrophic sites in South Carolina. Figure 3-14 presents the TP data collected at this site for the period 1989-1998 where the median TP concentration is 0.02 mg/L, and possibly 0.01 mg/L at times as measured by SCE&G (these latter data had a lower minimum detectable concentration). A closer look at the SCDHEC data for this station in comparison with the data collected at Rocky Creek and Blacks Bridge indicates that one major difference between the forebay and the upstream stations is that the TP is low essentially most of the year in the forebay. The upstream stations occasionally experience TP values as low as 0.02 mg/L (especially in the summer when inflow can be lower and algae consume the TP), but they increase significantly at times.

Summary for TP in Lake Murray, Including The Embayments

Table 3-2 summarizes the TP, chlorophyll *a*, and Secchi depth conditions at various locations in the inflows and Lake Murray. The changes in water quality as water moves from the inflow regions to the forebay are readily apparent: TP and chlorophyll *a* decreases and Secchi depth increases. In general these patterns are attributed to well-documented limnological processes that occur to some degree in every reservoir, and reservoirs with longer residence times exhibit more change than those with shorter residence times (Ruane and Hauser, 1991).

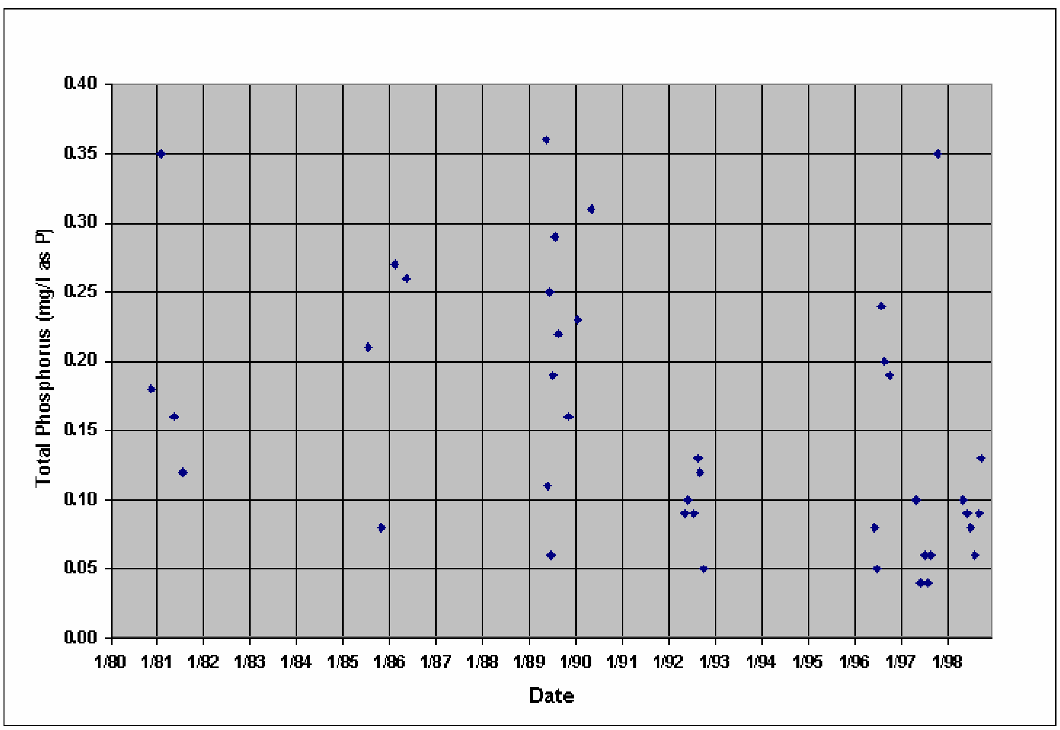


Figure 3-11. Total Phosphorus Collected at SCDHEC Station S-309 Located in the Bush River Embayment, Approximately 1.1 Miles Upstream of the Saluda River

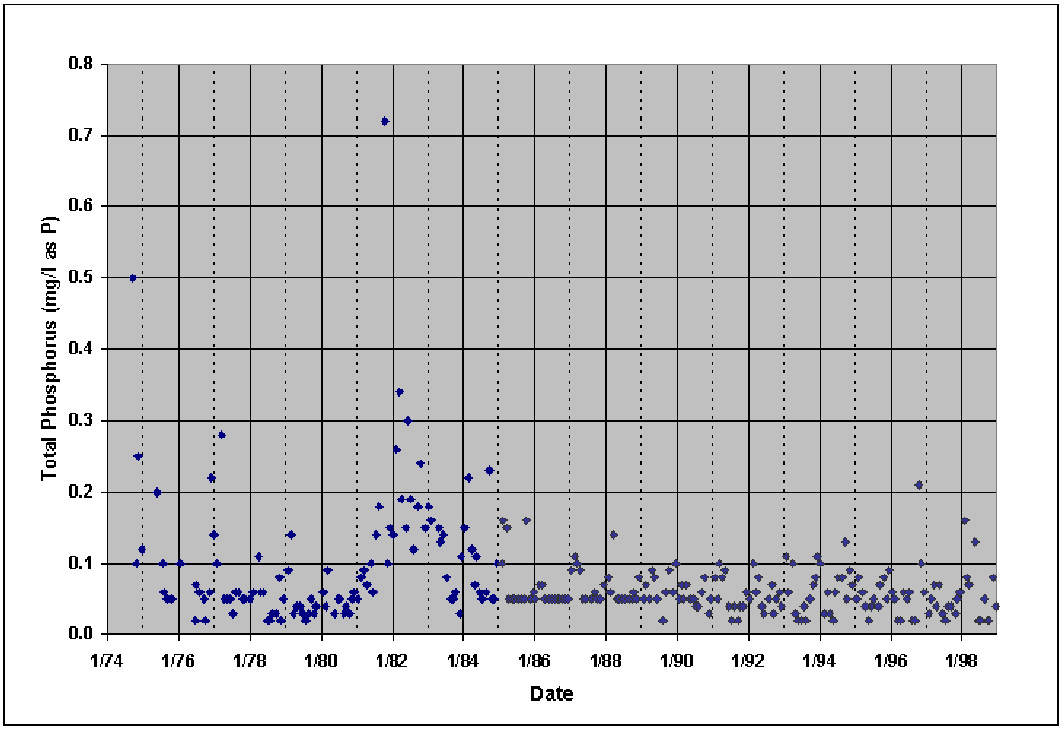


Figure 3-12. Total Phosphorus Collected at SCDHEC Station S-223 Located in the Saluda River at the Highway 391 Bridge

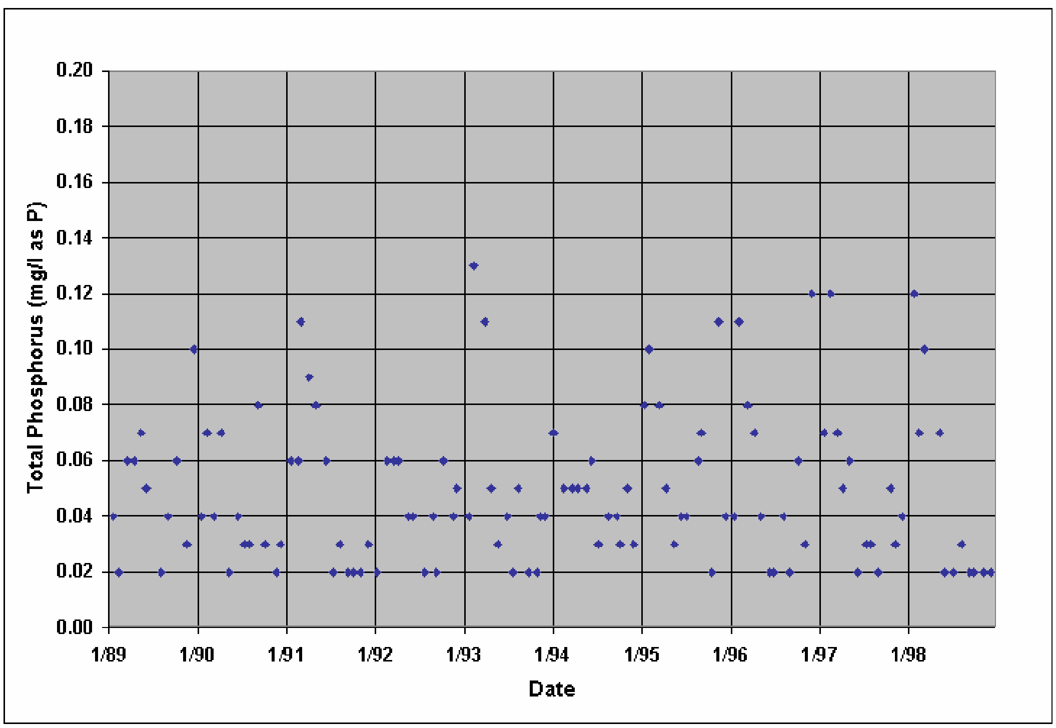


Figure 3-13. Total Phosphorus Collected at SCDHEC Station S-279 Located in Lake Murray near Rocky Creek, Approximately 17.7 Miles Upstream of Saluda Dam

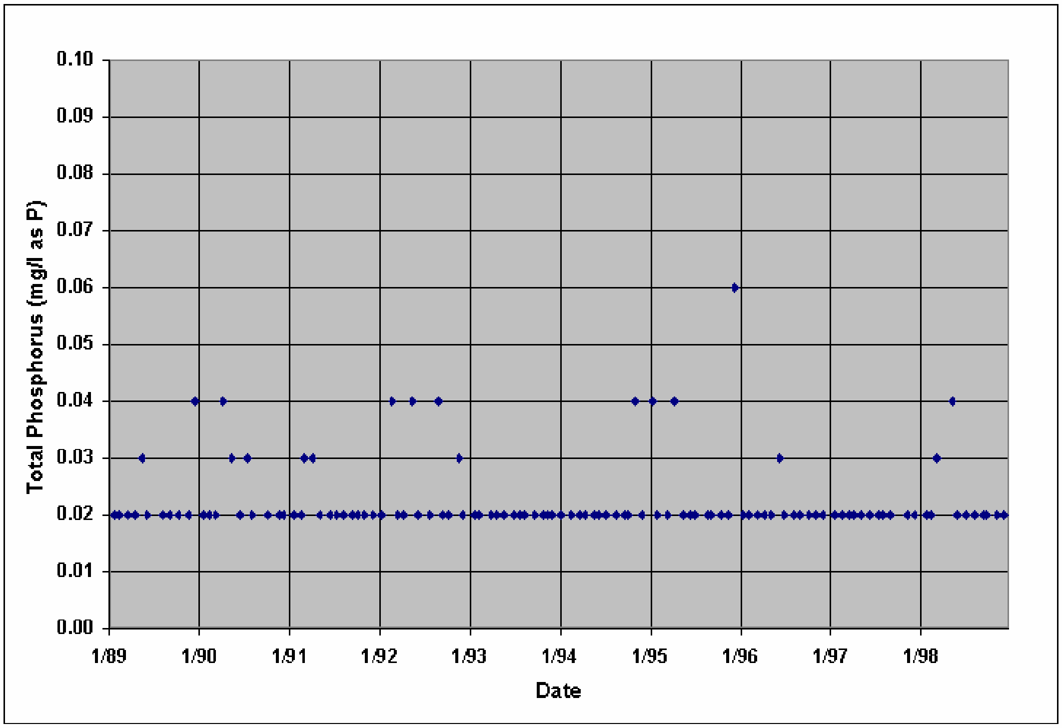


Figure 3-14. Total Phosphorus Collected at SCDHEC Station S-204 Located in the Forebay of Lake Murray

Table 3-2. Summary of TP, Chlorophyll *a*, and Secchi Depth Conditions at Various Locations in the Inflows and Lake Murray – Includes 1989-1998 Data Only

	Mean TP (mg/L)	Median TP (mg/L)	Mean Chlorophyll *a* (µg/L)	Mean Secchi depth (m)
Greenwood Dam (S-186)	0.032*	0.020	No data	No data
Ninety-Six Creek (S-093)	0.577	0.440	No data	No data
Little River (S-099)	0.083	0.070	No data	No data
Saluda River (S-295)	0.060	0.050	No data	No data
Bush River (S-102)	0.685	0.600	No data	No data
Bush River Embayment (S-309)	0.143	0.100	27.3	0.80
Blacks Bridge (S-223)	0.058	0.050	14.8	0.81
Little Saluda River (S-123)	0.167	0.140	No data	No data
Clouds Creek (S-255)	0.250	0.160	No data	No data

Rocky Creek (S-279)	0.049	0.040	11.9	1.15
Camping Creek (S-290)	0.136	0.120	No data	No data
Dreher Island (S-280)	0.030	0.020	6.5	1.92
4.2 Miles from Saluda Dam (S-273)	0.025	0.020	5.7	2.7
Ballentine Embayment (S-274)	0.023	0.020	5.7	2.9
Forebay (S-204)	0.023	0.020	7.3	2.8
* 39 out of 117 (33%) of the TP observations at this station were below the MDA of 0.02				

Temperature, Dissolved Oxygen, and pH

Lake Data

SCE&G has collected (or at times sponsored USGS to collect) water quality profiles throughout Lake Murray. DO and temperature data are useful for gleaning understanding of water quality dynamics in the lake. The data collected during the months of May, June, August, and September 1996 vividly illustrate the dynamics of DO and temperature in Lake Murray. It should be noted that hydrologic conditions were normal in 1996 but, near the end of August, SCE&G started drawing the lake down for aquatic plant management.

Here are some general patterns of DO that can be gleaned from the contour plots shown in Figure 3-15 which illustrate the DO dynamics of Lake Murray:

- DO starts decreasing in the upper part of Lake Murray in May.
- In the upper end of the lake by the end of June, DO is low (< 2 mg/L) in the metalimnion and near the sediments.
- In the lower two-thirds of Lake Murray by the end of June, DO is lower at the metalimnion than near the sediments, indicating significant DO demands in the water column. This is significant because it suggests that a dominant DO demand can be attributed to inflow water quality parameters like phosphorus and organic matter.
- In August, the DO is essentially zero throughout the metalimnion and is near 1 mg/L or less all along the sediments. However, the DO is greater than 3 mg/L from elevations 68 to 85 m in the forebay.
- In September, most of the hypolimnion and metalimnion experienced DO values <0.5 mg/L throughout the lake.
- In August of low flow years, the DO in the forebay is much greater than in normal and high flow years. In low flow years, the DO was generally greater than 3 mg/L at all depths in the forebay; whereas in normal flow years the DO was generally less than 3 mg/L and minimum DO levels were <0.5 mg/L.

- In September of low flow years, the DO in the forebay is marginally greater than in normal flow years. In low flow years, the DO was generally greater than 1.5 mg/L at all depths in the forebay; whereas in normal flow years the DO was generally about 0.5 mg/L and less.
- These observations in low flow years suggest that water displacement within the reservoir affects the DO distribution within the reservoir, (i.e., in normal and wet years, water movement through Lake Murray is greater and moves poor water quality, e.g., low DO, down through the metalimnion and hypolimnion more rapidly).

It is important to note that the low DO values in the upper end of the lake are caused by decomposition of algae and other inflowing organic matter that takes place in the water column as well as in the form of sediment oxygen demand (SOD) (Ruane and Hauser, 1991). If Lake Murray is like many other hydropower reservoirs, the low DO in the metalimnion all the way to the dam is caused by this decomposition of algae and other organic matter that initiates at the upper end of the lake.

Although the DO in the metalimnion appears to be only marginally lower than the DO levels observed near the sediments of the lake, the contour plots do not reveal the difference in the volumes of water with low DO in these two areas of the lake (i.e., the metalimnion volume compared to the volume of water near the sediments). The volume of the metalimnion (in July, this layer of the lake occupies an average elevation range from about 94 m to 99.5 m and ranges in temperature from about 17°C to 25°C) is about 350,000 ac-ft; whereas the volume of the water with low DO consumed by the bottom sediments is estimated to be about 15,000 ac-ft. The volume of water with DO depression in the metalimnion is about 25 times the volume of water with DO depression over the sediments. A rough estimate of the mass of the DO demands in these two areas of the lake is approximately proportional to the volumes of water in these two areas. Hence, it is estimated that the DO demands in the metalimnion (caused primarily by inflow water quality, algae, and SOD in the inflow region of the lake) are about 25 times greater than the DO demand attributed to the sediments in the deeper water of the lake. Following DO depletion in the metalimnion, DO consumption in the hypolimnion speeds up because more organic material (i.e., primarily dead algae) settles through the metalimnion without being decomposed.

Hence, even the low DO in the hypolimnion in the late summer can be attributed to DO demands that initiate in the water column (as opposed to the deep reservoir sediments.)

Low DO also occurs in the inflow regions of Lake Murray. Figure 3-16 and Figure 3-17 show data collected at the USGS monitors located in the Saluda River at Blacks Bridge and in the Little Saluda River at the Hwy 391 Bridge, respectively. The USGS has been monitoring DO and temperature at these locations since 1993, but these figures present data for 2001 and 2002 only. The data show that minimum DO levels are periodically less than the SCDHEC water quality standard in the upper 2 m of the lake. The occurrence of the low DO values in the upper 2 m of the lake was determined by correlating temperature values between the USGS monitor readings and monthly profiles collected at these locations.

The following is a summary of the excursions for the observed data (note that there were no data reported for about 50% of the time at Blacks Bridge and about 10% of the time on the Little Saluda River):

1. In the upper 2 m of the Saluda River At Blacks Bridge in 2001, there were about 10-12 daily minimum DO values reported to be less than 4 mg/L and the lowest value reported was 1.5 mg/L (the SCDHEC DO standard is 5 mg/L daily average and 4 mg/L minimum DO).
2. In the upper 2 m of the Little Saluda River arm in 2002, there were about 15 daily minimum DO values reported to be less than 4 mg/L and the lowest value reported was 1.6 mg/L; in addition, there were over 10 excursions of the daily average DO; i.e., over 10 values of average daily DO were less than 5 mg/L.

Figure 3-18 presents contour plots for the temperature dynamics in Lake Murray for the year 1996. It is instructive to track the 16°C contour line over the period of June through October. This shows how a dominant body of water moves through the lake. In June, this layer of water is at about elevation 95 m; in July, about elevation 92 m; in August, about elevation 89 m; in September, about elevation 78 m; and in October, all the water having a temperature of 16°C had been drawn out of the lake. This illustrates how low DO water in the metalimnion is drawn down in the lake to where it is eventually drawn out of the lake through the turbines.

The pH in the bottom of Lake Murray decreases as organic matter is oxidized by bacterial action that ends in the formation of carbon dioxide. Figure 3-19 shows how pH decreased in conjunction with decreasing DO levels below the epilimnion as organic matter was oxidized over the course of the summer months of 2001. This figure vividly demonstrates that oxidation of organic matter is correlated with low pH values in the releases from Saluda Hydro.

Tailwater Data

SCE&G has sponsored USGS monitoring of DO and temperature in the releases from the Saluda Project since 1989. The results of the DO and temperature monitoring in 1996 are presented in Figure 3-20 and Figure 3-21, respectively. The DO conditions for 1996 are presented because they do not reflect the effects of the aeration efforts that SCE&G implemented in 1997—starting in 1999, DO in the releases from Saluda Hydro dramatically improved except when flows were greater than about 6000 cfs in September and October. SCE&G plans to implement additional aeration measures but there are several alternatives that need evaluation; one being the reduction of nutrients in the inflows to Lake Murray.

The amount of water flow that passes through the turbines affects the amount of air that can be aspirated through the turbine system—a lower amount of flow, or gate setting, allows more air to be aspirated into the turbine system which, in turn, allows DO to be increased to a greater extent in the turbine releases. Over the period 1999-2002, the median DO increased to about 7.2 mg/L compared to a median DO of 2.7 mg/L for the years before 1999. The percentage of time that the DO was less than 5 mg/L decreased from 88% to 12%. The percentage of time that the DO was less than 3 mg/L decreased from about 55% to about 3%.

Part of the success of the turbine venting system can be attributed to the low flows that occurred in 1999-2002; i.e., SCE&G was able to operate the turbine venting without having to operate at higher flows as frequently as they would in normal and high flow years. The summertime cumulative flows in 1999-2001 were less than half of the normal cumulative flows observed in most of the other years for which DO data are available.

The current turbine venting system and modified operational scheme was developed using field studies in October 1998 (Saluda Hydroelectric Project Turbine Venting Study—1998, April 1999), as well as more recent studies to implement the use of hub baffles to allow increased aeration at higher unit and project flows.

The daily average DO drops to less than 4 mg/L periodically. These periods are associated with times when project flows are higher than about 6000 cfs. The ultimate capability of turbine venting for adding DO to the releases at the Saluda Project will not be known until the hub baffles, and perhaps other improvements, are added to the system and tested.

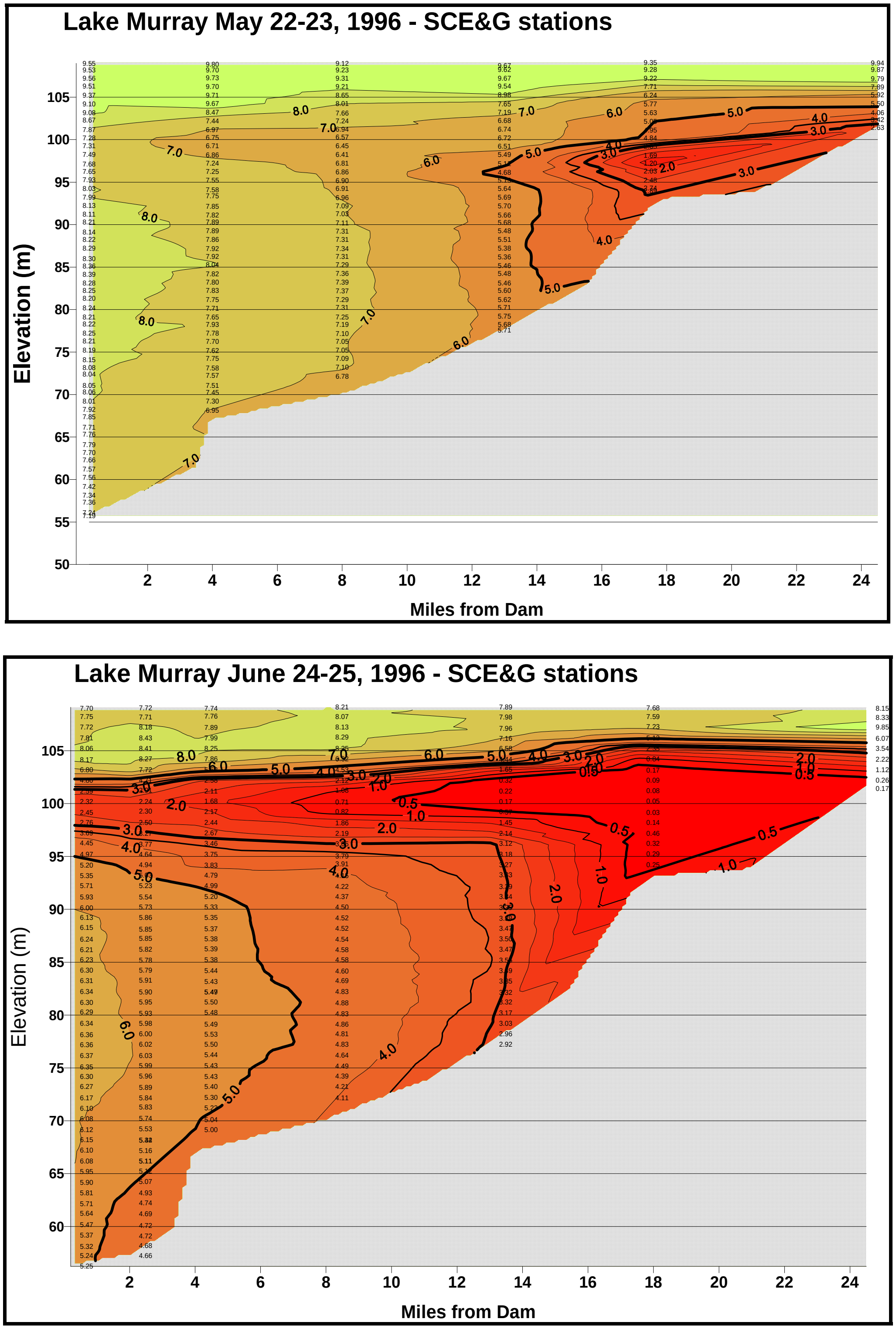
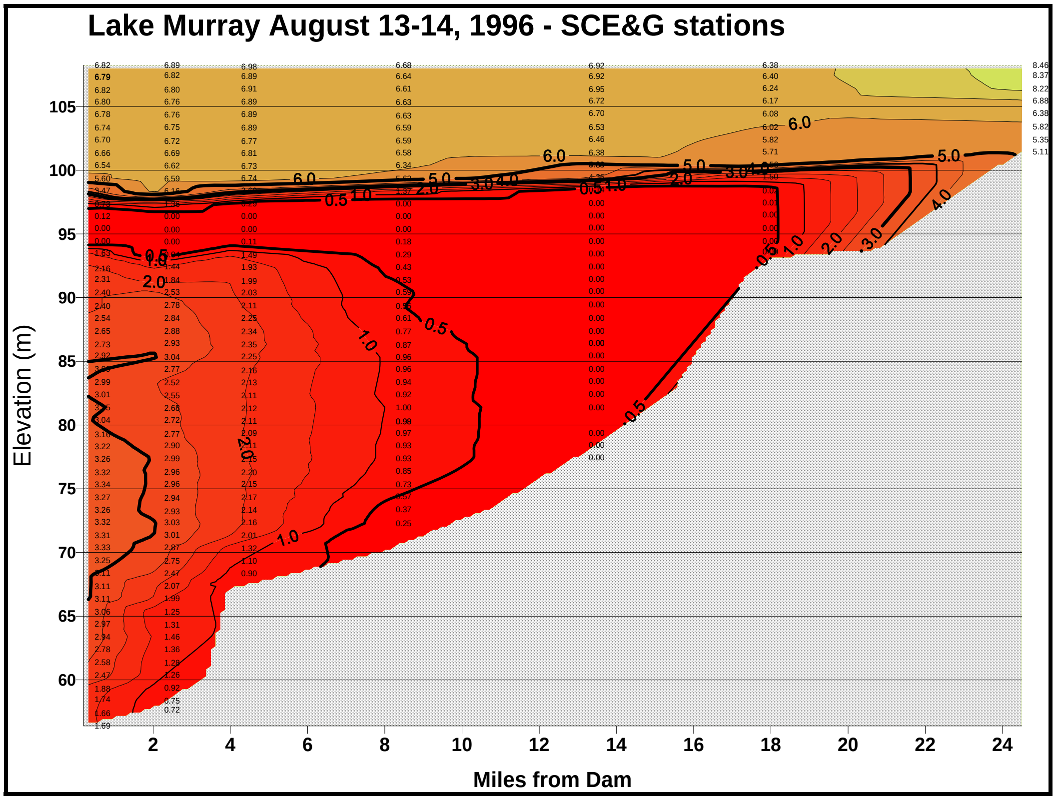


Figure 3-15. DO Measured in Lake Murray in 1996



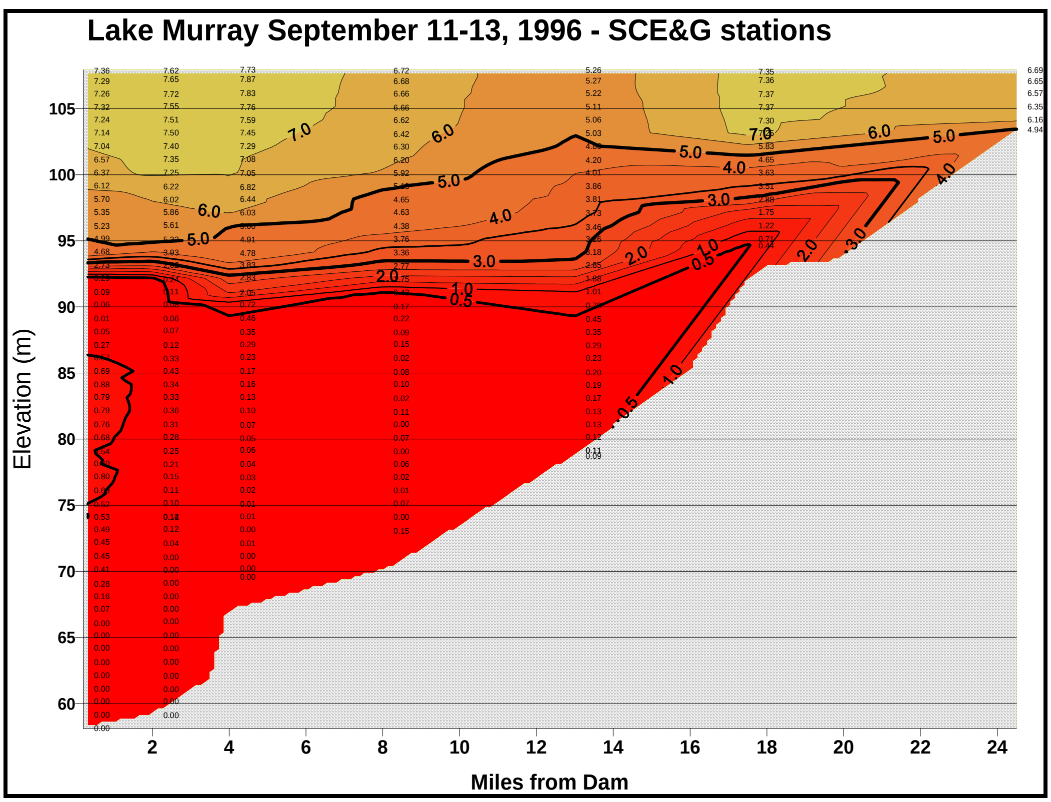


Figure 3-15, continued. DO Measured in Lake Murray in 1996

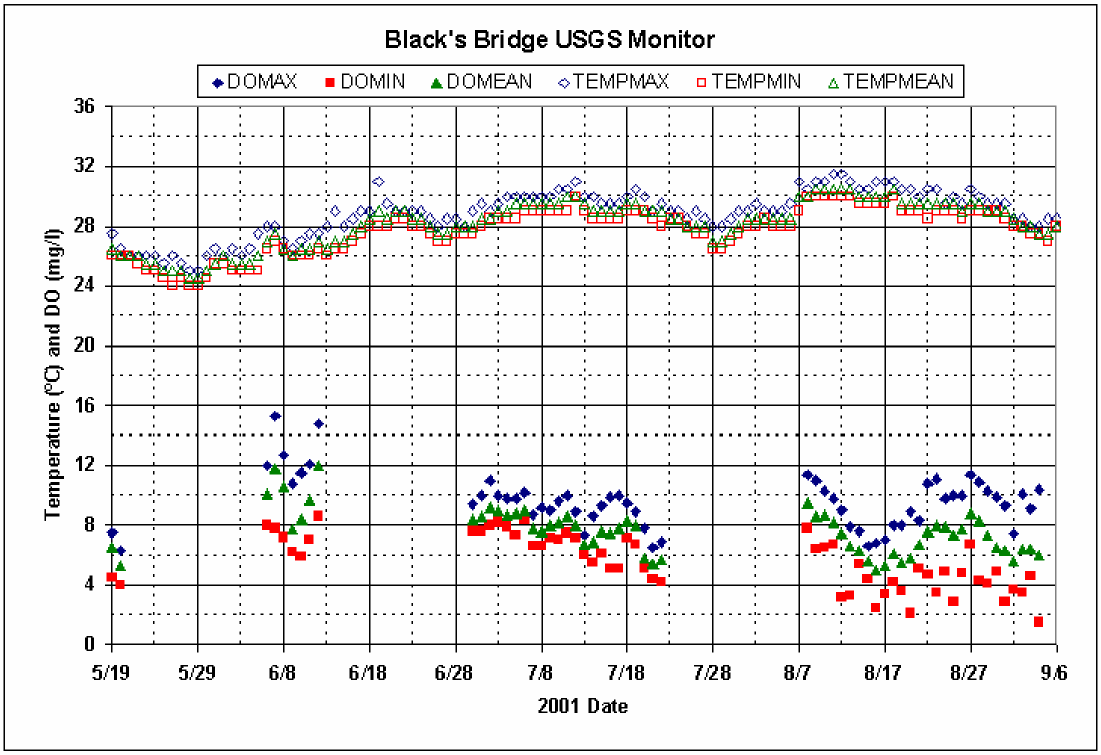


Figure 3-16. Daily DO and Temperature Data Collected at Blacks Bridge

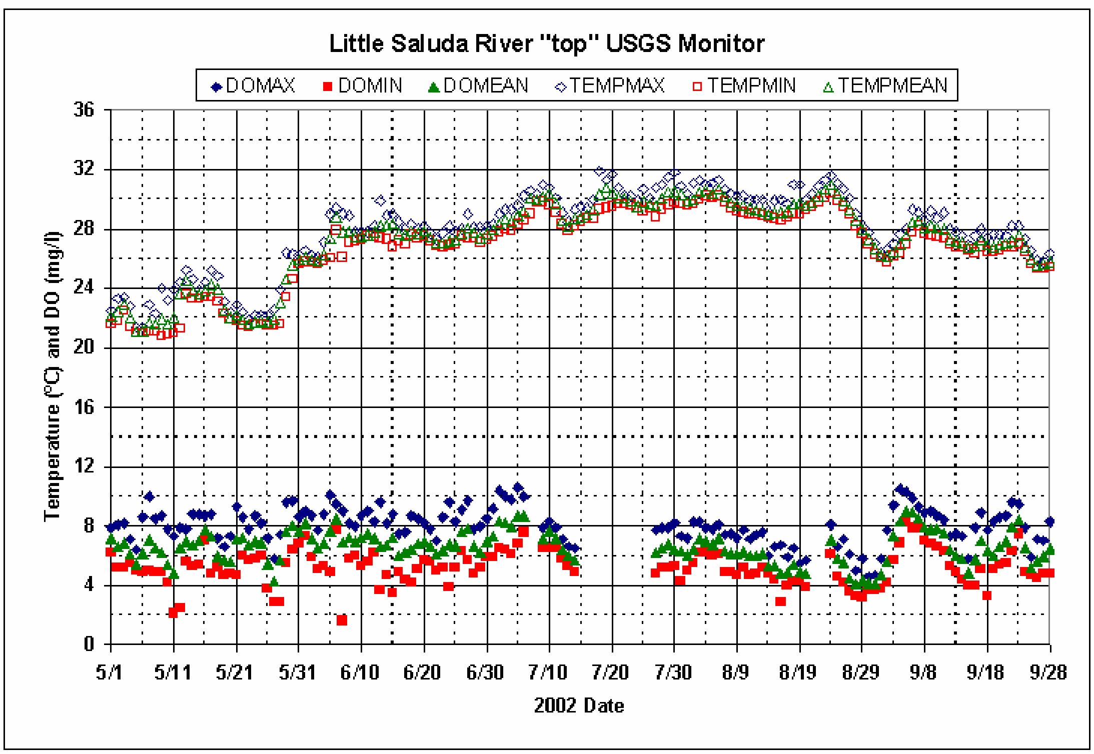
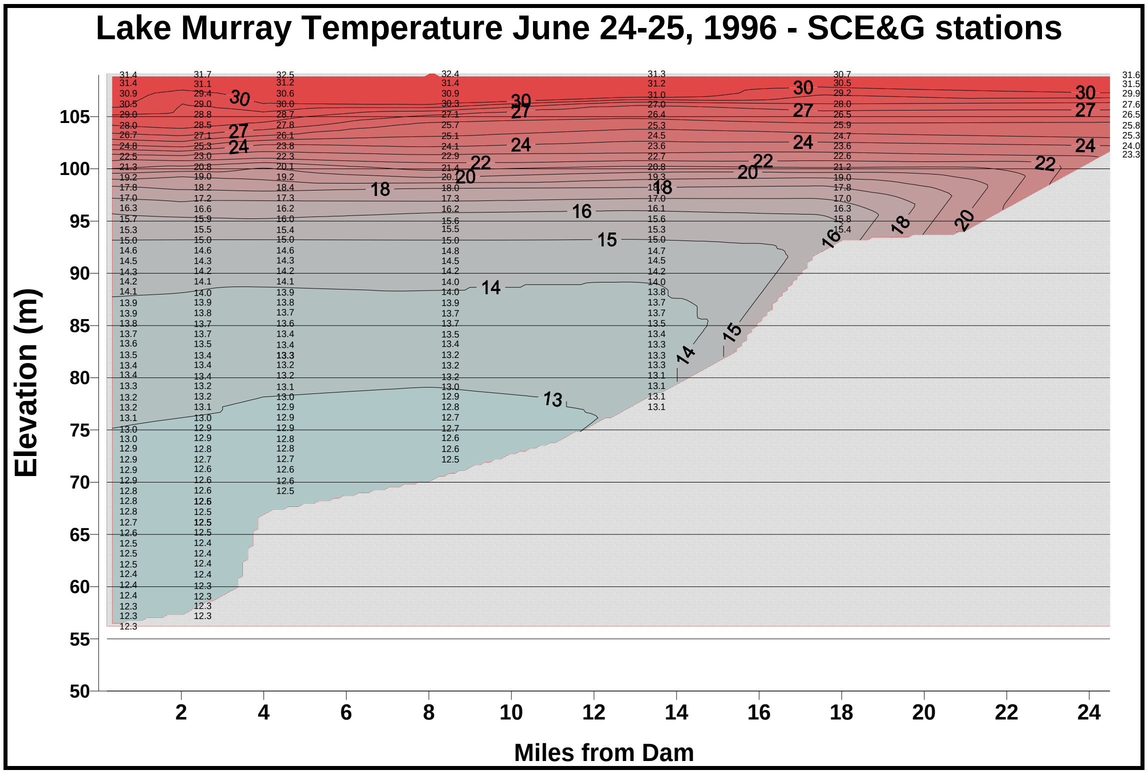


Figure 3-17. Daily DO and Temperature Data Collected on the Little Saluda River



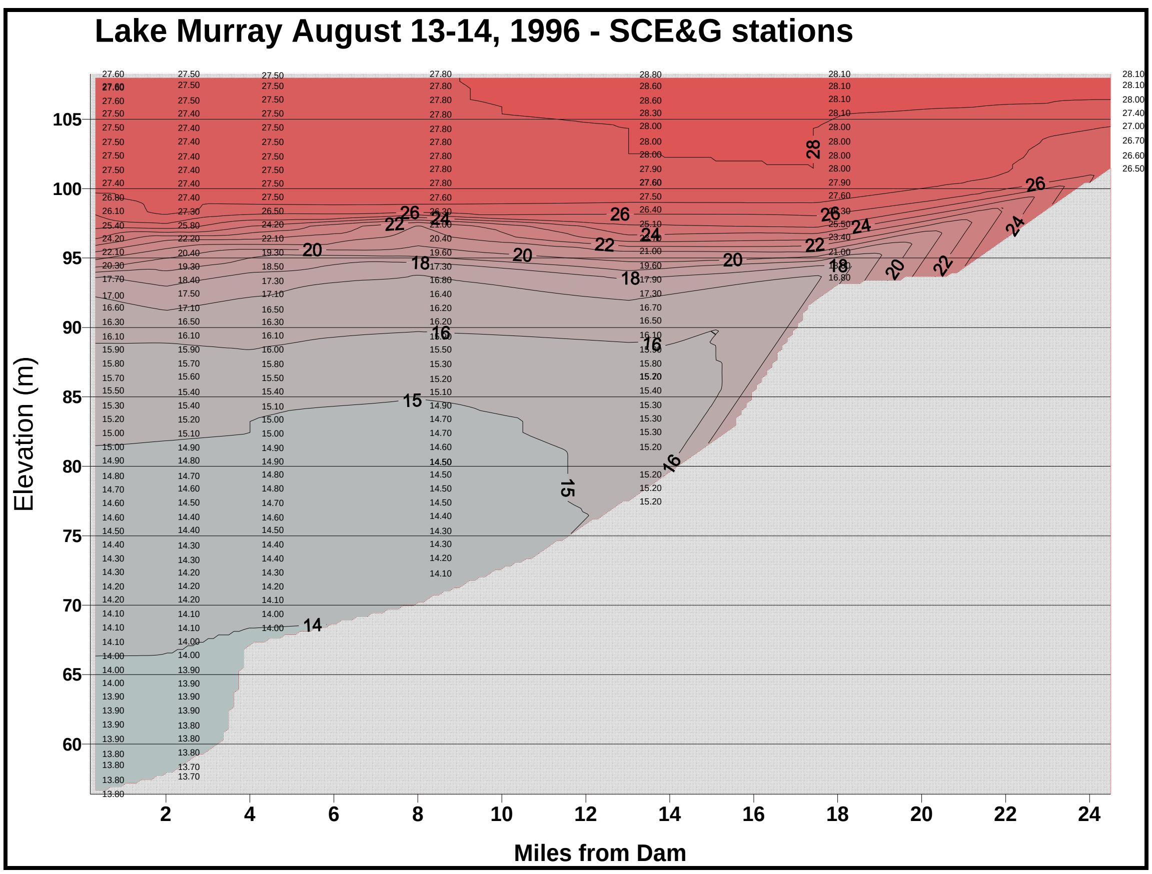
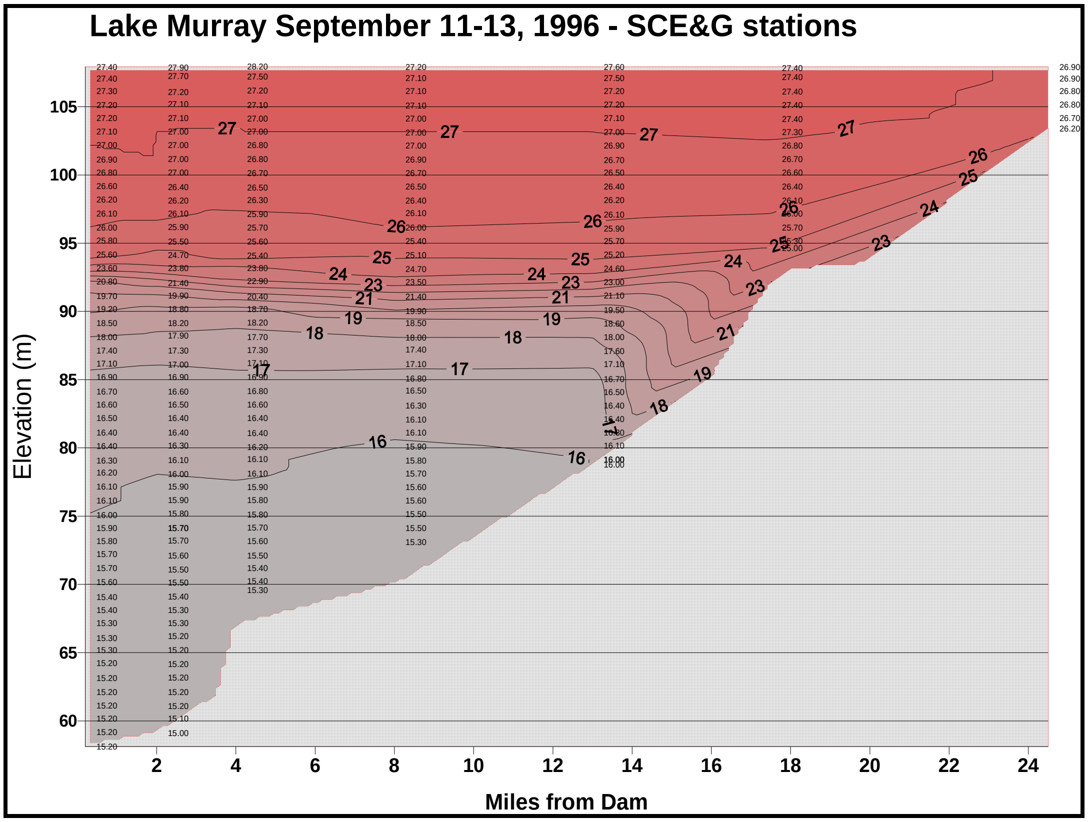


Figure 3-18. Temperature Measured in Lake Murray in 1996



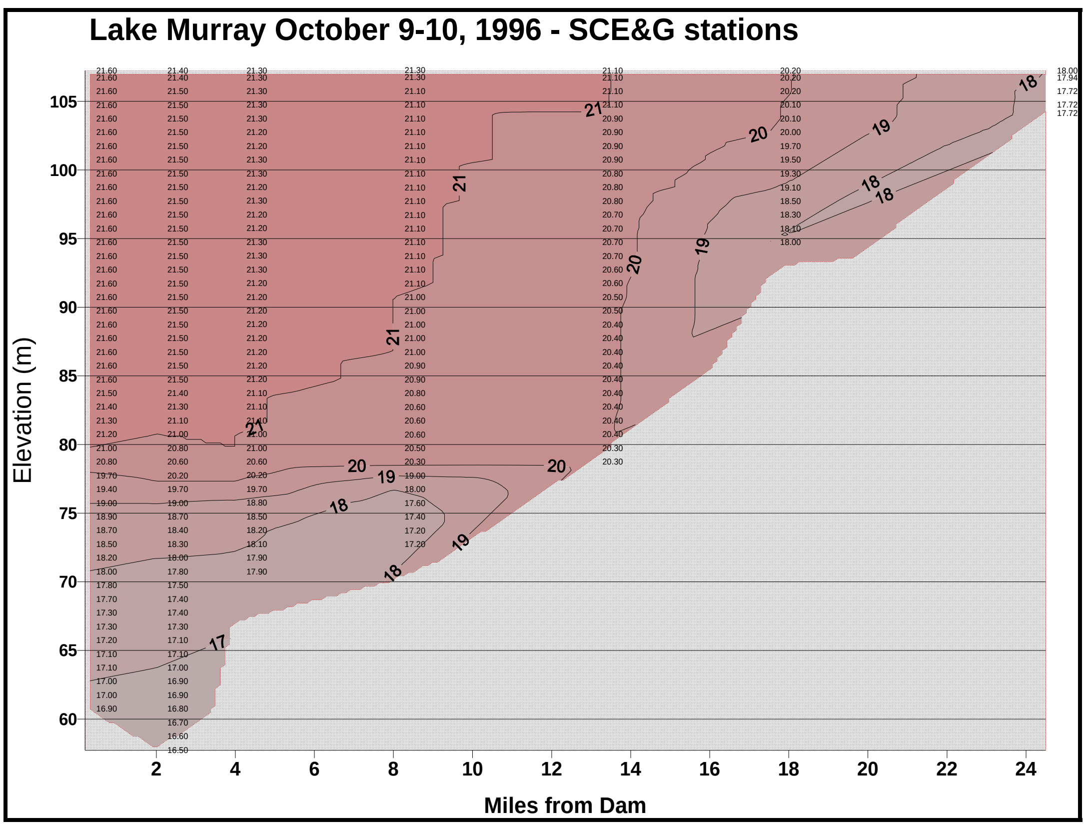


Figure 3-18, continued. Temperature Measured in Lake Murray in 1996

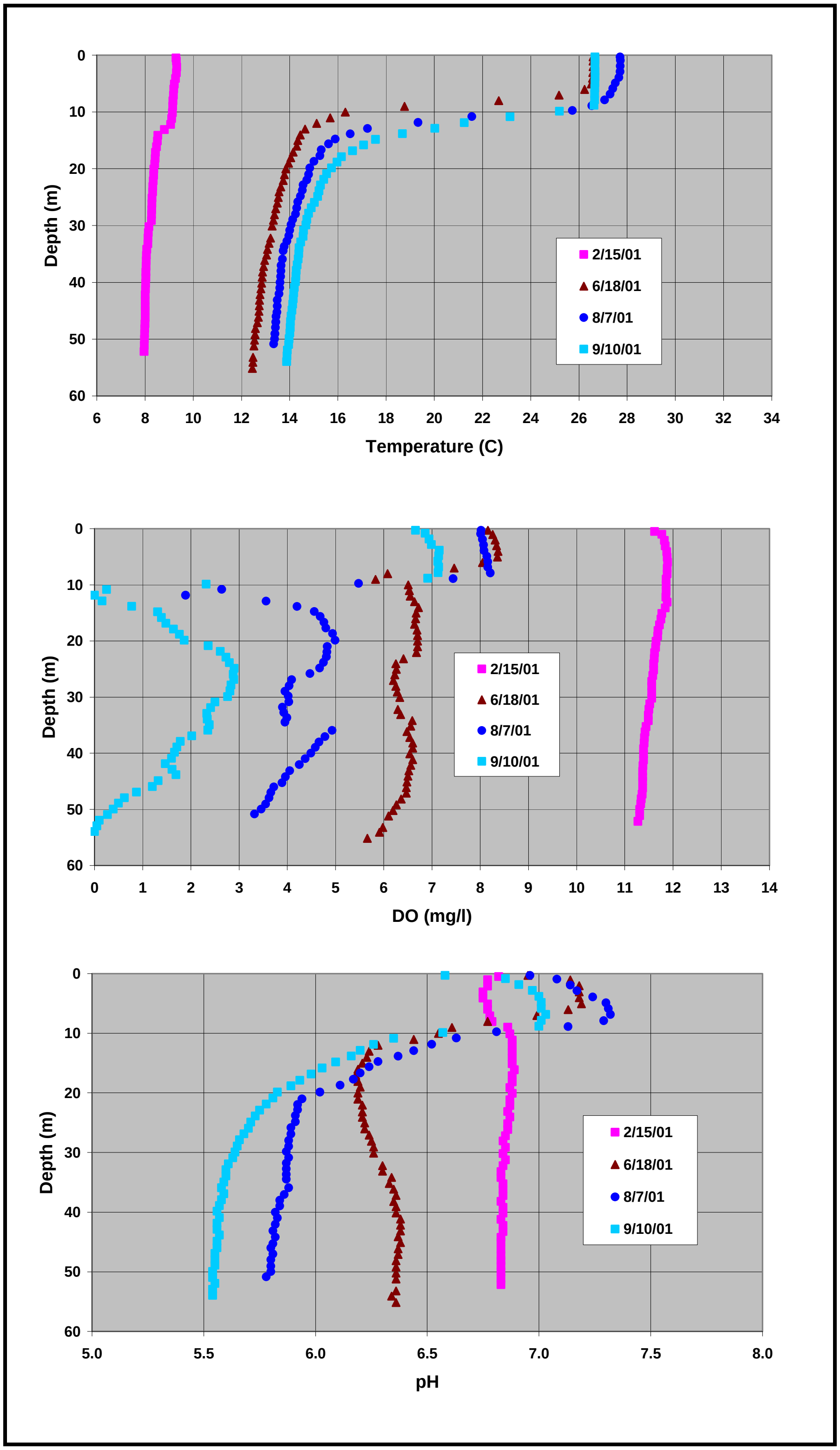


Figure 3-19. Temperature, DO, and pH profiles from 2001 showing the correlation between pH and low DO

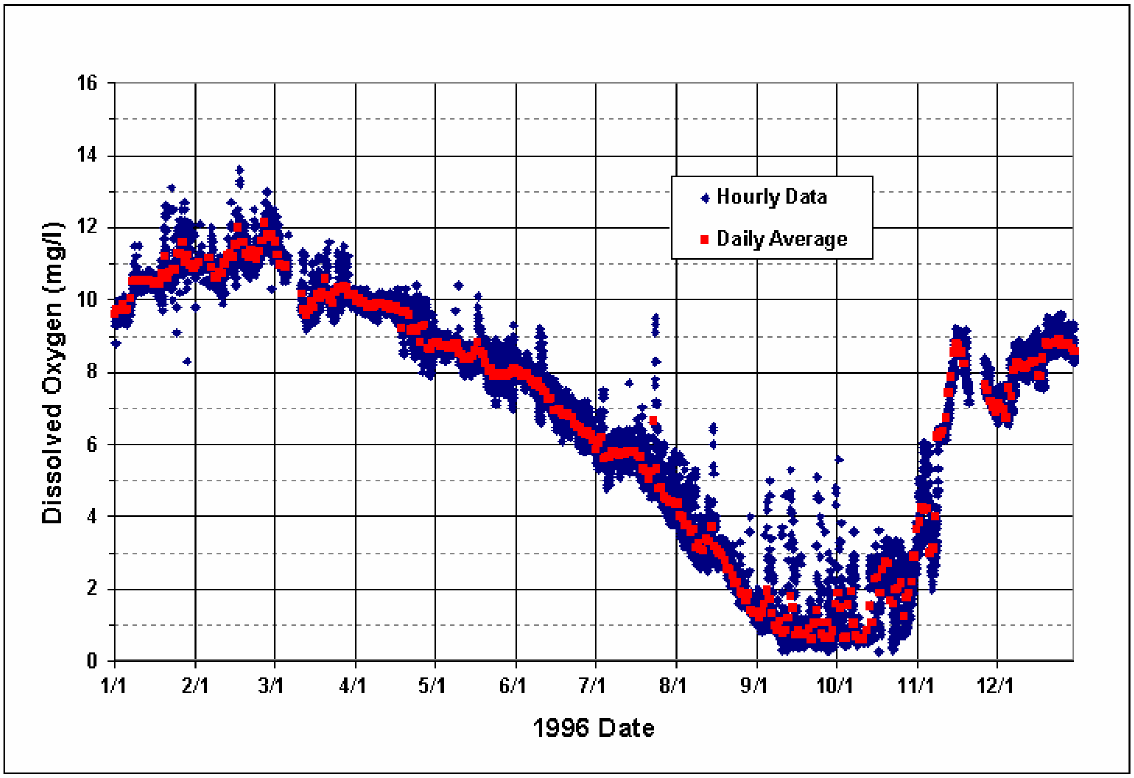


Figure 3-20. DO Measured by USGS in the Saluda Hydro Tailrace in 1996

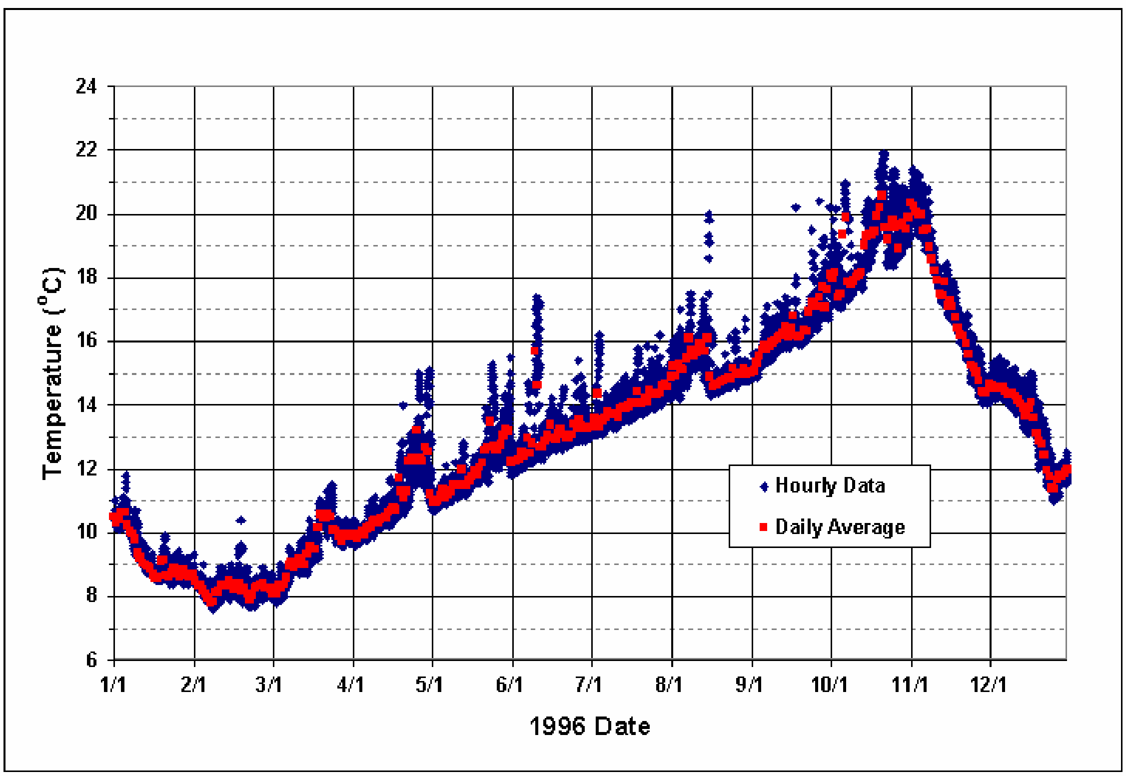


Figure 3-21. Temperature Measured by USGS in the Saluda Hydro Tailrace in 1996

Limnological Considerations for Effects of Phosphorus on Lake Murray

The size of a lake and its residence time for water passing through it significantly affects how phosphorus impacts water quality in the lake. Phosphorus causes algal growths in lakes and eventually decreases in the water column as the algae die and settle to the bottom, taking some of the phosphorus with them. Therefore, lakes with longer residence times usually result in lower phosphorus and algae levels in the lower regions of these lakes near their dams as the summer growing season progresses. The areal and longitudinal extent of phosphorus impacts on a reservoir, as well as the degree of impact on a reservoir, is significantly affected by the concentration of phosphorus in the inflows as well as the amount of flow that enters the reservoir.

A small amount of phosphorus causes significant algae and associated organic matter that results in demands on the DO in lakes. For example, the median phosphorus concentration in Ninety-Six Creek is about 0.44 mg/L. If all of this phosphorus was used to grow algae, it would cause about 73 mg/L of algae and eventually result in an oxygen demand of about 100 mg/L after the algae died and were decomposed by bacteria. In other words, the multipliers for the effects of phosphorus concentration on algal concentration and DO demand are 170 and 240, respectively; i.e., multiply phosphorus concentration by 170 and 240 to calculate the concentrations of algae and DO demand, respectively, that ultimately could occur. To put these numbers into perspective, typical levels of algae acceptable for water bodies at any one location are about 1-3 mg/L of algae and about 4-5 mg/L of DO demand. Fortunately in Lake Murray, the effects of Ninety-Six Creek, as well as the Bush River, are significantly diluted by the flow from Greenwood Dam that contains low concentrations of phosphorus, so Lake Murray is not directly exposed to the high concentrations of phosphorus from these inflows.

Point sources from wastewater treatment plants are known to contain relatively high concentrations of phosphorus that significantly affect water quality in lakes. Various types of nonpoint sources of phosphorus can cause similar effects, but these sources are dependant on characteristics of each watershed.

Limnologists often compare phosphorus levels in lakes with resulting water quality conditions to see how they relate. Data on lakes the size of Lake Murray were summarized to determine how DO associated with these lakes compared to the phosphorus levels in their inflows. Table 3-3 presents the results of this summary for 14 projects in the United States with residence times similar to Lake Murray (i.e., 400 days ± 75 days). Several DO metrics could have been used (e.g., lake profiles, levels of DO in their releases, etc), but due to the level of effort required to obtain DO data for these metrics a simpler metric was chosen: consideration of annual occurrence of zero DO in the releases from the projects for all years including low flow years when DO might not be as low as in other years.

Table 3-3 shows that there is high correlation between concentration of phosphorus in lake inflows and the occurrence of zero DO in their respective turbine releases. For the eleven reservoirs where TP was about 0.01 to 0.04 mg/L in the inflows, zero DO did not occur annually in the releases from these projects. On the other hand, for those reservoirs where TP was greater than about 0.06 mg/L in the inflows, DO was zero each year. It should be noted that these kinds of projects often experience their lowest DO conditions during mean and high flow years as opposed to low flow years like projects with less residence time. Most of the projects listed in the table (South Holston, Watauga, DeGray, Beaver, Broken Bow, Burton, Smith, Nantahala, and Thorpe) do not experience zero DO at any time, although several require some aeration to increase DO to desired objectives. It should be noted that there are other factors (i.e., outlet level, temperature, organic matter in inflows) that can affect DO in the releases from hydropower projects; but, in spite of these other factors, the simple correlation between phosphorus and DO in Table 3-3 is remarkable.

The results of this summary of actual conditions for lakes the size of Lake Murray vividly demonstrate that reduction of phosphorus in the inflows to Lake Murray should result in higher DO levels in the releases from Saluda Hydro.

Table 3-3. Summary of DO Conditions at 14 Reservoirs with Residence Times Similar to Lake Murray and Various Inflow Phosphorus Conditions

Relationship Between Low DO and Phosphorus for Hydropower Reservoirs with Residence Times of About 400 Days										
Name of dam	**River**	**Max. depth, ft**	**Normal storage, ac-ft**	**Surf. area, ac**	**Drain. area, sq mi**	**Mean flow, cfs**	**Resi-dence Time**	**Zero DO in releases, annually?**	**COMMENTS**	
BEAVER, AR	White	218	1,652,000	28,220	1186	1898	439	No	Low TP (0.02-0.04), but impacted by Fayettville	
BROKEN BOW, OK	Mountain Fork	175	920,000	14,200	754	1350	341	No	Low TP (0.03-0.04)	
BURTON, GA	Tallulah		108,000	2,775	118	142	385	No	Low TP (~ < 0.04)	
DEGRAY, AR	Caddo	171	654,700	13,400	453	725	455	No	Low TP (~ 0.02)	
HARTWELL, GA/SC	Savannah	185	2,550,000	55,950	2088	3670	347	probably	low metalimnion DO in Seneca Arm, but not Tugaloo Arm; probably due to TP	TP load could be 80% of load to Lake Murray; Hartwell has 56 days less residence time
LEWIS SMITH, AL	Sipsey Fork/ Warrior R	264	1,390,000	21,200	944	1510	464	No	Low TP (0.02-0.03)	
NANTAHALA, NC	Nantahala R	210	138,000	1,605	108	173	399	No	Low TP (~ 0.01)	
NARROWS, AR	Little Missouri	132	279,700	7,200	237	379	372	No	Low TP (0.02-0.04)	
PHILPOTT, VA	Smith	180	166,200	2,880	212	254	327	No	Low TP (0.02-0.03)	
SALUDA, SC	Saluda	170	2,118,000	50,000	2420	2683	398	Yes	High TP (0.08-0.1)	
SOUTH HOLSTON, TN	South Holston	240	657,500	7,580	703	980	338	No	Low TP (0.03), but low DO in metalimnion, probably due to elevated orthoP in one inflow	
TENKILLER, OK	Illinois	187	654,100	12,900	1610	805	410	probably	zero DO on bottom of lake; < 1 ppm in releases in Aug '95	receives high nutrients: ~ 0.08 TP; 12 TMDL sites in watershed for org/low DO
THORPE, NC	West Fork Tuckasegee	110	71,000	1,462	37	100	355	No	Low TP (~ 0.01)	
WATAUGA, TN	Watauga	309	568,700	6,430	468	710	404	No	Low TP (0.03)	
	Total projects where releases are greater than zero							**11**	**79** %	
	Total projects where releases have zero DO annually							**3**	**21**	
	Total projects							**14**	**100** %	

Before developing a CE-QUAL-W2 model for Lake Murray, a model of DeGray Reservoir, that has a similar residence time, was used to see how sensitive DO would be to phosphorus concentration in the inflows. To perform this evaluation, several modifications were made to the original CE-QUAL-W2 model for DeGray:

1. Inflows to the reservoir were set to high nutrients similar to those entering Lake Murray and low nutrient concentrations that enter DeGray.
2. Temperature in the model was adjusted so that the model would be representative of the southeast United States.
3. SOD in the "high nutrient model" was adjusted to account for the higher algal growths that occur as in Lake Murray.
4. The outlet level from the dam was set lower in the water column.

The results of this evaluation vividly indicated that DO in Lake Murray would be sensitive to reductions in phosphorus in the inflows, as shown in Figure 3-22.

It can therefore be concluded that DO in the forebays and turbine releases from lakes the size of Lake Murray are very sensitive to phosphorus in their inflows.

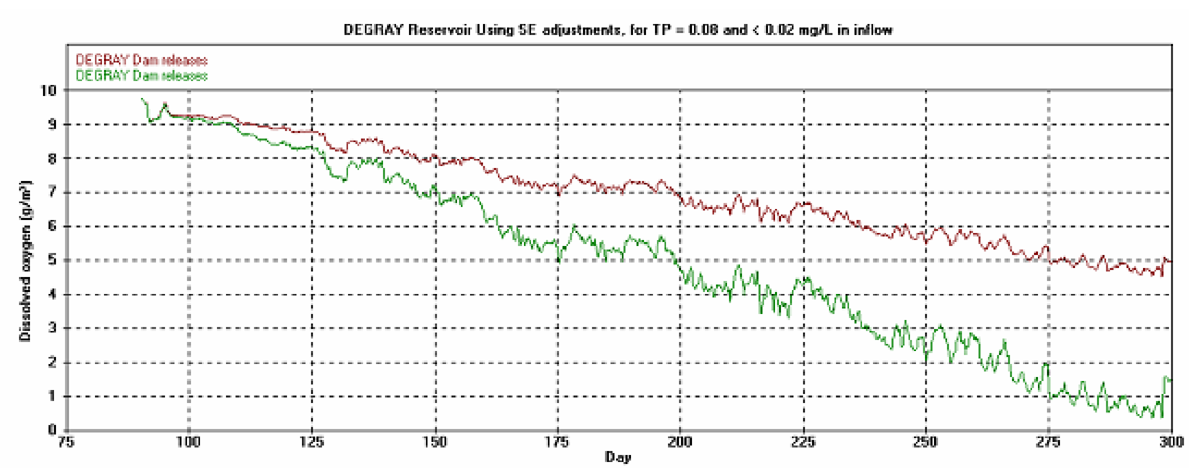


Figure 3-22. CE-QUAL-W2 Model Results Using the DeGray Model to See How DO in the Releases Responds to Higher Levels of TP—the Upper Curve is for Low TP Levels

Summary of Water Quality Analyses

- From a total of twelve stations on Lake Murray (including embayments), nutrients and pH were listed as the cause for non-supporting water uses at several stations. However, they were not designated as planned TMDL sites.
- The stations at Rocky Creek and in the Bush River arm of Lake Murray were reported to be among the most eutrophic sites on large lakes in South Carolina, and both of these locations were designated as non-supporting for aquatic life uses. All the locations between Rocky Creek and the dam, including the embayment locations, were reported to be among the least eutrophic in South Carolina.
- Low pH in the tailrace was the cause for non-supporting and partially supporting ratings in the tailrace in the 303(d) listings in 2004 and 2006.
- Watershed management has been recommended to reduce phosphorus loading to two areas of the lake: Bush River embayment and the Rocky Creek area of Lake Murray.
- The water quality in the releases from Greenwood Dam has improved dramatically over the last 20 years. In the late 1980s, nutrients and organic matter were reduced. In 1998, an aeration system was installed and DO in the releases is now usually greater than 5 mg/L.
- However, the TP load to Lake Murray still remains high due to nutrient loads from Ninety-Six Creek, Bush River, Little Saluda, and Clouds Creek. These tributaries to the upper end of Lake Murray contribute an estimated 71% of the TP load to Lake Murray while their streamflow contributions only total about 18%.
- Reductions of TP loads in Ninety-Six Creek, Bush River, Little Saluda, and Clouds Creek would improve water quality (trophic status, water clarity, reductions in algae, DO) in the upper areas of Lake Murray (Rocky Creek and upstream). If these waterways were reduced to the criteria set for lakes by SCDHEC, the inflows to Lake Murray would be among the cleanest 30% of the hydropower reservoirs reported in a recent EPA study (Crossman, 2001). DO in the reservoir as well as the releases also would likely improve.
- Further study (i.e., water quality modeling) would be required to determine how water quality might improve by using nutrient controls in the watershed.

- Considerations for internal nutrient cycling—eutrophication at Rocky Creek and low DO in the metalimnion (and subsequently in the turbine releases) could be partly attributed to internal nutrient cycling. Also, the nutrients released from the sediments in the upper region of the lake could be subject to upwelling induced by power pulse inflows from Lake Greenwood being cooler than the surface water. This upwelling could contribute additional P and N (i.e., NH_3) into the surface layer.
- Water quality problems (algae, anoxics, low DO) in the Little Saluda River embayment are partly caused by internal nutrient cycling due to the small watershed feeding this embayment (i.e., it is a sizeable body of water with relatively low potential for sediments to be flushed out.) Nutrients accumulate in a system like this and cycle over and over as they are taken up by algae, the algae die and settle, and then the nutrients are cycled up into the water column again.
- DO in the Saluda turbine releases probably would improve, and the Lake Murray metalimnion would not experience DO levels as low as current conditions if TP was reduced using point source controls in the watershed and/or by reducing internal nutrient cycling.
- Aeration of releases. The current turbine venting system with the addition of hub baffles has increased the minimum DO, especially when turbines are operated at flows up to about 6000 cfs. If nutrient sources in the watershed and associated DO demands in upreservoir sediments were reduced, DO in the LSR would likely increase more. A CE-QUAL-W2 model will be used for estimating the benefits of nutrient controls in the watershed and how DO conditions would change in the reservoir and turbine releases following nutrient reductions.
- Limnological considerations. Comparison to 13 other reservoirs having similar residence time showed TP in inflows significantly affects DO in the releases from such lakes. This was confirmed by modifying the CE-QUAL-W2 model on DeGray Reservoir which has low TP concentration in its inflows and DO levels greater than Saluda in its releases. After model settings were adjusted to be more like Lake Murray, the DO in the releases was much lower.

4. Approach to Water Quality Management for Lake Murray

Based on water quality analyses of data available on Lake Murray, its inflows, and the releases from Saluda Hydro, as well as consideration for water quality objectives for Lake Murray and Saluda Hydro, the following hypothesis was formulated to provide an approach for quantifying linkages between the causes and effects so that water quality management strategies could be developed:

> ***Hypothesis*:** A major portion of the water with low DO that passes through the turbines derives from low DO water in the metalimnion and much of the hypolimnion, which is low in DO due to the nutrients and organic matter in the Bush River, Ninety-Six Creek, and Little Saluda River. SOD in the inflow region of Lake Murray also causes low DO in the metalimnion, but this SOD, as well as nutrient releases from these sediments, can be attributed to the impacts of these same watershed nutrient and organic sources. As illustrated using the temperature dynamics in the lake, most of the water in the metalimnion and hypolimnion is eventually drawn out through the turbines. The low pH concerns that SCDHEC identified for the Saluda River downstream from Lake Murray can only be addressed by nutrient management in the watershed. The low DO excursions occurring in the inflow regions of the lake can only be addressed through similar watershed actions.

To prove this hypothesis, SCE&G decided that a water quality model like CE-QUAL-W2 was needed to simulate the complex, dynamic water quality linkages and processes as they currently occur, as well as how they would occur if nutrients and organic loads from the watershed were reduced. This model allows a quantitative assessment of the effects of the TP loads from watersheds on most of the water quality issues, including DO, in lakes and their releases. Also, the model can provide an assessment of the benefits of watershed TP controls to coolwater fish species that inhabit the metalimnion of lakes. In addition, the model allows an assessment of the potential eutrophication improvements in the upper regions of lakes where some of these areas are less than fully supporting water quality objectives.

CE-QUAL-W2

CE-QUAL-W2 (W2), is a two-dimensional, hydrodynamic and water quality model for reservoirs and rivers. The W2 model is deterministic (i.e., mechanistic) not stochastic. Modeled temperatures within Lake Murray are driven by boundary conditions including inflows, outflows and their withdrawal zones, and inflow temperatures, and by other forcing functions such as heat loadings and atmospheric heat exchange driven by meteorology. Modeled water quality within Lake Murray is driven by inflow water quality (especially temperature, organic matter, nutrients, turbidity, etc), transport of water through the lake, solar radiation and wind, algal production and death, bacterial decomposition, and sediment-water interactions. Calibration and application of the model to Lake Murray water quality required interdisciplinary knowledge of hydrodynamics, heat transfer, power plant operations, meteorology, numerical methods, computerized data assembly and analyses, physical/chemical/ biological processes and stoichiometry, limnological processes, lake sediment processes and sediment-water interactions, stream hydrologic and water quality processes, and statistics.

In planning mode (looking back and comparing effects of various operations), historical measurements are typically used as boundary conditions. In forecast mode (projecting into the future), boundary conditions are unknown so the user must take care to provide meaningful boundary condition projections. Since forecasts of future hydrologic conditions are not reliable, projecting boundary conditions often involves use of analogous historical years or sensitivity simulations covering a range of possible futures.

These studies and modeling efforts are based upon state-of-the-art approaches that are logical, sound extensions of well-founded research and studies conducted over the past half century. With any use of models it should be recognized that modeling results provide a general indicator of what is likely to occur under given sets of conditions. As is the case in all aquatic environments, natural conditions are more complex than models, so the models tend to reproduce the major patterns that are observed in the field, but will lack resolution, inputs, or formulations to reproduce all the minor patterns that are observed. Models are internally consistent and based on rigorous governing equations, so they can often help explain apparent discrepancies in field observations. The model results contained in this report are scientifically sound and can be used for regulatory decision-making purposes for determining the water quality benefits of reducing nutrient loads to Lake Murray.

In the course of calibrating the W2 model for Lake Murray, it was determined that the following modifications to version 3 would improve the performance of the model for meeting the objectives:

1. Provide for the phosphorus and nitrogen content of organic matter (i.e., ORGP and ORGN in the model control file) to be different for labile and refractory organic matter (note: labile matter decays over days and weeks; whereas refractory matter decays over months and years)—this was desired since refractory matter accounts for much of the organic matter, but has very little phosphorus and nitrogen content. This modification allowed a more effective calibration to the data through more direct control over mass of phosphorus and nitrogen in the system. The procedure for fractionating labile and refractory organic matter and estimating the phosphorus and nitrogen content of organic matter in the lake will be presented in a later section.
2. Provide for the release of organic matter from the sediments under hypoxic conditions—this was desired since this organic matter exerts an additional DO demand in the water column, and it allows the modeler to include this source of organic matter in the model to allow more effective calibrations to measured data. The release of organic matter from sediments has long been recognized, but has only recently been addressed in water quality modeling (DiToro, 2001; Chapra, 1997). Version 3.11 of CE-QUAL-W2 was modified to allow labile dissolved organic matter to be released from sediments (LDOMR) when the DO over the sediments was less than O2 LIMIT, the setting used to determine when sediments release anoxic products (i.e., when anaerobic processes occur at the sediment-water interface and release ammonia, phosphorus, and iron). LDOMR was set to be a fraction of the SOD, in a fashion similar to how other anoxic products are handled in W2. The setting for LDOMR was consistent with the stoichiometry for DO demands associated with organic matter presented by DiToro, 2001; Chapra, 1997)
3. Provide the option to use the Wuest wind drag coefficient—this was desired so that a higher level of mixing could be induced under low wind speed conditions. The W2 default formulation sets the drag coefficient to zero for winds less than 1 m s^{-1}.

However, according to Wüest and Lorke (2003), weak winds have drag coefficients that are significant. At high wind speeds, the Wuest formulation produces lower drag coefficient than the W2 default.

4. Provide for making W2 conserve phosphorus when ALGP (the phosphorus content in algal assemblages) is not equal to ORGP (the phosphorus content in organic matter).
5. Provide a way to precipitate phosphorus from the water column to help account for the effects of clay on phosphorus sorption and settling. Attempts to use the PARTP setting in W2 to account for the effects of clay yielded results that appeared to be erratic and cause erroneous results in other constituents. To pragmatically account for the effects of clay on phosphorus, the code was modified to allow precipitating phosphorus like CE-QUAL-W2 settles inorganic suspended solids. PO4S (phosphorus "settling" rate) was set in the modified control file to assist in calibrating the model to more closely represent the data on phosphorus. In an attempt to account for the effects of clay concentration on phosphorus precipitation, the settling can be linked to the concentration of total inorganic suspended solids. The PO4S value can be adjusted as a function of TISS (total inorganic suspended solids) by setting a lower and upper limit of ISS. In the control file, SSLLIM and SSULIM can be specified so that for the condition when TISS is below SSLLIM, the multiplier on PO4S = 0. For TISS >SSULIM, the multiplier on PO4S = 1.0. For TISS in between SSLIM and SSULIM, the multiplier on PO4S is a linear function of TISS, ranging from 0 to 1. While more accurate code could be developed to represent the effects of clays on phosphorus sorption and settling, it would require a considerable level of effort that was beyond the scope of this policy and planning modeling effort.

Documentation for the release version 3 of W2 is provided in the W2 user manual authored by Cole and Wells (2002), currently available at the following web address: www.loginetics.com/w2/docs.

W2i and AGPM

W2i is a graphical user interface and pre-processor for W2 that streamlines development and checking of W2 input files, viewing of bathymetry, locating meteorological stations, executing the W2 model, and launching of the Animation and Graphics Portfolio Manager (AGPM) post-processor. The AGPM is a graphical post-processor for W2 that includes a range of plot types, including animations, vertical profiles, time-series, time-depth plots, etc. AGPM is the primary vehicle for plotting and viewing outputs from the model.

Modeling Plan

Objectives

The objectives of the modeling effort are as follows.

- 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 blueback herring and striped bass.
- To assess the effects of operations of Unit 5 on habitat for fish in Lake Murray.
- To investigate the causes of fish kills that might be related to operations of Saluda Hydro

Modeling Approach

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

1. The objectives and scope of the model;
2. All available data;
3. Model settings, rates, and coefficients recommended in model manuals and other literature sources;
4. Approaches recommended in the user manuals for the model used;
5. 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.

Site-specific models like the one developed for Lake Murray are intended for specific, limited uses such as those stated above.

Due to data availability and hydrologic considerations, the years selected for calibration were 1992, 1996, and 1997. The year 1996 was originally chosen as the primary calibration year with the intention of applying the same coefficients and inflow water quality to 1992 and 1997 conditions to check model robustness. However, as the calibration and simulation testing process progressed, it was decided to calibrate models for each individual year. After developing calibrated models for all three years, it became apparent that one model could be developed for representing all three years if SOD was adjusted for each year. Calibrating the model to each year reduced the error for representing water quality conditions for each individual year, but the final model that could be used for all three years had similar low error. This approach will allow the model to be more suitable for the objectives for this project. This process will be discussed later in the "Model Calibration" section.

Water balance for specific calibration years was derived using daily Saluda Hydro releases and reservoir storage changes to back-calculate total daily inflows. Measured inflows were subtracted from total inflow, and the remainder of total inflow was apportioned by drainage area among the local inflows.

Water quality data collected by SCDHEC in the Lake Murray watershed were used to develop model inputs. Data collected in Lake Murray and the releases from Saluda Hydro by SCDHEC, USGS, and SCE&G and in 1992, 1996, and 1997 were used to calibrate the model.

The model was calibrated using available data to address the objectives—this approach was used since there were a lot of data available on Lake Murray and its inflows and outflows.

The following steps were taken to develop the model for Lake Murray:

- Obtained additional available data that have not already been placed in the Lake Murray database (e.g., met data; bathymetry; continuous temperature and DO data on releases from Lake Greenwood, inflows to Lake Murray, the forebay of Lake Murray, and the releases from Saluda Hydro; inflow flow rates; water level elevation; and any additional water quality data that were not obtained for the 2002 water quality assessment on Lake Murray).

- Prepared model inputs using the water quality database.
- Added the McMeekin water withdrawal and discharge.
- Calibrated the model to the following data collected in 1992, 1996, and 1997: pool elevation; TP in the lake; chlorophyll a in the lake; temperature and DO in the lake and releases from Saluda Hydro.
- Estimated the reduction in SOD that would occur if nutrient loads were reduced in the watershed.
- Determined the sensitivity of the model results to various model inputs and assumptions to see how the model responded to a range of water quality management strategies and to test the robustness of the model.
- Predicted the effects of reduced nutrient loads on water quality issues stated in the objectives.
- Conducted model test runs to evaluate the model for achieving the objectives stated above.

5. W2 Model Inputs

Bathymetry

In the Lake Murray W2 model, the reservoir is represented as a single waterbody containing nine branches and three tributaries. The difference between a branch and tributary designation in the W2 bathymetry is that a branch has volume that is modeled, while a tributary is a point source and therefore has no volume to be modeled. Figure 5-1 illustrates how the Lake Murray watershed was divided into branches and tributaries. After the branches were defined, the computational grid was created by dividing the reservoir longitudinally into segments and vertically into layers. The layers in the Lake Murray model are all one meter in height, but the length and width of the cells vary. Figure 5-2 shows how

Lake Murray was segmented. Segment lengths ranged from 1.1 to 3.9 kilometers (0.7 to 2.4 miles).

An Excel-based program was used to calculate reservoir volume and to create the contour grid in conjunction with Surfer software. The grid used for the volume calculations was based on depth data collected by USGS during hydrographic surveys of Lake Murray in 1996 and 1997. While the USGS measurements for these data were extensive, the transecting pattern used during the survey did not capture enough data along the thalweg to re-create an accurate representation of the old river channel. An additional depth survey was performed in April 2003 to collect depth data along the thalweg. Areas of Lake Murray included in this additional survey were the Saluda River from Saluda Dam to Blacks Bridge, as well as most of the Little Saluda River embayment and the downstream end of some of the other larger embayments. The combination of the USGS depth data and the data collected during the additional survey in 2003 were used to create the model bathymetry grid. Figure 5-3 shows the results of this volume versus elevation calculation along with the volume-elevation curve for the bathymetry used in the final model.

Due to the objectives of the model, the accurate simulation of the timing of DO recovery in the hypolimnion resulting from fall turnover was critical. The Lake Murray grid was adjusted during the calibration process to specifically improve the timing of fall turnover in the model. The reasoning for this adjustment is discussed further in the temperature calibration section of this report. The difference between the original bathymetry and the adjusted bathymetry can be seen in Figure 5-3. The plan view of the model grid is shown in Figure 5-4, and the side views of the model grid for each branch are shown in Figure 5-5 and Figure 5-6.

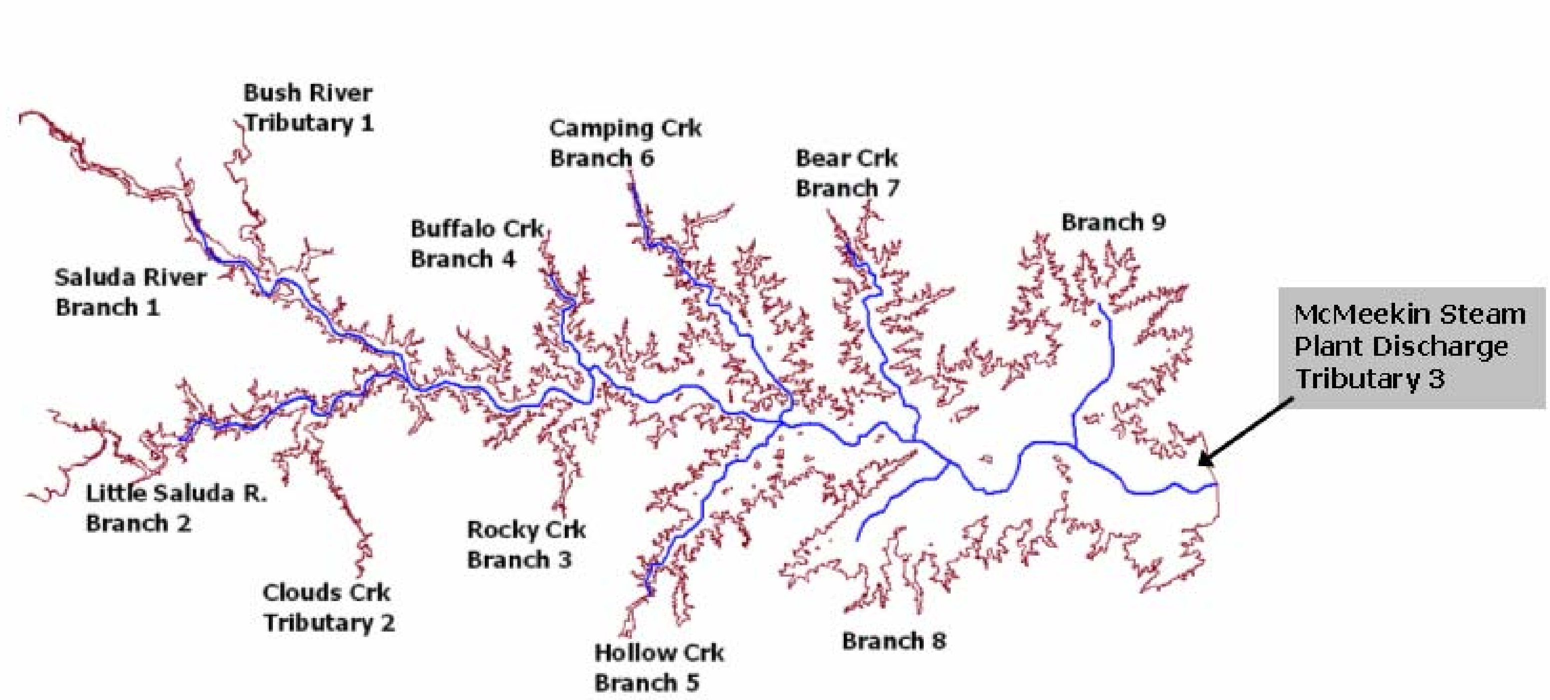


Figure 5-1. Plan view of Lake Murray with all Branches and Tributaries that are Included in the Model

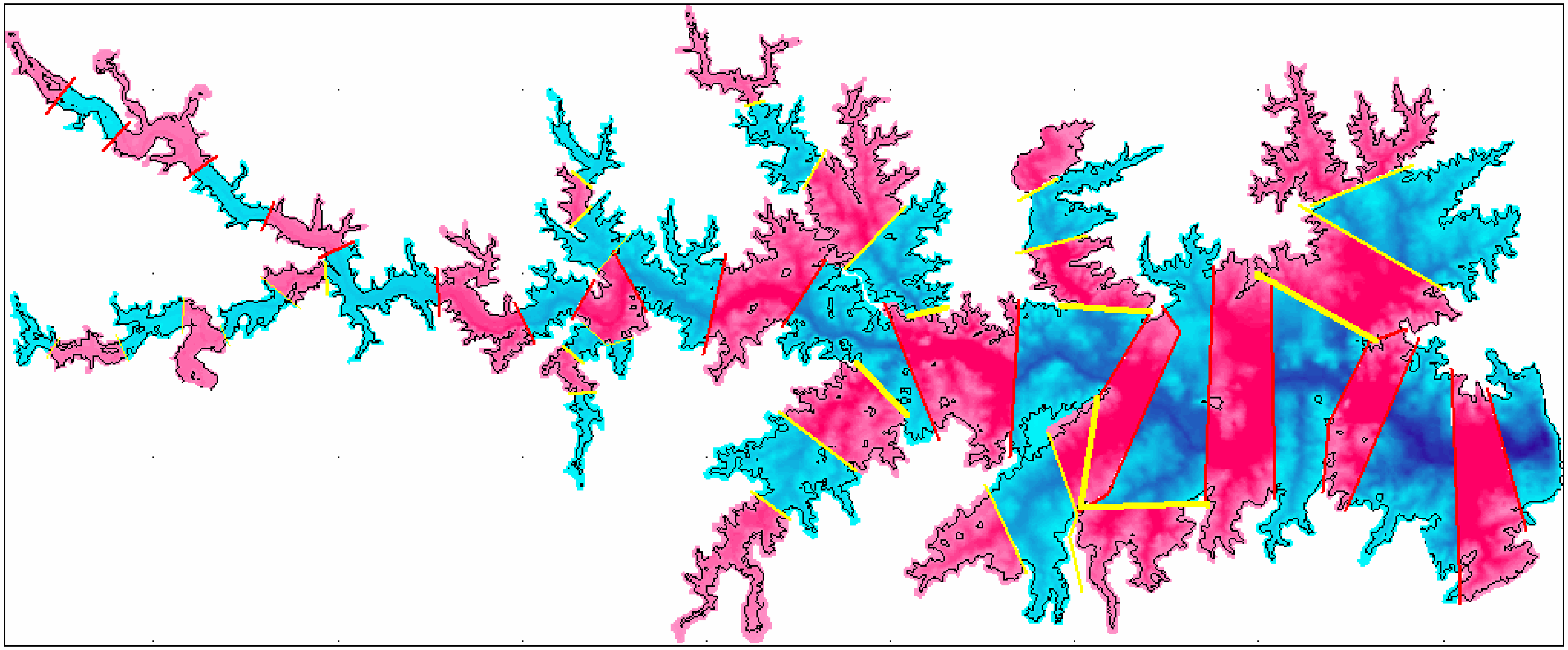


Figure 5-2. Plan View of Lake Murray Showing CE-QUAL-W2 Segmentation

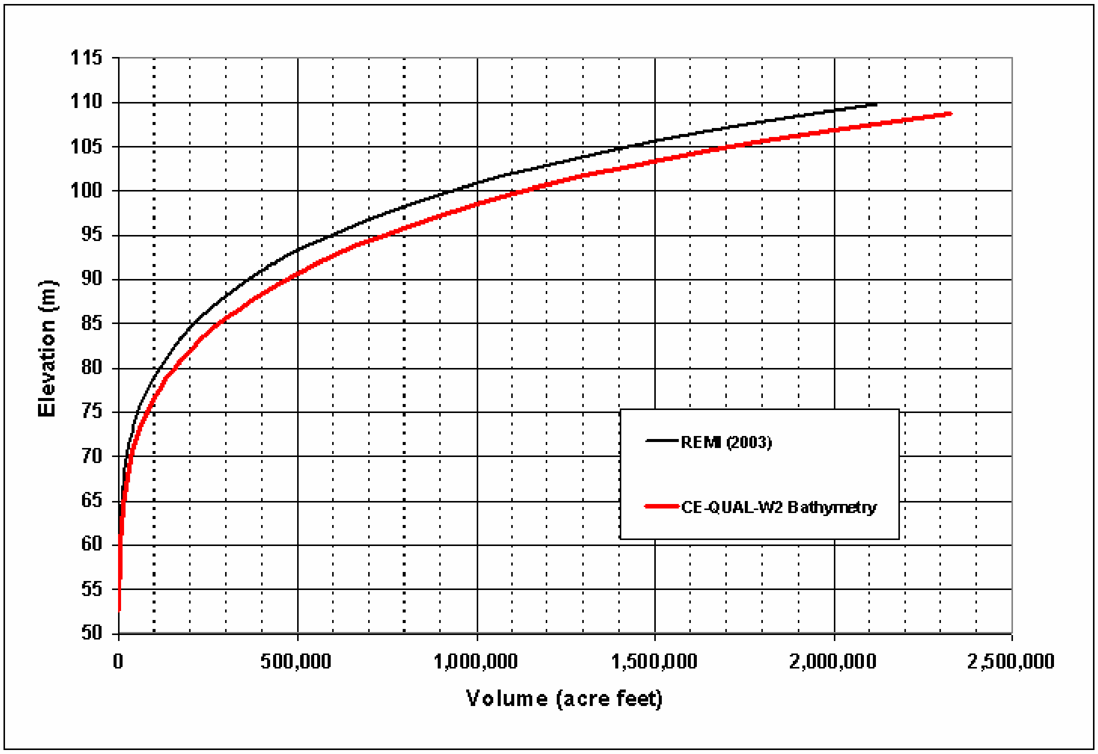


Figure 5-3. Lake Murray Volume-Elevation Curves

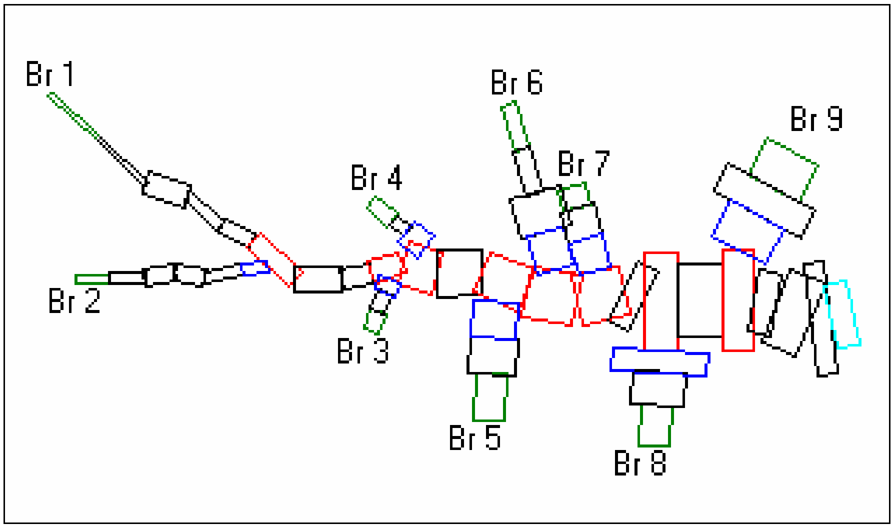


Figure 5-4. Plan View of Lake Murray Bathymetry

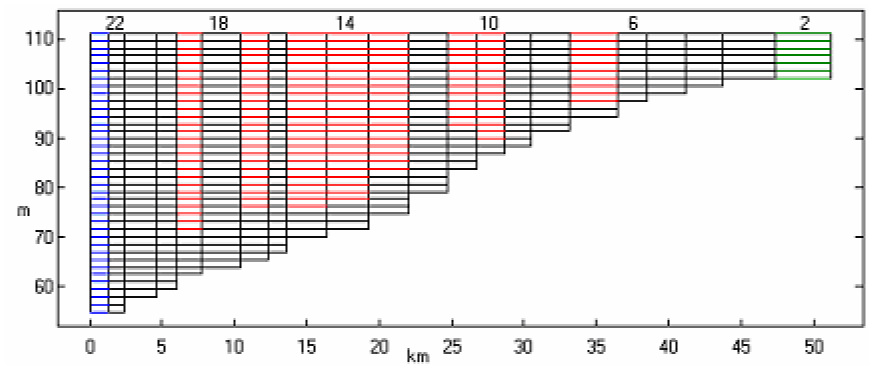


Figure 5-5. Side View of CE-QUAL-W2 Bathymetry for the Main Branch (Branch 1) of Lake Murray

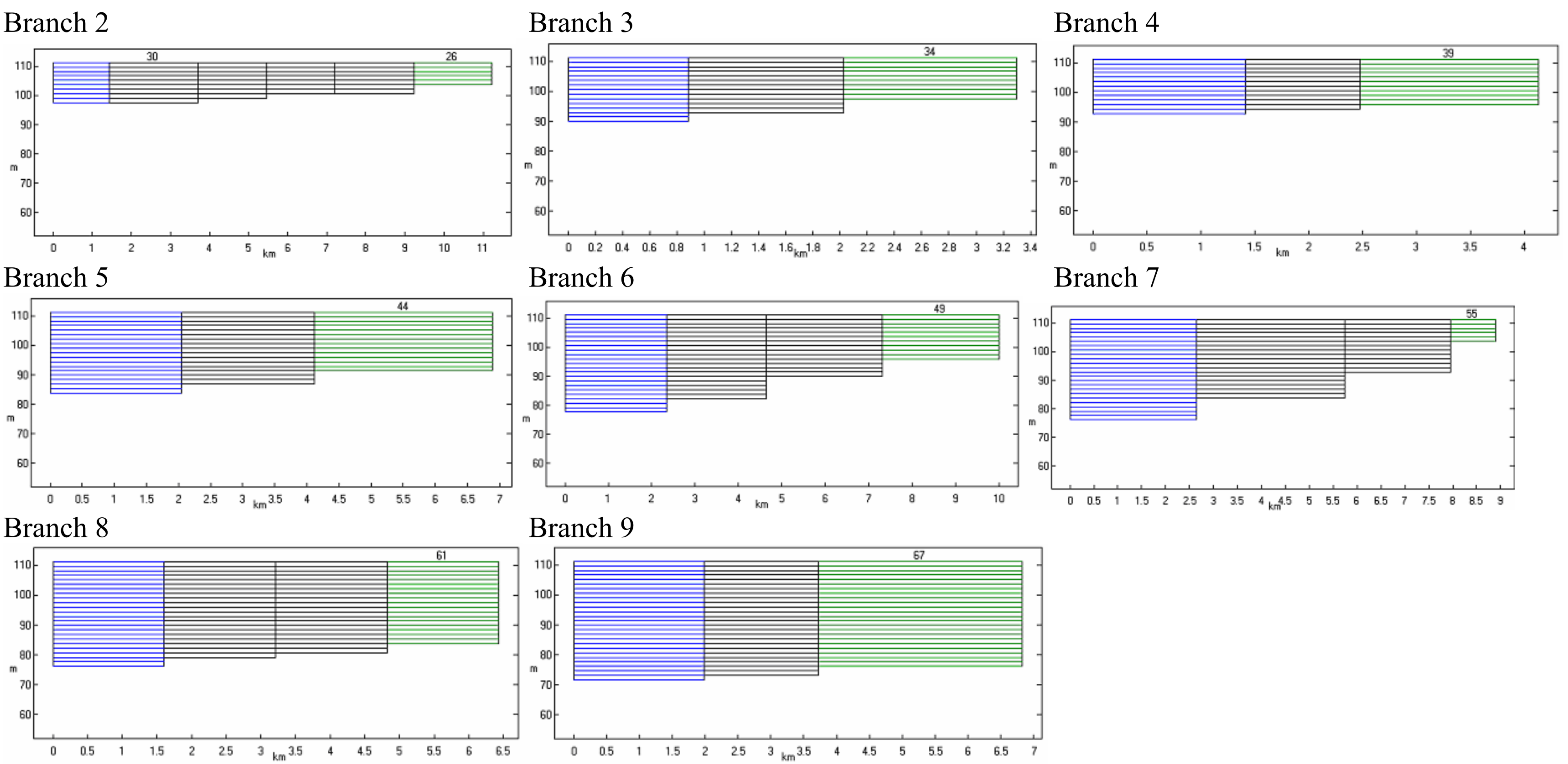


Figure 5-6. Side View of CE-QUAL-W2 Bathymetry for Lake Murray Branches 2-9

Inflows

In the Lake Murray model, the inflows are broken down into specific branch inflows, specific tributary inflows, and distributed tributary inflows. A branch inflow is a direct inflow into the upstream end of a branch. A tributary inflow is a point source inflow to some designated segment within a branch. A distributed tributary inflow is an inflow that is distributed among all segments of a branch. This inflow is put into the surface layer of the model, and the amount of flow entering each segment is proportional to its surface area.

To model the water surface of the reservoir, inflows for all years modeled were back-calculated by using the average daily discharge from Saluda Hydro, as measured at the gage 2500 feet downstream of the dam, and the daily change in reservoir volume. In cases where a USGS gage was installed on an inflow, that flow was subtracted from the total inflow needed to match the water surface and any remaining flow after all measured inflows were subtracted was distributed among the ungaged inflows according to proportion of drainage area. Figure 5-7 shows the location of the USGS gages used in the model. By distributing the remaining flow among the ungaged inflow, any errors in measured flows or water surface elevations were absorbed in the unmeasured local inflows, and evaporation and direct precipitation onto the lake were accounted for as well. Gaged inflows account for a large portion of the total inflow to Lake Murray so, at times, the sum of the gaged inflows exceeded the total inflow needed to maintain a reasonable match between the observed and modeled water surface. To prevent negative inflows during these times, gaged inflows were adjusted.

The Lake Murray watershed as highlighted in Figure 2-1 is 1,252 square miles. This drainage area had to be divided so that inflows to Lake Murray could be distributed in a way that would best represent flows entering Lake Murray. Figure 5-8 shows the sub-watershed boundaries used to proportion inflow by drainage area, and lists the drainage areas of the sub-watersheds. Once the drainage areas of these sub-watersheds were measured, the local inflow was apportioned accordingly. Each of these sub-watersheds has a unique flow time-series, and Table 5-2 lists the basis of how these time-series were created. One exception to the table is that, prior to May 21, 1992, the model inflow for the Little Saluda River was treated as an ungaged inflow and was therefore included in the distribution of the calculated local inflow according to drainage area. This was done since the USGS gage on the Little Saluda was not operational before this date. Flows measured in 1992, 1996, and 1997 at the four gages used in the model are shown in Figure 5-9. These plots illustrate the inflow patterns for the three years modeled as well as how the inflow was distributed. Table 5-3 lists the annual flow as well as the percentage of the total flow for each of the inflows represented for each year modeled.

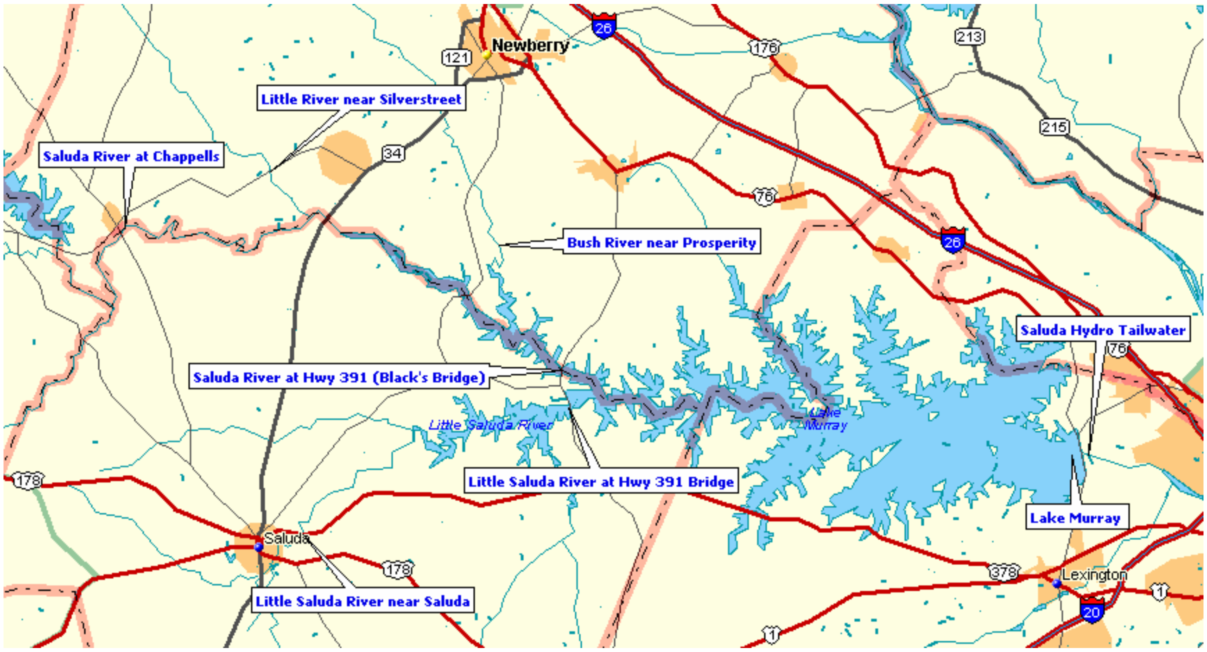


Figure 5-7. Map of Lake Murray Watershed Showing Location of USGS Monitors

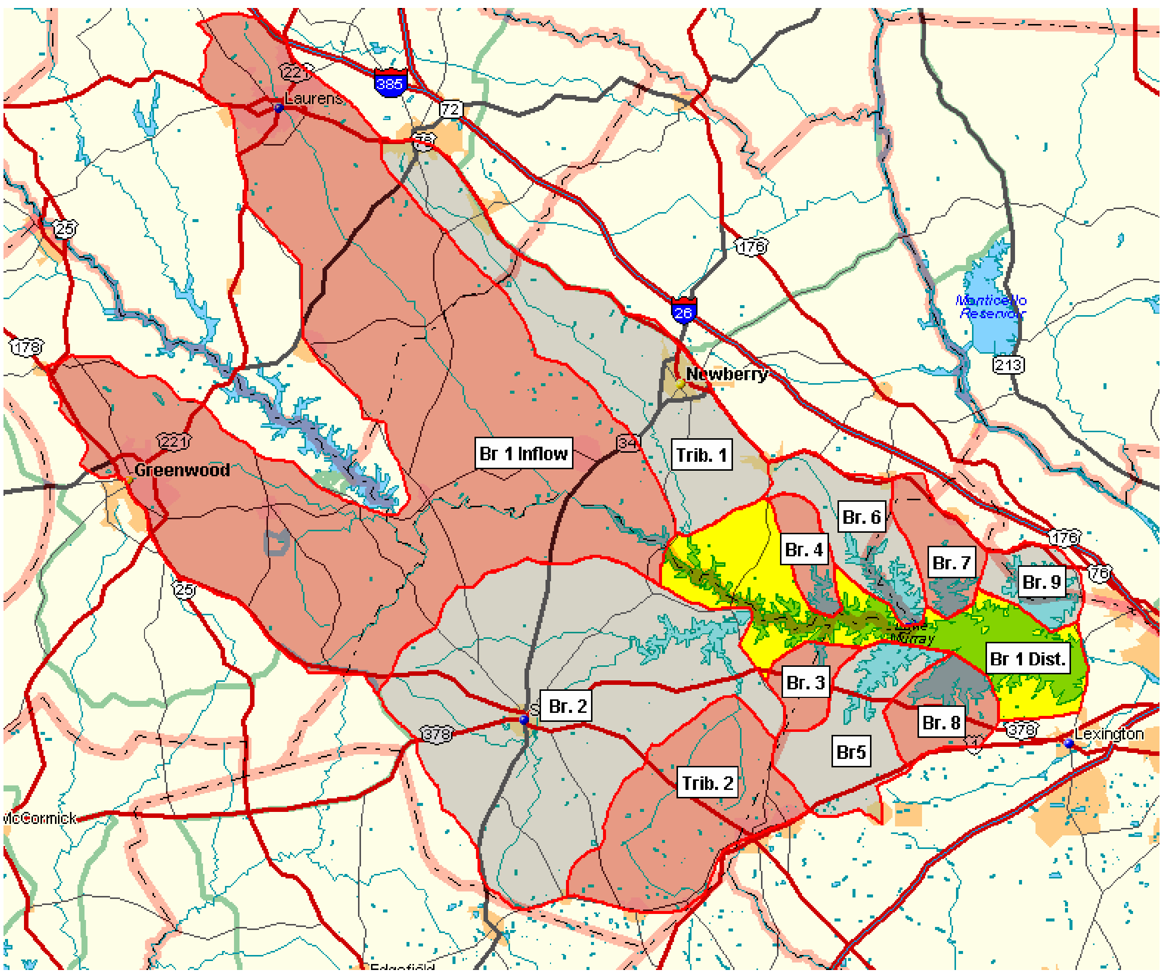


Figure 5-8. Map of Sub-watershed Drainage Area Boundaries

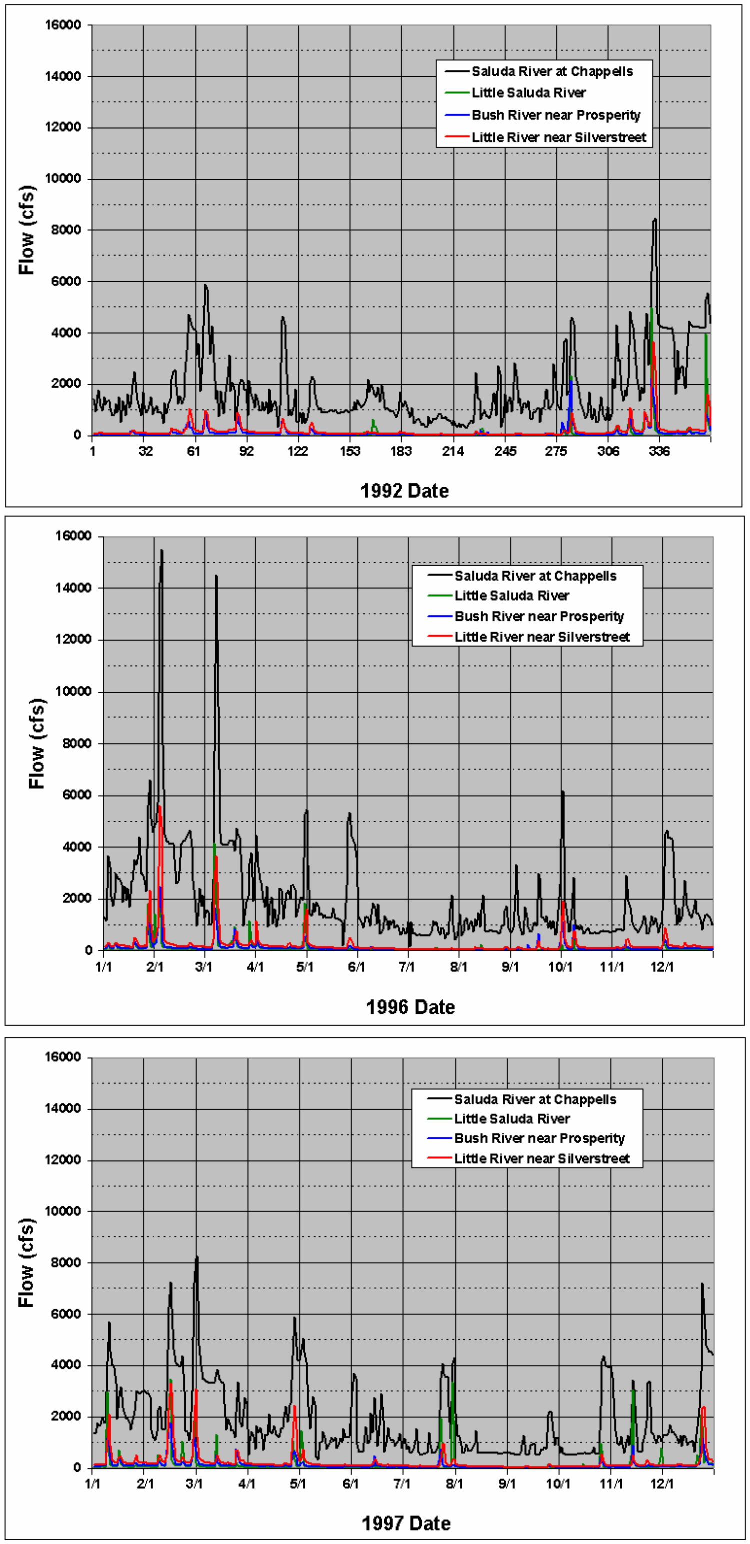


Figure 5-9. Inflow to Lake Murray for 1992, 1996 and 1997

Table 5-1. Drainage Areas of Inflows to the Lake Murray CE-QUAL-W2 Model

Location	Drainage Area (Square Miles)
Saluda River at Inflow to Lake Murray	1,686
Saluda River at Inflow to Lake Murray - not including upstream of Buzzard's Roost Dam (Branch 1 Inflow)	516
Bush River (Tributary 1)	115
Little Saluda River (Branch 2)	245
Clouds Creek	88
Rocky Creek (Branch 3)	15
Buffalo Creek (Branch 4)	15
Hollow Creek (Branch 5_	48
Camping Creek (Branch 6)	39
Bear Creek (Branch 7)	24
Branch 8	26
Branch 9	20
Remaining Local Inflow	101

Table 5-2. Description of Inflow to the Lake Murray CE-QUAL-W2 Model

Inflow	Description	Source of Flow	Comment
Branch 1 Boundary	**Saluda River Inflow to Lake Murray**	Saluda River gage at Chappells + Little River gage near Silverstreet + 16.5 % Calculated Local Inflow	This accounts for an estimated flow at the upstream boundary of the model
Branch 1 Distributed	**Local Inflow to Main Body of Lake Murray**	flow-ratio by drainage area	17.1 % of Calculated Local Inflow
Tributary 1	**Bush River Inflow to Lake Murray**	USGS Gage near Prosperity	1.0 * Bush River gage
Branch 2	**Little Saluda River Inflow to Lake Murray**	USGS Gage at Saluda	1.44 * Little Saluda R. gage
Branch 2 Distributed	**Local Inflow to Little Saluda Embayment**	flow-ratio by drainage area	19.9 % of Calculated Local Inflow
Tributary 2	**Clouds Creek Inflow to Lake Murray**	flow-ratio by drainage area	14.9 % of Calculated Local Inflow
Branch 3 Distributed	**Local Inflow to Rocky Creek Embayment**	flow-ratio by drainage area	2.6 % of Calculated Local Inflow
Branch 4 Distributed	**Local Inflow to Buffalo Creek Embayment**	flow-ratio by drainage area	2.5 % of Calculated Local Inflow
Branch 5 Distributed	**Local Inflow to Hollow Creek Embayment**	flow-ratio by drainage area	8.2 % of Calculated Local Inflow
Branch 6 Distributed	**Local Inflow to Camping Creek Embayment**	flow-ratio by drainage area	6.6 % of Calculated Local Inflow
Branch 7 Distributed	**Local Inflow to Bear Creek Embayment**	flow-ratio by drainage area	4.1 % of Calculated Local Inflow
Branch 8 Distributed	**Local Inflow to Unnamed Embayment**	flow-ratio by drainage area	4.5 % of Calculated Local Inflow
Branch 9 Distributed	**Local Inflow to Unnamed Embayment**	flow-ratio by drainage area	3.3 % of Calculated Local Inflow
Tributary 3	**McMeekin Steam Plant Discharge**	monthly average	assumed to be constant for entire month

Table 5-3. Annual Mean Flows for Inflows Included in the Lake Murray Reservoir Model

Location	1992		1996		1997	
	Mean Flow Used in Model (cfs)	% of Total	Mean Flow Used in Model (cfs)	% of Total	Mean Flow Used in Model (cfs)	% of Total
Saluda River at Inflow to Lake Murray	1,749	69.7	2,137	79.2	2,073	74.1
Bush River (Tributary 1)	108	4.3	126	4.7	121	4.3
Little Saluda River (Branch 2)	215	8.5	174	6.5	262	9.4
Clouds Creek	100	4.0	61	2.3	118	4.2
Rocky Creek (Branch 3)	18	0.7	11	0.4	12	0.4
Buffalo Creek (Branch 4)	18	0.7	10	0.4	12	0.4
Hollow Creek (Branch 5)	57	2.3	34	1.2	37	1.3
Camping Creek (Branch 6)	46	1.8	27	1.0	30	1.1
Bear Creek (Branch 7)	28	1.1	17	0.6	19	0.7
Branch 8	31	1.2	18	0.7	21	0.7
Branch 9	23	0.9	14	0.5	15	0.5
Remaining Local Inflow	119	4.7	70	3	79	2.8

Outflows

Dam Releases

The main outflow directly represented in the Lake Murray model was the flow that passes through the Saluda Hydro. Hourly discharge data used in the model came from the USGS gage 2500 feet downstream of Saluda Hydro. Detailed records of operations at Saluda Hydro were not available for any of the modeled years; therefore, unit operations were assumed based on typical operating practices during those years.

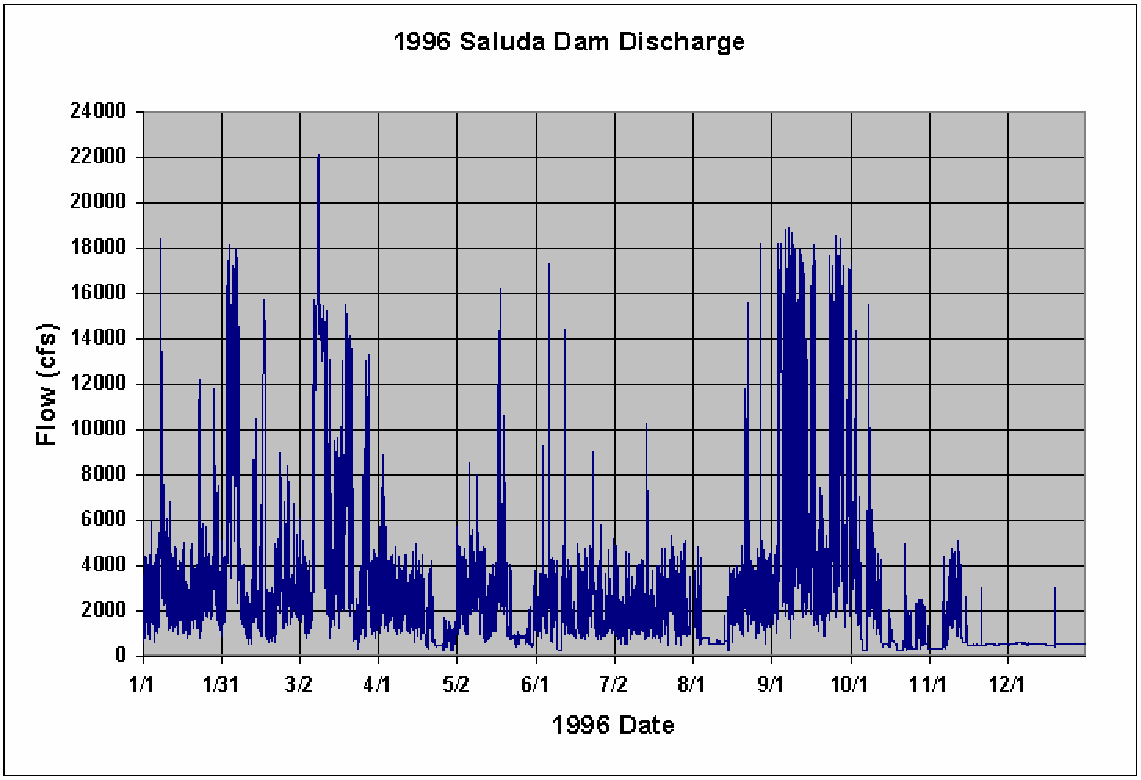
1. The first 9,600 cfs of discharge came from units 1, 3, and 4. These units were considered one outlet since data were not available that indicated which of the three units were operated.
2. Any discharge between 9,600 and 15,600 cfs was assumed to come from unit 5.
3. Any remaining discharge (i.e., >15,600 cfs) was assumed to come from unit 2.

Figure 5-10 illustrates this assumption by showing a plot of the hourly flow data from the USGS gage and the assumed distribution of discharge by unit for 1996.

McMeekin Steam Plant Cooling Water

The other withdrawal represented in the model was water that is circulated through McMeekin Steam Plant for cooling purposes. This water is withdrawn from the unit 4 penstock of Saluda hydro and, after circulating through the steam plant, was discharged into the unit 2 penstock. Since this water is withdrawn from the unit 4 penstock, the withdrawal in the model representing the McMeekin cooling water is not set up as a direct withdrawal. Instead, the amount of water being circulated through McMeekin is added to the amount released from Saluda Dam, resulting in the total withdrawal from the reservoir through the turbine intakes. The only flow information available for the circulation water through McMeekin was a monthly average and a monthly maximum intake/discharge value. In creating the flow time-series representing the model outflow, the monthly average flow was assumed to be constant for the entire month and was added to the hourly outflow time-series representing the units 1, 3, and 4 turbine releases.

When unit 2 at Saluda Dam is operating, the McMeekin discharge in the model was set to zero, since any discharge during unit 2 operations would be entrained by the turbine flow and would therefore not be discharged back into the lake. Table 5-4 presents temperature and flow information of the McMeekin circulating water for 1992, 1996, and 1997.



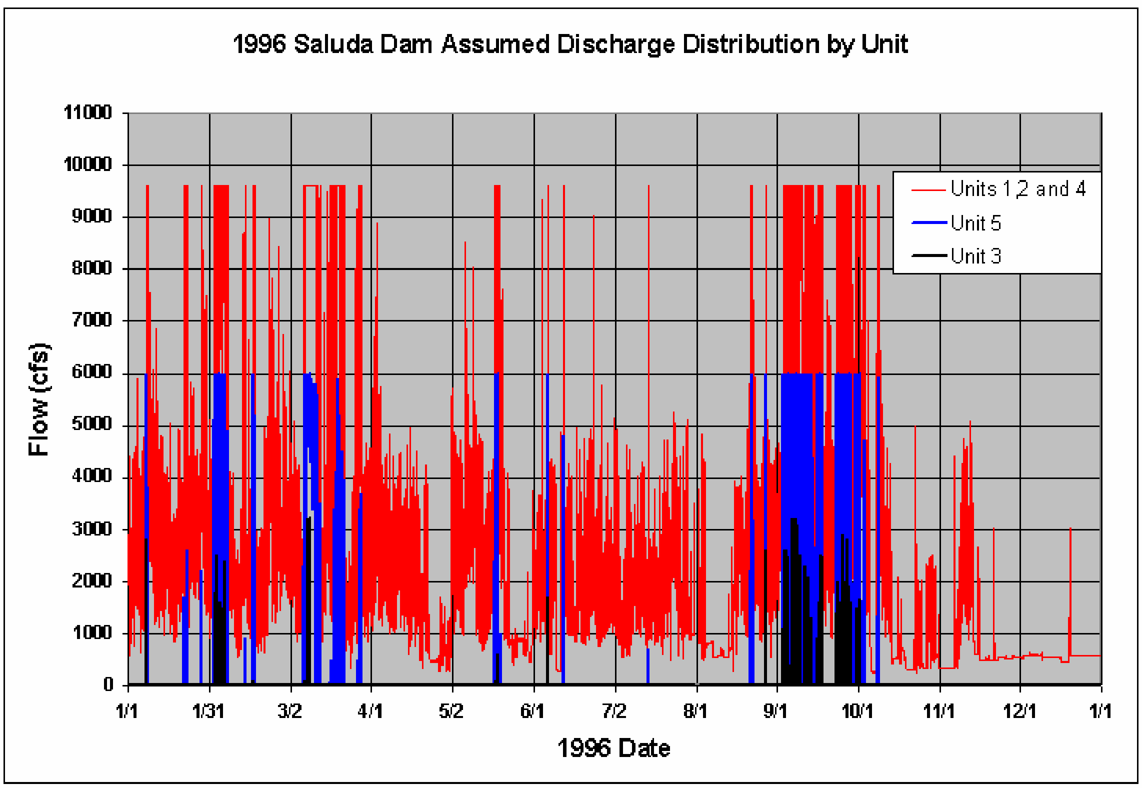


Figure 5-10. Hourly Discharge from Saluda Hydro and Assumed Flow Apportionment Among the Turbine Units

Table 5-4. Temperature and Flow Information for McMeekin Steam Plant for the Years 1992, 1996, and 1997

DATE	Discharge Temperature			Intake Temperature		Intake/Discharge Flow			
	Average °F	Average °C	MAX	Average °F	Max °F	Average (mgd)	Max (mgd)	Average (cfs)	Max (cfs)
Jan-92	65.5	18.6	74.5	51.5	54.0	163	163	252	252
Feb-92	62.3	16.8	66.5	49.0	49.0	163	163	252	252
Mar-92	66.0	18.9	71.5	51.0	53.0	163	163	252	252
Apr-92	67.7	19.8	71.5	53.0	54.0	159	163	246	252
May-92	68.5	20.3	75.5	54.0	55.0	163	163	252	252
Jun-92	69.5	20.8	75.5	56.0	57.0	163	163	252	252
Jul-92	72.2	22.3	75.5	57.0	58.0	163	163	252	252
Aug-92	72.2	22.3	78.0	58.0	59.0	163	163	252	252
Sep-92	76.4	24.7	80.0	60.0	61.0	163	163	252	252
Oct-92	78.4	25.8	80.0	62.0	63.0	90	163	139	252
Nov-92	76.2	24.6	84.0	62.0	65.0	106	163	164	252
Dec-92	65.3	18.5	78.5	54.0	59.0	163	163	252	252
Jan-96	63.9	17.7	79.4	49.0	51.9	163	163	252	252
Feb-96	61.6	16.4	68.5	46.6	47.4	163	163	252	252
Mar-96	62.7	17.1	71.4	48.4	50.8	163	163	252	252
Apr-96	66.1	18.9	70.4	50.7	51.6	163	163	252	252
May-96	69.8	21.0	74.3	52.9	53.8	163	163	252	252
Jun-96	71.3	21.8	76.0	54.9	55.8	163	163	252	252
Jul-96	73.2	22.9	77.7	56.6	57.6	163	163	252	252
Aug-96	74.1	23.4	80.9	58.2	59.1	155	163	240	252
Sep-96	76.6	24.8	83.5	60.9	62.8	82	82	126	126
Oct-96	78.0	25.6	86.9	64.4	66.3	82	82	126	126
Nov-96	76.2	24.6	84.0	62.4	66.4	126	163	195	252
Dec-96	68.0	20.0	81.1	55.4	57.7	163	163	252	252
Jan-97	63.1	17.3	74.3	50.1	52.0	114	163	177	252
Feb-97	59.5	15.3	65.2	48.2	49.4	82	82	126	126
Mar-97	63.0	17.2	69.3	50.2	51.2	163	163	252	252
Apr-97	67.0	19.4	72.3	52.9	53.9	163	163	252	252
May-97	68.7	20.4	74.7	55.4	56.8	163	163	252	252
Jun-97	72.4	22.4	80.0	58.6	60.0	163	163	252	252
Jul-97	77.4	25.2	83.8	61.1	62.7	163	163	252	252
Aug-97	80.5	26.9	87.0	63.6	64.4	163	163	252	252
Sep-97	83.3	28.5	88.7	65.3	66.5	163	163	252	252
Oct-97	83.3	28.5	87.7	66.5	67.3	84	163	130	252
Nov-97	83.3	28.5	87.7	66.5	67.3	54	163	84	252
Dec-97	70.0	21.1	76.1	55.7	57.9	163	163	252	252

Inflow Temperatures

The temperature of the inflows to the Lake Murray model was determined by analyzing historical temperature data collected at monitoring stations throughout the Lake Murray watershed. Temperature analyses for individual inflows are discussed in the following sections, and the plots presented in these sections show the data used to determine inflow temperature for all calibration and simulation model runs. Figure 3-1 presents the locations of the inflows and monitoring stations.

Monthly means of all temperature data collected at each monitoring station were calculated, and these monthly means were used as the basis for the temperature time-series for the respective inflow, except for the Saluda River, as will be discussed below.

Branch 1 - Saluda River Inflow into Lake Murray

Figure 5-11 shows the temperature data collected at two stations in the Saluda River upstream of Lake Murray. SCDHEC monitoring station S-295 is located at the Highway 39 bridge near Chappells, and S-047 is approximately three miles upstream of Lake Murray at the Highway 121 bridge. The monthly data from these two stations are plotted together to illustrate the temperatures observed in the Saluda River upstream of Lake Murray. This plot shows that temperatures at S-295 and S-047 are similar. The figure also illustrates the annual temperature pattern in the Saluda River upstream of Lake Murray. Since S-047 is closer to Lake Murray and is downstream of the Little River, it would normally be a more ideal location to use as the basis for the temperature of the Saluda River inflow to Lake Murray. However, in the twenty-two years prior to 1999, it was only sampled in 1992 and 1997; while S-295 was sampled every month from July 1988 through December 1998. Therefore, S-295 was used as the primary basis for the Saluda River inflow temperatures for all three calibration years. Figure 5-12 shows all temperature data observed at S-295 plotted by Julian Day along with the monthly mean and the model input time-series used for all modeled years.

Tributary 1 – Bush River Inflow into Lake Murray

SCDHEC station S-102 is located in the Bush River approximately 3.5 miles upstream of the Saluda River. SCDHEC monitored this station during the months of May-October since 1970, except for the years 1981, 1982, 1995, and 1996. The temperature data collected at this station were analyzed to estimate the temperature of the Bush River at the inflow to Lake Murray. The monthly averages of the May-October temperature data for the years of 1978-1997 were used in the model. These monthly averages as well as all temperature data collected at this station for the years 1978-1997 are plotted in Figure 5-13. The inflow temperature for the remaining months of the year was estimated based on temperature data collected in other inflows to Lake Murray. The same temperature time-series was used for all modeled years.

Branch 2 – Little Saluda River Inflow into Lake Murray

Temperature data collected at SCDHEC station S-123 were analyzed to estimate the temperature of the Little Saluda River at the inflow to Lake Murray. This station is located on the Little Saluda River approximately 3 miles upstream of Lake Murray and 14 miles upstream of the confluence of the Little Saluda and Saluda Rivers. In general, this station was sampled monthly starting in 1972, and the monthly averages of all temperatures observed during the years of 1978-1998 were used in the model. These monthly averages as well as all temperature data collected at this station for the years 1978-1998 are plotted in Figure 5-14. Temperature data collected in 1996 are highlighted in the plot to illustrate 1996 observed conditions. The same temperature time-series was used for all modeled years.

Tributary 2 – Clouds Creek Inflow into Little Saluda River Arm of Lake Murray

Temperature data collected at SCDHEC station S-255 were analyzed to estimate the temperature of Clouds Creek at the inflow to the Little Saluda Arm of Lake Murray. This station is located in Clouds Creek approximately 8.5 miles upstream of the Little Saluda River. Except for the years 1974, 1981, and 1982, temperature has generally been monitored during the months of May-October since 1973. The monthly averages of the May-October temperature samples for the years 1978-1997 were used in the model. These monthly averages as well as all temperature data collected at this station for the years 1978-1998 are plotted in Figure 5-15. The inflow temperature for the remaining months of the year was estimated based on temperature data collected in other inflows to Lake Murray. The same temperature time-series was used for all modeled years.

All Other Inflows into Lake Murray

Temperature data collected at SCDHEC station S-290 were analyzed to estimate the temperature of the inflow of the remaining branches and all distributed tributaries in the Lake Murray model. This station is located on Camping Creek approximately 11 miles upstream of the Saluda River. In general, this station has been sampled monthly since 1978, and the monthly averages of all temperatures observed during the years 1978-1998 were used in the model. These monthly averages as well as all temperature data collected at this station for the years 1978-1998 are plotted in Figure 5-16. Temperature data collected in 1996 are highlighted to illustrate 1996 observed conditions. The same temperature time-series was used for all modeled years.

Tributary 3 – Discharge from McMeekin Steam Plant into Saluda Hydro Unit 3

To simulate the effect that the McMeekin Steam Plant discharge has on temperature in Lake Murray a third tributary was added to the model. As mentioned earlier, the McMeekin cooling water is actually discharged into the Unit 2 penstock of Saluda Hydro. In the model, the discharge is treated as a point source to the most downstream segment of the model; which is the same segment where water is withdrawn for Saluda Hydro. This discharge is spread out over specified layers. The only temperature data available for the McMeekin discharge was monthly average and monthly maximum. In creating the temperature time-series for this discharge, the monthly average temperature was assumed to occur in the middle of each month and the discharge temperature value used in the model at any given time is based on linear interpolation between these mid-month values.

Simulation of the Effects of the McMeekin Thermal Discharge

The thermal discharge from McMeekin Steam Plant is discharged into the intake pipe for Unit 2. It was assumed that this warm water fills the intake pipe and moves upstream to where it is discharged into the lake. Since the water temperature of the thermal discharge is warmer than water in the hypolimnion, it rises as a plume until the temperature of the plume becomes the same as the water in the lake (i.e., the plume rises to the elevation of the layer of water in the lake that has the same temperature as the plume.) As the thermal plume rises it entrains cold water from the hypolimnion that dilutes the warm water in the plume; therefore, since the plume cools as it rises it does not rise as high as one might think given the temperature of the thermal discharge. Also, the water entrained by the plume is drawn from the hypolimnion so this entrainment serves to use colder water from the hypolimnion and reduce the volume of cold water in this lower body of water. These processes are described in Fischer, et al (1979).

CE-QUAL-W2 v 3.11 does not directly simulate the effects of thermal discharges to the bottom of lakes and the resulting rising thermal plume within the lake. Therefore, a tributary was placed in the model that would distribute the thermal discharge over a range of layers in the lake. This distribution was used to simulate the effects of the water actually entrained by the plume and then discharged into the lake where the plume temperature reaches a temperature similar to the water at some layer in the lake in the lower part of the metalimnion. In essence, the distributed thermal discharge was placed in the lower layers of the lake (i.e., between elevations 54 m and 90 m) to cause the hypolimnion to increase slightly in temperature to represent the cold water used through entrainment by the thermal plume.

To estimate the amount of plume dilution that might take place in the plume formed by the McMeekin thermal discharge, the following formulation was used

$$S = 0.089\, g'^{1/3} y^{5/3} / Q^{2/3}, \qquad \text{Fischer et al (1979), eq 10.5}$$

where S is the centerline dilution, $g' = g\, \Delta\rho/\rho$, ρ is the density of the discharge, $\Delta\rho$ is the density difference between the ambient fluid and the discharge fluid, g is the gravitational acceleration, y is the vertical distance above the thermal discharge, and Q is the discharge through the diffuser. This formulation strongly indicated that the thermal plume induced by the McMeekin discharge is pretty much diluted and becomes insignificant within about 30 m of rise from the bottom, i.e., before reaching about elevation 90 m and essentially the bottom of the metalimnion for most of the summer months.

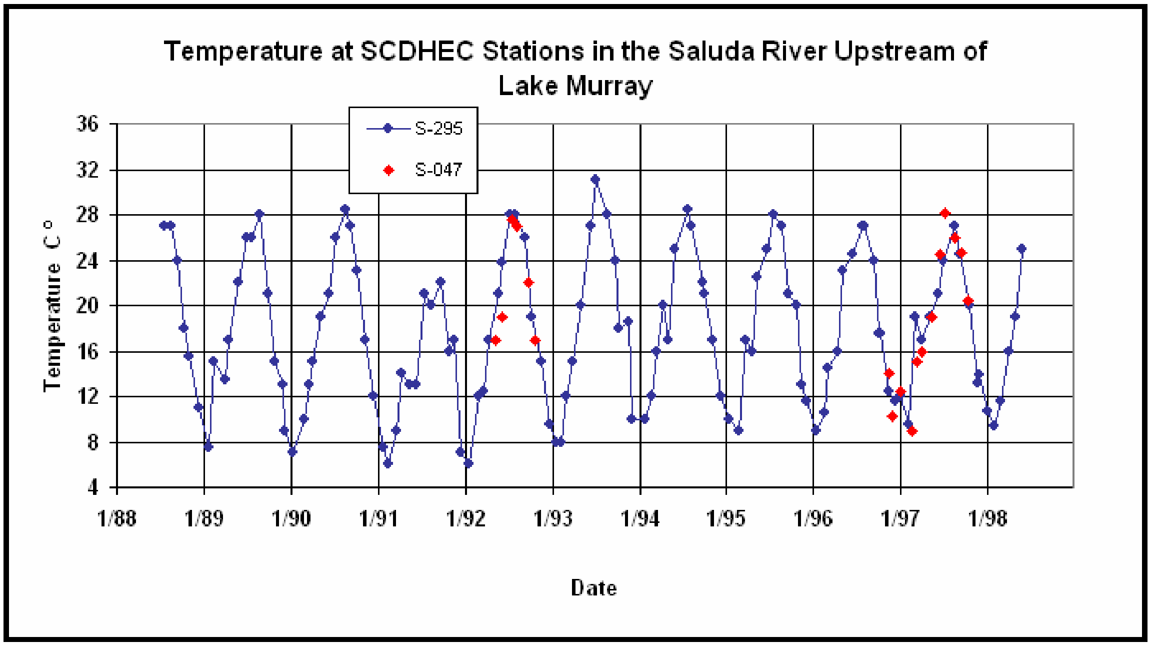


Figure 5-11. Temperatures Observed in the Saluda River Upstream of Lake Murray

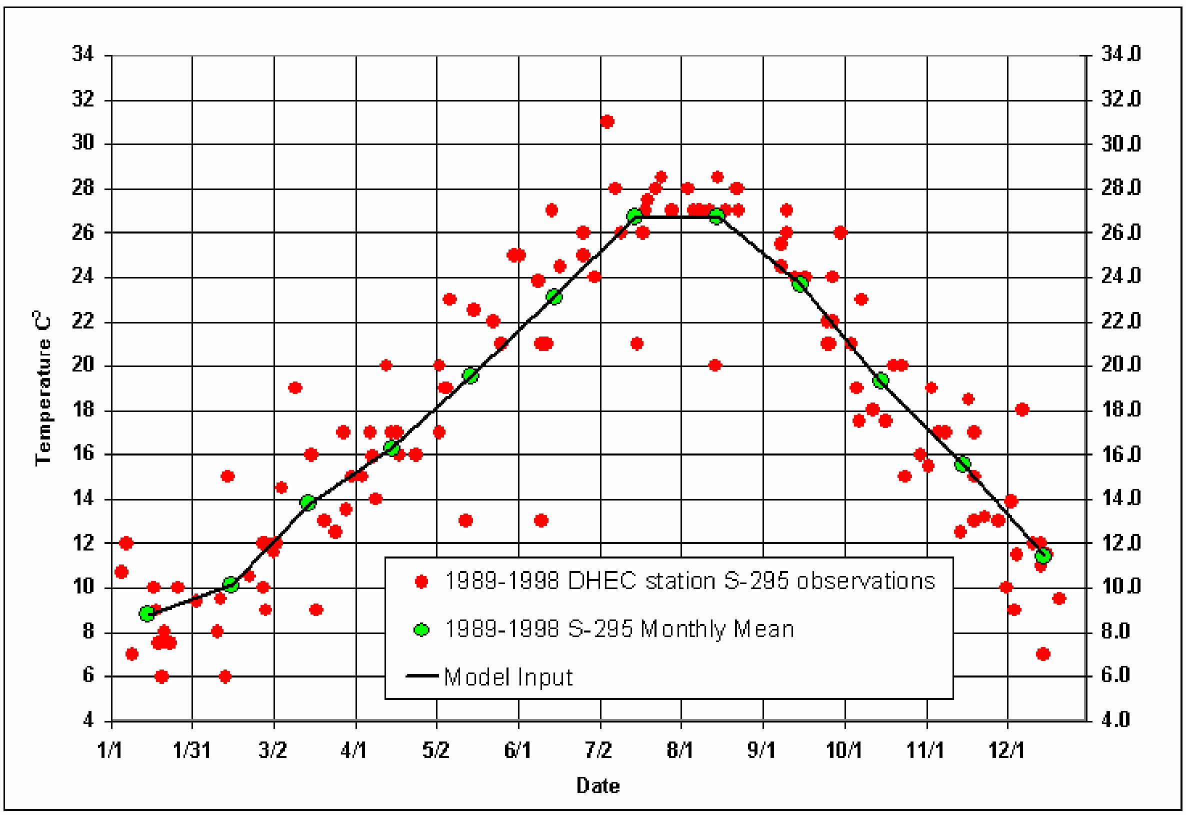


Figure 5-12. Inflow Temperature Analysis for Branch 1 (Saluda River)

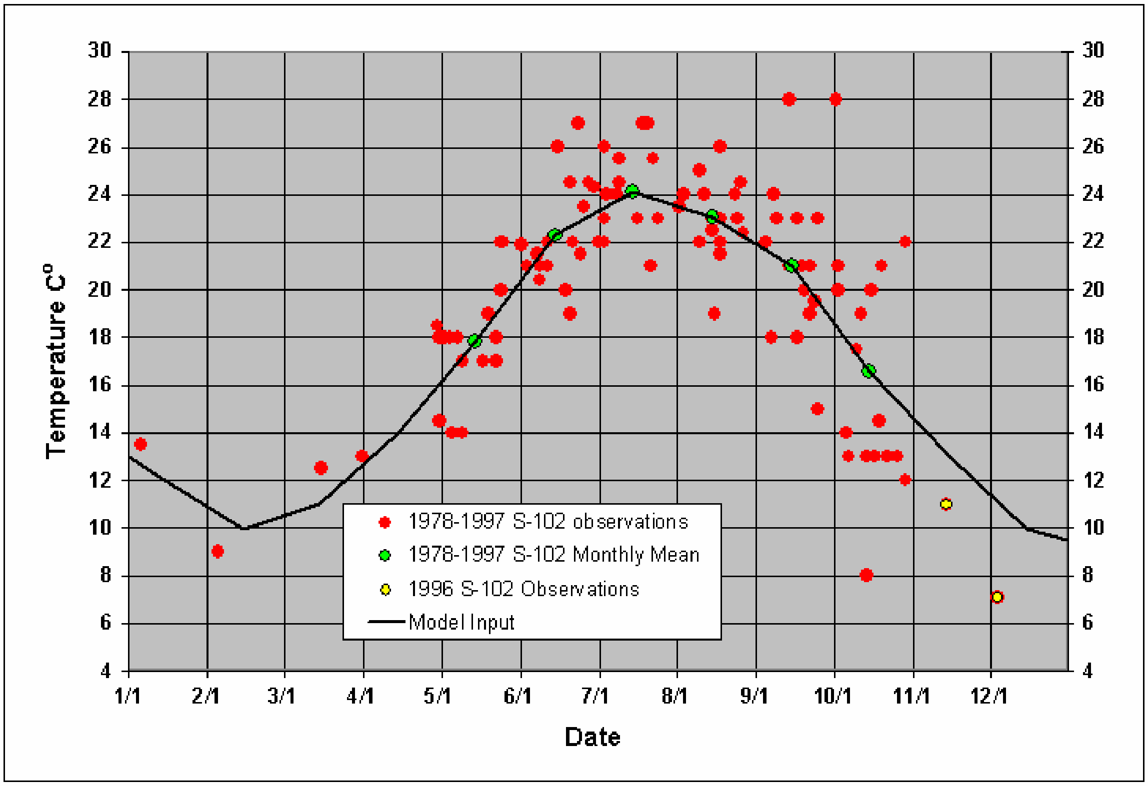


Figure 5-13. Inflow Temperature Analysis for Tributary 1 (Bush River)

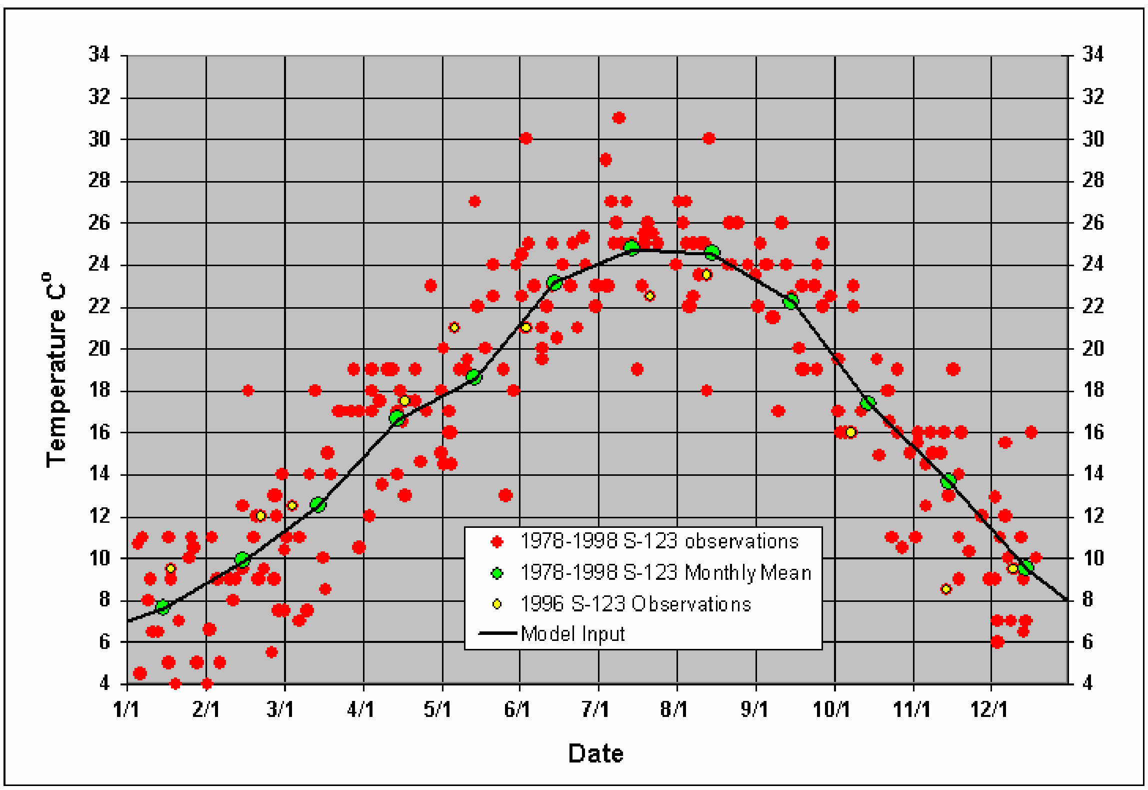


Figure 5-14. Inflow Temperature Analysis for Branch 2 (Little Saluda River)

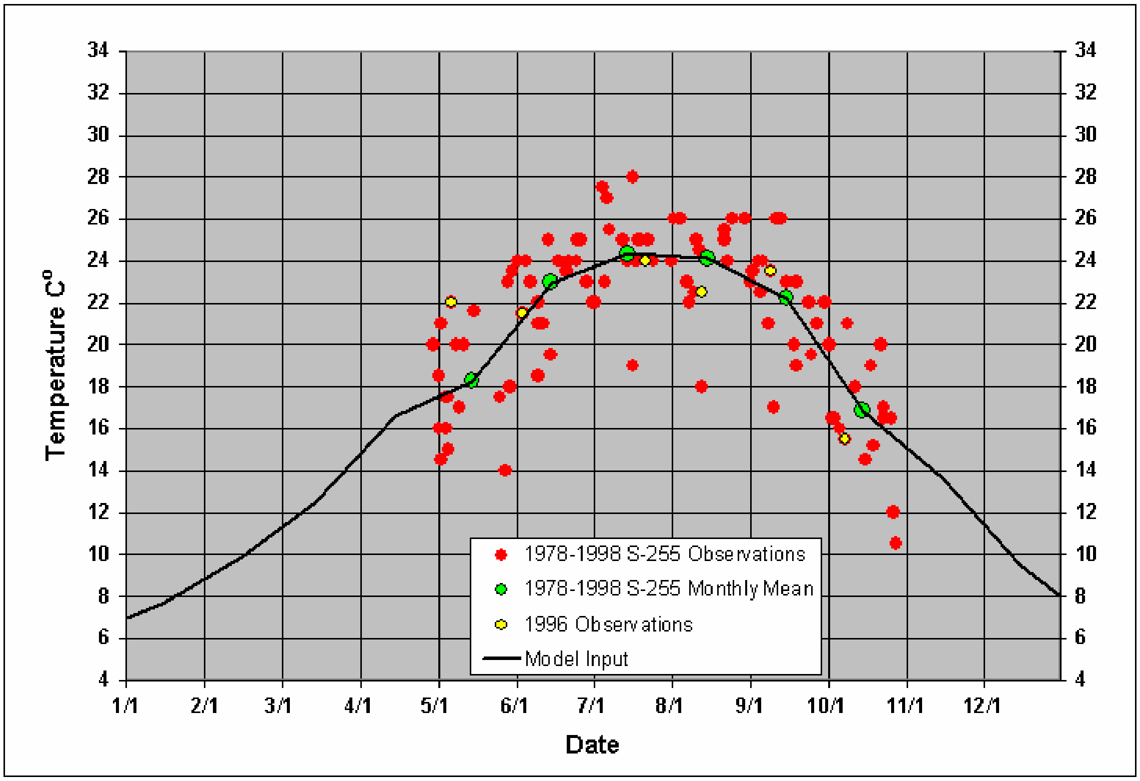


Figure 5-15. Inflow Temperature Analysis for Tributary 2 (Clouds Creek)

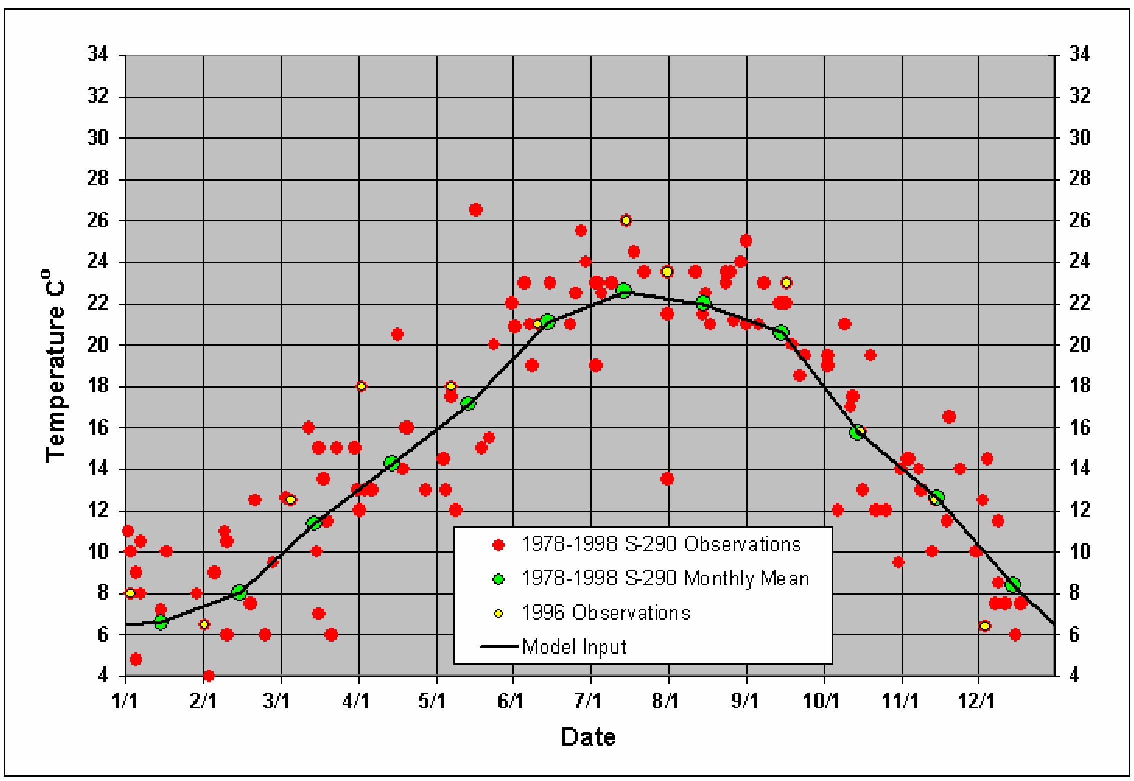


Figure 5-16. Inflow Temperature Analysis for Branches 3-9 and All Distributed Tributaries

Inflow Dissolved Oxygen

Like temperature, the DO time-series for inflows into Lake Murray were derived from monthly averages of historical DO data. Determination of the DO time-series used for each inflow in the Lake Murray model is discussed below. See Figure 3-1 for locations of monitoring stations where data were collected. A more detailed description of the location of each monitoring station can be found in the Inflow Temperature section of this report.

Branch 1 - Saluda River inflow into Lake Murray

Figure 5-17 shows all historical DO data collected at the two SCDHEC stations in the free-flowing section of the Saluda River upstream of Lake Murray. There does not appear to be any significant difference in DO between these two locations. Therefore, since much more DO data are available for S-295, the data from this station were used in determining the inflow DO time-series for the Saluda River. Figure 5-18 shows all DO data observed at S-295 plotted by Julian Day along with the monthly mean which is the basis for the model input DO time-series used for all modeled years.

All Other Natural Inflows

The DO time-series used for the remaining inflows was the monthly means from the monitoring station that best represented the inflow. The historical data and the model input for each inflow are shown in Figure 5-19 through Figure 5-22.

Tributary 3 – Discharge from McMeekin Steam Plant into Saluda Hydro Unit 3

Daily values were used to represent the concentrations of water quality constituents in the McMeekin discharge. It was assumed that water quality concentrations in the McMeekin Steam Plant discharge did not change as the water passed through the plant. Therefore, the model derived DO concentration every 24 hours at mid-night at the elevation of the McMeekin intake (unit 1 penstock) was used as DO concentration in the McMeekin discharge.

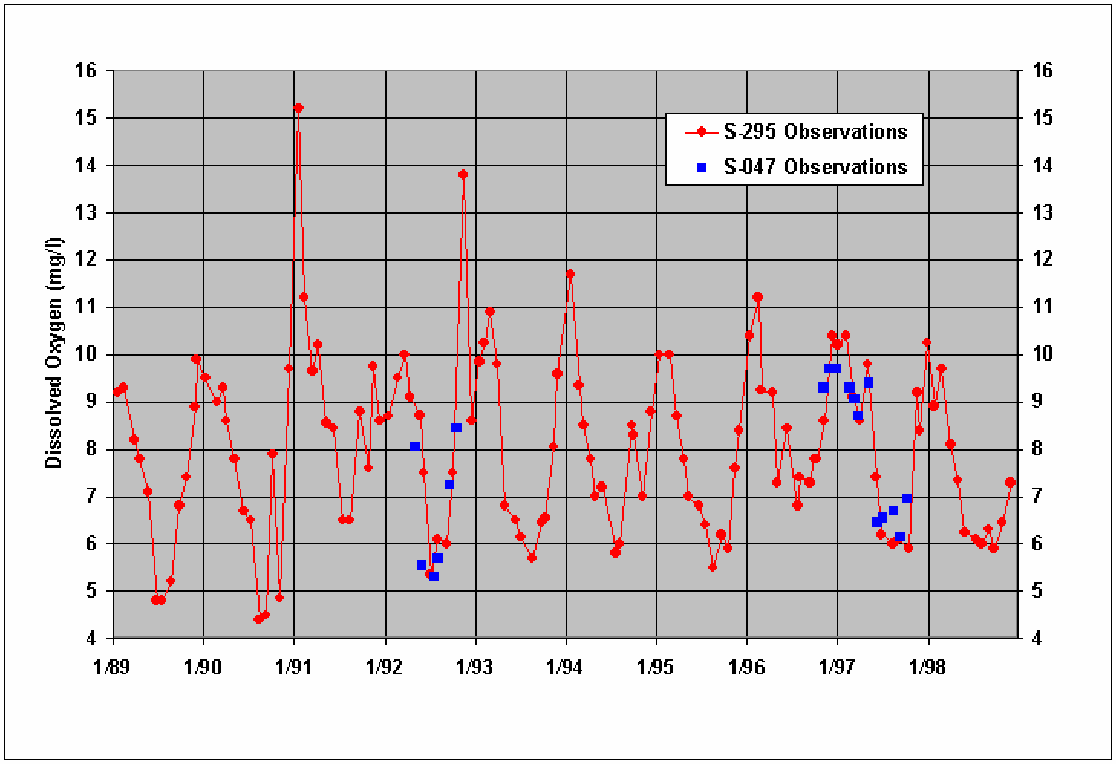


Figure 5-17. DO observed in the Saluda River Upstream of Lake Murray

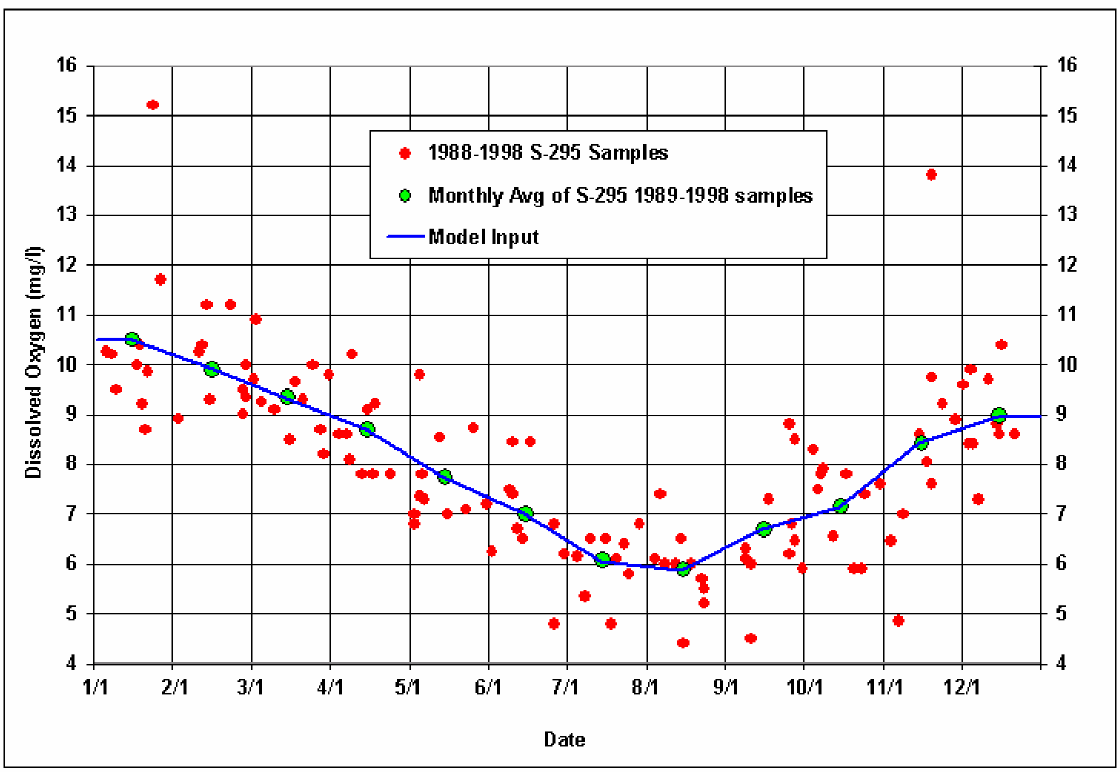


Figure 5-18. Inflow DO Analysis for Branch 1 (Saluda River)

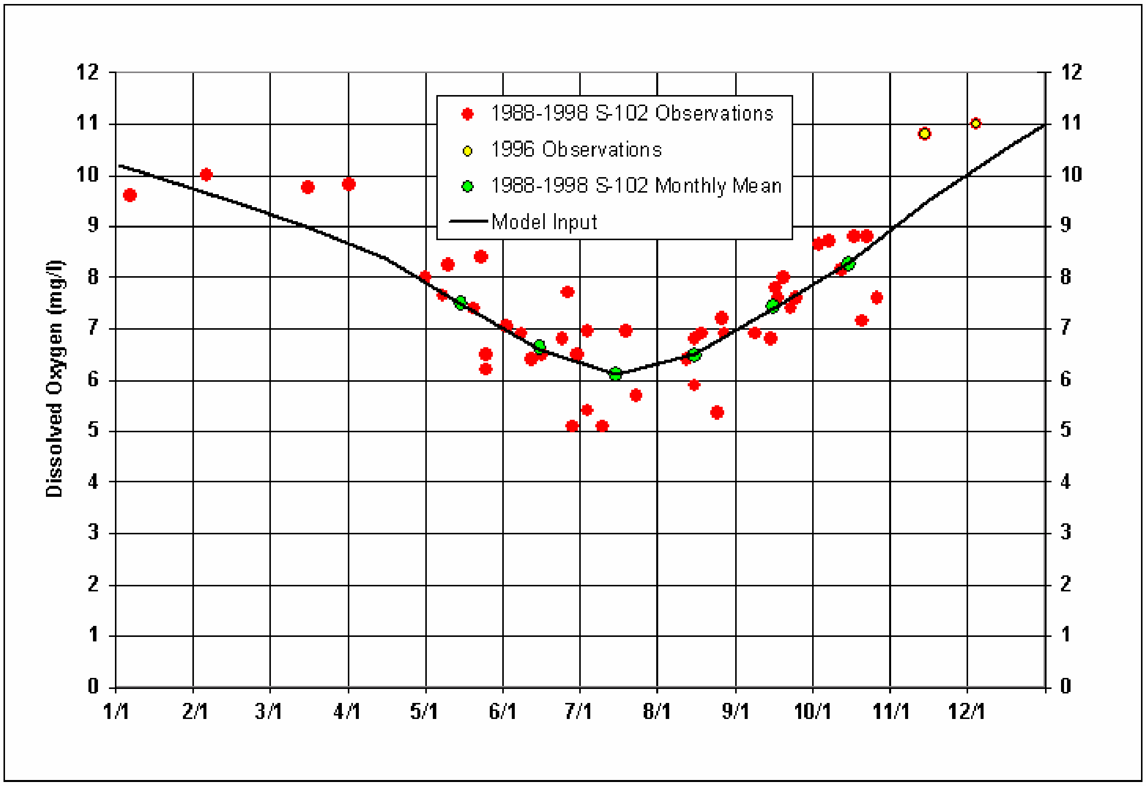


Figure 5-19. Inflow DO Analysis for Tributary 1 (Bush River)

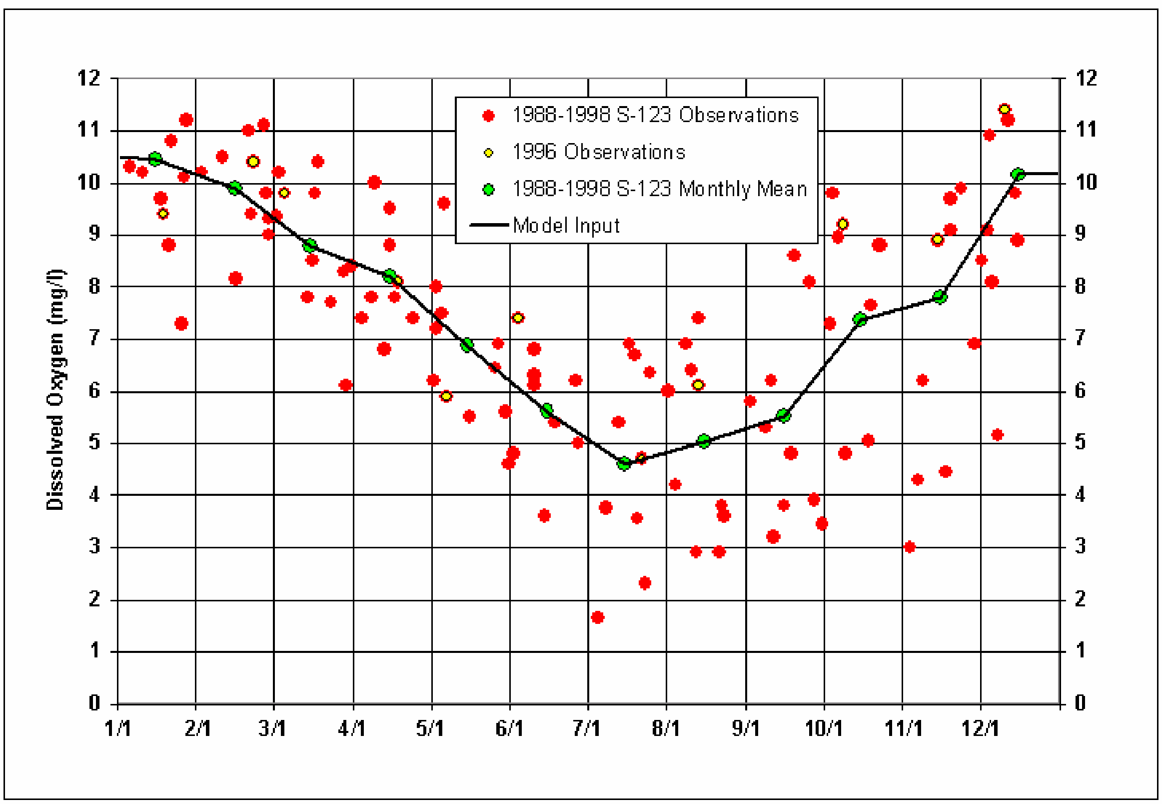


Figure 5-20. Inflow DO Analysis for Branch 2 (Little Saluda River)

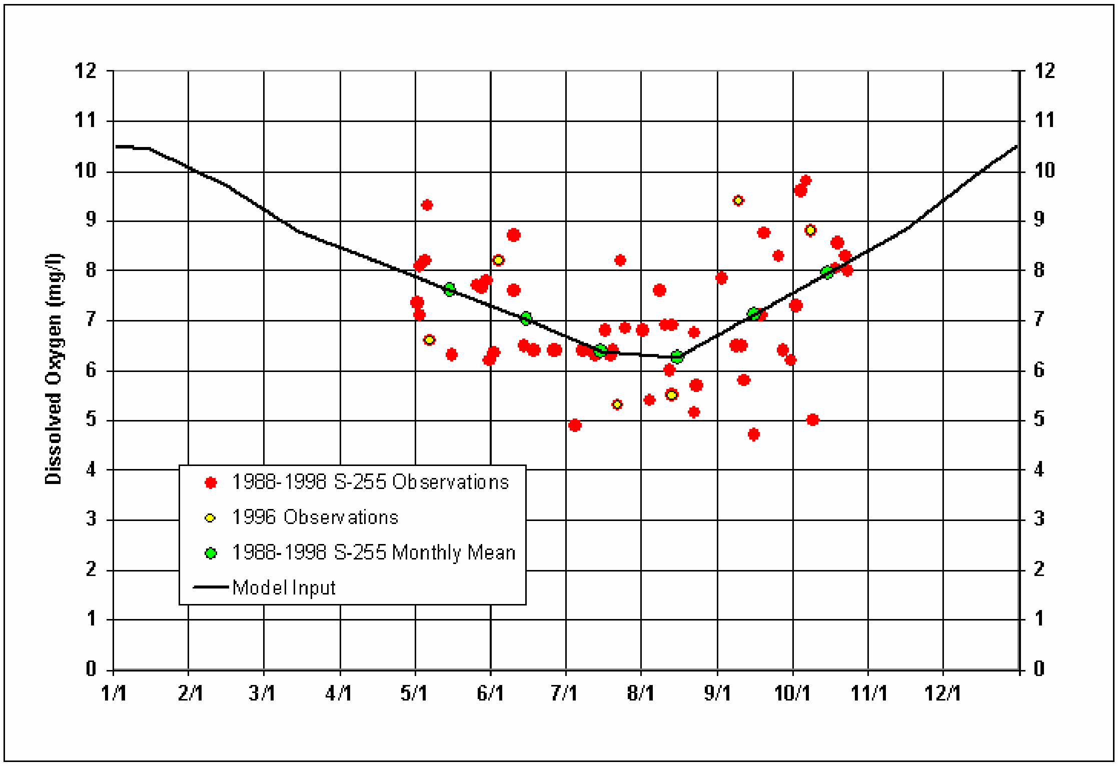


Figure 5-21. Inflow DO Analysis for Tributary 2 (Clouds Creek)

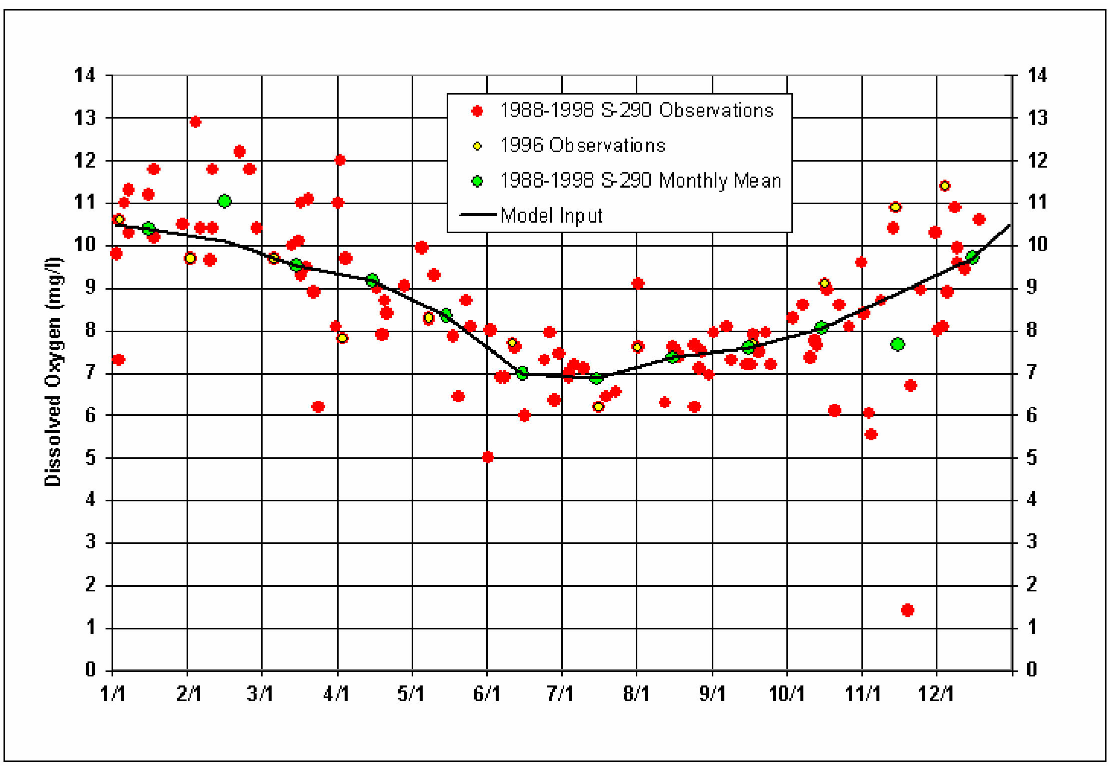


Figure 5-22. Inflow DO Analysis for Branch 3-9

Determination of Labile and Refractory Organic Matter and Nutrient Content of Organic Matter

Organic matter and its phosphorus and nitrogen content are important components in ecosystem models like CE-QUAL-W2. In the release version of W2 all organic matter is assumed to have the same nutrient content, i.e., ORGP and ORGN are the same for both labile and refractory matter.

Considering that special studies are required to fractionate organic matter into the labile and refractory components, it was necessary to develop a procedure to estimate the organic fractions.

To estimate refractory organic carbon (TOC_R) and labile organic carbon (TOC_L), these two equations were used:

$$TOC = TOC_L + TOC_R$$

$$TON = TON_L + TON_R$$

Where:

TON_L is the nitrogen content of labile organic matter, and TON_R is the nitrogen content of refractory organic matter.

Solving for these two equations:

$$TOC = TOC_L + TOC_R$$

$$(TON/TOC)*TOC = (TON_L/TOC_L)*TOC_L + (TON_R/TOC_R)*TOC_R$$

Where:

TON/TOC was calculated using available data;

$TON_L/TOC_L = 1/5.6$ (i.e., N/C = 8/45 or 7.2/40 from Wetzel, 2001; Bowie et al, 1985; Sterner and Elser, 2002); and

$TON_R/TOC_R = 1/50$ (Wetzel 2001) (also consistent with others)

Solving for TOC_L,

$$TOC_L = 6.31*(TON – 0.02*TOC)$$

Using available data collected by SCDHEC during the years 1989 through 1998, these equations were used to estimate the labile and refractory fractions of organic matter and the nutrient content of these fractions. The results are presented in Table 5-5. As mentioned previously, the code for the W2 model was revised to allow the use of ORGPL and ORGNL for labile organic matter, and ORGPR and ORGNR for refractory organic matter. Based on the above references, ORGPR was assumed to be 0.1*ORGPL and ORGNR was assumed to be 0.1*ORGNL.

To address the issue of luxury uptake by algae, especially for phosphorus, an iterative procedure was used to calculate ORGP by using the following equation and matching the phosphorus that was assumed to be in organic matter based on the data collected 1989 through 1998:

(Organic P—calc) = ORGP (LDOM + LPOM + adjROM),

where; adjROM was assumed to be 10% of calculated ROM, and calculated ROM was based on TOC and calculated TOC_L using the above equation (i.e., ROM = 2.2*(TOC- TOC_L). The figure 10% is based on observations in the differences between TON_L and TON_R, as well as other literature inferences (Sterner and Elser, 2002) and data from Everglade studies (Dierberg, 2003). Also, the 10% figure results in a robust estimate of adjROM considering there can be significant deviations without significant differences in the estimates for ORGP and ORGN.

For the purpose of estimating ORGP it is preferable to have data on ortho-phosphate (O-P) so that the phosphorus associated with organic matter can be estimated. Since O-P data were not available, estimates of O-P were developed based on experience in the Catawba-Wateree watershed. Using these estimates of O-P, ORGP was calculated for the inflow and release from Lake Murray and found to be 0.008 and 0.004, respectively. Considering that W2 allows only one value of ORGP to be used, an average of these two values was used for Lake Murray. Therefore, for the Lake Murray W2 model, ORGP was set to 0.006. After selecting this value, O-P was back-calculated for all the inflows to Lake Murray.

The estimated stoichiometric values for Carbon/Phosphorus in organic matter and the values of ORGP and ORGN used in the model are consistent with those presented by Wetzel (2001).

Table 5-5. Fractionation of Total Phosphorus Data to Account for Amount Tied up in Organic Matter

	Murray -Saluda River Inflow		Saluda R mouth -S-298--est for tailrace, acct for 12-mile Cr		Bush River				Murray -Little Saluda River Inflow		Murray -Cloud Cr Inflow		Murray -Camping Cr Inflow	
	all years	Basis	all years	Basis	1992	1996	1997	Basis	all years	Basis	all years	Basis	all years	Basis
TOC	4.30	Median 1988-1998	3.40	Estimated-S-298	6.00	6.00	6.00	Estimated S-102	7.75	Median 1989-1998-S-123	8.95	Median 1989-1998 S-290	8.95	Median 1989-1998 S-290
DOC	4.20	TOC reduced by 0.1			5.90	5.90	5.90	TOC reduced by 0.1	7.65	TOC reduced by 0.1	8.85	TOC reduced by 0.1	8.85	TOC reduced by 0.1
TP	0.050	Median 1988-1998	0.028	Estimated-S-298	0.620	0.450	0.440	Mean of calculated daily	0.140	Median 1989-1998-S-123	0.160	Median 1989-1998 S-255	0.120	Median 1989-1998 S-290
OP	0.020	Calculated	0.010	Estimated-S-298	0.552	0.382	0.372	Calculated	0.058	Calculated	0.105	Calculated	0.065	Calculated
TKN	0.40	Median 1988-1998	0.40	Estimated-S-298	0.61	0.61	0.61	Median 1989-1997 S-102	0.85	Median 1989-1998-S-123	0.60	Median 1989-1998 S-290	0.60	Median 1989-1998 S-290
diss TKN	0.36	TKN reduced by 10%	0.35	TKN reduced by 10%	0.55	0.55	0.55	TKN reduced by 10%	0.77	TKN reduced by 10%	0.54	TKN reduced by 10%	0.54	TKN reduced by 10%
NHx	0.06	Median 1988-1998	0.08	Estimated-S-298	0.08	0.08	0.08	Median 1988-1997	0.10	Median 1989-1998-S-123	0.05	estimated based on data	0.05	est. based on data S-290
NOx	0.29	Median 1988-1998	0.34	Estimated-S-298	1.32	1.32	1.32	Median 1989-1997	0.44	Median 1989-1998-S-123	0.305	Median 1989-1997 S-255	0.20	Median 1989-1998
NHx + NOx (TIN)	0.35	Calculated	0.42	Estimated-S-298	1.40	1.40	1.40	Calculated	0.54	Calculated	0.36	Calculated	0.25	Calculated
DTKN-NHx (DTON)	0.30	Calculated	0.27	Calculated	0.47	0.47	0.47	Calculated	0.67	Calculated	0.49	Calculated	0.49	Calculated
LOC	1.36	Calculated	1.70	Calculated	2.21	2.21	2.21	Calculated	3.23	Calculated	1.97	Calculated	1.96	Calculated
LDOM--calc	3.00	Calculated	3.75	Calculated	4.87	4.87	4.87	Calculated	7.10	Calculated	4.34	Calculated	4.31	Calculated
RDOM--calc	6.46	Calculated	3.73	Calculated	8.33	8.33	8.33	Calculated	9.95	Calculated	15.35	Calculated	15.38	Calculated
RDOM adj	0.65	Calculated	0.37	Calculated	0.83	0.83	0.83	Calculated	0.99	Calculated	1.53	Calculated	1.54	Calculated
TOM (using adj ROM))	5.04	Calculated	4.69	Calculated	11.29	11.29	11.29	Calculated	13.74	Calculated	9.14	Calculated	9.12	Calculated
TOM	11.03	Calculated	8.12	Calculated	19.48	19.48	19.48	Calculated	23.38	Calculated	23.36	Calculated	23.36	Calculated
TDOM (TOC*2.2)	9.46	Calculated	7.48	Calculated	13.20	13.20	13.20	Calculated	17.05	Calculated	19.69	Calculated	19.69	Calculated
ROC	2.94	Calculated	1.70	Calculated	3.79	3.79	3.79	Calculated	4.52	Calculated	6.98	Calculated	6.99	Calculated
%ROC	68.3	Calculated	49.9	Calculated	63.1	63.1	63.1	Calculated	58.3	Calculated	77.9	Calculated	78.1	Calculated
Org P--obs	0.0302	Calculated	0.0183	Calculated	0.0678	0.0678	0.0678	Calculated	0.0824	Calculated	0.0548	Calculated	0.0547	Calculated
Org P--calc	0.0302	Calculated	0.0183	Calculated	0.0678	0.0678	0.0678	Calculated	0.0824	Calculated	0.0548	Calculated	0.0547	Calculated
ORGP--determined so Org P--calc is ~ same as Org P--obs	0.006		0.0039		0.006	0.006	0.006		0.006		0.006		0.006	
Org N--obs	0.34	Calculated	0.32	Calculated	0.53	0.53	0.53	Calculated	0.75	Calculated	0.55	Calculated	0.55	Calculated
Org N--calc	0.34	Calculated	0.30	Calculated	0.77	0.77	0.77	Calculated	0.93	Calculated	0.62	Calculated	0.62	Calculated
ORGN	0.068		0.064		0.068	0.068	0.068		0.068		0.068		0.068	
N or P deficiency	Moderate P deficiency		Moderate P deficiency		No P deficiency	No P deficiency	No P deficiency		No P deficiency		No P deficiency		No P deficiency	
adj C/org P	55	Calculated	102	Calculated	38	38	38	Calculated	45	Calculated	49	Calculated	49	Calculated
TOC/org P	142	Calculated	186	Calculated	89	89	89	Calculated	94	Calculated	163	Calculated	164	Calculated
adj C/org N	5.5	Calculated	6.9	Calculated	5.5	5.5	5.5	Calculated	5.5	Calculated	5.5	Calculated	5.4	Calculated
TOC/org N	14.3	Calculated	12.6	Calculated	12.8	12.8	12.8	Calculated	11.7	Calculated	18.3	Calculated	18.3	Calculated
TN/TP	13.8	Calculated	26.4	Calculated	3.1	4.3	4.4	Calculated	9.2	Calculated	5.7	Calculated	6.7	Calculated
TIN/OP	17.7	Calculated	43.2	Calculated	2.5	3.7	3.8	Calculated	9.3	Calculated	3.4	Calculated	3.8	Calculated
TSS	8.20	est. using filtered turbidity	1.0	est. using C-W info	23.0	23.0	23.0	estimated using turbidity	24.0	est. using turb. -S-123	13.0	est. using turbidity	13.0	est. using turbidity
ash free TSS (VSS)	1.72	calculated	0.7	calculated	6.9	6.9	6.9	calculated	7.0	calculated	4.0	calculated	4.0	calculated
inorganic suspended solids	6.48	Calculated	0.3		16.1	16.1	16.1	Calculated	17.0		9.0		9.0	
Volatile S/TSS	21%	est. using C-W info	70%	est. using C-W info	30%	30%	30%	est. using C-W info	29%	est. using C-W info	31%	est. using C-W info	31%	est. using C-W info
Estimated LPOM	1.39	Calculated	0.57	Calculated	5.59	5.59	5.59	Calculated	5.64	Calculated	3.26	Calculated	3.26	Calculated
Estimated RPOM	0.17	Calculated	0.07	Calculated	0.69	0.69	0.69	Calculated	0.70	Calculated	0.40	Calculated	0.40	Calculated
POM, (TKN-dTKN)*C/N*2.2	0.49	Calculated	0.76	Calculated	0.74	0.74	0.74	Calculated	1.04	Calculated	0.72	Calculated	0.72	Calculated
POM, (TP-OP)*C/P*2.2	3.64	Calculated	4.12	Calculated	5.70	5.70	5.70	Calculated	8.10	Calculated	5.88	Calculated	5.85	Calculated
POM(P)/Volatile S	2.12	Calculated	5.88	Calculated	0.83	0.83	0.83	Calculated	1.16	Calculated	1.46	Calculated	1.45	Calculated

Inflow Phosphorus and Organic Matter

Phosphorus concentrations used for the inflows to the Lake Murray model were determined by analyzing TP data collected at SCDHEC monitoring stations throughout the Lake Murray watershed. The model simulates the effects of dissolved phosphorus and various forms of organic phosphorus. Dissolved phosphorus which was determined based on the procedure described above for O-P is a direct input to the model through branch and tributary inflows, while organic phosphorus is included in the inflows as a part of the organic matter that is directly entered into the model. Organic matter inputs to the model are fractionated into labile dissolved organic matter (LDOM) and labile particulate organic matter (LPOM) as well as refractory dissolved organic matter (RDOM) and refractory particulate organic matter (RPOM).

TP measurements include phosphorus that is associated with various kinds of organic and inorganic matter which is not immediately available for algal use in CE-QUAL-W2. Dissolved phosphorus that is available for algal growth was estimated for the inflow inputs by subtracting the amount of phosphorus in the organic matter from the TP values. It should be noted that in CE-QUAL-W2 phosphorus associated with the various forms of organic matter is eventually released to the water as the organic matter is oxidized; therefore, much of the phosphorus in organic matter is made available for algal growth, especially that phosphorus associated with LDOM. Refractory organic matter oxidizes slowly, so much of it does not become available for algal growth since the unoxidized portion passes through Lake Murray. Particulate organic matter (POM) settles in the water column of the lake, so much of the phosphorus associated with POM does not become available for algal growth in the surface layer of the lake in the model.

The calculations used to apportion the TP between the various fractions of organic matter and dissolved phosphorus in each inflow are shown in Table 5-5. The resulting dissolved phosphorus time-series used in each of the inflows to the Lake Murray model are shown in Figure 5-23. Phosphorus and organic matter analyses for the primary inflows are discussed in the following paragraphs. A more detailed description of the location of each monitoring station can be found in the Inflow Temperature section of this report.

Branch 1 - Saluda River Inflow into Lake Murray

Figure 5-24 is a plot of TP data collected in the years 1989 through 1998 in the free-flowing section of the Saluda River between Buzzards Roost Dam and Lake Murray. As mentioned in the inflow temperature discussion station because it is closer to Lake Murray S-047 would better represent the inflow to Lake Murray, but data collection at this station was limited to only two years. In Figure 5-25, all the TP data collected at S-295 for the years 1989-1998 is plotted by Julian Day along with the average for each month. Since there did not appear to be a dominant annual pattern in the TP data, the median of all the data was used as the basis to calculate the dissolved phosphorus input for the model. The median of the TOC, TKN, nitrate, and ammonia data collected at the same location were also used to calculate the LDOM, LPOM, RDOM and RPOM in the Saluda River inflow. As shown in Table 5-5, the phosphorus in the organic matter was calculated to be 0.030 mg/L, which was then subtracted from the median TP to calculate the constant dissolved phosphorus concentration of 0.020 mg/L used in the model for the Saluda River inflow.

Tributary 1 – Bush River Inflow into Lake Murray

All of the inflows were analyzed to determine if there was a relationship between flow and TP, but only the Bush River was found to have such a relationship. Figure 5-26 illustrates the relationship found between TP measured in 1997 at station S-102 and flow measured on the same day at the USGS gage located approximately 2 miles upstream. Data for 1997 were used because it was the only year in which TP was measured at this station every month. The regression equation resulting from this relationship was used to calculate a daily TP concentration for the Bush River for each of the years modeled, and monthly means were calculated from the daily values. Figures 5-27 through 5-29 show the calculated daily TP concentrations and the monthly means for 1992, 1996, and 1997, respectively.

Dissolved and particulate organic matter were calculated based on measured TP, TKN, ammonia, and nitrate data and an estimated TOC. These calculations showed that about 15% of the TP was associated with organic matter in the Bush River, so the monthly mean TP values calculated for each year using the regression equation were multiplied by 0.85 to develop the dissolved phosphorus time-series used in the model for each respective year.

Branch 2 – Little Saluda River Inflow into Lake Murray

LDOM, RDOM, LPOM, RPOM and phosphorus concentrations in the model inflow representing the Little Saluda River were estimated based on TOC, TP, TKN, ammonia, and nitrate data collected in the Little Saluda River at SCDHEC station S-123. TP data from this station observed between 1989 through 1998 are plotted along with the monthly mean in Figure 5-30. The TP observations from 1996 are highlighted on the graph to illustrate the variability between the monthly samples within one year. Since there appeared to be an annual pattern in the TP measured at this station, the monthly averages were used as the basis for the input to the model. As shown in Table 5-5, about 59% of the TP was associated with organic matter in the Little Saluda River, so the monthly mean TP values were multiplied by 0.41 to create the dissolved phosphorus time-series used in the model. The same dissolved phosphorus time-series was used for all years modeled and is plotted with the Little Saluda River TP data in Figure 5-30.

Tributary 2 – Clouds Creek Inflow into Little Saluda River Arm of Lake Murray

The Clouds Creek organic matter and phosphorus concentrations in the model inflow are based on TP, ammonia, and nitrate data collected in Clouds Creek at SCDHEC station S-255 along with TOC and TKN data collected in Camping Creek at station S-290. Figure 5-31 shows all of the TP data collected at the Clouds Creek monitoring station along with the monthly mean for the years 1989-1998. There did not appear to be an annual pattern in the TP data, so a constant value was used for the entire year in the model input. As seen in Table 5-5, 0.055 mg/L was calculated as the amount of phosphorus associated with the organic matter in Clouds Creek, and this value is subtracted from the median TP (0.16 mg/L) to get the dissolved phosphorus concentration used in the model input for this inflow. The same dissolved phosphorus time-series was used for all years modeled.

All Other Natural Inflows into Lake Murray

Inflow organic matter and phosphorus concentrations used for the remaining natural inflows to the model were based on TOC, TP, TKN, ammonia, and nitrate data collected in Camping Creek at station S-290. This station was used because it is not downstream of a known point source of phosphorus. It is assumed that phosphorus concentrations measured in this creek are representative of phosphorus concentrations in all inflows to Lake Murray that are unaffected by a point-source.

TP data collected in Camping Creek is summarized in Figure 5-32. Since there was no obvious annual pattern, the median of all the TP data collected in the years 1989-1998 was used as the basis for the inflow phosphorus concentration to Lake Murray. As seen in Table 5-5, 0.055 mg/L was calculated as the amount of phosphorus associated with the organic matter in Clouds Creek, and this value is subtracted from the median TP (0.12 mg/L) to get the dissolved phosphorus concentration used in the model input for this inflow. The same dissolved phosphorus time-series was used for all years modeled.

Tributary 3 – Discharge from McMeekin Steam Plant into Saluda Hydro Unit 3

Like DO, it was assumed that dissolved phosphorus concentrations did not change as the water passed through the McMeekin Steam plant. Therefore the model derived dissolved phosphorus concentration every 24 hours at mid-night at the elevation of the McMeekin intake (unit 4 penstock) was used as dissolved phosphorus concentration in the McMeekin discharge.

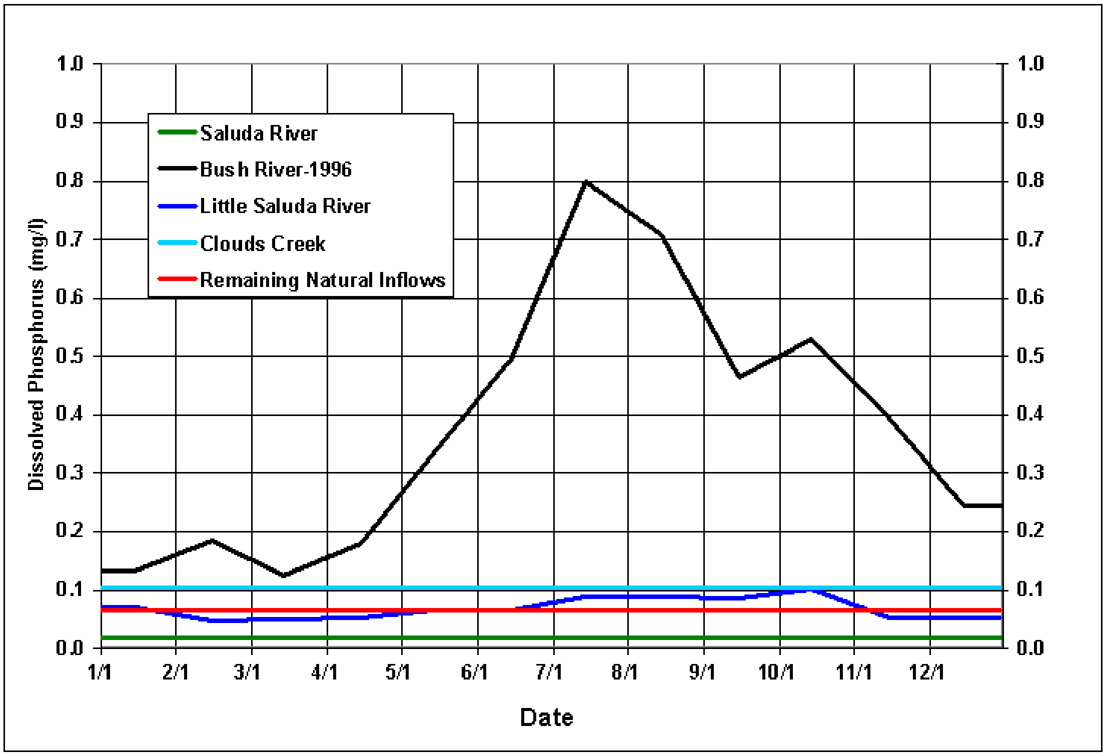


Figure 5-23. Inflow Dissolved Phosphorus Concentrations for Model Inflows to Lake Murray

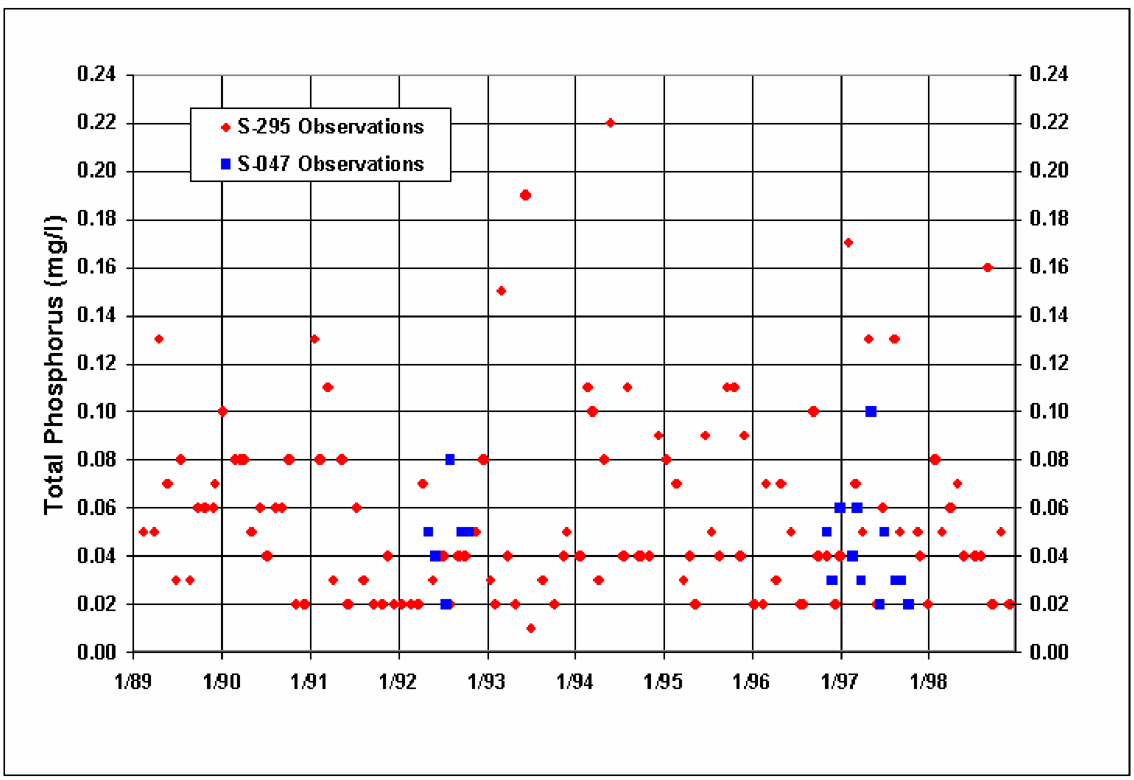


Figure 5-24. Total Phosphorus in the Saluda River Upstream of Lake Murray

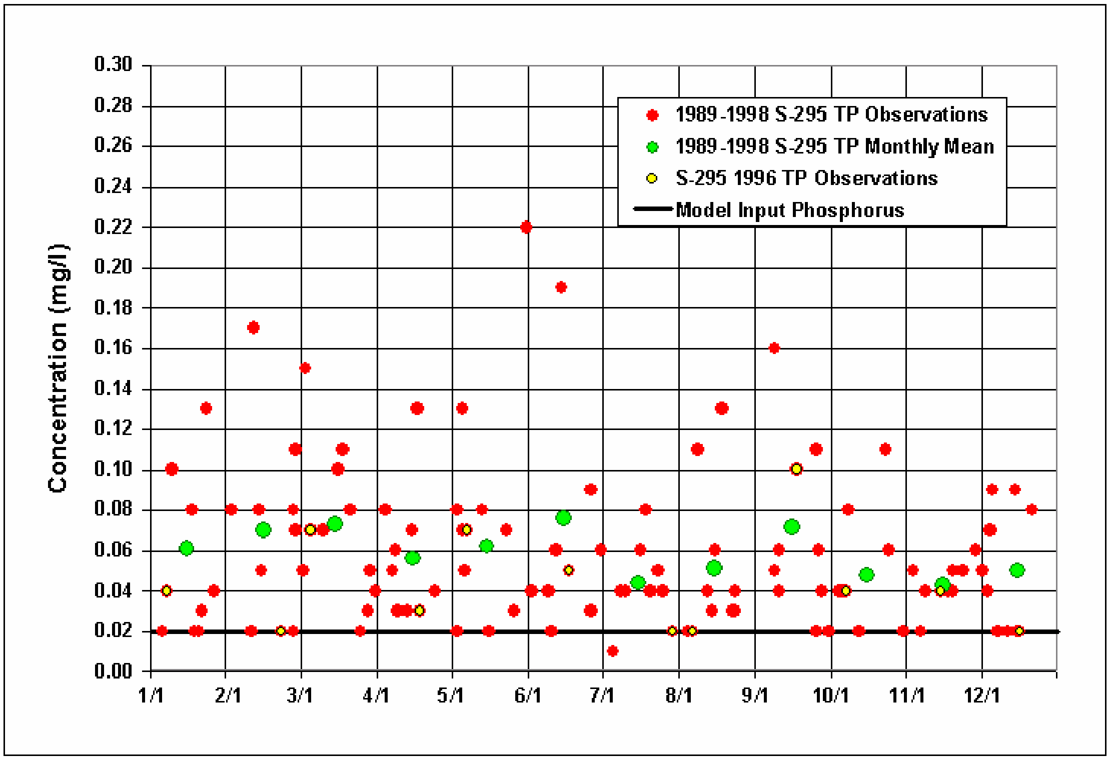


Figure 5-25. Inflow Phosphorus Analysis for Branch 1 (Saluda River)

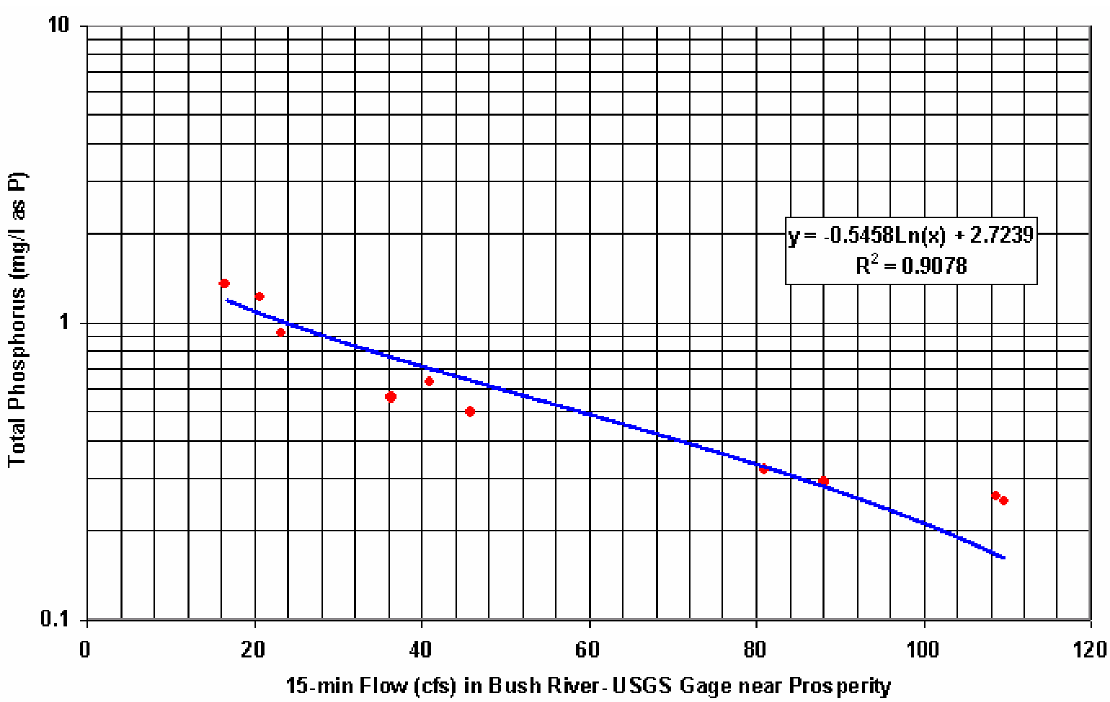


Figure 5-26. Phosphorus versus Flow Relationship Found in the Bush River (Station S-102) Using 1997 data

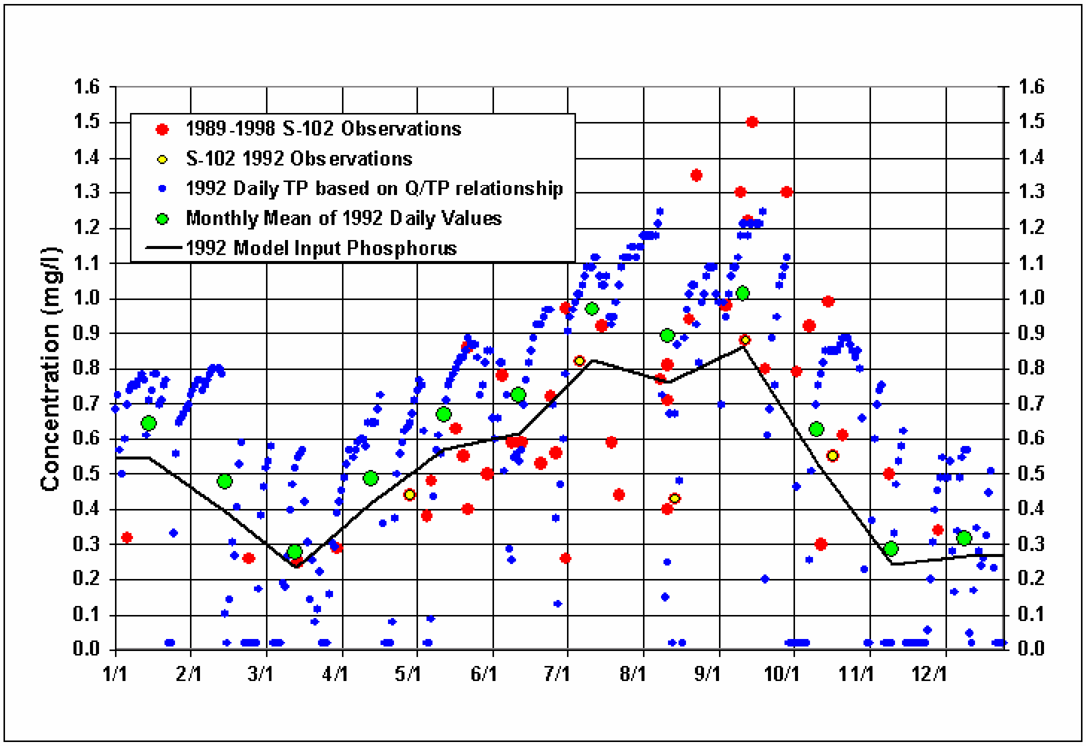


Figure 5-27. 1992 Inflow Phosphorus Analysis for Tributary 1 (Bush River)

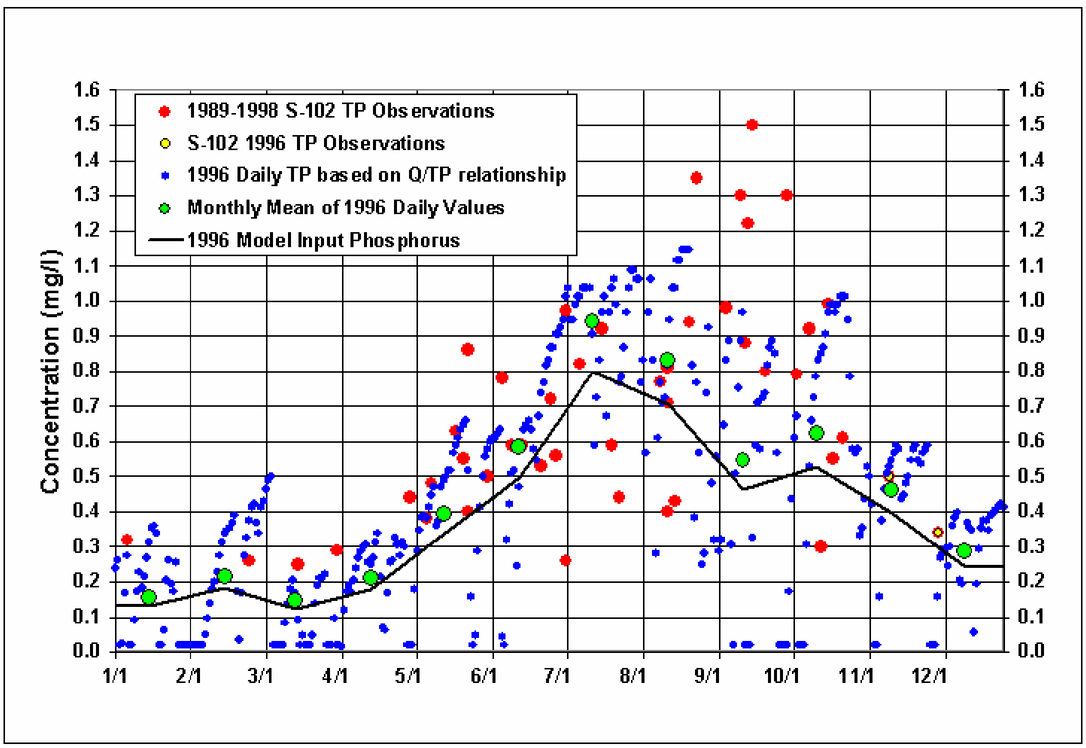


Figure 5-28. 1996 Inflow Phosphorus Analysis for Tributary 1 (Bush River)

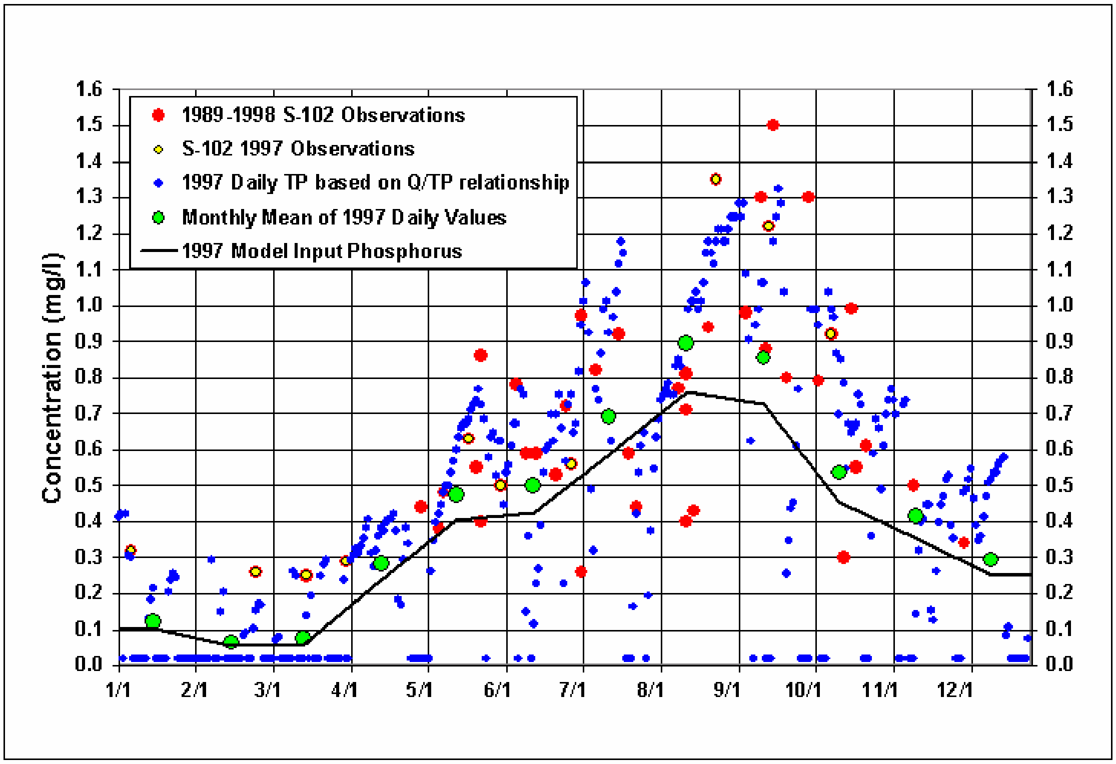


Figure 5-29. 1997 Inflow Phosphorus Analysis for Tributary 1 (Bush River)

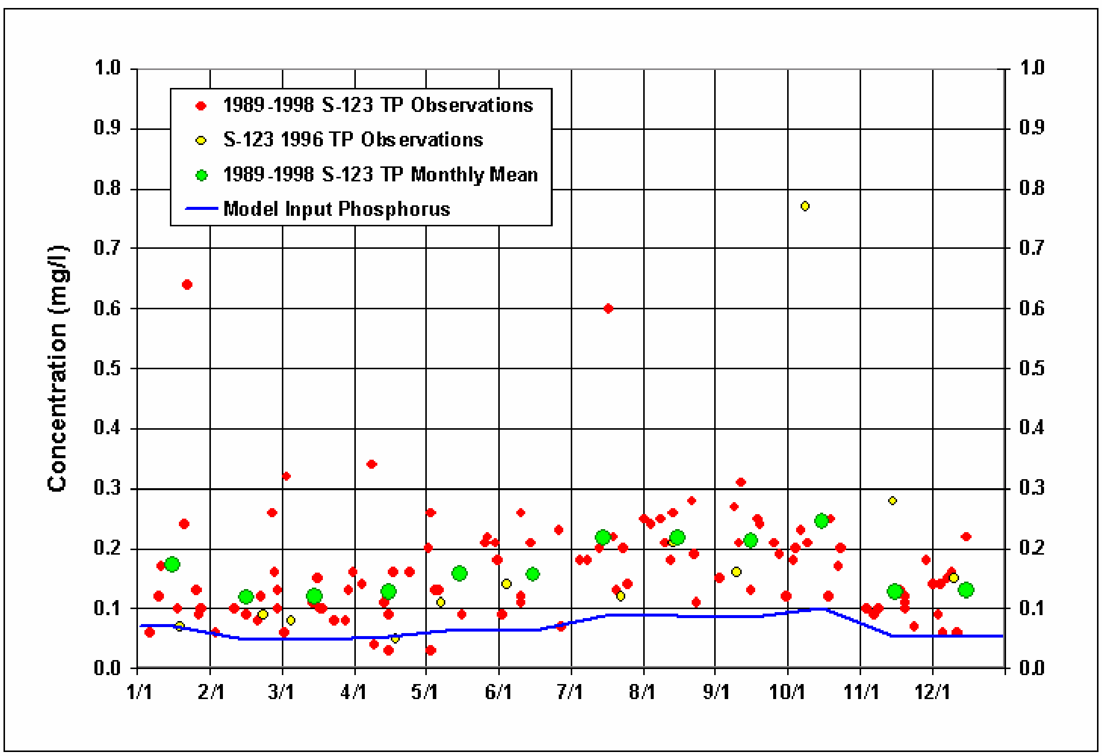


Figure 5-30. Inflow Phosphorus Analysis for Branch 2 (Little Saluda River)

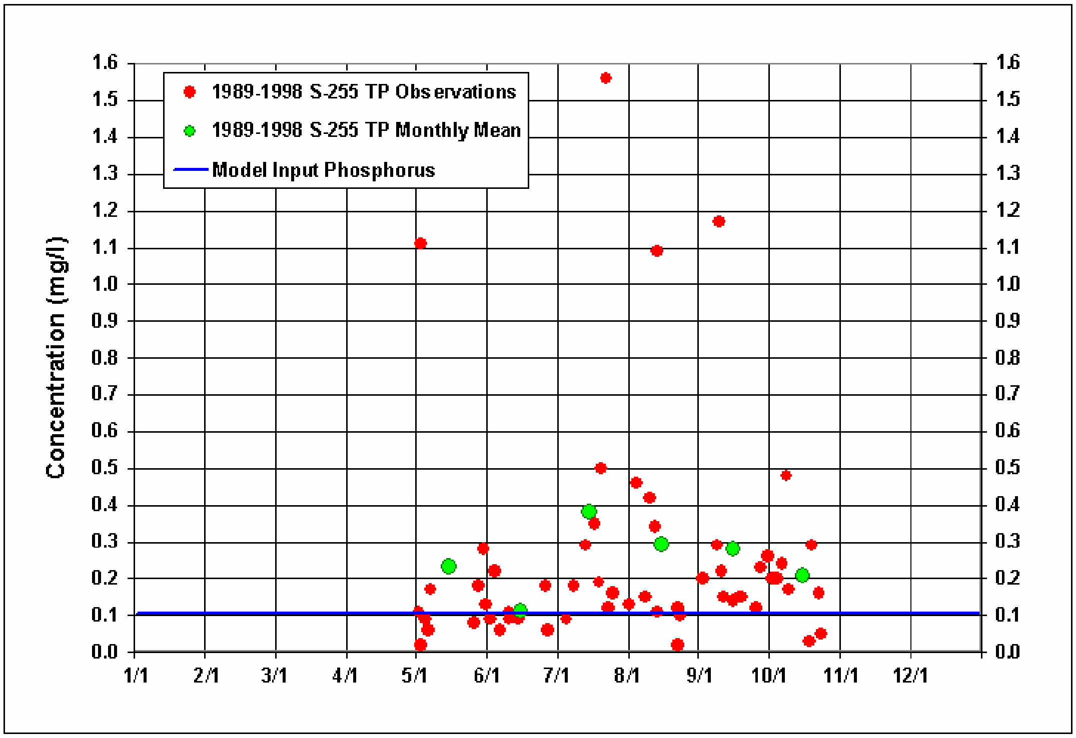


Figure 5-31. Inflow Phosphorus Analysis for Tributary 2 (Clouds Creek)

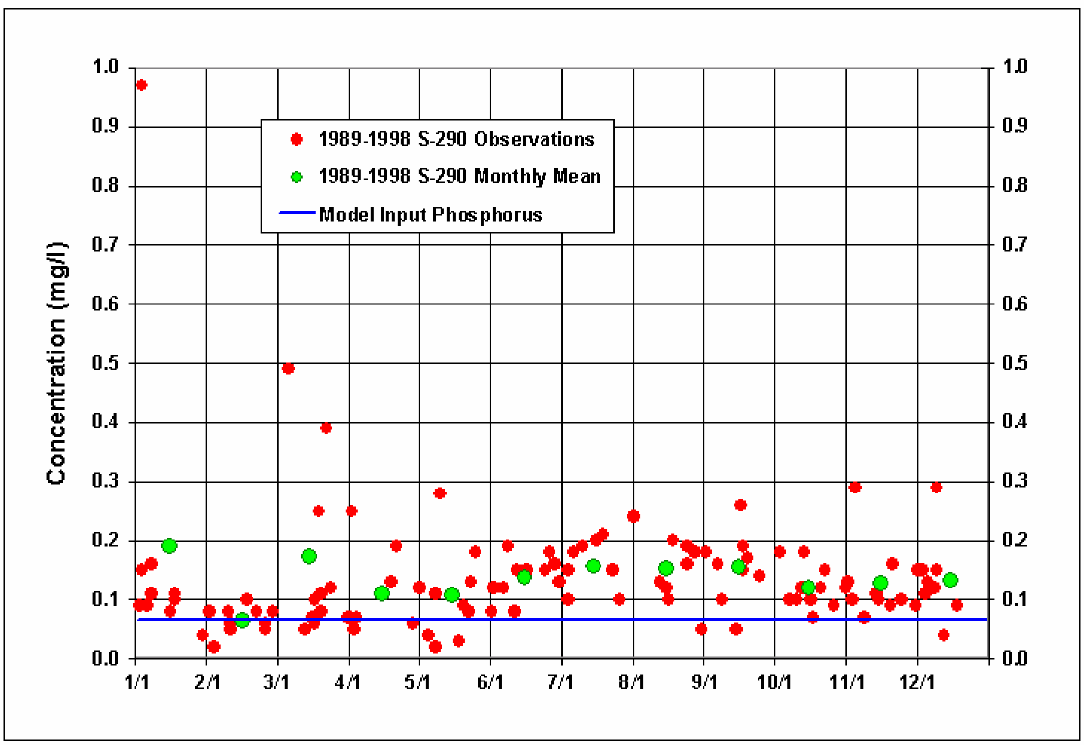


Figure 5-32. Total Phosphorus in Camping Creek

Other Inflow Parameters

Inorganic Suspended Solids

Data were not available on inorganic suspended solids, so data on turbidity for the years 1989 through 1998 were analyzed and determined to have a mean of 8.2 NTUs in the Saluda River during the period when algae grow. A value of 6.5 mg/L was used for inorganic suspended solids in the inflows to the model. The main effect of inorganic suspended solids in the model is to reduce light available for algal growths; however, the main consideration for the Lake Murray model is the total algal mass that will affect the DO in the lake so emphasis during model calibration was placed on simulating algal conditions in the lake rather than variables like suspended solids that are only one of several variables that affect algal growth.

Nitrate and Ammonium

Data from the same stations used in the temperature, DO, and phosphorus analyses were used to estimate the nitrate-nitrite and ammonium concentrations in the inflows to Lake Murray. Figure 5-33 and Figure 5-34 show the time-series used for the inflows for all years modeled.

Algae

Three algae groups were modeled, and there were no data available that indicated how much algae was in the inflows to Lake Murray. Algae concentrations in all inflows were assumed to be relatively low for all years modeled.

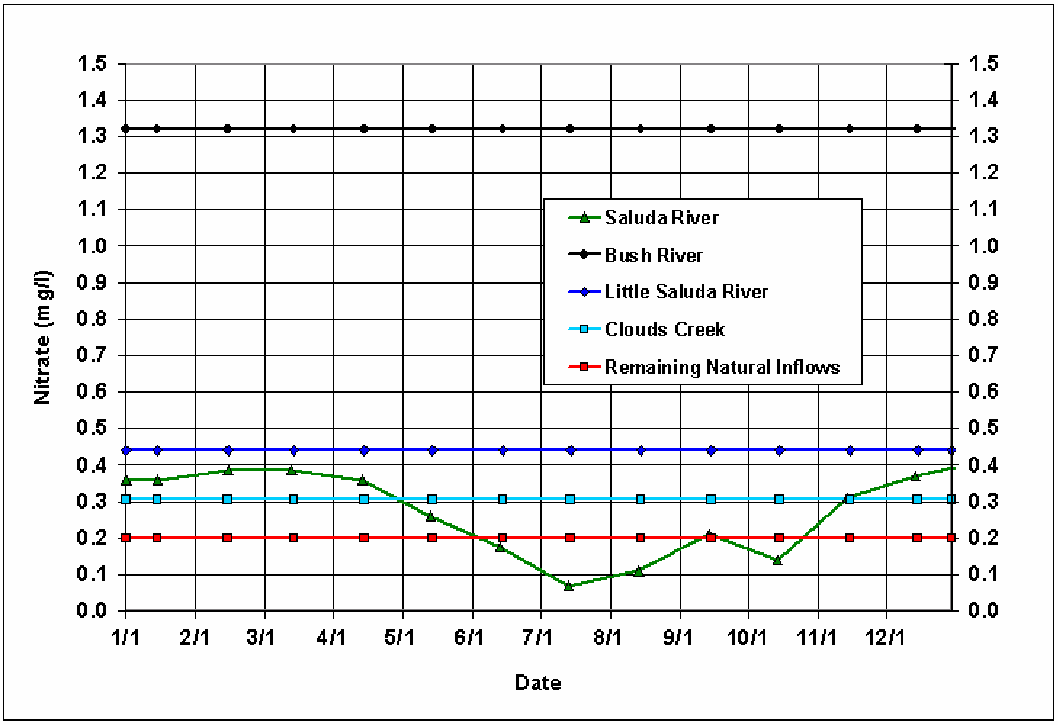


Figure 5-33. Nitrate Concentrations in the Inflows to the Lake Murray CE-QUAL-W2 Model

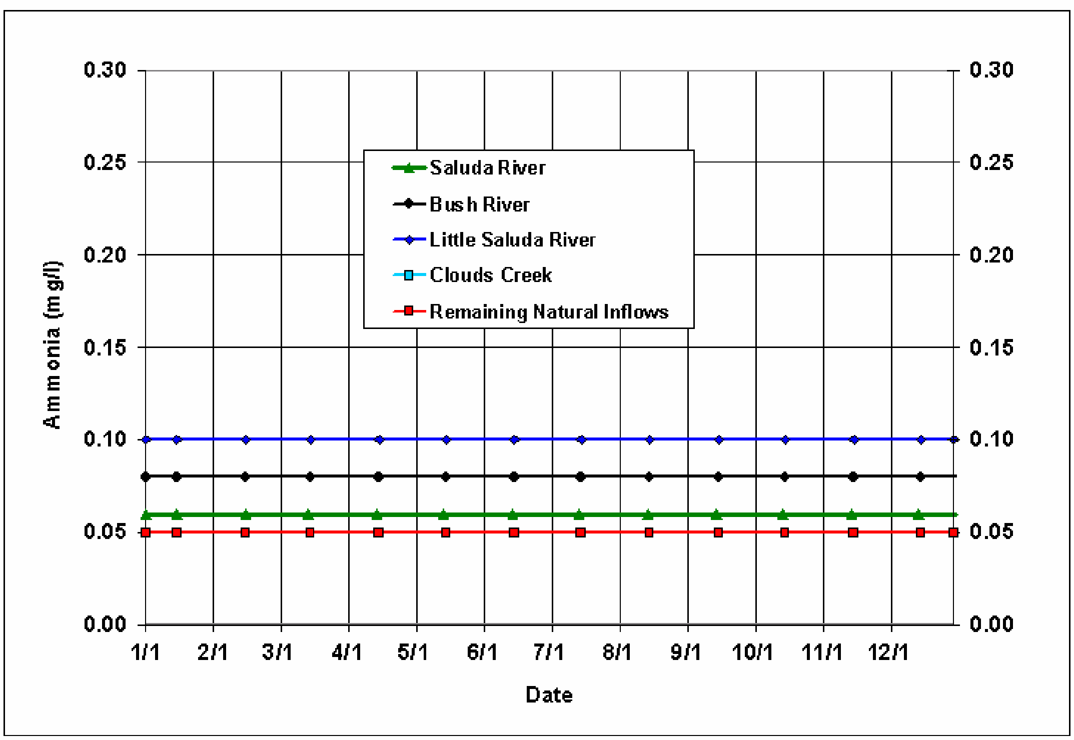


Figure 5-34. Ammonium Concentrations in the Inflows to the Lake Murray CE-QUAL-W2 Model

Initial Conditions

The initial conditions used for all three years modeled are shown in Table 5-6, and the model was set so that the same initial conditions were uniform throughout the lake. For the 1996 model runs the model was started as early as possible which was January 8, since meteorological data were not available for January 1-7. Starting the model simulation this early in the year allows the uniform temperature and water quality to be replaced with conditions that are more representative of the inflows for the years modeled. For the 1992 and 1997 model runs the start time was chosen by determining when the reservoir temperature had stabilized between the winter cooling and the spring warming. The starting dates for 1992 and 1997 were February 19 and February 22, respectively.

Initial conditions for phosphorus, nitrate-nitrite, ammonium, and organic matter were based on historical data collected in the forebay. SCDHEC only measures chlorophyll *a* from May through October in Lake Murray so initial algae concentrations were assumed.

Table 5-6. Lake Murray Water Quality Initial Conditions

Constituent	**Initial Concentration**		
	1992	1996	1997
Inorganic Suspended Solids, mg/L	2.0		
Phosphate, mg/L	0.01		
Ammonium, mg/L	0.03		
Nitrate-Nitrite, mg/L	0.15		
Labile Dissolved Organic Matter, mg/L	0.1		
Refractory Diss. Org. Matter, mg/L	8.0		
Labile Particulate Org. Matter, mg/L	0.1		
Refractory Particulate Org. Matter, mg/L	0.1		
Algae, mg/L	0.09	0.04	0.09
Dissolved Oxygen, mg/L	10.5	10.5	10.0
Total Inorganic Carbon mg/L	6.0	4.5	6.0
Alkalinity mg/L	20	15	20

Meteorology

The meteorological parameters used in the Lake Murray model include air temperature, dewpoint temperature, wind speed, wind direction, and estimation of cloud cover. Hourly meteorological data from two stations in the Columbia, South Carolina area and one station in the Augusta, Georgia area were tested during calibration. One set of the Columbia data and the Augusta data were derived from the World Meteorological Organization's International Surface Weather Observations (ISWO). The second set of Columbia data came from the National Climatic Data Center (NCDC). The model is sensitive to which meteorological data are used, but as would be expected, due to their proximity to Lake Murray, the Columbia stations produced more accurate simulations of water temperature overall than did the Augusta station. There are days in which the use of the Augusta data produced a better match to the observed data, which illustrates that some discrepancies in the predicted versus observed comparison are the result of the meteorological data used in the model not being a perfect representation of conditions at Lake Murray.

Other than a few small gaps, data from the ISWO station in Columbia were available for the whole year, but data from the NCDC station were only available after July 1. As shown in Figure 5-35 through Figure 5-39, 1996 data from the two Columbia stations were very similar, but when used in the model they produced slightly different results. Since the ISWO data were available for almost all of 1996, it was used for the 1996 calibration. However, there was an eight-day period from September 1 through September 8 in 1996 when data from the Columbia ISWO station were not available. Since simulation of fall turnover was critical to simulating DO recovery in the tailwater, and the data from the two Columbia stations were so similar, data from the NCDC meteorological station were used to fill this gap. Data from the respective years observed at the Columbia ISWO station were also used in the 1992 and 1997 calibrations.

Wind Sheltering Coefficients

In CE-QUAL-W2, the wind sheltering coefficient (WSC) is a direct multiplier of the wind speed in the meteorological input. The WSC was set to 0.9 for the entire 1992 and 1997 calibrations and most of the 1996 calibration. The WSC was reduced (i.e., reducing the effect of wind in the model) to 0.7 in mid-August of the 1996 calibration to slow down the turnover of the lake, which was occurring too early in the model due to the unusually high outflow related to a special drawdown that occurred in 1996. The WSC was not varied in 1992 or 1997 in an attempt to produce a robust temperature calibration.

Sediment Oxygen Demand

In CE-QUAL-W2, the zero-order SOD is user defined and can vary by segment. During the water quality calibration process, SOD is first estimated and then, as calibration proceeds, it is adjusted to improve the DO calibration. This process and the actual SOD values used in the model will be discussed later in the "Model Calibration" section of this report.

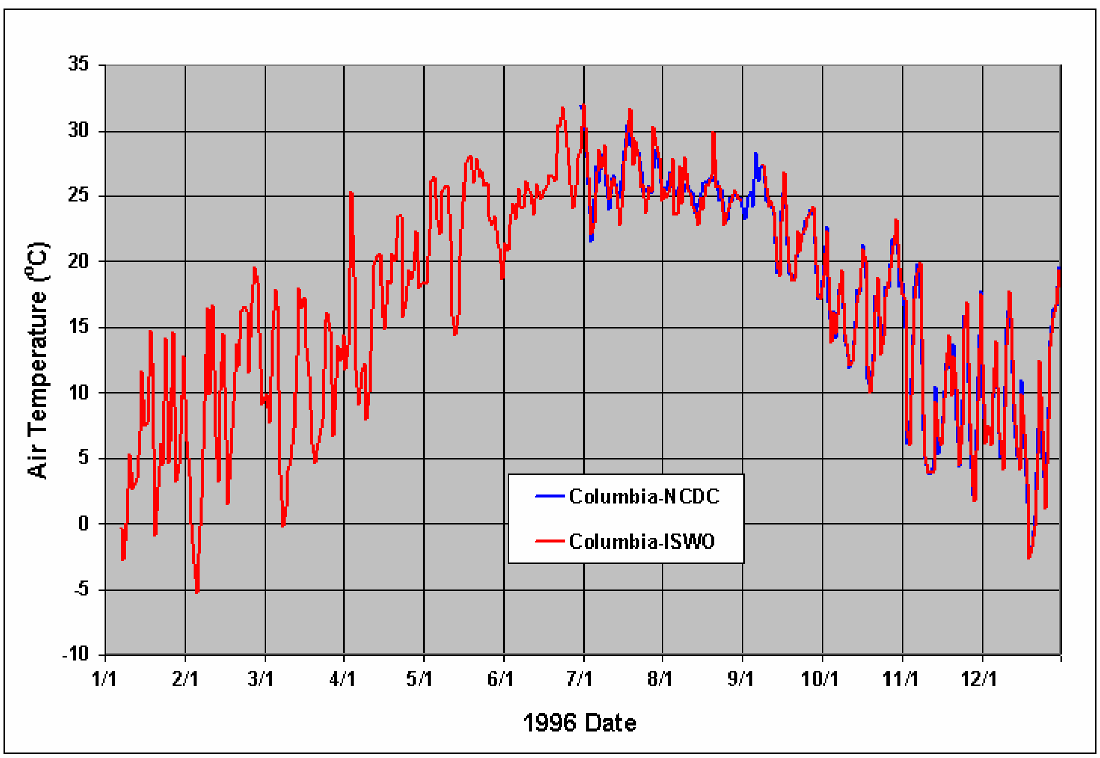


Figure 5-35. 1996 Daily Average Air Temperature Measured at Two Columbia, SC Meteorological Stations

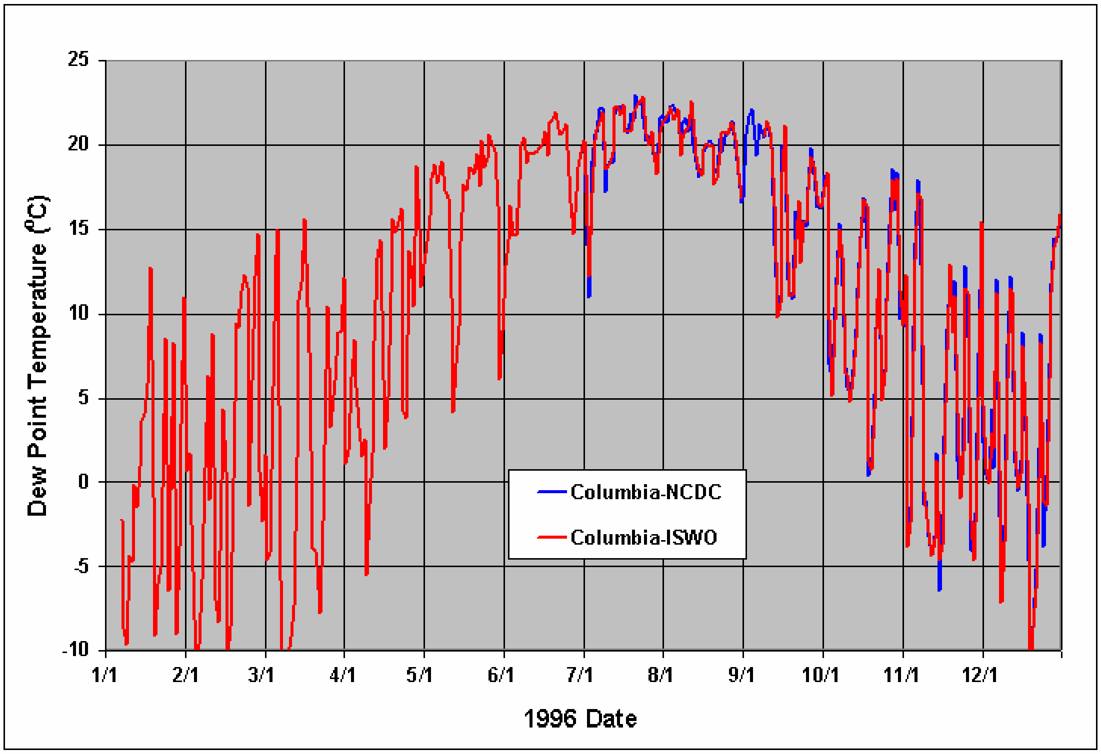


Figure 5-36. 1996 Daily Average Dew Point Temperature Measured at Two Columbia, SC Meteorological Stations

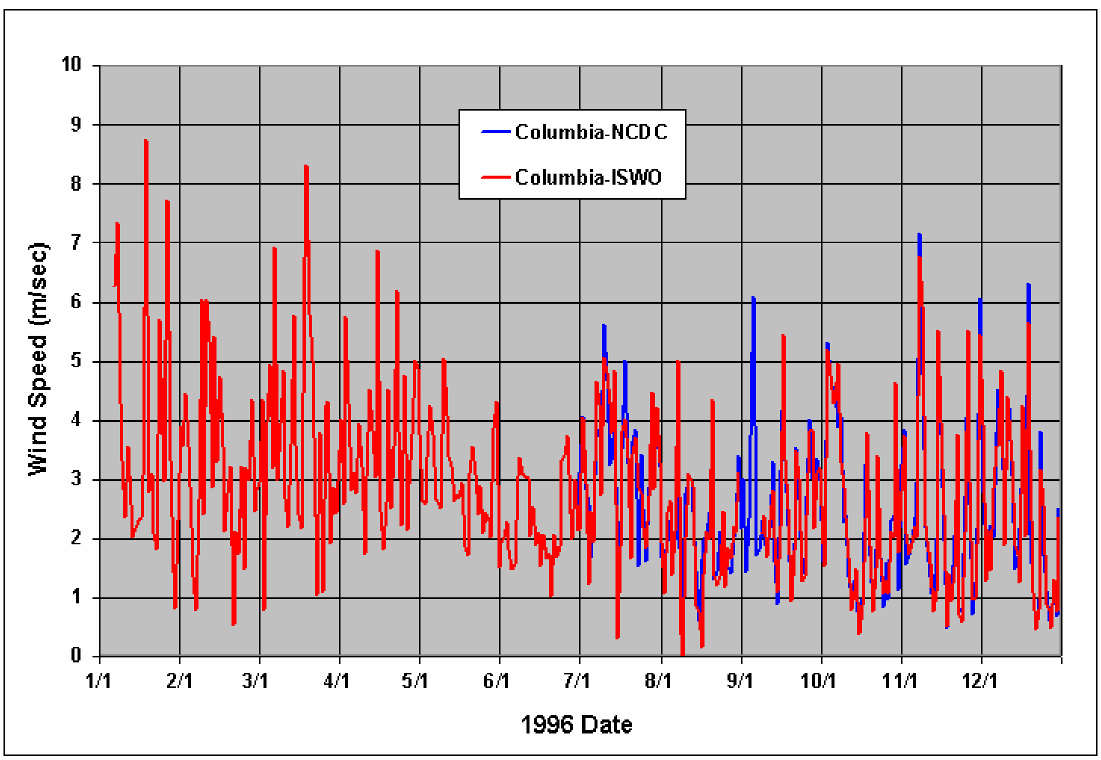


Figure 5-37. 1996 Daily Average Wind Speed Measured at Two Columbia, SC Meteorological Stations

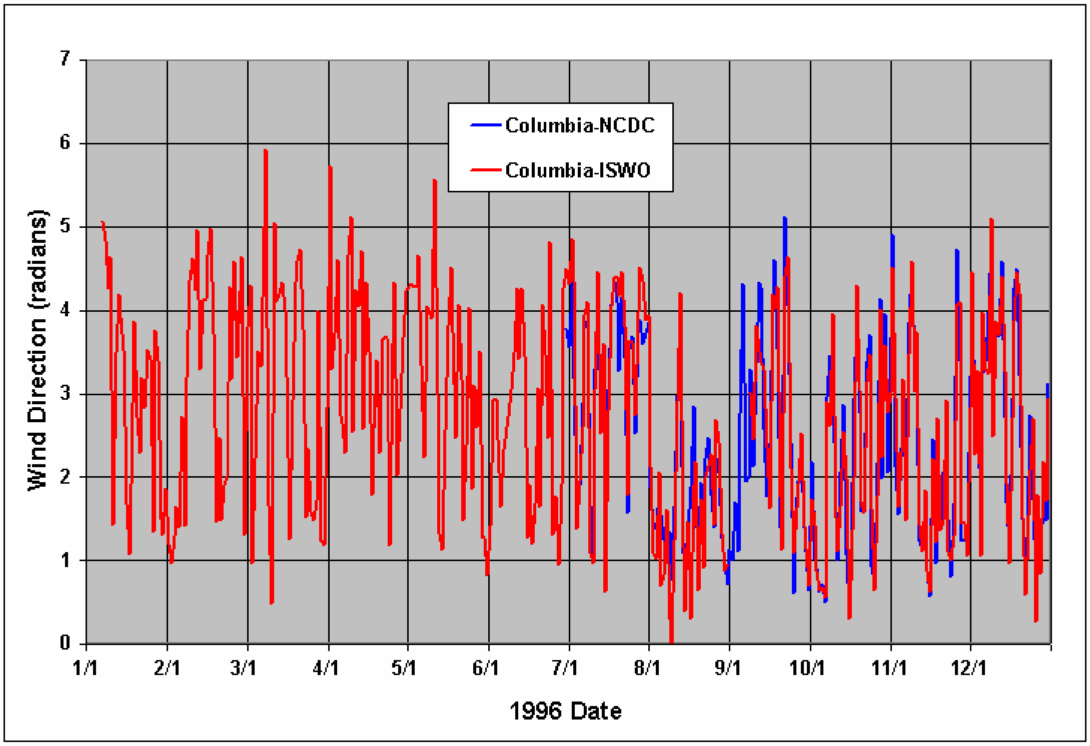


Figure 5-38. 1996 Daily Average Wind Direction Measured at Two Columbia, SC Meteorological Stations

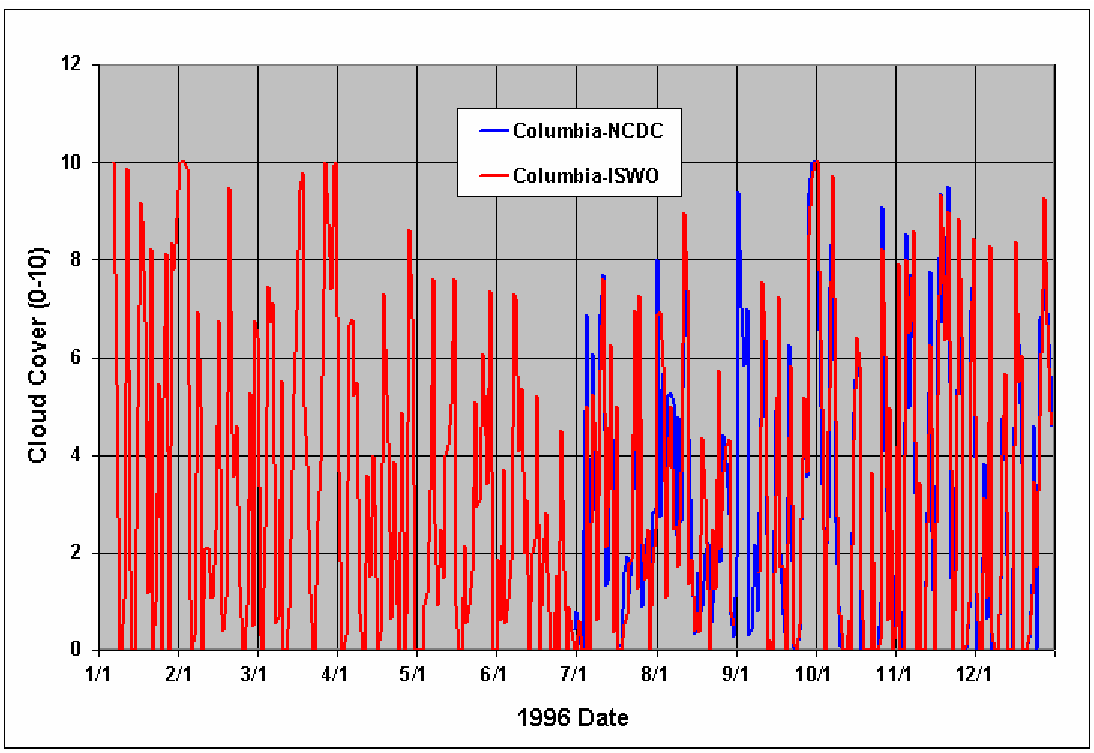


Figure 5-39. 1996 Daily Average Cloud Cover Measured at Two Columbia, SC Meteorological Stations

6. Model Calibration

Calibration is achieved when model predictions reasonably match observed data considering the objectives for the model. The AGPM post-processor enables the modeler to evaluate results using various graphics. Many of these graphics are presented in the following sections as each aspect of the calibration is discussed. One of the primary evaluations of the accuracy of the Lake Murray model was the comparison of model-predicted temperature and DO profiles with existing profile data. SCE&G and SCDHEC have monitoring stations throughout Lake Murray, and location information of the primary stations used to evaluate model performance is provided in Table 6-1.

The hydraulic and heat exchange coefficients used to calibrate the model are listed in Table 6-2, and those coefficients that pertain to temperature and water quality calibration are shown in Table 6-3.

These tables show that the same coefficients were used for all three calibration years. During the calibration process 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 using over 300 runs, the differences in model settings for the different years converged and in the end were reconciled such that zero-order SOD was the only variable that needed to be varied each year. This approach was selected considering that the model would be used for evaluating water quality conditions for years other than the three years used for calibration. Since model robustness for evaluating different hydrological and meteorological conditions was an important consideration, developing a model that had only one main variable for sensitivity was highly desirable.

It should be noted that calibrations for the individual years using different coefficients for each year for algal growth, organic matter settling rates, organic matter and algal stoichiometry, SOD, organic matter decay rates, etc., were developed that had similar statistical results for “goodness-of-fit.” These models might be better for applications for the specific years that were calibrated, but they would not be as robust considering that the model with only the SOD adjustment was calibrated using three years of data.

Table 6-1. Primary SCE&G and SCDHEC Lake Murray Monitoring Stations Used for Model Calibration Confirmation

SCE&G			SCDHEC			Kilometer Range of Model Segment Used for Comparison
Station ID	Miles from Saluda Dam	Kilometers from Saluda Dam	Station ID	Miles from Saluda Dam	Kilometers from Saluda Dam	
1-SP	0.1	0.2	S-204	0.1	0.2	0 - 1.3
2-NA	3.8	6.1	S-273	4.2	6.8	6.0 - 7.7
3-NA	13.1	21.1	S-280	12.2	19.6	19.3 - 22.1
4-NA	17.6	28.3	S-279	17.7	28.4	26.8 - 28.7
			S-223	24.6	39.6	36.5 - 38.5

Table 6-2. Hydraulic Coefficients in Model Calibration

Heat Exchange (Heat Exchange)

SLHTC	term-by-term or equilibrium temperature computations for surface heat exchange	TERM
RHEVAP	Turns ON/OFF Ryan-Harleman evaporation formula	OFF
FETCHC	Turns ON/OFF fetch calculations	OFF
AFW	a coefficient in the wind speed formulation	9.2
BFW	b coefficient in the wind speed formulation	0.6
CFW	c coefficient in the wind speed formulation	2.0

Transport Scheme (TRANSPORT)

SLTRC	Transport solution scheme, ULTIMATE, QUICKEST, or UPWIND	ULTIMATE
THETA	Time-weighting for vertical advection scheme	0.55

Hydraulic Coefficients (HYD COEF)

AX	Longitudinal eddy viscosity, m^2 sec^{-1}	1.0
DX	Longitudinal eddy diffusivity, m^2 sec^{-1}	1.0
CBHE	Coefficient of bottom heat exchange, W m^2 sec^{-1}	7.0E-08
TSED	Sediment (ground) temperature, ^oC	17.0
FI	Interfacial friction factor	0.0
TSEDF	Heat lost to sediments that is added back to water column	0.0
FRICC	Bottom friction solution, MANN or CHEZY	CHEZY = 70

EDDY VISC

AZC	Form of vertical turbulence closure algorithm, NICK, PARAB, RNG, W2, W2N	W2
AZSLC	Specifies either implicit or explicit treatment of the vertical eddy viscosity	IMP
AZMAX	Maximum value for vertical eddy viscosity, m2 sec-1	1.0E-03

Table 6-3. Water Quality Coefficients Used in Model Calibration

Extinction Coefficient (EX COEF)		**Calibration Value**		
EXH2O	Extinction for pure water, m^{-1}	0.45		
EXSS	Extinction due to inorganic suspended solids, m^{-1}	0.1		
EXOM	Extinction due to organic suspended solids, m^{-1}	0.1		
BETA	Fraction of incident solar radiation absorbed at the water surface	0.45		
EXC	Read extinction coefficients, ON or OFF	OFF		
Algal Extinction (ALG EX)		**diatoms**	**greens**	**cyano**
EXA	Algal light extinction, m^{-1}	0.2	0.2	0.2
Suspended Solids (S SOLIDS)				
SSS	Suspended solids settling rate, m day^{-1}	1.0		
Algal Rates (ALGAL RATE)		**diatoms**	**greens**	**cyano**
AG	Maximum algal growth rate, day^{-1}	1.6	1.6	1.6
AR	Maximum algal respiration rate, day^{-1}	0.04	0.04	0.04
AE	Maximum algal excretion rate, day^{-1}	0.04	0.04	0.04
AM	Maximum algal mortality rate, day^{-1}	0.08	0.1	0.1
AS	Algal settling rate, day^{-1}	0.1	0.08	0.02
AHSP	Algal half-saturation for phosphorus limited growth, g m^{-3}	0.003	0.003	0.003
AHSN	Algal half-saturation for nitrogen limited growth, g m^{-3}	0.014	0.014	0.014
AHSSI	Algal half-saturation for silica limited growth, g m^{-3}	0.0	0.0	0.0
ASAT	Light saturation intensity at maximum photosynthetic rate, W m^{-2}	150	150	150
Algal Temperature Rate Coefficients (ALGAL TEMP)				
AT1	Lower temperature for algal growth, ^oC	0	10	20
AT2	Lower temperature for maximum algal growth, ^oC	17	20	28
AT3	Upper temperature for maximum algal growth, ^oC	22	35	35
AT4	Upper temperature for algal growth, ^oC	40	40	40
Algal Stoichiometry (ALG STOICH)				
ALGP	Stoichiometric equivalent between algal biomass and phosphorus	0.006	0.006	0.006
ALGN	Stoichiometric equivalent between algal biomass and nitrogen	0.07	0.07	0.07
ALGC	Stoichiometric equivalent between algal biomass and carbon	0.45	0.45	0.45
ALGSI	Stoichiometric equivalent between algal biomass and silica	0.18	0.18	0.18
ALCHLA	Ratio between algal biomass and chlorophyll a	225	200	140
ALPOM	Fraction of algal biomass converted to part. Org. matter when algae die	0.8	0.8	0.8
Dissolved Organic Matter (DOM)				
LDOMDK	Labile DOM decay rate, day^{-1}	0.12		
RDOMDK	Refactory DOM decay rate, day^{-1}	0.001		
LRDDK	Labile to refractory DOM decay rate, day^{-1}	0.01		
LDOMR	Sediment release rate of LDOM, fraction of SOD	0.55		
Particulate Organic Matter (POM)				
LPOMDK	Labile POM decay rate, day^{-1}	0.08		
RPOMDK	Refactory POM decay rate, day^{-1}	0.001		
LRPDK	Labile to refractory POM decay rate, day^{-1}	0.01		
POMS	POM settling rate, m day^{-1}	0.3		

Table 6-3 (continued). Water Quality Coefficients Used in Model Calibration

			Calibration Value		
Organic Matter Stoichiometry (OM STOICH)					
	ORGP	Stoichiometric equivalent between labile organic matter and phophorus	0.006		
	ORGN	Stoichiometric equivalent between labile organic matter and nitrogen	0.07		
	ORGC	Stoichiometric equivalent between organic matter and carbon	0.45		
	ORGSI	Stoichiometric equivalent between organic matter and silica	0.18		
	ORGPR	Stoichiometric equivalent between refractory organic matter and phophorus	0.0006		
	ORGNR	Stoichiometric equivalent between refractory organic matter and nitrogen	0.007		
Organic Matter Temperature Rate Multipliers (OM RATE)					
	OMT1	Lower temperature for organic matter decay, ^oC	5		
	OMT2	Upper temperature for organic matter decay, ^oC	30		
Inorganic Phosphorus (PHOSPHOR)					
	PO4R	Sediment release rate of phosphorus, fraction of SOD	0.004		
	PARTP	Phosphorus partitioning coefficient for suspended solids	0		
	PO4S	PO4 settling rate, m day^{-1}	0.05		
Ammonium (AMMONIUM)					
	NH4R	Sediment release rate of ammonium, fraction of SOD	0.04		
	NH4DK	Ammonium decay rate, day^{-1}	0.12		
Ammonium Temperature Rate Multipliers (NH4 RATE)					
	NH4T1	Lower temperature for ammonia decay, ^oC	5		
	NH4T2	Lower temperature for maximum ammonia decay, ^oC	30		
Nitrate (NITRATE)					
	NO3DK	Nitrate decay rate, day^{-1}	0.03		
	NO3S	Denitrification rate from sediments, m day^{-1}	0.3		
Nitrate Temperature Rate Multipliers (NO3 RATE)					
	NO3T1	Lower temperature for nitrate decay, ^oC	5		
	NO3T2	Lower temperature for maximum nitrate decay, ^oC	30		
Iron (IRON)					
	FER	Iron sediment release rate, fraction of SOD	0.5		
	FES	Iron settling velocity, m day-1	2		
Sediment Carbon Dioxide Release (SED CO2)					
	CO2R	Sediment release rate of Carbon Dioxide, fraction of SOD	1.0		
Oxygen Stoichiometry 1 (STOICH 1)					
	O2NH4	Oxygen stoichiometry for nitrification	4.57		
	O2OM	Oxygen stoichiometry for organic matter decay	1.4		
Oxygen Stoichiometry 2 (STOICH 2)			**diatoms**	**greens**	**cyano**
	O2AR	Oxygen stoichiometry for algal respiration	1.1	1.1	1.1
	O2AG	Oxygen stoichiometry for algal primary production	1.4	1.4	1.4
Oxygen Limit (O2 LIMIT)					
	O2LIM	Dissolved Oxygen concentration at which anaerobic processes begin, g m^{-3}	0.5		
Sediment Compartment (SEDIMENT)					
	SEDC	Turns ON/OFF the first-order sediment compartment	ON		
	SEDCI	Initial sediment concentration, g m^{-2}	0.0		
	SEDK	sediment decay rate, day^{-1}	0.04		
	FSOD	Fraction of the zero-order SOD rate used	1.0(1992), 0.8(1996), 0.3(1997)		
	FSED	Fraction of the first-order sediment rate used	1		
SOD Temperature Rate Multipliers (SOD RATE)					
	SODT1	Lower temperature for zero-order SOD or first-order sediment decay, ^oC	5		
	SODT2	Upper temperature for zero-order SOD or first-order sediment decay, ^oC	30		

This approach of adjusting the SOD between years was used early on in the 1997 model when it became obvious that the DO demands were not as high in Lake Murray in 1997 as they were in 1992 and 1996. The SOD in the 1992 and 1996 were kept the same between years until very late in the calibration process. After thorough review of model inputs and coefficients and sensitivity runs to determine the effect of changing those coefficients that differed between years, it was decided to decrease the SOD in the 1996 model to reduce the DO demand. An example of one of these differences that was reconciled is the algal growth rate, which was lower in the 1996 and 1997 calibrations than in the 1992 calibration. When the algal growth rate in the 1996 and 1997 models was changed to match 1992, the DO demand increased and the models appeared to then be under-predicting DO. In order to counteract this, the SOD was decreased in the 1996 and 1997 models.

As mentioned before the SOD is defined for each segment in the model, and in general the SOD in the Lake Murray model decreases from upstream to downstream. Instead of adjusting the SOD of individual segments to calibrate the different years, the SOD multiplier (FSOD) was adjusted, thus changing the all the SOD values in the model for each year modeled. The actual SOD values used in the model are shown in Table 14.

Table 6-4. Zero Order Sediment Oxygen Demand Values used in the Lake Murray CE-QUAL-W2 Model

	Sediment Oxygen Demand (SOD), grams O_2/m2/day											
	Saluda River Arm (Branch 1)					Little Saluda River Arm (Branch 2)						All Other Branches
Segment Range (Km)	0.0 - 1.3	1.3 2.5	2.5 - 4.6	4.6 - 26.8	26.8 - 51.3	0.0 - 1.5	1.5 - 3.7	3.7 - 5.5	5.5 - 7.2	7.2 - 9.2	9.2 - 11.2	
1992 SOD	0.20	0.30	0.40	0.70	0.80	1.50	1.20	1.00	0.80	0.70	0.60	0.30
1996 SOD (1992 value * 0.8)	0.16	0.24	0.32	0.56	0.64	1.20	0.96	0.80	0.64	0.56	0.48	0.24
1997 SOD (1992 value * 0.3)	0.06	0.09	0.12	0.21	0.24	0.45	0.36	0.30	0.24	0.21	0.18	0.09

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. The significance and a summary of these statistics with regard to the Lake Murray model will be discussed in the temperature and DO calibration sections. In figures showing comparisons between observed and modeled temperature and DO profiles, there are three model-predicted profiles shown. The solid black line is the model prediction from the time shown on each plot. The red and blue lines are the predictions from the same on the previous and following days, respectively.

Temperature and DO calibration was also confirmed by comparing model-predicted time-series to data collected at continuous monitoring stations maintained by the USGS. Model-predicted time-series of chlorophyll *a* and nutrient concentrations at a depth of one meter were compared to surface samples collected by SCDHEC in the years of 1989 through 1998.

Headwater Calibration

The development of a model requires a balance of inflows and outflows that will reproduce the measured lake level elevations. Water balance was confirmed by comparing predicted and observed midnight lake level elevations. Figure 6-1 through Figure 6-3 show how model-predicted water surface elevations matched observed lake level elevations for the 1992, 1996, and 1997 calibration periods.

Temperature Calibration

Plots of model-predicted and observed temperature profiles at four locations in Lake Murray for the 1992, 1996, and 1997 model calibrations are shown in Figure 6-4 through Figure 6-15. As illustrated in these plots, major patterns of annual stratification and turnover were modeled well for all three years.

As mentioned before, the differences between predicted and measured profiles were evaluated using two descriptive statistics: AME and RMS. These statistics are shown on the plots of each profile comparison, and a summary of the statistics from all dates and locations shown in Figure 6-4 through Figure 6-15 for all three years is presented in Table 6-5 through Table 6-7. These tables show that the overall AME for 1992, 1996, and 1997 when all profiles and dates are included each year is 0.75 C°, 0.57 C°, and 0.58 C°, respectively. Many expert modelers consider a model to be acceptable when the AME is less than 1 C°.

Temperature calibration was also confirmed by comparing the hourly observed temperatures from two locations. One location was approximately 2500 feet downstream of the Saluda Hydro releases. Figure 6-16 through Figure 6-18 show the model-predicted Saluda release temperatures plotted with the observed release temperature data for 1992, 1996, and 1997, respectively. The modeled release temperatures depend on discharge from the project, discharge distribution across the units, centerline elevation of the unit intakes, withdrawal zone characteristics, and the simulated temperature profiles just upstream of the dam. In the Lake Murray model, there are no limitations on the withdrawal zone of any of the units.

The second location where model predictions were compared to hourly observations was in the forebay of the reservoir at the elevation of the unit 5 intake. This monitor is not on the unit 5 intake tower, but instead is mounted on one of the adjacent towers. The exact elevation of this monitor is unknown but, for comparison purposes, was assumed to be at the same elevation as the centerline of the unit 5 intake (elev. 84.4m). Figure 6-19 through Figure 6-21 show the model-predicted temperature and the hourly observed temperature from this elevation for 1992, 1996, and 1997, respectively. Temperatures measured at this elevation during monthly sampling by SCE&G sand SCDHEC are also shown on these plots.

In general, the temperature calibrations are good, but there is a tendency for the modeled temperature in the hypolimnion and the releases from Saluda Hydro to be lower than the data. This tendency was caused by the model bathymetry having more volume than the actual reservoir which was discussed earlier. W2 has a tendency to mix the water column too rapidly as turnover approaches, resulting in turnover occurring too early. In order to counteract this problem, the model was calibrated to allow cooler water in the hypolimnion than that observed, so the timing of turnover would better match actual conditions. This balance was deemed important because modeled DO under predicted low nutrient conditions was at its lowest immediately before lake turnover. The effects of reduced phosphorus in the inflows was initially modeled using a first-generation calibrated model, and it revealed that the minimum DO period was shifted to about two months later and it did not occur until immediately before turnover—since turnover in the model occurred too early, the model was recalibrated so that turnover would occur closer to actual dates. It should be noted that these marginally cooler temperatures in the model for the lower depths of the lake did not measurably affect environmental processes that affect DO. Also, by comparing modeled temperatures with observed temperatures in the tailwater, it can be seen that the extra residence time of water in the bottom of the lake was usually only about one week and occasionally about two weeks.

Temperature calibration is very important because temperature significantly affects many of the other water quality constituents: The movement of water through the lake and the residence time of water at various locations and depths of the lake is affected by the temperature of the inflows as well as the thermal structure of the lake; the volume of various layers of the lake that are significant limnologically are affected by thermal structure; the rates of essentially all water quality processes are affected by temperature; and lake turnover is affected by the thermal structure of the lake.

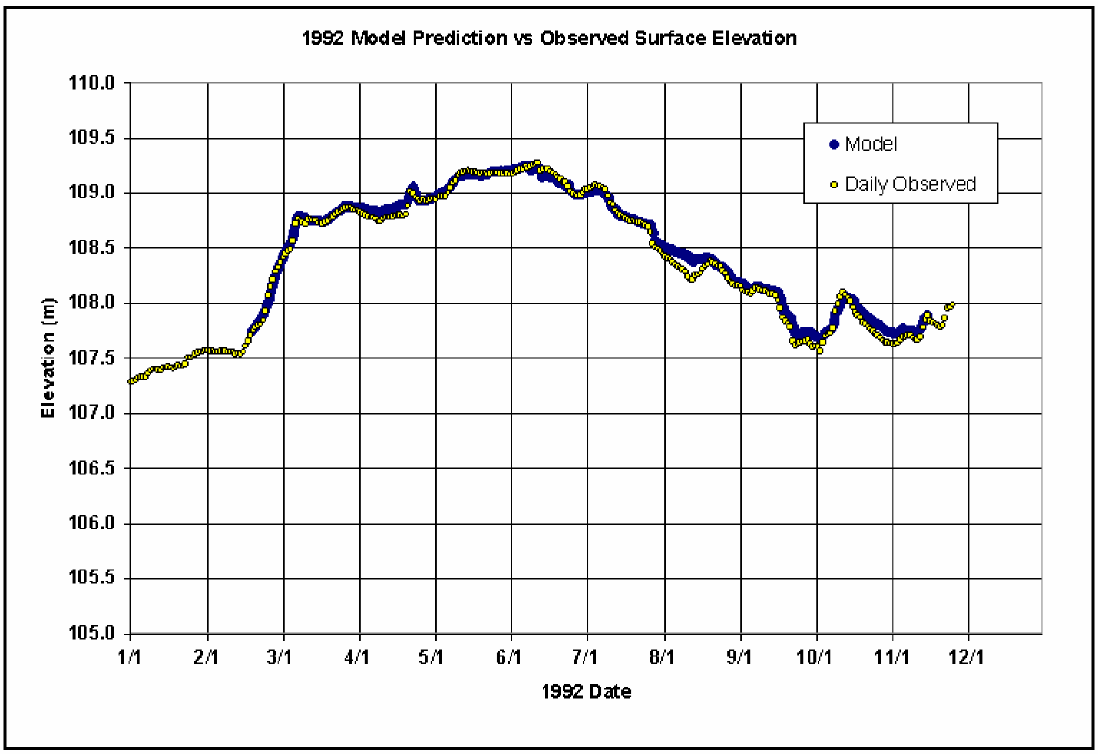


Figure 6-1. 1992 Modeled and Measured Lake Murray Headwater Elevations

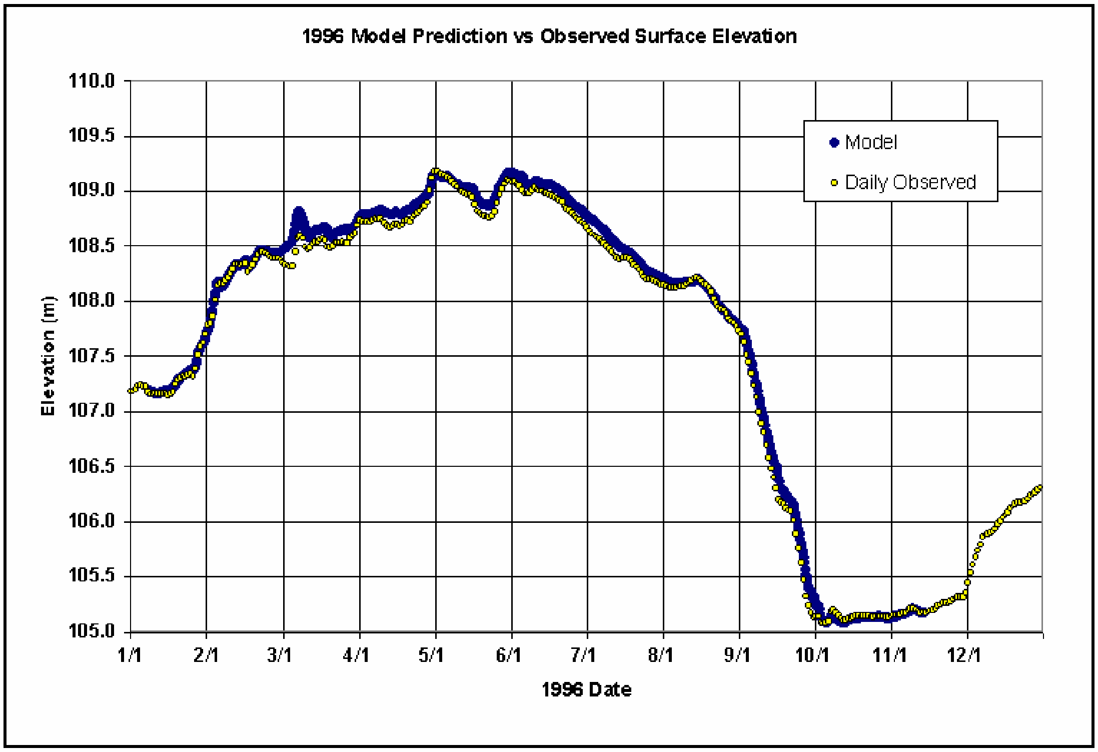


Figure 6-2. 1996 Modeled and Measured Lake Murray Headwater Elevations

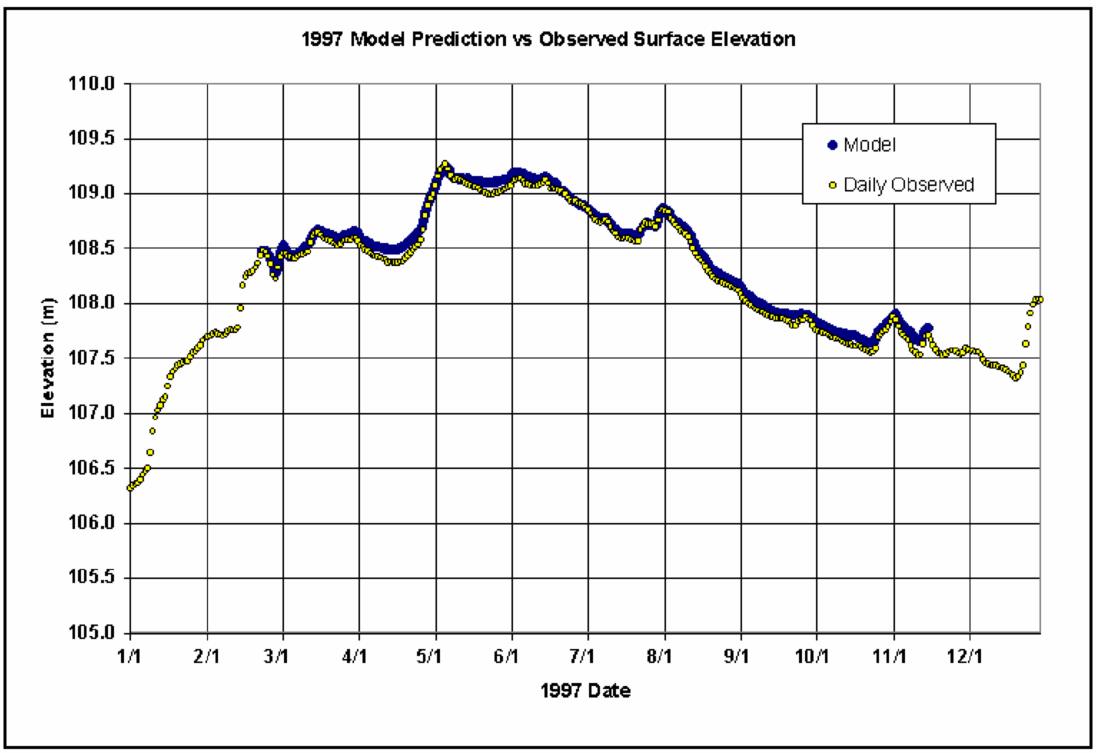


Figure 6-3. 1997 Modeled and Measured Lake Murray Headwater Elevations

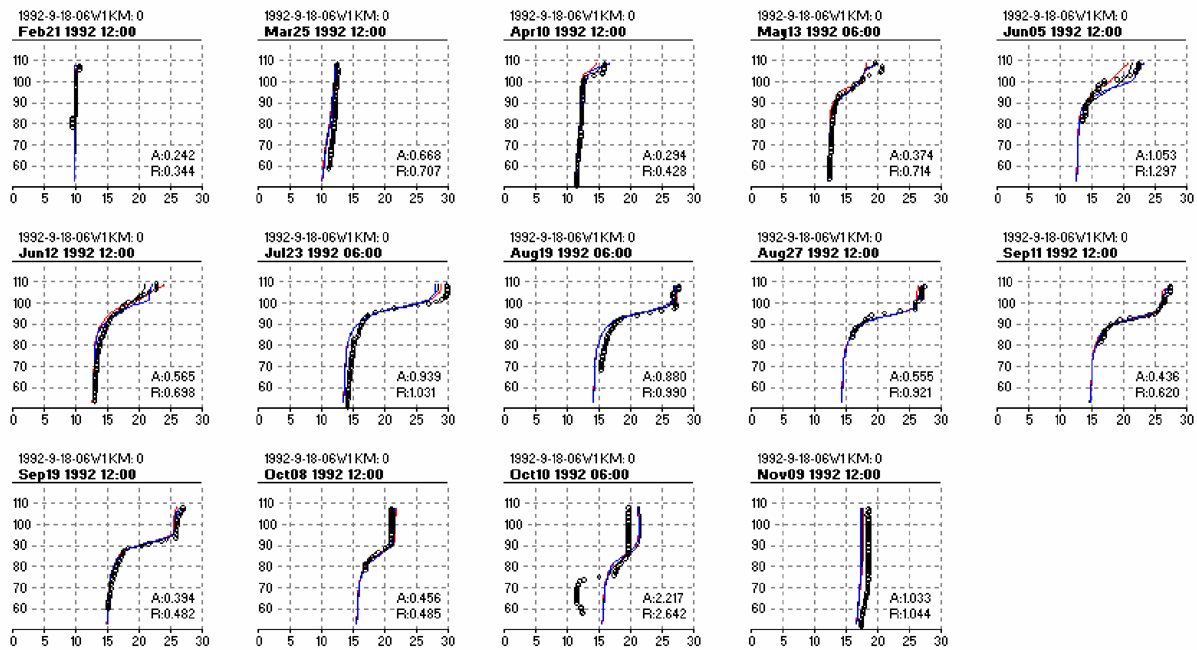


Figure 6-4. 1992 Modeled and Observed Temperature Profiles in the Forebay of Lake Murray; Overall Statistics: ABS = 0.75, RMS = 1.07

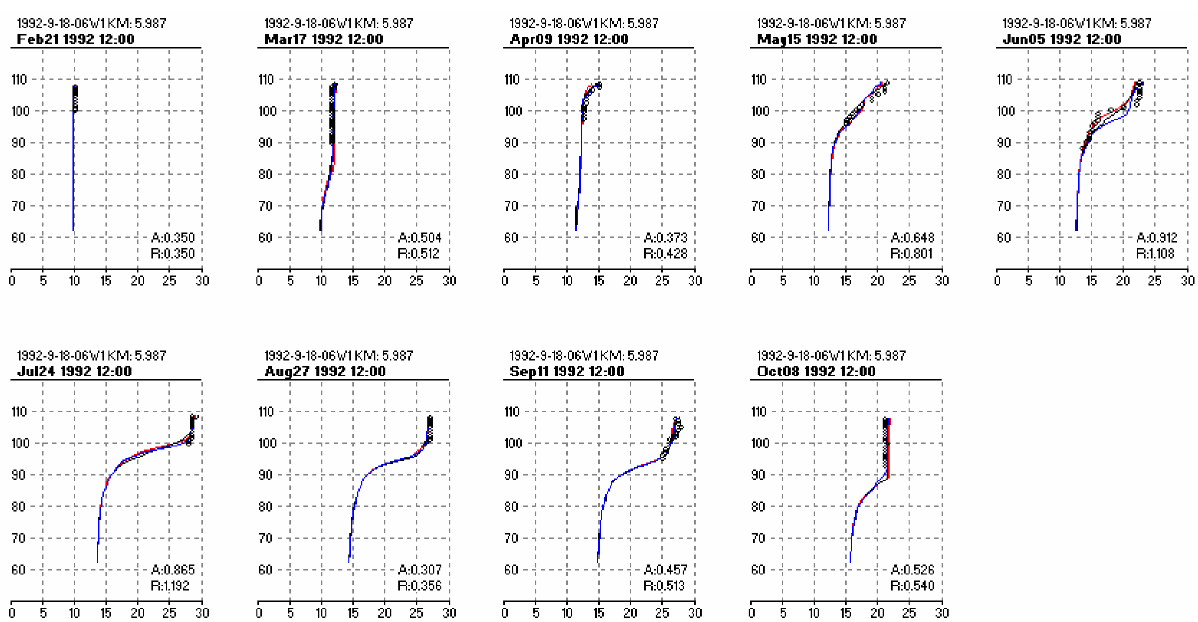


Figure 6-5. 1992 Modeled and Observed Temperature Profiles Six Kilometers Upstream of Saluda Dam; Overall Statistics: ABS = 0.58, RMS = 0.73

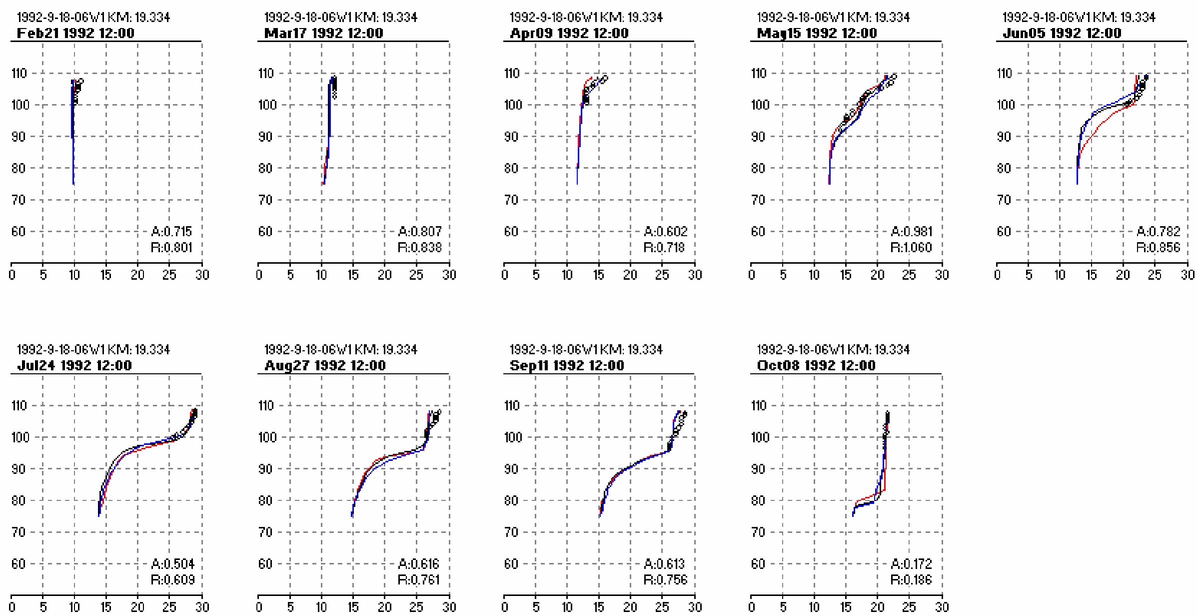


Figure 6-6. 1992 Modeled and Observed Temperature Profiles 19 Kilometers Upstream of Saluda Dam; Overall Statistics: ABS = 0.66, RMS = 0.78

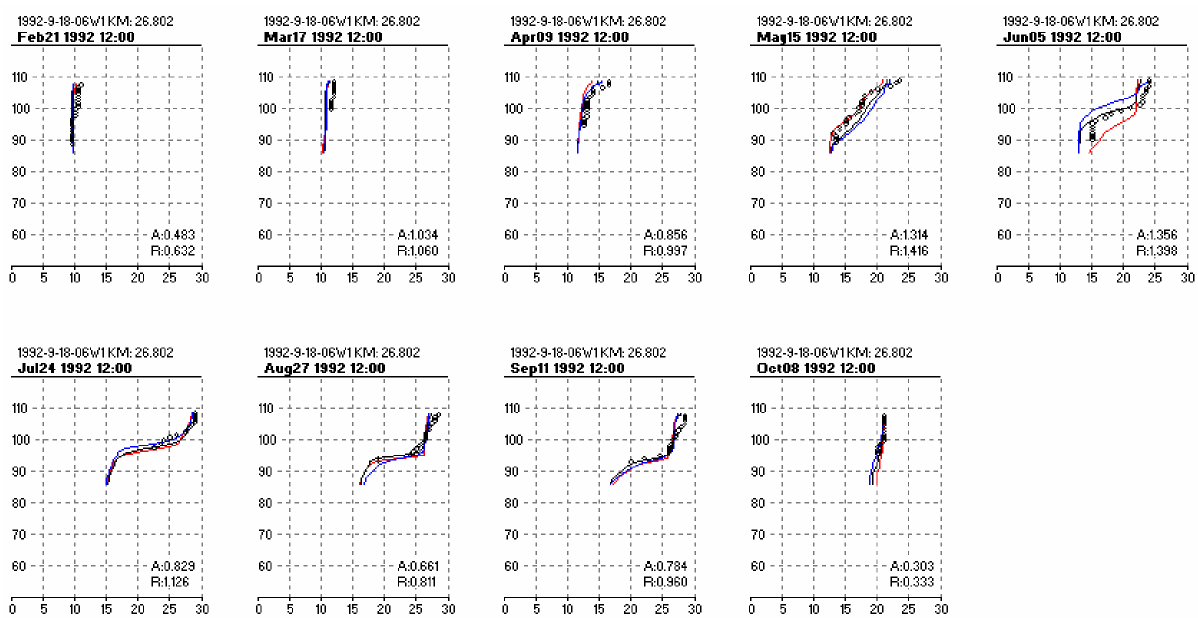


Figure 6-7. 1992 Modeled and Observed Temperature Profiles 27 Kilometers Upstream of Saluda Dam; Overall Statistics: ABS = 0.87, RMS = 1.05

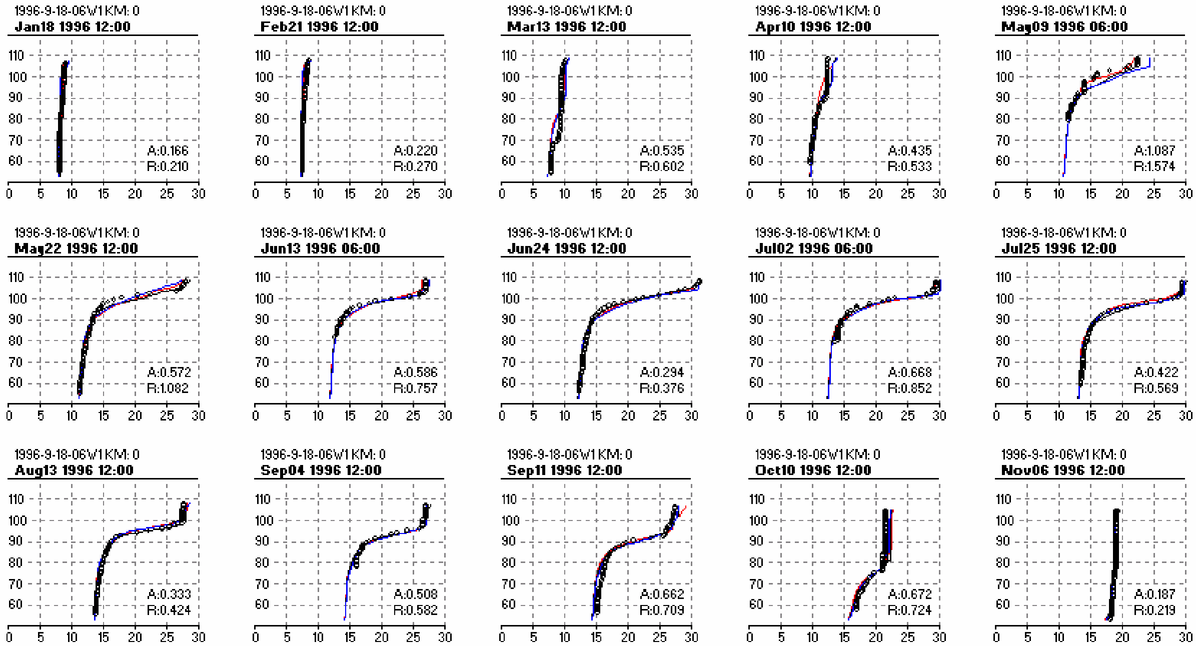


Figure 6-8. 1996 Modeled and Observed Temperature Profiles in the Forebay of Lake Murray; Overall Statistics: ABS = 0.46, RMS = 0.66

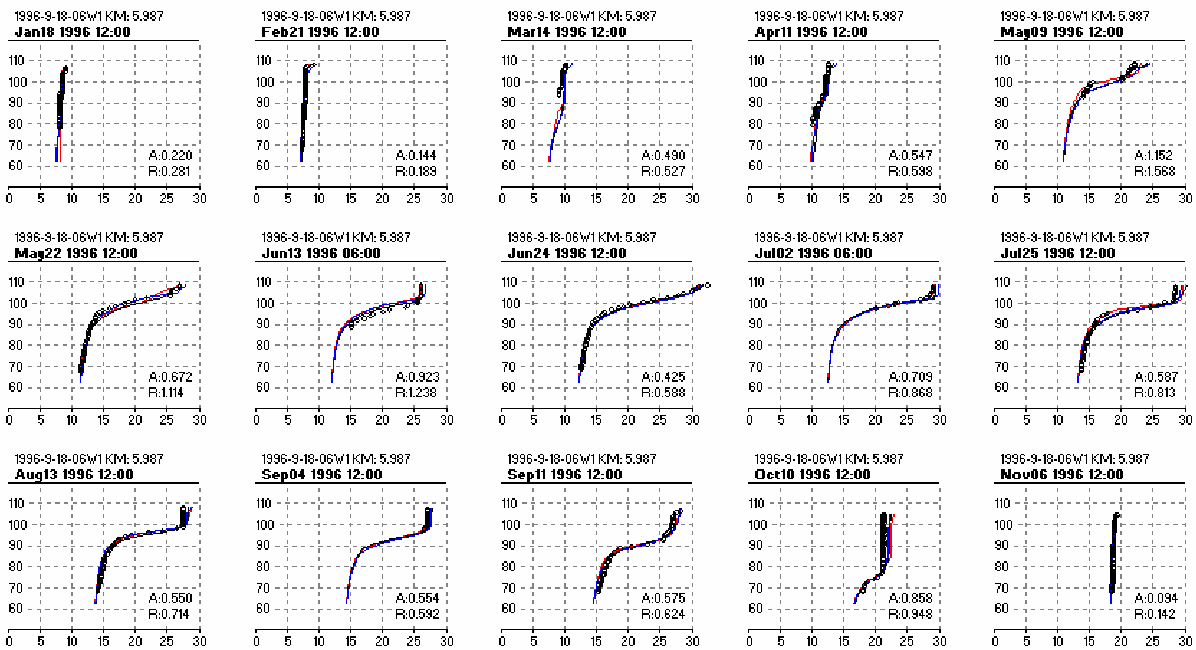


Figure 6-9. 1996 Modeled and Observed Temperature Profiles Six Kilometers Upstream of Saluda Dam; Overall Statistics: ABS = 0.53, RMS = 0.77

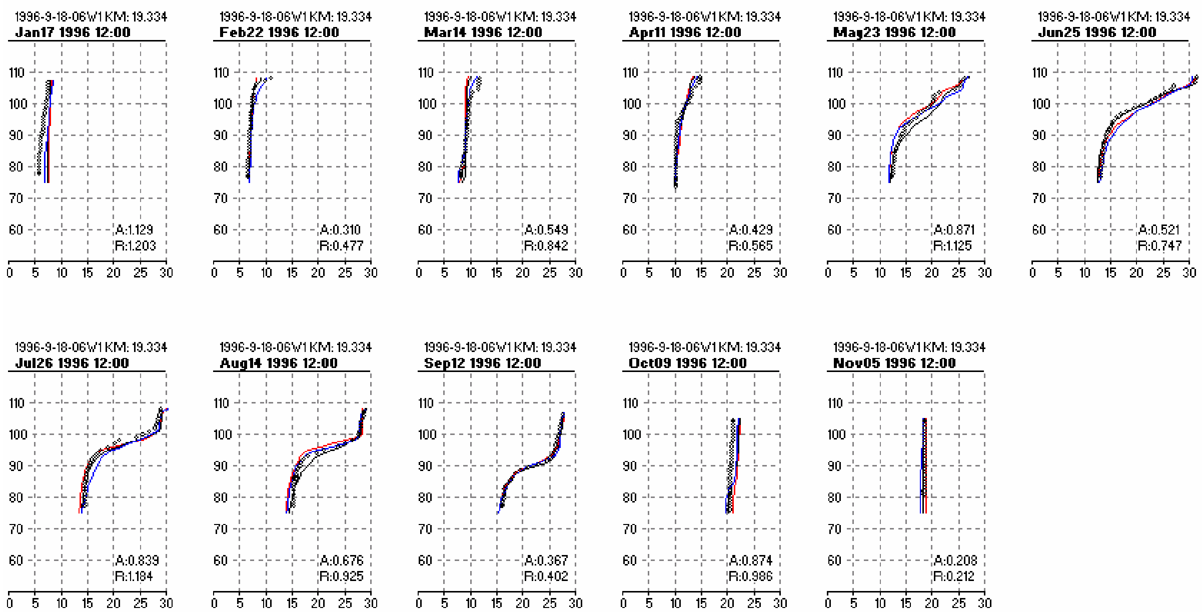


Figure 6-10. 1996 Modeled and Observed Temperature Profiles 19 Kilometers Upstream of Saluda Dam; Overall Statistics: ABS = 0.62, RMS = 0.85

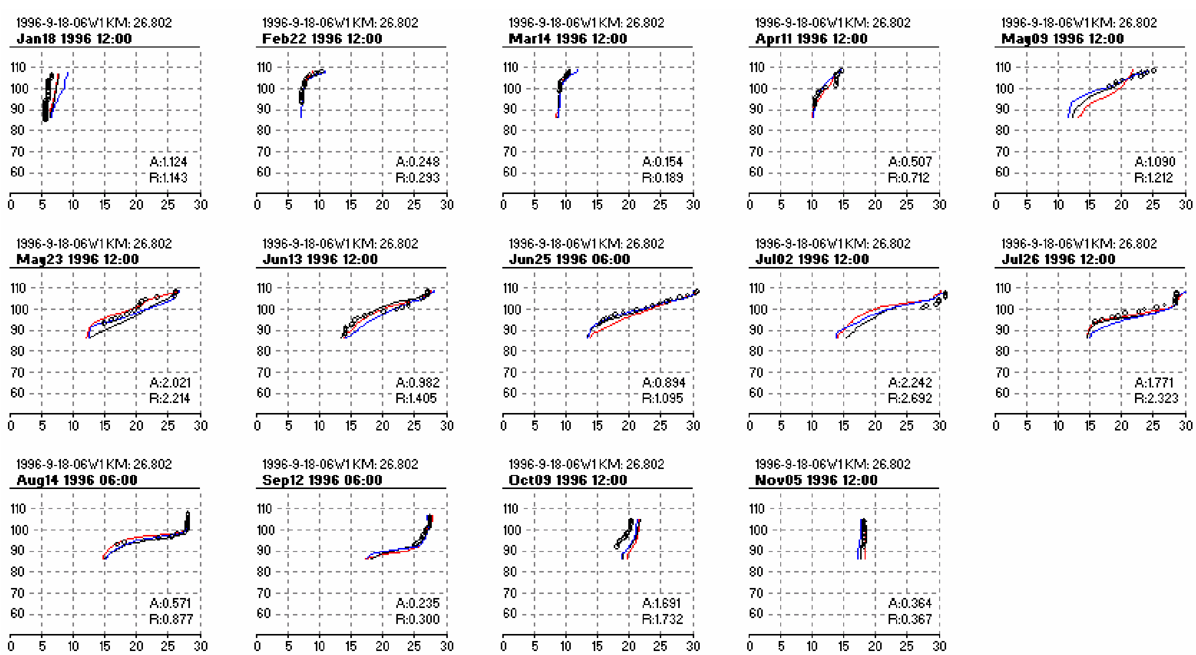


Figure 6-11. 1996 Modeled and Observed Temperature Profiles 27 Kilometers Upstream of Saluda Dam; Overall Statistics: ABS = 0.98, RMS = 1.38

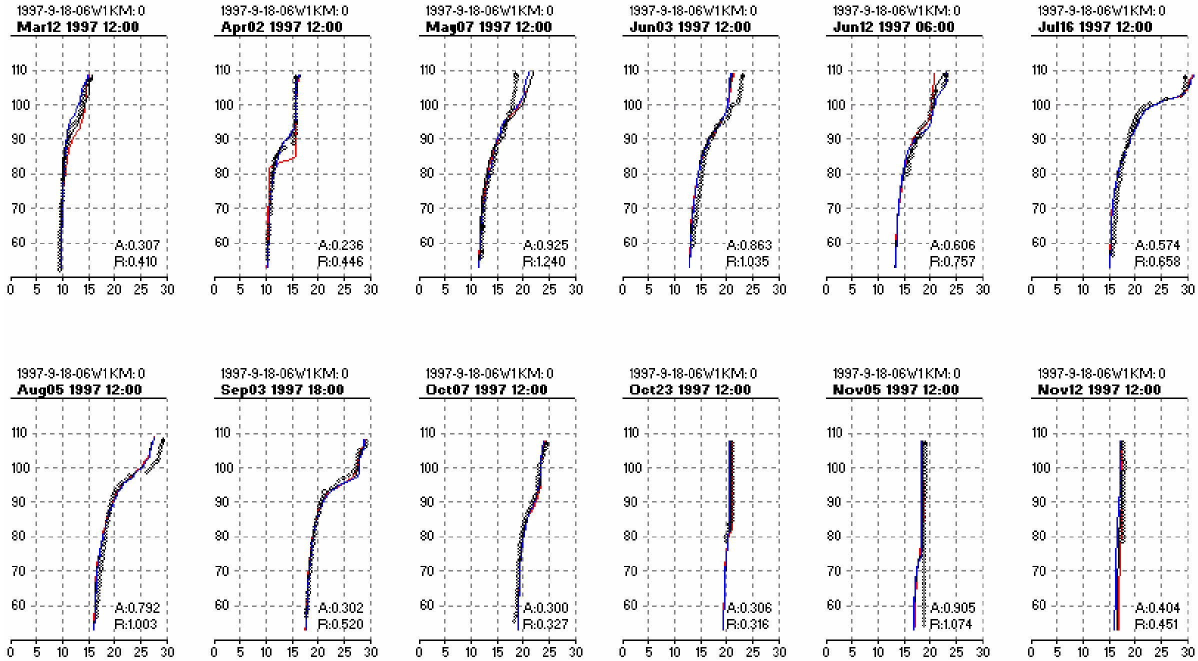


Figure 6-12. 1997 Modeled and Observed Temperature Profiles in the Forebay of Lake Murray; Overall Statistics: ABS = 0.56, RMS = 0.78

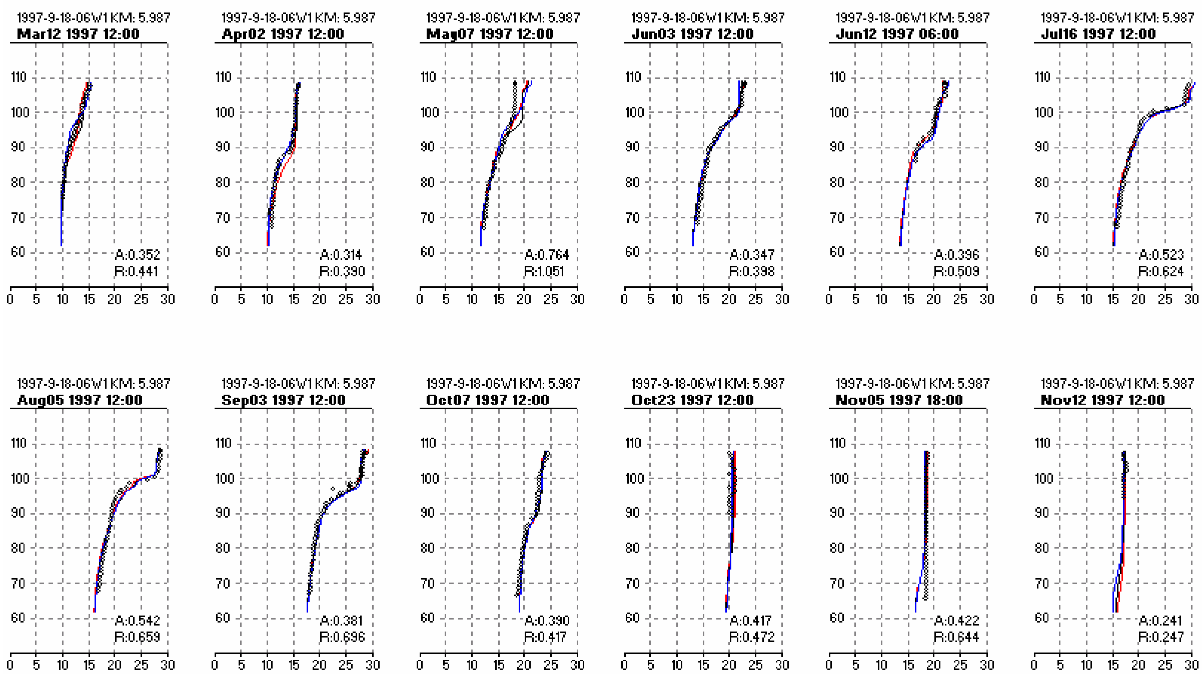


Figure 6-13. 1997 Modeled and Observed Temperature Profiles Six Kilometers Upstream of Saluda Dam; Overall Statistics: ABS = 0.44, RMS = 0.61

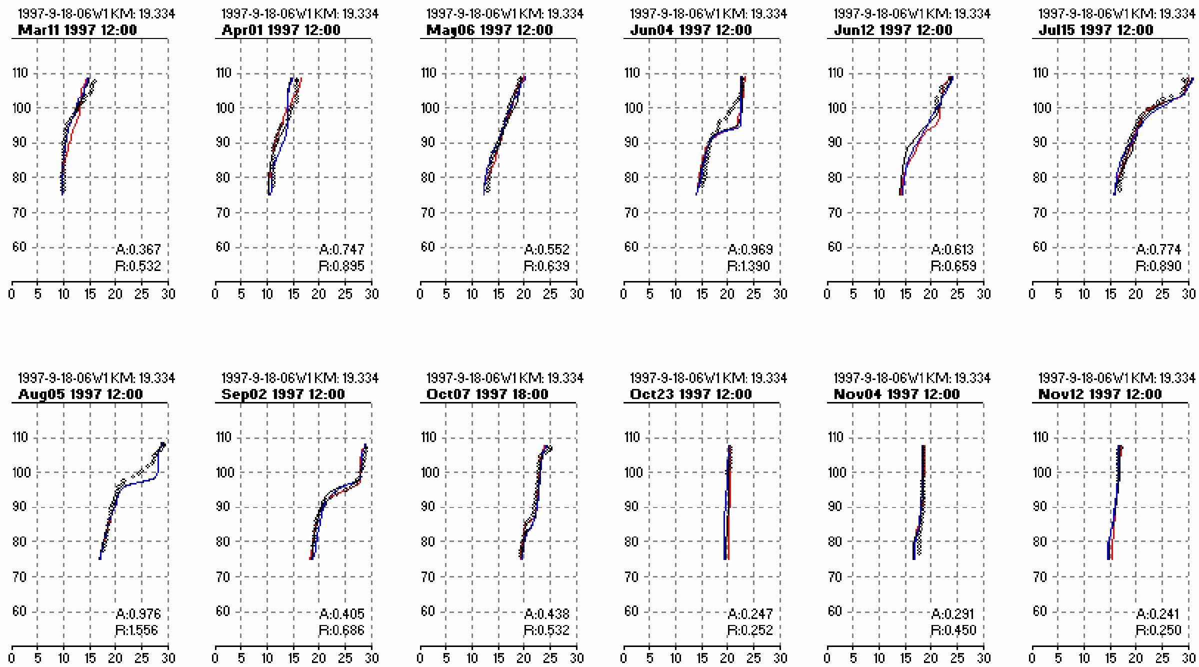


Figure 6-14. 1997 Modeled and Observed Temperature Profiles 19 Kilometers Upstream of Saluda Dam; Overall Statistics: ABS = 0.59, RMS = 0.88

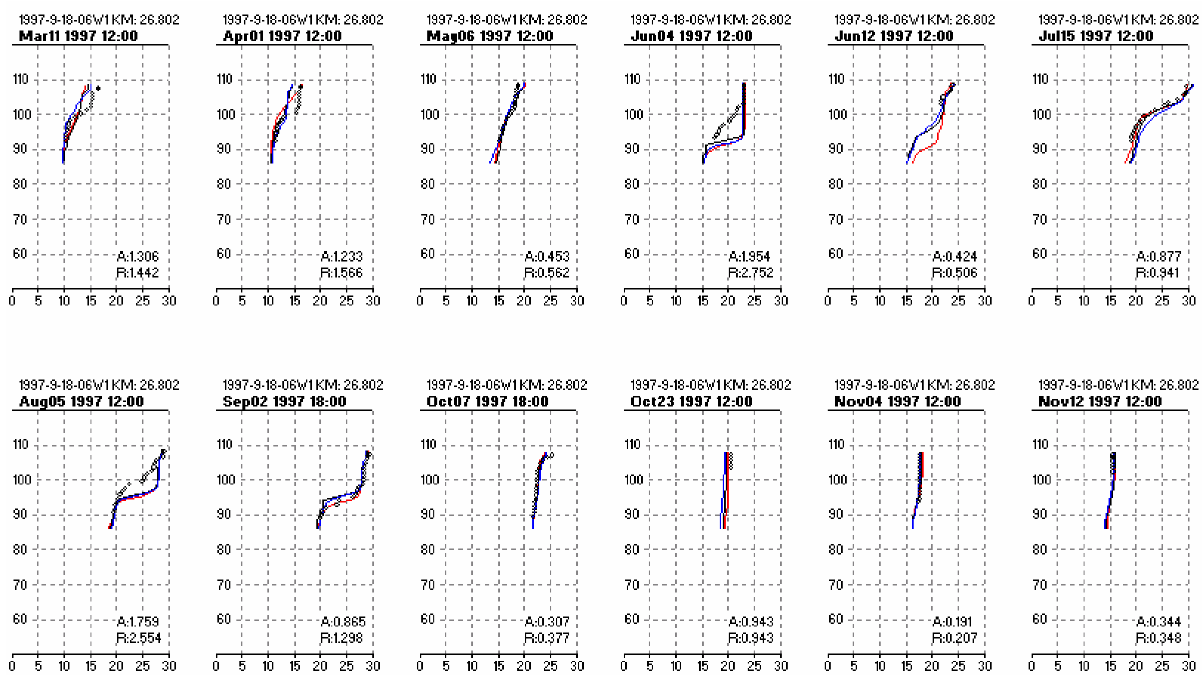


Figure 6-15. 1997 Modeled and Observed Temperature Profiles 27 Kilometers Upstream of Saluda Dam; Overall Statistics: ABS = 0.95, RMS = 1.50

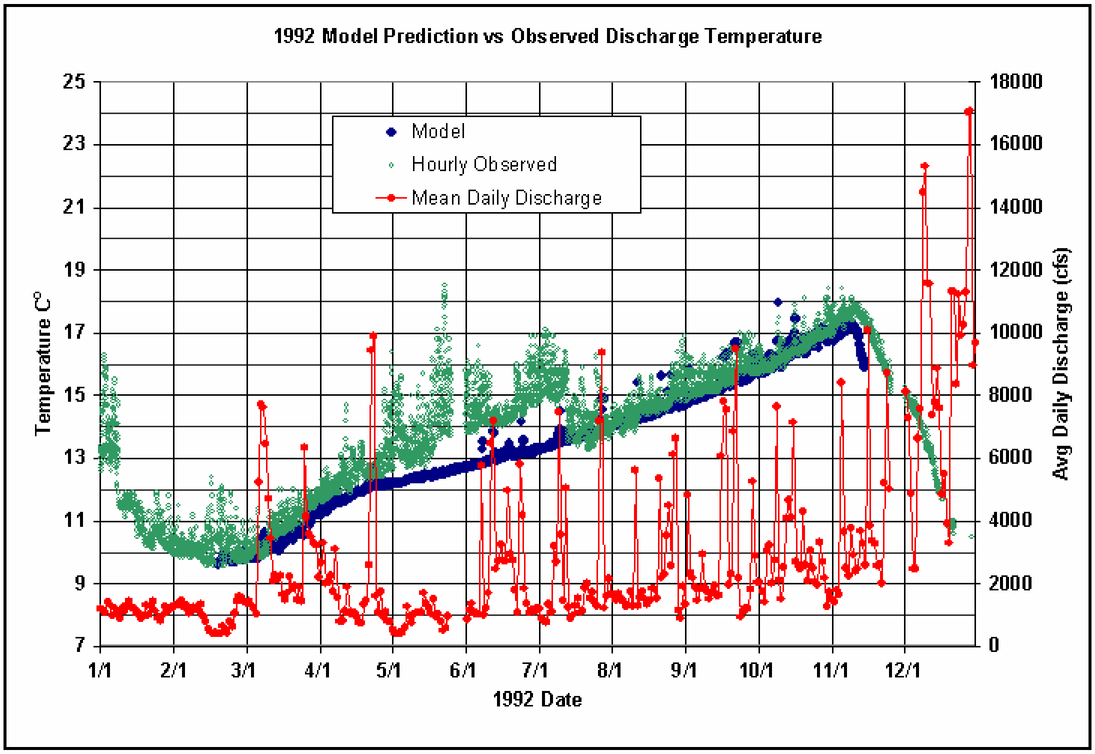


Figure 6-16. 1992 Comparison of Modeled versus Measured Saluda Release Temperatures

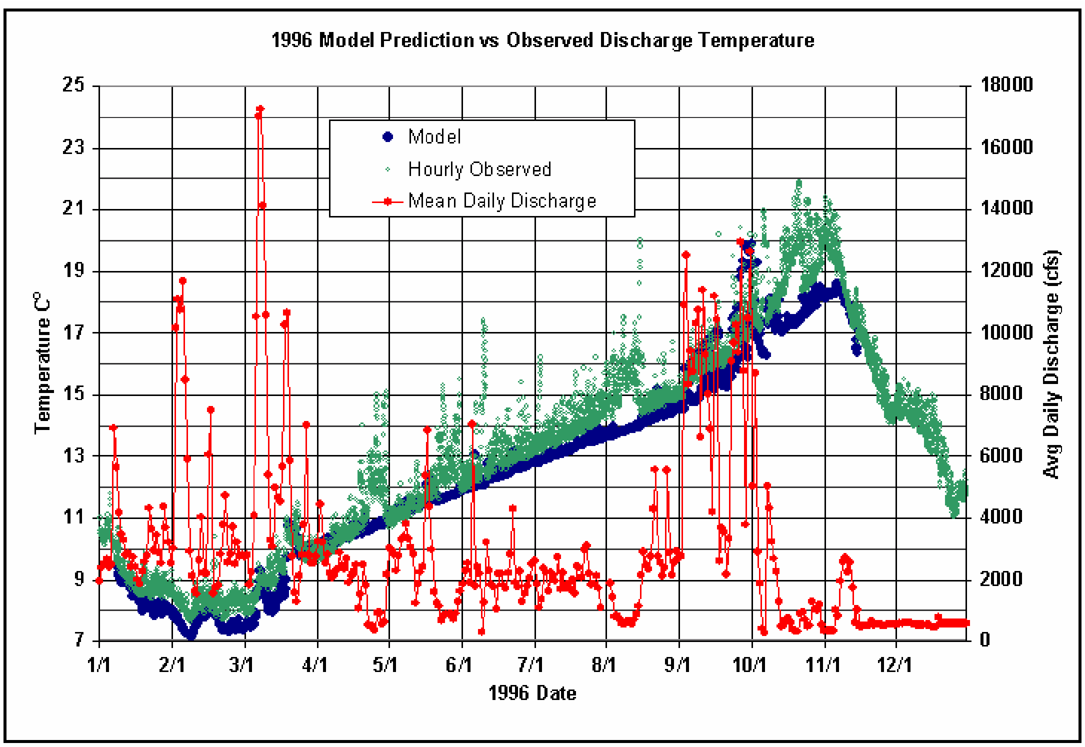


Figure 6-17. 1996 Comparison of Modeled versus Measured Saluda Release Temperatures

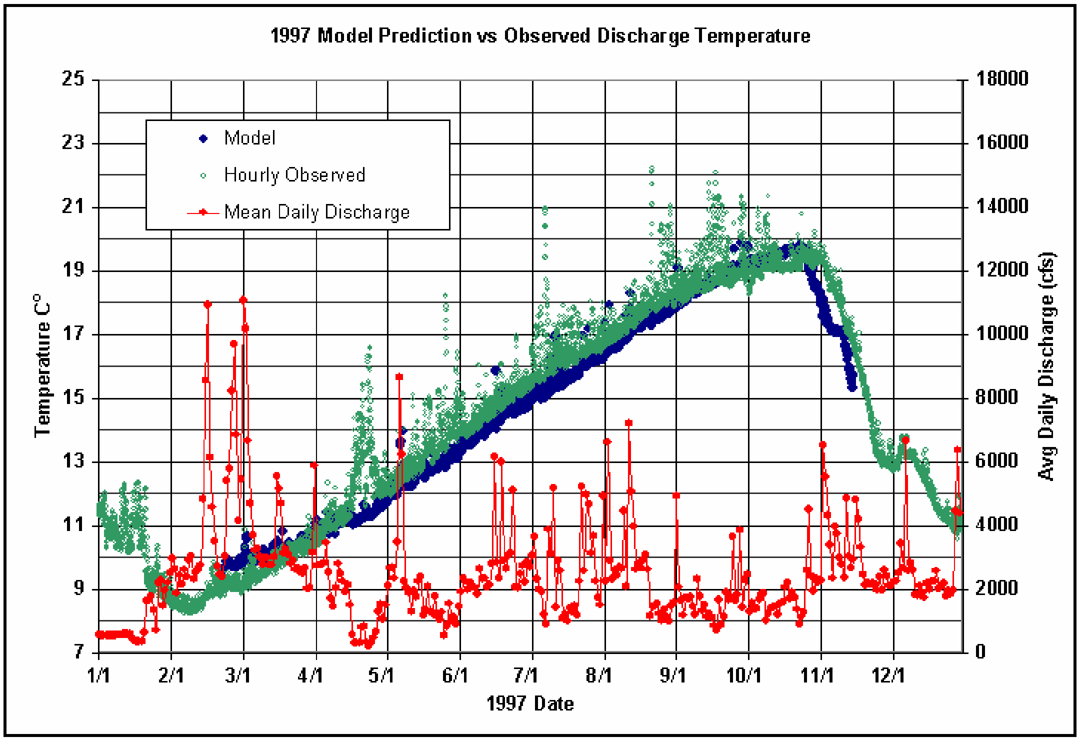


Figure 6-18. 1997 Comparison of Modeled versus Measured Saluda Release Temperatures

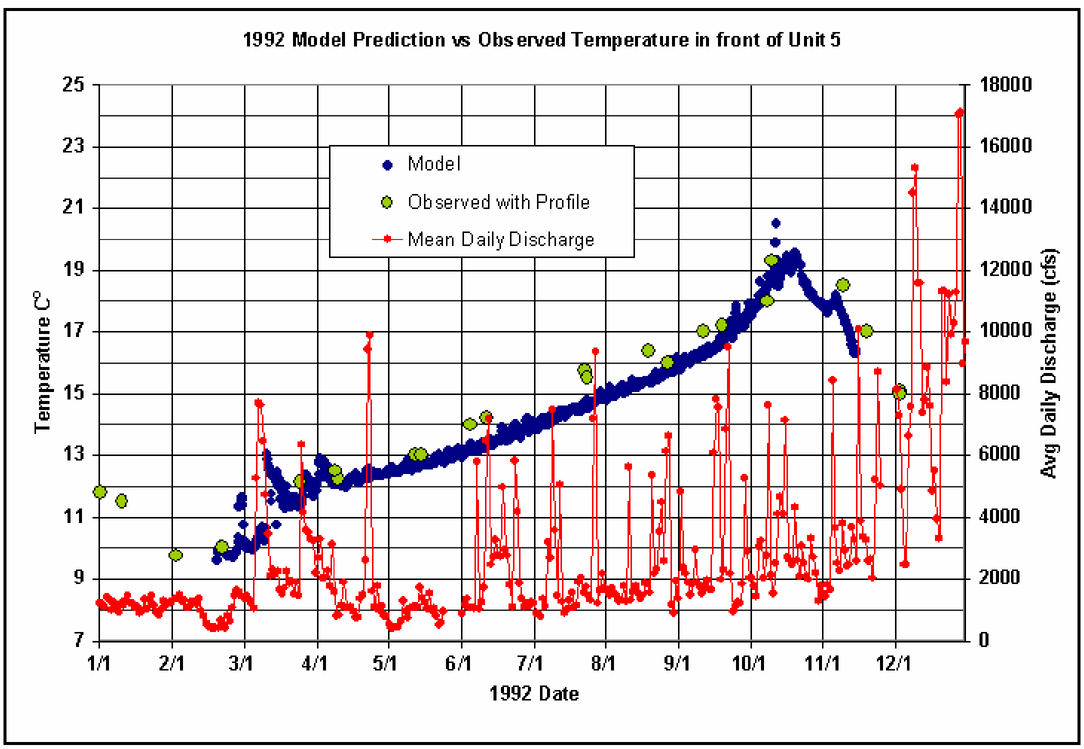


Figure 6-19. 1992 Comparison of Modeled versus Measured Temperature in Front of the Unit 5 Intake

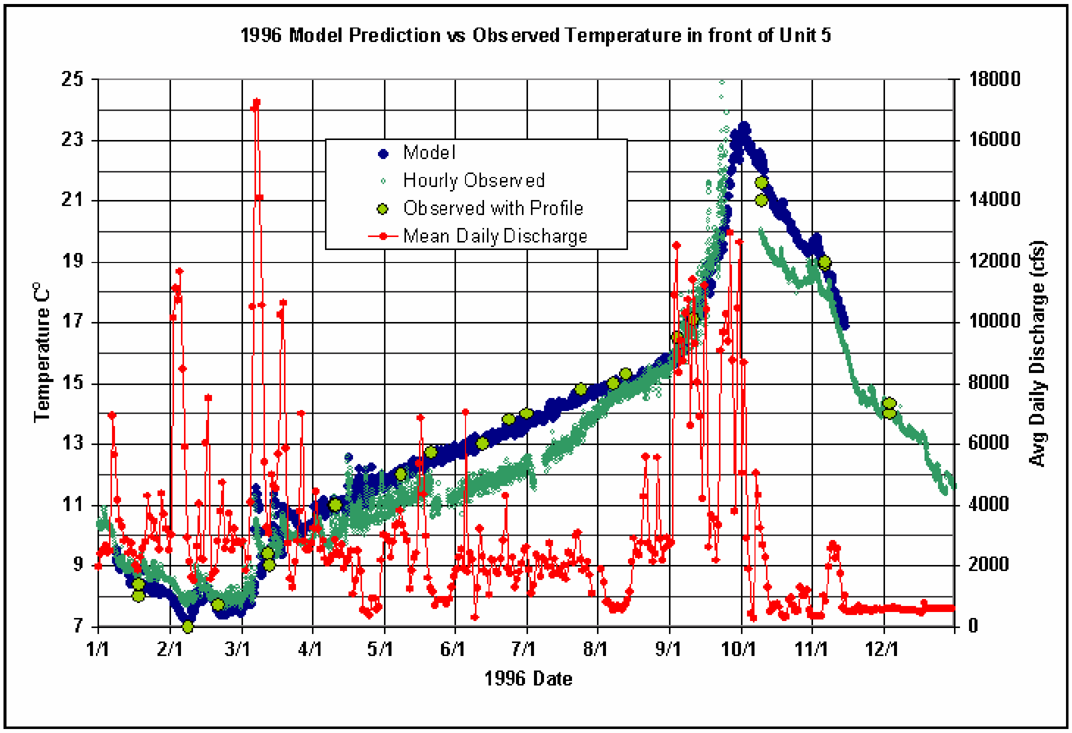


Figure 6-20. 1996 Comparison of Modeled versus Measured Temperature in Front of the Unit 5 Intake

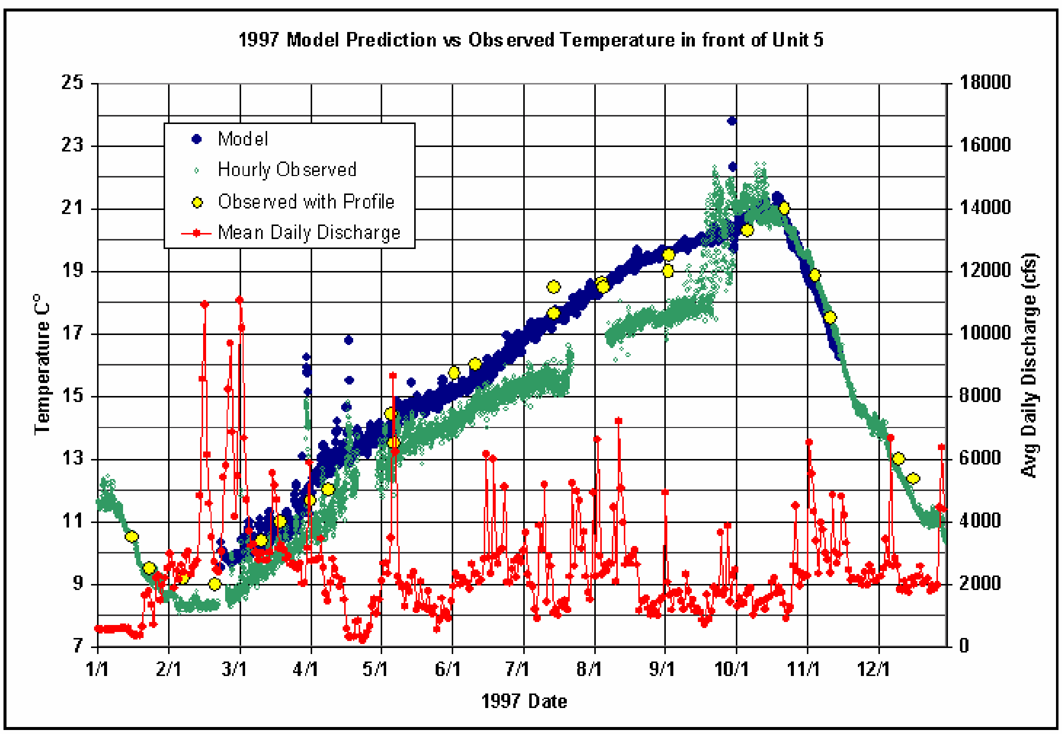


Figure 6-21. 1997 Comparison of Modeled versus Measured Temperature in Front of the Unit 5 Intake

Table 6-5. 1992 Temperature Statistics

1992 Temperature

		Kilometers From Dam									
		0.0		6.0		19.3		26.8		Average	
Date	**Julian Day**	**AME**	**RMS**	**AME**	**RMS**	**AME**	**RMS**	**AME**	**RMS**	**AME**	**RMS**
2/21	**52**	0.24	0.34	0.35	0.35	0.72	0.80	0.48	0.63	**0.45**	**0.53**
3/17	**77**			0.50	0.51	0.81	0.84	1.03	1.06	**0.78**	**0.80**
3/25	**85**	0.67	0.71							**0.67**	**0.71**
4/9-10	**100-101**	0.29	0.43	0.37	0.43	0.60	0.72	0.86	1.00	**0.53**	**0.64**
5/13	**134**	0.37	0.71							**0.37**	**0.71**
5/15	**136**			0.65	0.80	0.98	1.06	1.31	1.42	**0.98**	**1.09**
6/5	**157**	1.05	1.30	0.91	1.11	0.78	0.86	1.36	1.40	**1.03**	**1.16**
6/12	**164**	0.57	0.70							**0.57**	**0.70**
7/23-24	**205-206**	0.94	1.03	0.87	1.19	0.50	0.61	0.83	1.13	**0.78**	**0.99**
8/19	**232**	0.88	0.99							**0.88**	**0.99**
8/27	**240**	0.56	0.92	0.31	0.36	0.62	0.76	0.66	0.81	**0.53**	**0.71**
9/11	**255**	0.44	0.62	0.46	0.51	0.61	0.76	0.78	0.96	**0.57**	**0.71**
9/19	**263**	0.39	0.48							**0.39**	**0.48**
10/8	**282**	0.46	0.49	0.53	0.54	0.17	0.19	0.30	0.33	**0.36**	**0.39**
10/10	**284**	2.22	2.64							**2.22**	**2.64**
11/9	**314**	1.03	1.04							**1.03**	**1.04**
	Overall	**0.75**	**1.07**	**0.58**	**0.73**	**0.66**	**0.78**	**0.87**	**1.05**	**0.75**	**1.06**

Table 6-6. 1996 Temperature Statistics

1996 Temperature

		Kilometers From Dam									
		0.0		6.0		19.3		26.8		Average	
Date	Julian Day	AME	RMS	AME	RMS	AME	RMS	AME	RMS	AME	RMS
1/17-18	17-18	0.17	0.21	0.22	0.28	1.13	1.20	1.12	1.14	**0.66**	**0.71**
2/21-22	52-53	0.22	0.27	0.14	0.19	0.31	0.48	0.25	0.29	**0.23**	**0.31**
3/13-14	73-74	0.54	0.61	0.49	0.53	0.55	0.84	0.15	0.19	**0.43**	**0.54**
4/10-11	101-103	0.44	0.52	0.55	0.60	0.43	0.57	0.51	0.71	**0.48**	**0.60**
5/9-10	130-131	1.09	1.61	1.15	1.57			1.09	1.21	**1.11**	**1.46**
5/22-23	143-144	0.57	1.09	0.67	1.11	0.87	1.13	2.02	2.21	**1.03**	**1.39**
6/13	165	0.59	0.78	0.92	1.24			0.98	1.41	**0.83**	**1.14**
6/24-25	176-177	0.29	0.38	0.43	0.59	0.52	0.75	0.89	1.10	**0.53**	**0.70**
7/2	184	0.67	0.86	0.71	0.87			2.24	2.69	**1.21**	**1.47**
7/25-26	207-208	0.42	0.58	0.59	0.81	0.84	1.18	1.77	2.32	**0.90**	**1.22**
8/13-14	226-227	0.33	0.43	0.55	0.71	0.68	0.93	0.57	0.88	**0.53**	**0.74**
9/4	248	0.51	0.58	0.55	0.59					**0.53**	**0.59**
9/11-12	255-257	0.66	0.71	0.58	0.62	0.37	0.40	0.24	0.30	**0.46**	**0.51**
10/9-10	283-284	0.67	0.72	0.86	0.95	0.87	0.99	1.69	1.73	**1.02**	**1.10**
11/5-6	310-311	0.19	0.21	0.09	0.14	0.21	0.21	0.36	0.37	**0.21**	**0.23**
	Overall	**0.46**	**0.66**	**0.53**	**0.77**	**0.62**	**0.86**	**0.98**	**1.38**	**0.57**	**0.85**

Table 6-7. 1997 Temperature Statistics

1997 Temperature

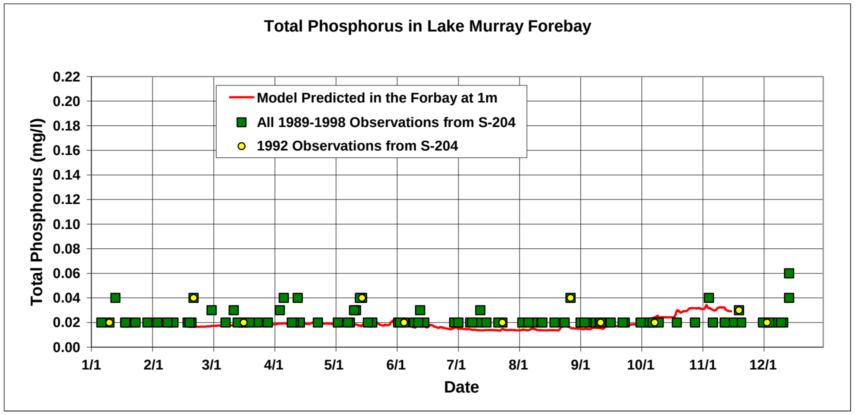
		Kilometers From Dam									
		0.0		6.0		19.3		26.8		Average	
Date	Julian Day	AME	RMS	AME	RMS	AME	RMS	AME	RMS	AME	RMS
3/12	71	0.31	0.41	0.35	0.44	0.37	0.53	1.31	1.44	**0.58**	**0.71**
4/2	92	0.24	0.45	0.31	0.39	0.75	0.90	1.23	1.57	**0.63**	**0.82**
5/6-7	126-127	0.93	1.24	0.76	1.05	0.55	0.64	0.45	0.56	**0.67**	**0.87**
6/3-4	154-155	0.86	1.04	0.35	0.40	0.97	1.39	1.95	2.75	**1.03**	**1.39**
6/12	163	0.61	0.76	0.40	0.51	0.61	0.66	0.42	0.51	**0.51**	**0.61**
7/15-16	196-197	0.57	0.66	0.52	0.62	0.77	0.89	0.88	0.94	**0.69**	**0.78**
8/5	217	0.79	1.00	0.54	0.66	0.98	1.56	1.76	2.55	**1.02**	**1.44**
9/2-3	245-246	0.30	0.52	0.38	0.70	0.41	0.69	0.87	1.30	**0.49**	**0.80**
10/7	280	0.30	0.33	0.39	0.42	0.44	0.53	0.31	0.38	**0.36**	**0.41**
10/23	296	0.31	0.32	0.42	0.47	0.25	0.25	0.94	0.94	**0.48**	**0.50**
11/4-5	309	0.91	1.07	0.42	0.64	0.29	0.45	0.19	0.21	**0.45**	**0.59**
11/12	316	0.40	0.45	0.24	0.25	0.24	0.25	0.34	0.35	**0.31**	**0.32**
	Overall	**0.56**	**0.78**	**0.44**	**0.61**	**0.59**	**0.88**	**0.95**	**1.50**	**0.58**	**0.87**

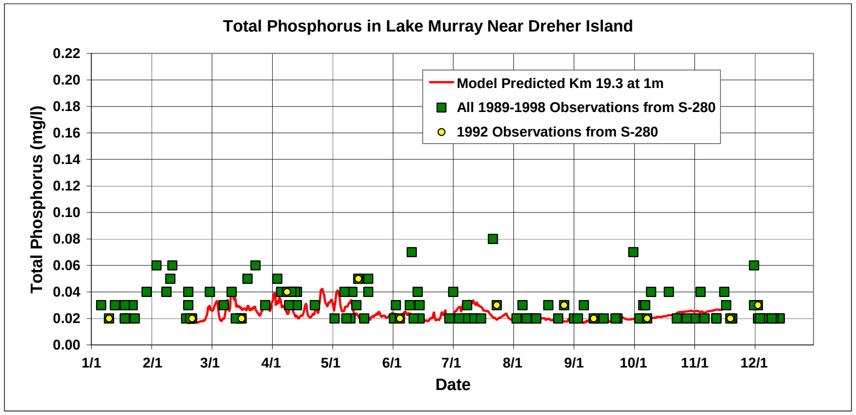
Water Quality Calibration

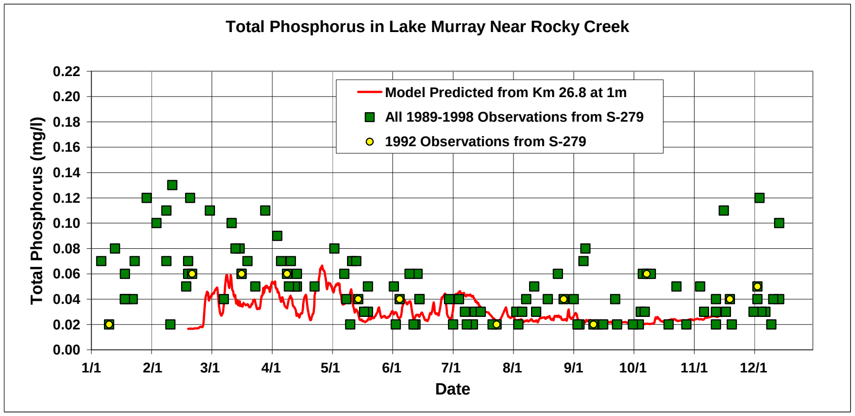
Phosphorus and Nitrate

Predicted concentrations of TP for 1992, 1996, and 1997 were compared to observed data from four locations in the reservoir and these comparisons are shown in Figure 6-22 through Figure 6-24. Figure 6-25 through Figure 6-27 show model-predicted TP in the releases from Saluda Hydro for all three years compared to observed data from the SCDHEC monitoring station in the Saluda River below Saluda Dam. The main constituent that affects the objectives for the model is TP since it is the main nutrient that affects algal growth. The model-derived TP concentrations represent normal TP levels observed in Lake Murray.

The same set of comparisons were also made for Nitrate-Nitrite, and these comparisons are shown in Figure 6-28 through Figure 6-33.







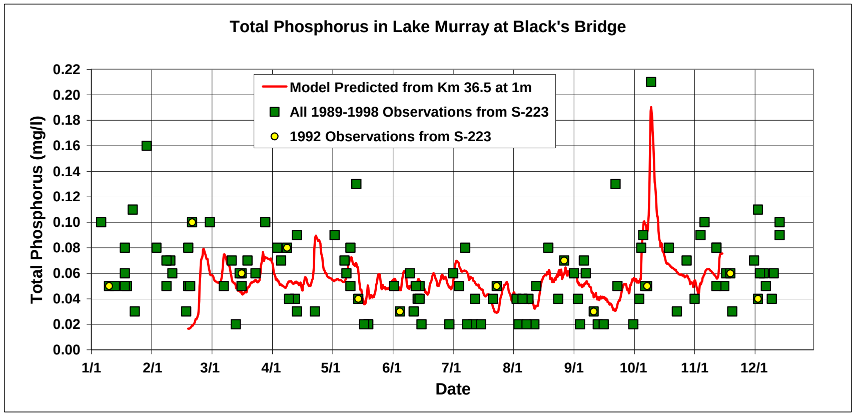


Figure 6-22. 1992 Comparison of Modeled Derived versus Measured Total Phosphorus at Four Locations in Lake Murray

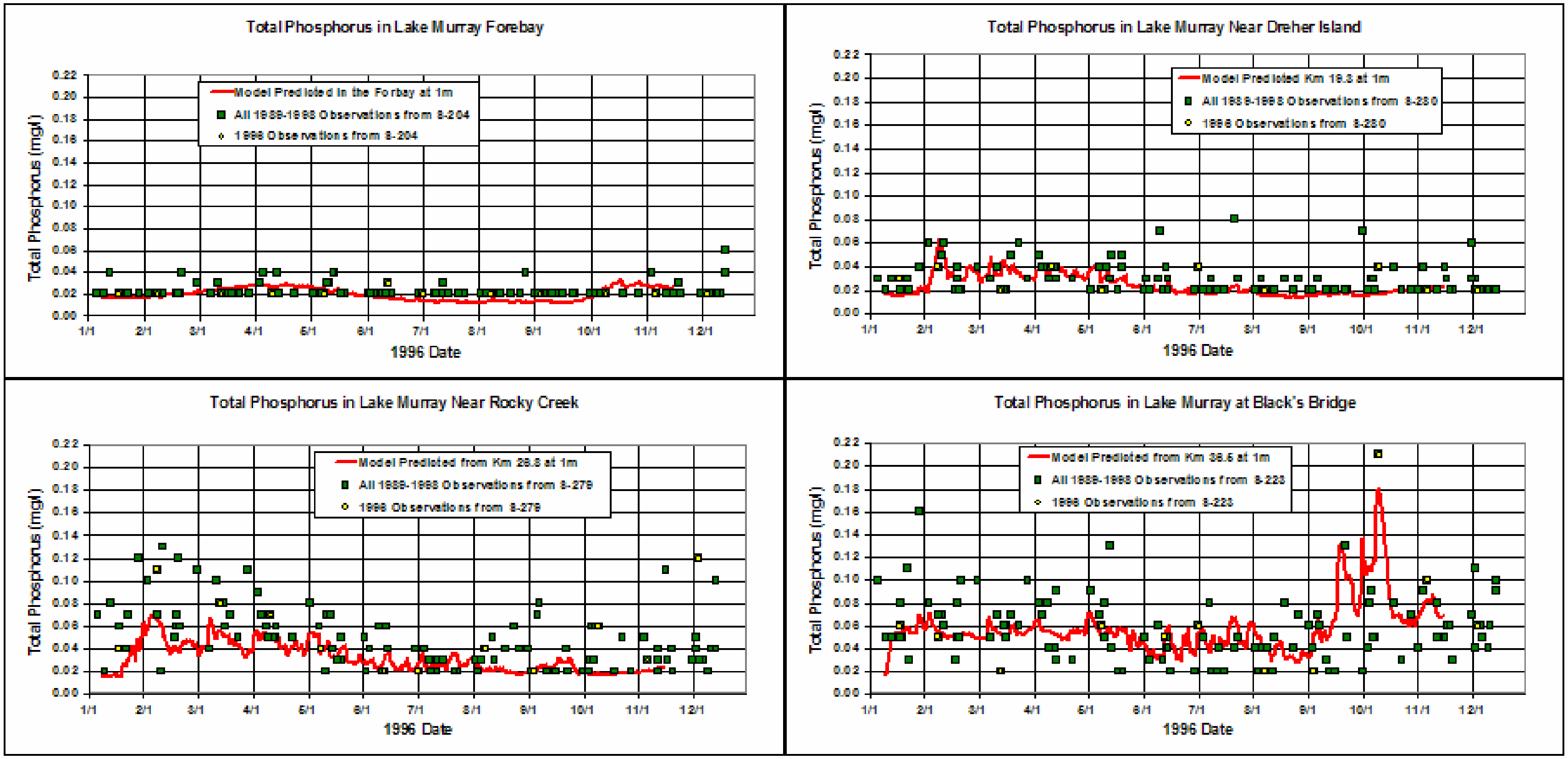


Figure 6-23. 1996 Comparison of Modeled Derived versus Measured Total Phosphorus at Four Locations in Lake Murray

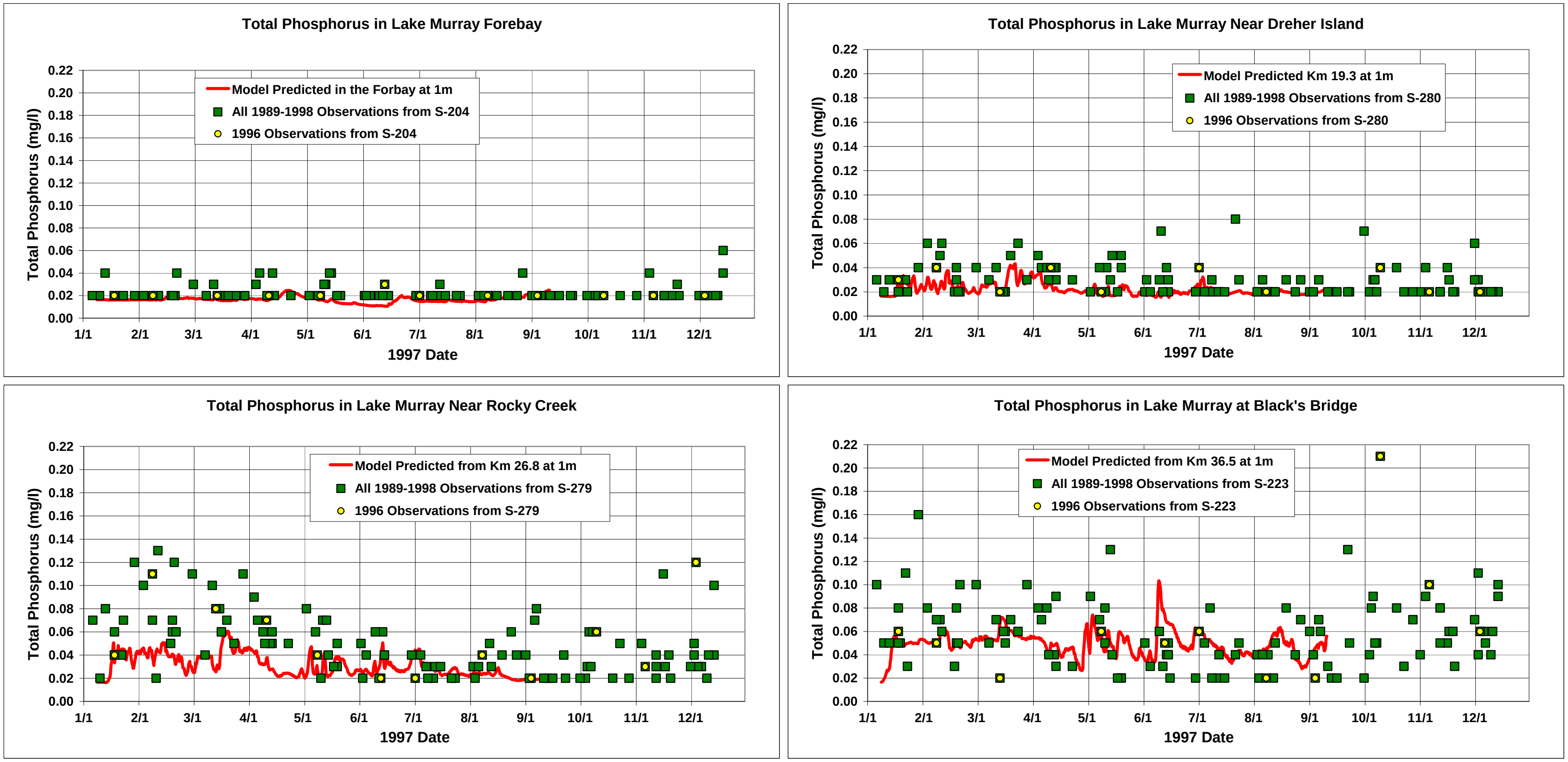


Figure 6-24. 1997 Comparison of Modeled Derived versus Measured Total Phosphorus at Four Locations in Lake Murray

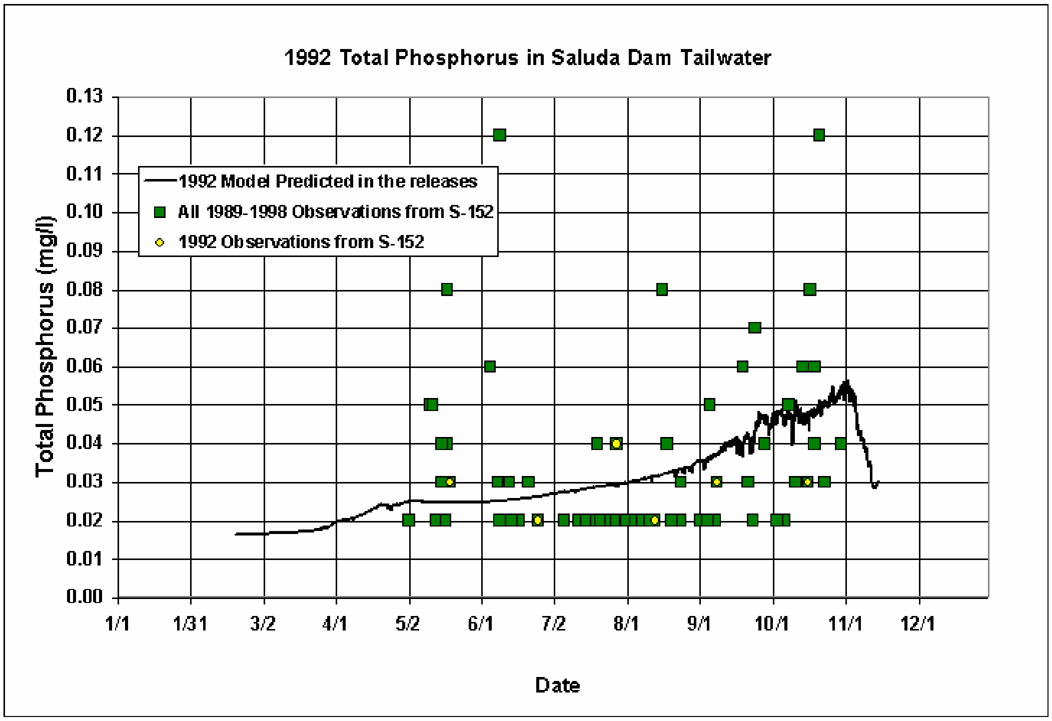


Figure 6-25. 1992 Comparison of Modeled Derived versus Measured Total Phosphorus in the Releases from Saluda Dam

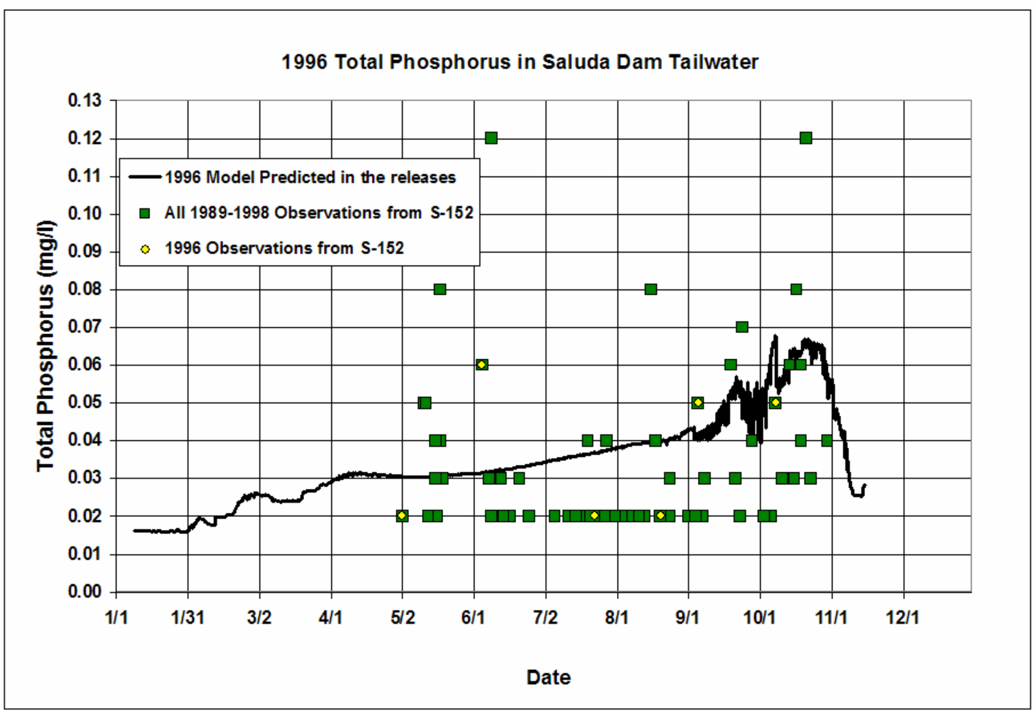


Figure 6-26. 1996 Comparison of Modeled Derived versus Measured Total Phosphorus in the Releases from Saluda Dam

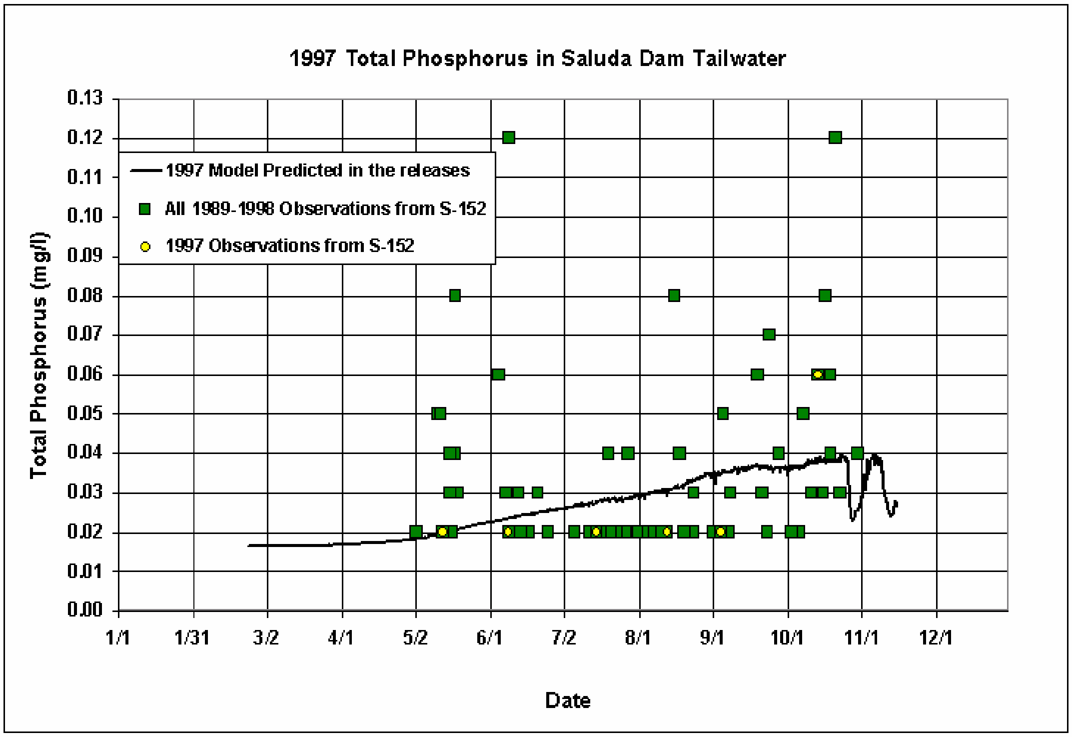


Figure 6-27. 1997 Comparison of Modeled Derived versus Measured Total Phosphorus in the Releases from Saluda Dam

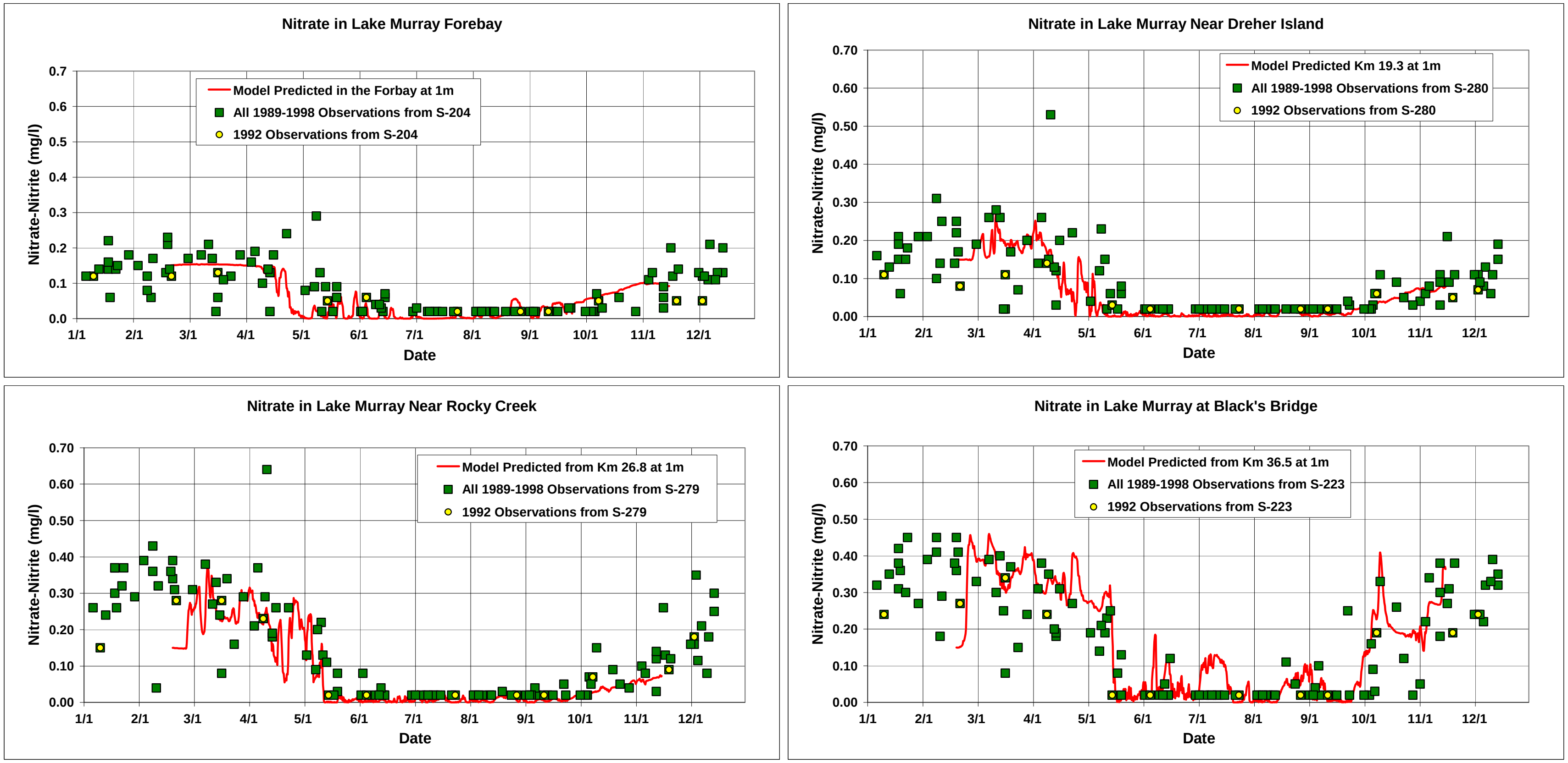


Figure 6-28. 1992 Comparison of Modeled versus Measured Nitrate-Nitrite at Four Locations in Lake Murray

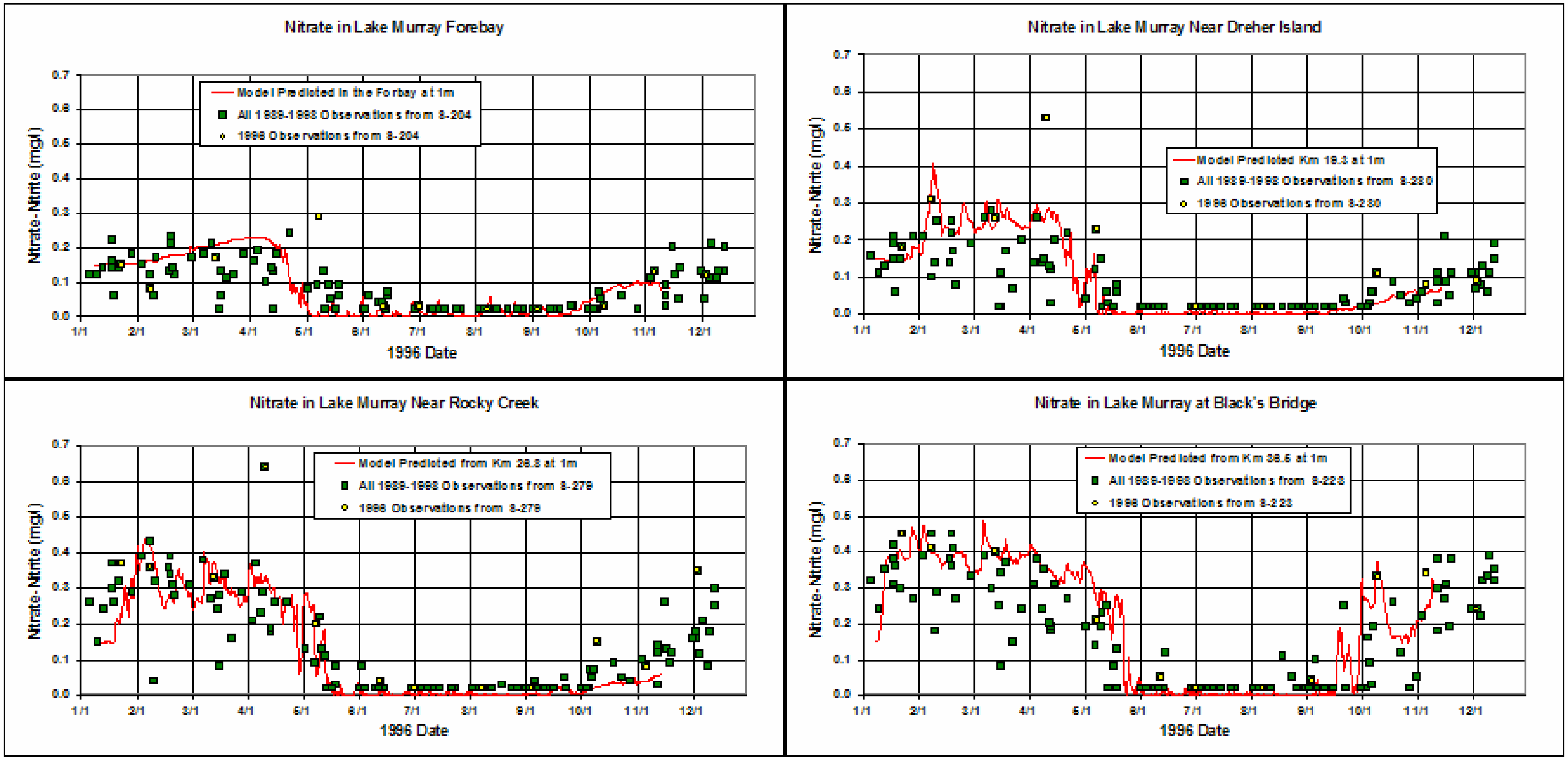


Figure 6-29. 1996 Comparison of Modeled versus Measured Nitrate-Nitrite at Four Locations in Lake Murray

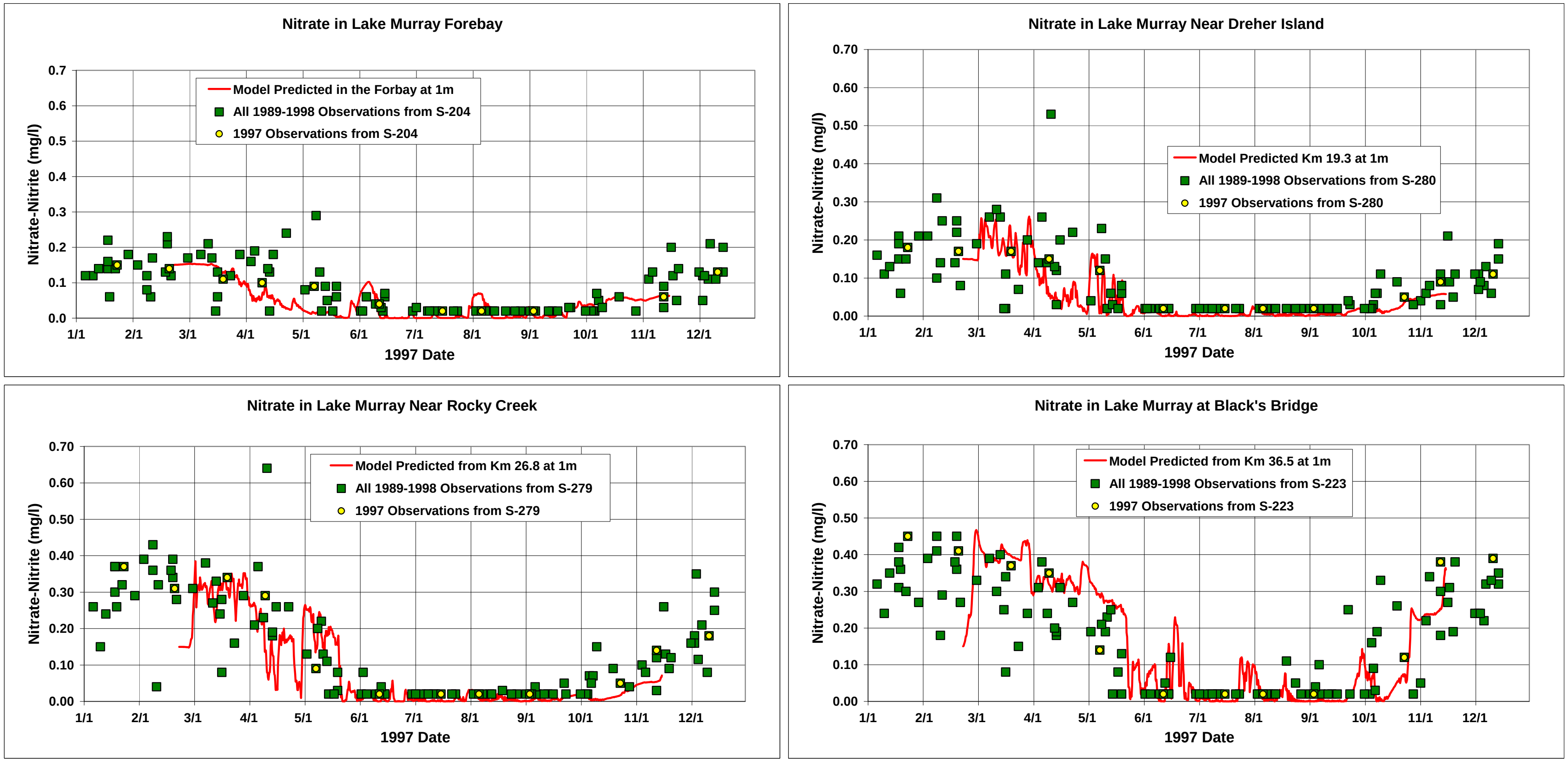


Figure 6-30. 1997 Comparison of Modeled versus Measured Nitrate-Nitrite at Four Locations in Lake Murray

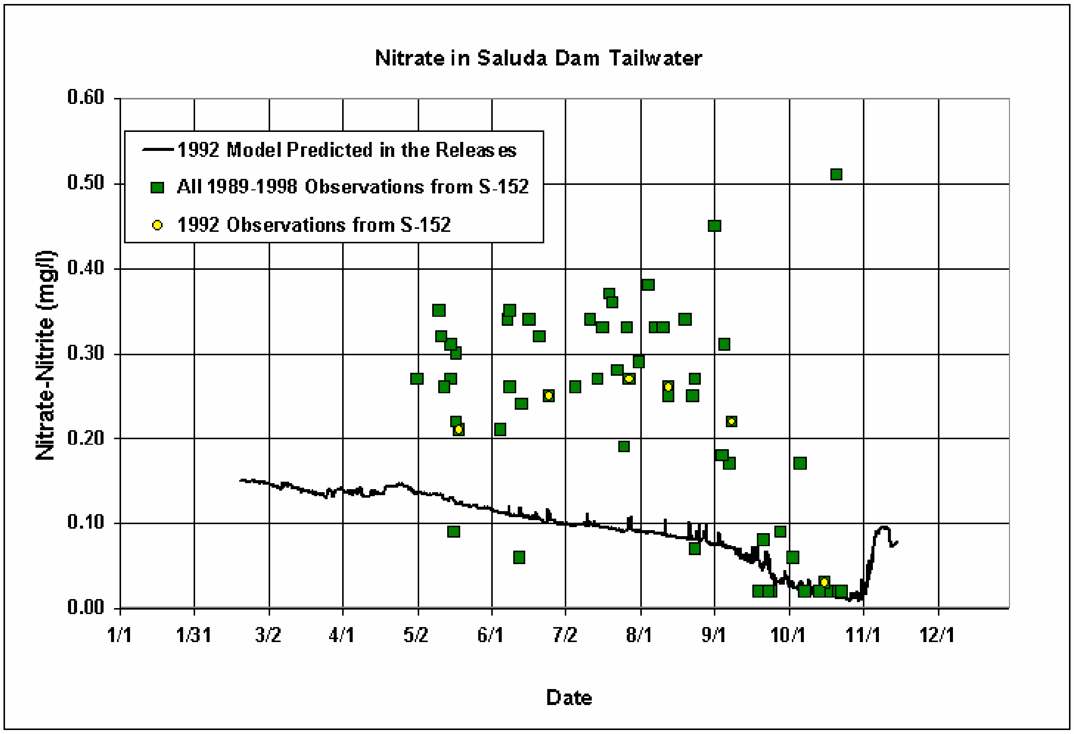


Figure 6-31. 1992 Comparison of Modeled Derived versus Measured Nitrate in the Releases from Saluda Dam

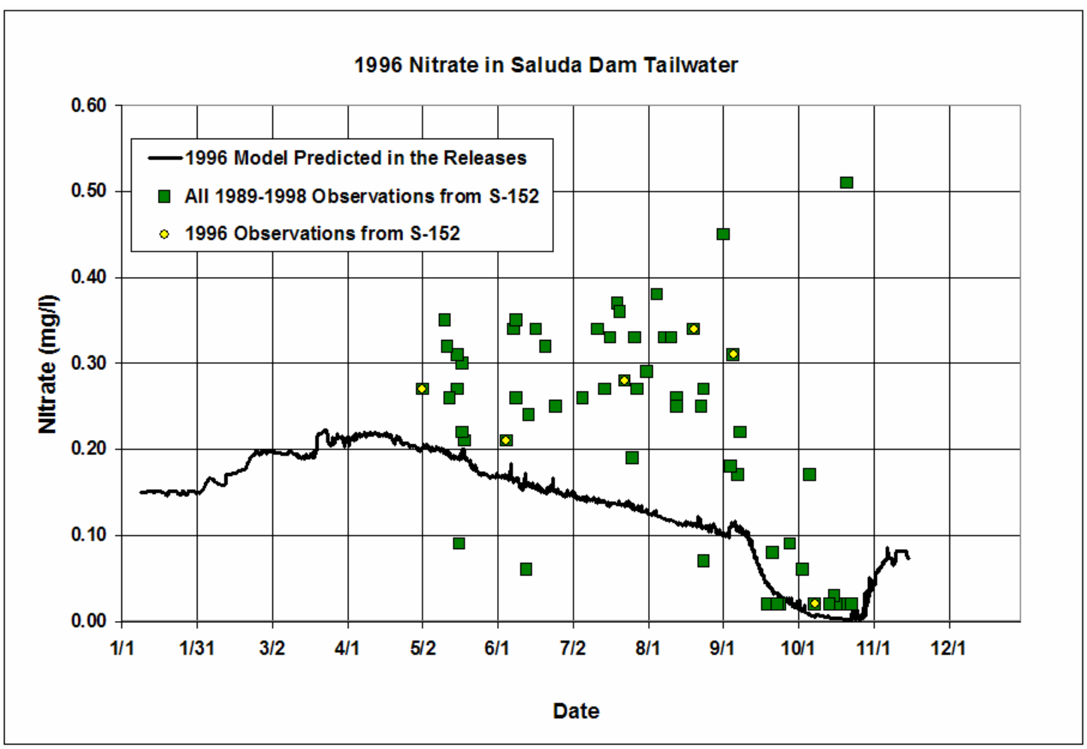


Figure 6-32. 1996 Comparison of Modeled Derived versus Measured Nitrate in the Releases from Saluda Dam

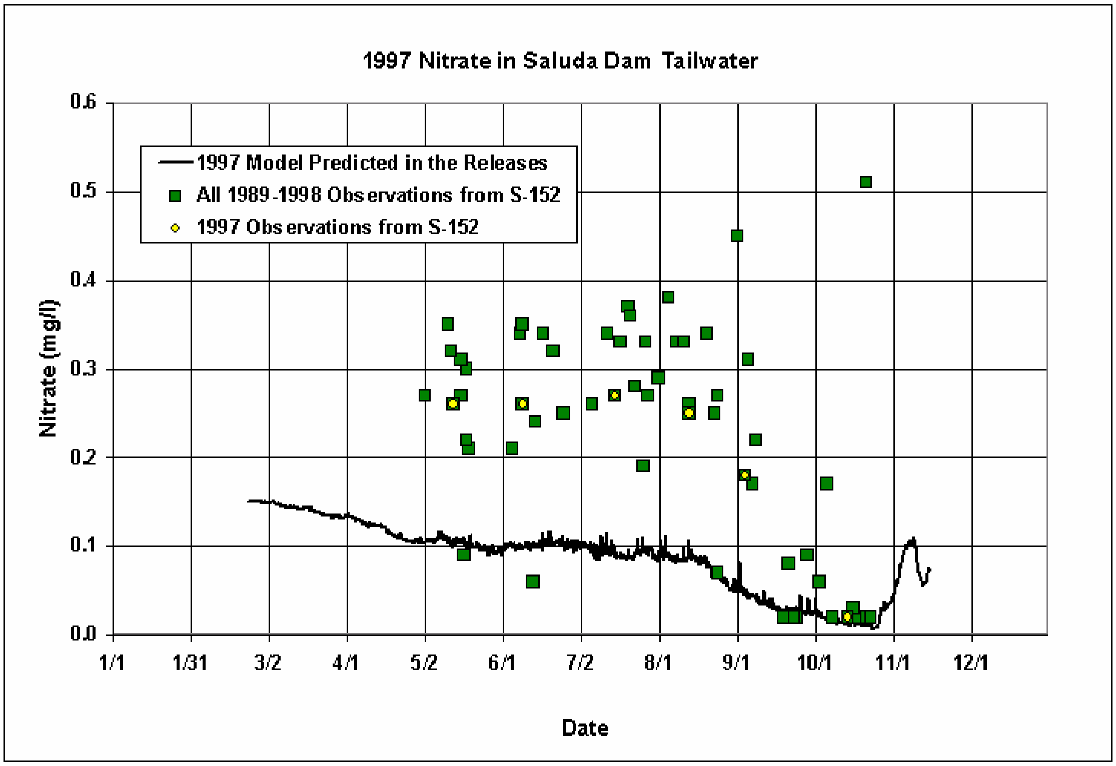


Figure 6-33. 1997 Comparison of Modeled Derived versus Measured Nitrate in the Releases from Saluda Dam

Algae

Model-derived chlorophyll *a* concentrations were compared to historical SCDHEC chlorophyll *a* data from four monitoring stations in the lake. Figure 6-34 through Figure 6-36 show the model-predicted chlorophyll *a* at these locations for 1992, 1996, and 1997, respectively, along with all chlorophyll *a* observations from the period 1995 through 1998. Chlorophyll *a* samples were collected during the months of May through October at these locations, but lake DO profiles indicated that algae growth typically started around mid-April. Model-predicted algae concentrations were considered to be representative of algal levels in the lake considering the amount of data available to verify results and that the main objective for modeling algae was to account for the effects of algal levels on DO in the lake.

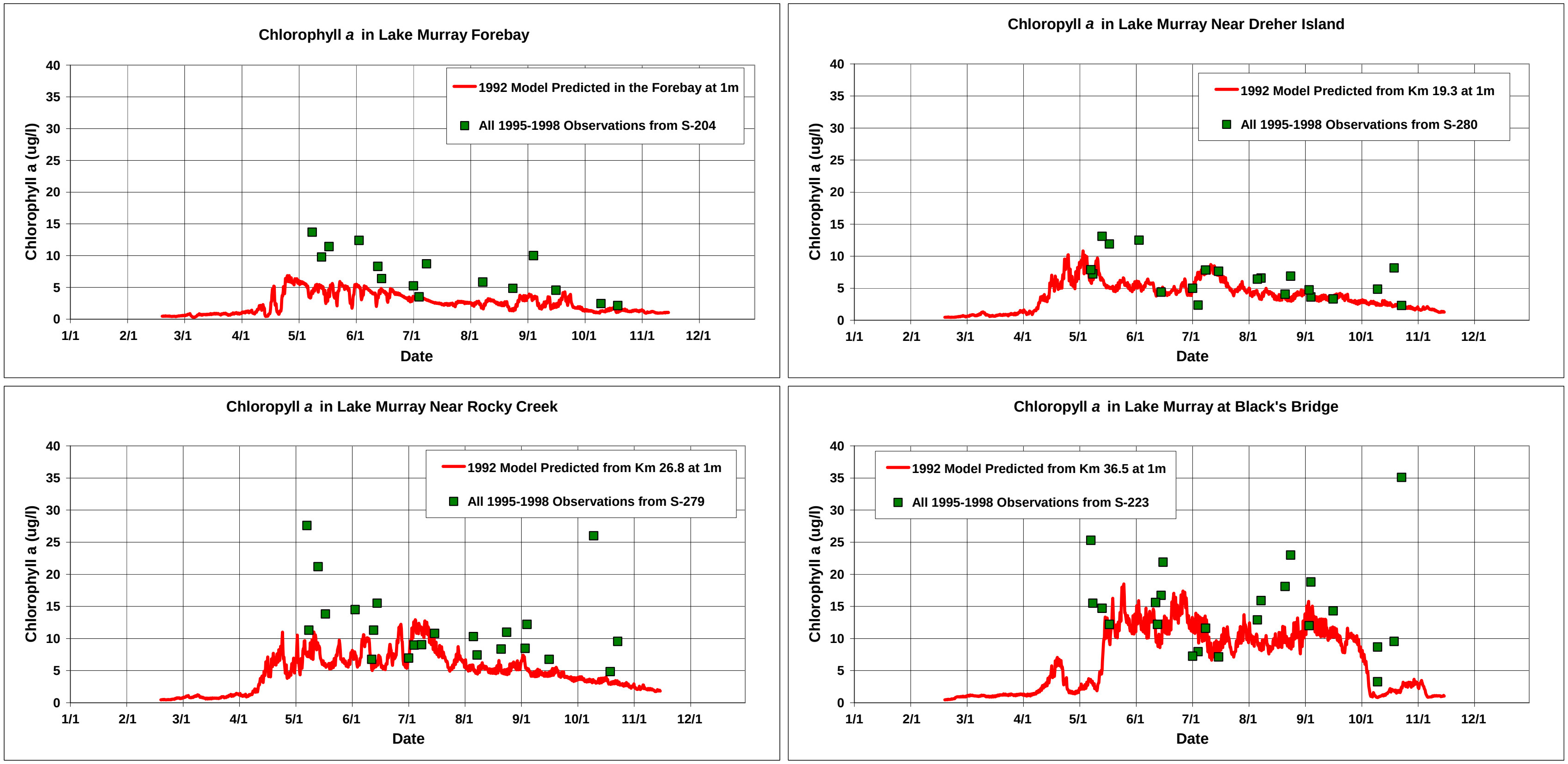


Figure 6-34. 1992 Comparison of Modeled versus Measured Chlorophyll *a* at Four Locations in Lake Murray

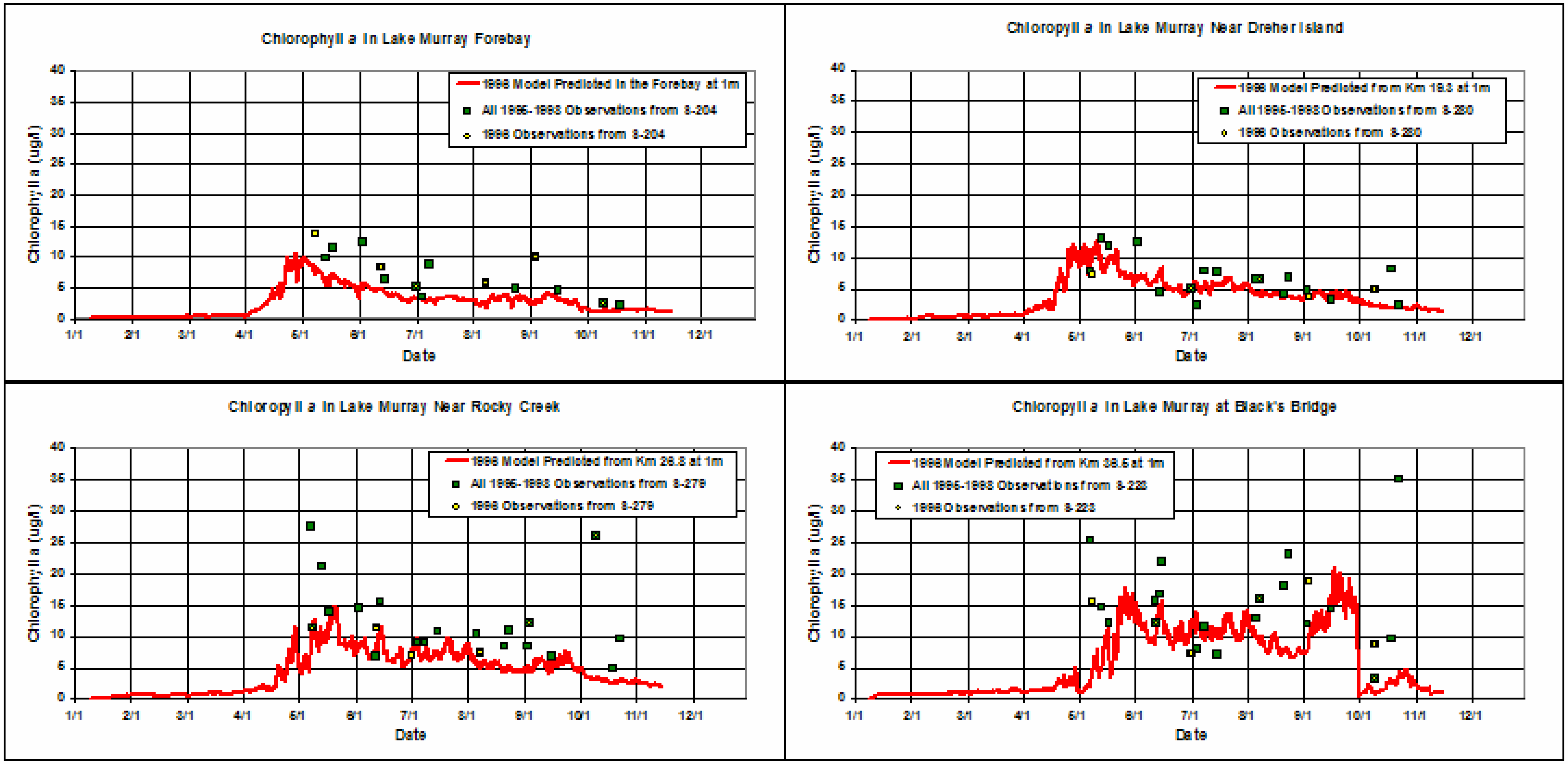


Figure 6-35. 1996 Comparison of Modeled versus Measured Chlorophyll *a* at Four Locations in Lake Murray

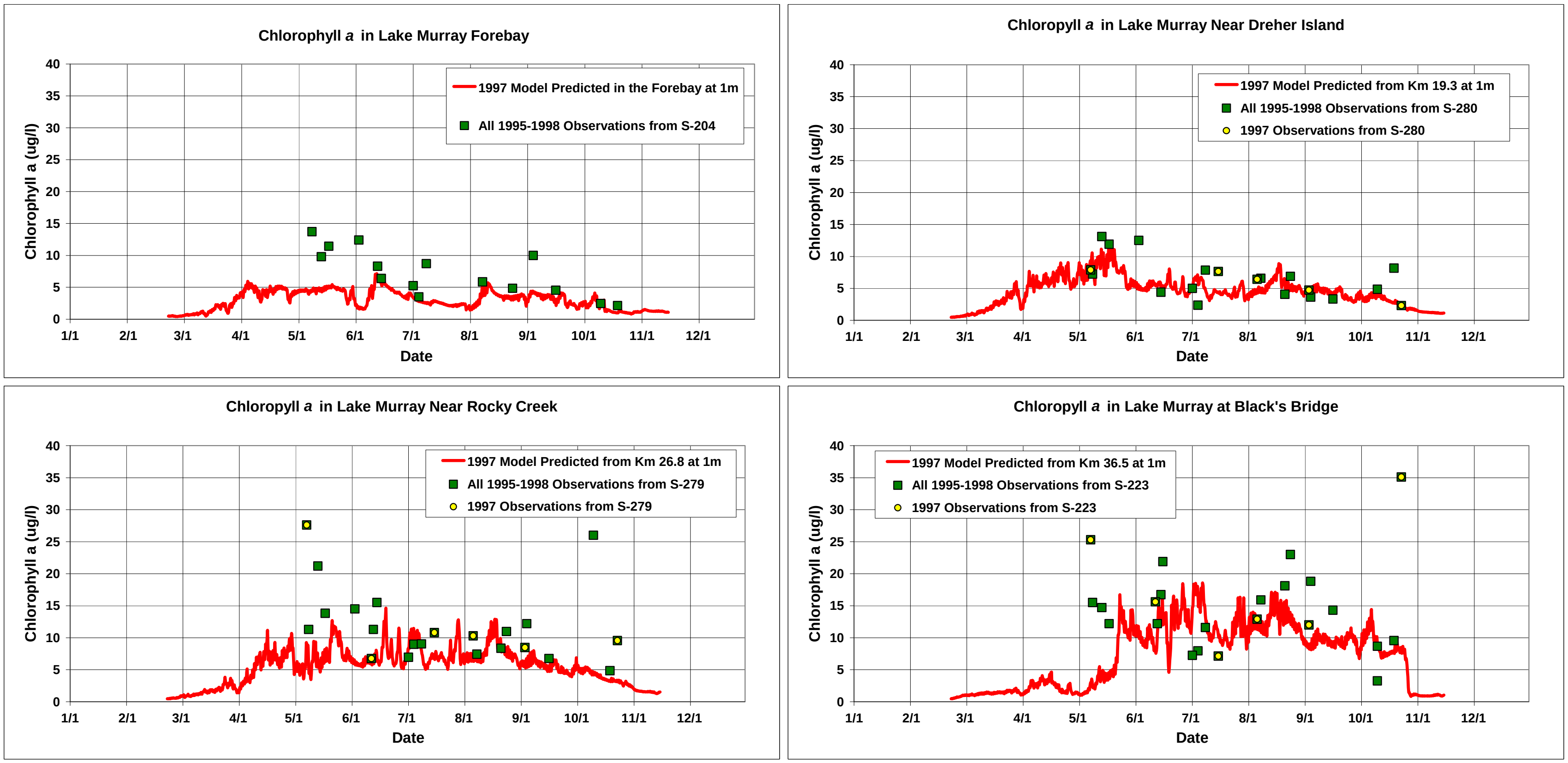


Figure 6-36. 1997 Comparison of Modeled versus Measured Chlorophyll *a* at Four Locations in Lake Murray

TKN and TOC

Model-derived TKN was compared to observed TKN data near the surface in the forebay of Lake Murray. This comparison for 1992, 1996, and 1997 is shown in Figure 6-37 through Figure 6-39, respectively. Model-derived TOC was also compared to observed data near the surface in the forebay of Lake Murray, and these comparisons are shown in Figure 6-40 through Figure 6-42. The results in these figures show that the model predictions were representative of actual conditions in Lake Murray. Model-derived TKN values were lower than the data, but this likely is caused by the way CE-QUAL-W2 decomposes LPOM in that it does not yield LDOM as part of its decomposition process.

Dissolved Oxygen

Plots of model-predicted and observed DO profiles at four locations in Lake Murray for the 1992, 1996 and 1997 model calibrations are shown in Figure 6-43 through Figure 6-54.

Like temperature, comparisons between predicted and observed DO were made for the continuous monitors in the tailrace and at the same elevation in the lake as the intake for unit 5. The comparisons between the release monitor and model-predicted release DO for 1992, 1996, and 1997 are shown in Figure 6-55 through Figure 6-57, respectively. Figure 6-58 through Figure 6-60 show how modeled DO compared to the hourly DO observations at the USGS monitor near the intake for unit 5, as well as DO observations from lake profiles at approximately the same elevation.

Overall, the modeled annual DO dynamics in Lake Murray are representative of actual DO conditions in Lake Murray. As can be seen in the DO profiles, the location and timing of the on-set of DO depletion is captured reasonably well in all three years. This is illustrated by comparison of modeled and observed profiles collected in May and June of 1996. The May 22 and 23 DO profiles from all four locations show that the DO is transient but is starting to become depleted, especially at the two upstream stations. By June 25 the DO dropped to zero at some point in the water column at both the upstream locations. At the forebay station however, the mid-depth level of low oxygen water is evident, but the DO is still above 2 mg/L throughout the water column. The model captured this pattern, as well as the continuing DO depletion in the hypolimnion and the DO recovery that occurred when the lake mixed in early November.

Since DO conditions in the forebay are so important to the objectives for the modeling, a good DO calibration in the forebay was emphasized as the calibration process progressed. A summary of the statistics from all dates and locations shown in Figure 6-43 through Figure 6-54 for 1992, 1996, and 1997 is presented in Table 6-8 through Table 6-10, respectively. These tables show that the overall AME for 1992, 1996, and 1997 when all profiles and dates are included each year is 0.79, 0.65 and 0.84 mg/L, respectively. Many modelers consider a model to be acceptable when the AME is less than 2 mg/L DO.

The modeled DO in the releases from Saluda Hydro generally matched the data collected at the USGS monitor below the dam for all three years, especially in 1992 and 1996, and the turnover of the lake has been captured well in all three years. In the 1997 calibration, the DO in the model appears to be too low from mid-August until the DO recovers in late October. For 1997, the modeled DO was about 1 mg/L lower than the measurements at the USGS monitor during the period mid-August through mid-September; however, the modeled DO was representative of observed conditions during mid-September through November. This pattern of modeled DO being lower in 1997 likely was due to turbine aeration increasing the DO in the tailrace—in 1997 SCE&G implemented their first increment of aeration. The comparison between 1997 modeled and observed DO profiles in the lake and at the elevation of the unit 5 intake (discussed below) do not support what is seen in the tailrace.

The modeled DO in the lake at the elevation of the unit 5 intake generally matched data collected at this location for all three years, especially in 1992 and 1996 when the model DO essentially matched the DO observed at the same elevation in the forebay profiles. There was no continuous monitor at this elevation in 1992, so there is no hourly data shown in Figure 6-58. In 1996, the model matches the hourly data from the USGS monitor well from mid-May through September. The March and April hourly data from this monitor in 1996 is suspect based on analysis of the DO profiles collected during this time period. The data from the continuous monitor reports that the DO is less than 8 mg/L for most of the month of April, but as shown with the April 11 profiles from the two stations in the downstream part of the lake (Figure 6-47 and Figure 6-48), the DO was over 9 mg/L throughout the water column. In 1997, the modeled DO was 0.5-1 mg/L higher than the measurements at the USGS monitor at unit 5 during the period mid-March through mid-September. The amount of time that the DO is below 4 mg/L at this elevation is captured by the model in all three years.

Alkalinity and pH

Model-predicted Alkalinity was compared to data collected near the surface in the forebay of Lake Murray and Figure 6-61 through Figure 6-63 show these comparisons for 1992, 1996, and 1997, respectively.

Model-derived pH was compared to observations in the forebay of Lake Murray and in the releases from Saluda Hydro. Figure 6-64 through Figure 6-66 show the comparison between modeled and observed pH in the forebay near the surface of Lake Murray for 1992, 1996, and 1997 respectively, and Figure 6-67 shows modeled and observed pH profiles in the forebay for 1996. Figure 6-68 through Figure 6-70 show modeled and observed pH in the releases from Saluda Hydro for 1992, 1996, and 1997 respectively.

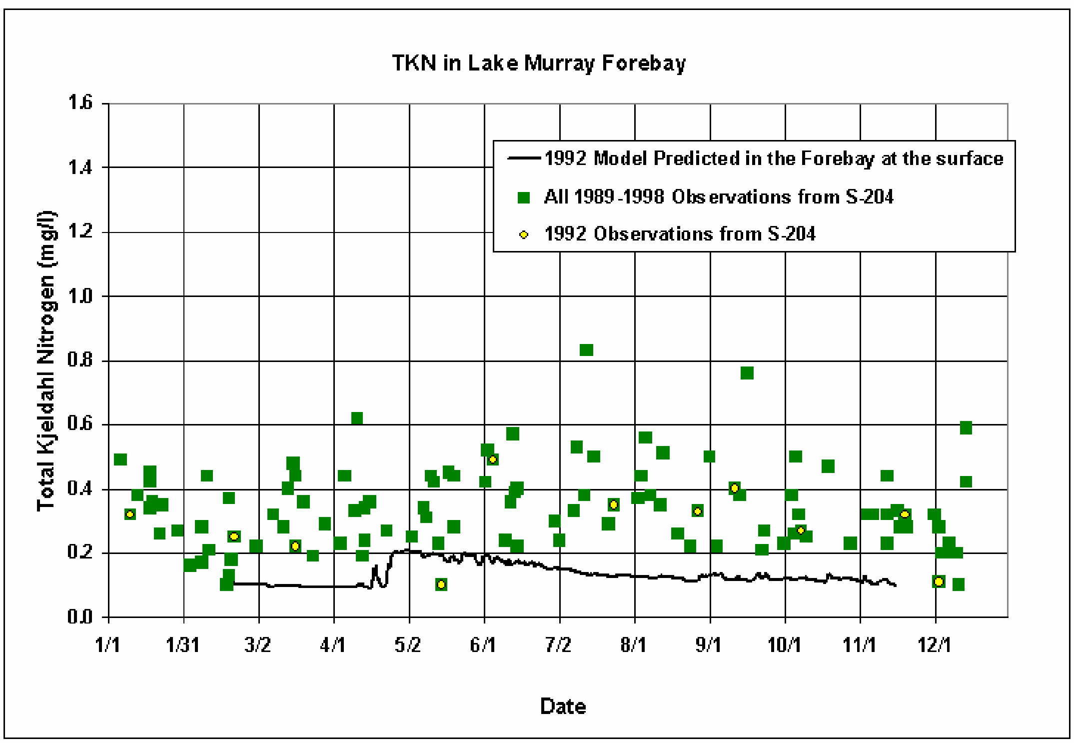


Figure 6-37. 1992 Comparison of Modeled Derived versus Measured TKN at the Surface in the Forebay of Lake Murray

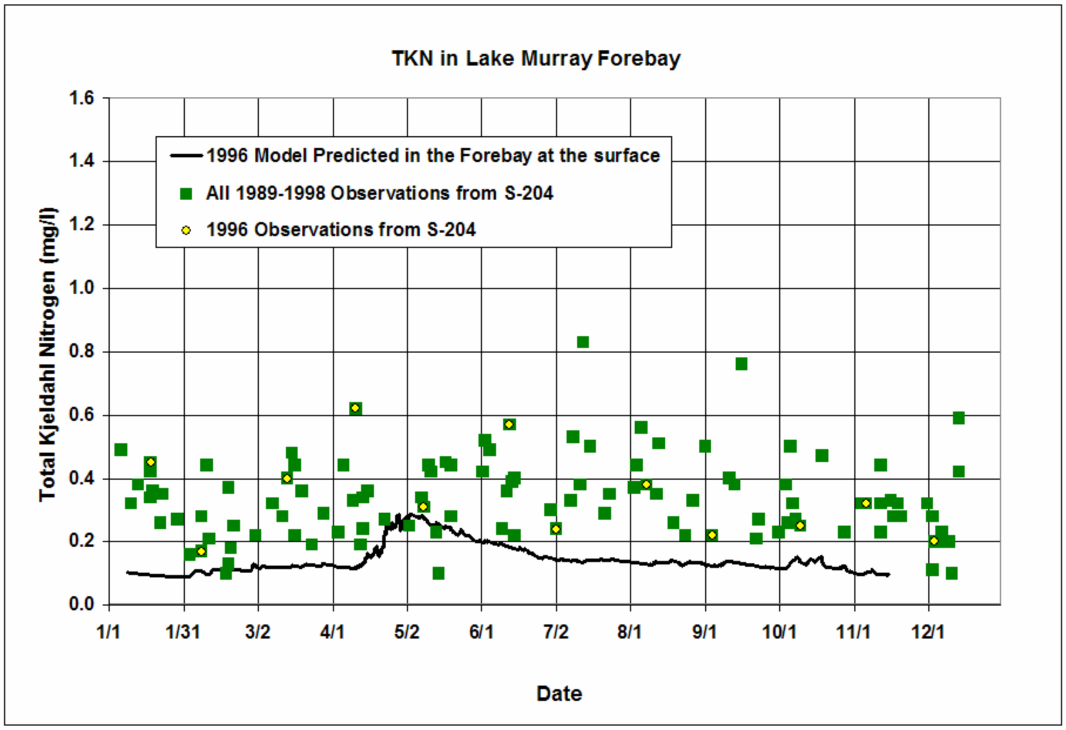


Figure 6-38. 1996 Comparison of Modeled Derived versus Measured TKN at the Surface in the Forebay of Lake Murray

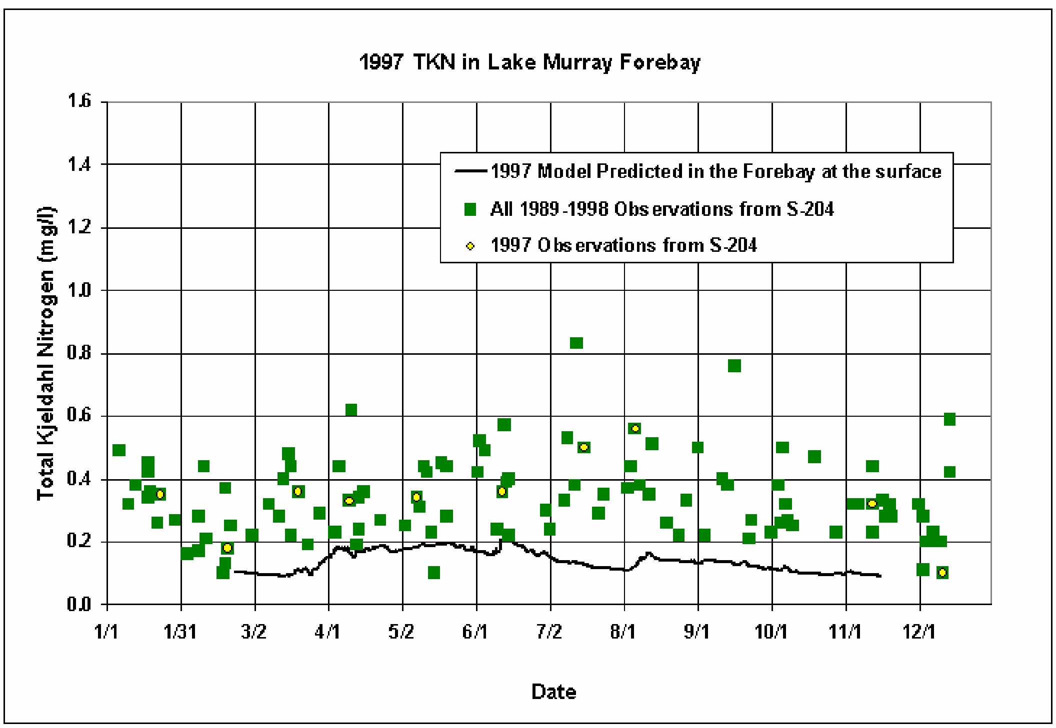


Figure 6-39. 1997 Comparison of Modeled Derived versus Measured TKN at the Surface in the Forebay of Lake Murray

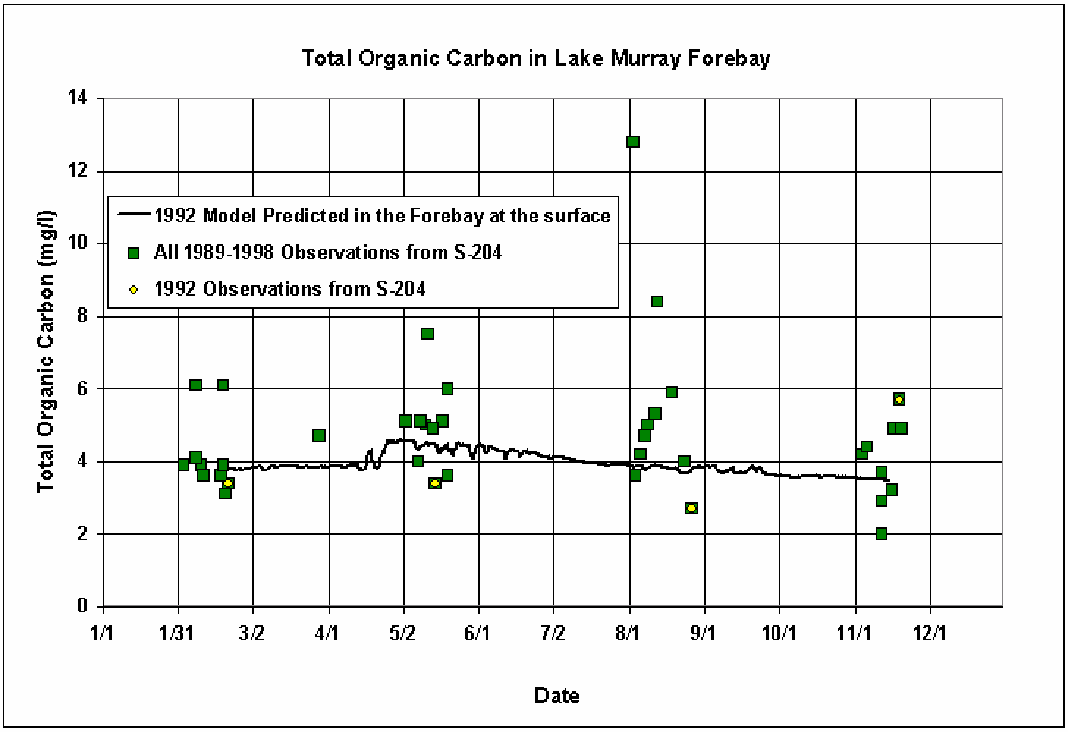


Figure 6-40. 1992 Comparison of Modeled Derived versus Measured TOC at the Surface in the Forebay of Lake Murray

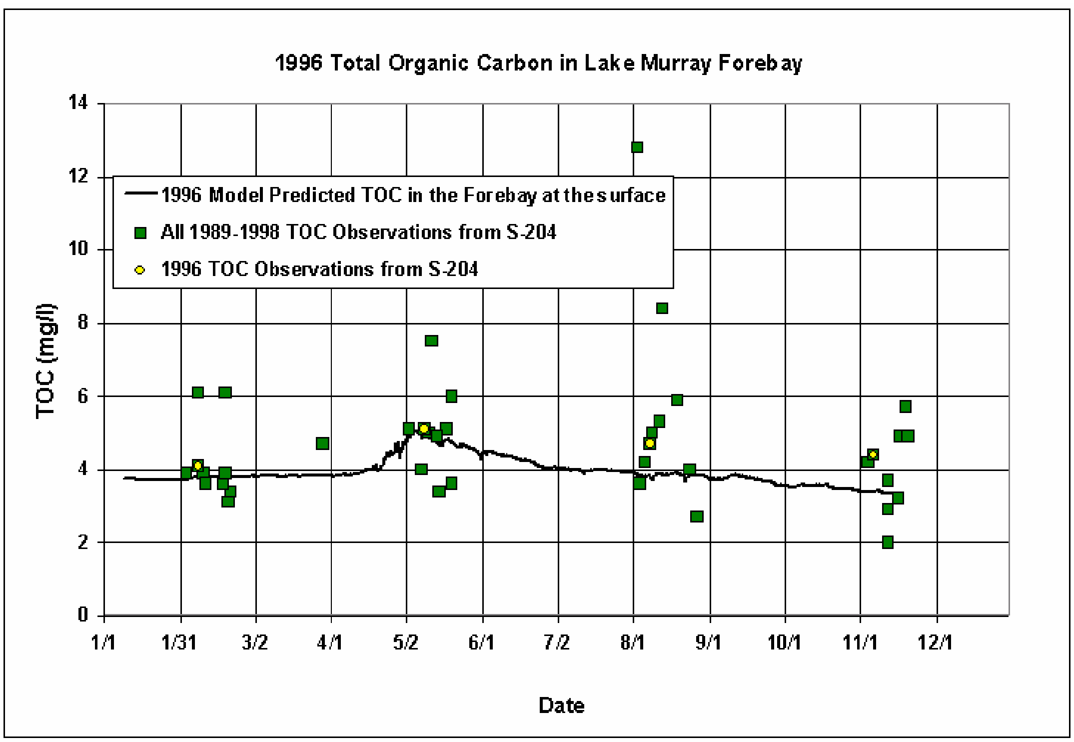


Figure 6-41. 1996 Comparison of Modeled Derived versus Measured TOC at the Surface in the Forebay of Lake Murray

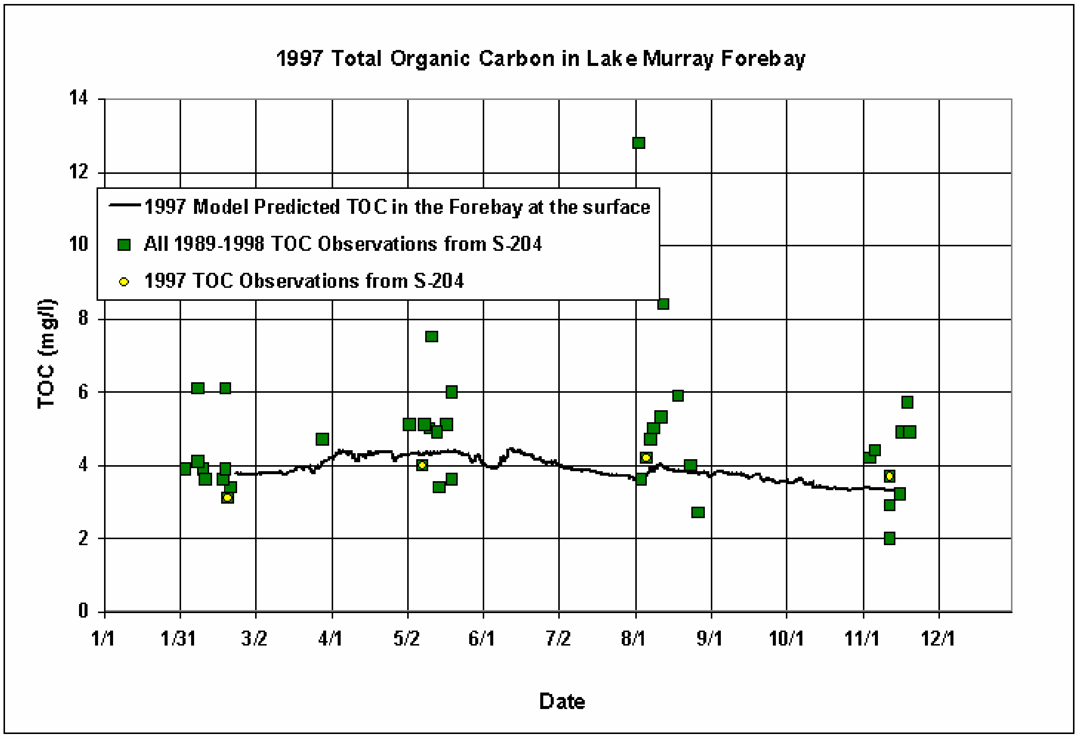


Figure 6-42. 1997 Comparison of Modeled Derived versus Measured TOC at the Surface in the Forebay of Lake Murray

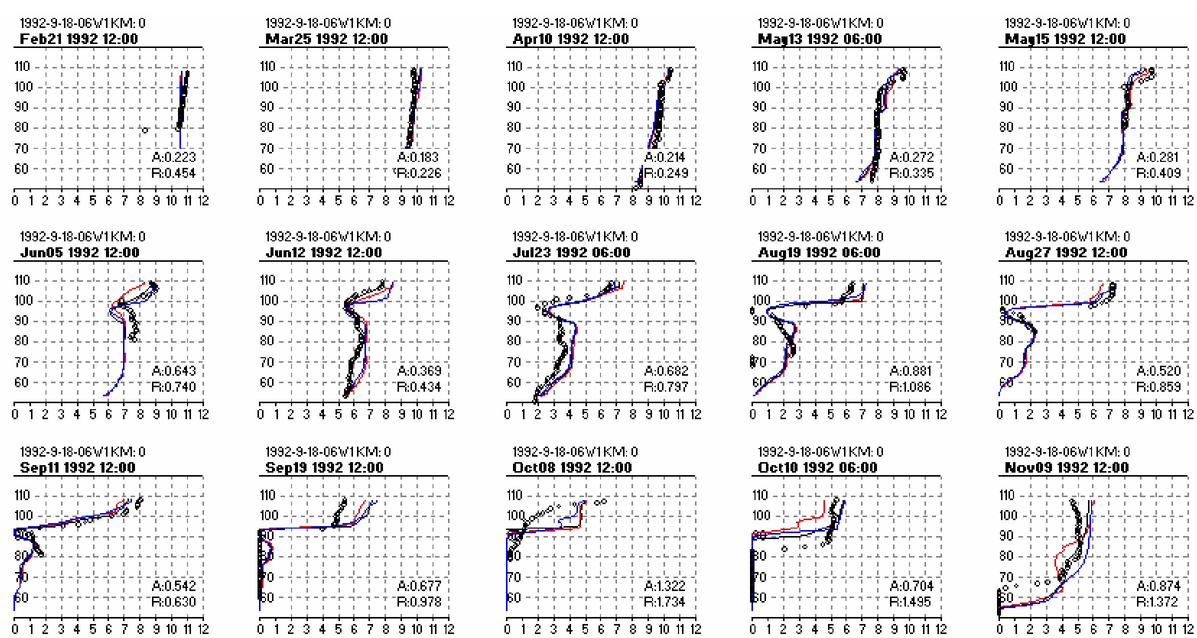


Figure 6-43. 1992 Modeled and Observed DO Profiles in the Forebay of Lake Murray; Overall Statistics: ABS = 0.55, RMS = 0.90

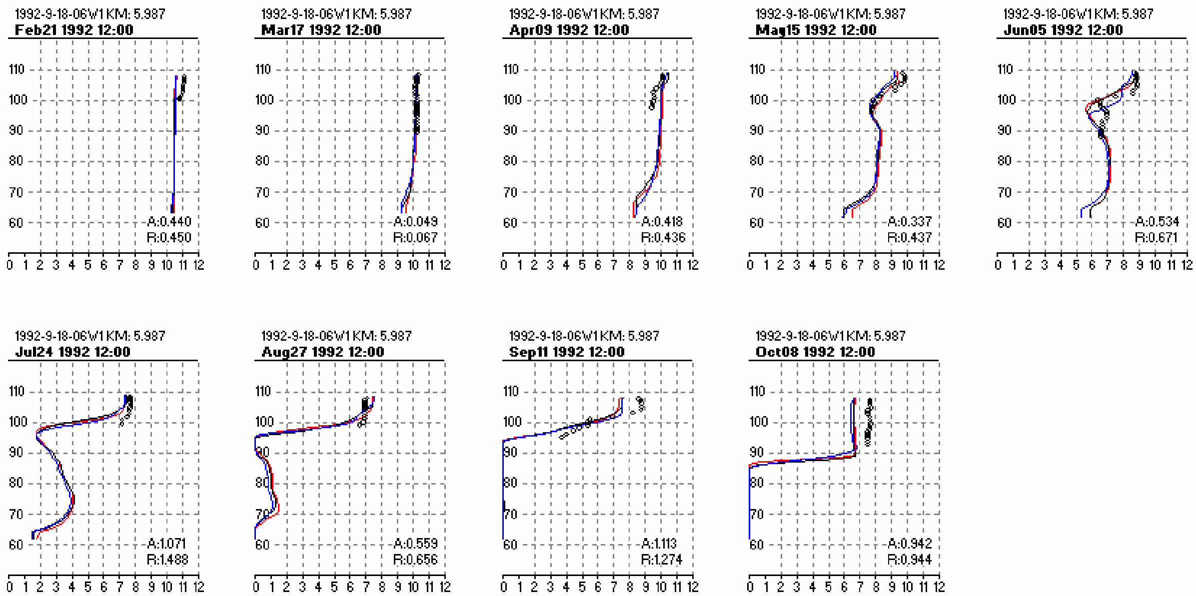


Figure 6-44. 1992 Modeled and Observed DO Profiles Six Kilometers Upstream of Saluda Dam; Overall Statistics: ABS = 0.58, RMS = 0.80

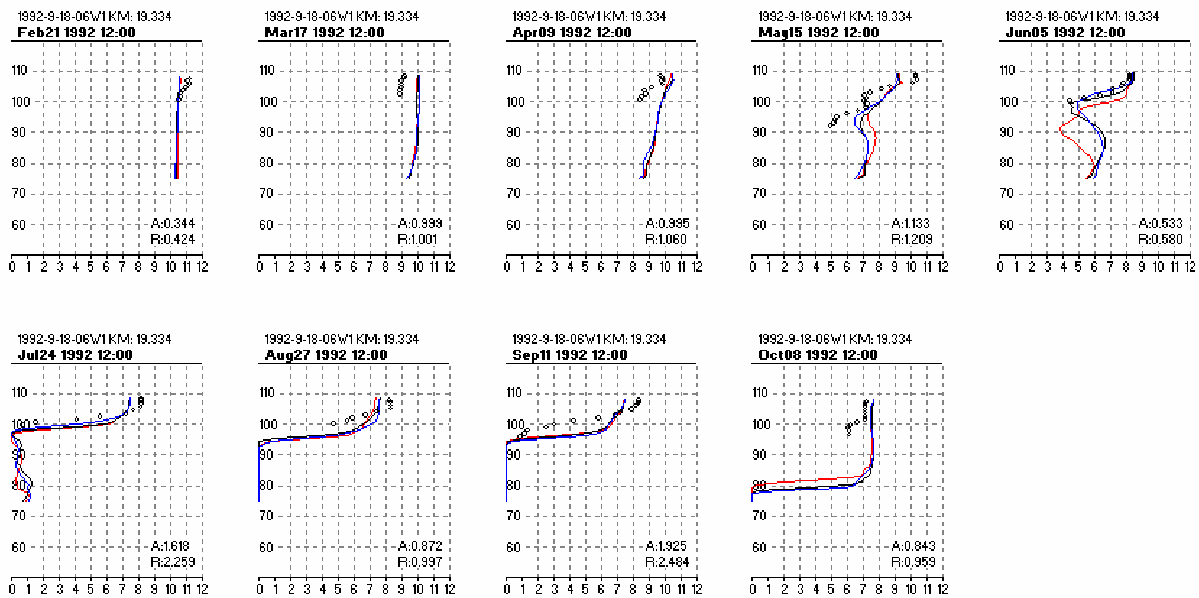


Figure 6-45. 1992 Modeled and Observed DO Profiles 19 Kilometers Upstream of Saluda Dam; Overall Statistics: ABS = 1.08, RMS = 1.44

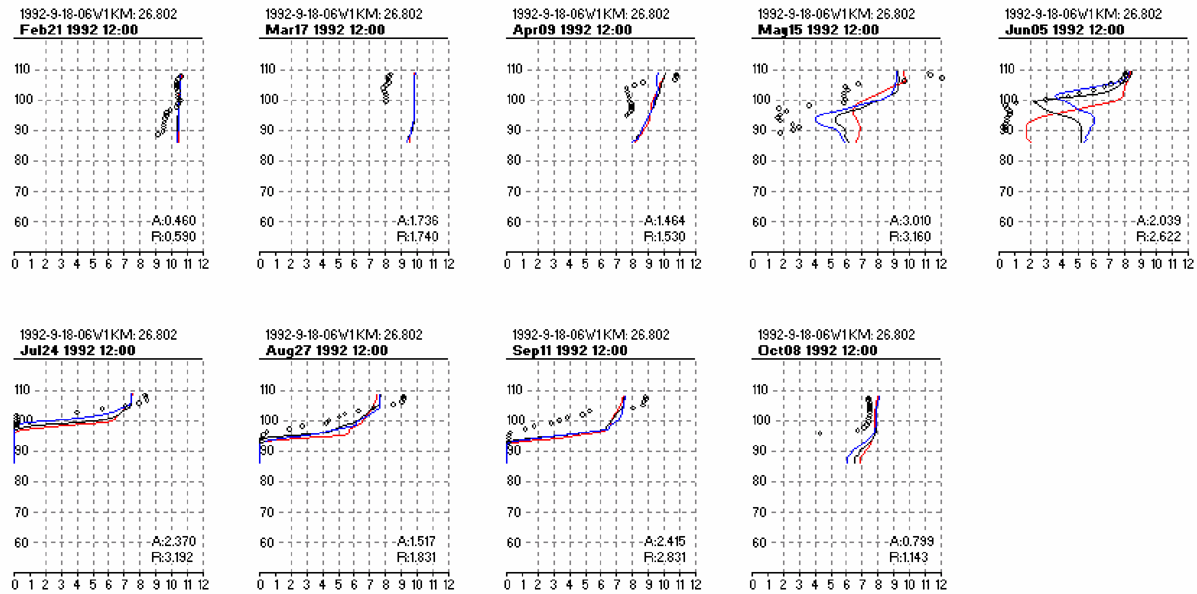


Figure 6-46. 1992 Modeled and Observed DO Profiles 27 Kilometers Upstream of Saluda Dam; Overall Statistics: ABS = 1.78, RMS = 2.28

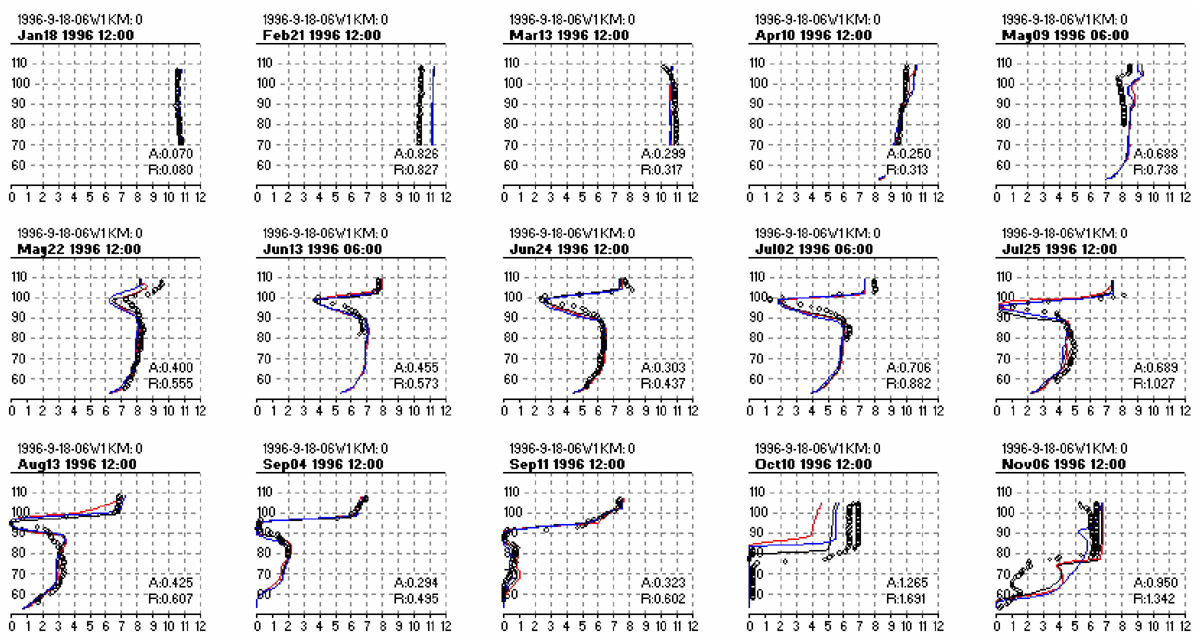


Figure 6-47. 1996 Modeled and Observed DO Profiles in the Forebay of Lake Murray; Overall Statistics: ABS = 0.57, RMS = 0.89

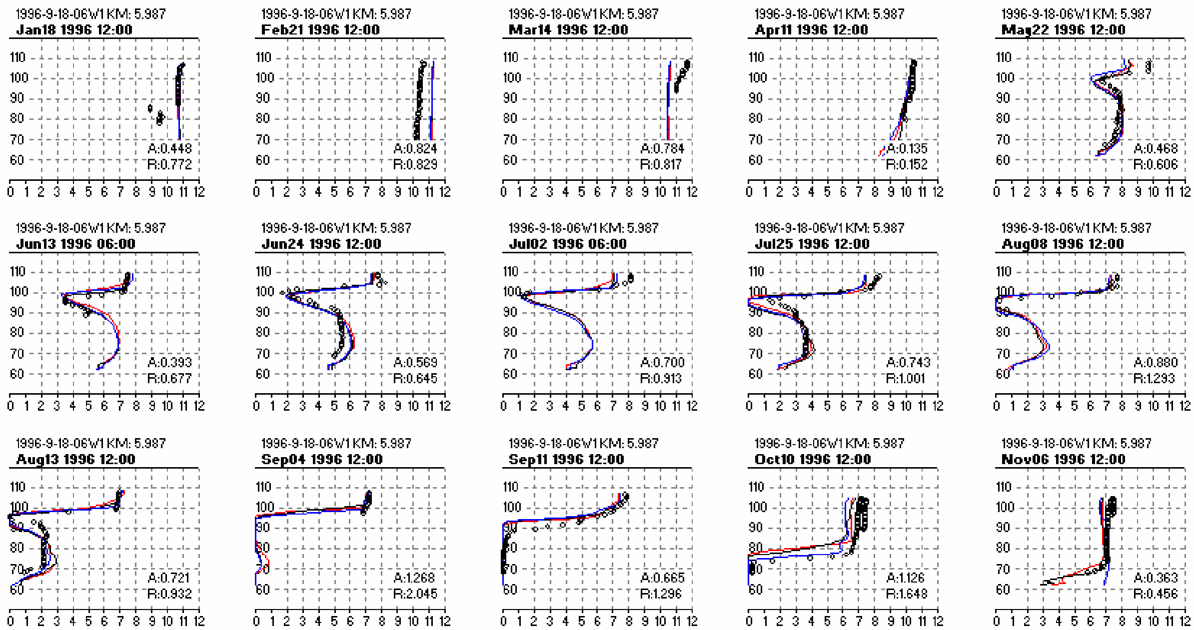


Figure 6-48. 1996 Modeled and Observed DO Profiles Six Kilometers Upstream of Saluda Dam; Overall Statistics: ABS = 0.65, RMS = 1.00

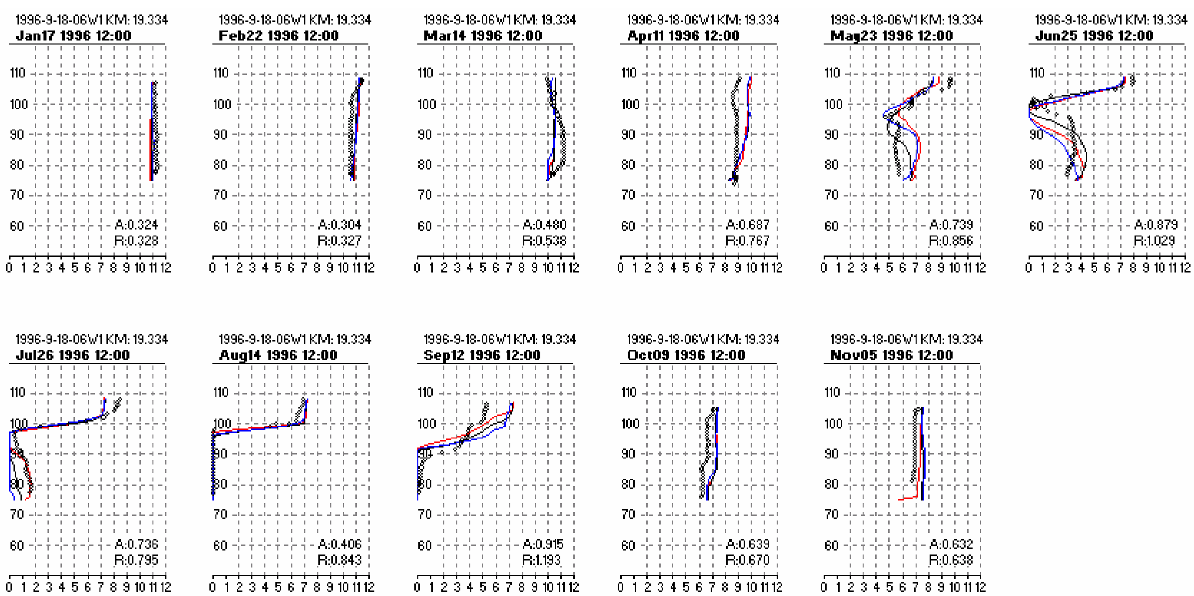


Figure 6-49. 1996 Modeled and Observed DO Profiles 19 Kilometers Upstream of Saluda Dam; Overall Statistics: ABS = 0.61, RMS = 0.77

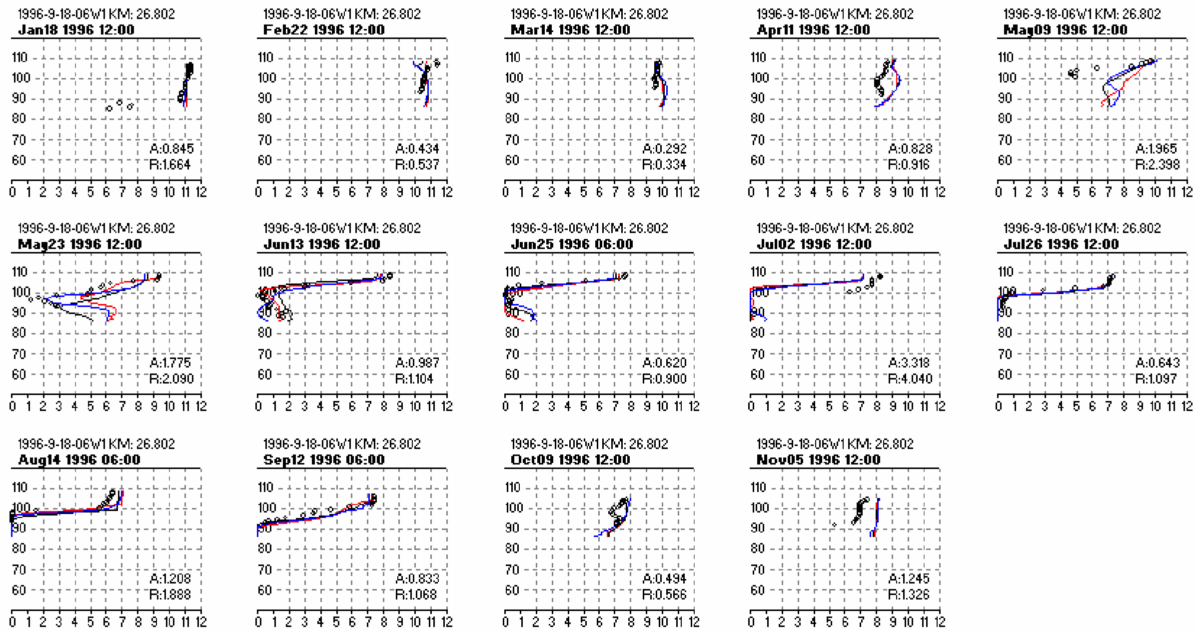


Figure 6-50. 1996 Modeled and Observed DO Profiles 27 Kilometers Upstream of Saluda Dam; Overall Statistics: ABS = 1.01, RMS = 1.54

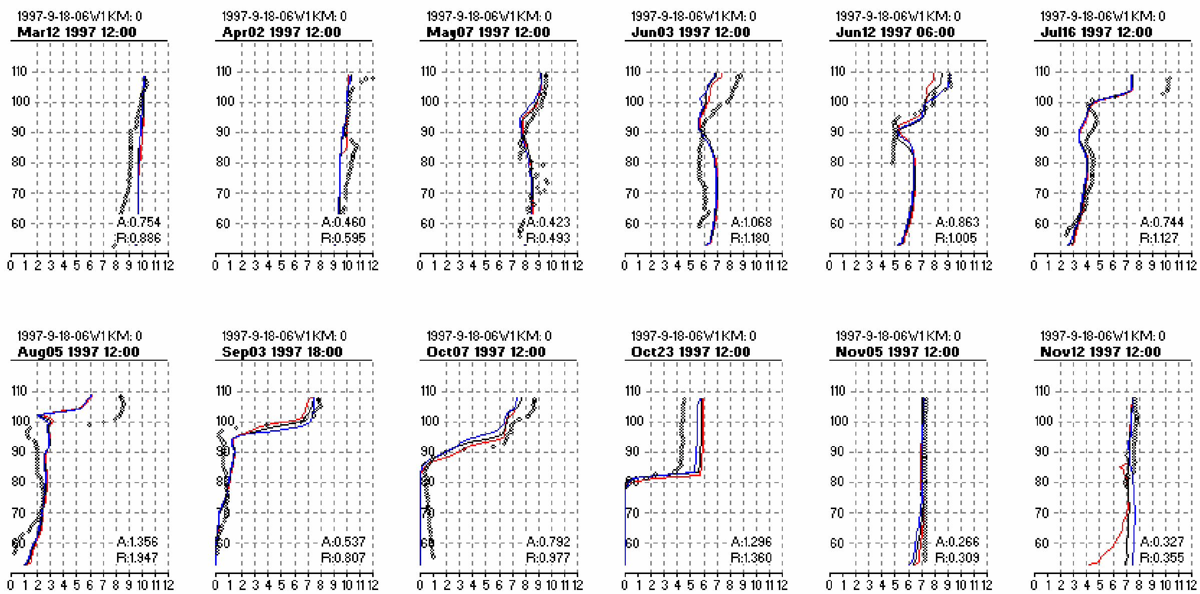


Figure 6-51. 1997 Modeled and Observed DO Profiles in the Forebay of Lake Murray; Overall Statistics: ABS = 0.73, RMS = 1.02

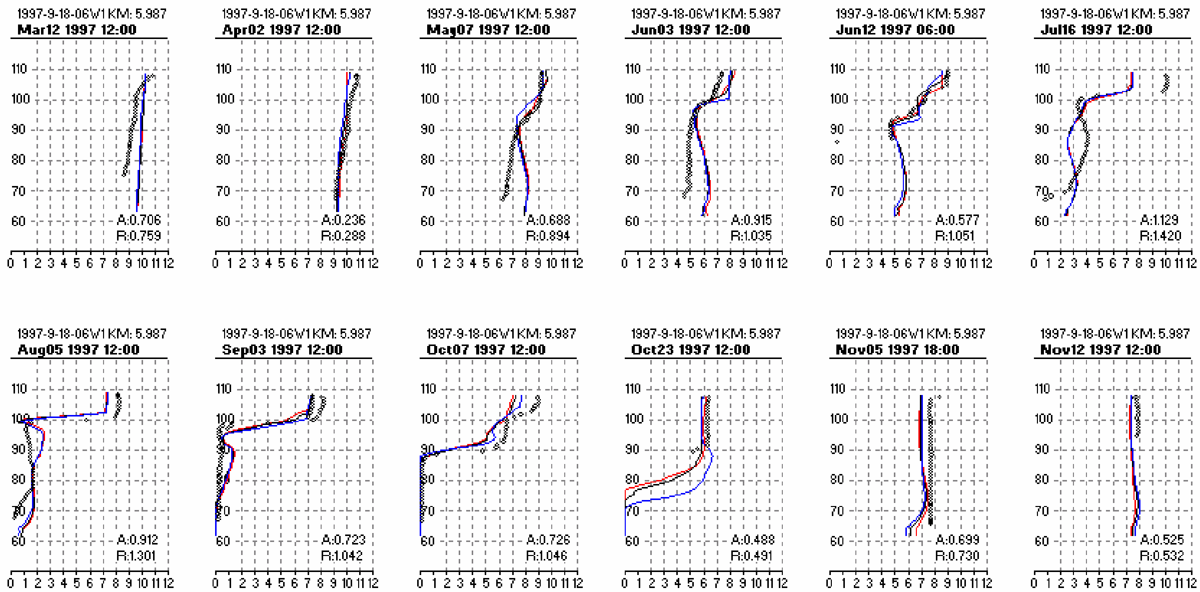


Figure 6-52. 1997 Modeled and Observed DO Profiles Six Kilometers Upstream of Saluda Dam; Overall Statistics: ABS = 0.72, RMS = 0.98

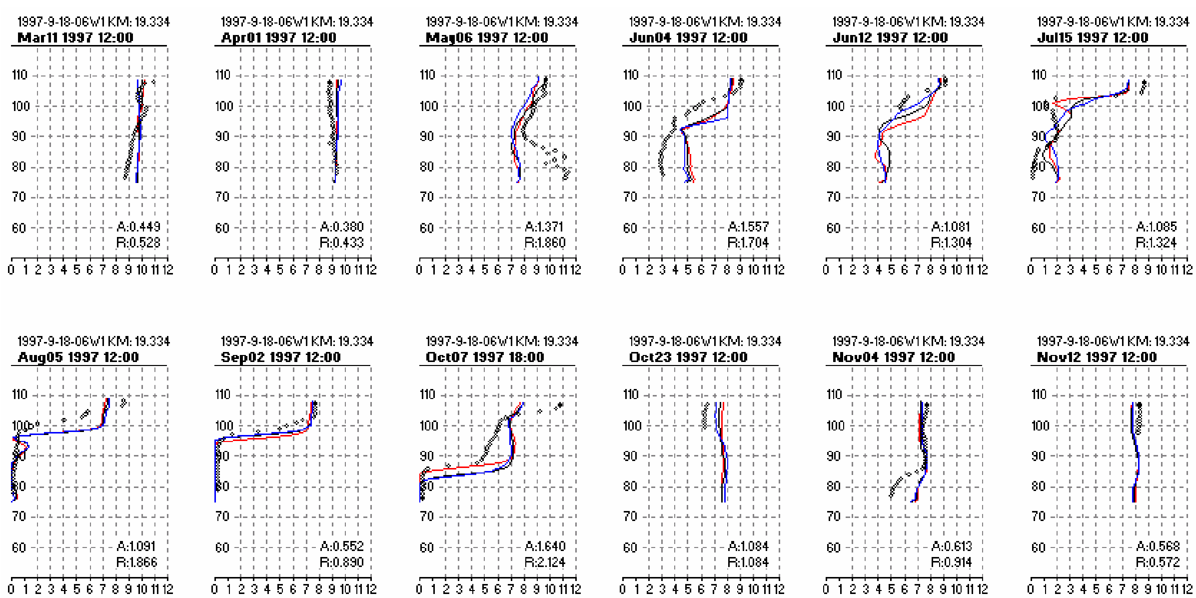


Figure 6-53. 1997 Modeled and Observed DO Profiles 19 Kilometers Upstream of Saluda Dam; Overall Statistics: ABS = 0.97, RMS = 1.40

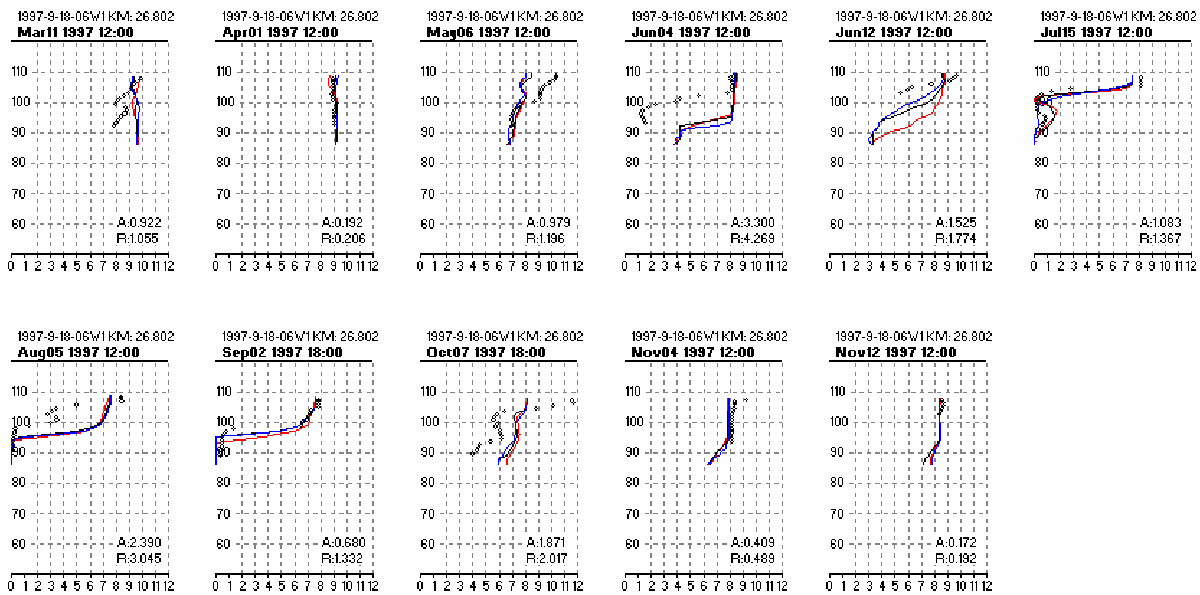


Figure 6-54. 1997 Modeled and Observed DO Profiles 27 Kilometers Upstream of Saluda Dam; Overall Statistics: ABS = 1.30, RMS = 2.02

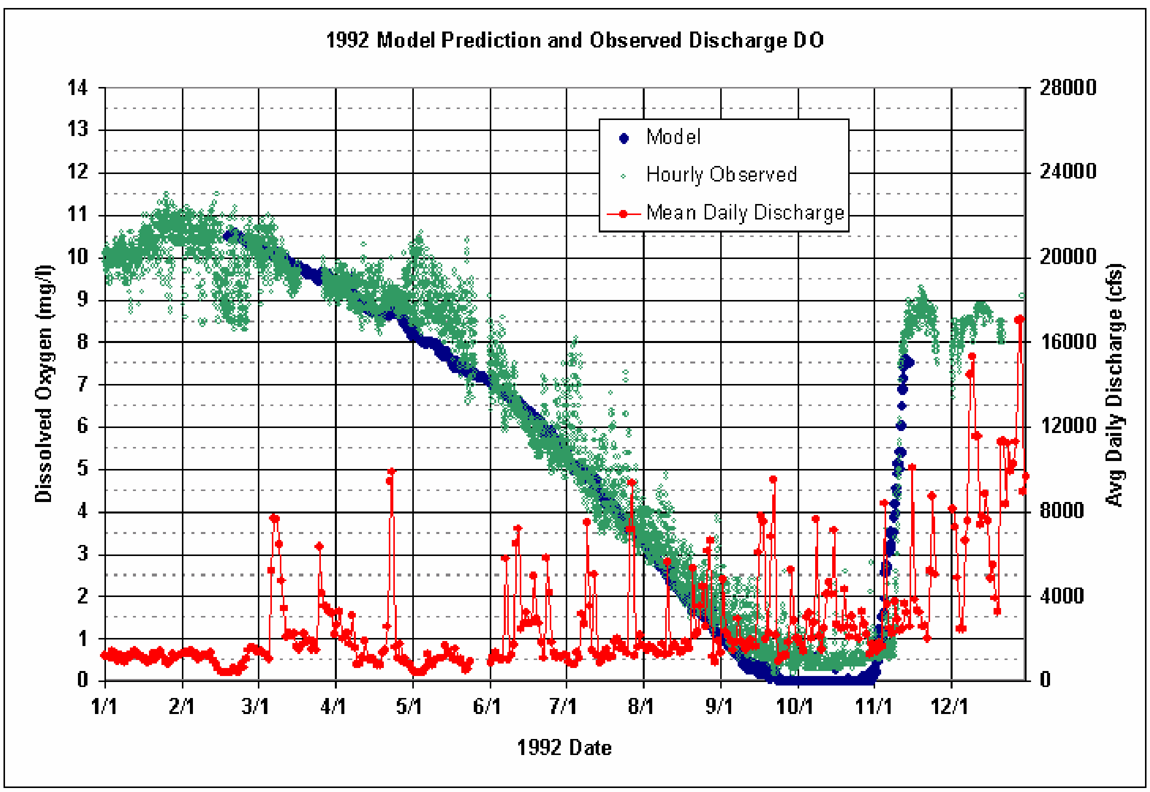


Figure 6-55. 1992 Comparison of Modeled versus Measured Saluda Release DO

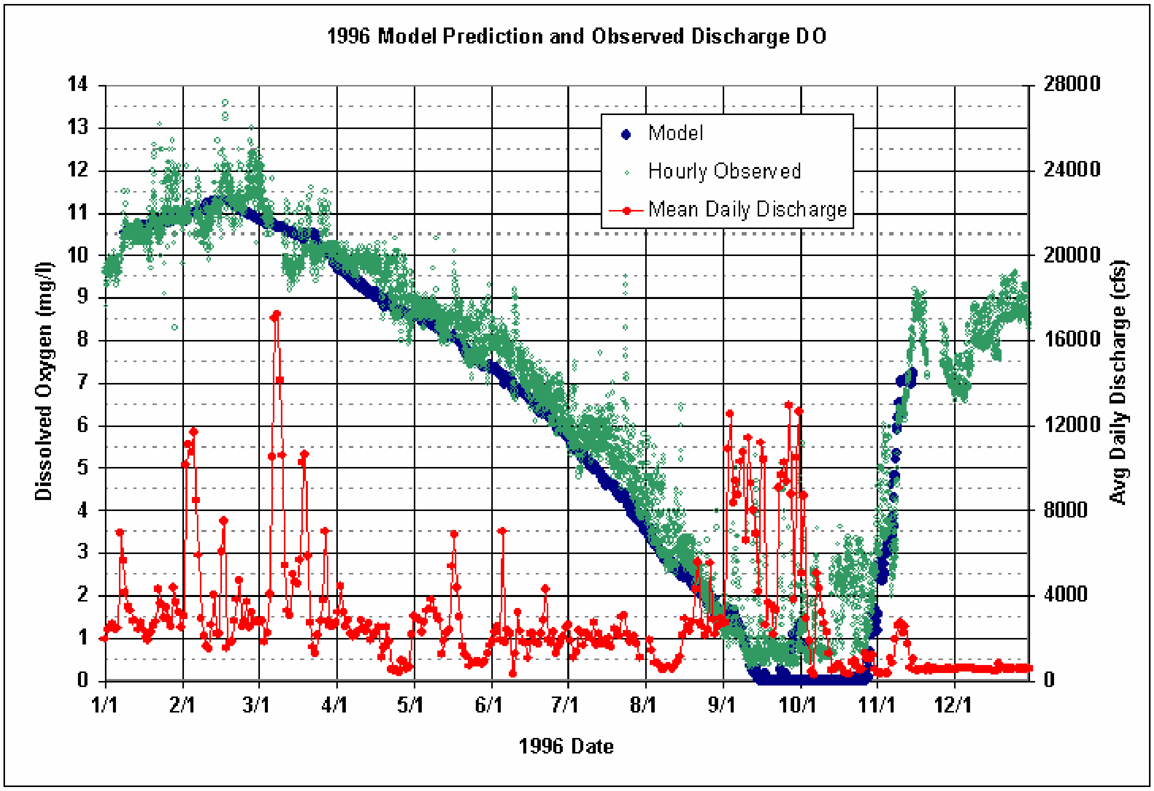


Figure 6-56. 1996 Comparison of Modeled versus Measured Saluda Release DO

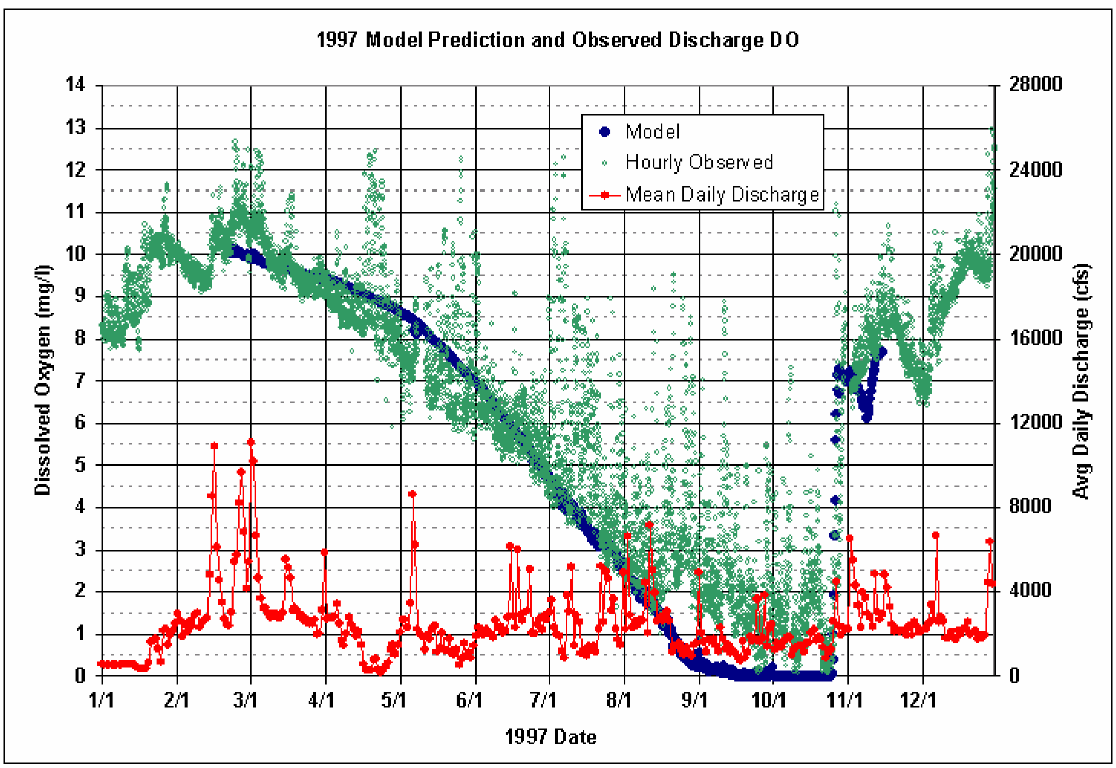


Figure 6-57. 1997 Comparison of Modeled versus Measured Saluda Release DO

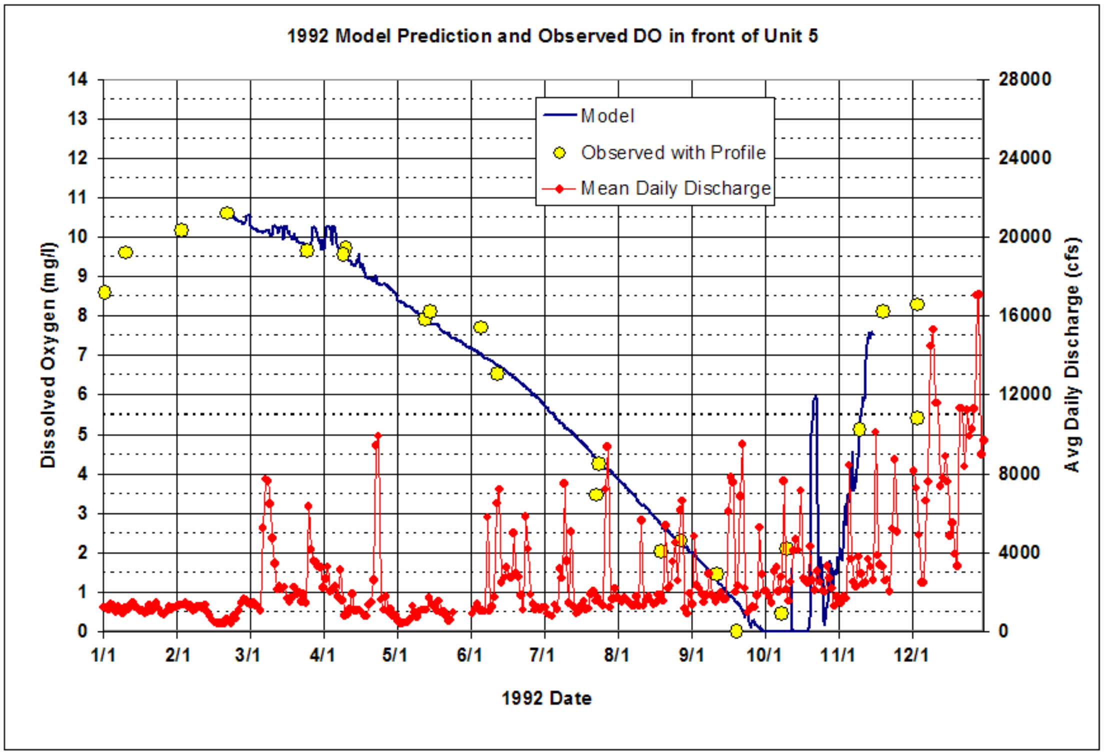


Figure 6-58. 1992 Modeled versus Measured DO at the level of the Unit 5 Intake

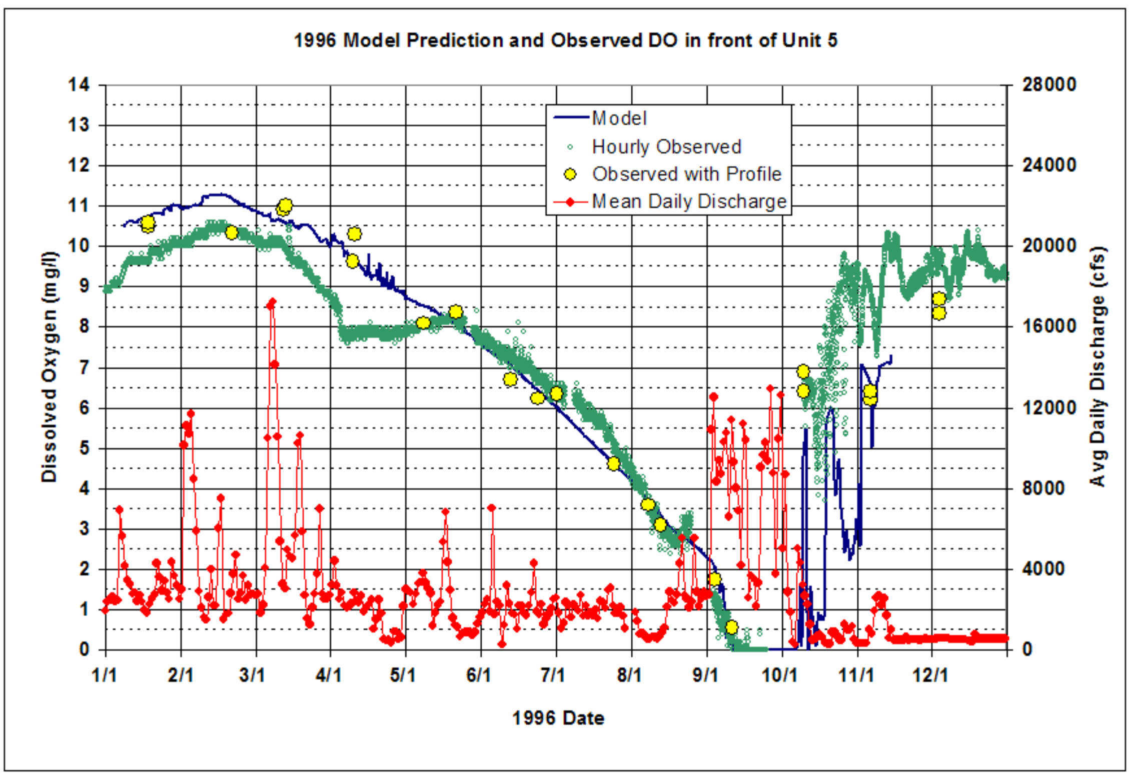


Figure 6-59. 1996 Modeled versus Measured DO at the level of the Unit 5 Intake

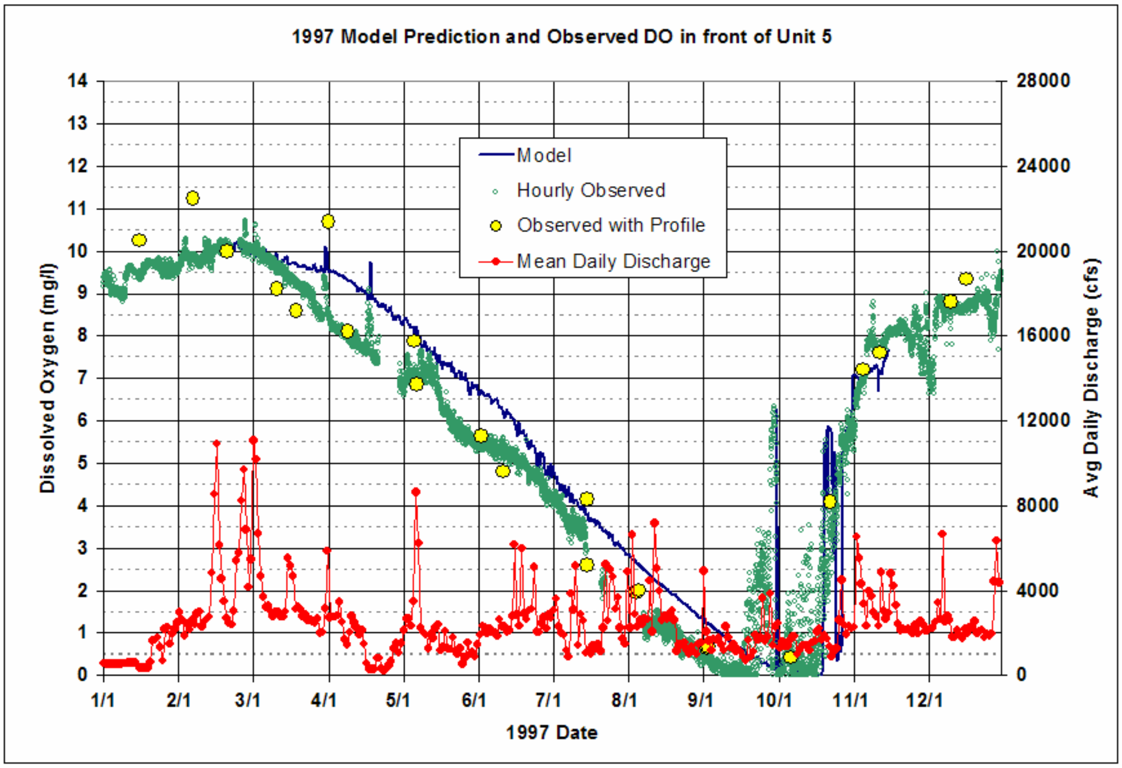


Figure 6-60. 1997 Modeled versus Measured DO at the level of the Unit 5 Intake

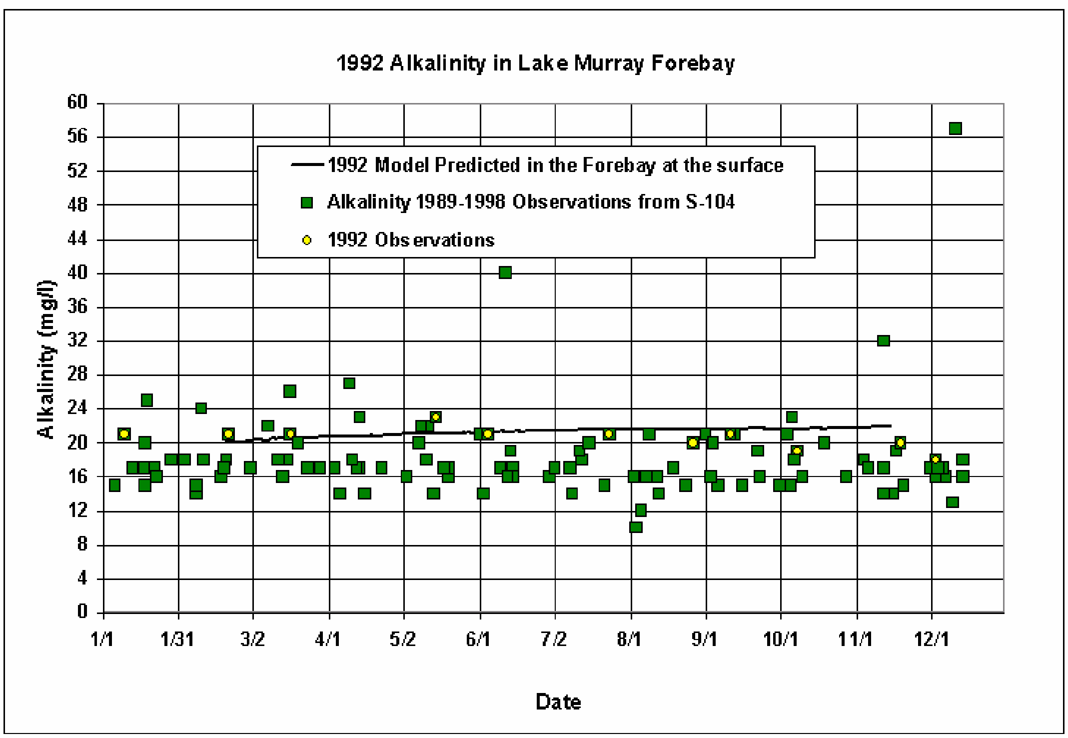


Figure 6-61. 1992 Comparison of Modeled Derived versus Measured Alkalinity at the Surface in the Forebay of Lake Murray

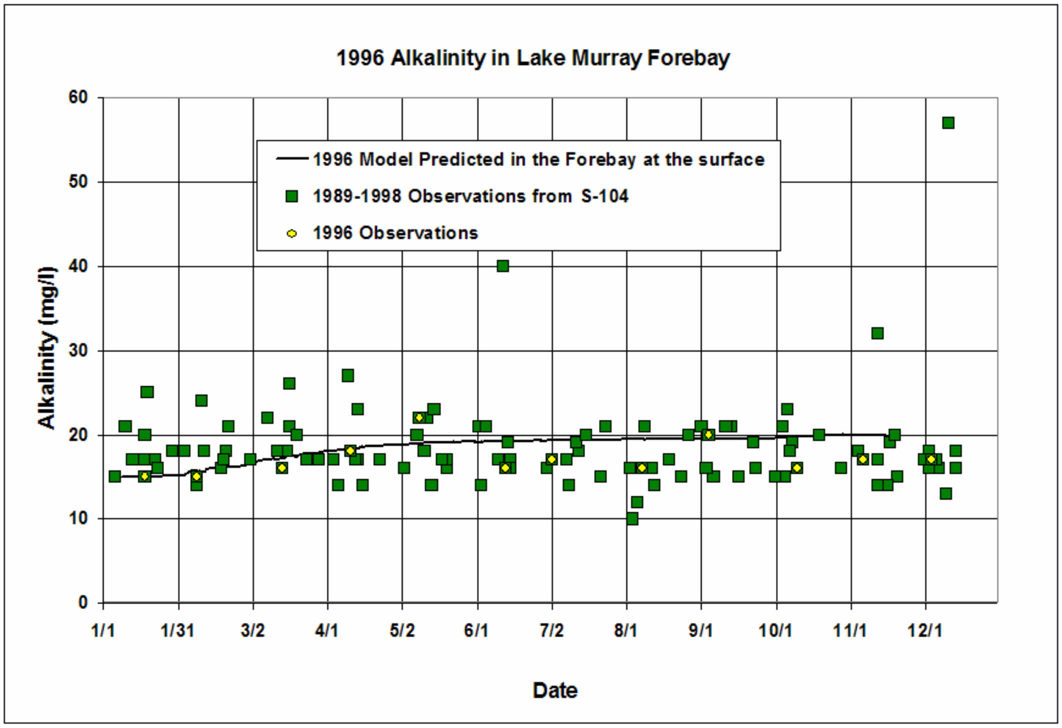


Figure 6-62. 1996 Comparison of Modeled Derived versus Measured Alkalinity at the Surface in the Forebay of Lake Murray

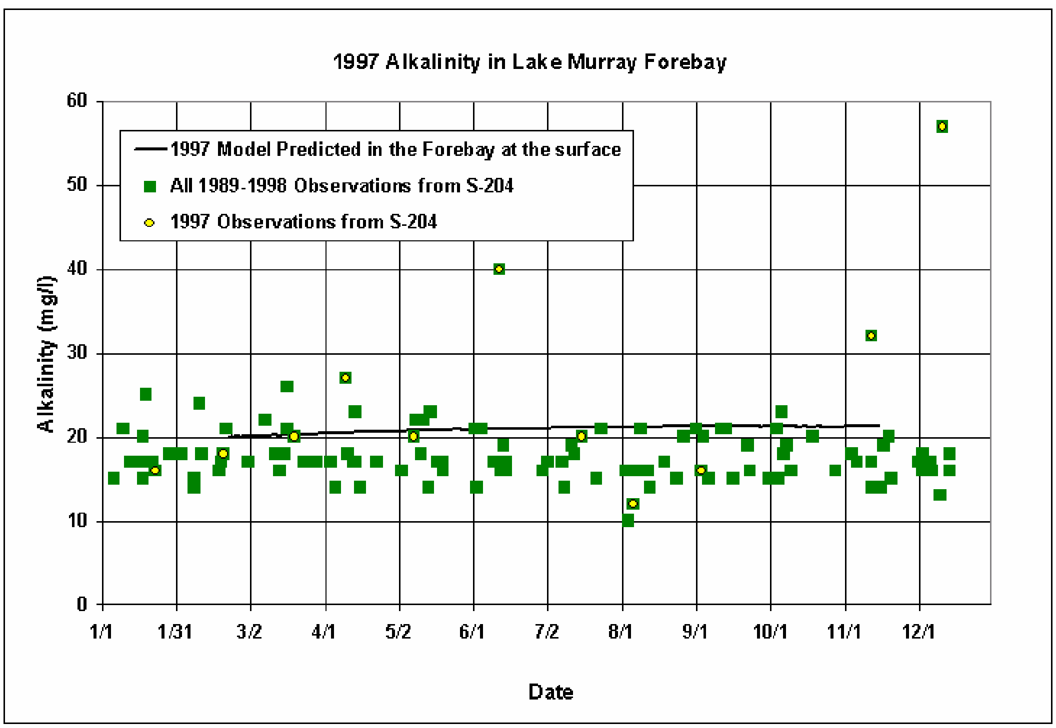


Figure 6-63. 1997 Comparison of Modeled Derived versus Measured Alkalinity at the Surface in the Forebay of Lake Murray

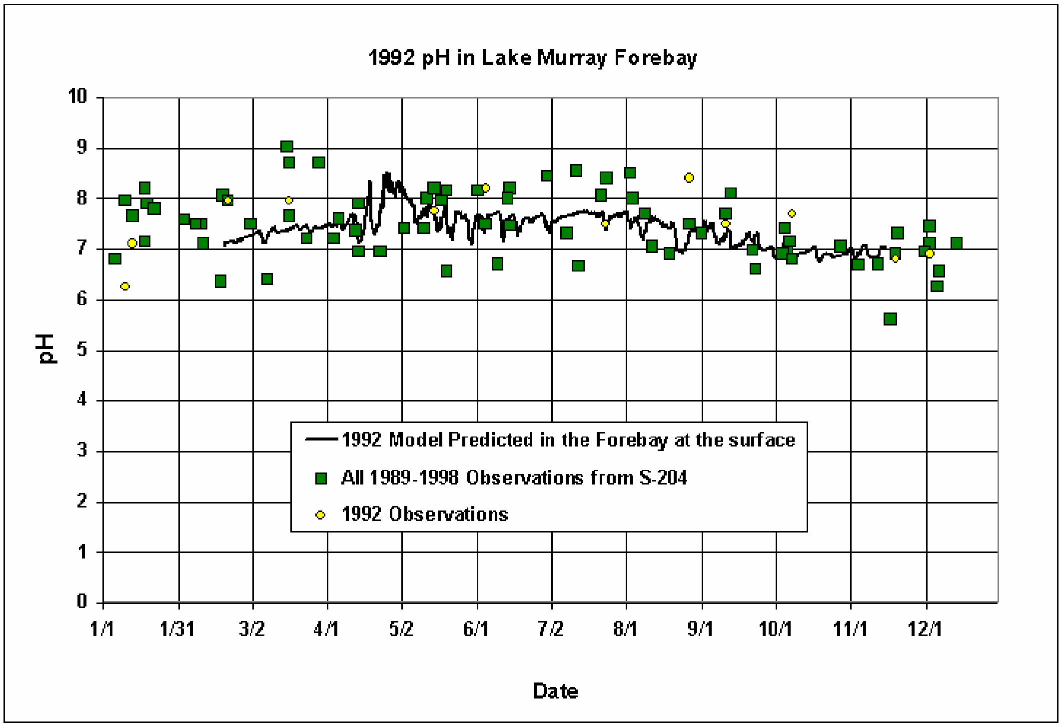


Figure 6-64. 1992 Comparison of Modeled Derived versus Measured pH at the Surface in the Forebay of Lake Murray

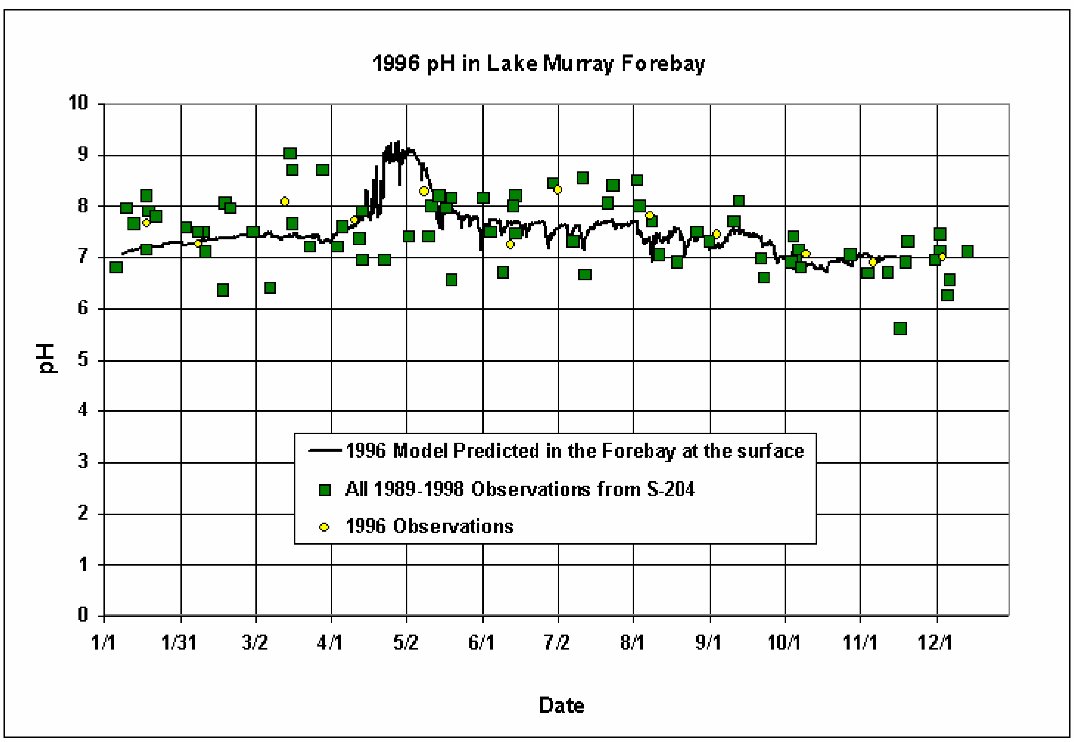


Figure 6-65. 1996 Comparison of Modeled Derived versus Measured pH at the Surface in the Forebay of Lake Murray

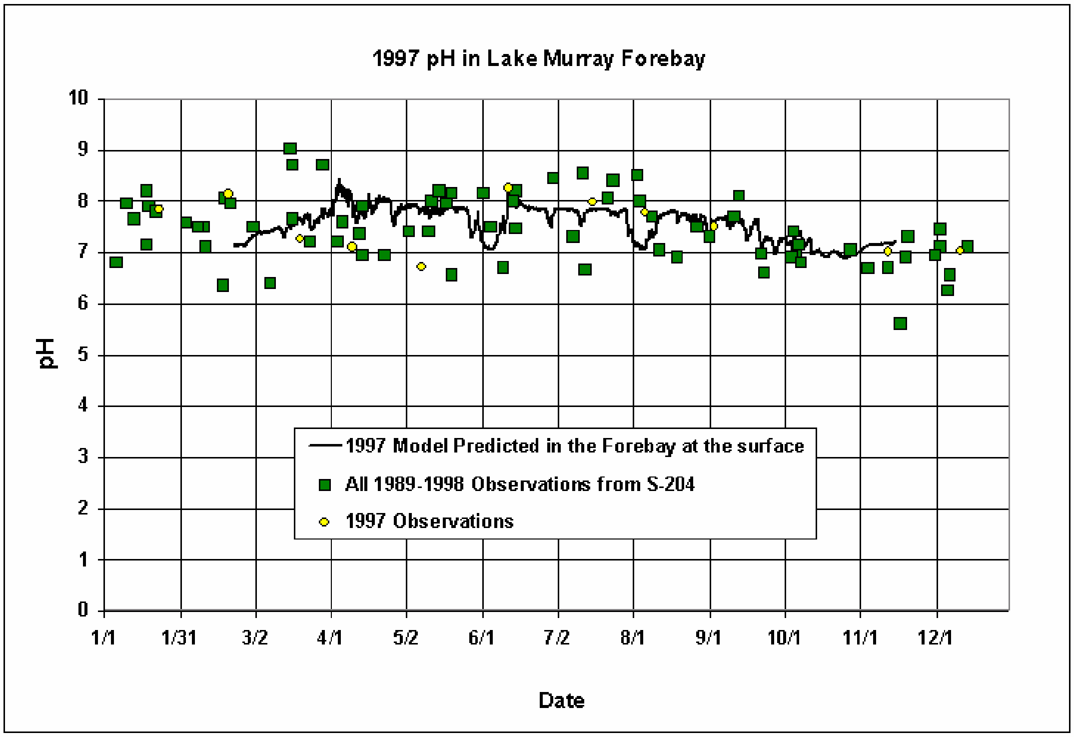


Figure 6-66. 1997 Comparison of Modeled Derived versus Measured pH at the Surface in the Forebay of Lake Murray

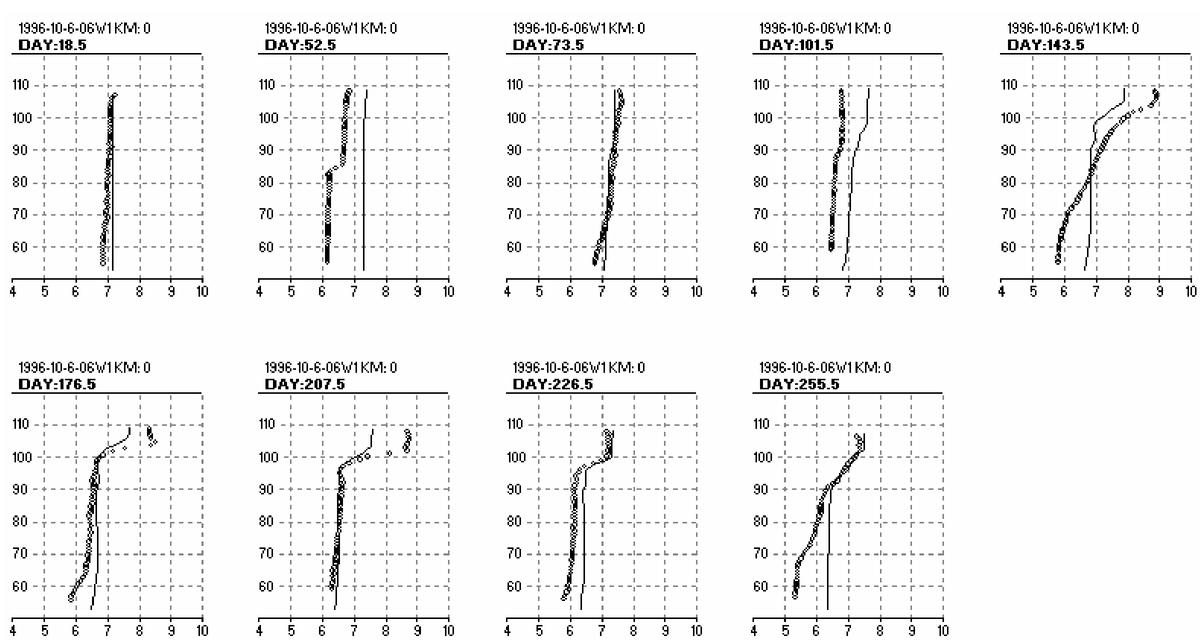


Figure 6-67. 1996 Modeled and Observed pH Profiles in the Forebay of Lake Murray

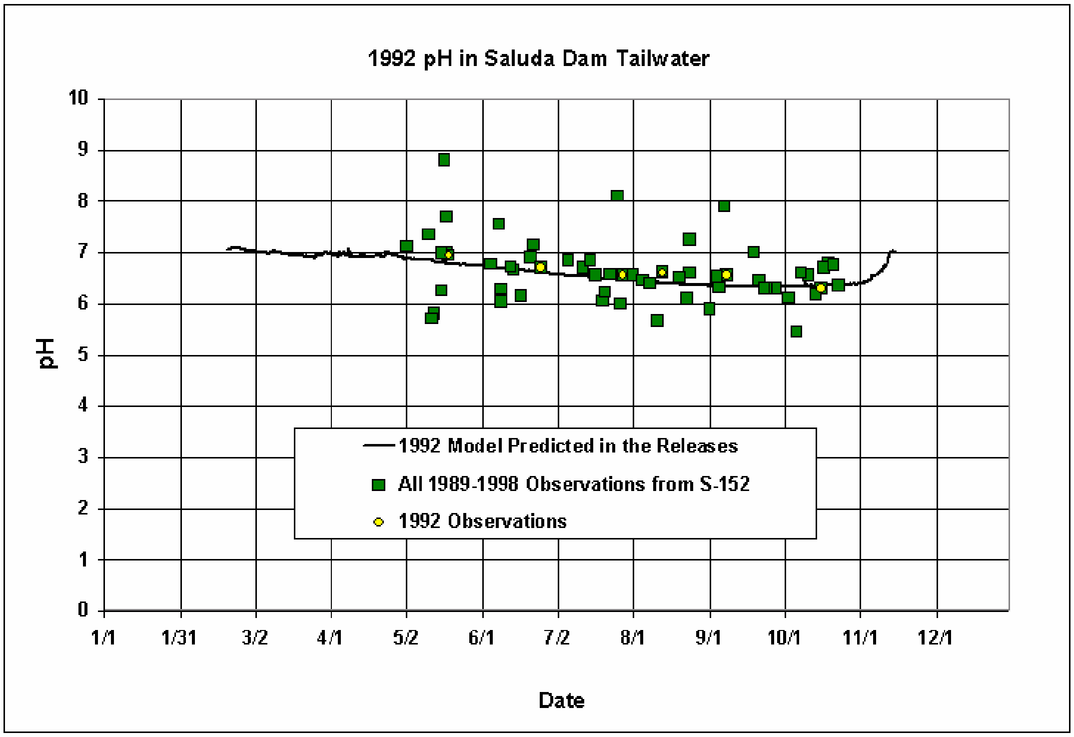


Figure 6-68. 1992 Comparison of Modeled Derived versus Measured pH in the Releases from Saluda Dam

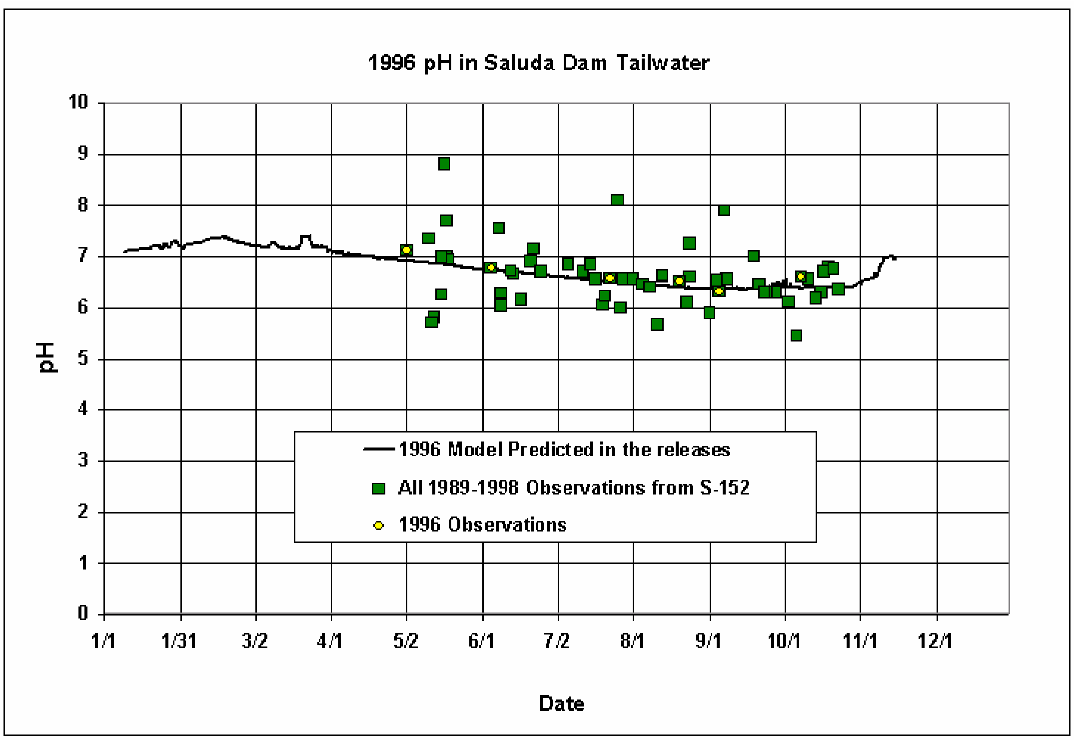


Figure 6-69. 1996 Comparison of Modeled Derived versus Measured pH in the Releases from Saluda Dam

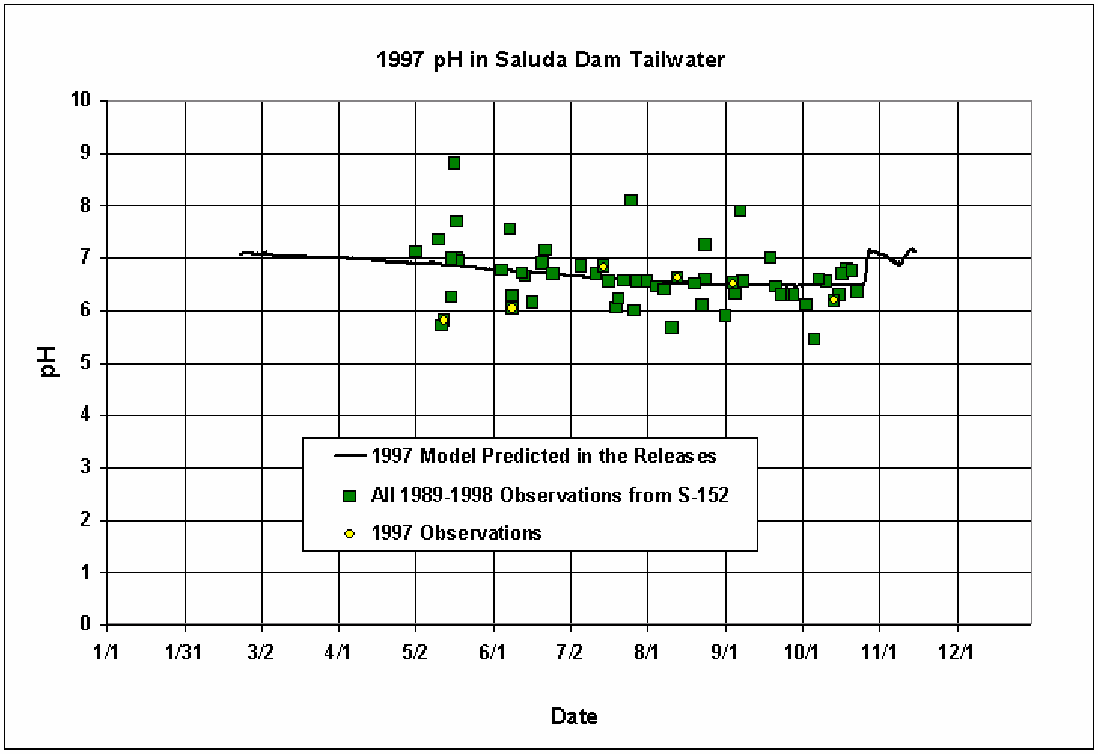


Figure 6-70. 1997 Comparison of Modeled Derived versus Measured pH in the Releases from Saluda Dam

Table 6-8. 1992 DO Statistics

1992 DO

		Kilometers From Dam									
		0.0		6.0		19.3		26.8		Average	
Date	Julian Day	AME	RMS	AME	RMS	AME	RMS	AME	RMS	AME	RMS
2/21	52	0.22	0.45	0.44	0.45	0.34	0.42	0.46	0.59	0.37	0.48
3/17	77			0.05	0.07	1.00	1.00	1.74	1.74	0.93	0.94
3/25	85	0.18	0.23							0.18	0.23
4/9-10	100-101	0.21	0.25	0.42	0.44	1.00	1.06	1.46	1.53	0.77	0.82
5/13	134	0.27	0.34							0.27	0.34
5/15	136			0.34	0.44	1.13	1.21	3.01	3.16	1.49	1.60
6/5	157	0.64	0.74	0.53	0.67	0.53	0.58	2.04	2.62	0.94	1.15
6/12	164	0.37	0.43							0.37	0.43
7/23-24	205-206	0.68	0.80	1.07	1.49	1.62	2.26	2.37	3.19	1.44	1.93
8/19	232	0.88	1.09							0.88	1.09
8/27	240	0.52	0.86	0.56	0.66	0.87	1.00	1.52	1.83	0.87	1.09
9/11	255	0.54	0.63	1.11	1.27	1.93	2.48	2.42	2.83	1.50	1.80
9/19	263	0.68	0.98							0.68	0.98
10/8	282	1.32	1.73	0.94	0.94	0.84	0.96	0.80	1.14	0.98	1.20
10/10	284	0.70	1.50							0.70	1.50
11/9	314	0.87	1.37							0.87	1.37
	Overall	0.56	0.91	0.58	0.80	1.08	1.44	1.78	2.28	0.79	1.25

Table 6-9. 1996 DO Statistics

1996 DO

		Kilometers From Dam									
		0.0		6.0		19.3		26.8		Average	
Date	Julian Day	AME	RMS	AME	RMS	AME	RMS	AME	RMS	AME	RMS
1/17-18	17-18	0.07	0.08	0.45	0.77	0.32	0.33	0.85	1.66	**0.42**	**0.71**
2/21-22	52-53	0.83	0.83	0.82	0.83	0.30	0.33	0.43	0.54	**0.60**	**0.63**
3/13-14	73-74	0.30	0.32	0.78	0.82	0.48	0.54	0.29	0.33	**0.46**	**0.50**
4/10-11	101-103	0.25	0.31	0.14	0.15	0.69	0.77	0.83	0.92	**0.48**	**0.54**
5/9-10	130-131	0.69	0.74	0.47	0.61			1.97	2.40	**1.04**	**1.25**
5/22-23	143-144	0.40	0.56	0.39	0.68	0.74	0.86	1.78	2.09	**0.83**	**1.04**
6/13	165	0.46	0.57	0.57	0.65			0.99	1.10	**0.67**	**0.77**
6/24-25	176-177	0.30	0.44	0.70	0.91	0.88	1.03	0.62	0.90	**0.63**	**0.82**
7/2	184	0.71	0.88	0.74	1.00			3.32	4.04	**1.59**	**1.97**
7/25-26	207-208	0.69	1.03	0.88	1.29	0.74	0.80	0.64	1.10	**0.74**	**1.05**
8/13-14	226-227	0.43	0.61	0.72	0.93	0.41	0.84	1.21	1.89	**0.69**	**1.07**
9/4	248	0.29	0.50	1.27	2.05					**0.78**	**1.27**
9/11-12	255-257	0.32	0.60	0.67	1.30	0.92	1.19	0.83	1.07	**0.68**	**1.04**
10/9-10	283-284	1.27	1.69	1.13	1.65	0.64	0.67	0.49	0.57	**0.88**	**1.14**
11/5-6	310-311	0.95	1.34	0.36	0.46	0.63	0.64	1.25	1.33	**0.80**	**0.94**
	Overall	**0.57**	**0.89**	**0.65**	**1.00**	**0.61**	**0.77**	**1.01**	**1.54**	**0.65**	**1.00**

Table 6-10. 1997 DO Statistics

1997 DO

		Kilometers From Dam									
		0.0		6.0		19.3		26.8		Average	
Date	Julian Day	AME	RMS	AME	RMS	AME	RMS	AME	RMS	AME	RMS
3/12	71	0.75	0.89	0.71	0.76	0.45	0.53	0.92	1.06	**0.71**	**0.81**
4/2	92	0.46	0.60	0.24	0.29	0.38	0.43	0.19	0.21	**0.32**	**0.38**
5/6-7	126-127	0.42	0.49	0.69	0.89	1.37	1.86	0.98	1.20	**0.87**	**1.11**
6/3-4	154-155	1.07	1.18	0.92	1.04	1.56	1.70	3.30	4.27	**1.71**	**2.05**
6/12	163	0.86	1.01	0.58	1.05	1.08	1.30	1.53	1.77	**1.01**	**1.28**
7/15-16	196-197	0.74	1.13	1.13	1.42	1.09	1.32	1.08	1.37	**1.01**	**1.31**
8/5	217	1.36	1.95	0.91	1.30	1.09	1.87	2.39	3.05	**1.44**	**2.04**
9/2-3	245-246	0.54	0.81	0.72	1.04	0.55	0.89	0.68	1.33	**0.62**	**1.02**
10/7	280	0.79	0.98	0.73	1.05	1.64	2.12	1.87	2.02	**1.26**	**1.54**
10/23	296	1.30	1.36	0.49	0.49	1.08	1.08			**0.96**	**0.98**
11/4-5	309	0.27	0.31	0.70	0.73	0.61	0.91	0.41	0.49	**0.50**	**0.61**
11/12	316	0.33	0.36	0.53	0.53	0.57	0.57	0.17	0.19	**0.40**	**0.41**
	Overall	**0.73**	**1.02**	**0.72**	**0.98**	**0.97**	**1.40**	**1.30**	**2.02**	**0.84**	**1.25**

Summary of Calibration

- 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 lake.
- The model is well-suited for addressing the following objectives: DO in the releases from Saluda Hydro; DO in the metalimnion which is the habitat for blueback 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 in this report.

7. Applications for the Model

SCE&G developed the W2 model to determine the effectiveness of phosphorous reductions in Lake Murray on improving DO in the main body of the lake and its releases, as well as to investigate the relationships between reservoir operations and fish habitat in the lake for blueback herring and striped bass. As presented in the previous section, the W2 model for Lake Murray is well-calibrated to address these issues.

Reduced Phosphorus in the Inflows

Estimated Future Concentrations of Phosphorus for Inflows

As discussed previously, phosphorus concentrations in the inflows to Lake Murray are relatively high compared to the SCDHEC criteria for nutrients in lakes as well as for lakes like Lake Murray based on limnological comparisons to other lakes of similar size. In addition, the phosphorus concentrations in the inflows are ranked at about the 75-80 percentile for lakes that are not designated as TMDL sites and at the 40-45 percentile level for lakes that are designated as TMDL sites.

The SCDHEC criteria for nutrients provide avenues for addressing excessive nutrient loads from point and non-point sources and are briefly summarized as follows:

> Section E, Item 9. In order to protect and maintain lakes and other waters of the State, consideration needs to be given to the control of nutrients reaching the waters of the State. Therefore, the Department shall control nutrients as prescribed below.
>
> a. Discharges of nutrients from all sources, including point and nonpoint, to waters of the State shall be prohibited or limited if the discharge would result in or if the waters experience growths of microscopic or macroscopic vegetation such that the water quality standards would be violated or the existing or classified uses of the water would be impaired. Loading of nutrients shall be addressed on an individual basis as necessary to ensure compliance with the narrative and numeric criteria.
>
> b. Numeric nutrient criteria for lakes are based on ….
>
>   1. For the Blue Ridge Mountains…
>   2. For the Piedmont and Southeastern Plains eco-regions of the State, TP shall not exceed 0.06 mg/L…

c. In evaluating the effects of nutrients upon the quality of lakes and other waters of the State, the Department may consider, but not be limited to, such factors as the hydrology and morphometry of the waterbody, the existing and projected trophic state, characteristics of the loadings, and other control mechanisms in order to protect the existing and classified uses of the waters
d. The Department shall take appropriate action to include, but not limited to: establishing numeric effluent limitations in permits, establishing TMDLs, establishing waste load allocations, and establishing load allocations for nutrients to ensure that the lakes attain and maintain the above narrative and numeric criteria and other applicable water quality standards.
e. The criteria specific to lakes shall be applicable to all portions of the lake. For this purpose, the Department shall define the applicable area to be that area covered when measured at full pool elevation.

Although these criteria are for lakes, major tributaries like the Saluda River, the Little Saluda River, and the Bush River essentially form the upper part of Lake Murray so there is little difference between river concentrations and lake concentrations. Also, the concentrations of TP in the Bush River and Ninety-Six Creek are so high that they need to be reduced so as to reduce the production of organic matter (i.e., aquatic plants, epiphytes, periphyton) in the free-flowing streams that eventually end up in Lake Murray. Several States are implementing phosphorus criteria for streams to reduce the formation of organic matter in these streams (EPA; Heiskary, 2002).

In some situations State-wide criteria are insufficient to protect water quality, and site-specific water quality criteria are needed to protect water uses. One could argue that the effects of Ninety-Six Creek are diluted by the Saluda River flowing from Lake Greenwood and therefore the water quality criteria are met. However, if the phosphorus load from Ninety-Six Creek impacts Lake Murray water uses (i.e., habitat for striped bass and blueback herring, eutrophication of the lake, low DO in the inflow regions of the lake, low DO and pH in the releases from Saluda Hydro, millions of dollars in costs for water quality improvements by SCE&G), consideration should be given to reducing phosphorus in Ninety-Six Creek to levels that would alleviate impacts to downstream water users. In essence, the case could be made that Lake Murray does not have the capacity to assimilate the phosphorus loads from Ninety-Six Creek and the Bush River without significantly affecting other water uses. Additionally, some of the water quality problems in Lake Murray (i.e., eutrophication, low DO in the inflow regions of the lake, low pH in the releases from Saluda Hydro, and habitat for striped bass and blueback herring) can reasonably be addressed only by phosphorus reductions. It is readily apparent that phosphorus reduction is the only alternative that has such far-reaching positive impacts to water quality and reducing water use impairments.

For modeling the effects of reducing phosphorus in the tributary inflows, it was assumed that all tributaries (including Ninety-Six Creek) would be limited to 0.06 mg/L of TP and Lake Greenwood would continue to release water containing only 0.02 mg/L. Under these conditions the mean TP in the Saluda River inflow to Lake Murray would be about 0.027 mg/L compared to the current concentration of 0.05 mg/L. It should be noted that these levels of phosphorus in the inflows would be expected to significantly improve DO in the releases based on the review of other lakes having residence times similar to Lake Murray—see the section on Limnological considerations. Using these assumptions the total load of phosphorus entering Lake Murray would be reduced 61%, from 1098 to 430 lbs/day of TP. The mean concentration of TP in all inflows upstream from Rocky Creek would be reduced from 0.08 mg/L to 0.03 mg/L. The distribution of phosphorus loads allocated to the various inflows (see Figure 7-1) would more closely track the hydrologic distribution of flows as shown in Figure 3-10.

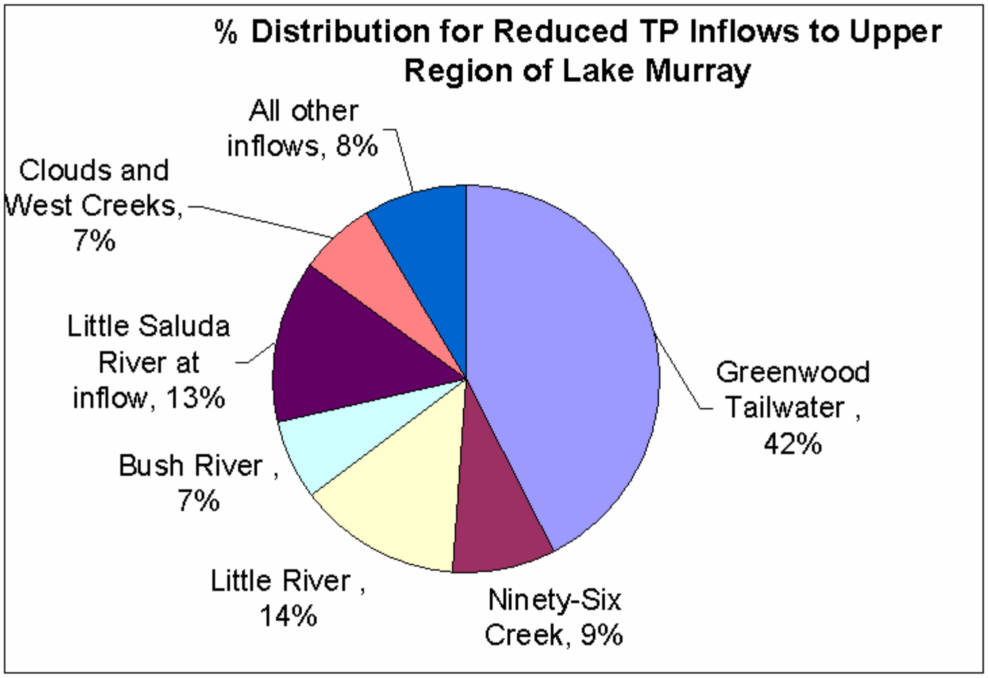


Figure 7-1. Percent Distribution of TP Loads to the Upper Region of Lake Murray for the Assumed Reductions in TP

Estimated Sediment Oxygen Demand for Lower Phosphorus in Inflows

SOD in CE-QUAL-W2 is represented by a first-order component and a zero-order component. The first-order SOD accounts for the decomposition of LOM that settles to the bottom sediments, primarily as algae die. The first-order SOD for predicted water quality conditions (i.e., for predicted conditions involving lower nutrients in the inflows) is adjusted within the model as a function of the amount of algae that is produced in the water column. The zero-order SOD accounts for various types of less labile organic matter such as allochthonous suspended and bed load material, cell wall material from algae and bacteria that settle to the bottom of the lake, and buried organic materials. The zero-order SOD is not internally adjusted within the model for lower nutrients in the inflows so it must be adjusted externally. Chapra (1997) reports that a number of investigators (Chapra and Canale, 1991; DiToro, et al., 1990) have reported that SOD and areal hypolimnetic oxygen demand generally appears to be proportional to organic or phosphorus loading in the following manner:

$$SOD_p = SOD_c \, [P_p/P_c]^{1/2},$$

where SOD_p is predicted SOD, SOD_c is the current SOD, P_p is predicted phosphorus load, and P_c is the current phosphorus load. For illustration purposes, if the current inflow phosphorus concentration averaged 0.08 mg/L and it was reduced to 0.02 mg/L (i.e., a 75% reduction), the SOD_c would be reduced by one-half (i.e., a 50% reduction).

Predicted zero-order SOD reductions were estimated using the reduction in TP in the inflows. The reduction in zero-order SOD was determined to be 32%.

To consider the range of sensitivity of lake water quality to the reduction in zero-order SOD, the model runs for simulations were conducted with and without this reduction.

Results of Model Simulations

Results from the reduced phosphorus runs under 1992, 1996, and 1997 conditions are shown in Figure 7-2 through Figure 7-4. These figures show that the length of time that the DO in the release from Saluda Hydro was less than 5 mg/L was much shorter under reduced phosphorus conditions. Minimum release DO in the reduced phosphorus scenario for 1992, 1996, and 1997 was 1.15, 0.07, and 2.90 mg/L, respectively. The period of time that DO was less than 5 mg/L was reduced from 18 weeks to 11 weeks in 1992, 17 weeks to 9 weeks in 1996, and 17 weeks to 10 weeks in 1997.

Figure 7-5 through Figure 7-12 are longitudinal DO contour plots from the low DO period of 1996, and illustrate the effect that reduced phosphorus has throughout the lake. These figures show how reduced phosphorus in the inflows dramatically improved DO in the main body of the lake. Although DO was still near zero near the lake sediments at various locations as the stratification period progressed, the lake volume with low DO water was significantly reduced. Figure 7-13 through Figure 7-15 show the volume of water in the model that is within defined criteria for 1992, 1996, and 1997, respectively. The criteria were temperature $\leq$25.0 C° and DO $\geq$3.0 mg/L and were chosen to illustrate availability of habitat suitable for striped bass. These figures illustrate how the volume of the lake that is suitable for striped bass decreases each summer as the water temperature increases and the DO decreases. The top plot in each figure shows the volume of the lake that fits within the criteria when the models are run using current phosphorus concentrations in the inflows, and the bottom plot in each figure shows the volume of the lake that fits within the criteria when the models are run using reduced phosphorus concentrations in the inflows. In all three years, there are at least a few weeks when there is no volume that satisfies this criteria modeled with current phosphorus loads. However, with reduced phosphorus in the inflows, there is always some volume that complies with the criteria.

Figure 7-16 through Figure 7-18 show the difference in the DO levels observed at the elevation of the unit 5 intake under current and reduced phosphorus conditions for 1992, 1996, and 1997, respectively. Under current conditions the DO at this elevation was at or near zero mg/L for about 30 days in all three years modeled. As can be seen in the forebay DO profiles from 1992 and 1996 (Figure 6-43 and Figure 6-47, respectively), prior to the DO being zero at the elevation of the unit 5 intake, it was zero above this elevation which left a large portion of the water column where DO was unsuitable for fish. In 1997 the DO depletion was more uniform throughout the water column (Figure 6-51). As the DO at the Unit 5 intake level dropped to zero, the fish had no where to escape and either died or were entrained by Unit 5 if it was operated. However, with phosphorus reduced in the inflows, DO dropped to a minimum of 2.4, 1.6, and 3.5 mg/L in 1992, 1996, and 1997, respectively, and this large volume of water did not become isolated from suitable areas with higher DO levels. The habitat concern for striped bass and blueback herring was eliminated—the pocket of high DO that has occurred under current conditions and that has congregated fish in front of the dam would no longer occur and fish would be free to inhabit other portions of the lake. These plots illustrate that with the inflow phosphorus reduced, there would no longer be "schooling" of blueback herring in front of the Unit 5 intake in the late summer, so operations of Unit 5 would no longer be a concern.

Figure 7-19 through Figure 7-21 shows the comparison of chlorophyll *a* under current conditions and reduced phosphorus conditions at four locations for the three years modeled, and again the results indicate significant changes in water quality. It is readily apparent that eutrophication levels would decrease significantly. Although the DO at the inflow regions at the locations of the USGS monitors were not specifically modeled, it is apparent that minimum DO levels associated with algal activity would significantly improve.

Plots showing a comparison of pH in the releases from Saluda Hydro between current conditions and reduced phosphorus conditions are shown in Figure 7-22 through Figure 7-24. These plots show how pH in the releases from Lake Murray would improve if phosphorus was reduced in the inflows. This increase occurs because pH is directly affected by decomposition of organic matter that derives from algal production; i.e., as decomposition occurs, carbon dioxide is formed and causes the decrease in pH, and since algal levels decreased about 55-60%, there would be about 55-60% less carbon dioxide formed and this reduction would prevent pH from getting as low as it does currently**.**

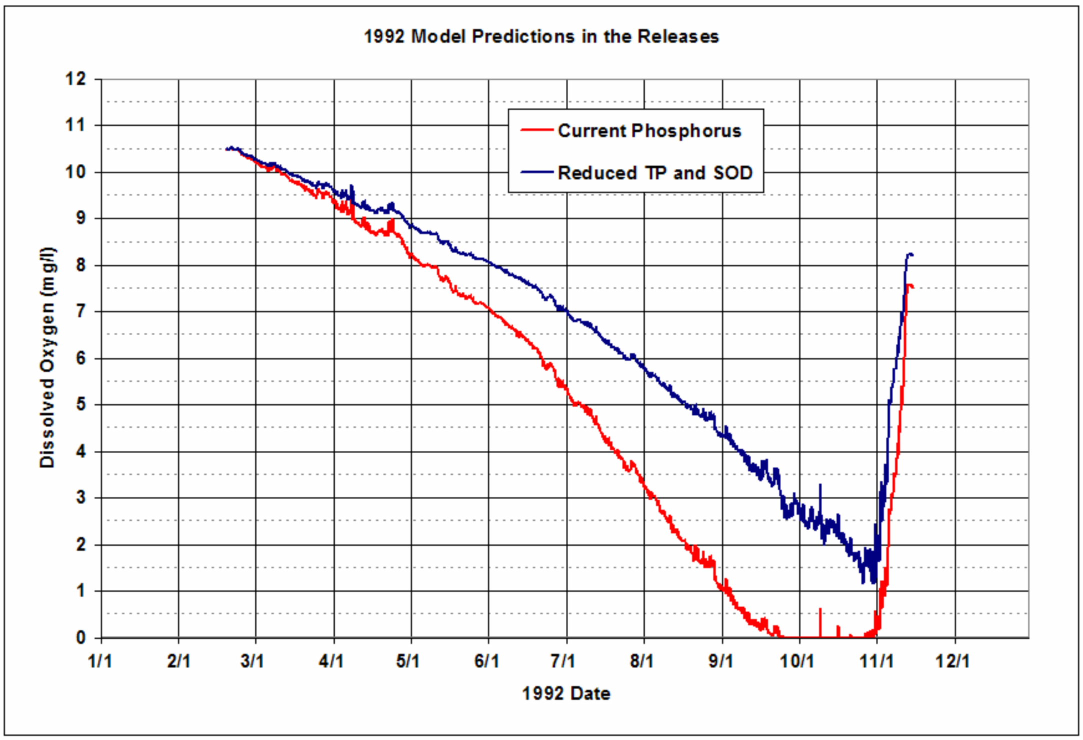


Figure 7-2. 1992 Release DO for Current Phosphorus Loads and Reduced Phosphorus

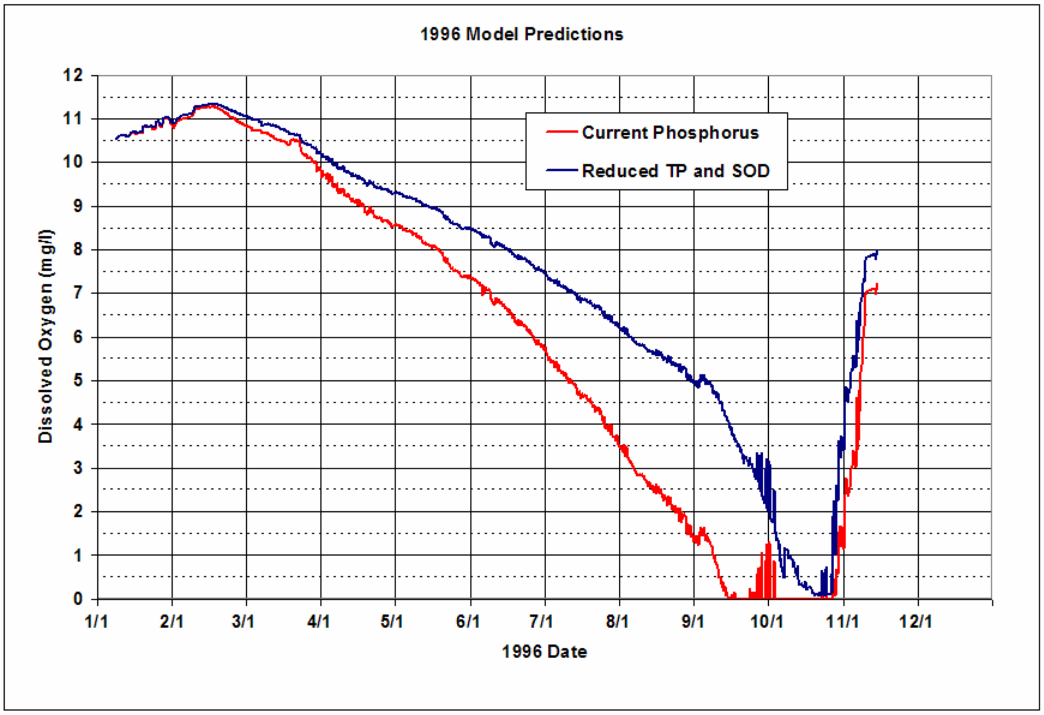


Figure 7-3. 1996 Release DO for Current Phosphorus Loads and Reduced Phosphorus

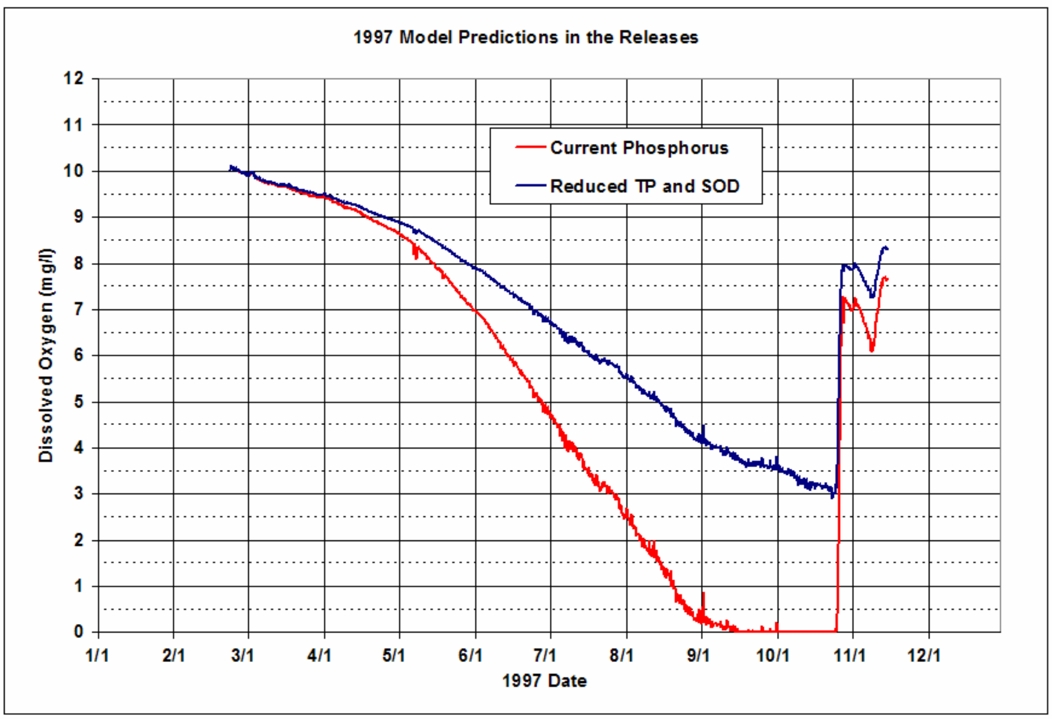


Figure 7-4. 1997 Release DO for Current Phosphorus Loads and Reduced Phosphorus

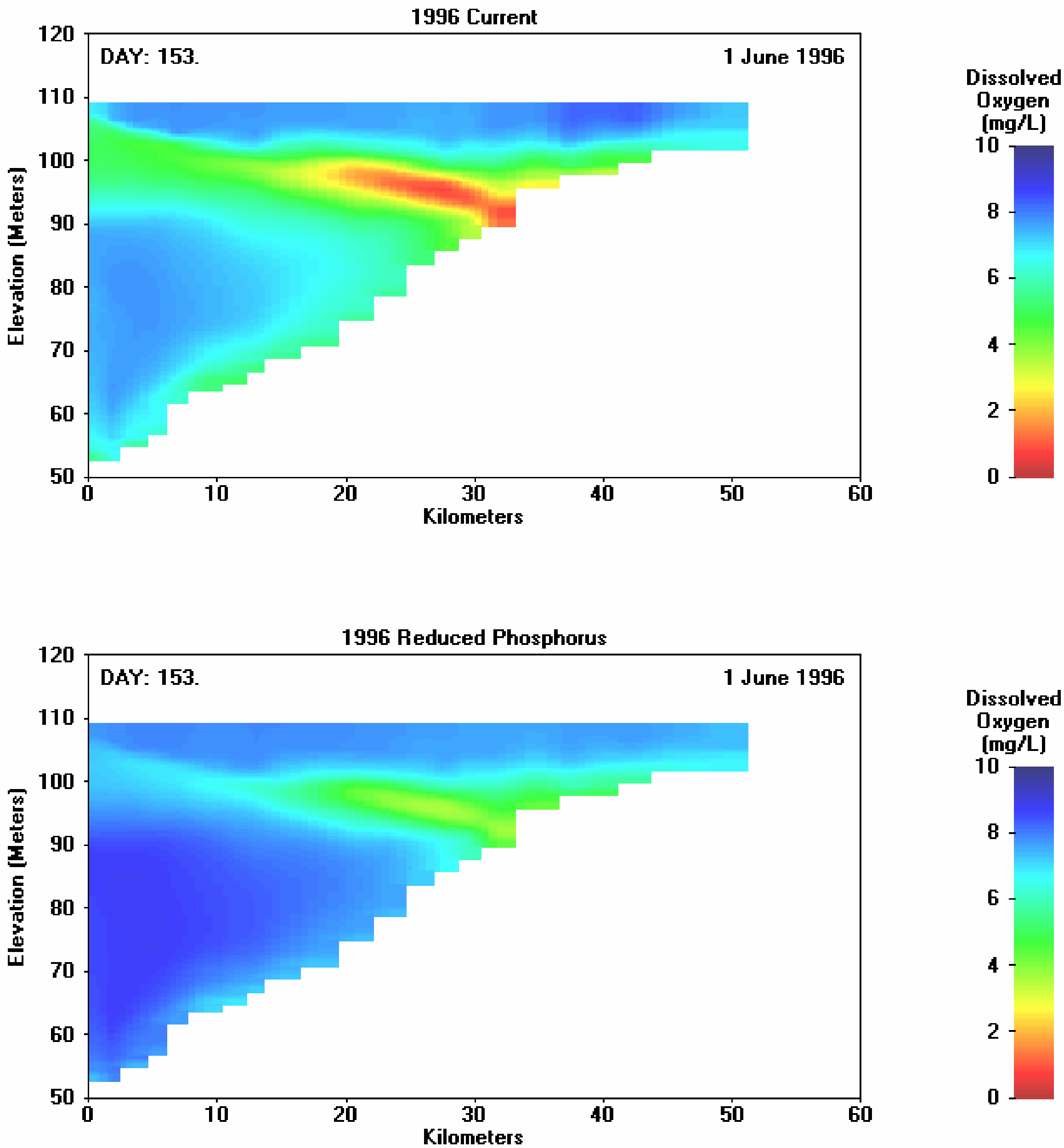


Figure 7-5. 1996 Longitudinal Plots of DO for Current and Reduced Phosphorus on June 1

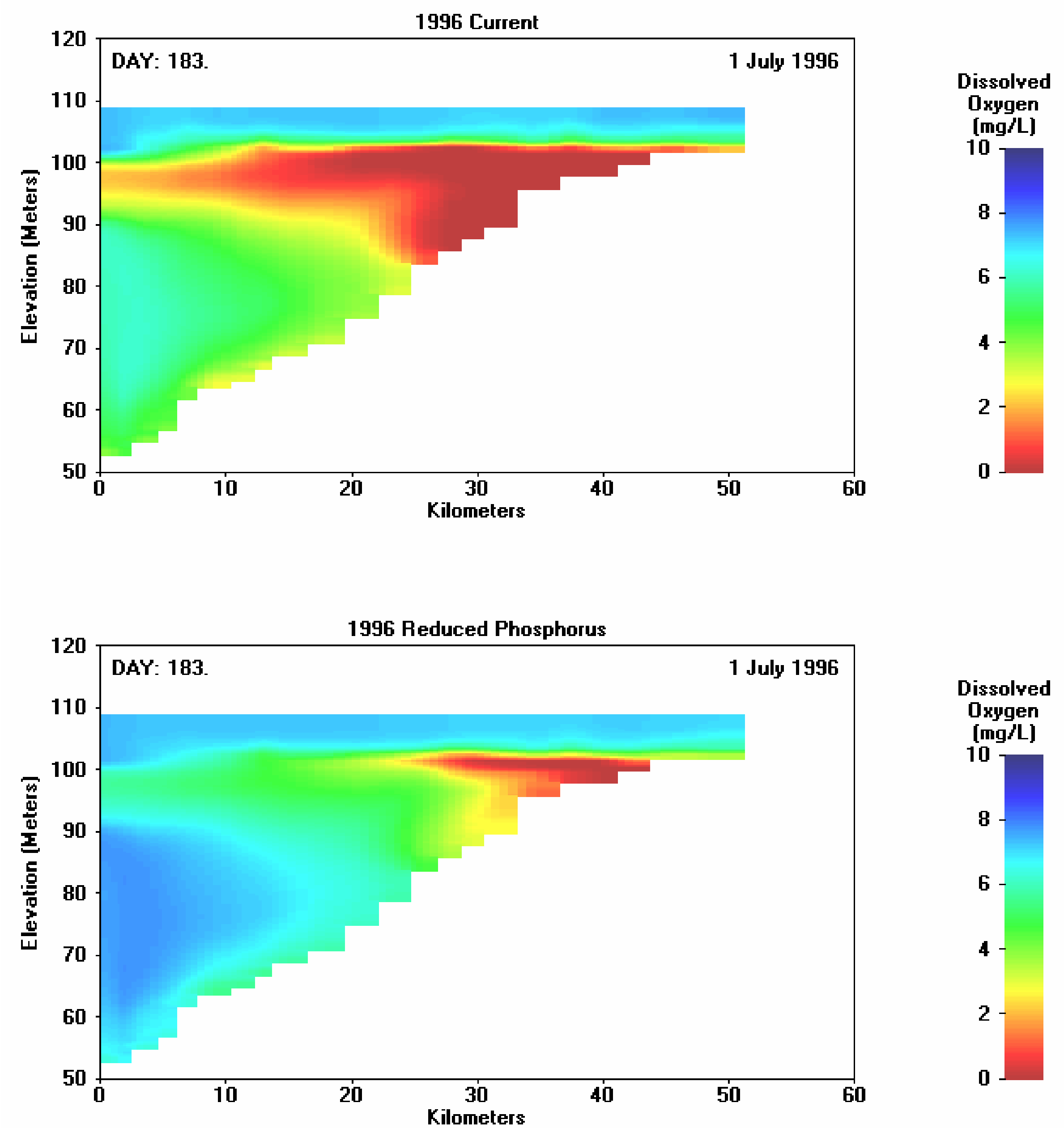


Figure 7-6. 1996 Longitudinal Plots of DO for Current and Reduced Phosphorus on July 1

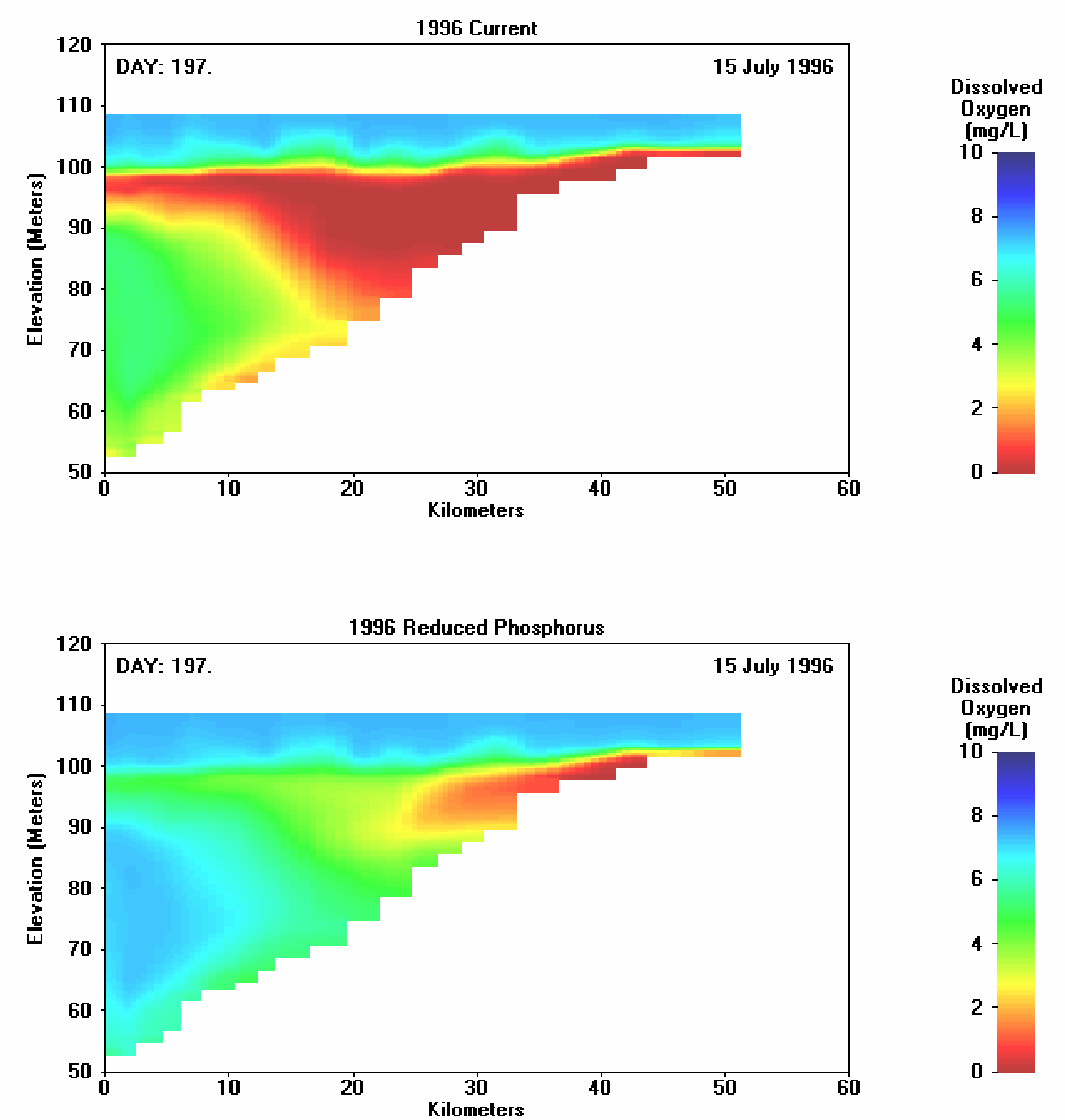


Figure 7-7. 1996 Longitudinal Plots of DO for Current and Reduced Phosphorus on July 15

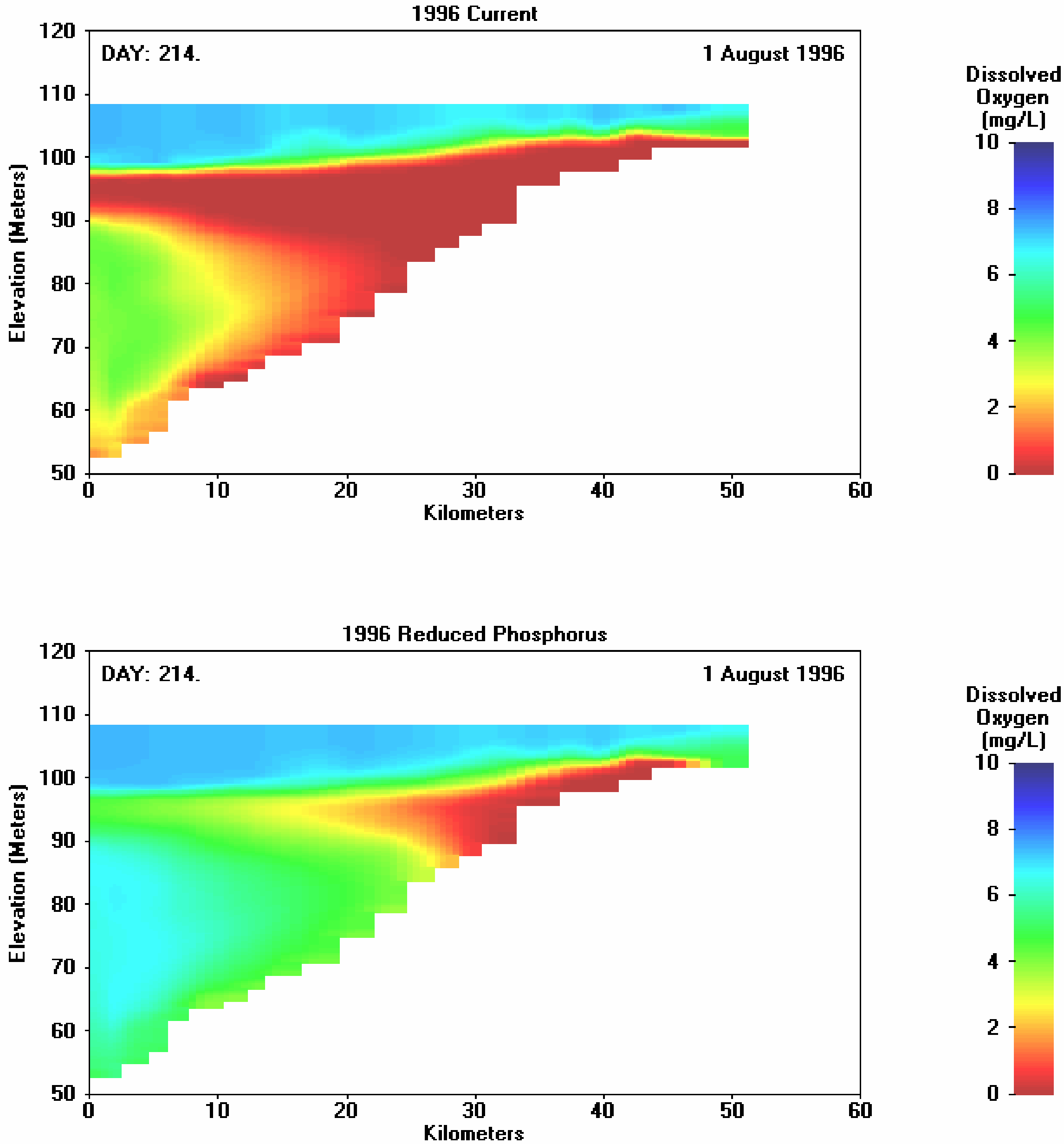


Figure 7-8. 1996 Longitudinal Plots of DO for Current and Reduced Phosphorus Day on August 1

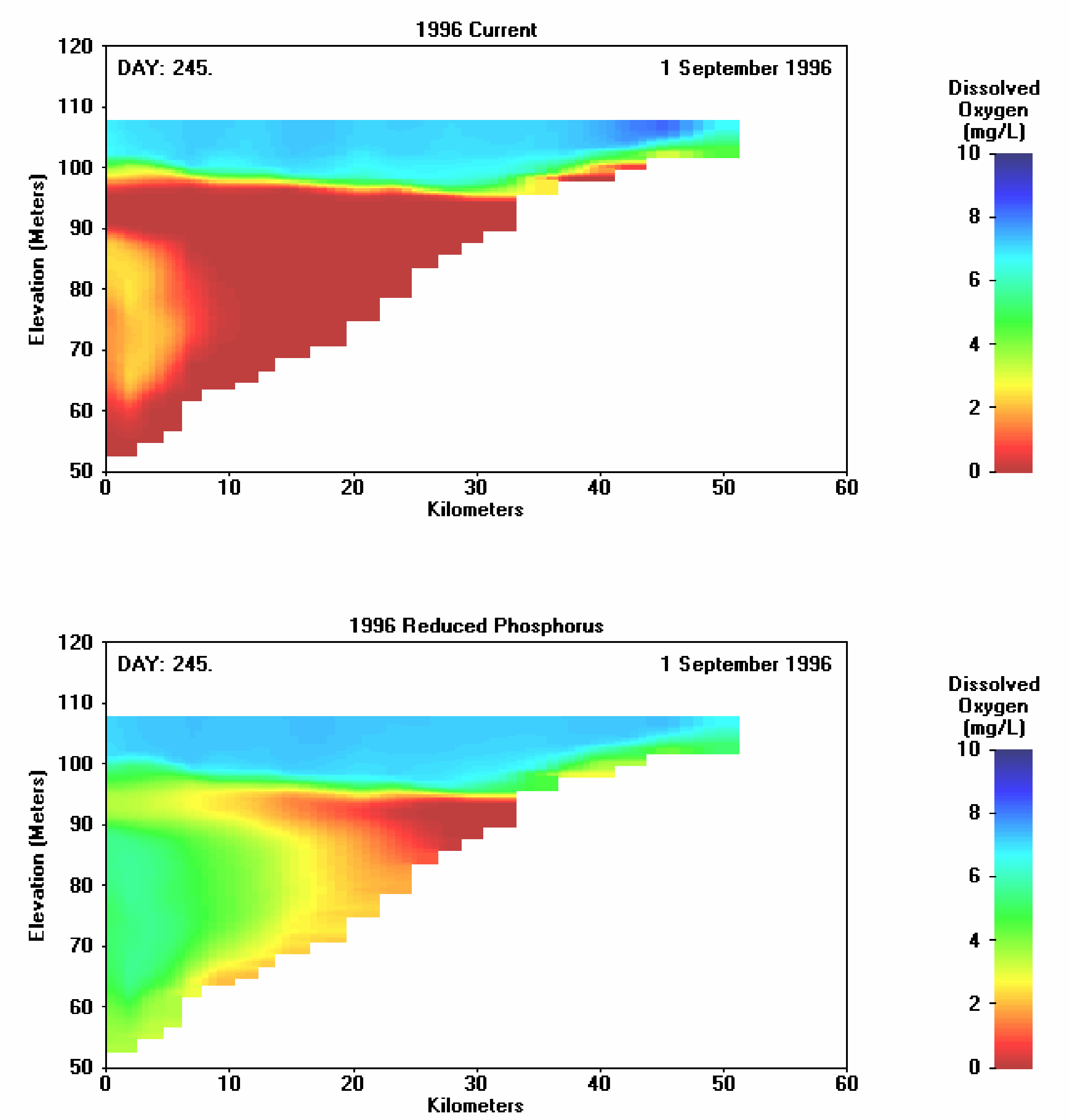


Figure 7-9. 1996 Longitudinal Plots of DO for Current and Reduced Phosphorus on September 1

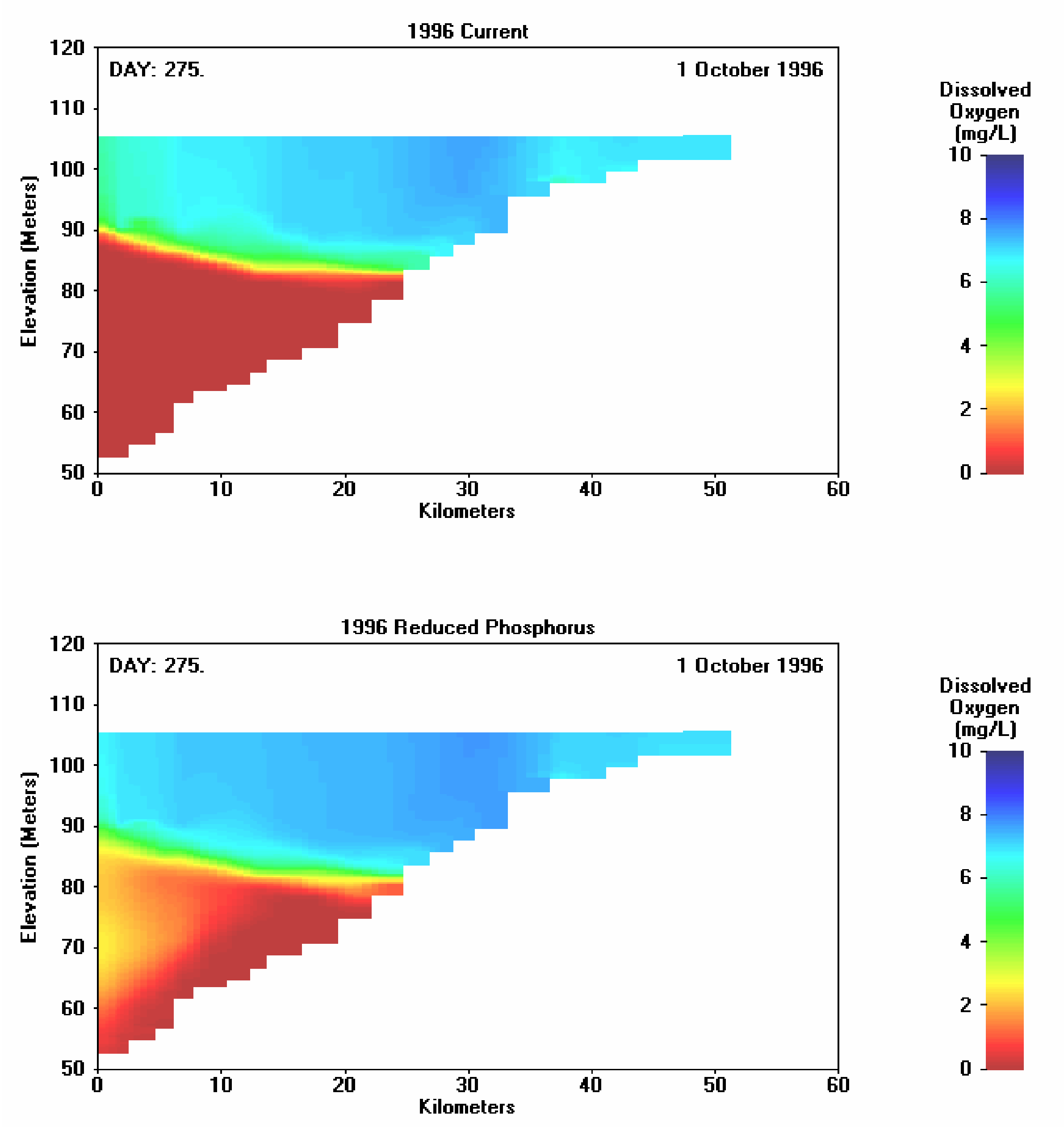
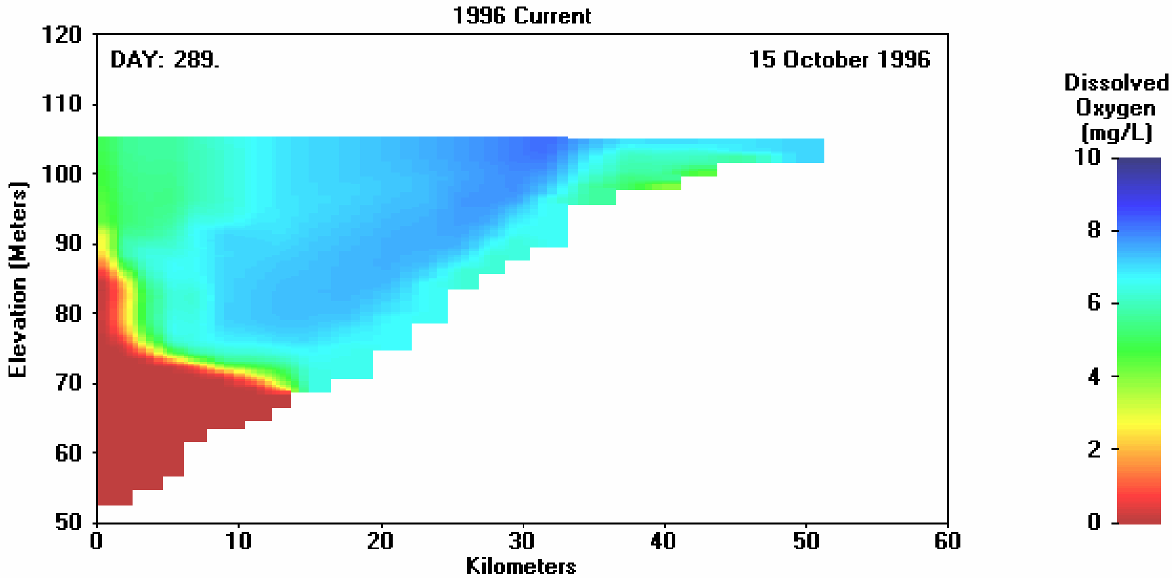


Figure 7-10. 1996 Longitudinal Plots of DO for Current and Reduced Phosphorus on October 1



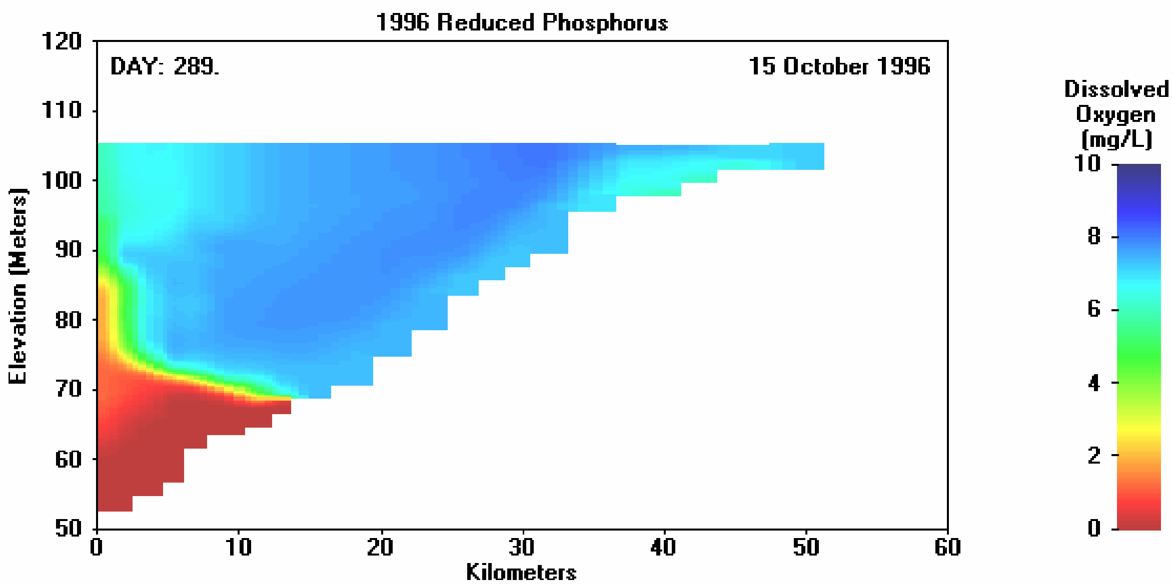
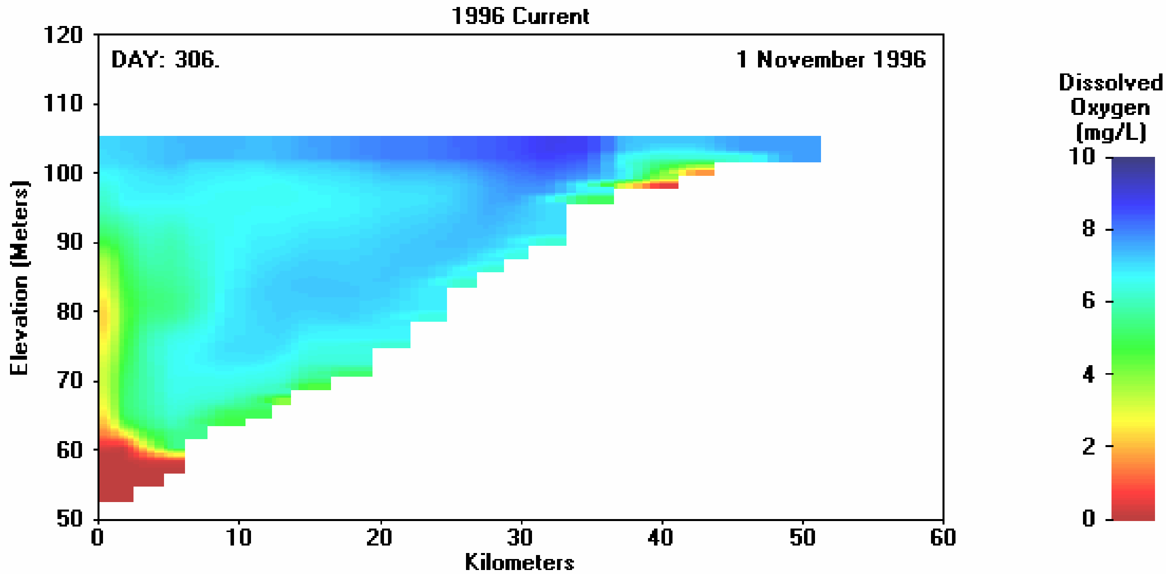


Figure 7-11. 1996 Longitudinal Plots of DO for Current and Reduced Phosphorus on October 15



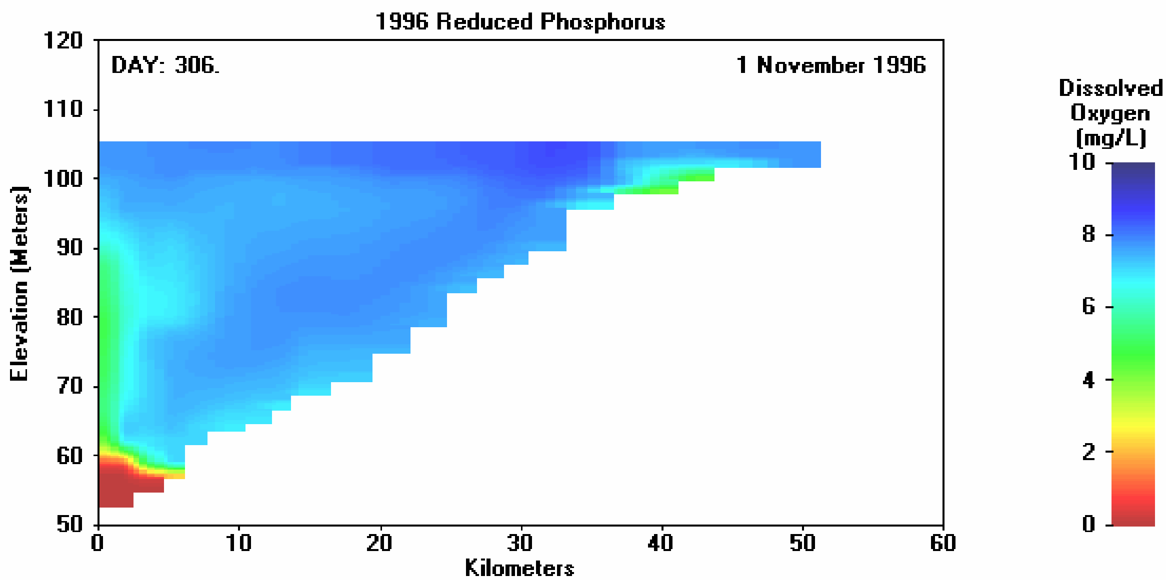


Figure 7-12. 1996 Longitudinal Plots of DO for Current and Reduced Phosphorus on November 1

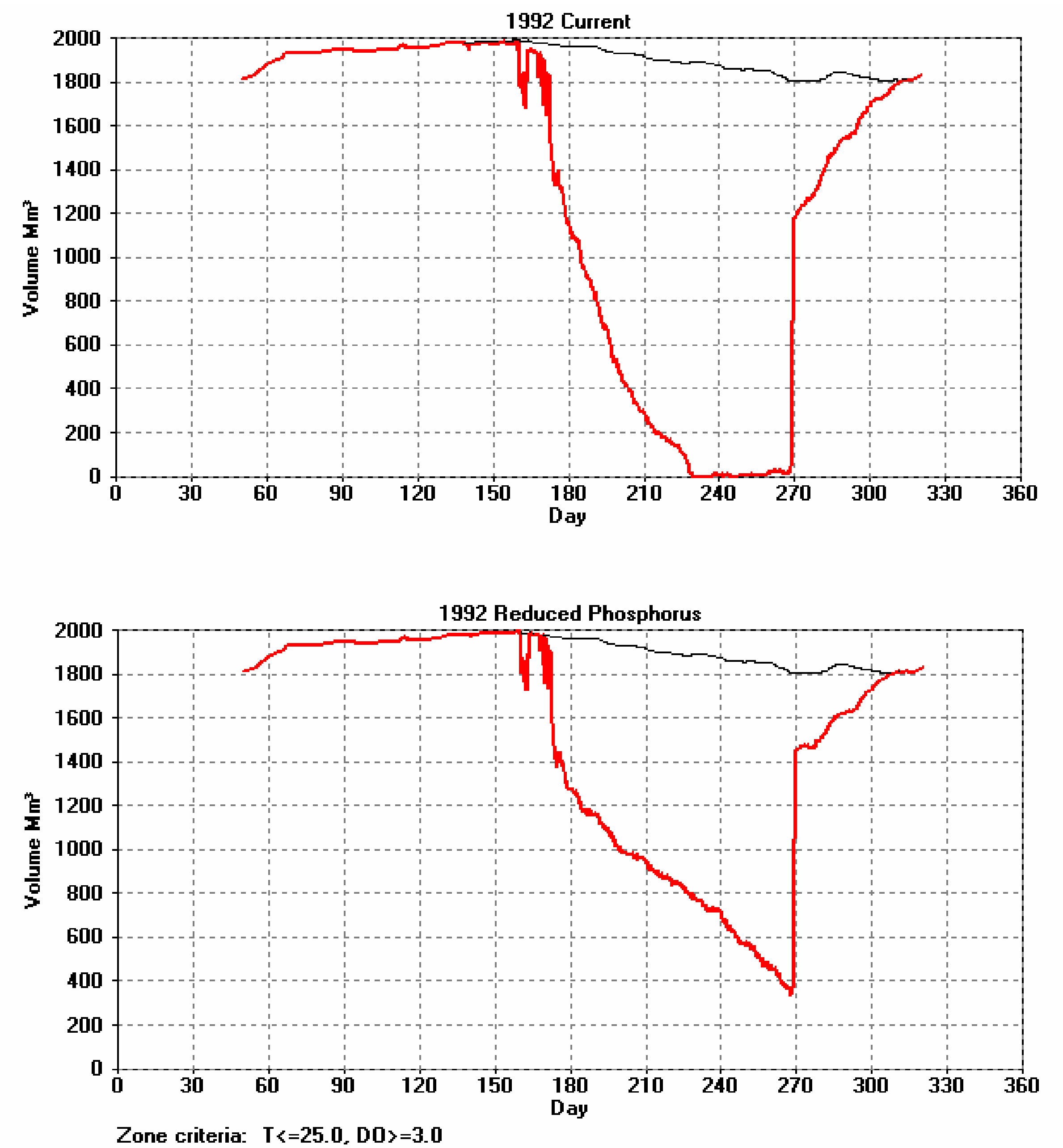


Figure 7-13. 1992 Zone Volume Plots for Current and Reduced Phosphorus

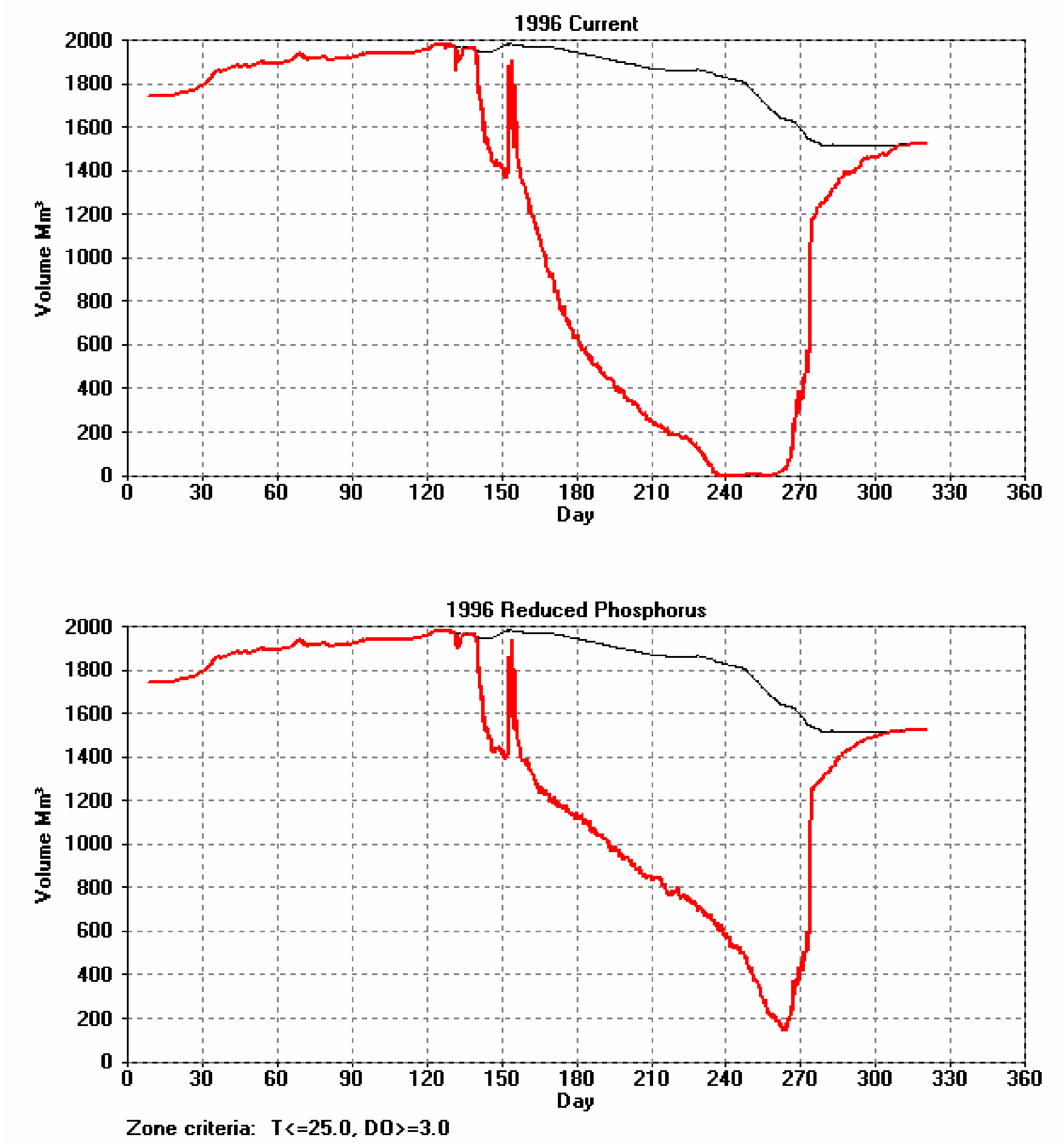


Figure 7-14. 1996 Zone Volume Plots for Current and Reduced Phosphorus

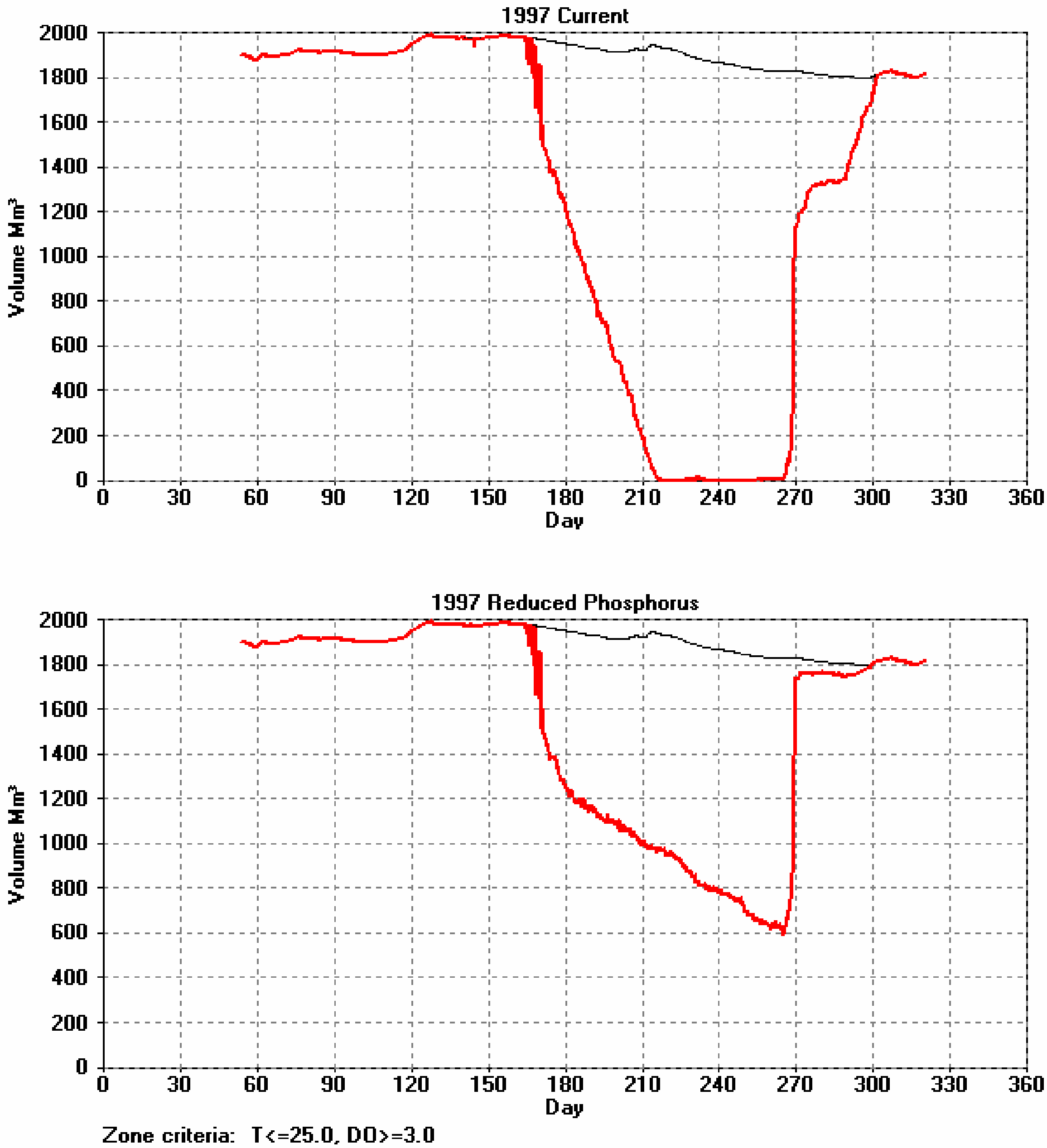


Figure 7-15. 1997 Zone Volume Plots for Current and Reduced Phosphorus

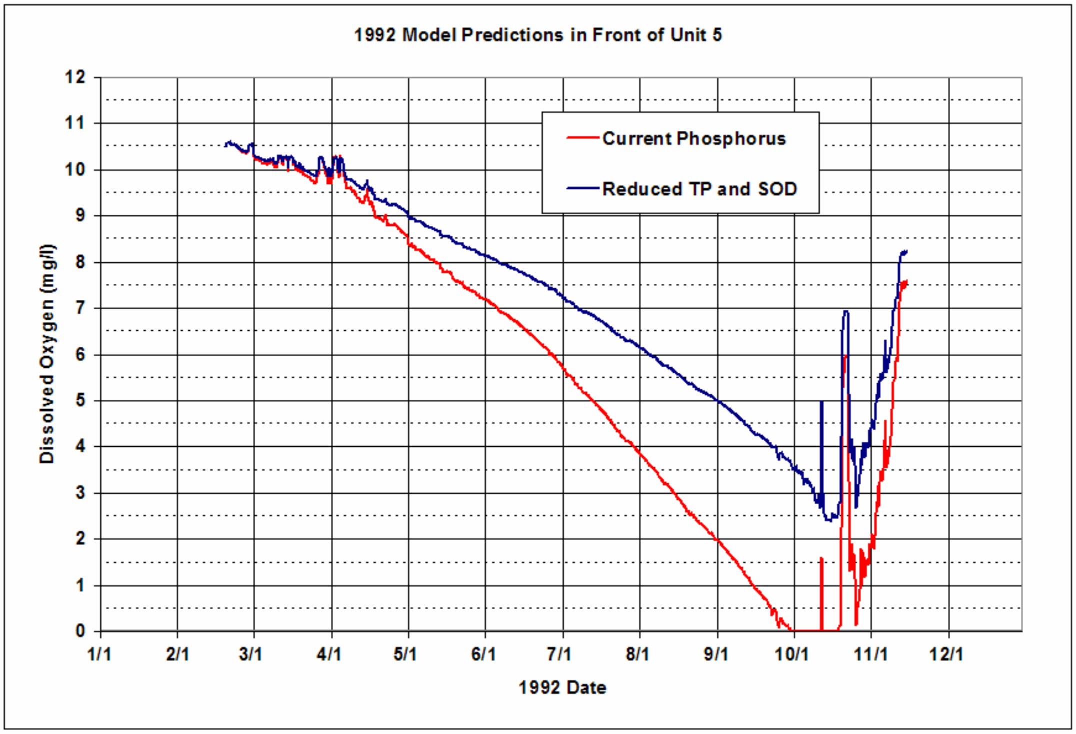


Figure 7-16. 1992 DO at the Level of the Unit 5 Intake for Current and Reduced Phosphorus

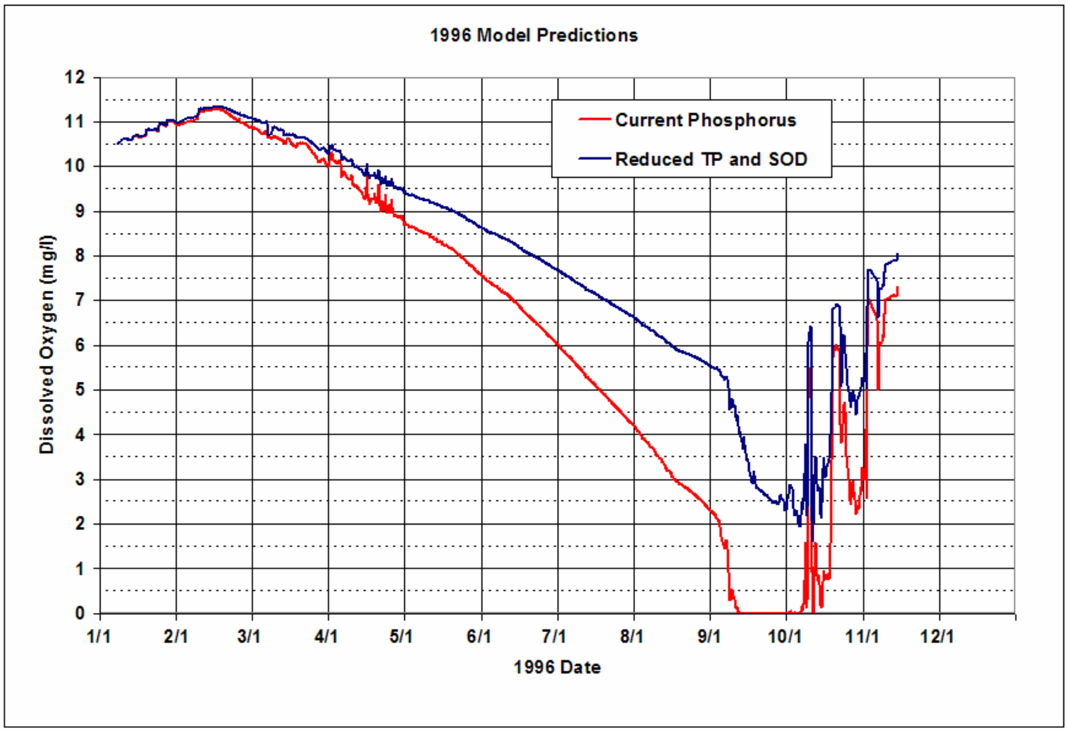


Figure 7-17. 1996 DO at the Level of the Unit 5 Intake for Current and Reduced Phosphorus

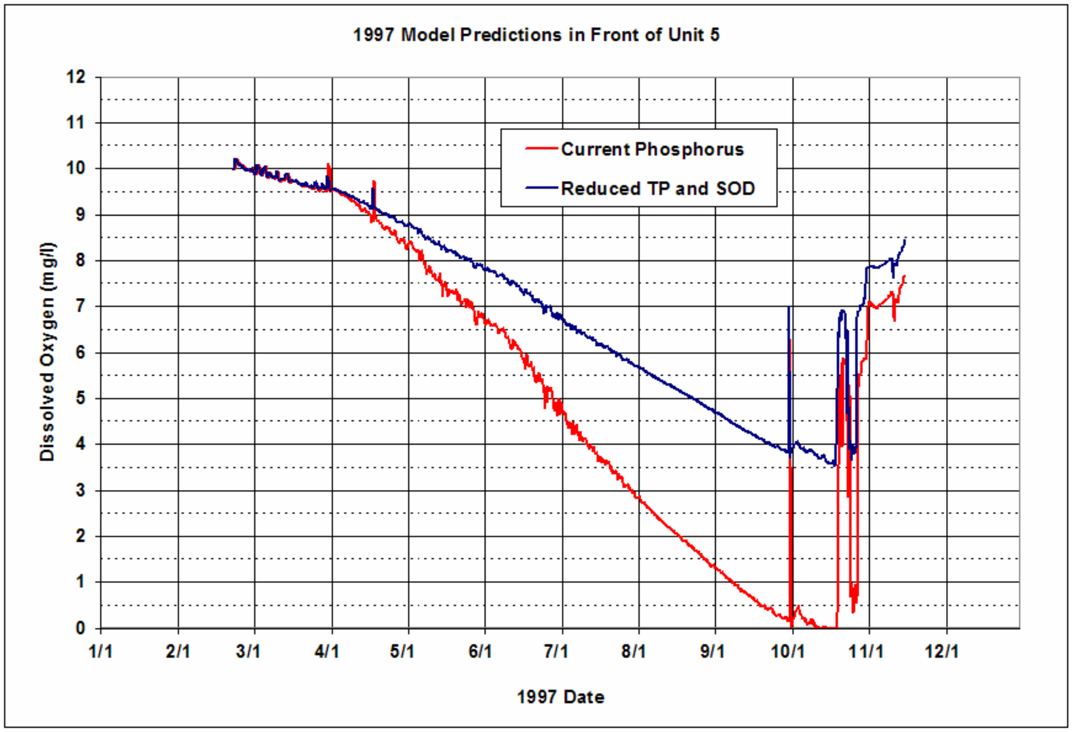


Figure 7-18. 1997 DO at the Level of the Unit 5 Intake for Current and Reduced Phosphorus

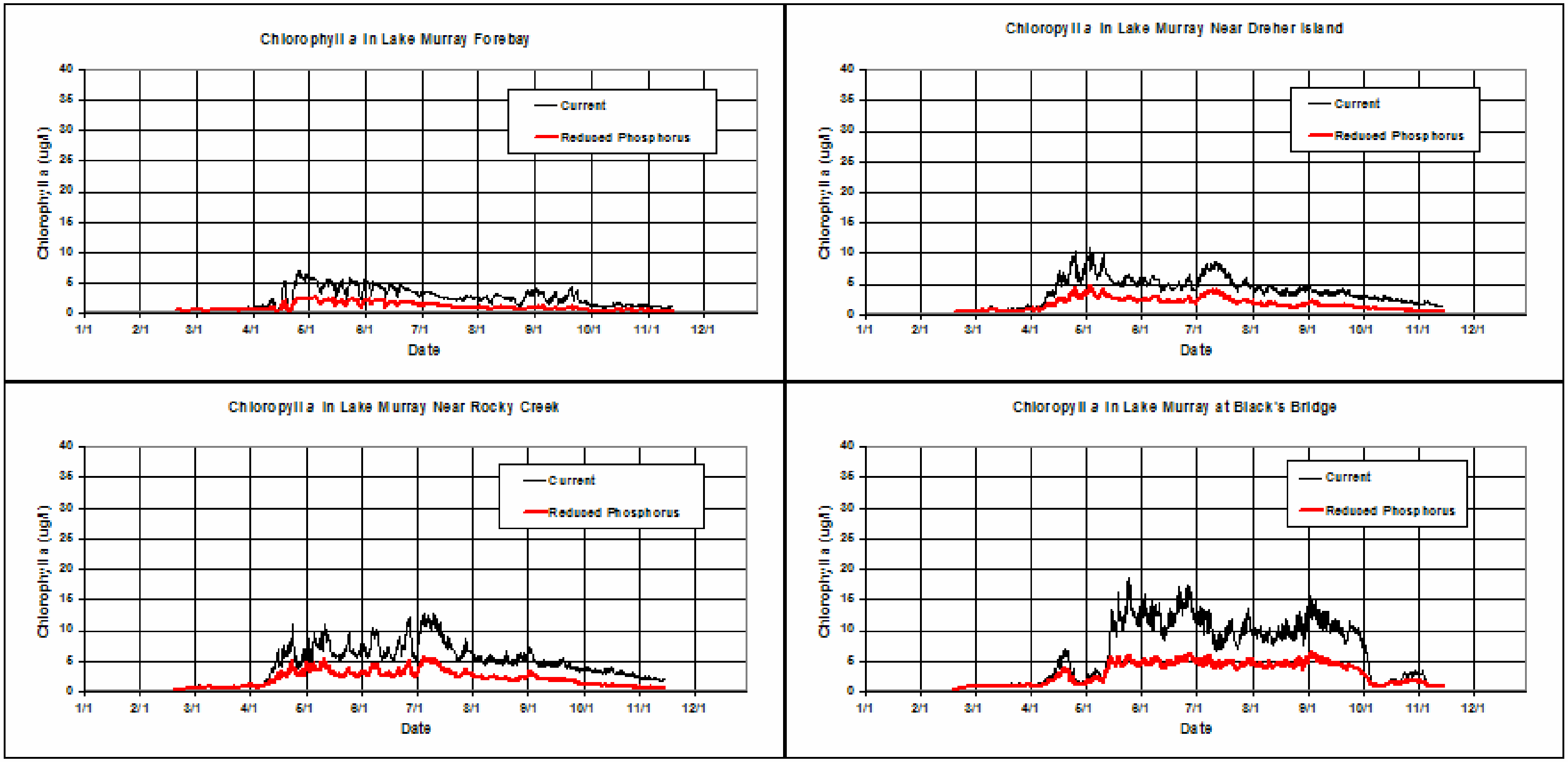


Figure 7-19. Comparison of 1992 Current and Reduced Phosphorus Predictions of Chlorophyll *a* at 1 Meter Depth at Four Locations in Lake Murray

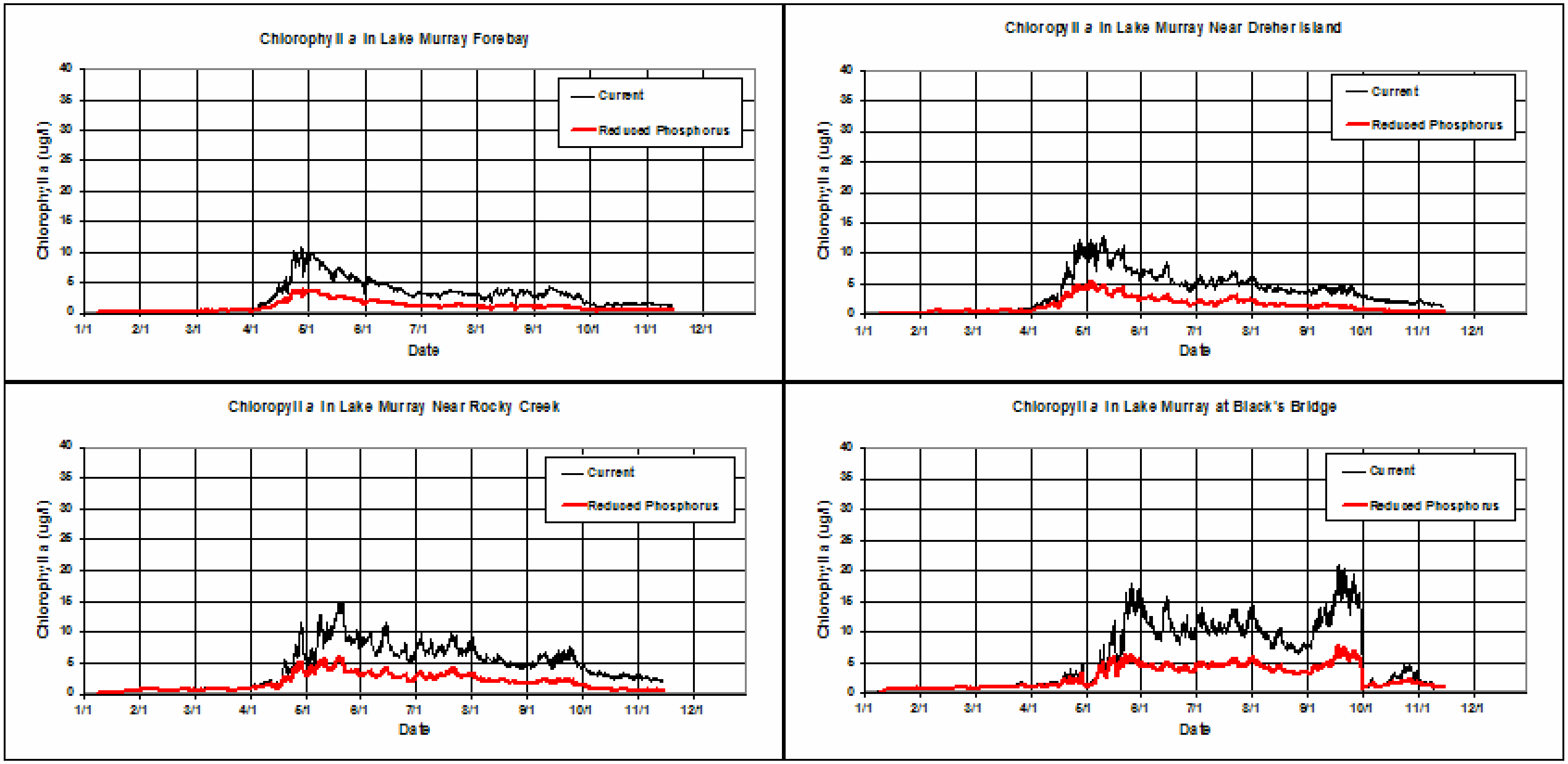


Figure 7-20. Comparison of 1996 Current and Reduced Phosphorus Predictions of Chlorophyll *a* at 1 Meter Depth at Four Locations in Lake Murray

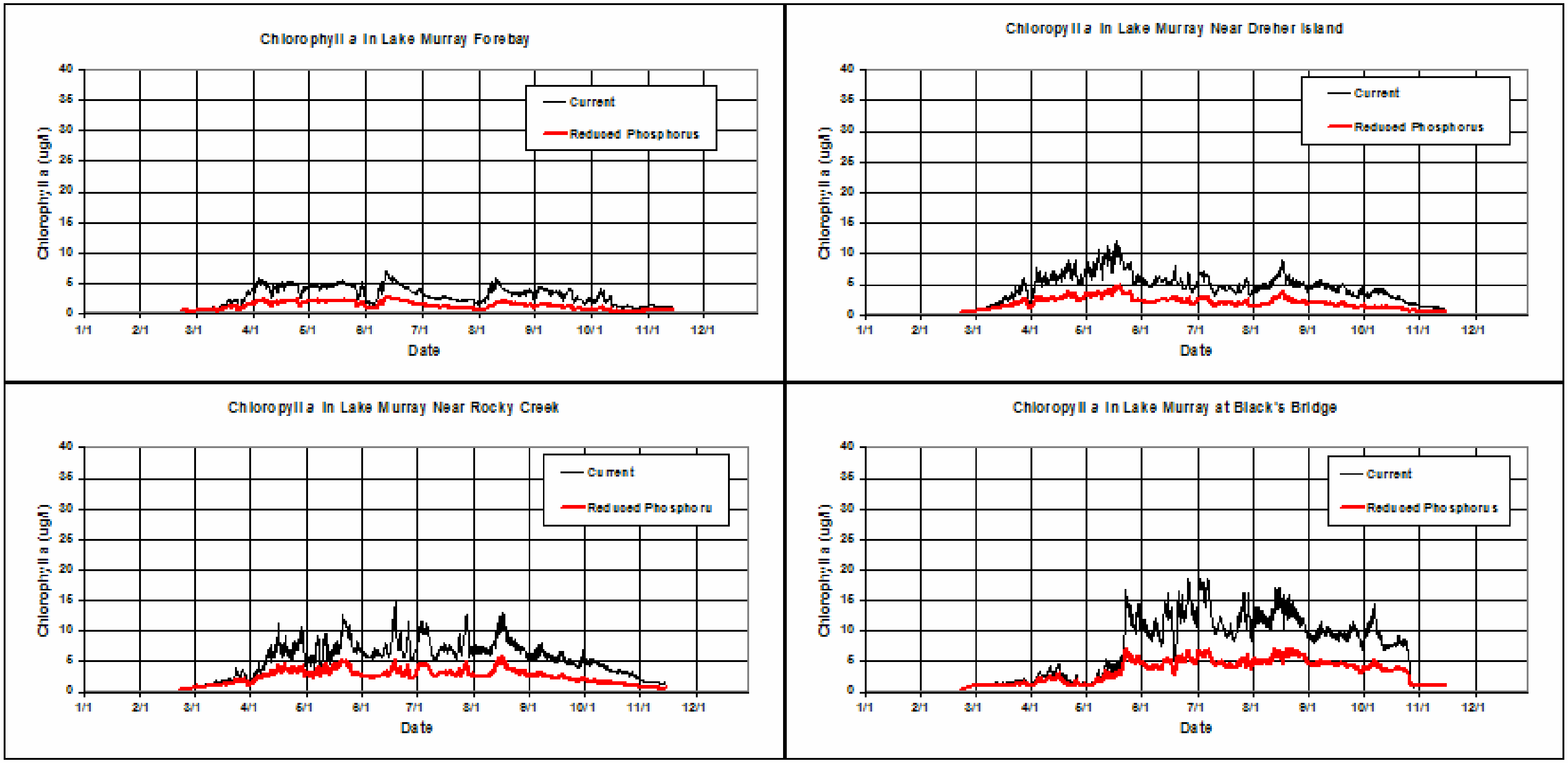


Figure 7-21. Comparison of 1997 Current and Reduced Phosphorus Predictions of Chlorophyll a at 1 Meter Depth at Four Locations in Lake Murray

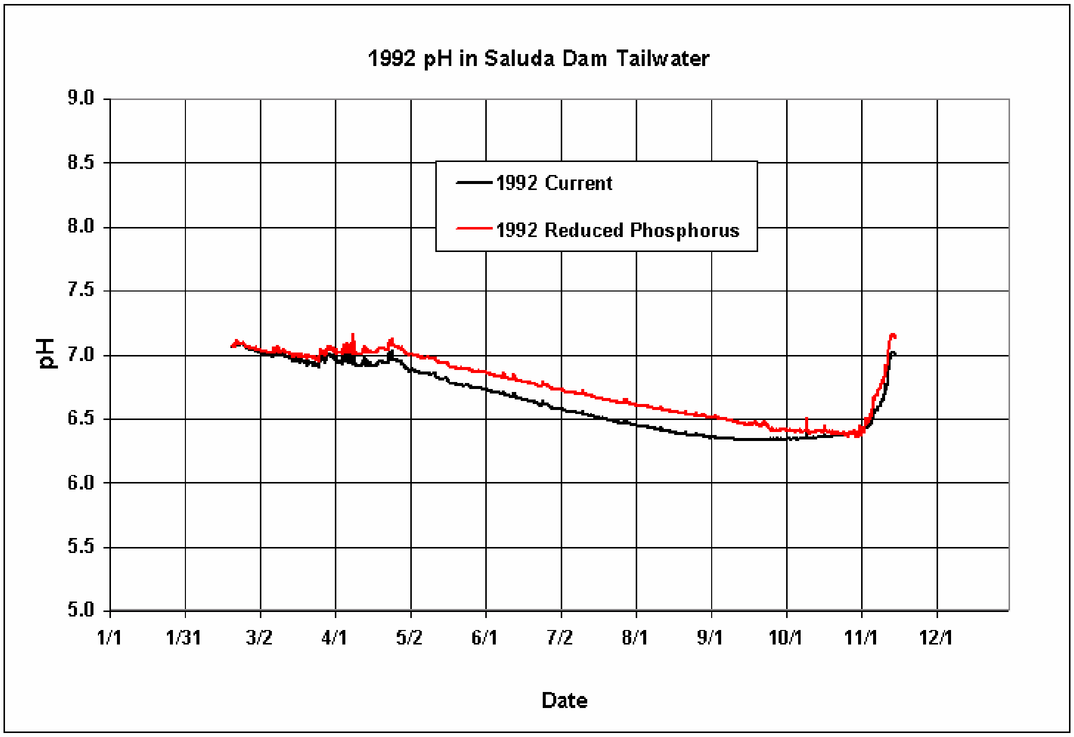


Figure 7-22. Comparison of 1992 Current and Reduced Phosphorus Predictions of pH in the Releases from Saluda Hydro

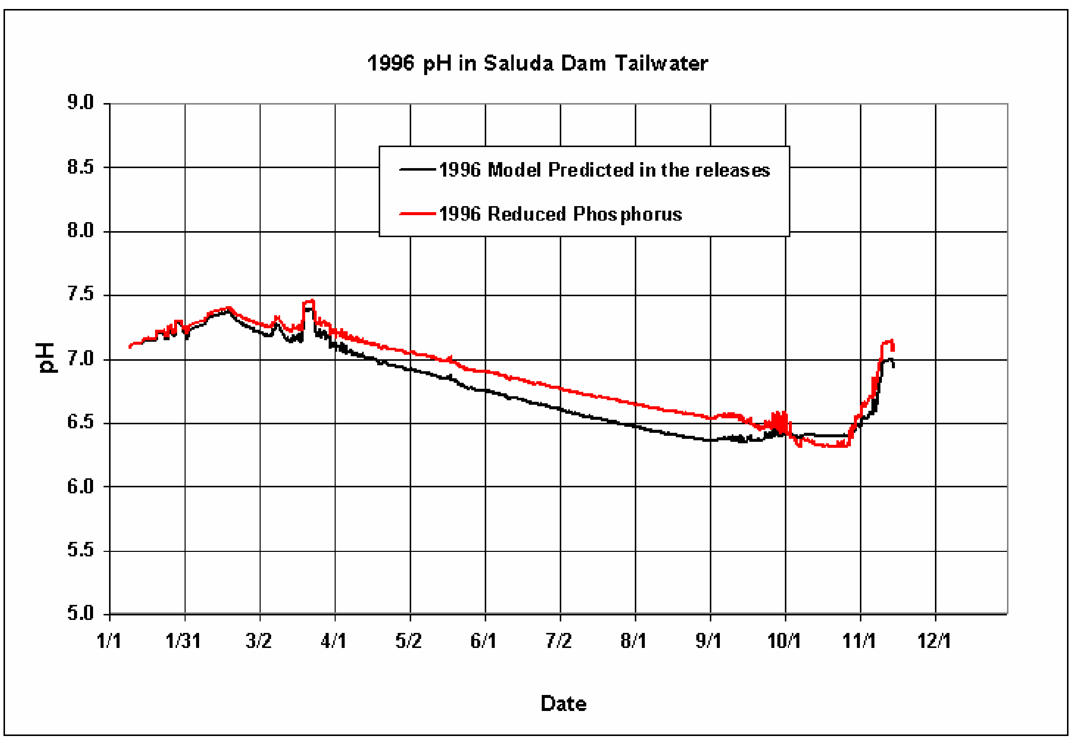


Figure 7-23. Comparison of 1996 Current and Reduced Phosphorus Predictions of pH in the Releases from Saluda Hydro

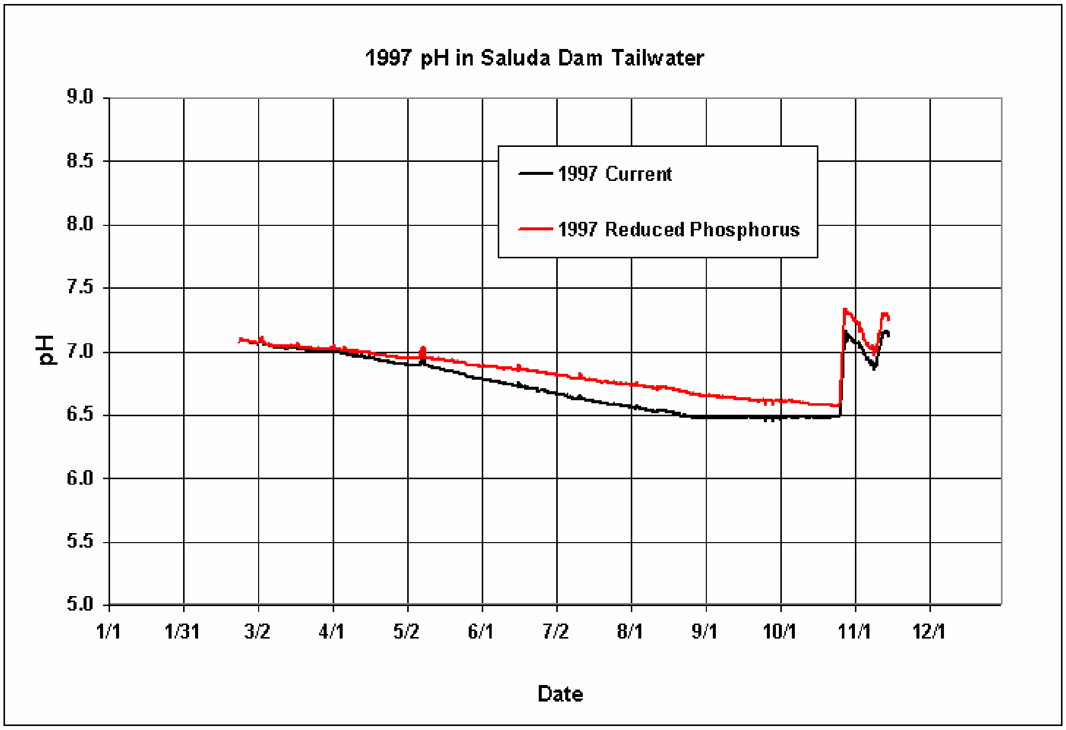


Figure 7-24. Comparison of 1997 Current and Reduced Phosphorus Predictions of pH in the Releases from Saluda Hydro

Case for Reduced Phosphorus in the Inflows and Without the Special Drawdown in 1996

It was observed during preliminary modeling simulations with reduced nutrients that the low DO regions of the metalimnion were significantly affected during the drawdown period: the metalimnion containing the low DO in the lake moved downward more rapidly as the pool level was drawn down—see the metalimnetic low DO dynamics in Figure 7-11 through Figure 7-13. This downward movement of the low DO water suggests that if it was not pulled down rapidly, it might not impact DO in the releases as early in the low DO period. As shown in Figure 7-25, the special drawdown of Lake Murray during late August and September 1996 was abnormal compared to most other years. Such draw downs occurred three times over the period 1990-2004 or about once every five years. In 1996, the special lake draw down was for aquatic plant control in the lake; in 1990, it was for maintenance of the intake towers; and in 2003, it was for dam remediation efforts.

When the reduced phosphorus scenario was run with 1996 conditions but with a more typical drawdown, the minimum DO concentrations in the release were about 1 mg/L higher and the low DO period was shorter. As shown in Figure 7-26, without the special drawdown, the DO in the release decreased at a slower rate, and the length of time that the DO was less than 2 mg/L was about half as long as it would have been with the special drawdown.

Assuming that special drawdowns can be scheduled at other times like after October and phosphorus was reduced in the inflows, the minimum DO could be increased by about 1 mg/L to a minimum DO of about 1 mg/L. Figure 7-27 shows the predicted DO at the elevation of the unit 5 intake under current conditions as well as with reduced phosphorus and no special drawdown.

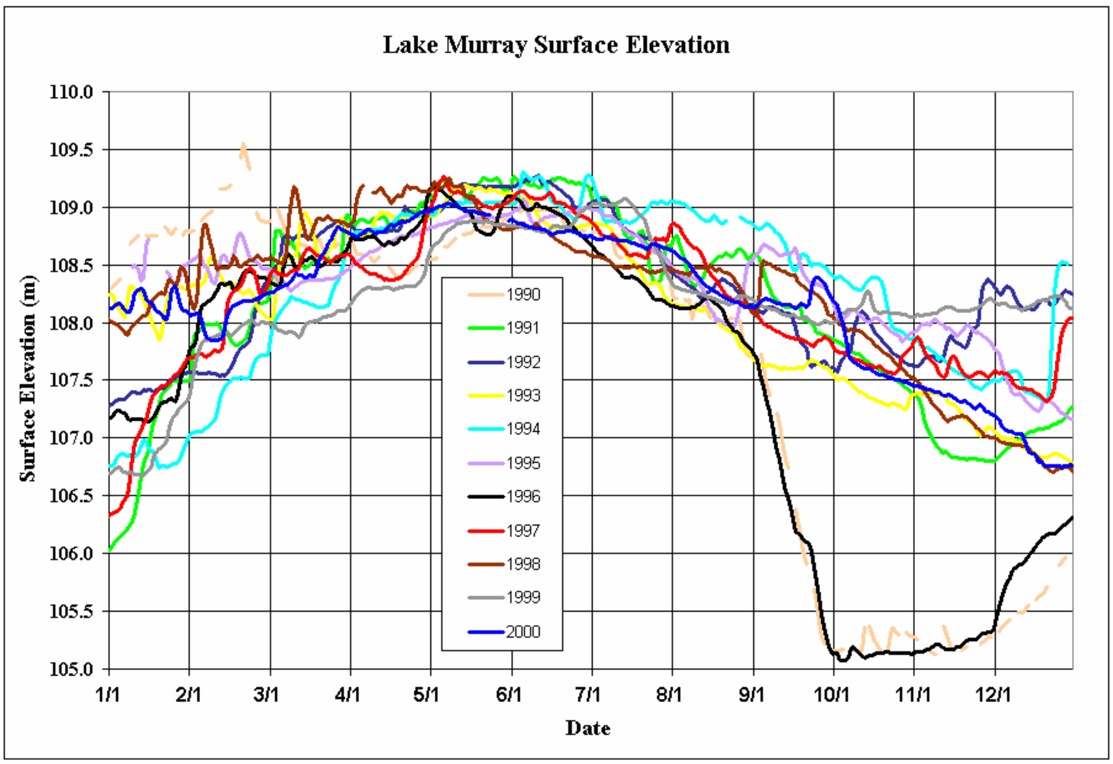


Figure 7-25. Water Surface Elevations for Various Years at Lake Murray

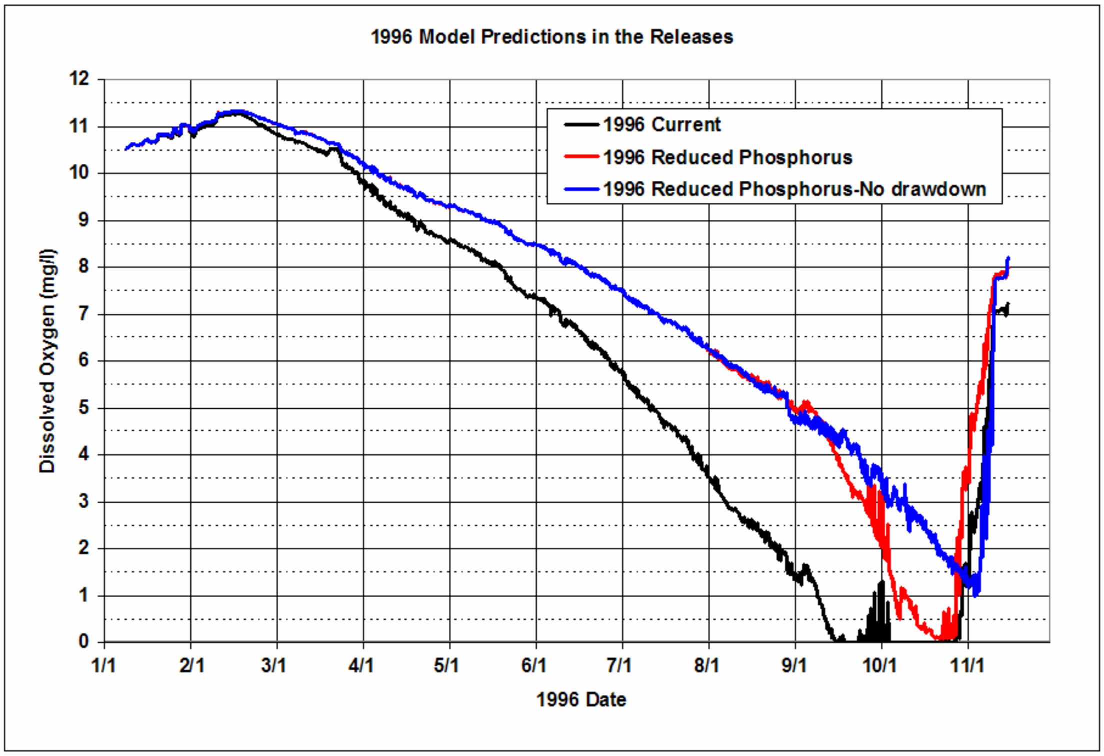


Figure 7-26. 1996 Release DO for Current and Reduced Phosphorus, and without the Special Drawdown

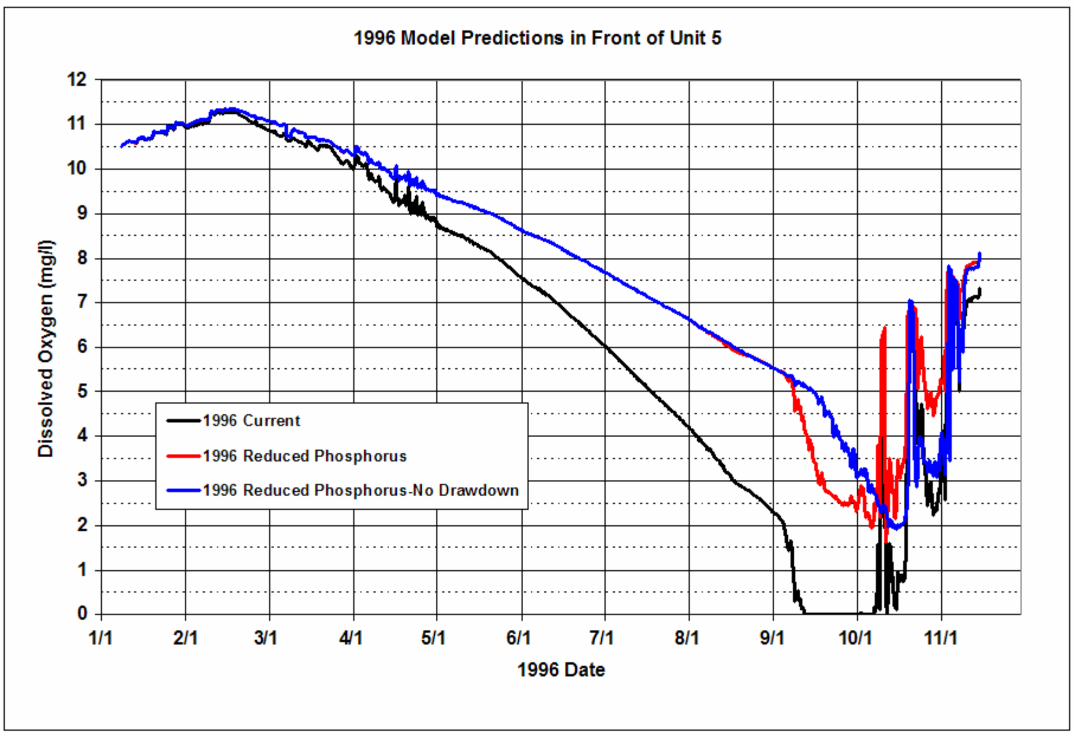


Figure 7-27. 1996 DO at the Elevation of the Unit 5 Intake for Current and Reduced Phosphorus, and without the Special Drawdown

8. Conclusions

Several water quality issues associated with Lake Murray need consideration for water quality management:

- low DO in the releases from Saluda Hydro,
- restrictions for operating Unit 5 due to entrainment of blueback herring,
- eutrophication in the upper regions of Lake Murray,
- DO less than the State standard in the inflow regions of the lake,
- reduced striped bass habitat in the lake due to low DO in the regions of the lake where their temperature preferences occur, and
- low pH in the Lower Saluda River (LSR).

SCE&G decided to address these issues using a two-dimensional water quality model, CE-QUAL-W2, that simulates the effects of inflow water quality on in-lake water quality as well as the releases from the lake. This modeling effort was based on using all available water quality data on Lake Murray and its inflows, as well as using external comparisons of results 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 blueback herring and striped bass.
- To assess the effects of operations of Unit 5 on habitat for fish in Lake Murray.
- 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 lake.
- The model is well-suited for addressing the following objectives: DO in the releases from Saluda Hydro; DO in the metalimnion which is the habitat for blueback 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 in this report.

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. 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 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. The results also showed restrictions for operating Unit 5 due to current concerns about entrainment of blueback herring would be eliminated. In addition, the model results showed that trophic status and striped bass habitat 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.

Finally, five of the six water quality issues identified above (the exception being DO in the LSR) can only be addressed practically by using phosphorus reduction in the watershed. Phosphorus reductions are not only the most cost-effective approach but also the only practical approach considering that costs for other alternatives would be an "order-of-magnitude" greater, and there are no proven technologies for addressing these issues on the scale of Lake Murray. Also, point source discharges to some of the inflows, especially Ninety-Six Creek and the Bush River, are so high that there is no alternative but to reduce phosphorus in their discharges if water quality objectives for Lake Murray are to be achieved.

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