Water Quality Data Analysis and CE-QUAL-W2 Modeling for Lake Murray

Presented by Andy Sawyer and Jim Ruane

Reservoir Environmental Management, Inc

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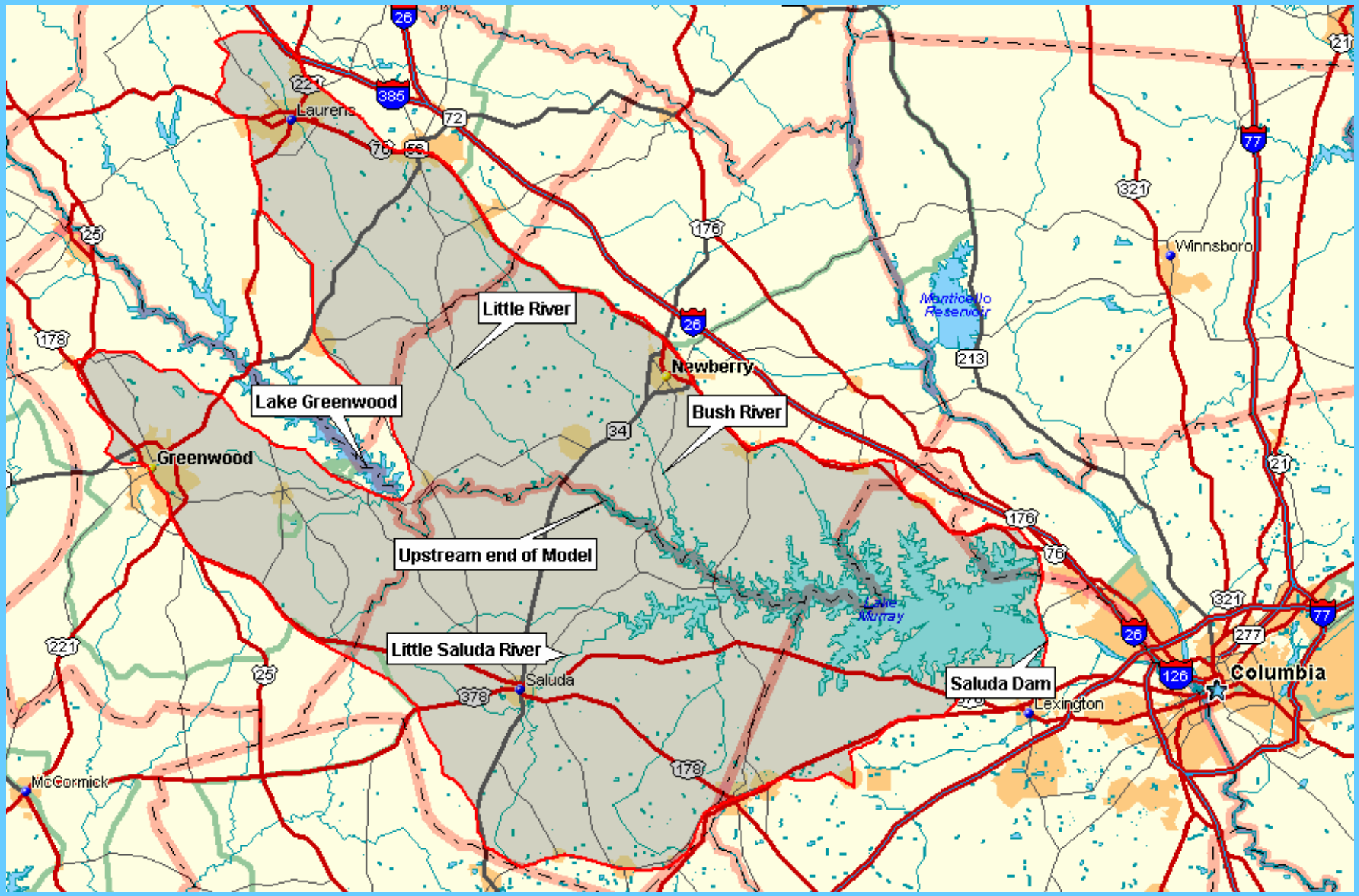
Overview of Presentation

- Review water quality data, especially for dominant constituents that affect water quality in Lake Murray and its releases
- Present the calibration of the CE-QUAL-W2 model that's used to simulate water quality in Lake Murray
- Illustrate use of the model to explore management strategies for improving water quality and uses of the lake

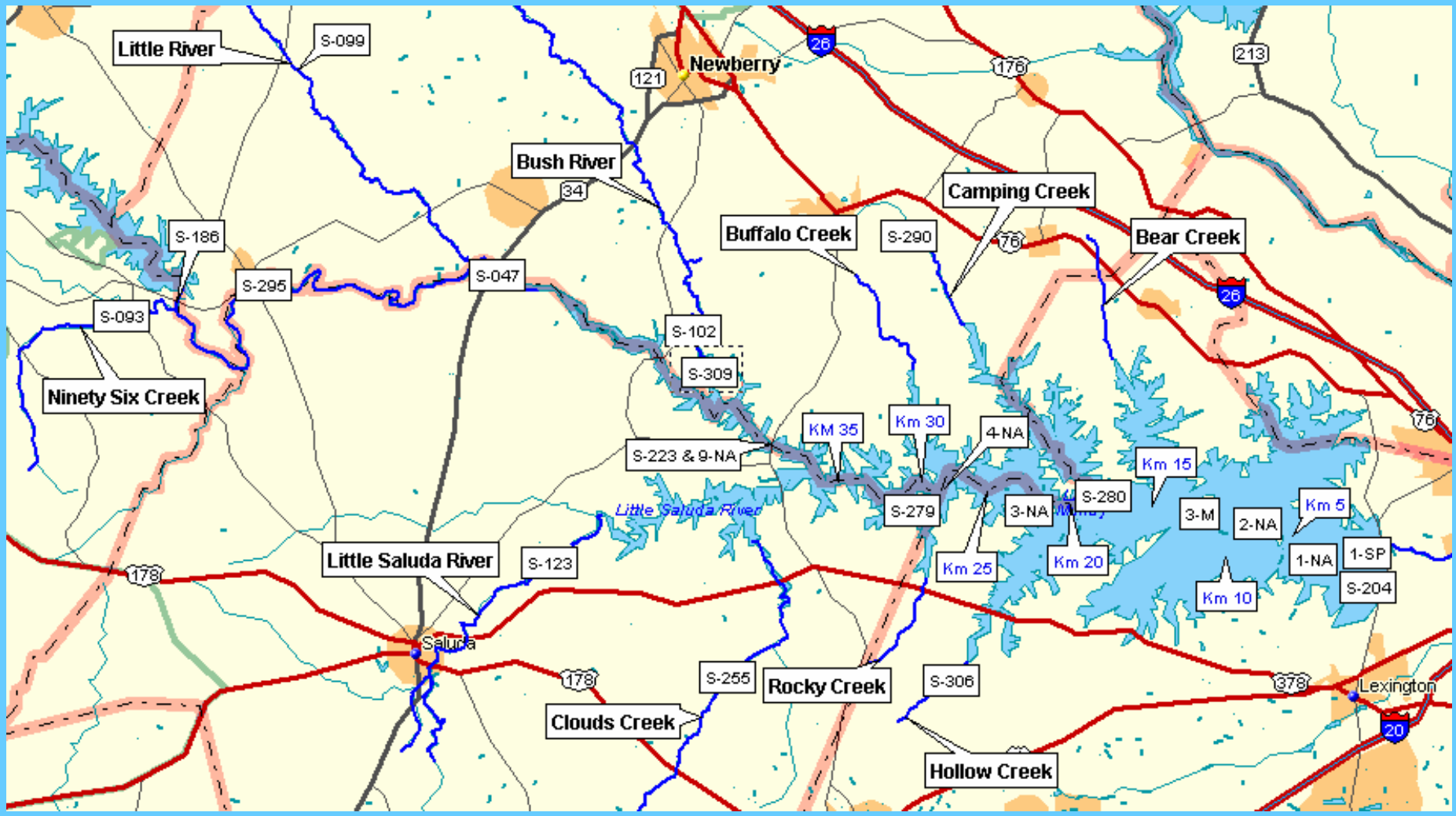
Preliminary Assessment of Historical Data through 1998

- This assessment was conducted in preparation for relicensing, using the available data at the time of the assessment in 2001
- Available data were organized using the DASLER software program
- Also, reports on water quality were reviewed: ERC report, prepared for relicensing in 1975; and DHEC reports in 1995 and 1998
- Some of the key findings will be presented in the first part of this presentation

Lake Murray Watershed



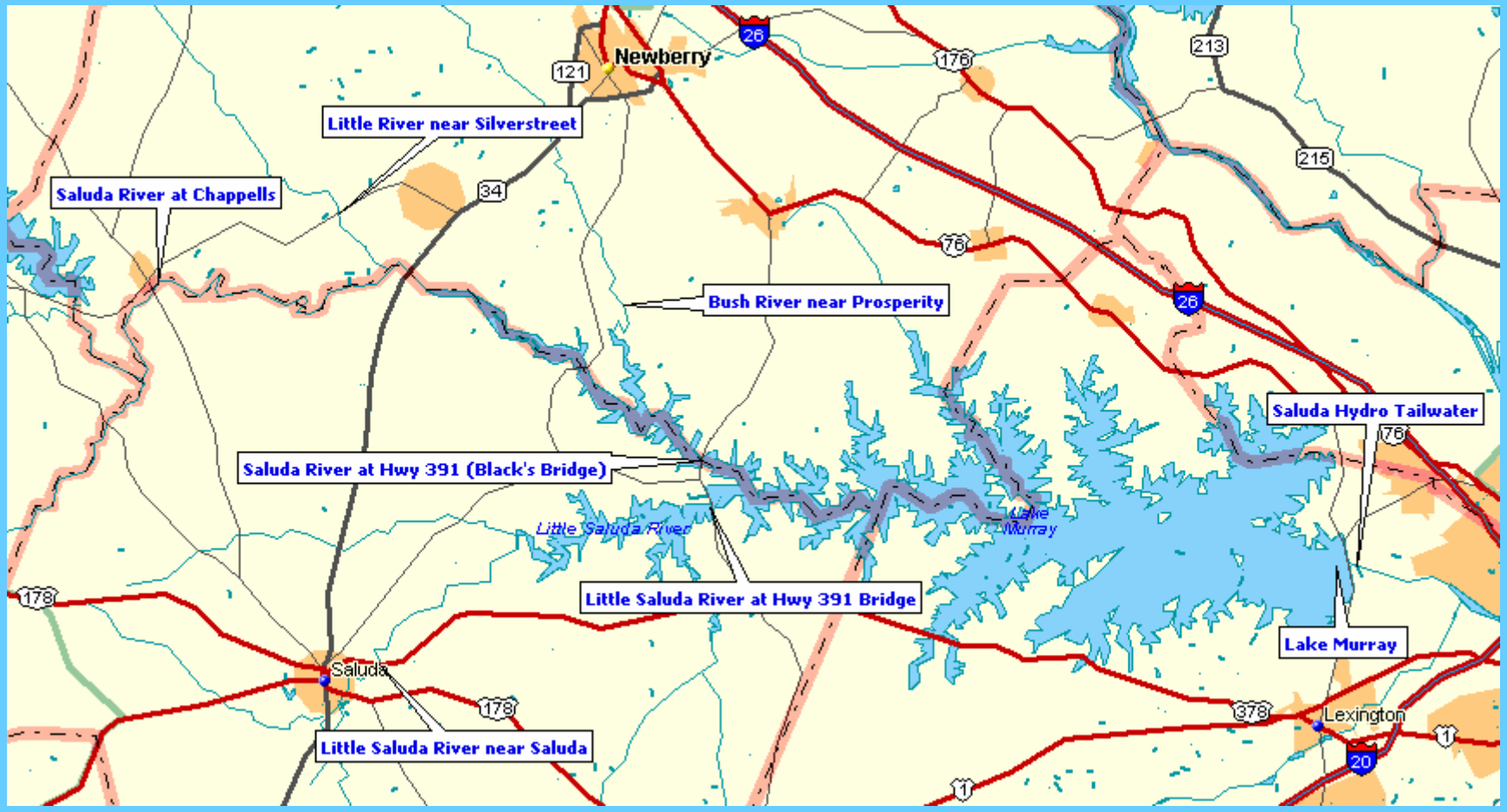
Primary SCDHEC and SCE&G Monitoring Stations used for Lake Murray Water Quality Analyses

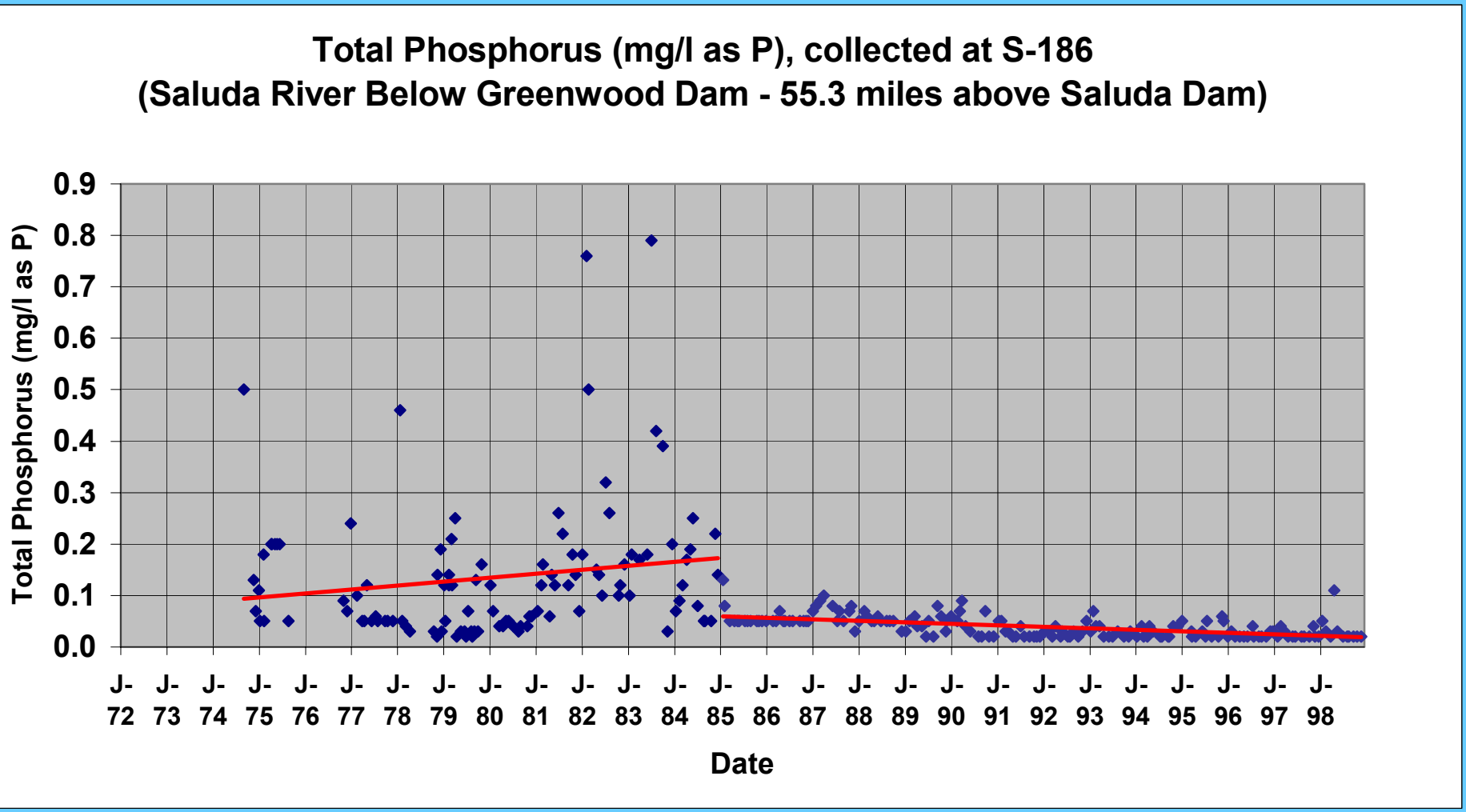


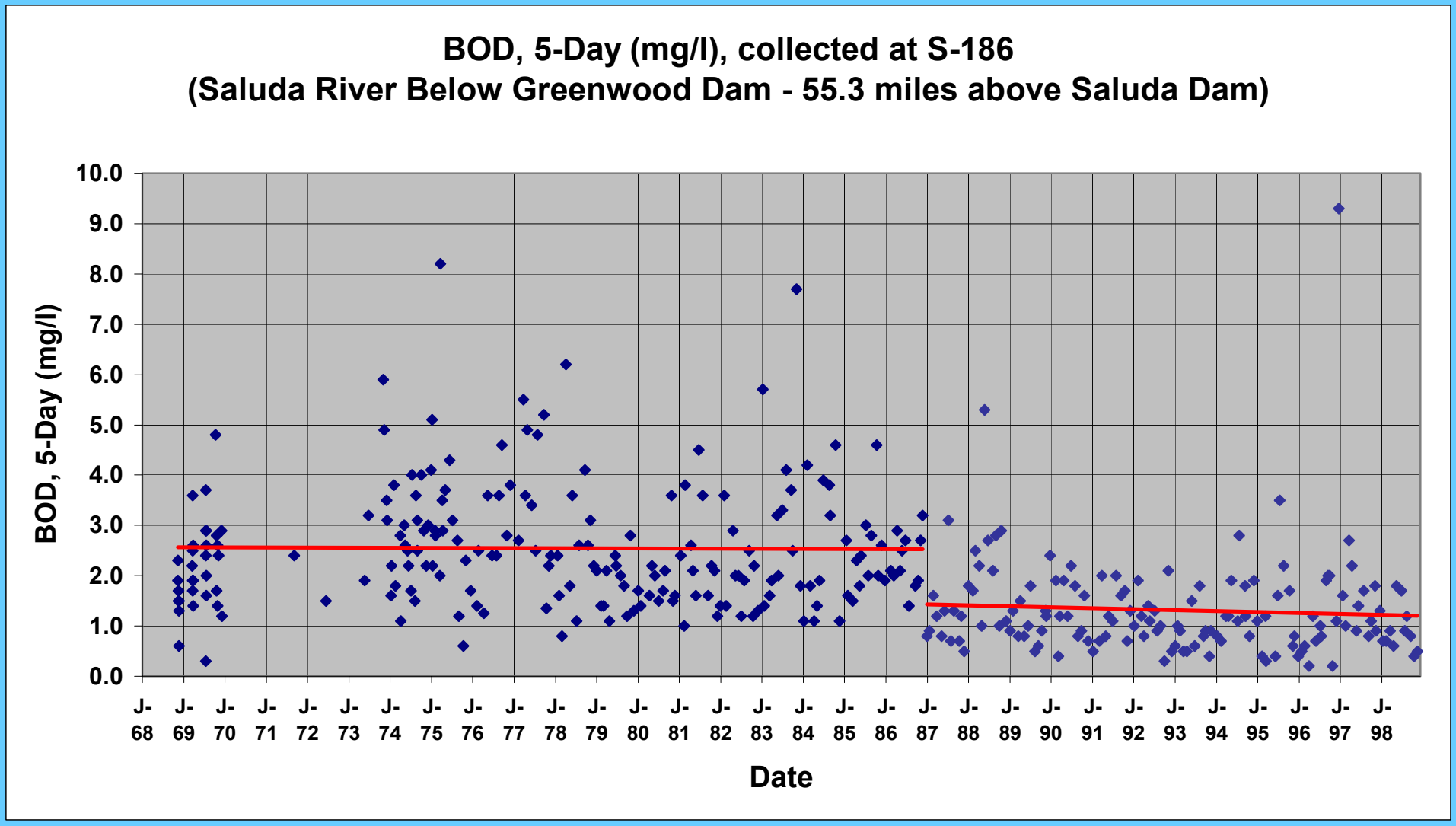
Stations with "S" prefix are SCDHEC monitoring stations

Others are SCE&G Monitoring Stations

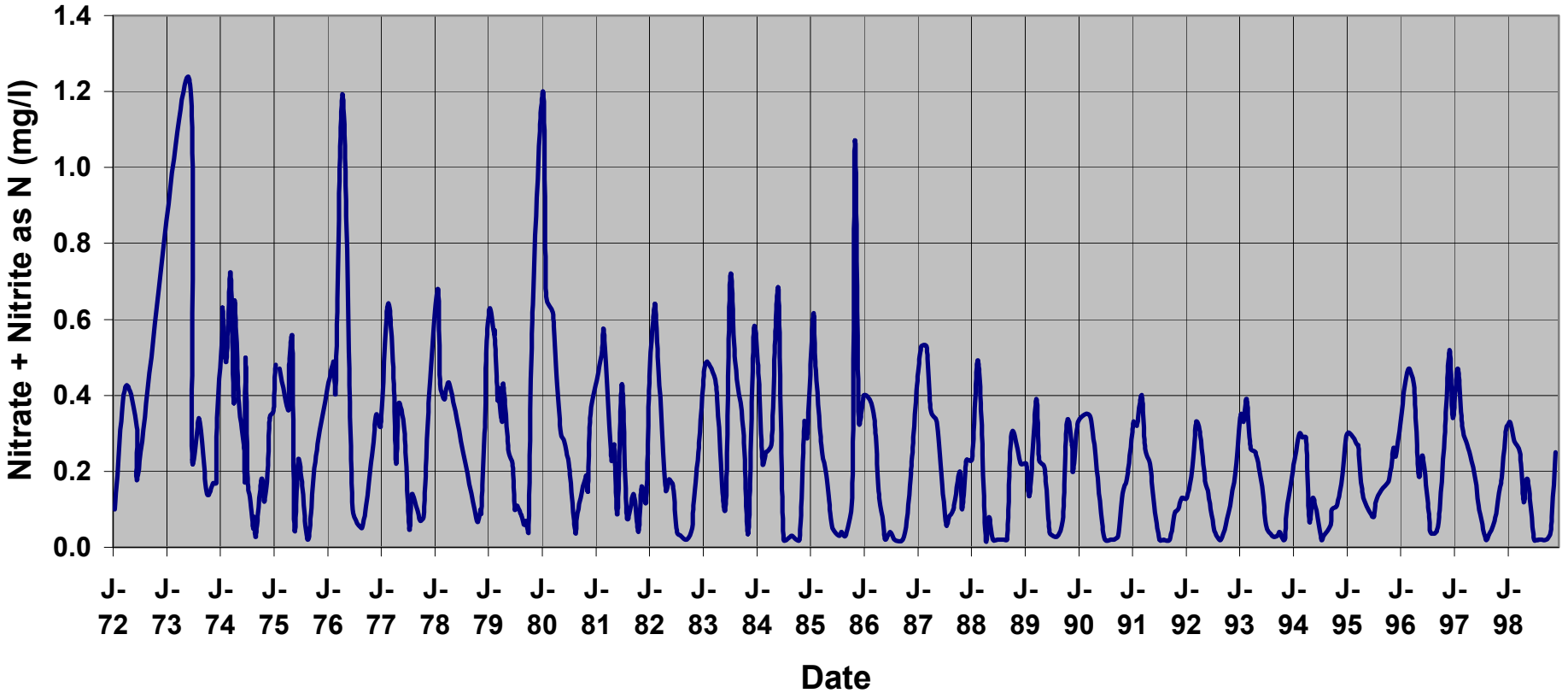
Map of Lake Murray Watershed Showing Location of USGS Monitors



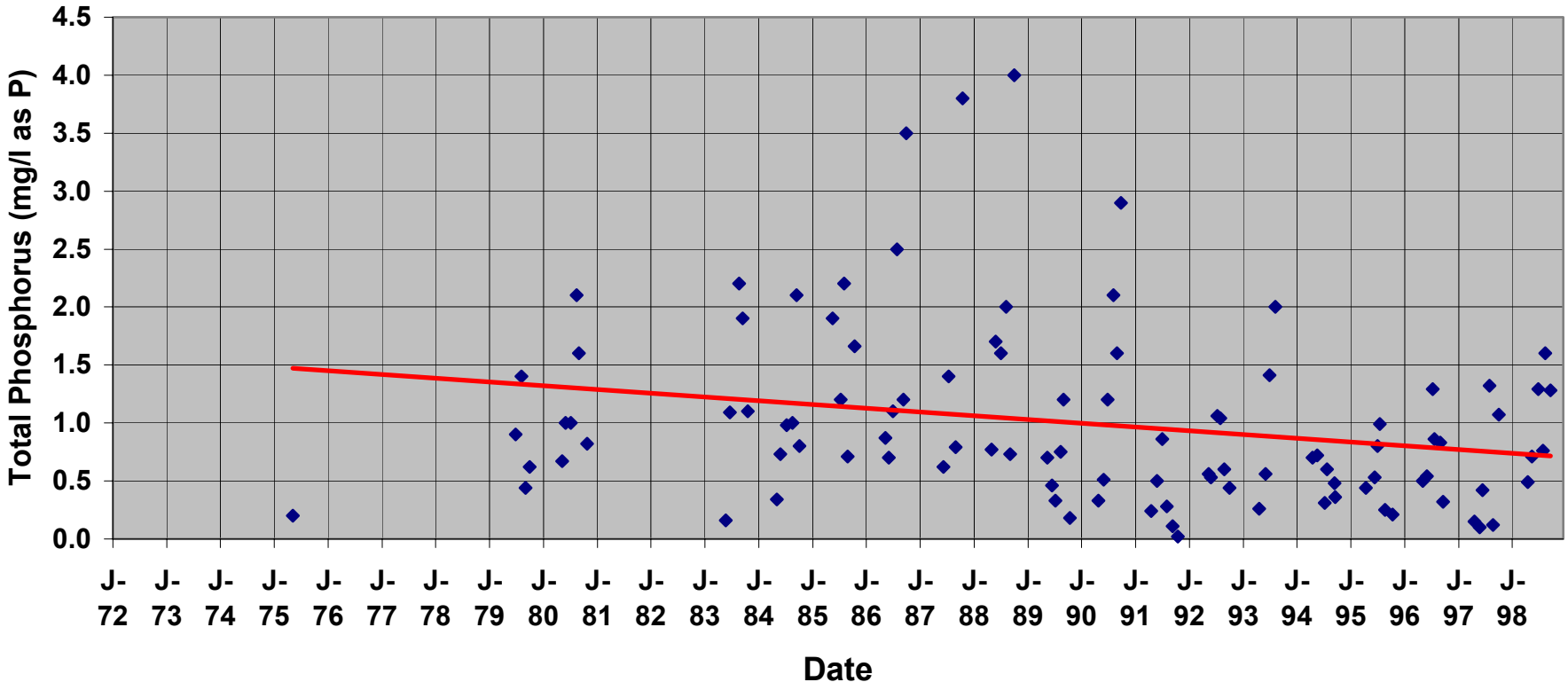

Total Phosphorus (mg/l as P), collected at S-186
(Saluda River Below Greenwood Dam - 55.3 miles above Saluda Dam)
Total Phosphorus (mg/l as P)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
J-72 J-73 J-74 J-75 J-76 J-77 J-78 J-79 J-80 J-81 J-82 J-83 J-84 J-85 J-86 J-87 J-88 J-89 J-90 J-91 J-92 J-93 J-94 J-95 J-96 J-97 J-98
Date

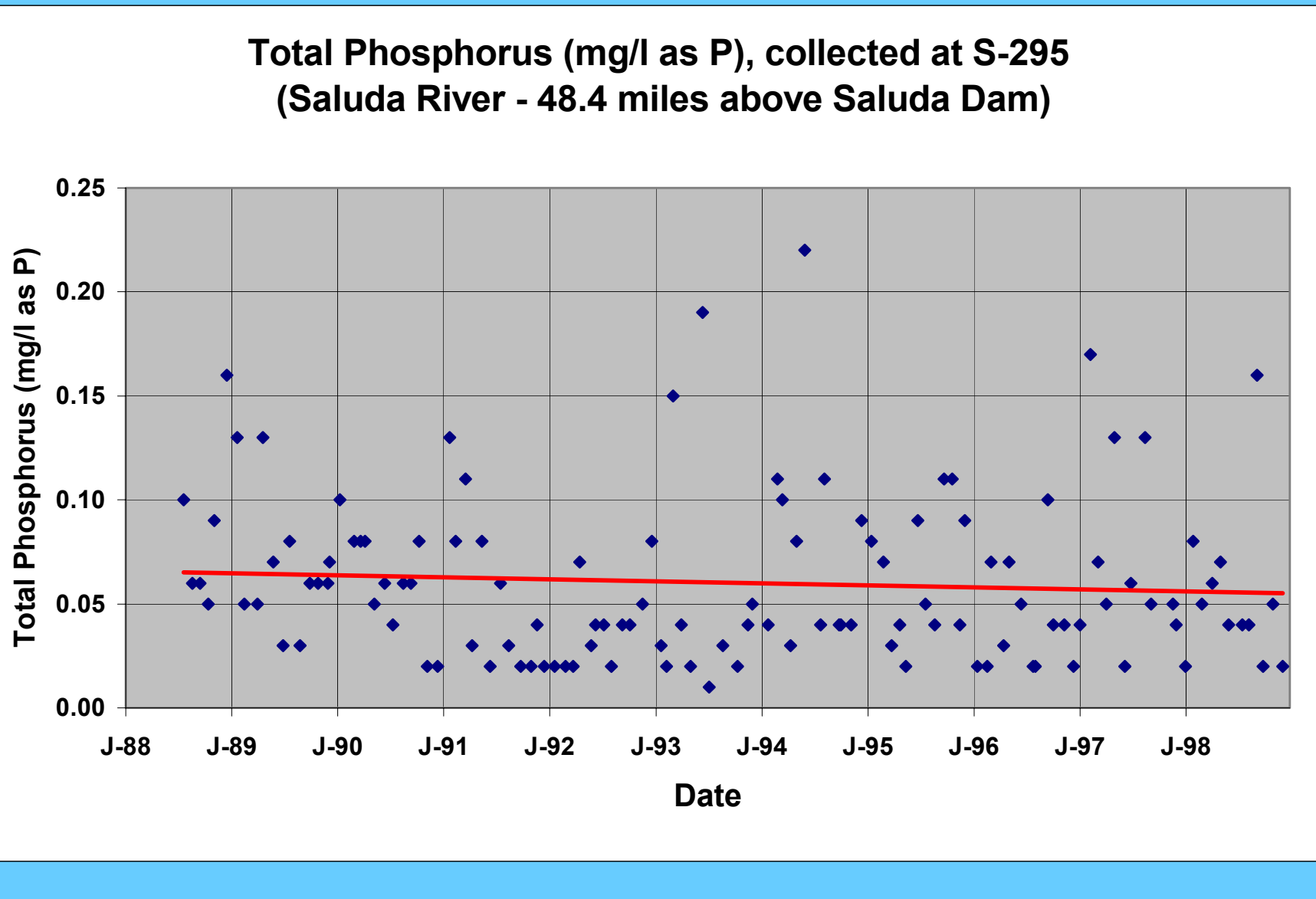

BOD, 5-Day (mg/l), collected at S-186
(Saluda River Below Greenwood Dam - 55.3 miles above Saluda Dam)
BOD, 5-Day (mg/l)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
J-68 J-69 J-70 J-71 J-72 J-73 J-74 J-75 J-76 J-77 J-78 J-79 J-80 J-81 J-82 J-83 J-84 J-85 J-86 J-87 J-88 J-89 J-90 J-91 J-92 J-93 J-94 J-95 J-96 J-97 J-98
Date

Nitrate + Nitrite as N (mg/l), collected at S-186
(Saluda River Below Greenwood Dam - 55.3 miles above Saluda Dam)

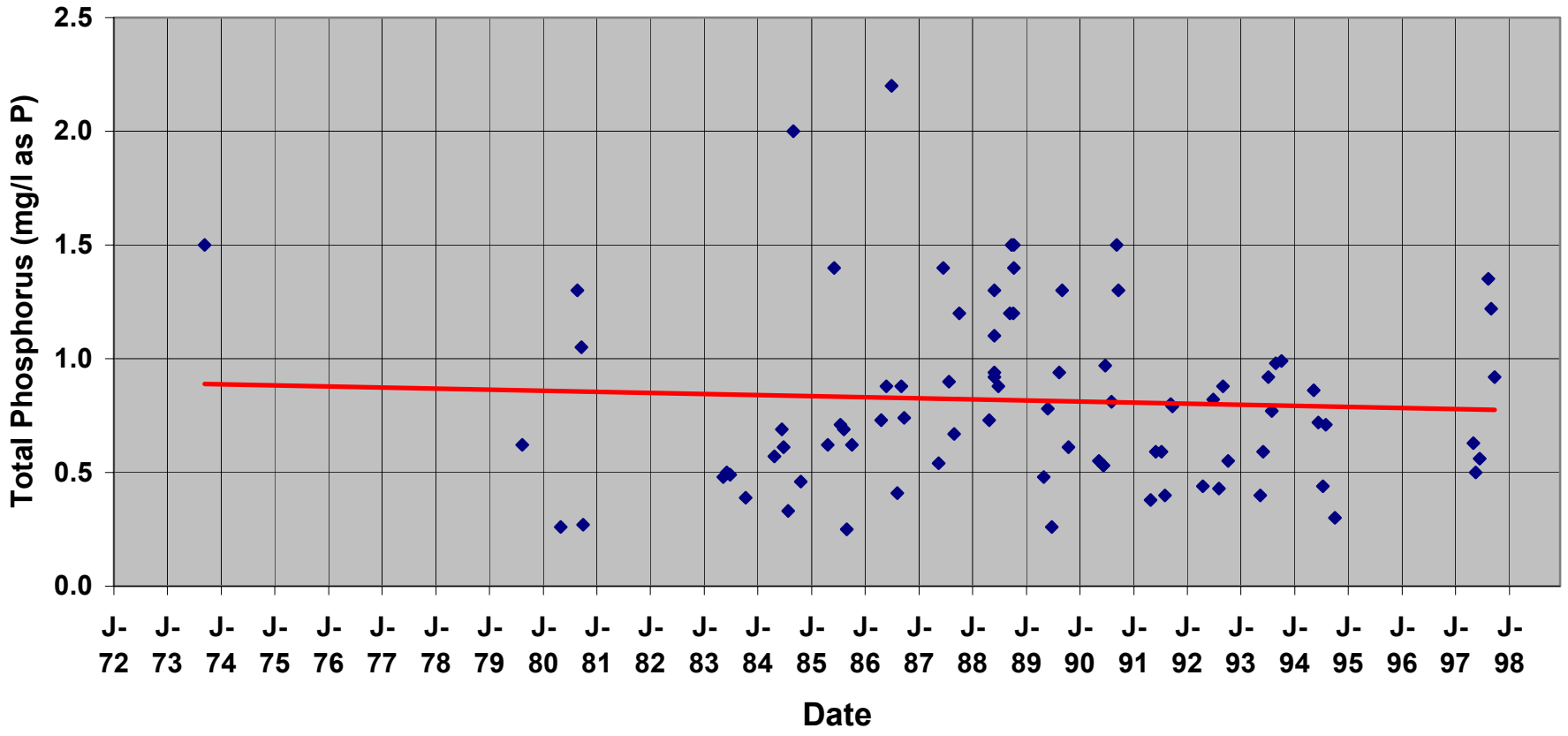


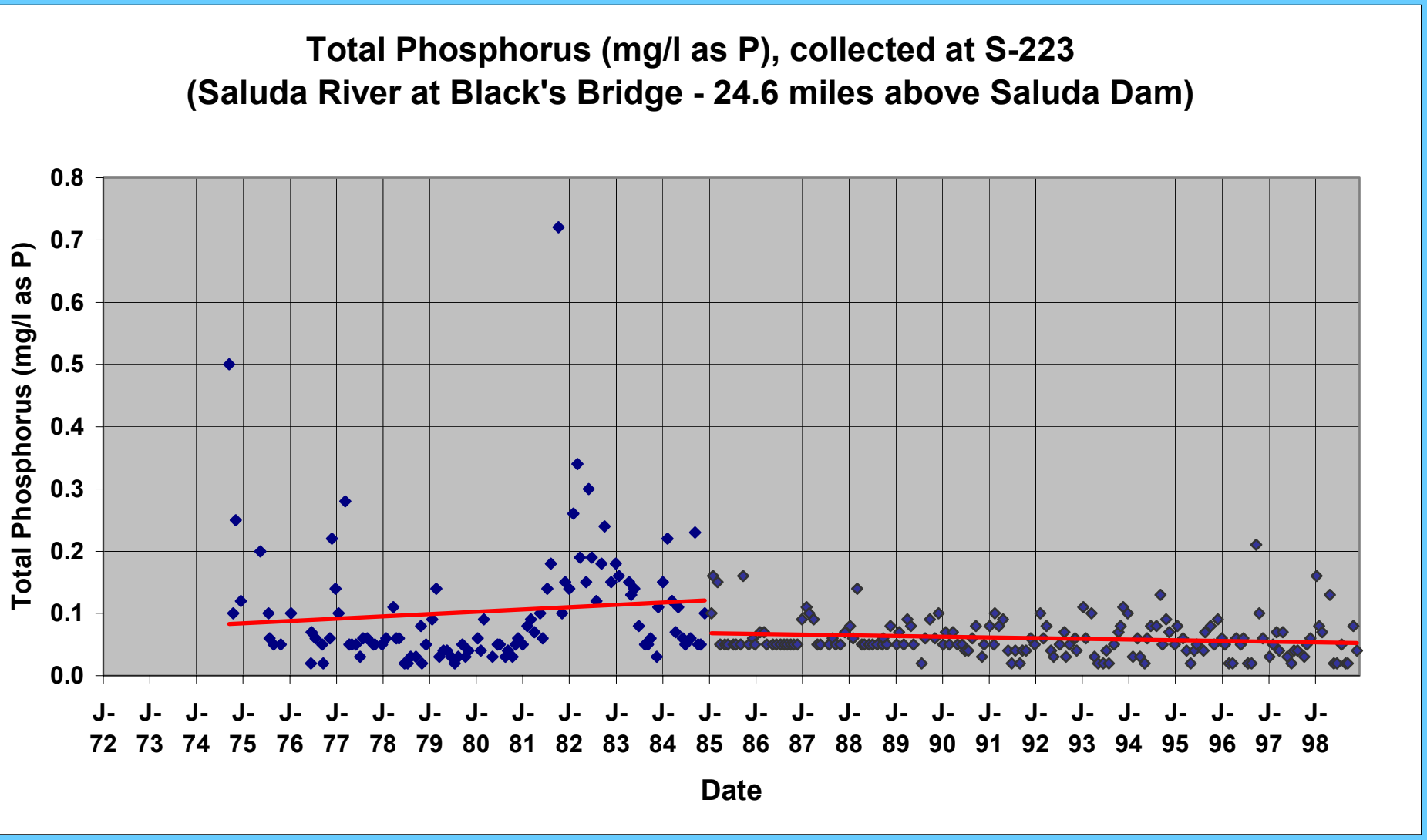
Total Phosphorus (mg/l as P), collected at S-093, Summer Data Only
(Ninety-Six Creek-approx. 2 miles upstream of Saluda R.)



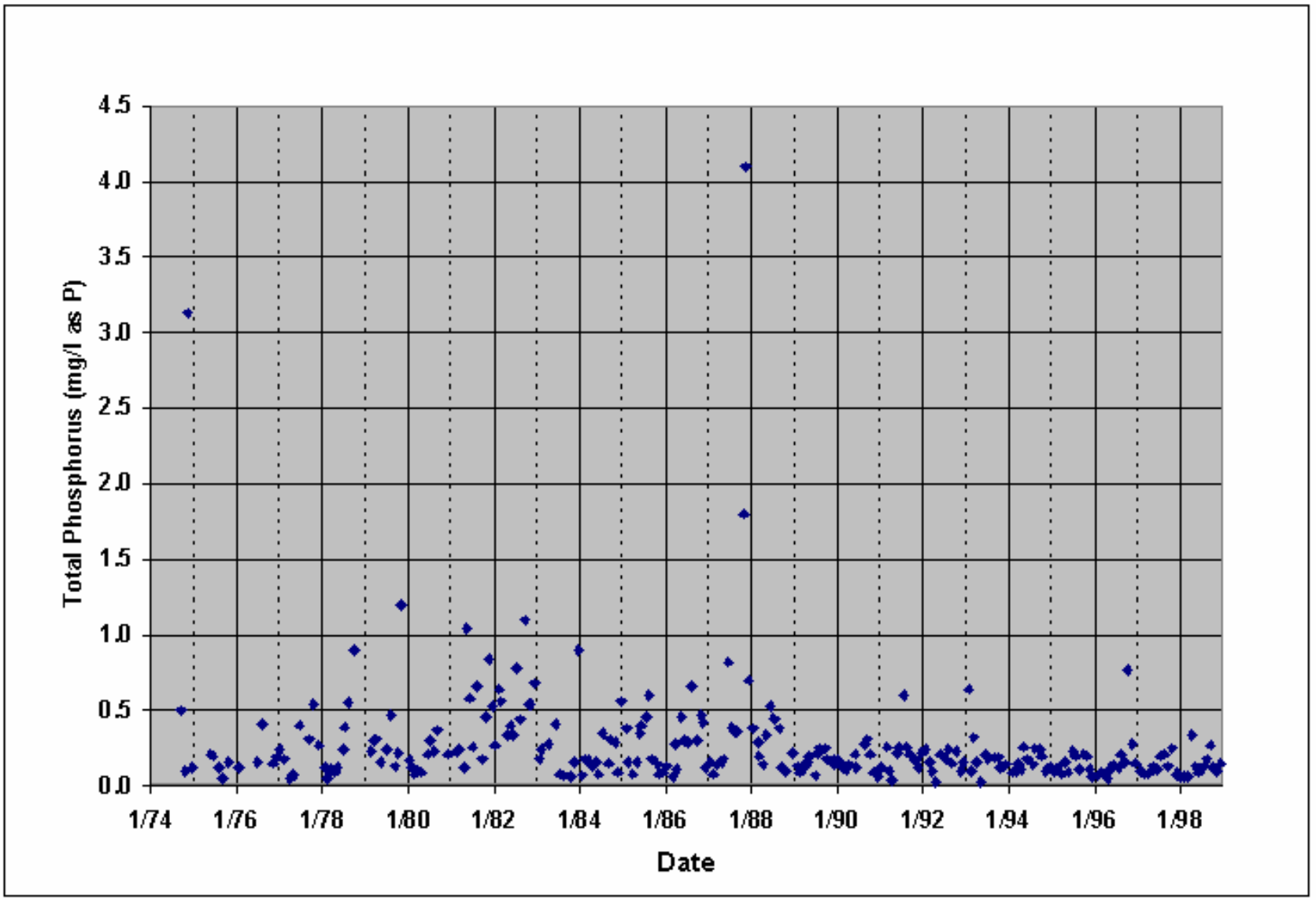

Total Phosphorus (mg/l as P), collected at S-295
(Saluda River - 48.4 miles above Saluda Dam)
Total Phosphorus (mg/l as P)
0.25
0.20
0.15
0.10
0.05
0.00
J-88
J-89
J-90
J-91
J-92
J-93
J-94
J-95
J-96
J-97
J-98
Date

Total Phosphorus (mg/l as P), collected at S-102, Summer Data Only (Bush River, 3.5 miles upstream from Saluda River)

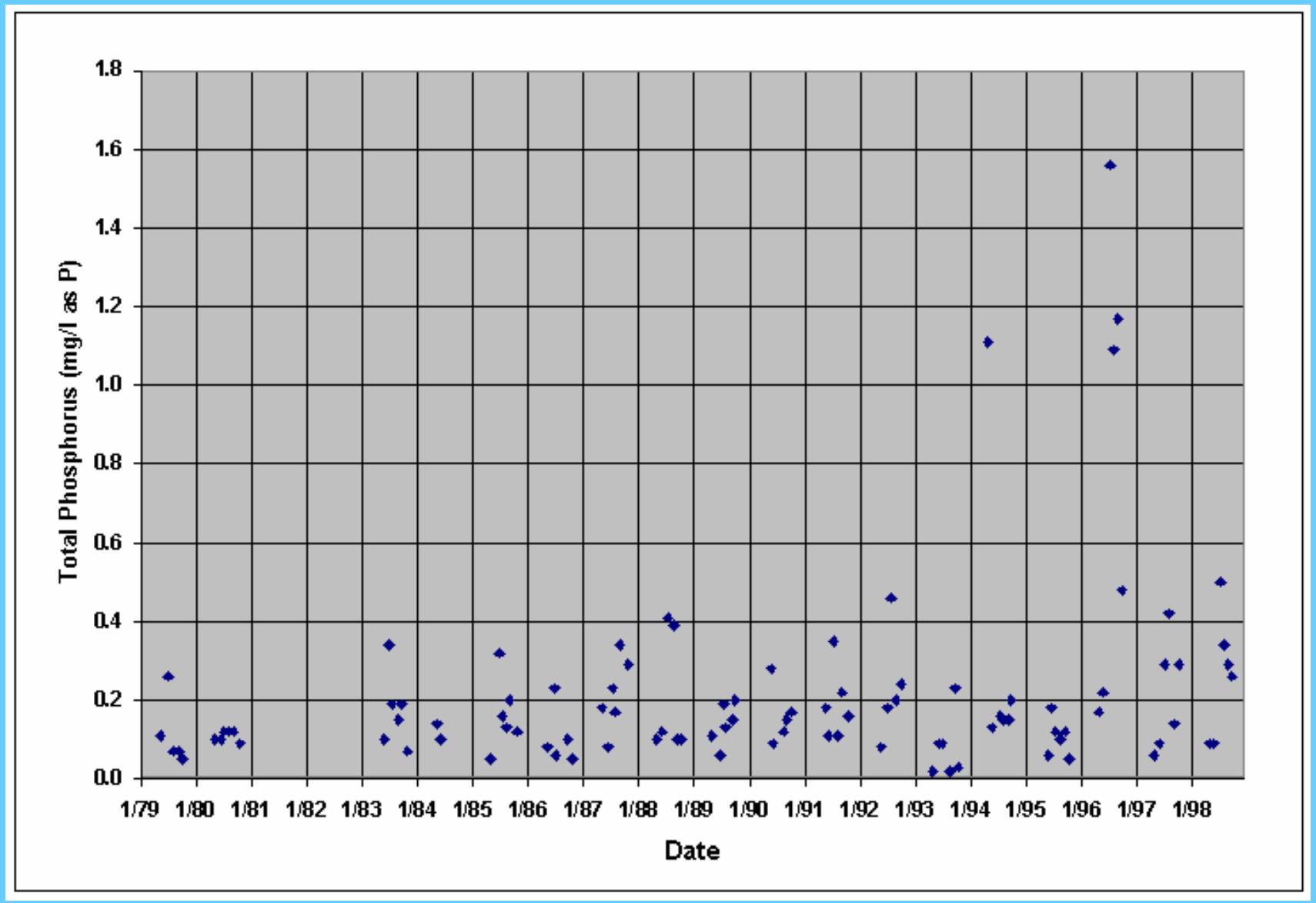


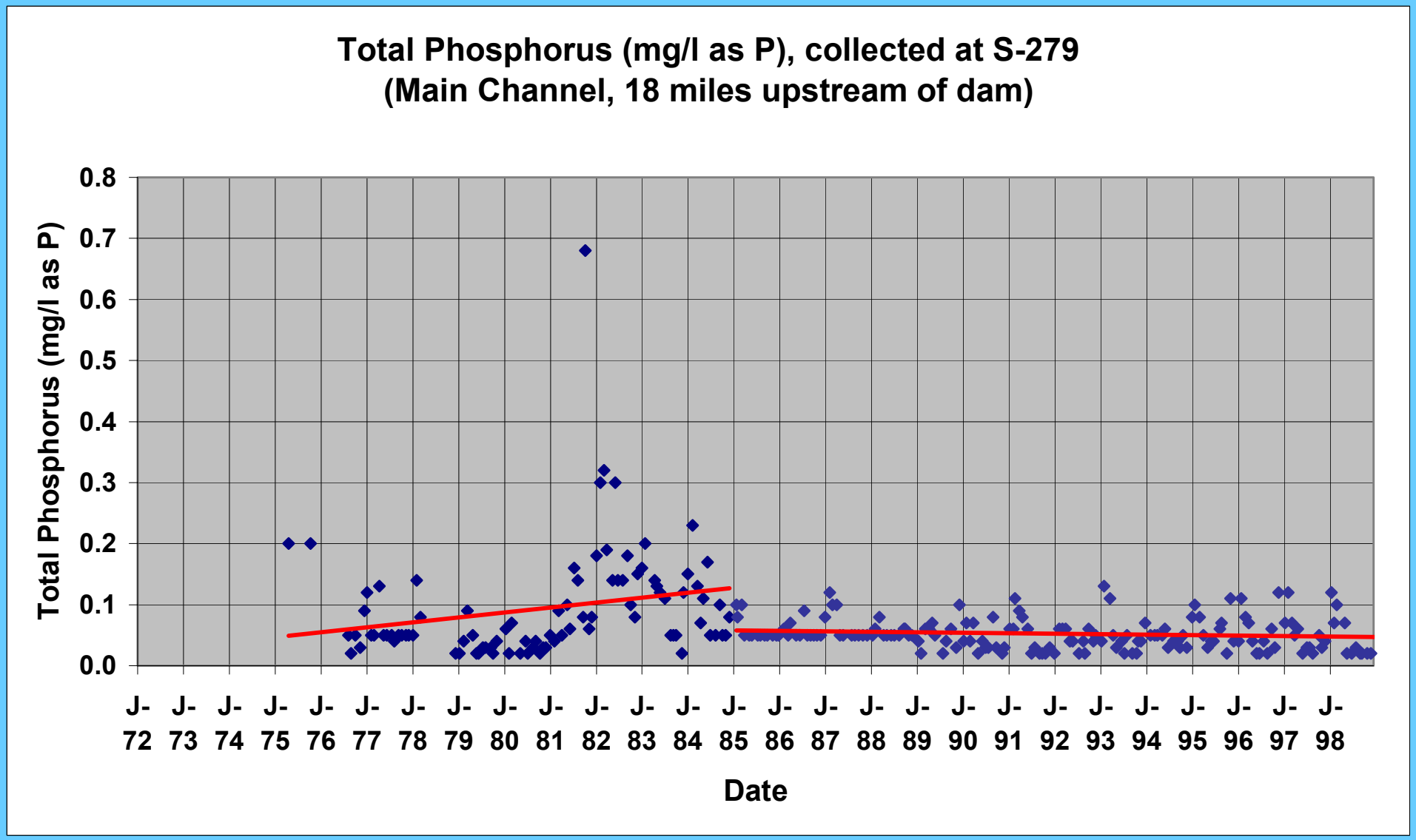

Total Phosphorus (mg/l as P), collected at S-223
(Saluda River at Black's Bridge - 24.6 miles above Saluda Dam)
Total Phosphorus (mg/l as P)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
J-72
J-73
J-74
J-75
J-76
J-77
J-78
J-79
J-80
J-81
J-82
J-83
J-84
J-85
J-86
J-87
J-88
J-89
J-90
J-91
J-92
J-93
J-94
J-95
J-96
J-97
J-98
Date

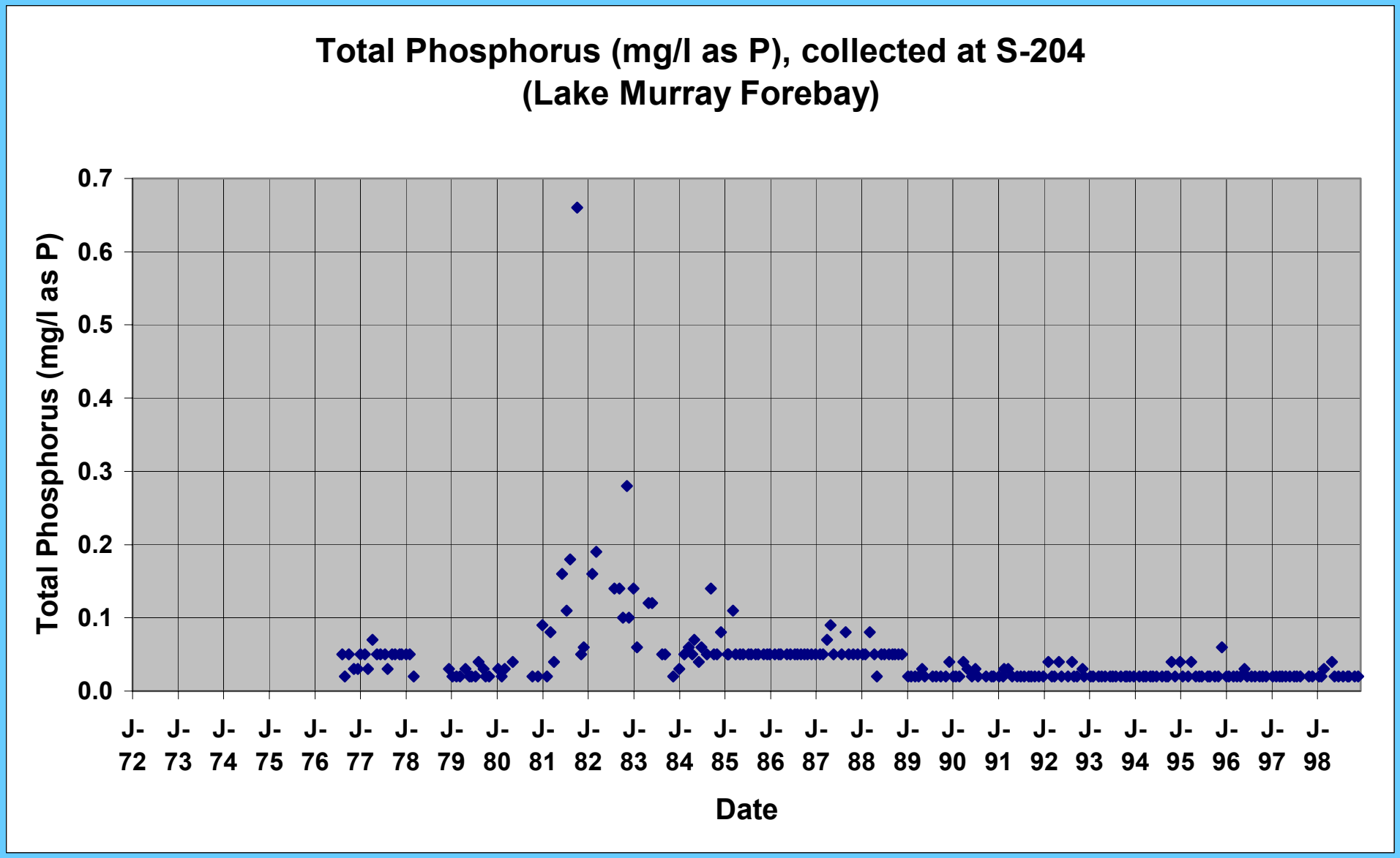
TP Measured in the Little Saluda River (SCDHEC Station S-123)



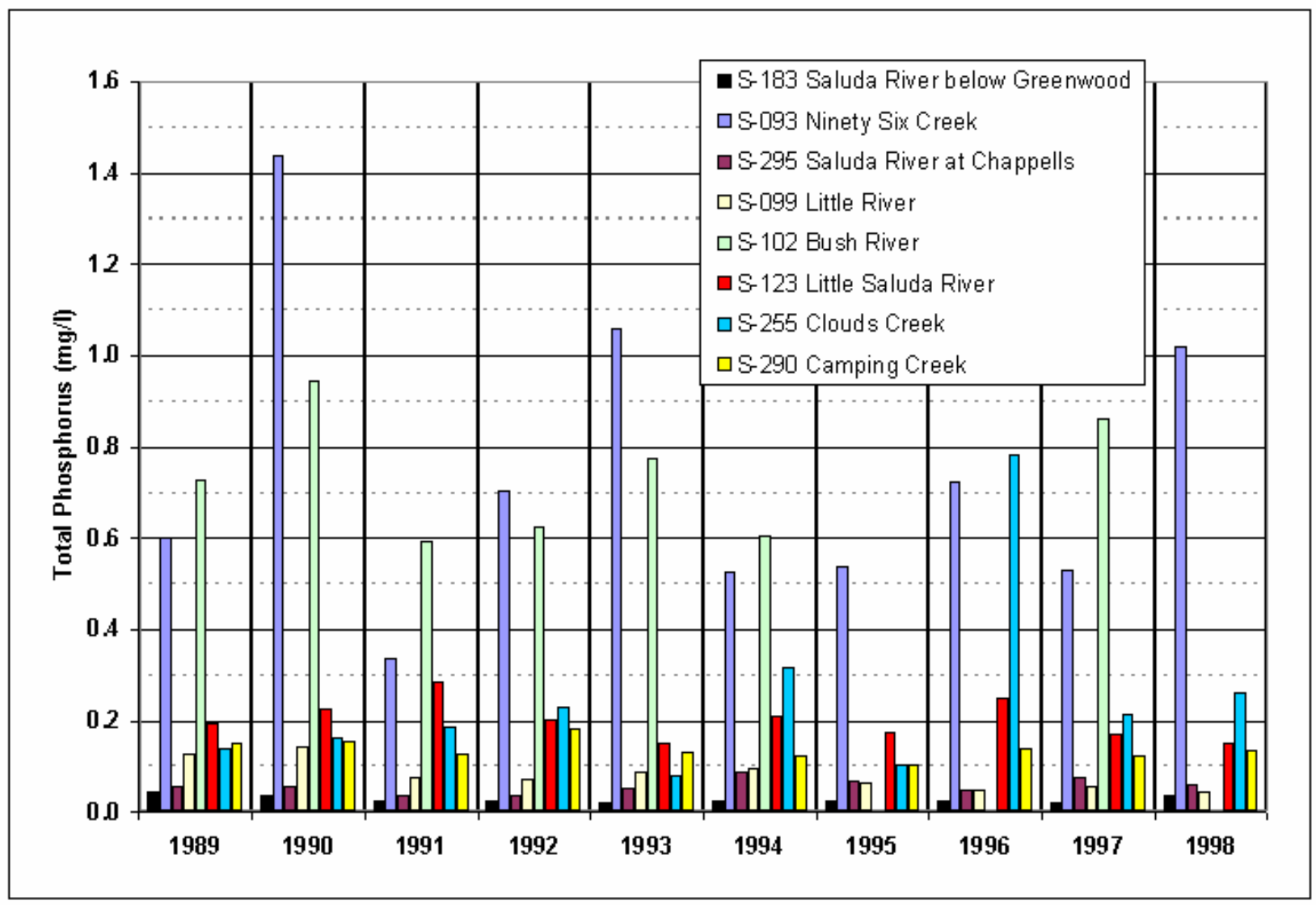
TP Measured in Clouds Creek (SCDHEC Station S-255)




Total Phosphorus (mg/l as P), collected at S-279
(Main Channel, 18 miles upstream of dam)
Total Phosphorus (mg/l as P)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
J-72 J-73 J-74 J-75 J-76 J-77 J-78 J-79 J-80 J-81 J-82 J-83 J-84 J-85 J-86 J-87 J-88 J-89 J-90 J-91 J-92 J-93 J-94 J-95 J-96 J-97 J-98
Date

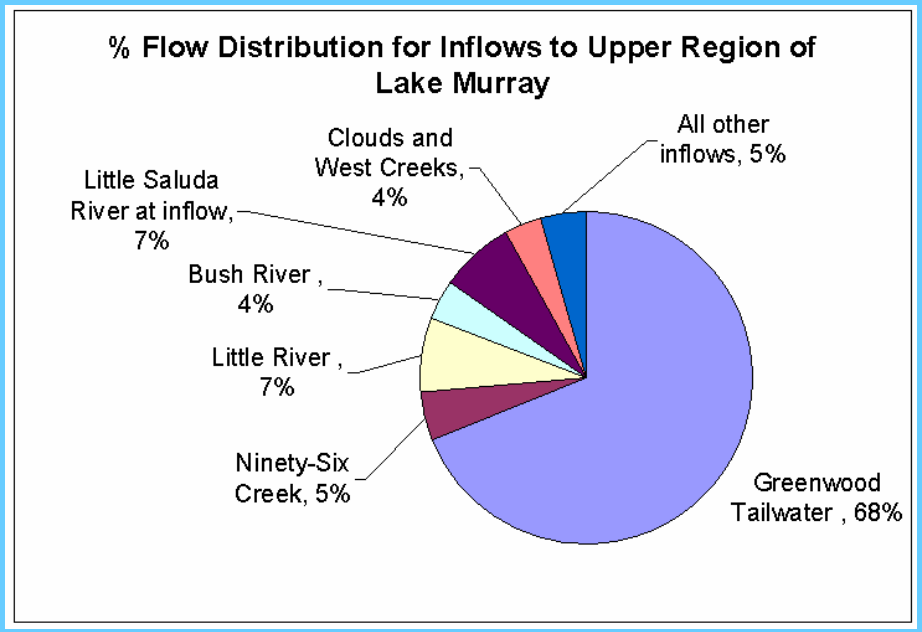

Total Phosphorus (mg/l as P), collected at S-204
(Lake Murray Forebay)
Total Phosphorus (mg/l as P)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
J-72
J-73
J-74
J-75
J-76
J-77
J-78
J-79
J-80
J-81
J-82
J-83
J-84
J-85
J-86
J-87
J-88
J-89
J-90
J-91
J-92
J-93
J-94
J-95
J-96
J-97
J-98
Date

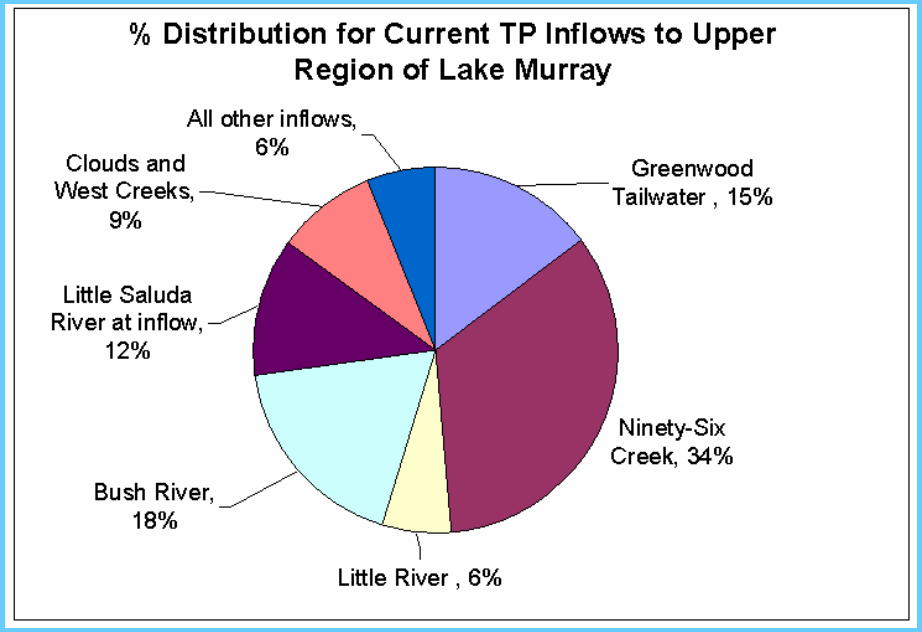
May-October Means of TP Measured at SCDHEC Stations Located in the Inflows to Lake Murray



	Mean Streamflow (cfs)	Percent of Total Flow
Saluda Hydro	2683	100
Lake Murray Direct Inflows		
Saluda River at inflow	2098	78.2
Bush River	92	3.4
Little Saluda River	180	6.7
Clouds and West Creek	89	3.3
Beaver Dam Creek	26	1.0
Camping Creek	31	1.2
Hollow and Horse Creeks	39	39
all other local drainage	129	4.8
Between inflow and Saluda Dam	585	21.8
Upstream Inflows		
96 Creek	115	
Little River	182	

Inflow and Phosphorus Loads to Upper Regions of Lake Murray





Percent contributions to the upper regions of Lake Murray of total phosphorous loadings and mean stream flows

Lake Murray Tributary	Mean Streamflow %	Phosphorus Load %	Ratio of Phosphorus Load to Flow
Bush River	4	18	4.5
Little Saluda River	7	12	1.7
Clouds and West Creeks	4	9	2.2
Ninety-Six Creek	5	34	6.8
Little River	7	6	0.9
Saluda River	68	15	0.2
All other flows	5	6	1.2

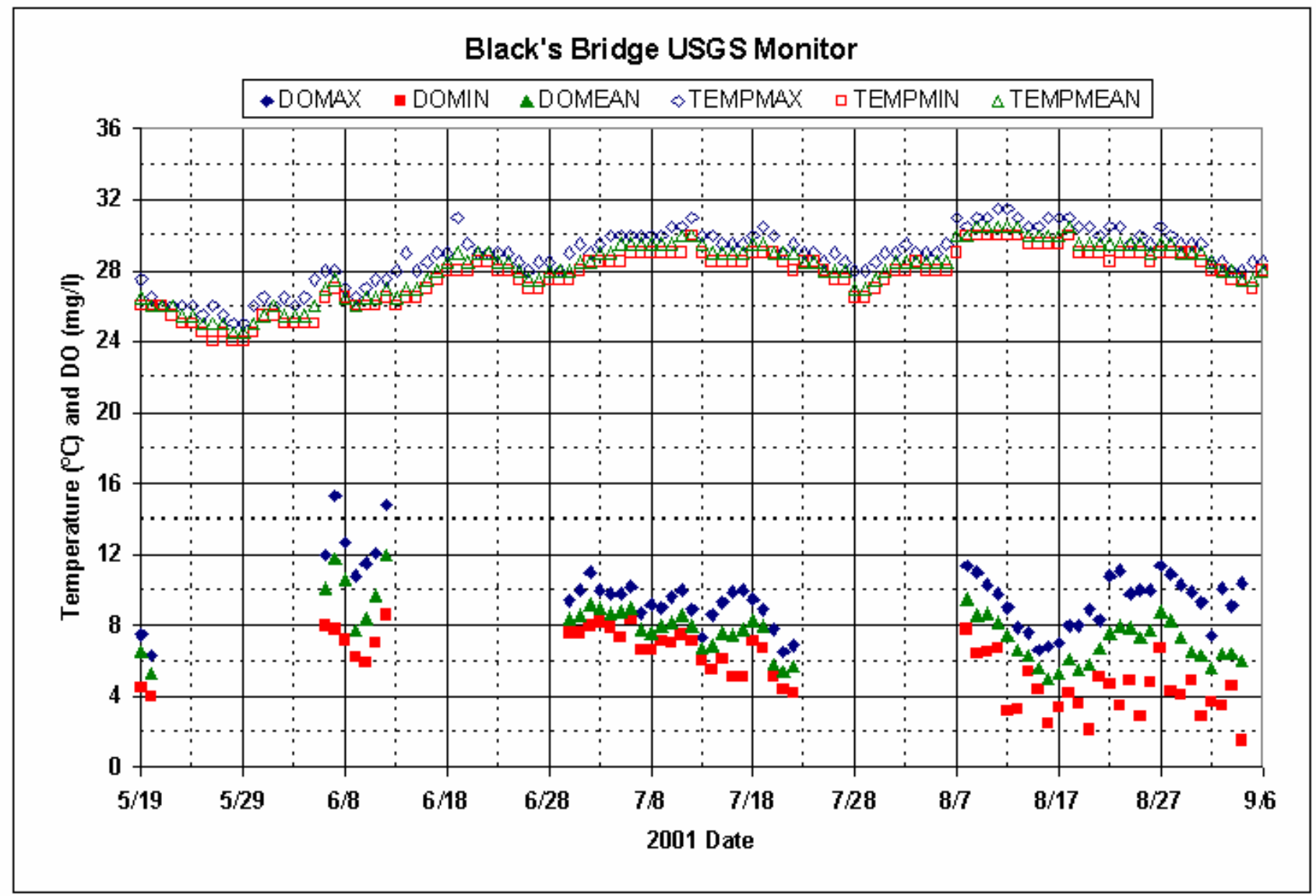
Summary of TP, chlorophyll *a*, and secchi depth conditions at various locations in the inflows and Lake Murray – Includes DHEC data only

	Total Phosphorus (mg/l)	Chlorophyll *a* (µg/l)	Secchi depth (m)
Greenwood Dam (S-186)	0.022	No data	No data
Ninety-Six Creek (S-093)	0.74	No data	No data
Little River (S-099)	0.08	No data	No data
Bush River Embayment (S-309)	0.12	28.6	0.7
Clouds Creek (S-255)	0.25	No data	No data
Blacks Bridge (S-223)	0.06	14.77	1.01
Rocky Creek (S-279)	0.05	11.9	1.4
Dreher Island (S-280)	0.03	6.5	2.0
4.2 Miles from Saluda Dam (S-273)	0.02	5.5	2.8
Ballentine Embayment (S-274)	0.02	5.7	2.4
Forebay (S-204)	0.02	7.3	2.7

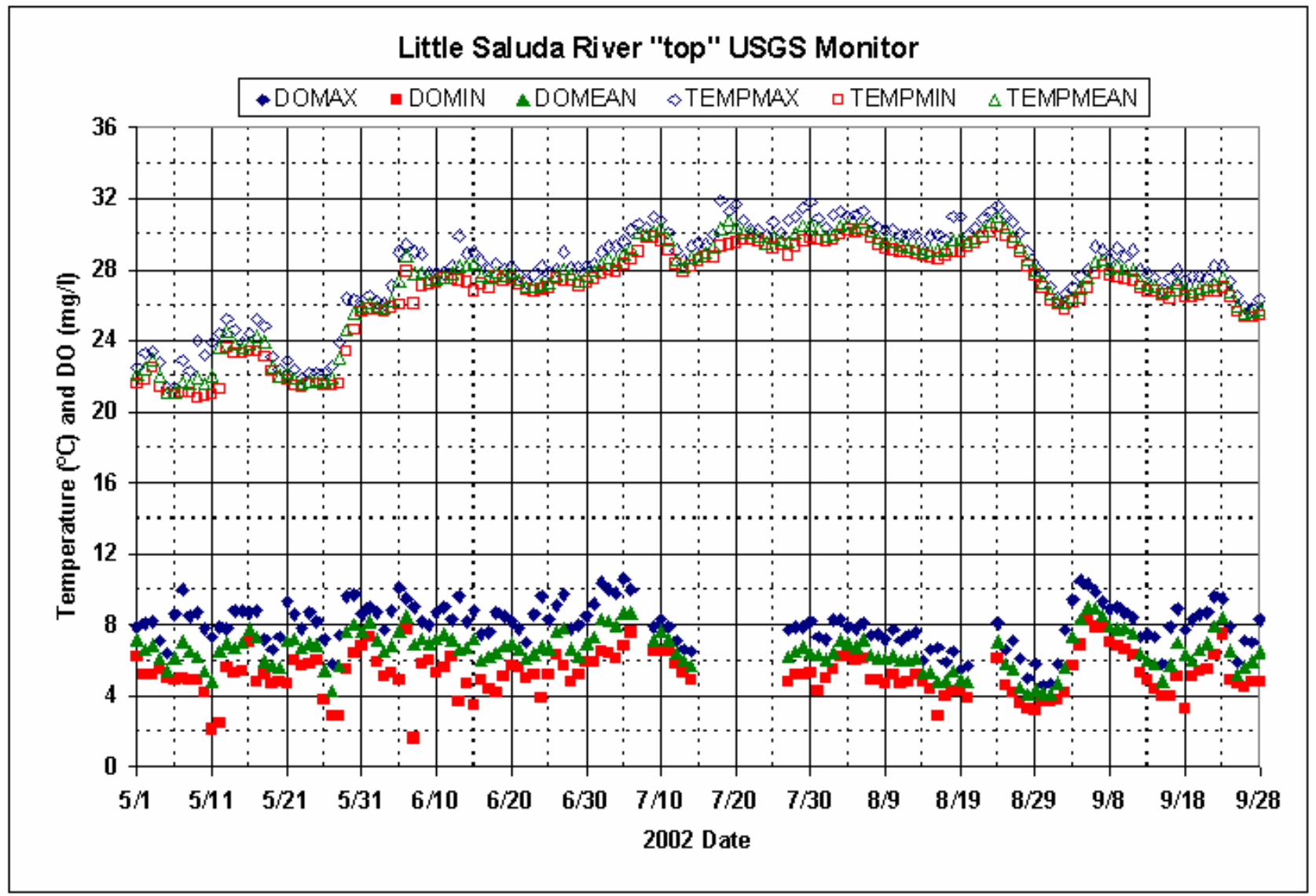
Summary of DO conditions at 14 reservoirs with residence times similar to Lake Murray and various inflow phosphorus conditions

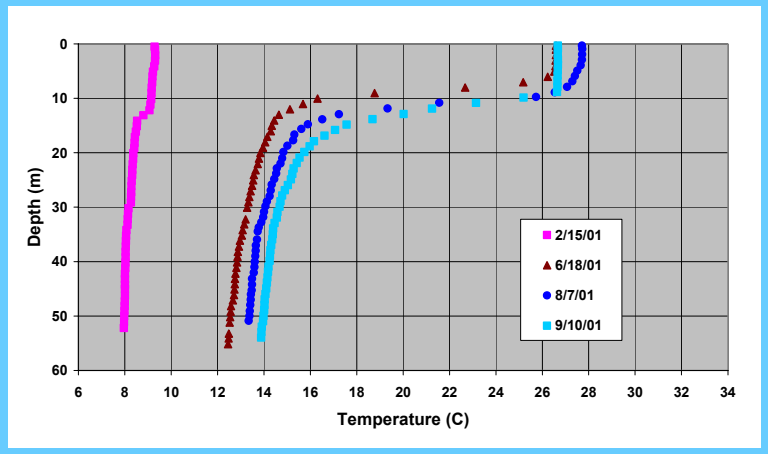
Relationship Between Low DO and Phosphorus for Hydropower Reservoirs with Residence Times of About 400 Days									
Name of dam	**River**	**Max. depth, ft**	**Normal storage, ac-ft**	**Surf. area, ac**	**Drain. area, sq mi**	**Mean flow, cfs**	**Resi-dence Time**	**Zero DO in releases, annually?**	**COMMENTS**
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	Yes	low metalimnion DO in Seneca Arm, but not Tugaloo Arm; probably due to TP — TP load could be 80% of load to Lake Murray, and 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** %

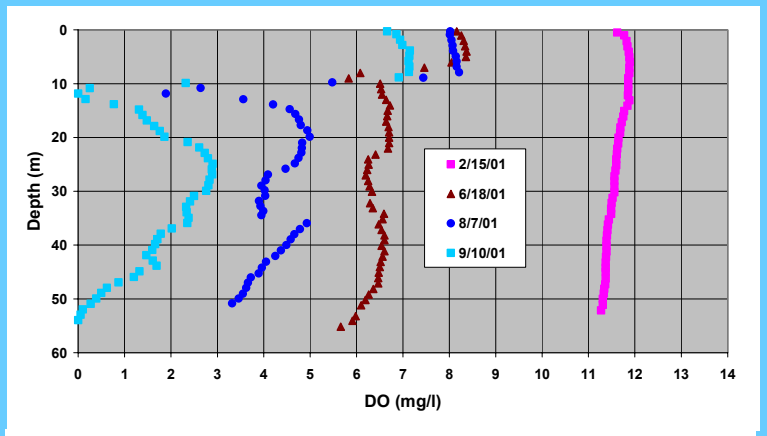
Daily DO and Temperature Data Collected at Hwy 391 Bridge

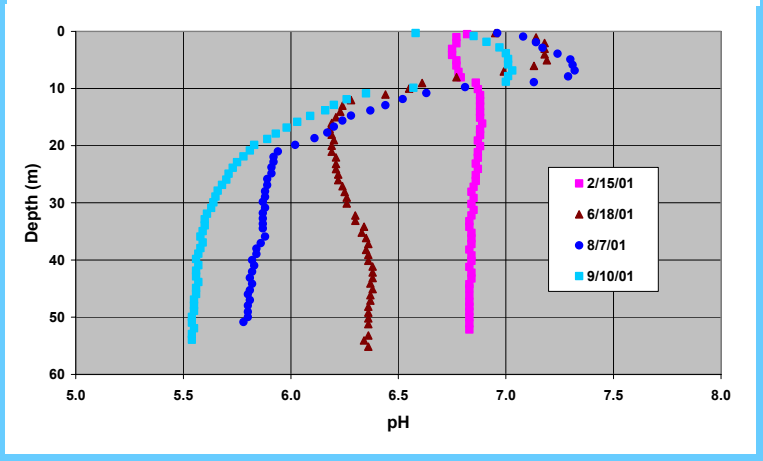


Daily DO and Temperature Data Collected on the Little Saluda River



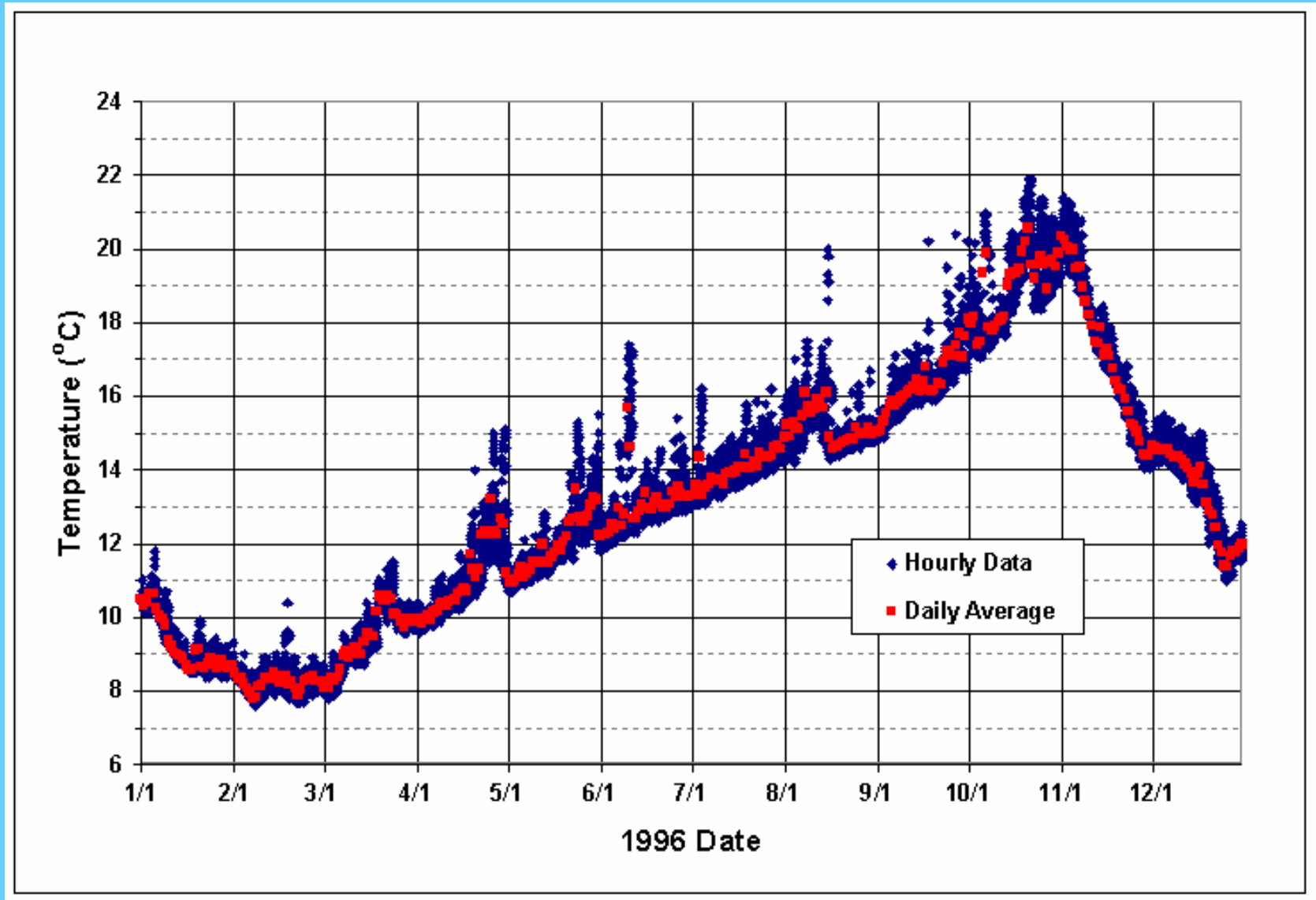




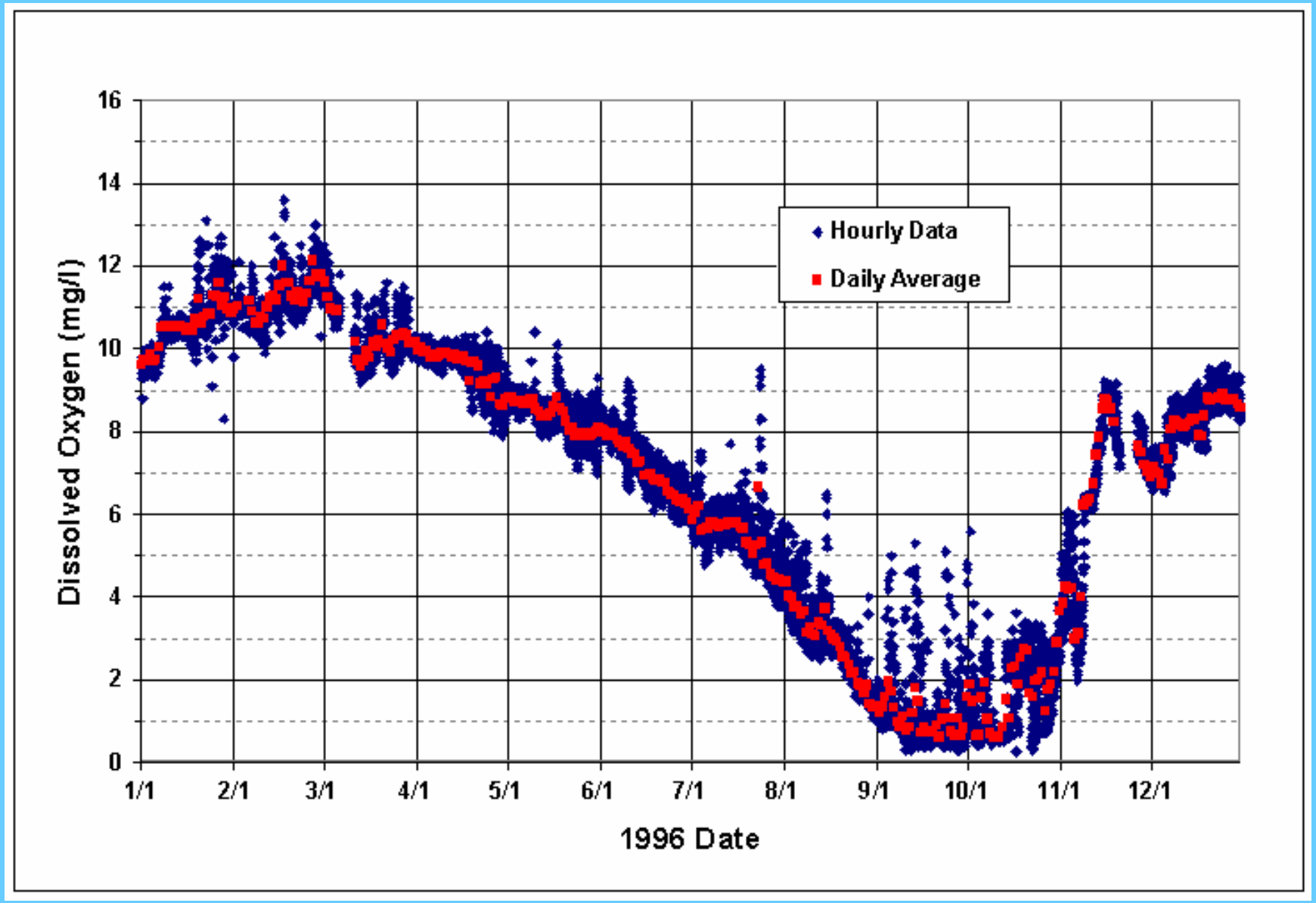


Temperature, DO, and pH profiles from 2001 showing the correlation between pH and low DO

Temperature Measured in the Saluda Hydro Tailrace in 1996



DO Measured in the Saluda Hydro Tailrace in 1996



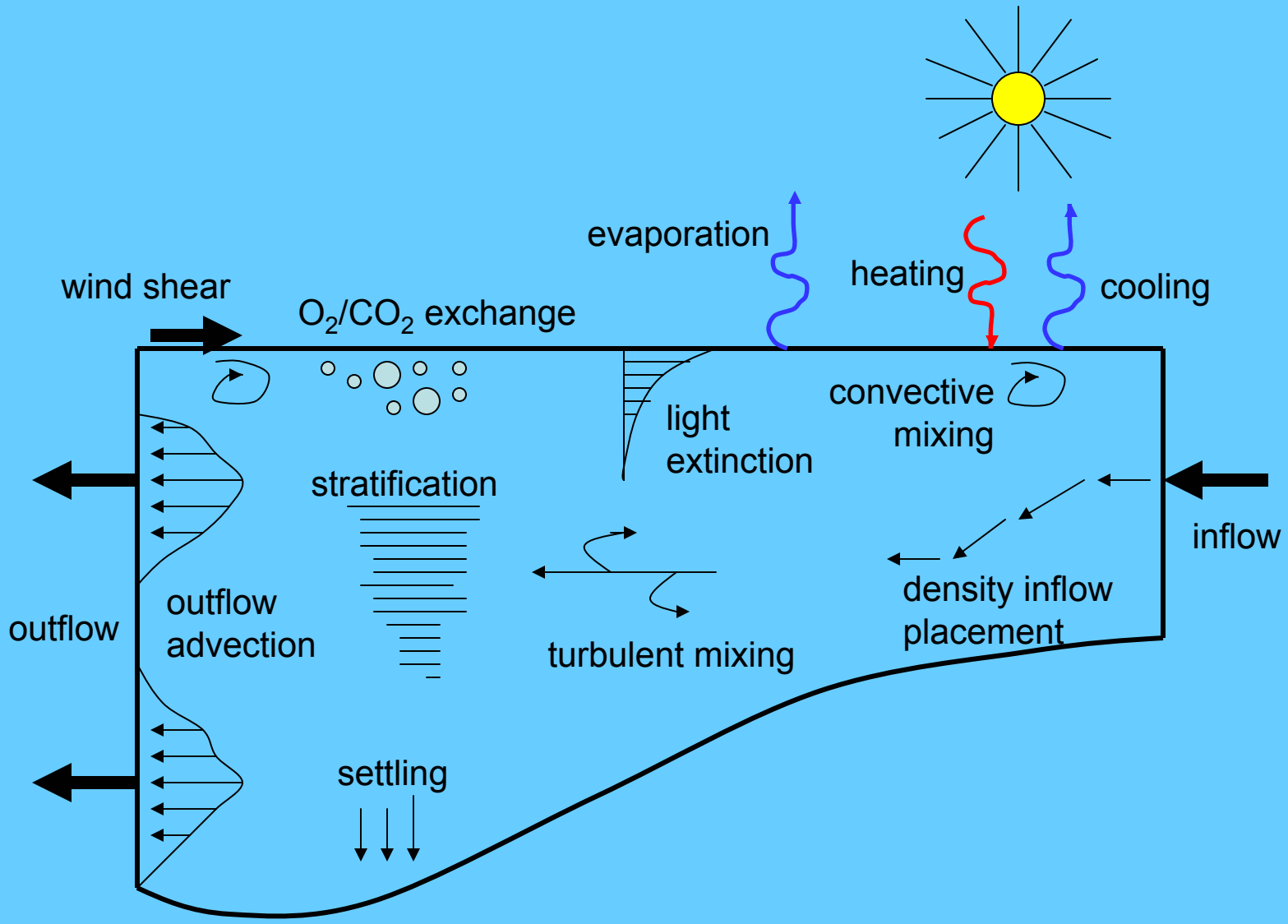
Summary of Key Issues at the Time of the 2001 Assessment and When the CE-QUAL-W2 Model Was Developed

- low DO in the releases from Saluda Hydro,
- restrictions for operating Unit 5 due to entrainment of blue-back 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)
- Fecal coliforms were identified as an issue on several inflows to Lake Murray, but not on the lake itself
- Copper was identified as an issue, but this was State-wide

Lake thermal stratification

- Temperature affects the density of water, so lakes stratify—warmer water floats on top—most lakes stratify 5 to 10 months
- Significantly affected by meteorological conditions, inflow temperatures, residence time and outlet level, cooling water use
- Nominal residence times range from 1 day to 2 years
- Outlet levels range from the surface to the bottom
- Inflow temperature can be natural or affected by upstream reservoir releases and thermal discharges
- Temperature affects almost all other water quality issues

Physical processes



Focus: DO dynamics in water

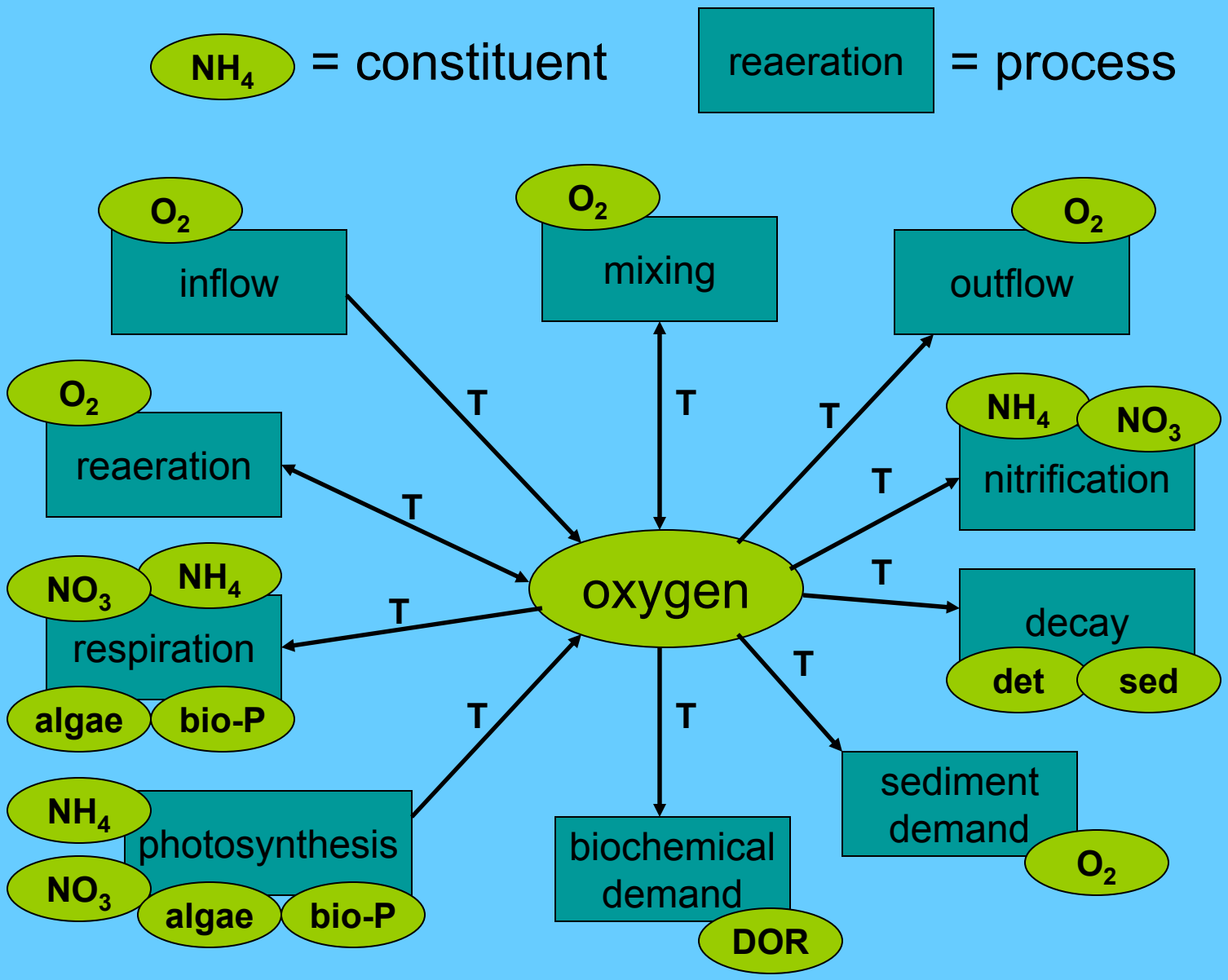
DO in clean water is often near saturation with respect to the atmosphere; however, many other "sources and sinks" affect DO:

- Plant photosynthesis produces DO
- DO is consumed by plant respiration and decomposition of organic matter in wastewater discharges, sediments, and dead plants/algae
- DO is also consumed in the oxidation of ammonia, sulfide, dissolved organic matter, and reduced iron
- DO can be lost to the atmosphere when it is supersaturated in water

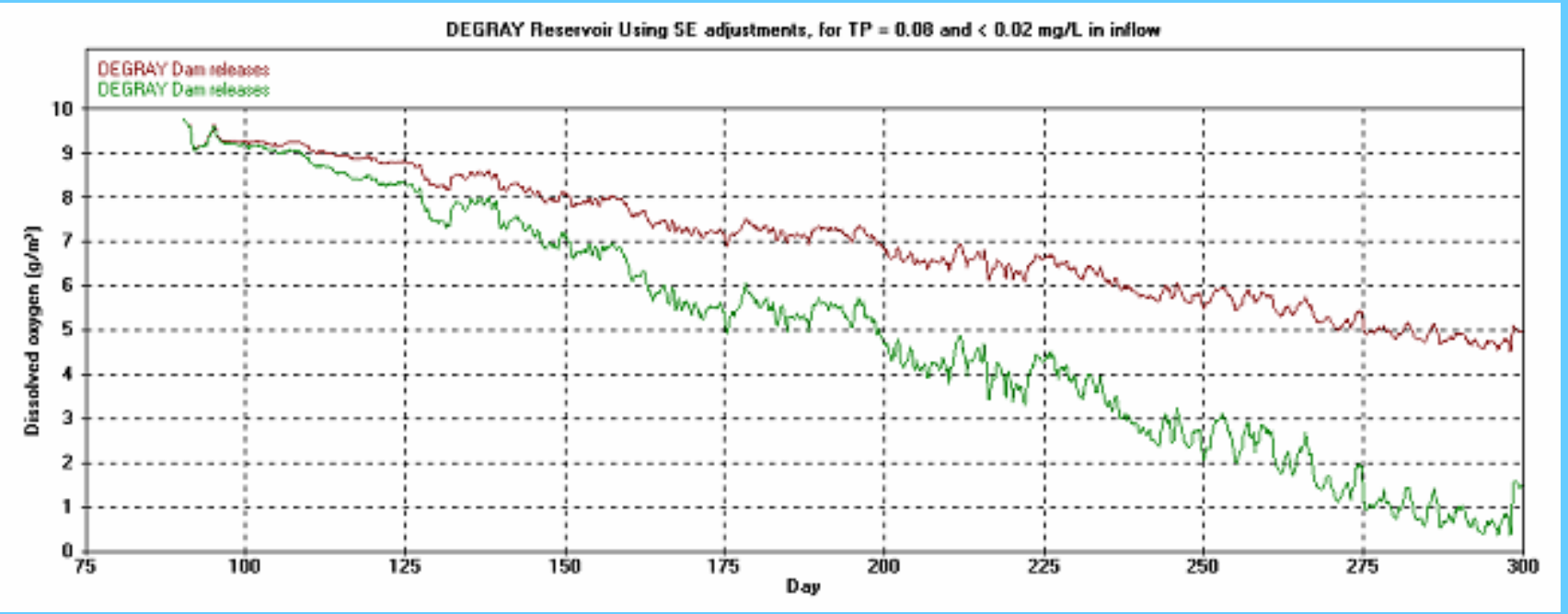
Focus: DO dynamics in reservoirs

- Thermal stratification affects contact of cooler water with the atmosphere and solar radiation; therefore, deeper water usually has lower DO
- Water currents affect the distribution of DO in reservoirs
- Algae grow in the surface layer and usually produce DO; then, they die and add organic matter to the deeper water where it is decomposed and DO is consumed
- Sediment oxygen demand also consumes DO
- Inflowing organic matter also decomposes and consumes DO
- Sediment releases of ammonia, sulfide, methane, and iron can also cause DO consumption
- Inflow DO
- Residence time, outlet levels/withdrawal zone, and water depth are significant variables that affect DO dynamics

Highly coupled constituents



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

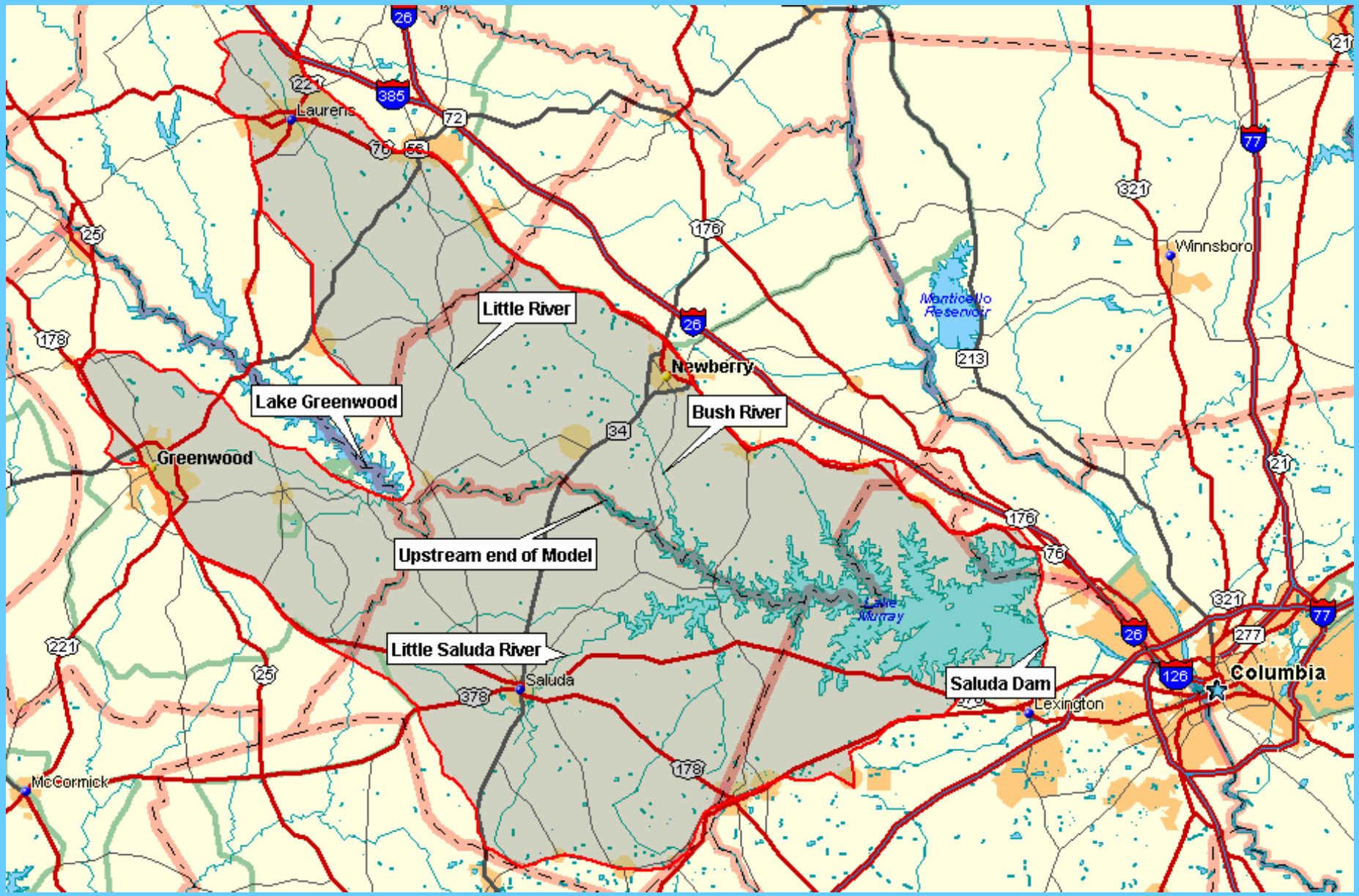


Issues Addressed by Focusing on Phosphorus and Using the CE-QUAL-W2 Two-Dimensional Water Quality Model

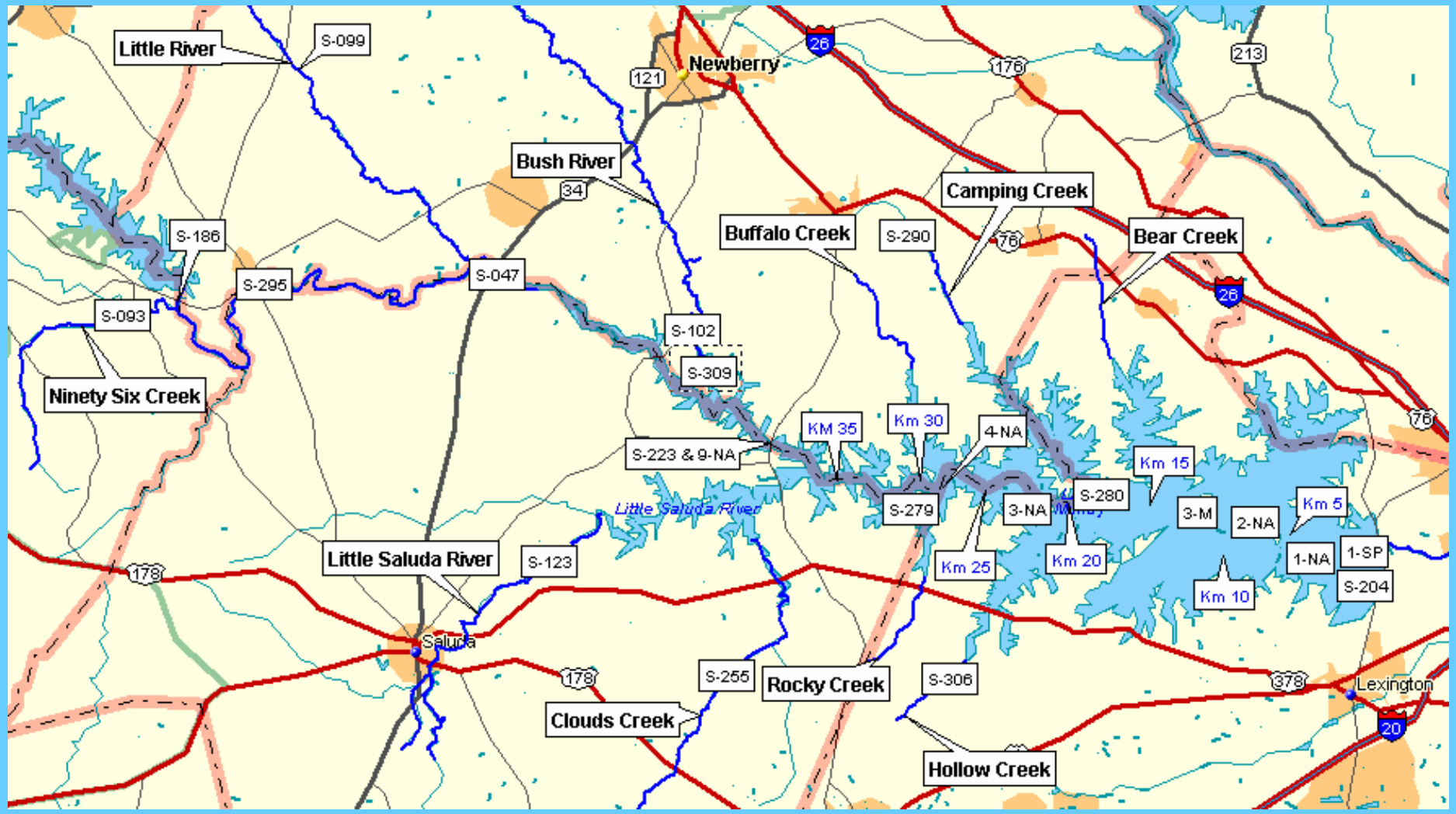
- low DO in the releases from Saluda Hydro,
- restrictions for operating Unit 5 due to entrainment of blue-back herring,
- eutrophication in the upper regions of Lake Murray,
- DO less than the State standard in the inflow regions of the lake,
- reduced striped bass habitat in the lake due to low DO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

Temperature, DO, Age and Chlorophyll a Animation

Lake Murray Watershed



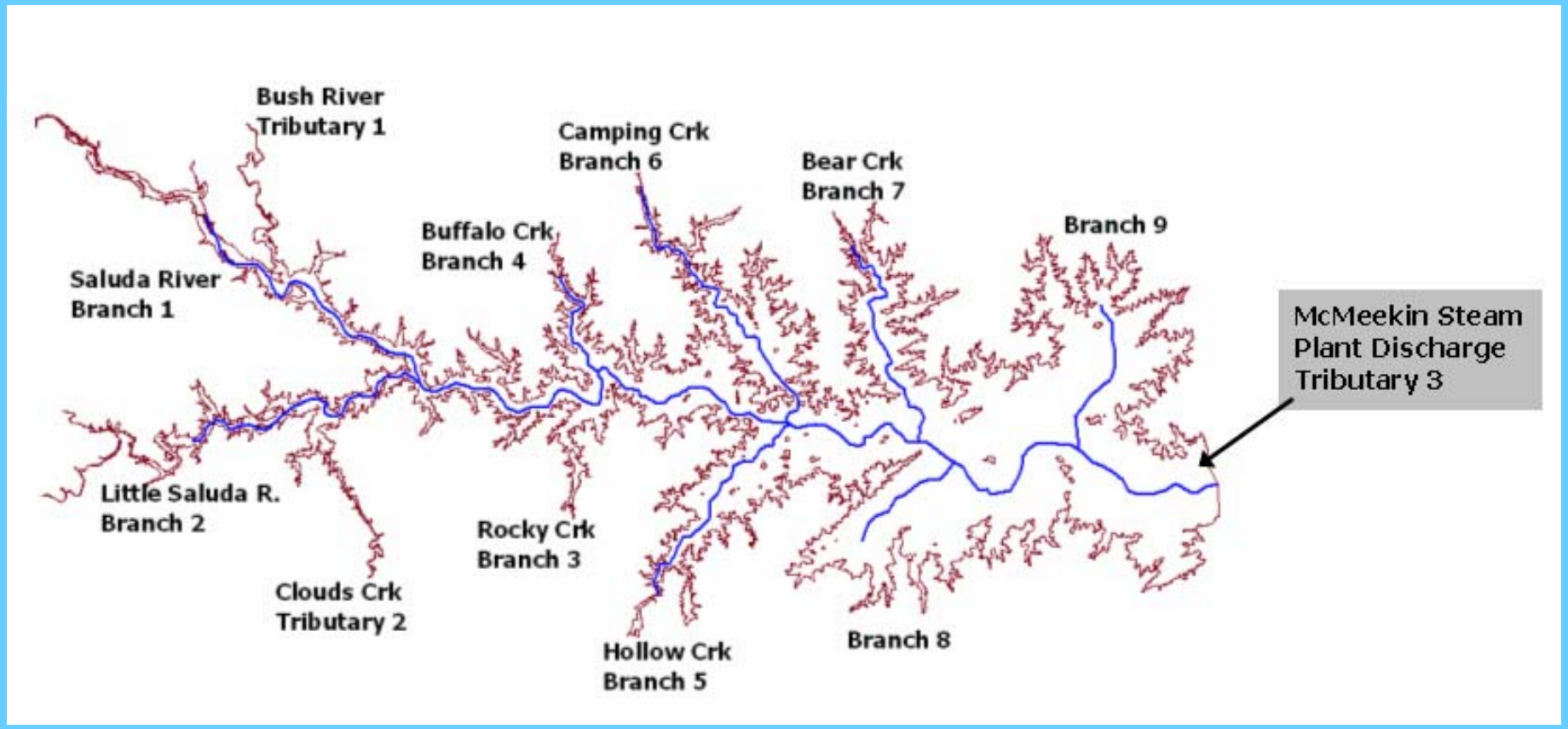
Primary SCDHEC and SCE&G Monitoring Stations used for Lake Murray Water Quality Analyses



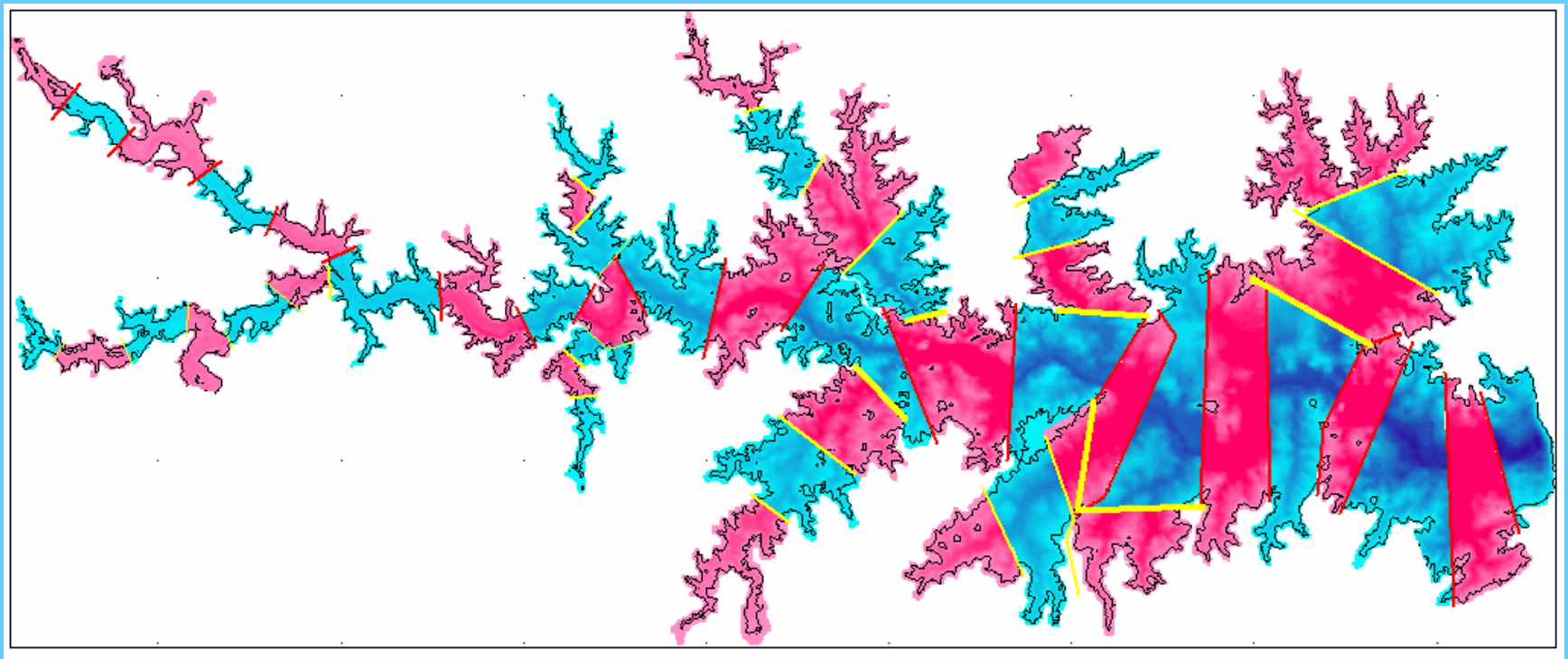
Physical Characteristics of Lake Murray

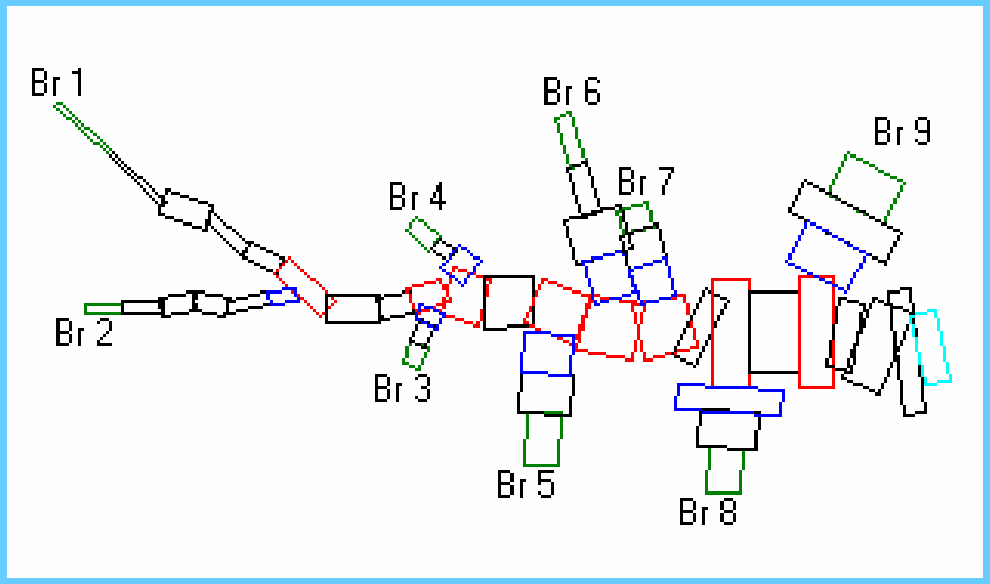
	U.S. Customary System	Metric System
Maximum depth	175 feet	53.3 m
Total lake volume	2,317,000 ac-ft	2,636 hm^3
Average Annual Flow	2778 cfs	78.7 cms
Nominal Residence Time	417 days	417 days
Depth of outlets, Units 1-4	175 feet	53 m
Depth of outlets, Unit 5	110 feet	33.5 m
Flow Capacity - Units 1-4	3000 cfs	85 cms
Flow Capacity, Unit 5	6000 cfs	170 cms

Plan view of Lake Murray with all Branches and Tributaries that are Included in the Model

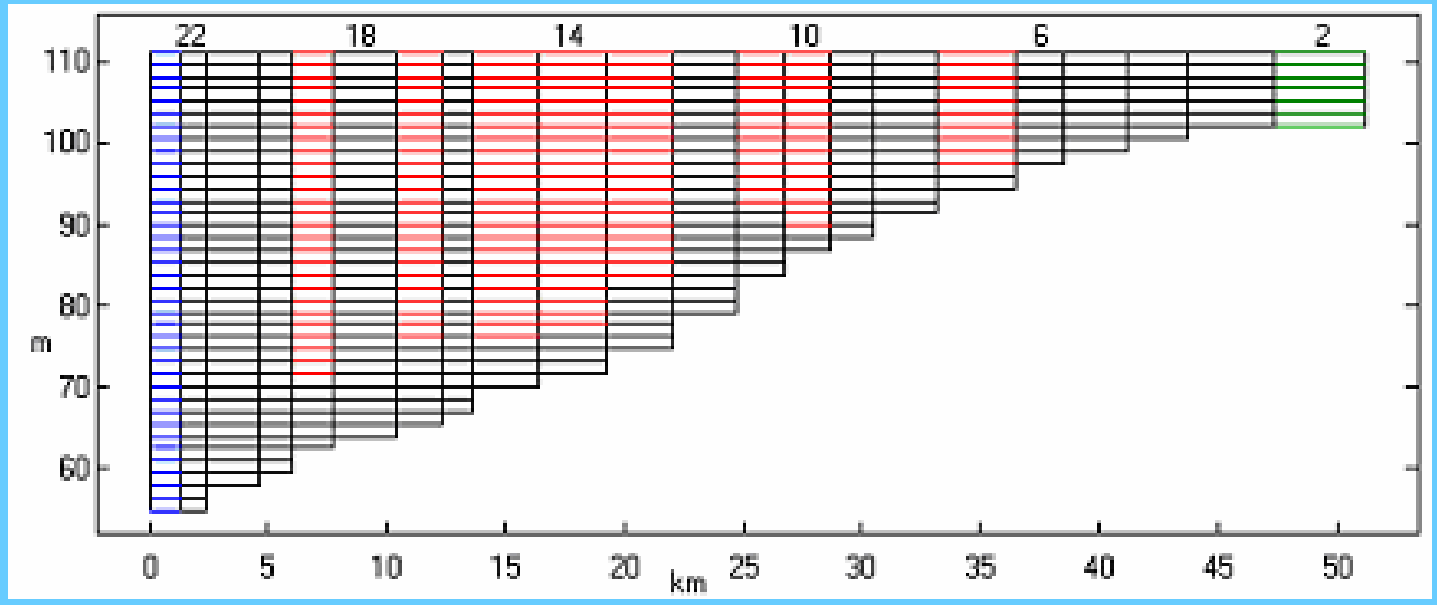


Plan View of Lake Murray Showing CE-QUAL-W2 Segmentation

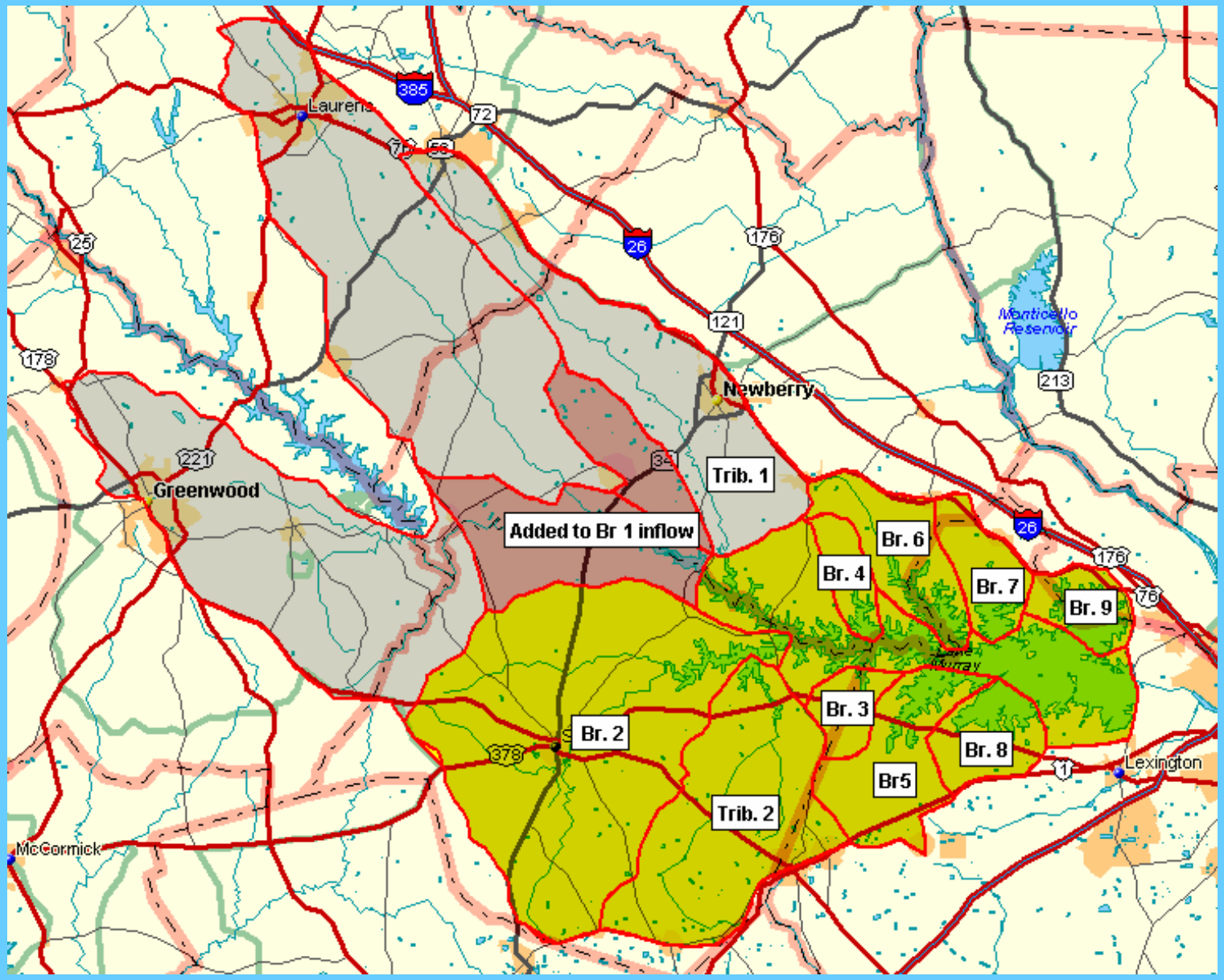




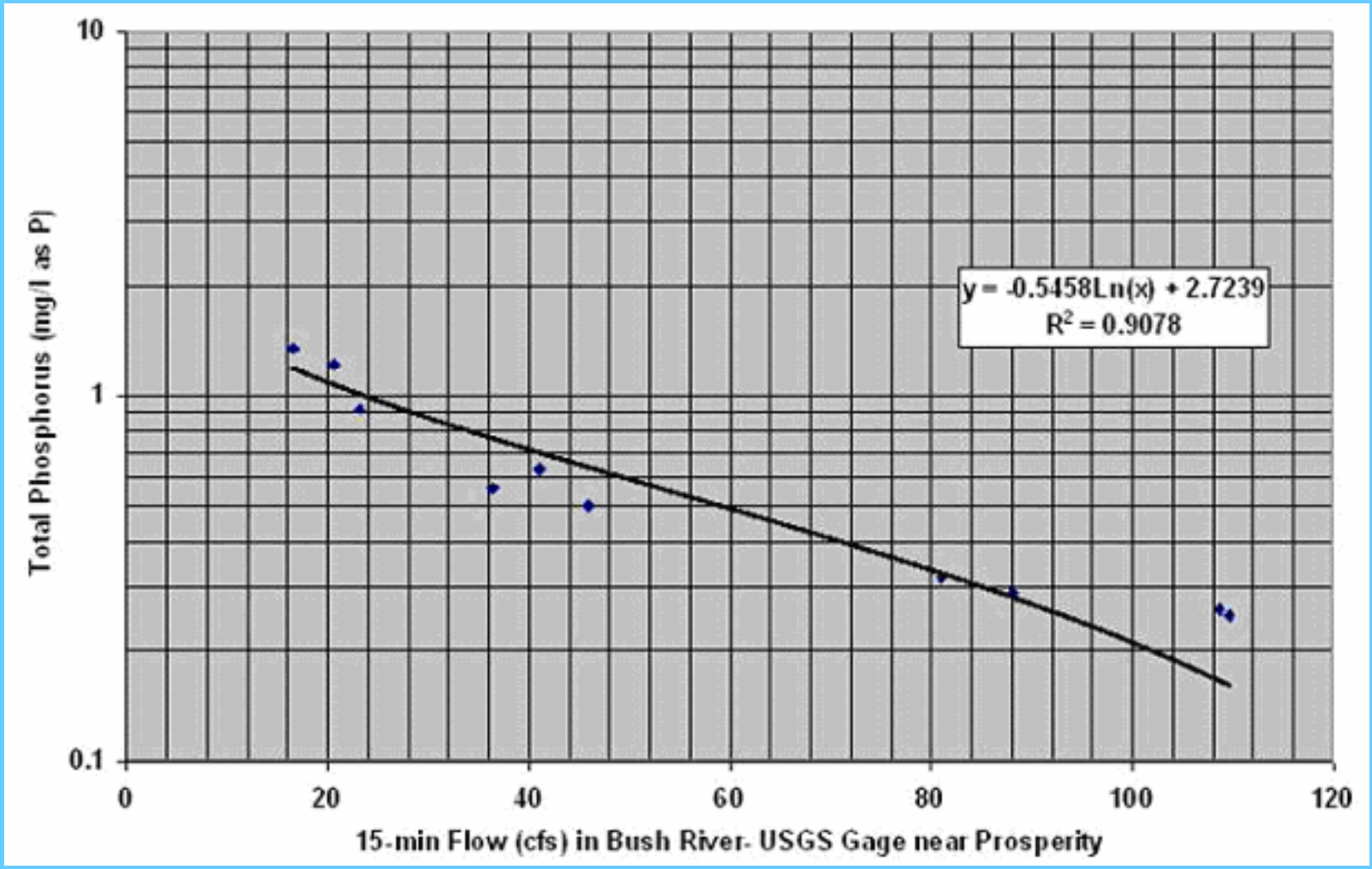
CE-QUAL-W2 Bathymetry for the Main Branch (Branch 1) of Lake Murray



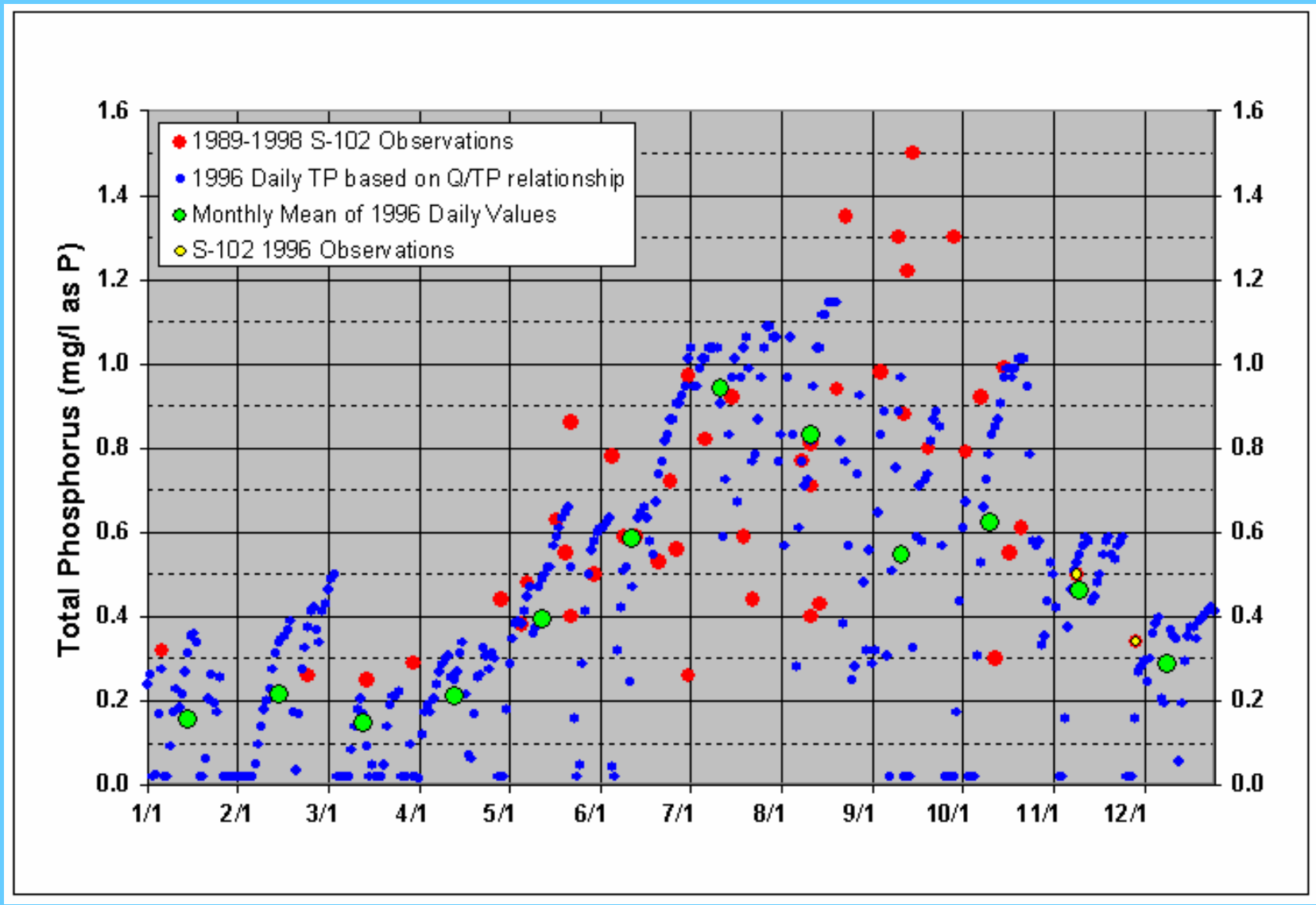
Map of Subwatershed Drainage Area Boundaries



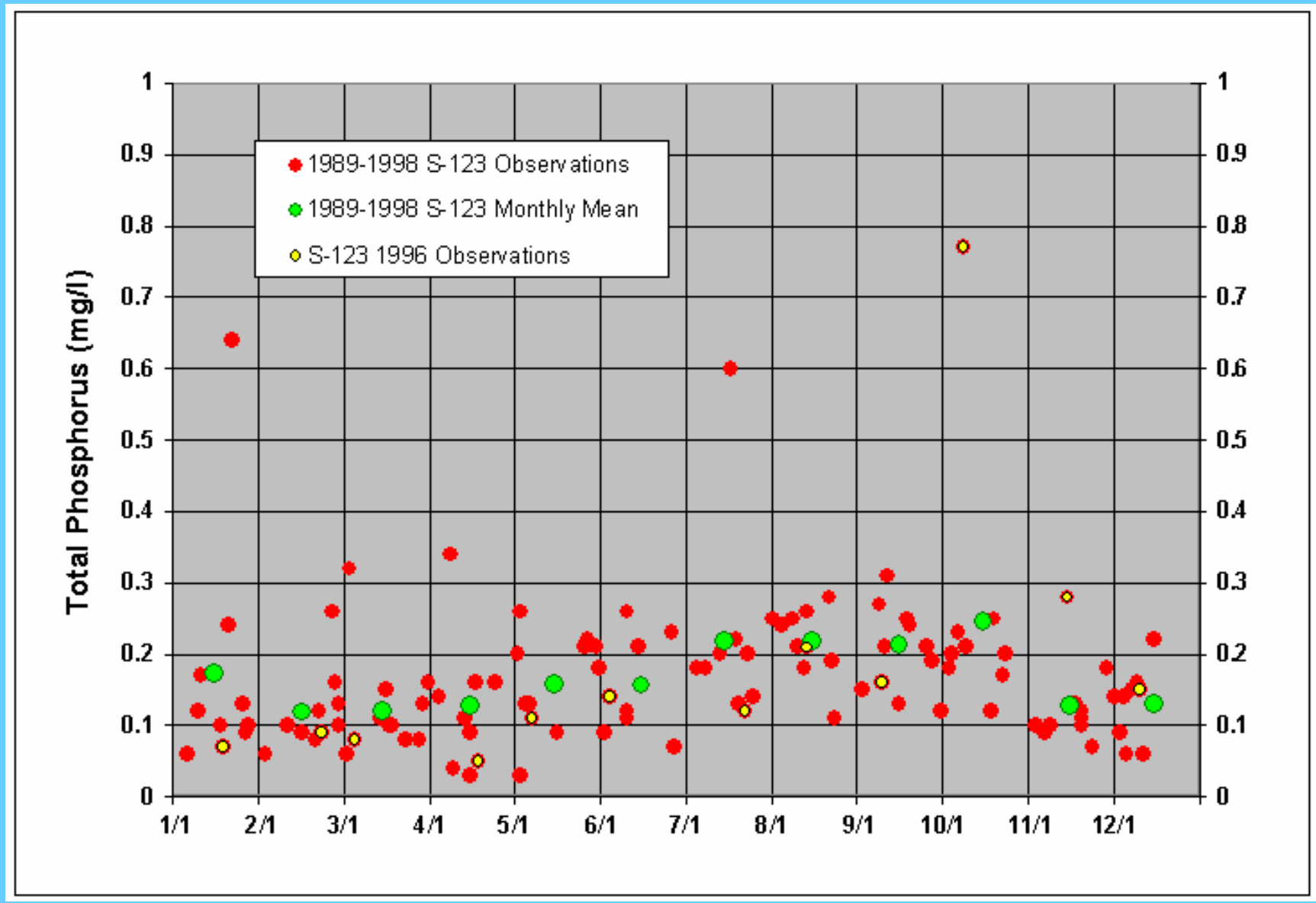
Phosphorus versus Flow Relationship found in the Bush River (Station S-102) using 1997 data



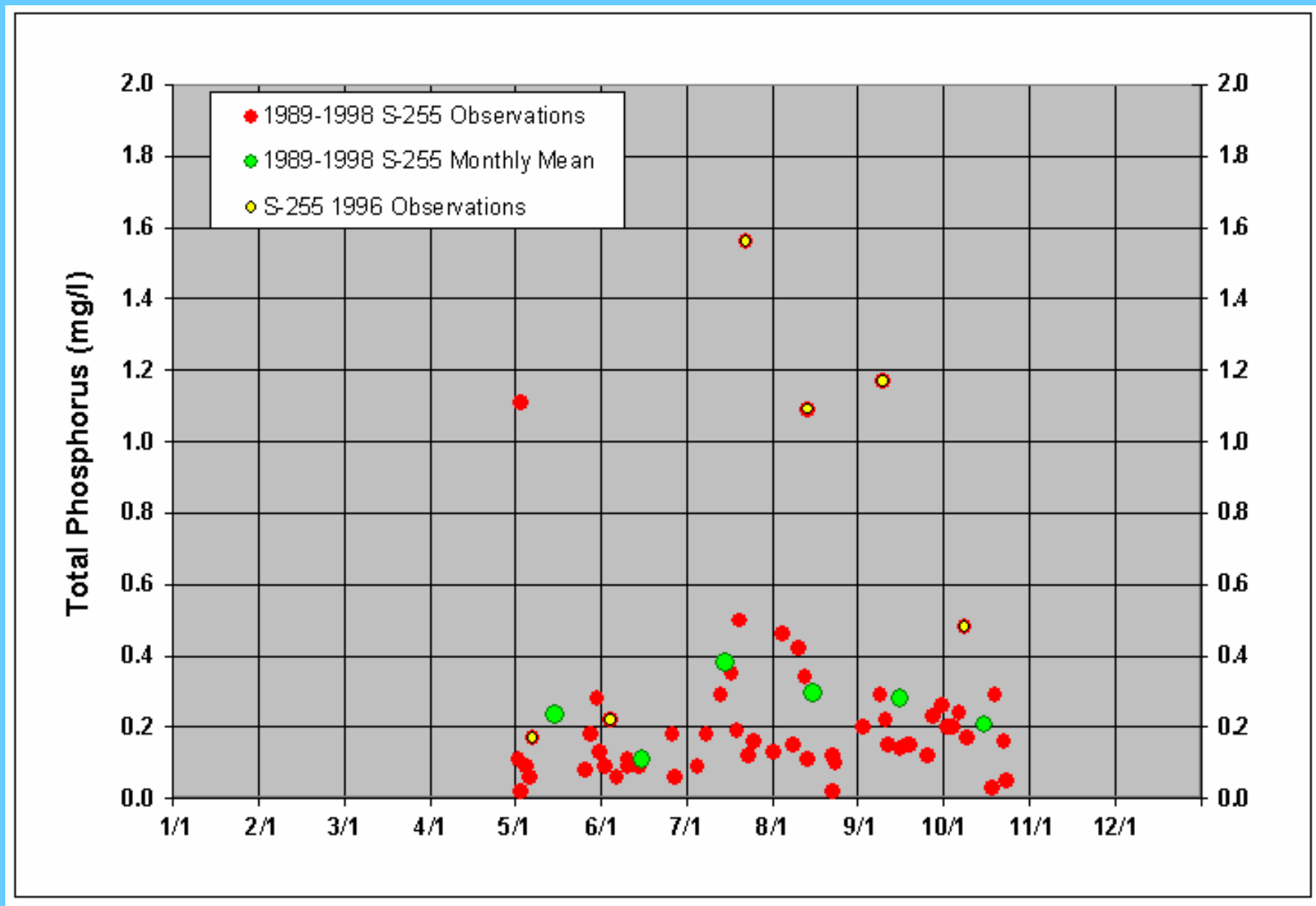
1996 Inflow Phosphorus Analysis for Bush River Inflow to Lake Murray



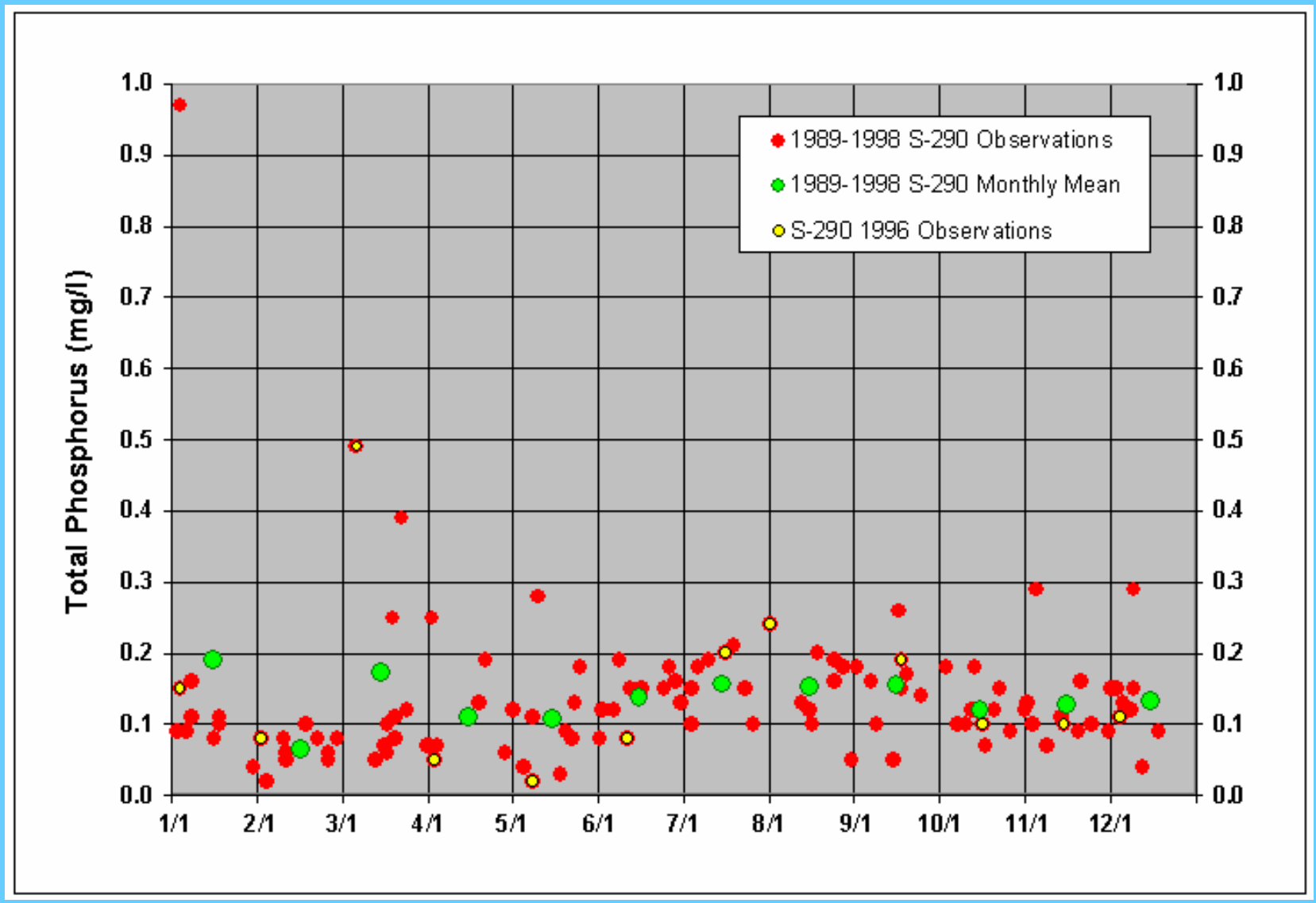
Total Phosphorus in the Little Saluda River



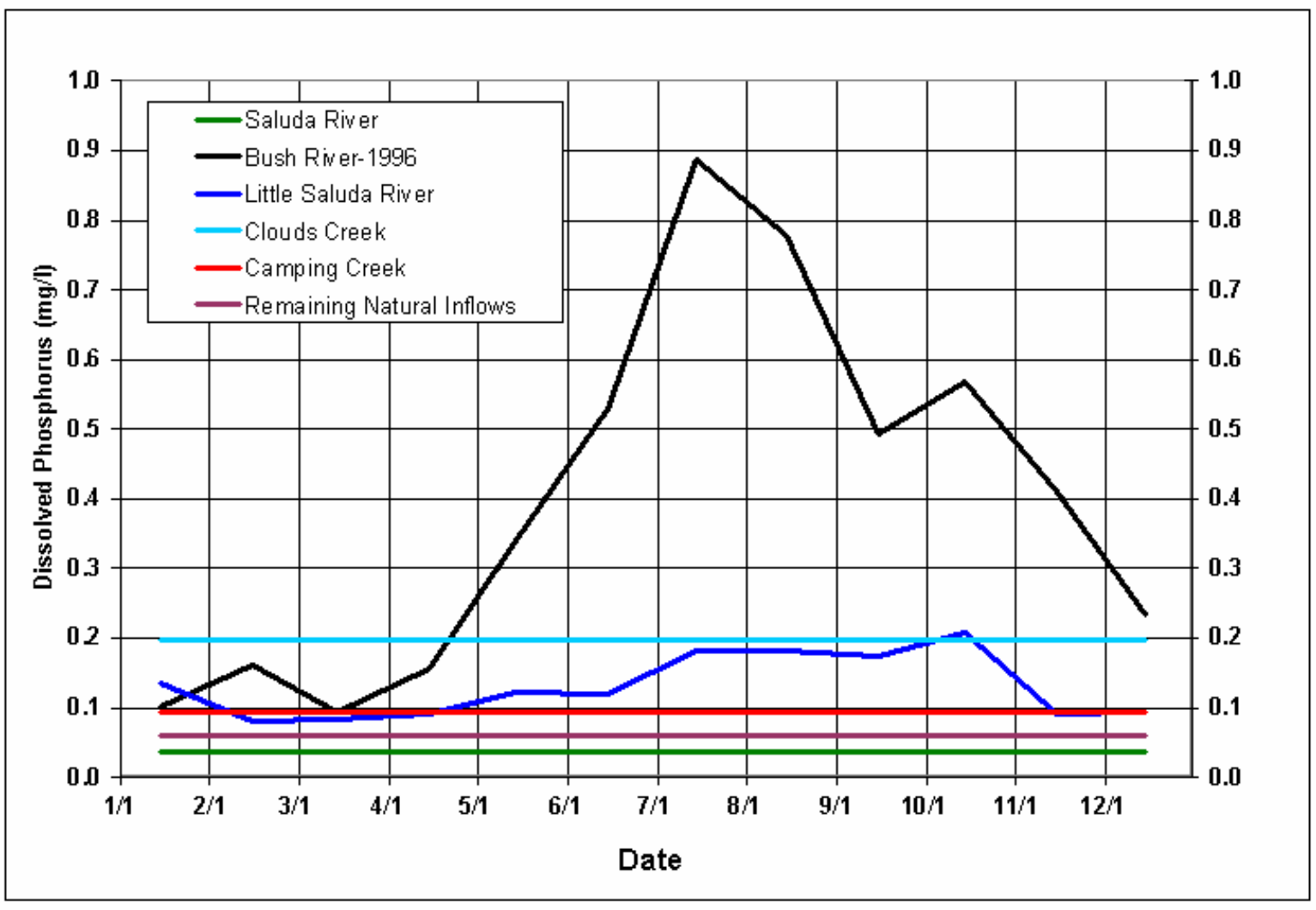
Total Phosphorus Clouds Creek



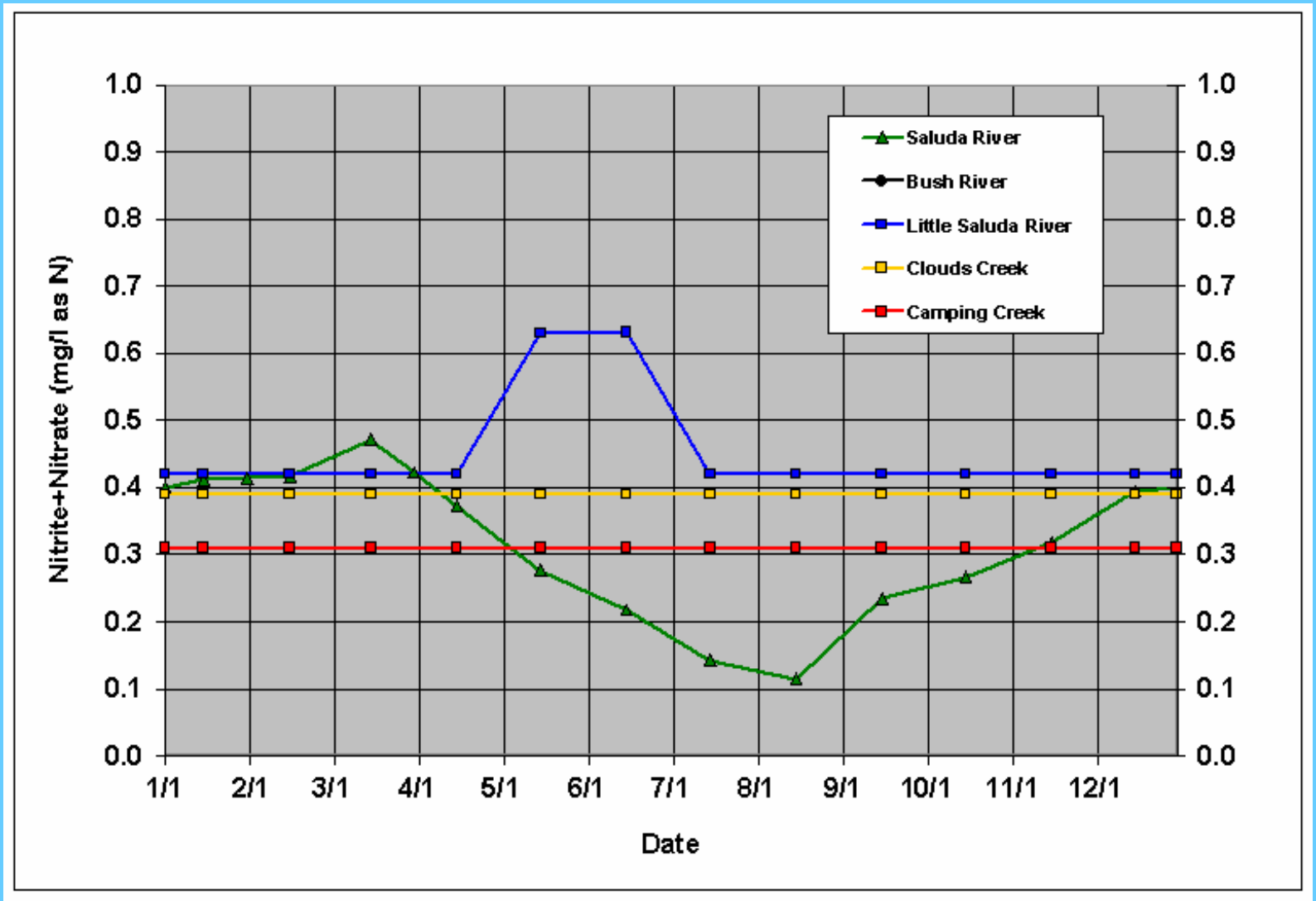
Total Phosphorus in Camping Creek



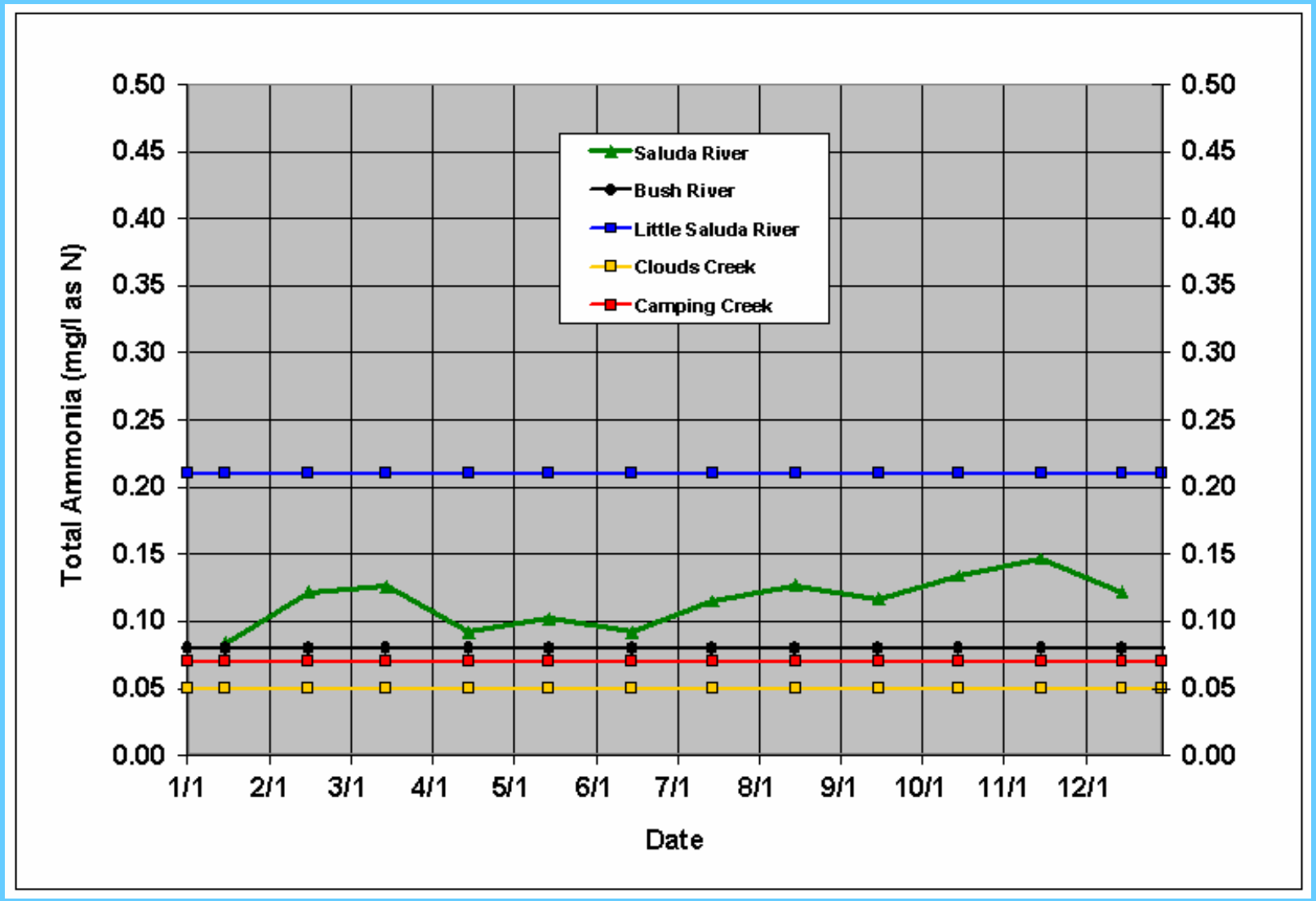
Inflow Dissolved Phosphorus Concentrations for Model Inflows to Lake Murray



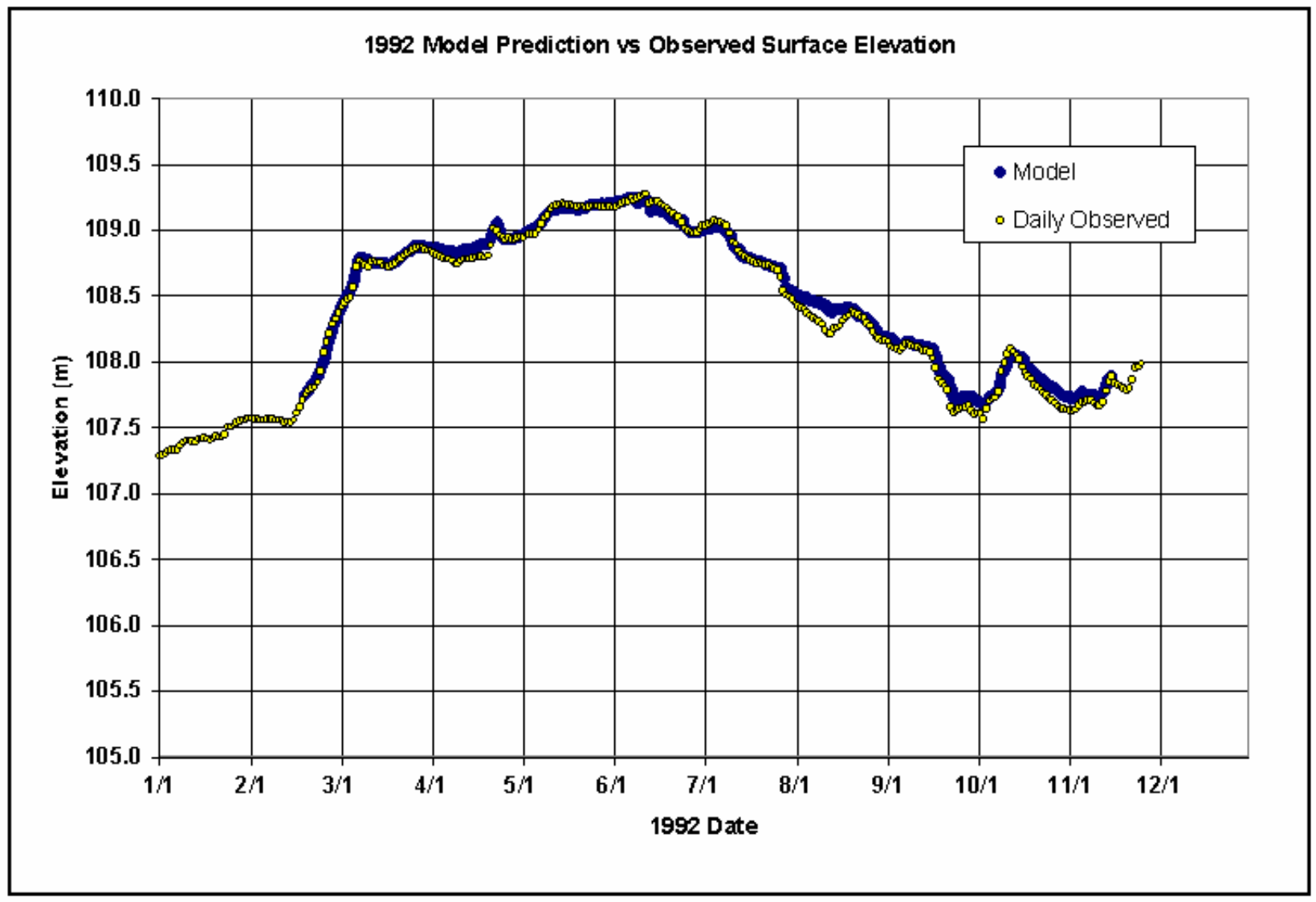
Nitrate Concentrations in the Inflows to the Lake Murray CE-QUAL-W2 Model



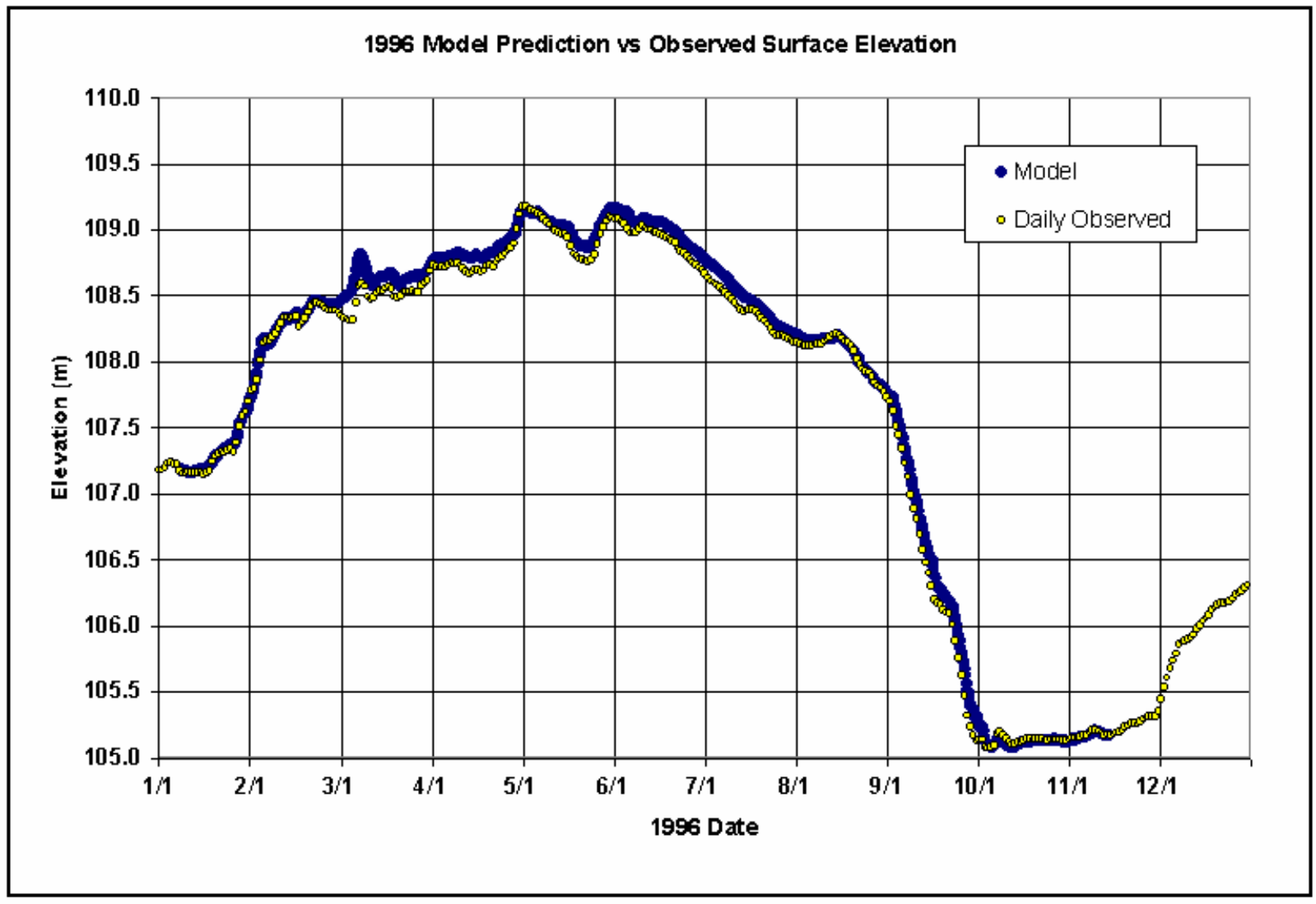
Ammonium Concentrations in the Inflows to the Lake Murray CE-QUAL-W2 Model



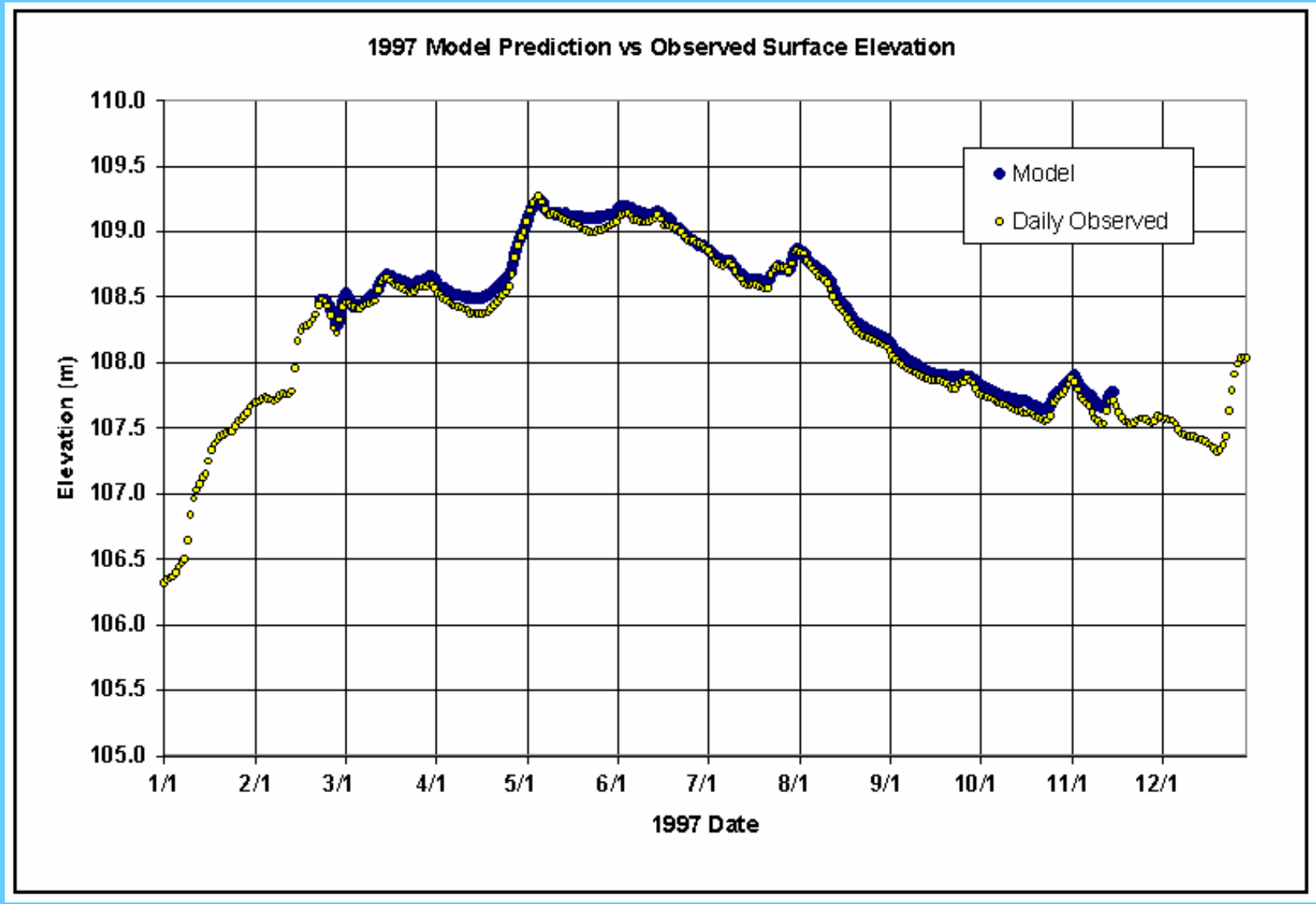
1992 Modeled and Measured Lake Murray Headwater Elevations



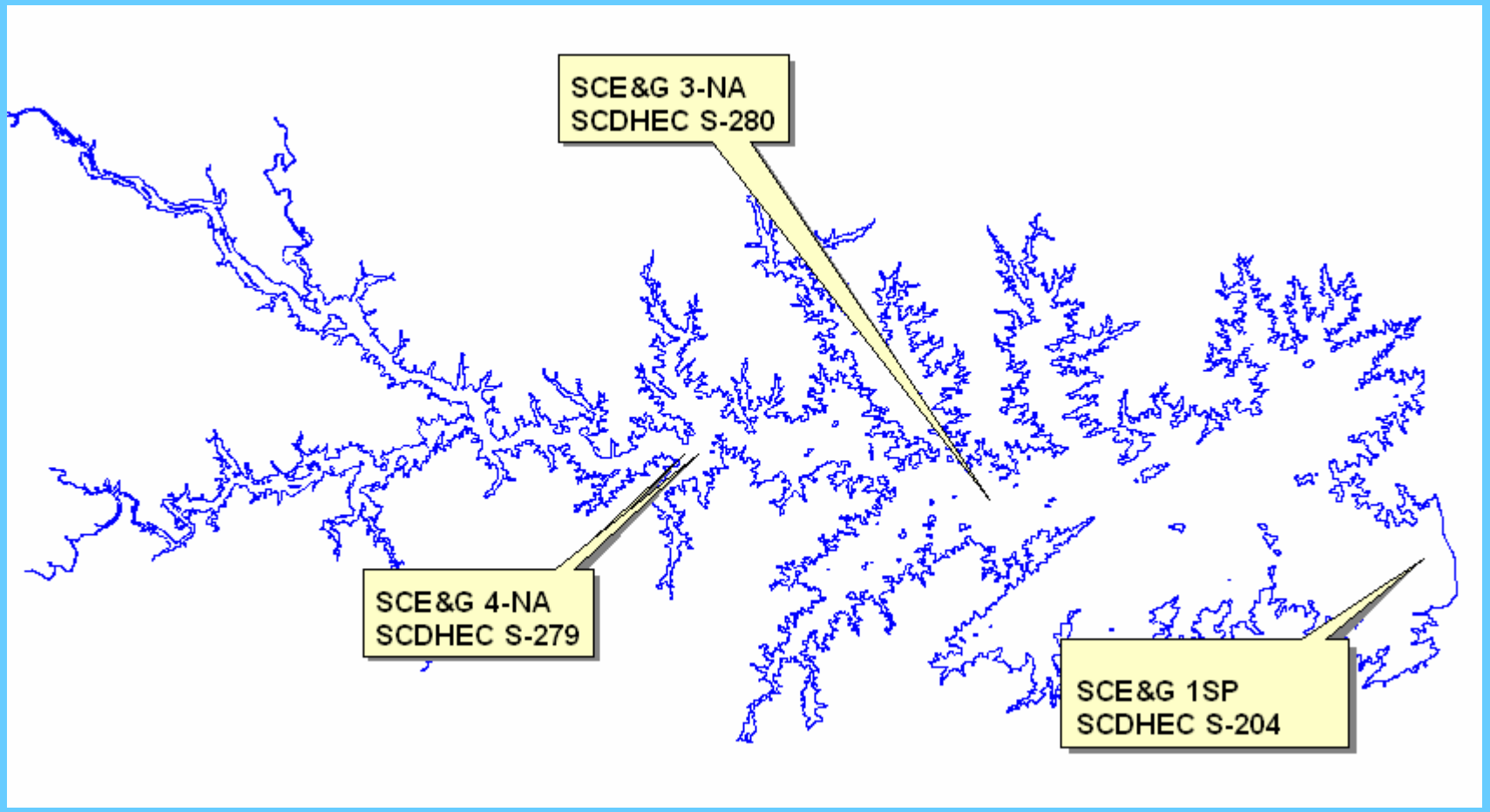
1996 Modeled and Measured Lake Murray Headwater Elevations



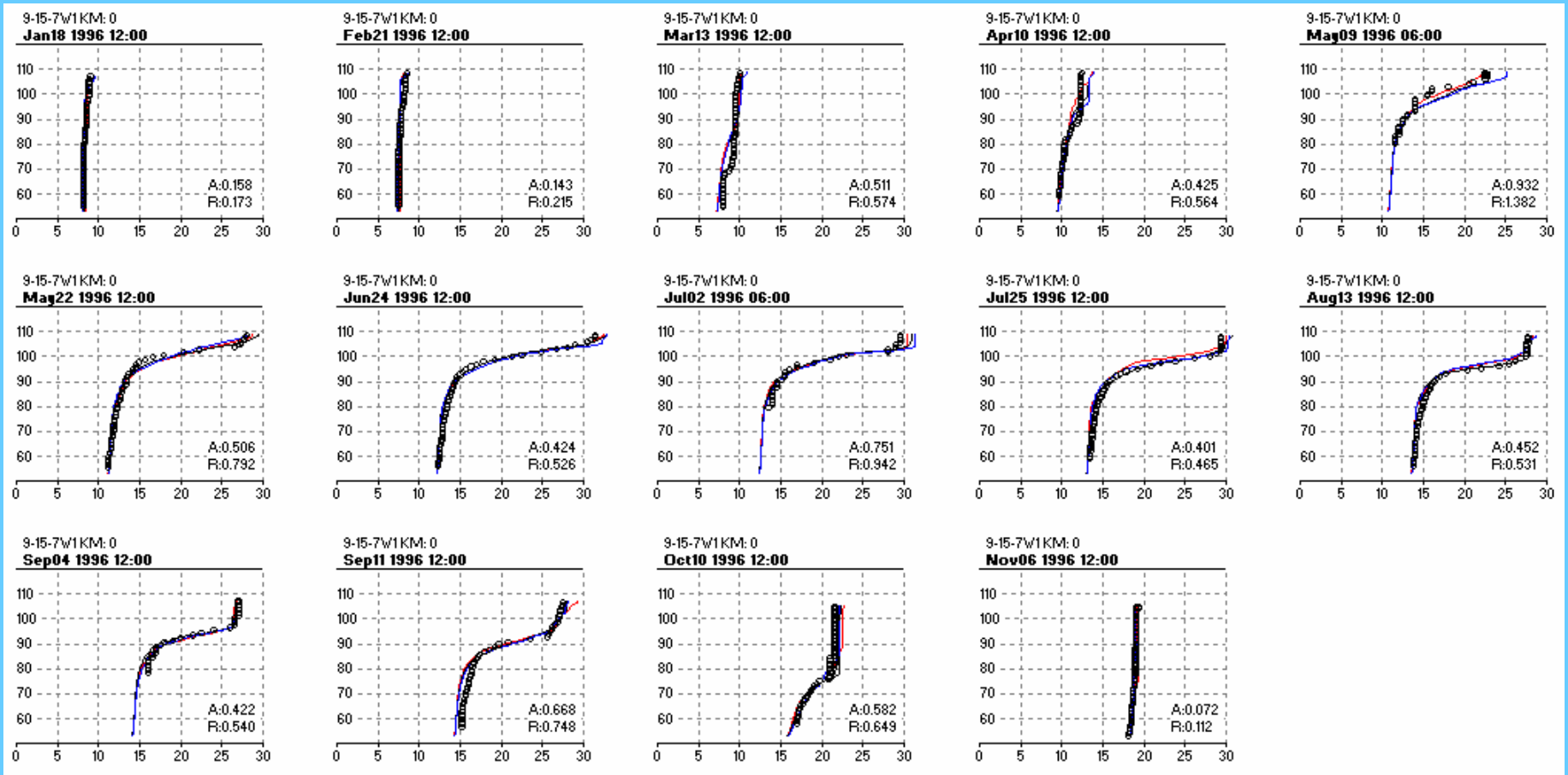
1997 Modeled and Measured Lake Murray Headwater Elevations



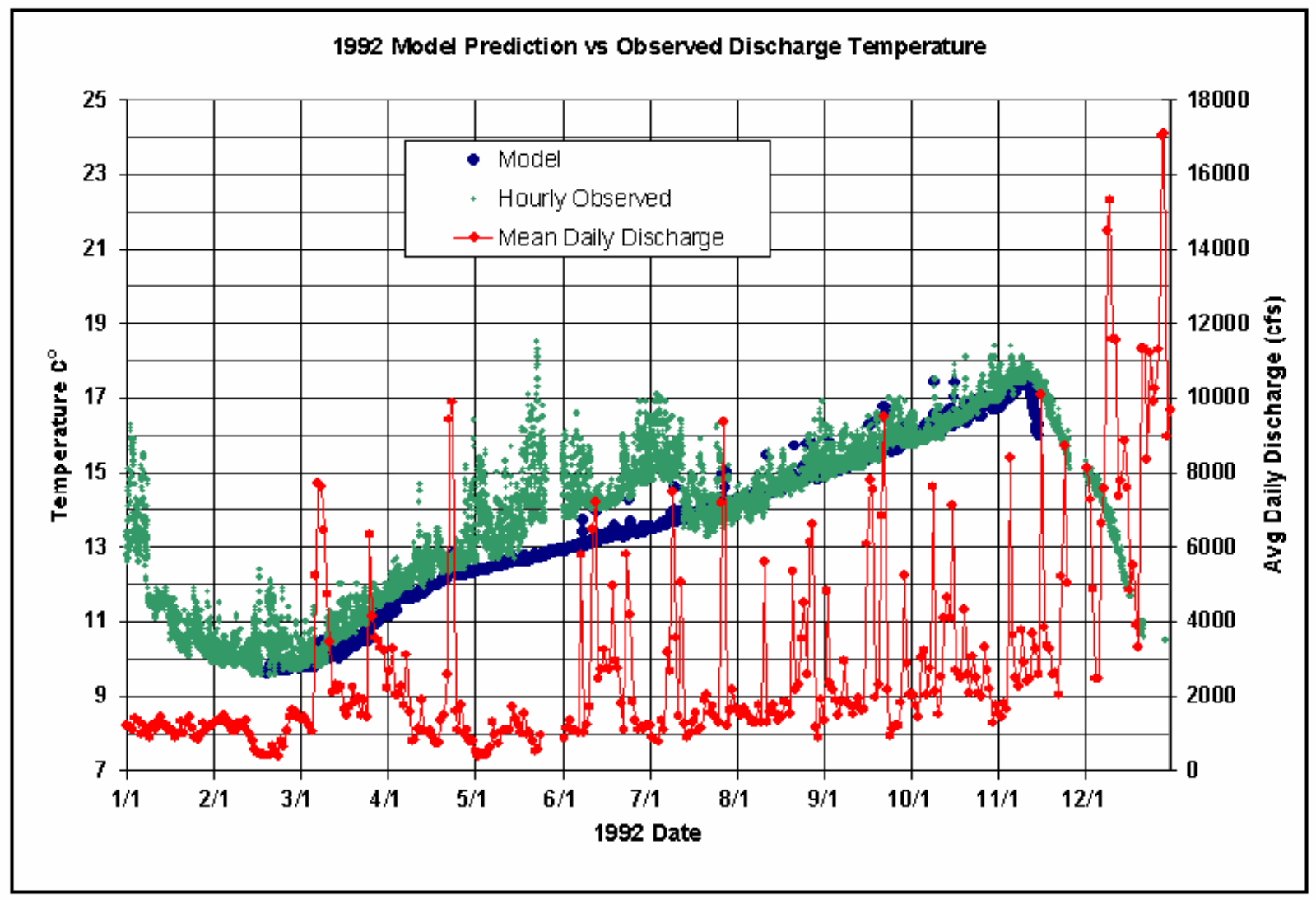
Primary Water Quality Calibration Locations



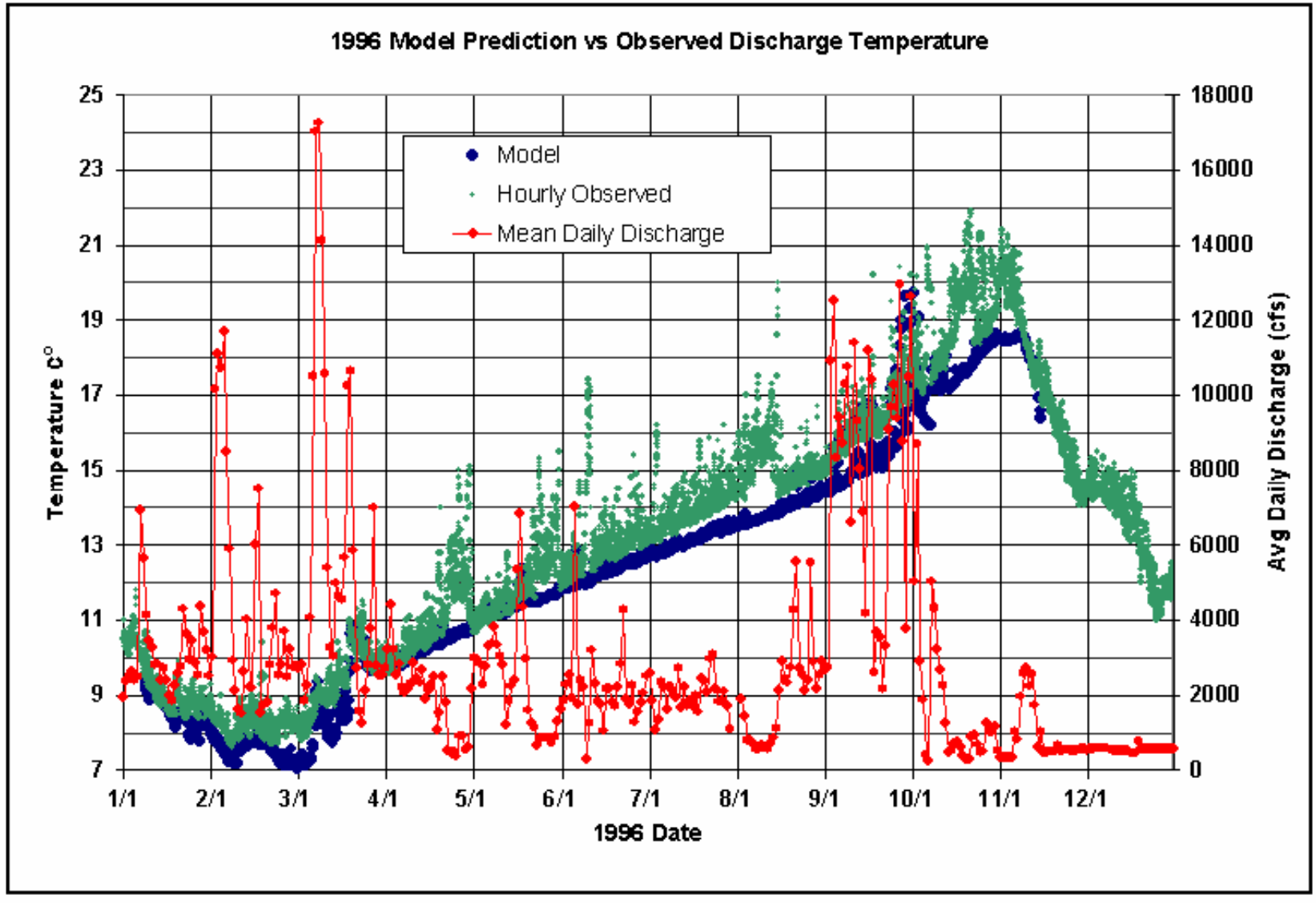
1996 Lake Murray Forebay Temperature Profiles
Model vs. Data



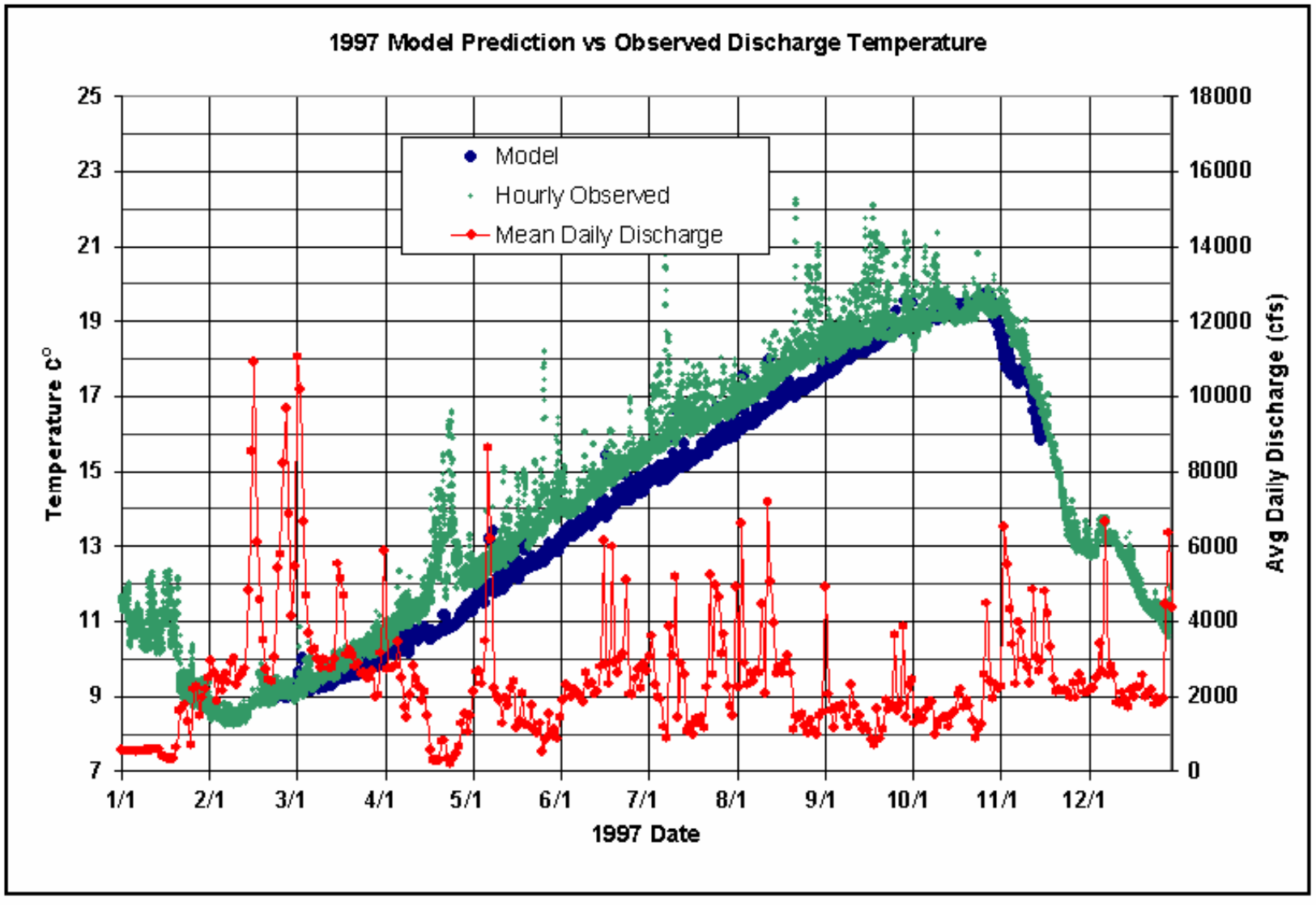
1992 Comparison of Modeled versus Measured Saluda Release Temperatures



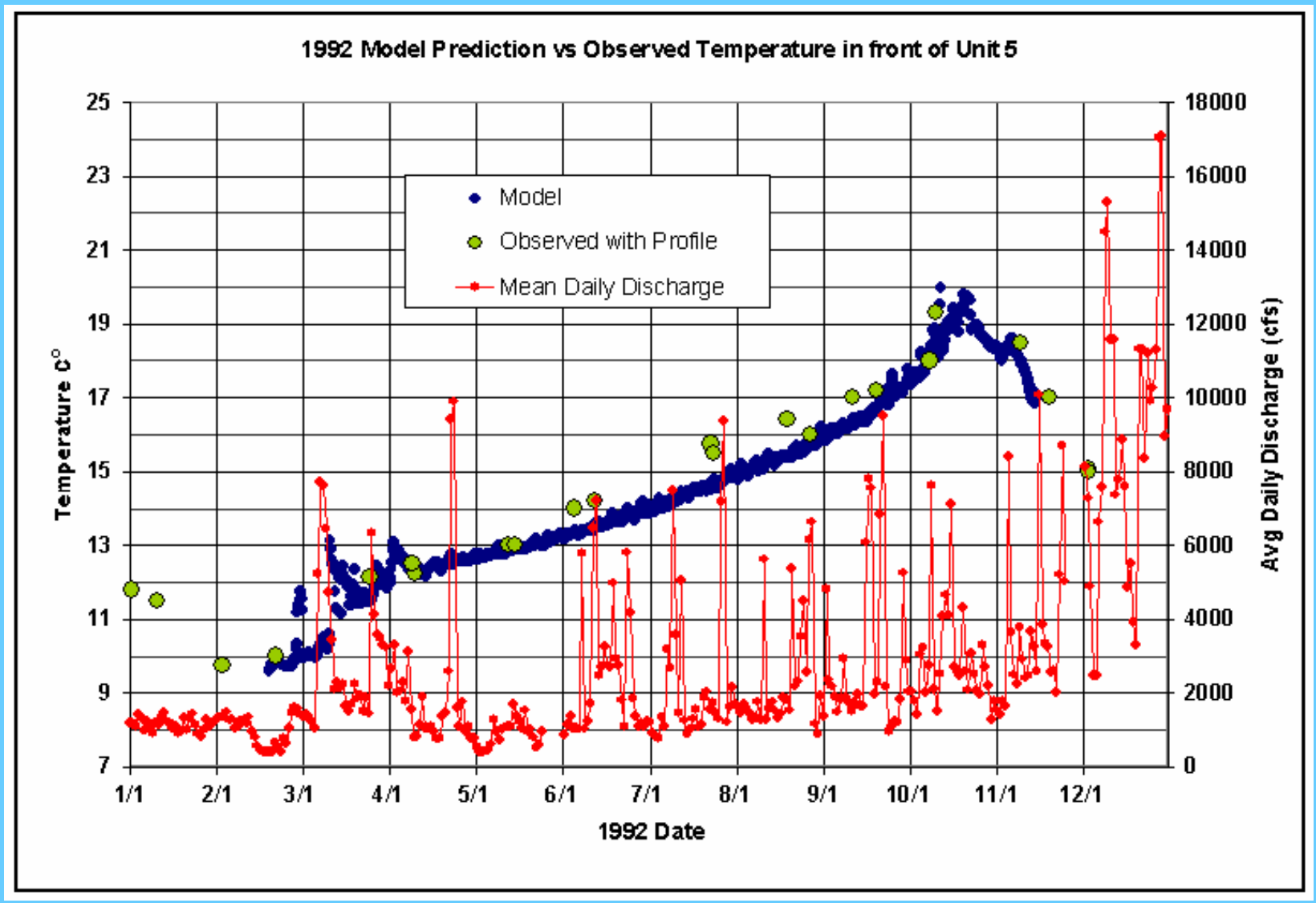
1996 Comparison of Modeled versus Measured Saluda Release Temperatures



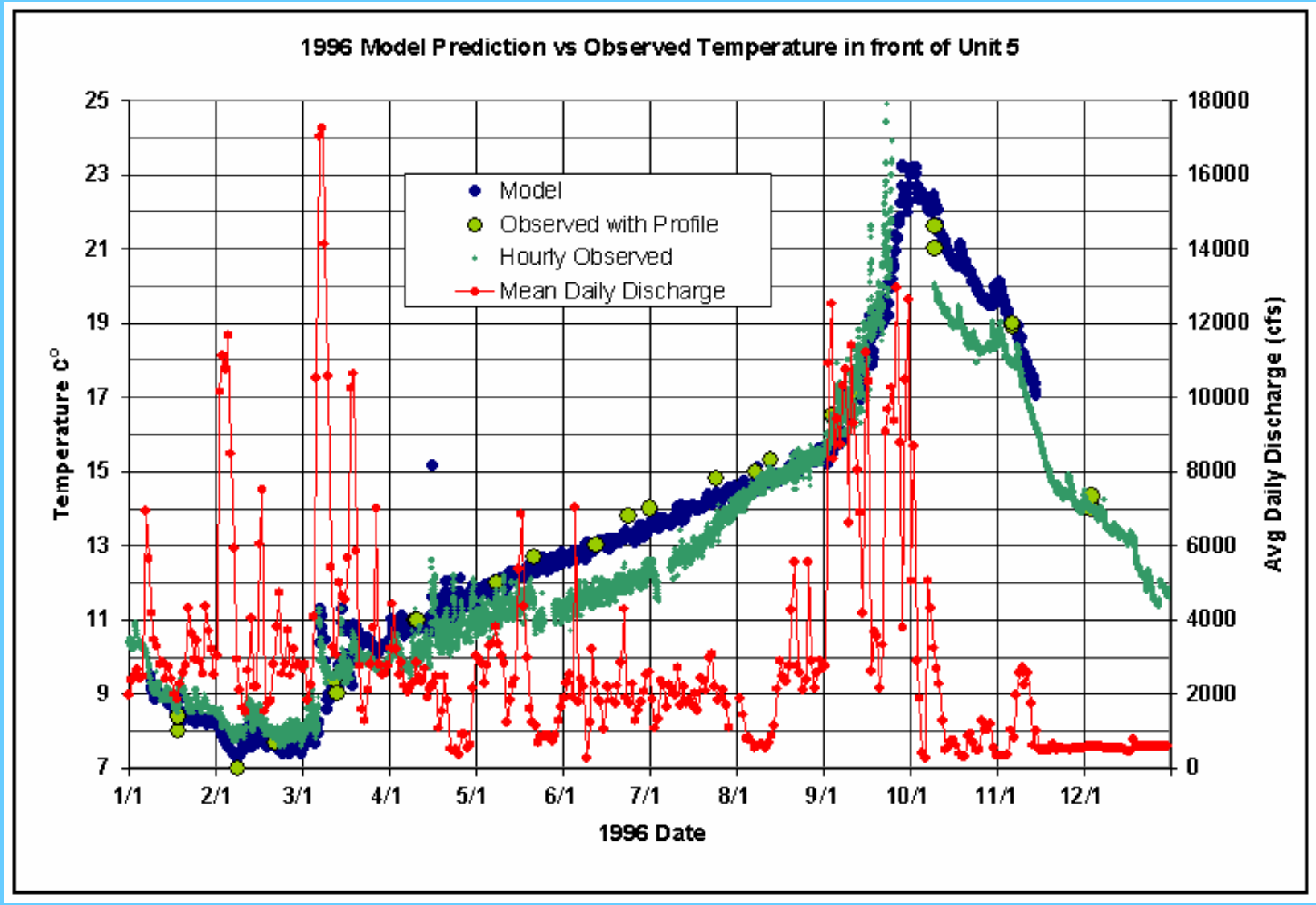
1997 Comparison of Modeled versus Measured Saluda Release Temperatures



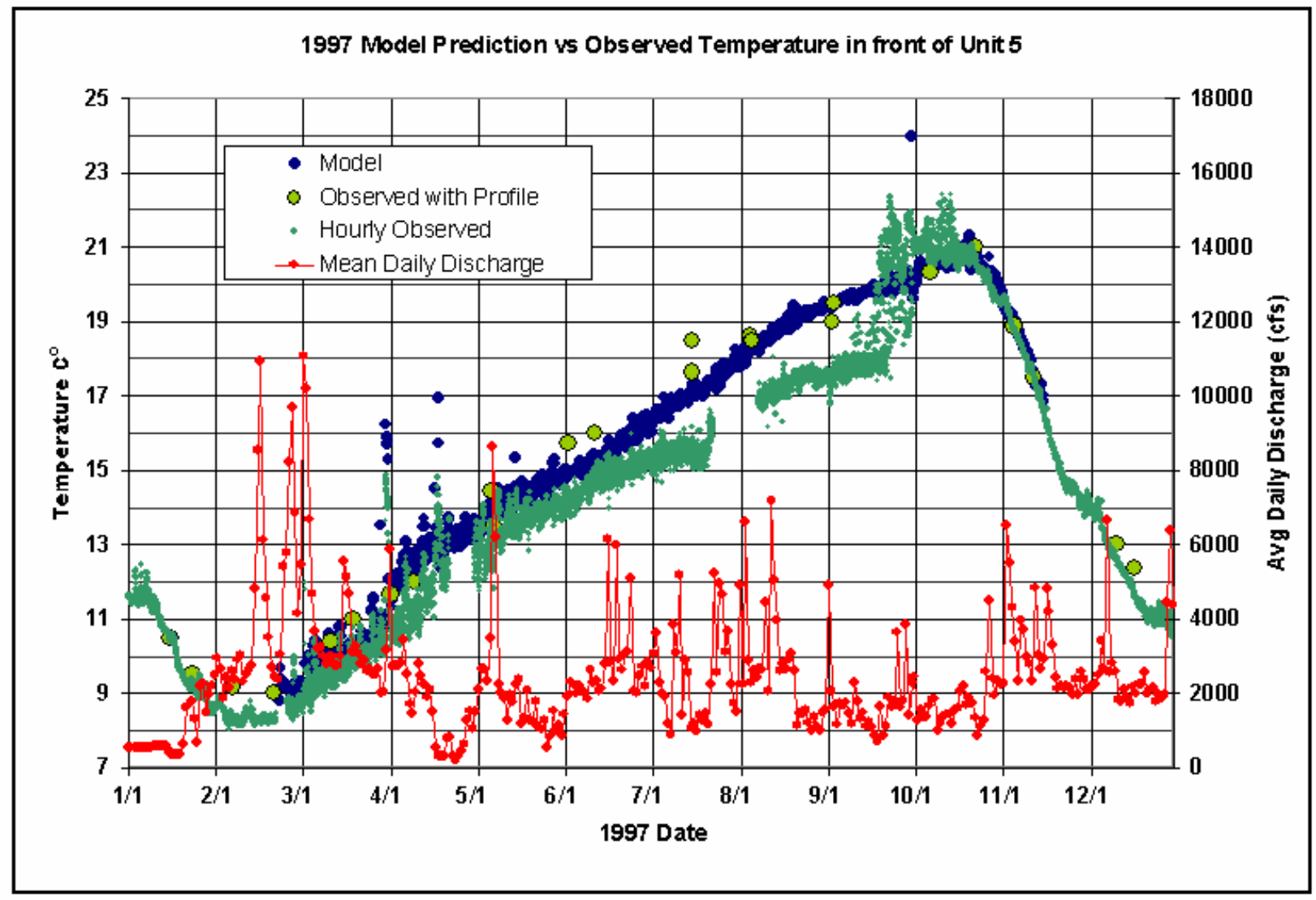
1992 Comparison of Modeled versus Measured Temperature in Front of the Unit 5 Intake



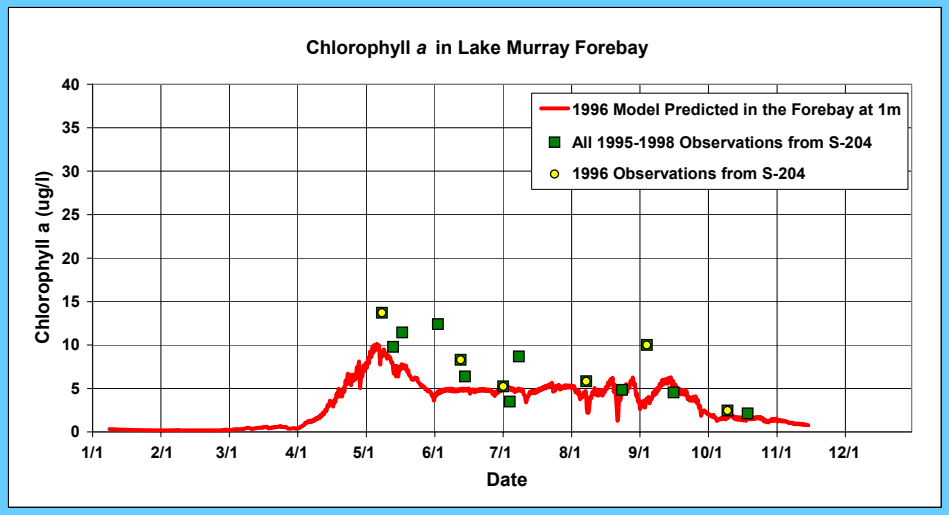
1996 Comparison of Modeled versus Measured Temperature in Front of the Unit 5 Intake

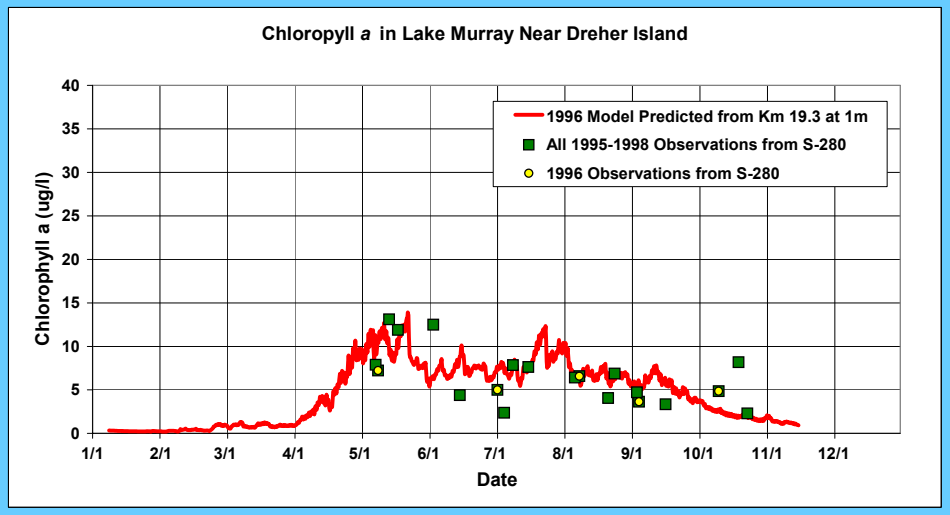


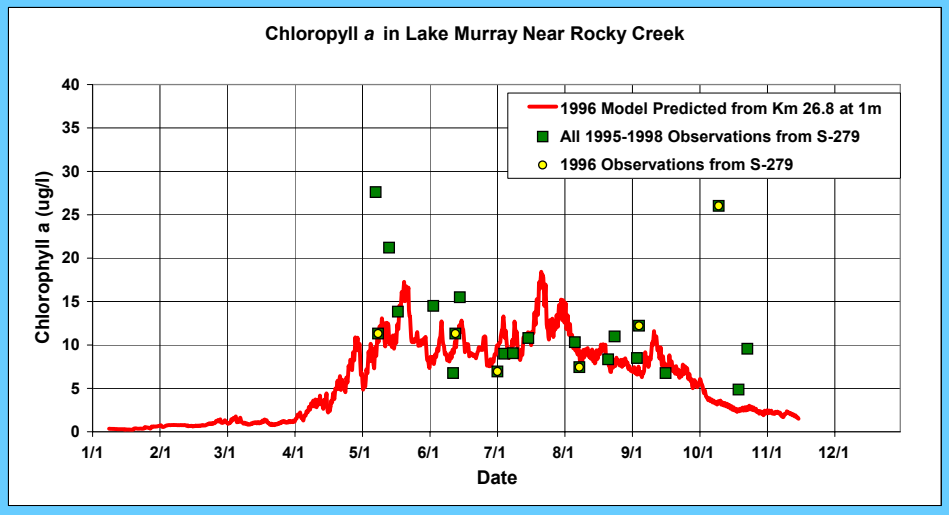
1997 Comparison of Modeled versus Measured Temperature in Front of the Unit 5 Intake

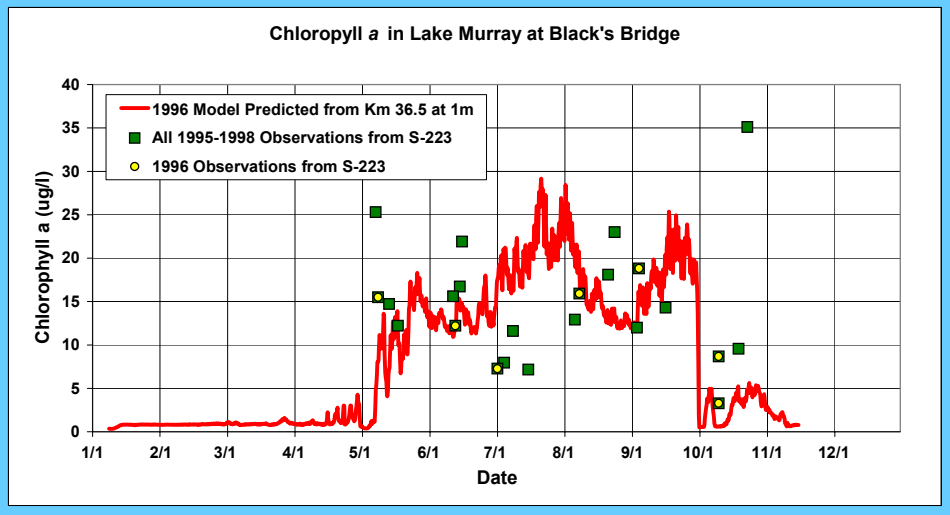


1996 Chlorophyll *a* at Four Locations in Lake Murray Model vs. Data

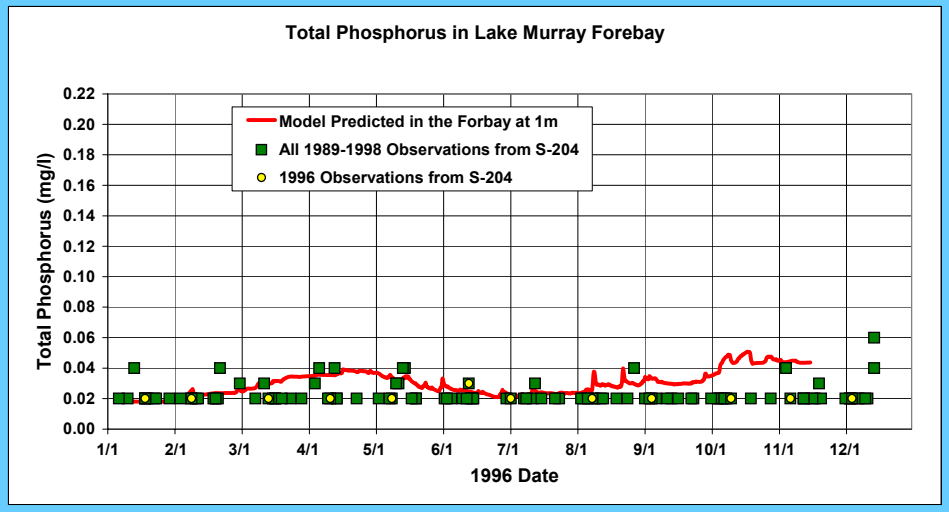


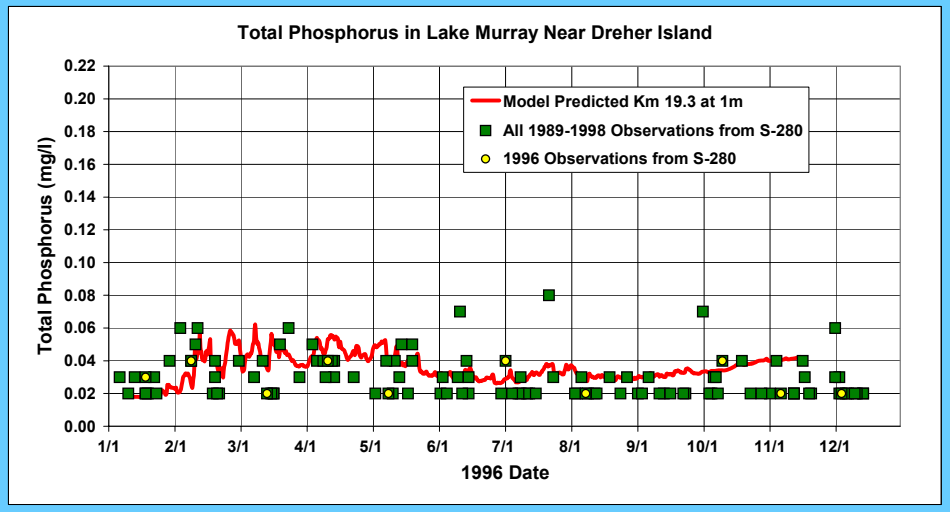


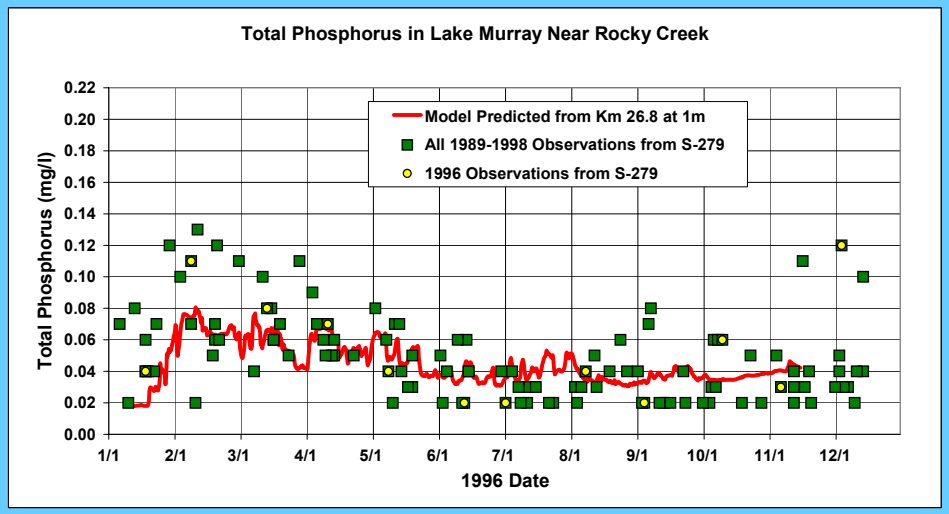


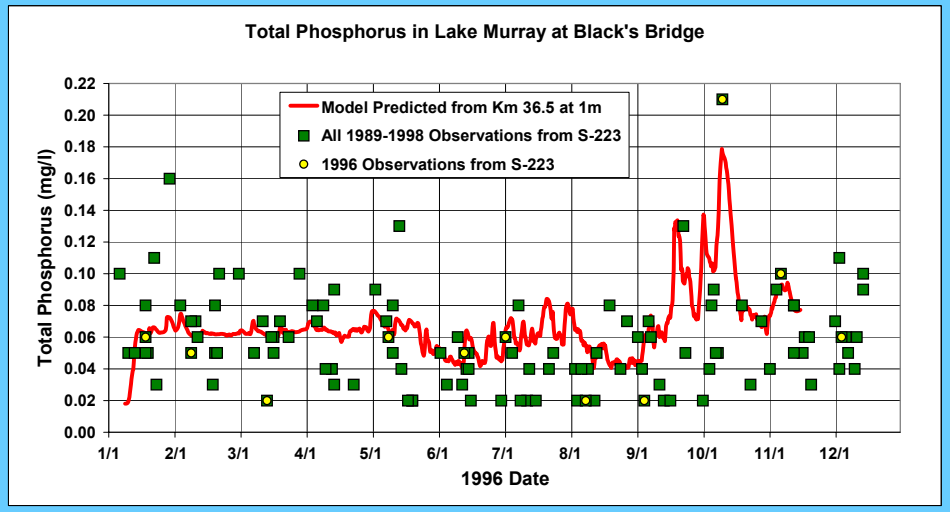


Comparison of Modeled Derived versus Measured Total Phosphorus for 1996 at Four Locations in Lake Murray

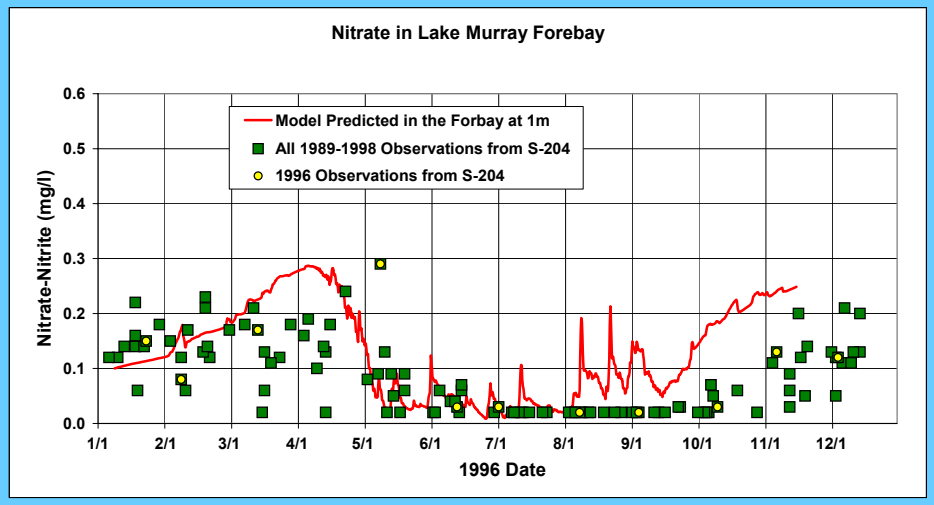


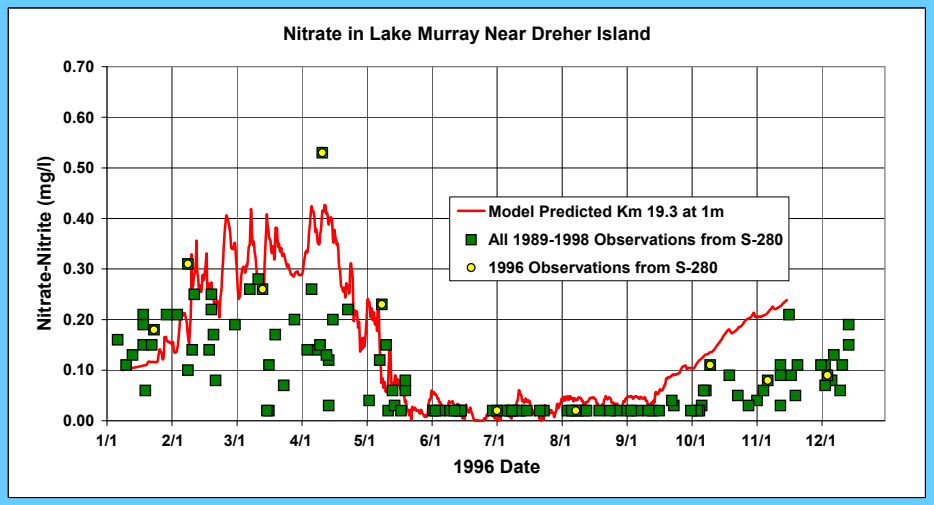


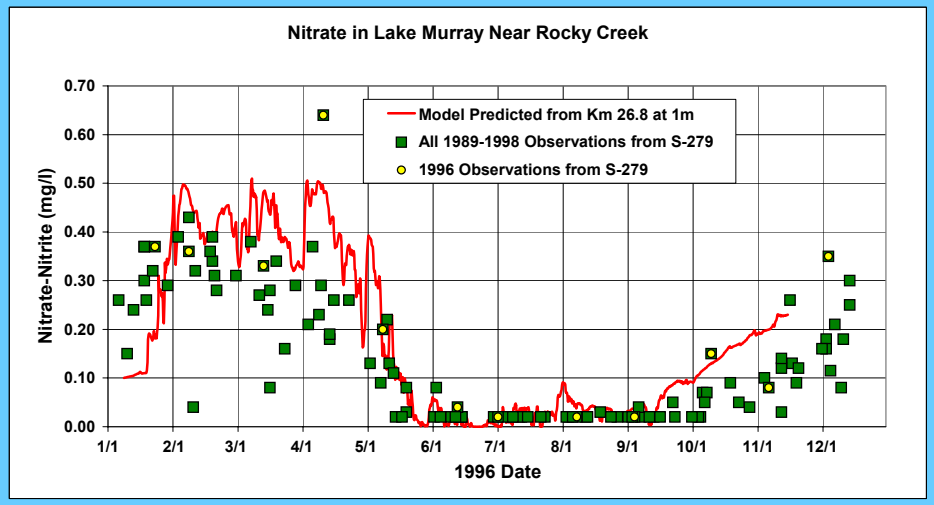


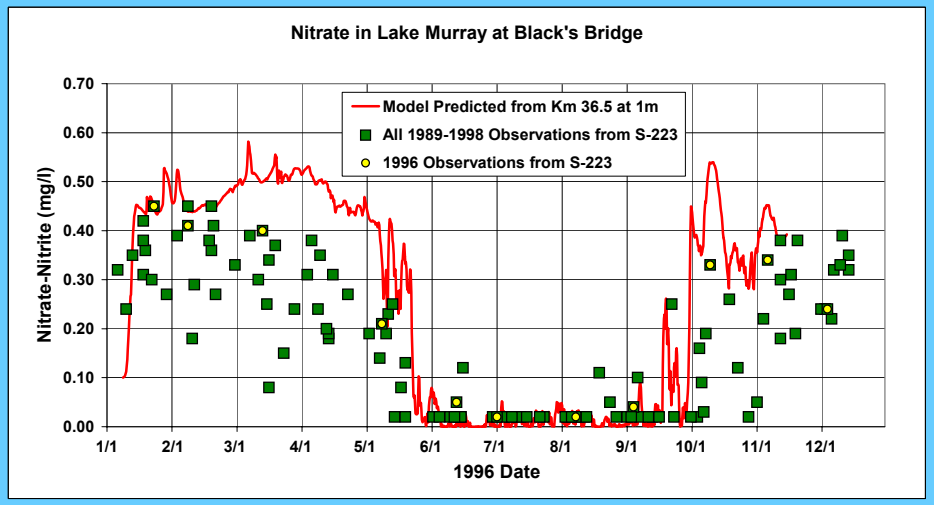


Comparison of Modeled versus Measured Nitrate for 1996 at Four Locations in Lake Murray

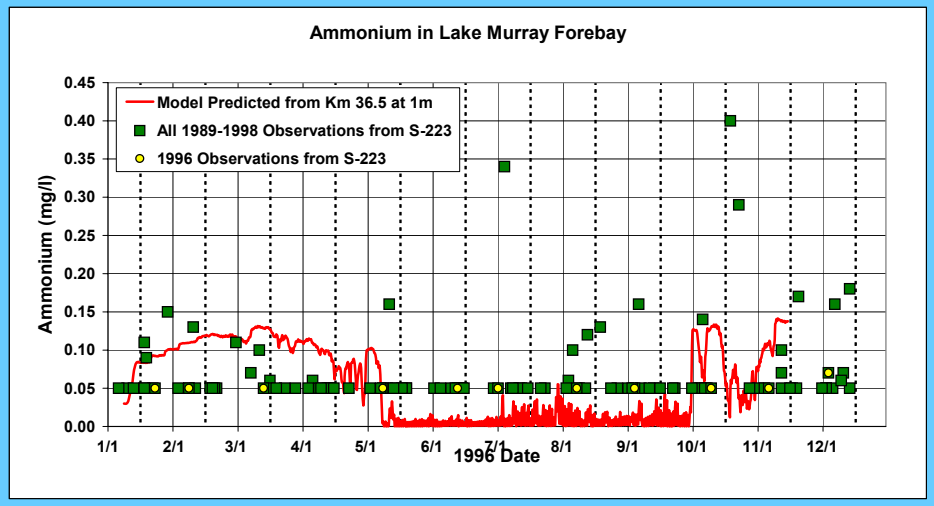


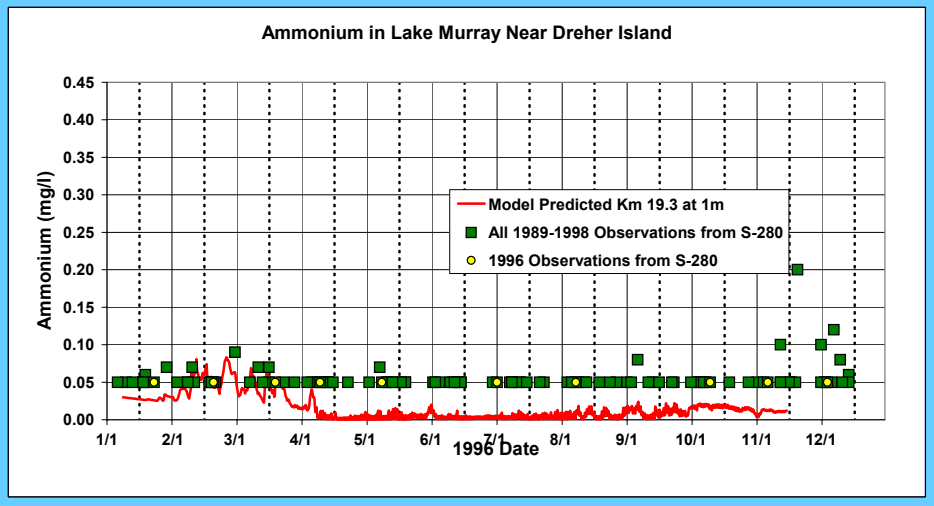


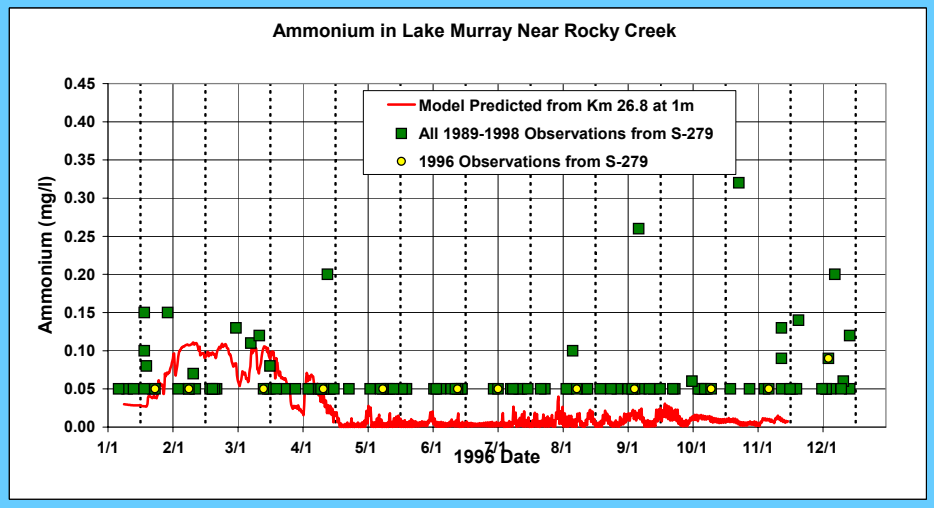


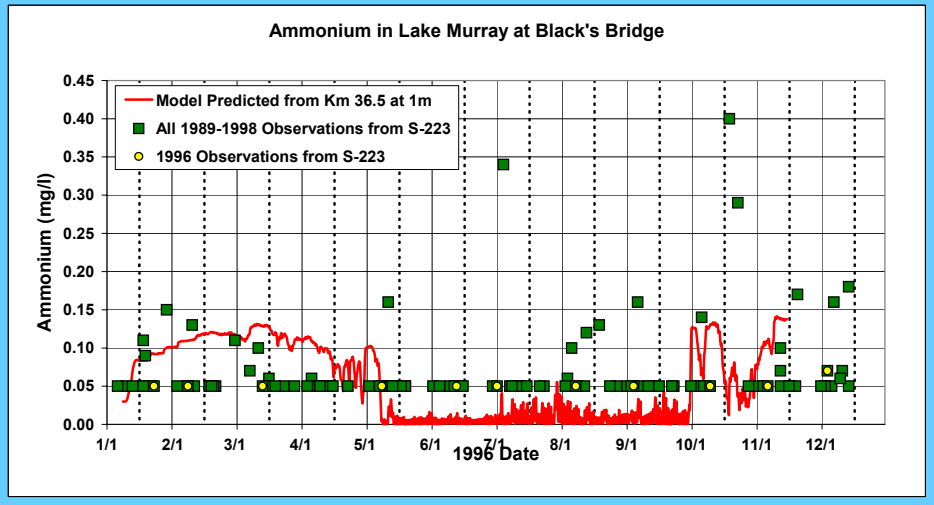


Comparison of Modeled versus Measured Ammonium for 1996 at Four Locations in Lake Murray

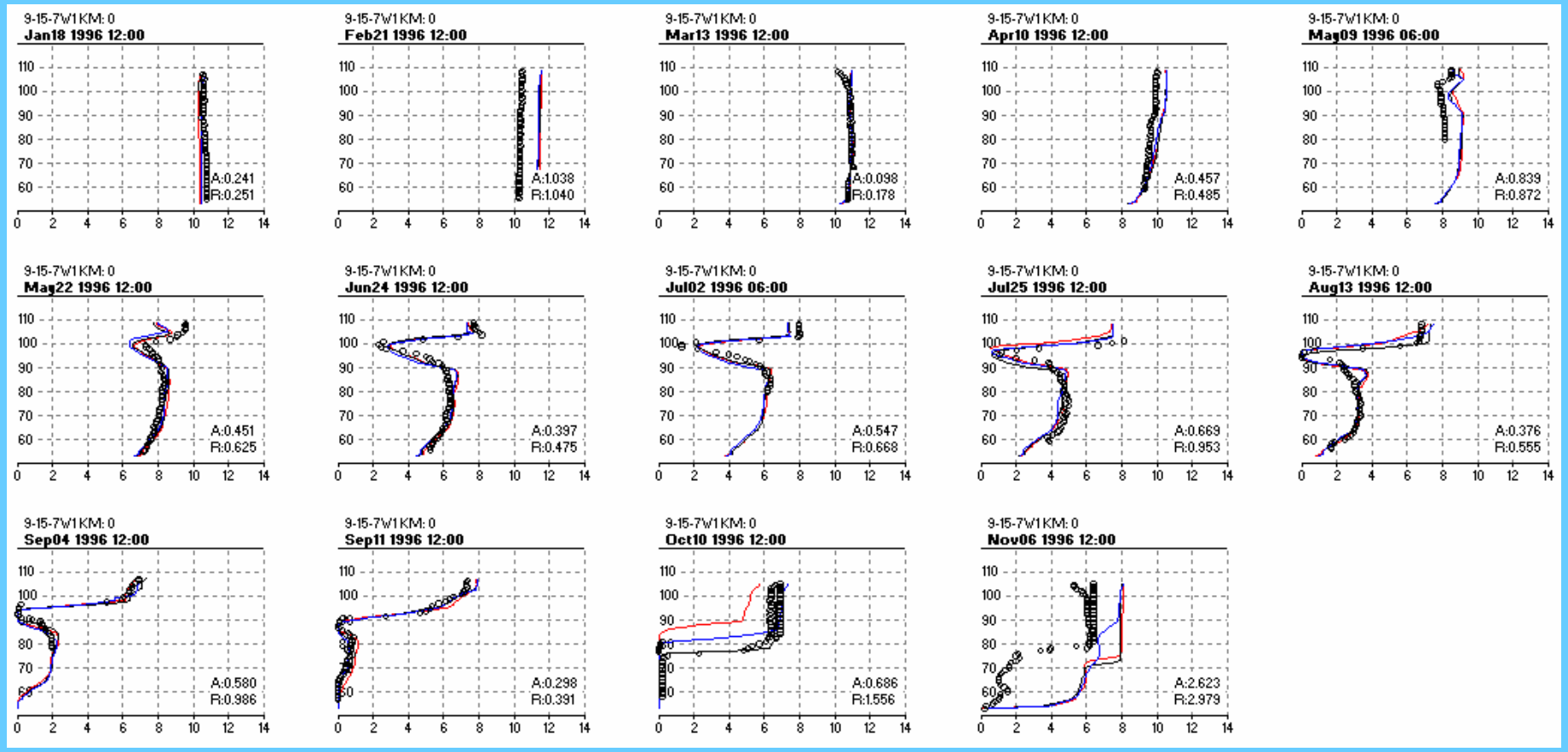




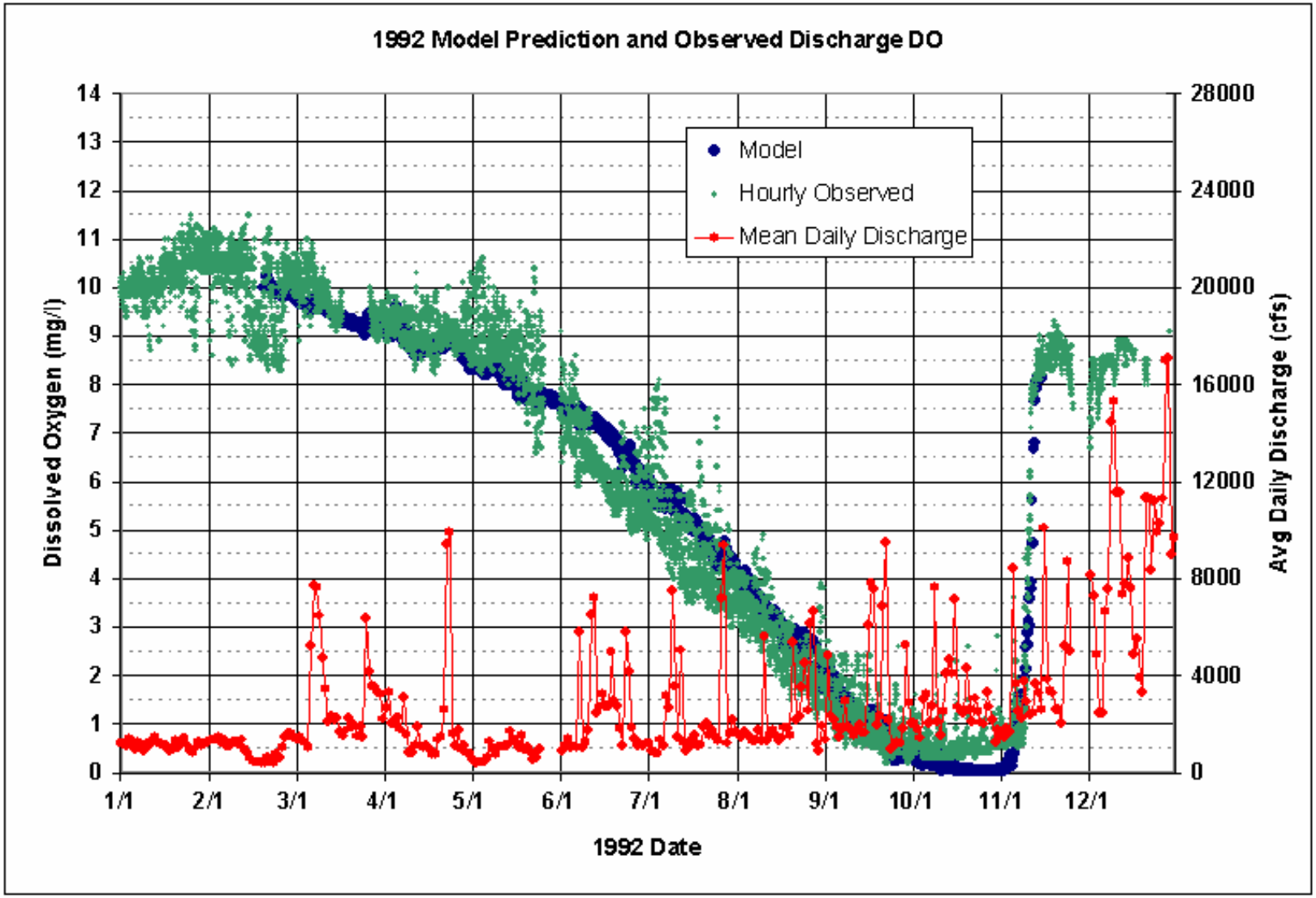




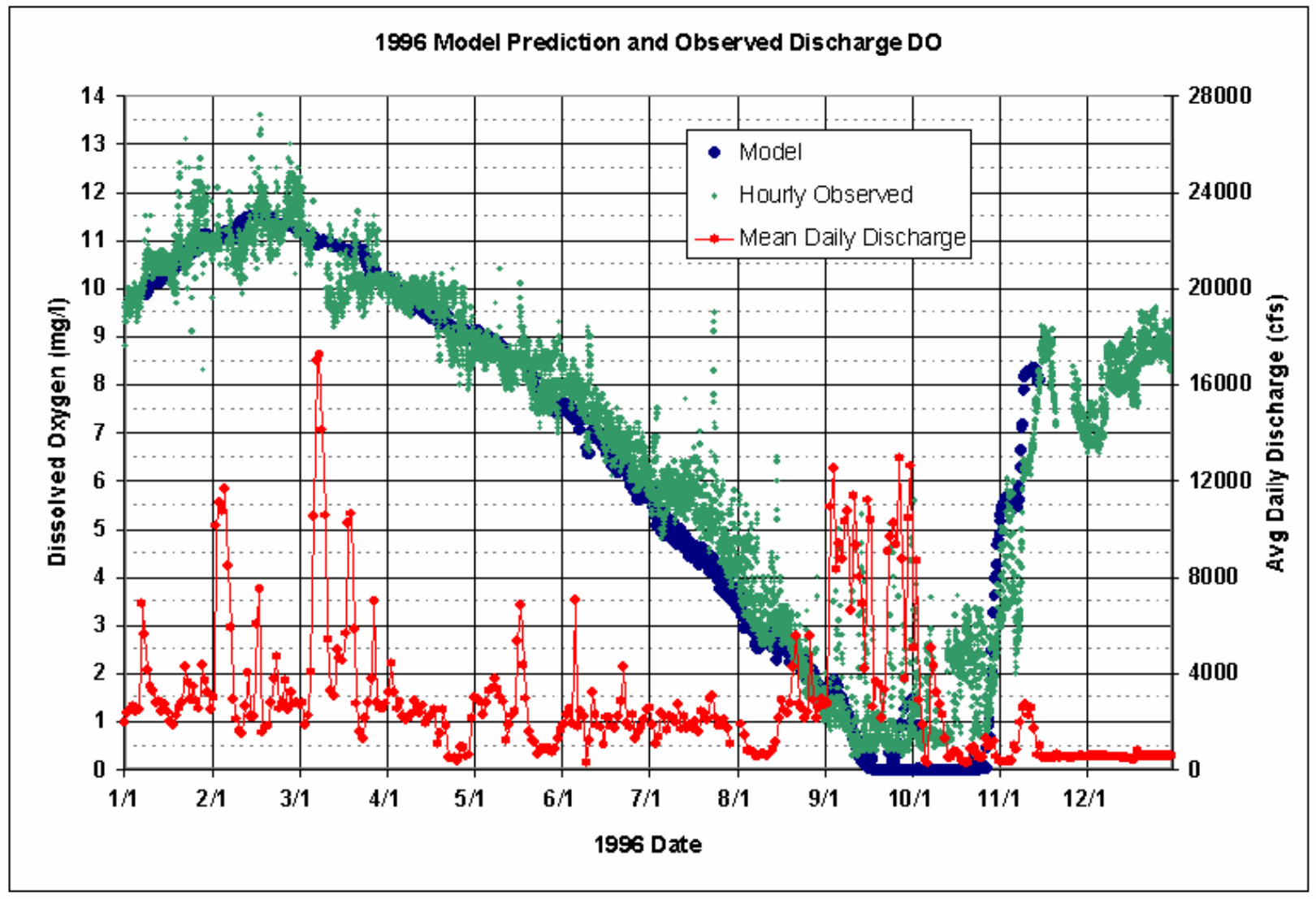
1996 Lake Murray Forebay Dissolved Oxygen Profiles Model vs. Data



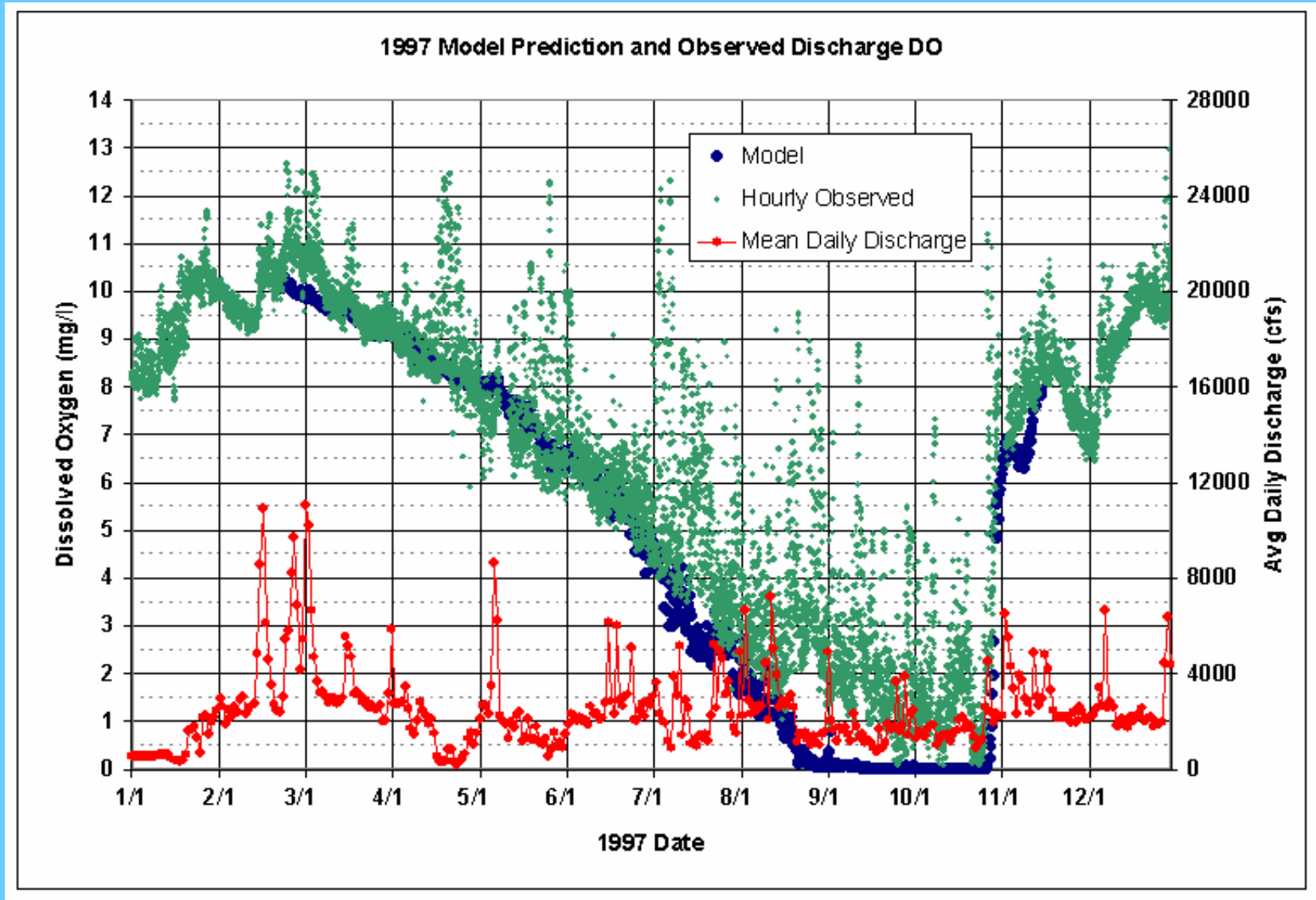
1992 Comparison of Modeled versus Measured Saluda Release DO



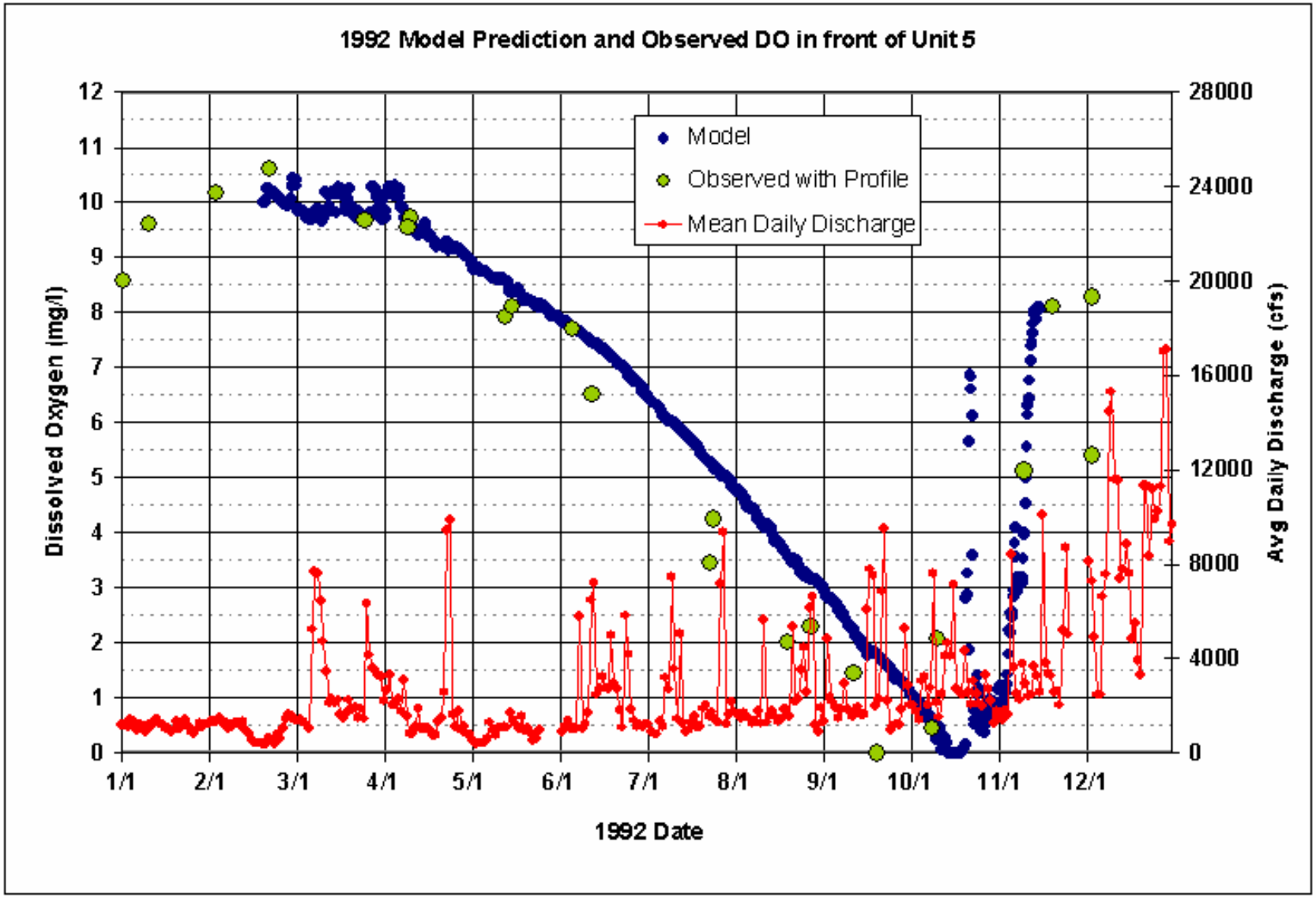
1996 Comparison of Modeled versus Measured Saluda Release DO



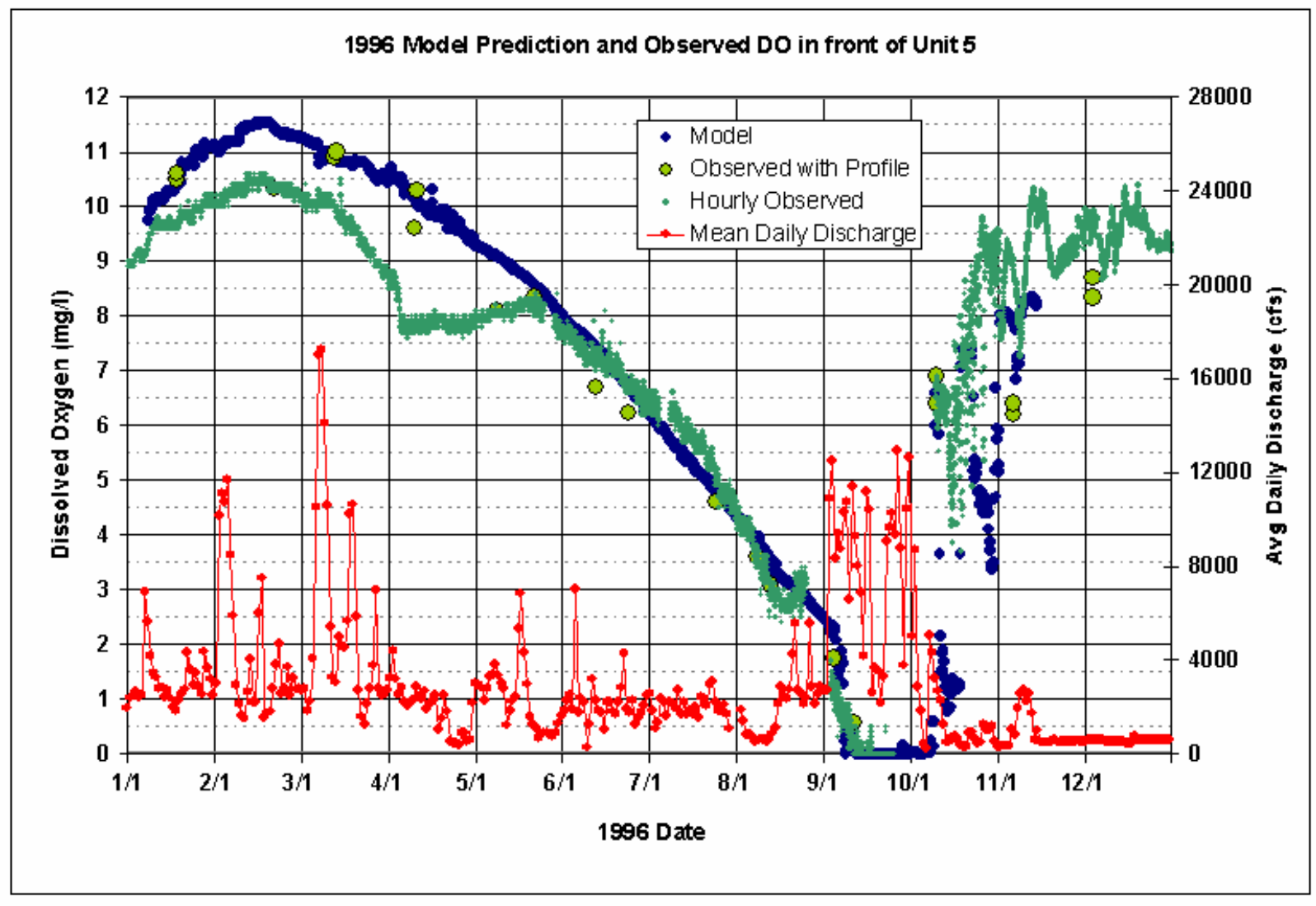
1997 Comparison of Modeled versus Measured Saluda Release DO



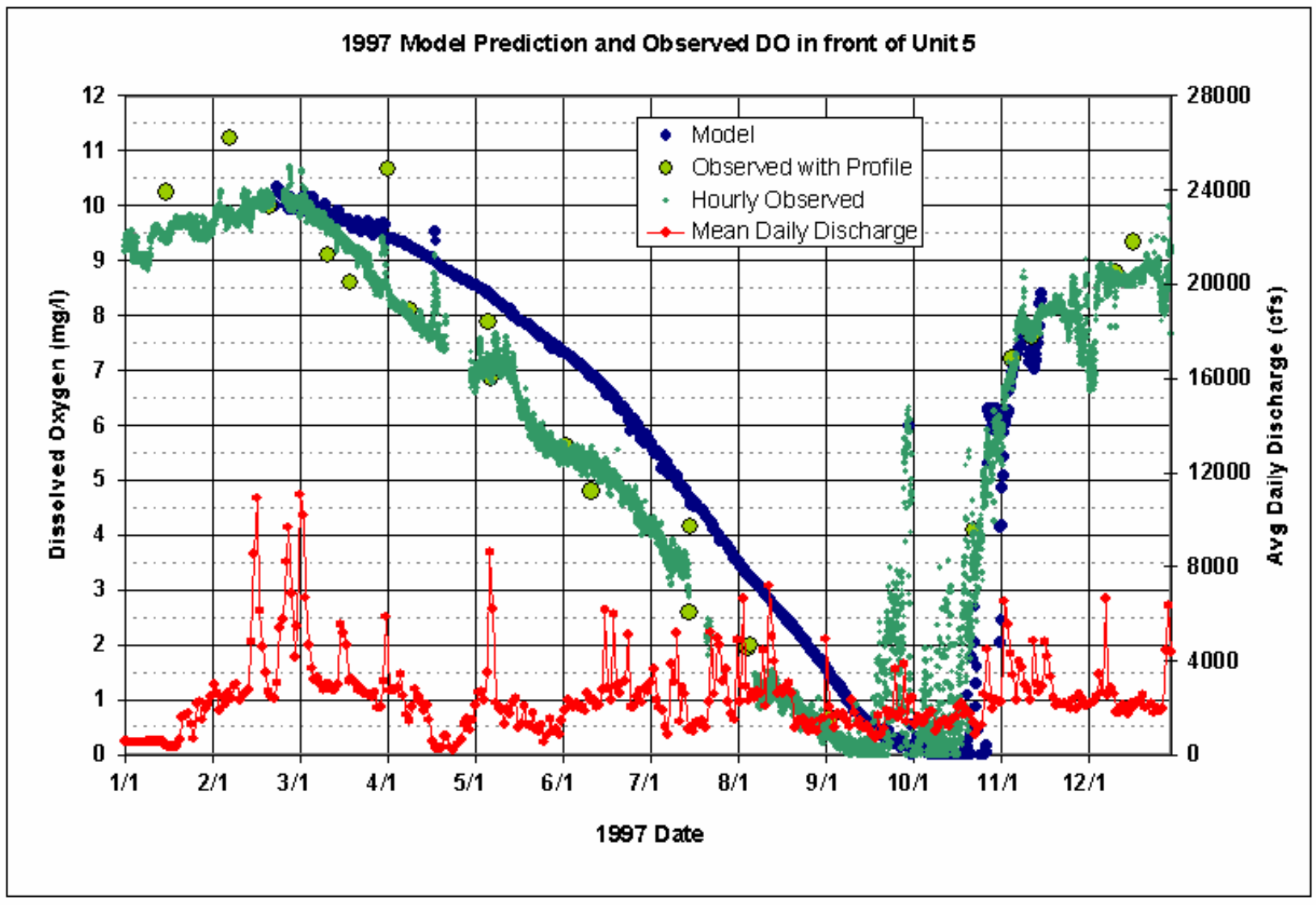
1992 Modeled versus Measured DO at the level of the Unit 5 Intake



1996 Modeled versus Measured DO at the level of the Unit 5 Intake



1997 Modeled versus Measured DO at the level of the Unit 5 Intake



1996 Statistics

1996 Temperature

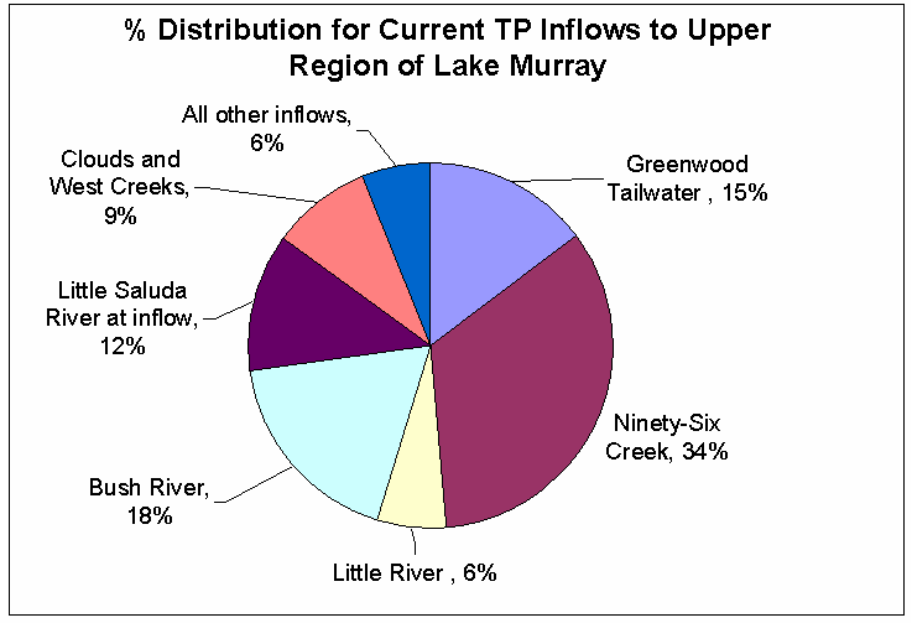
		Kilometers From Dam									
		0.0		2.5		12.3		19.3		Average	
Date	Julian Day	AME	RMS	AME	RMS	AME	RMS	AME	RMS	AME	RMS
2/21-22	52-53	0.14	0.22	0.12	0.13	0.25	0.47	0.22	0.44	**0.18**	**0.32**
3/13-14	73-74	0.51	0.57	0.47	0.51	0.48	0.52	0.52	0.70	**0.50**	**0.58**
4/10-11	101-103	0.43	0.56	0.43	0.51	0.50	0.60	0.46	0.60	**0.45**	**0.57**
5/22-23	143-144	0.51	0.79			0.69	1.03	0.63	0.85	**0.61**	**0.89**
6/24-25	176-177	0.42	0.53	0.46	0.69	0.43	0.63	0.54	0.80	**0.47**	**0.66**
7/25-26	207-208	0.40	0.47	0.60	0.73	0.67	0.94	0.61	0.75	**0.57**	**0.72**
8/13-14	226-227	0.45	0.53	0.40	0.47	0.45	0.63	0.76	1.09	**0.52**	**0.68**
9/11-13	255-257	0.67	0.75	0.56	0.62	0.39	0.52	0.17	0.21	**0.45**	**0.52**
10/9-10	283-284	0.58	0.65	0.50	0.57	0.91	0.99	0.83	0.90	**0.71**	**0.78**
11/5-6	310-311	0.07	0.11	0.17	0.18	0.19	0.22	0.04	0.05	**0.12**	**0.14**
		0.42	**0.52**	**0.41**	**0.49**	**0.50**	**0.65**	**0.48**	**0.64**	0.45	0.57

1996 DO

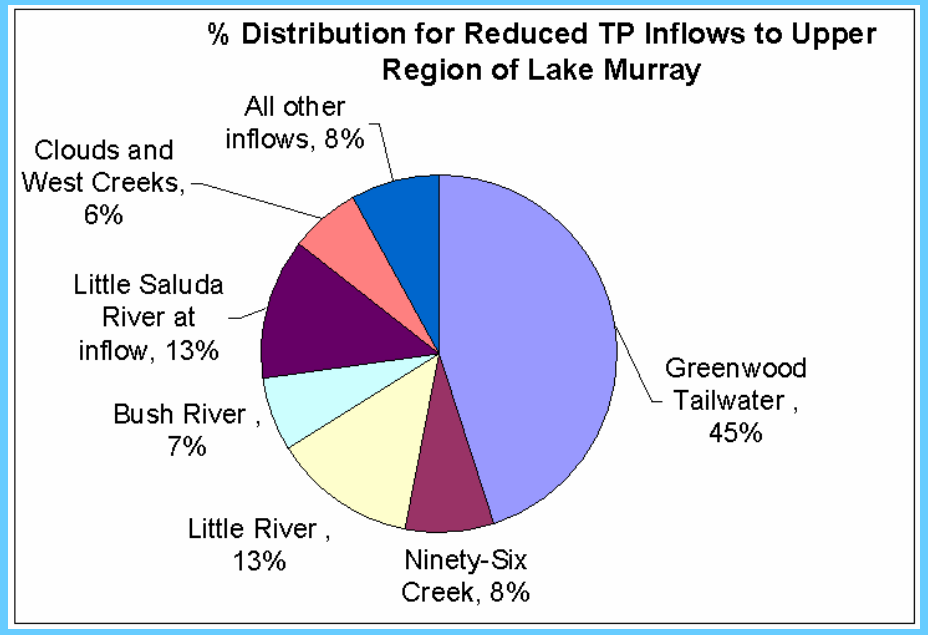
		Kilometers From Dam									
		0.0		2.5		12.3		19.3		Average	
Date	Julian Day	AME	RMS	AME	RMS	AME	RMS	AME	RMS	AME	RMS
2/21-22	52-53	1.04	1.04	1.04	1.04	0.62	0.67	0.78	0.82	**0.87**	**0.89**
3/13-14	73-74	0.10	0.18	0.21	0.23	0.24	0.28	0.48	0.56	**0.26**	**0.31**
4/10-11	101-103	0.46	0.49	0.56	0.59	0.82	0.88	1.10	1.21	**0.73**	**0.79**
5/22-23	143-144	0.45	0.63			0.39	0.44	0.74	0.85	**0.53**	**0.64**
6/24-25	176-177	0.40	0.48	0.75	0.87	0.62	0.74	0.64	0.92	**0.60**	**0.75**
7/25-26	207-208	0.67	0.95	1.01	1.27	0.49	0.73	0.91	0.99	**0.77**	**0.98**
8/13-14	226-227	0.38	0.56	0.82	0.98	0.50	0.62	0.62	1.20	**0.58**	**0.84**
9/11-13	255-257	0.30	0.39	0.24	0.45	0.60	0.93	0.79	1.12	**0.48**	**0.72**
10/9-10	283-284	0.69	1.56	0.93	1.52	0.83	0.90	1.36	1.37	**0.95**	**1.34**
		0.50	**0.70**	**0.69**	**0.87**	**0.57**	**0.69**	**0.82**	**1.00**	0.65	0.81

Distribution of TP Loads to the Upper Region of Lake Murray

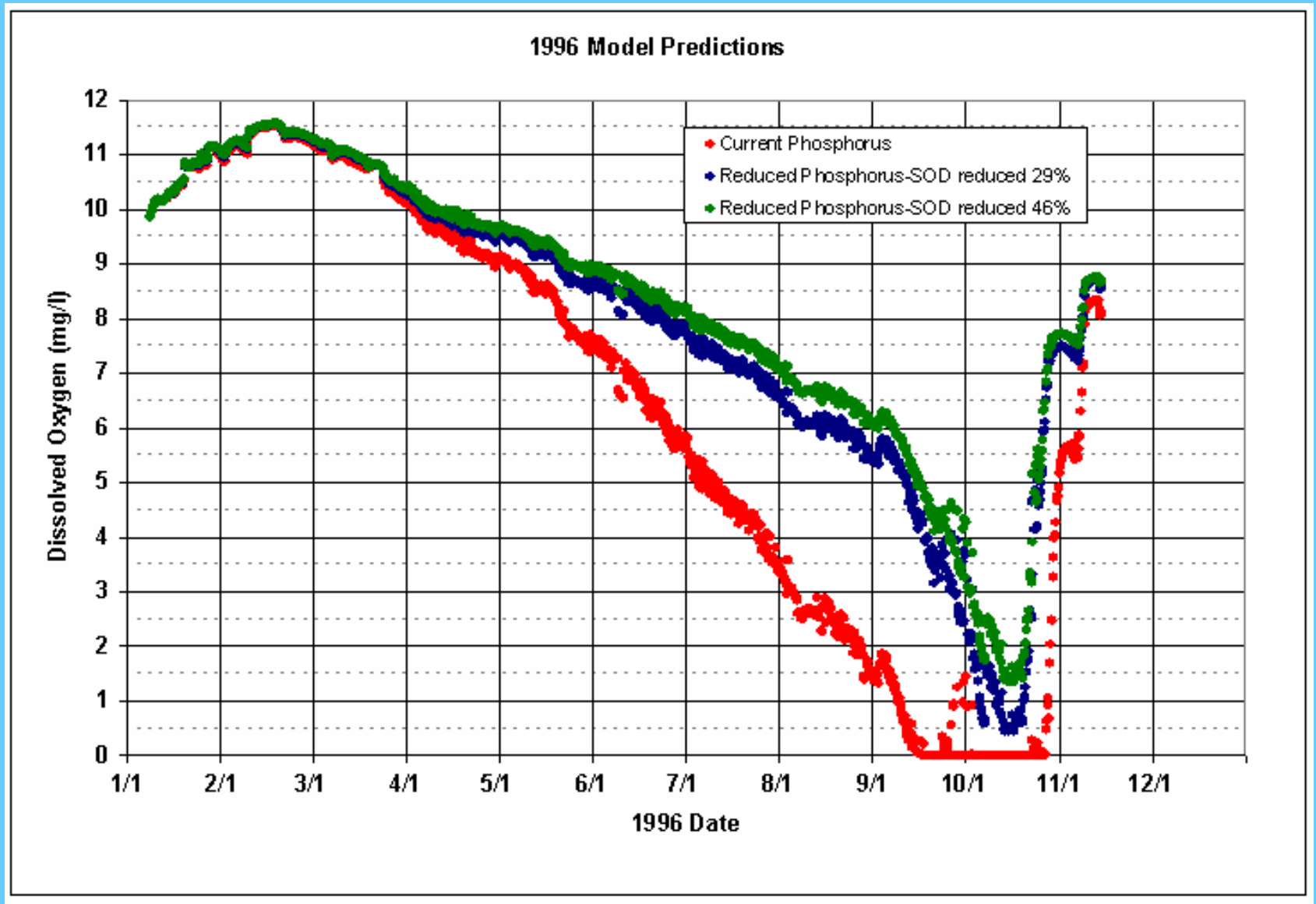
Current



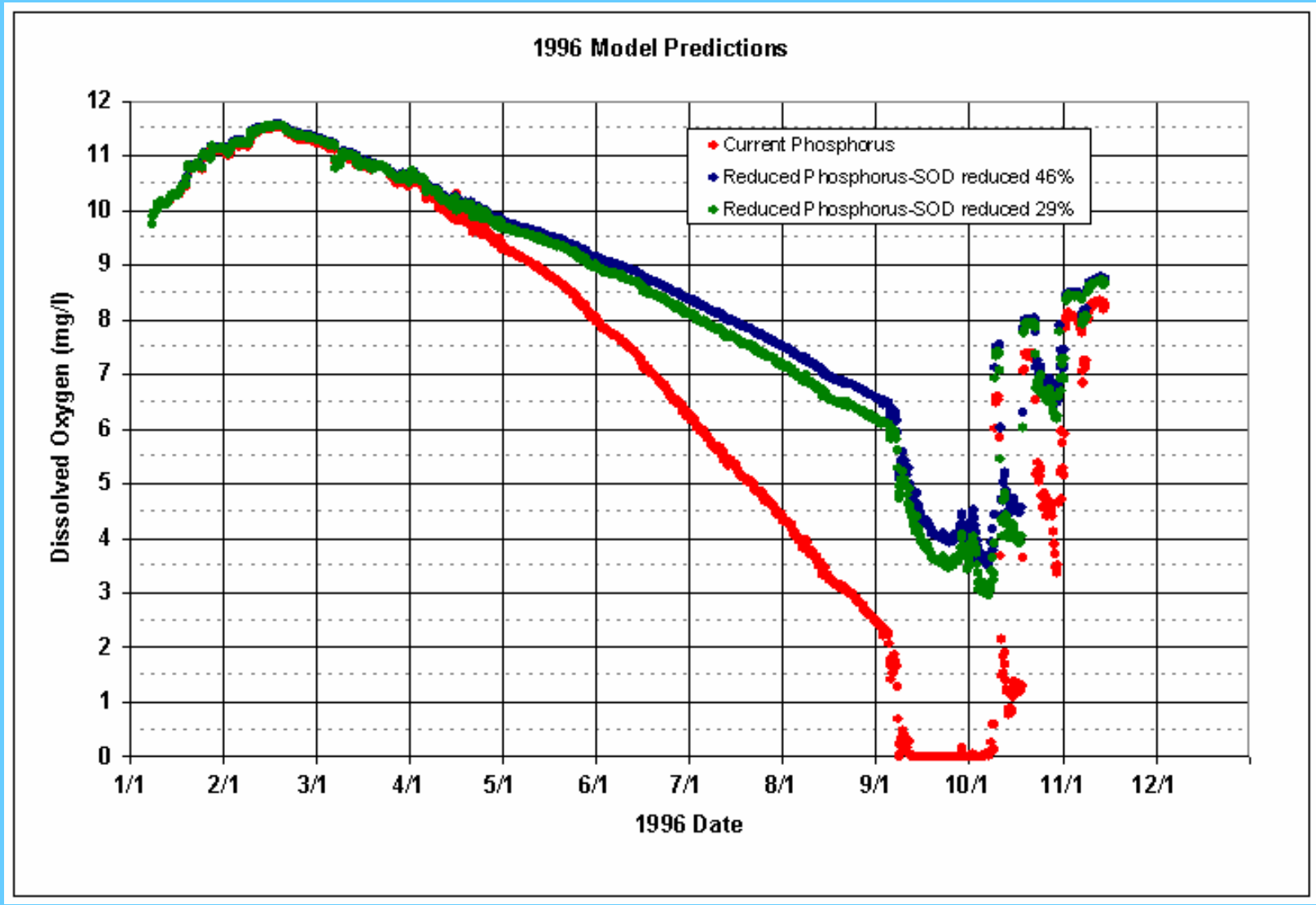
Assumed Reductions in TP



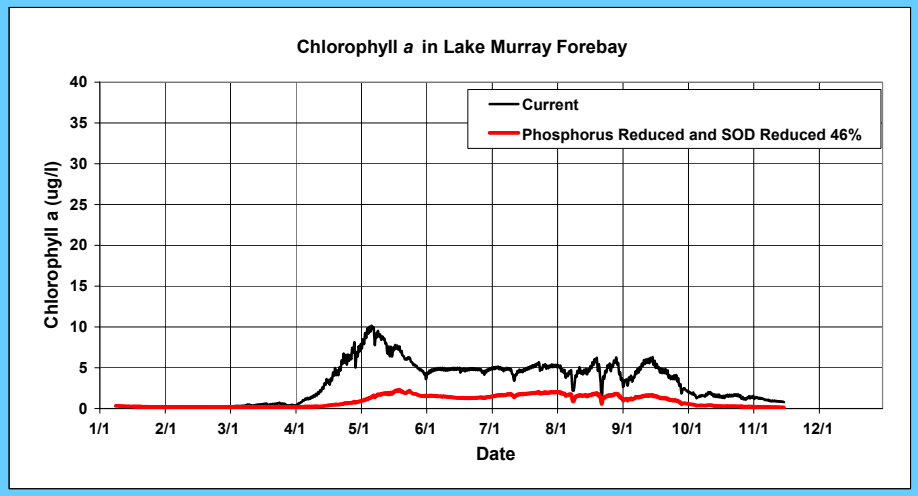
1996 Discharge DO for Current Phosphorus Loads and Two Scenarios for Reduced Phosphorus

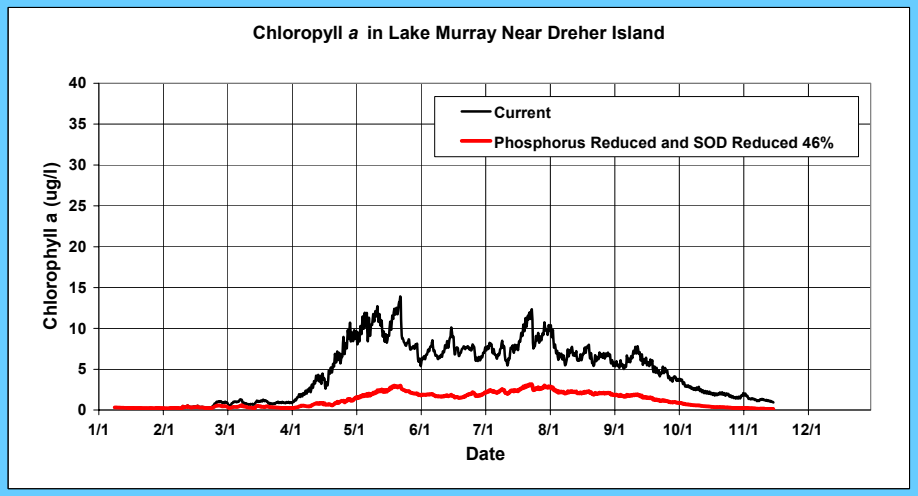


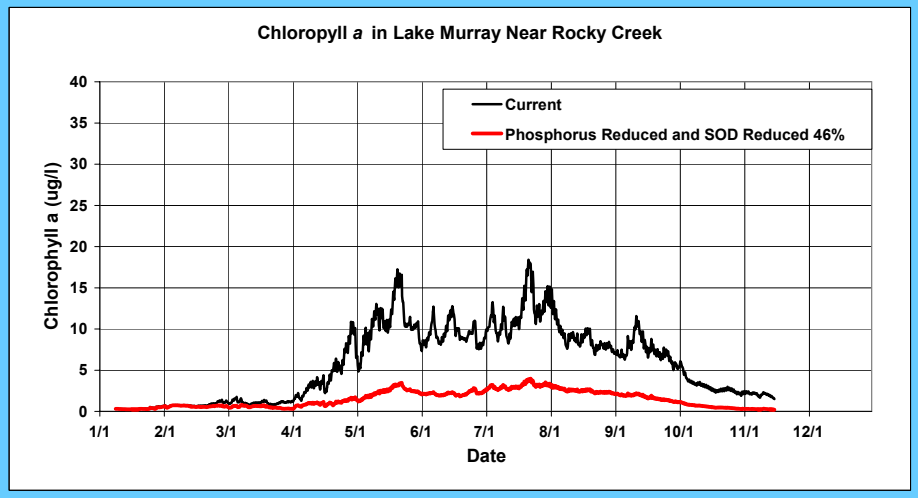
1996 DO at the Level of the Unit 5 Intake for Current and Reduced Phosphorus

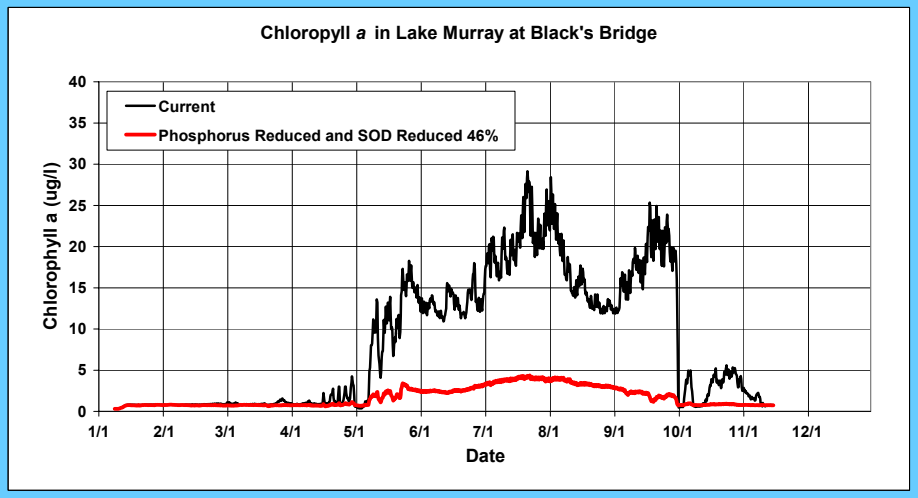


Comparison of 1996 Current and Reduced Phosphorus Predictions of Chlorophyll *a* at 1 Meter Depth at Four Locations in Lake Murray





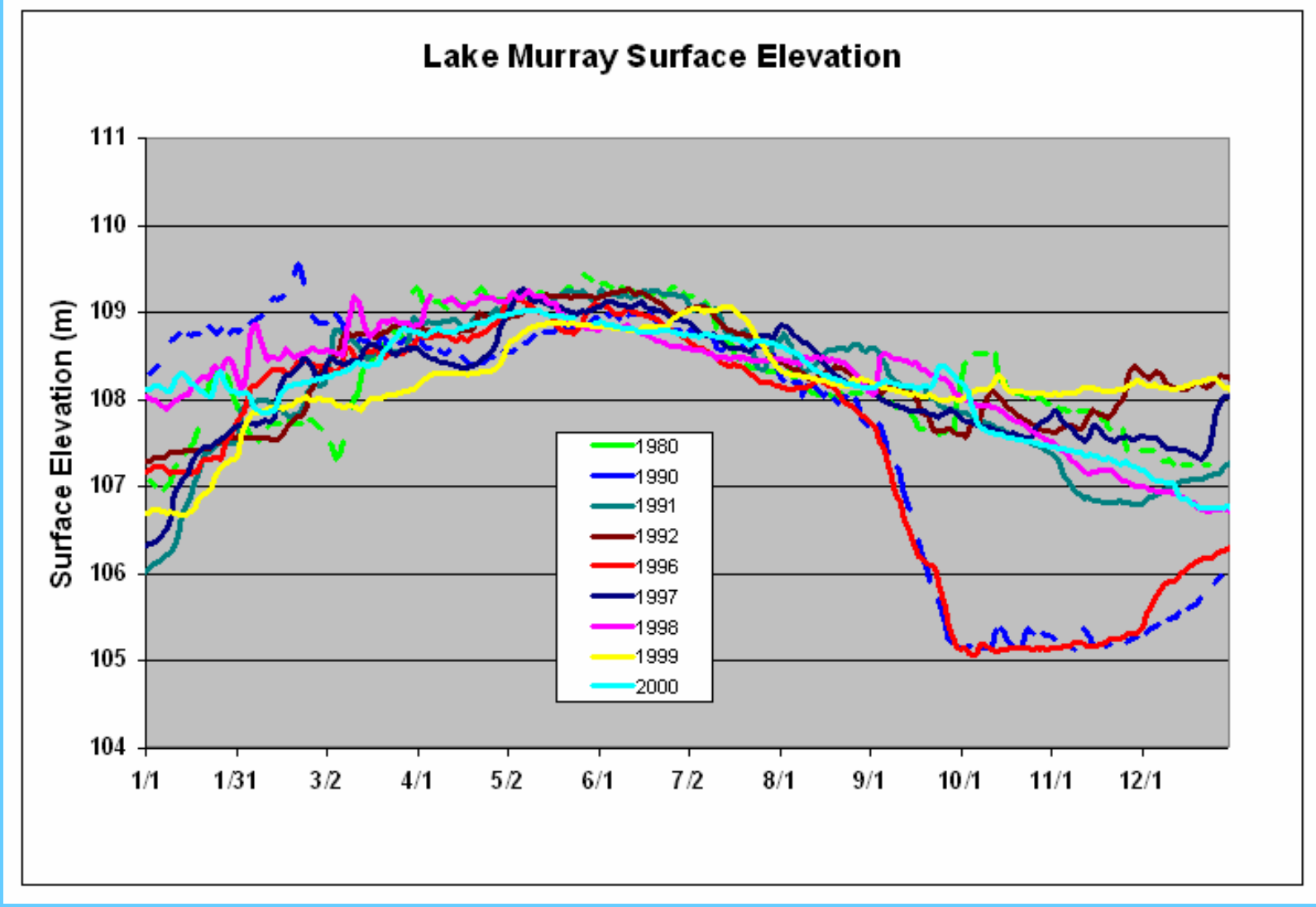




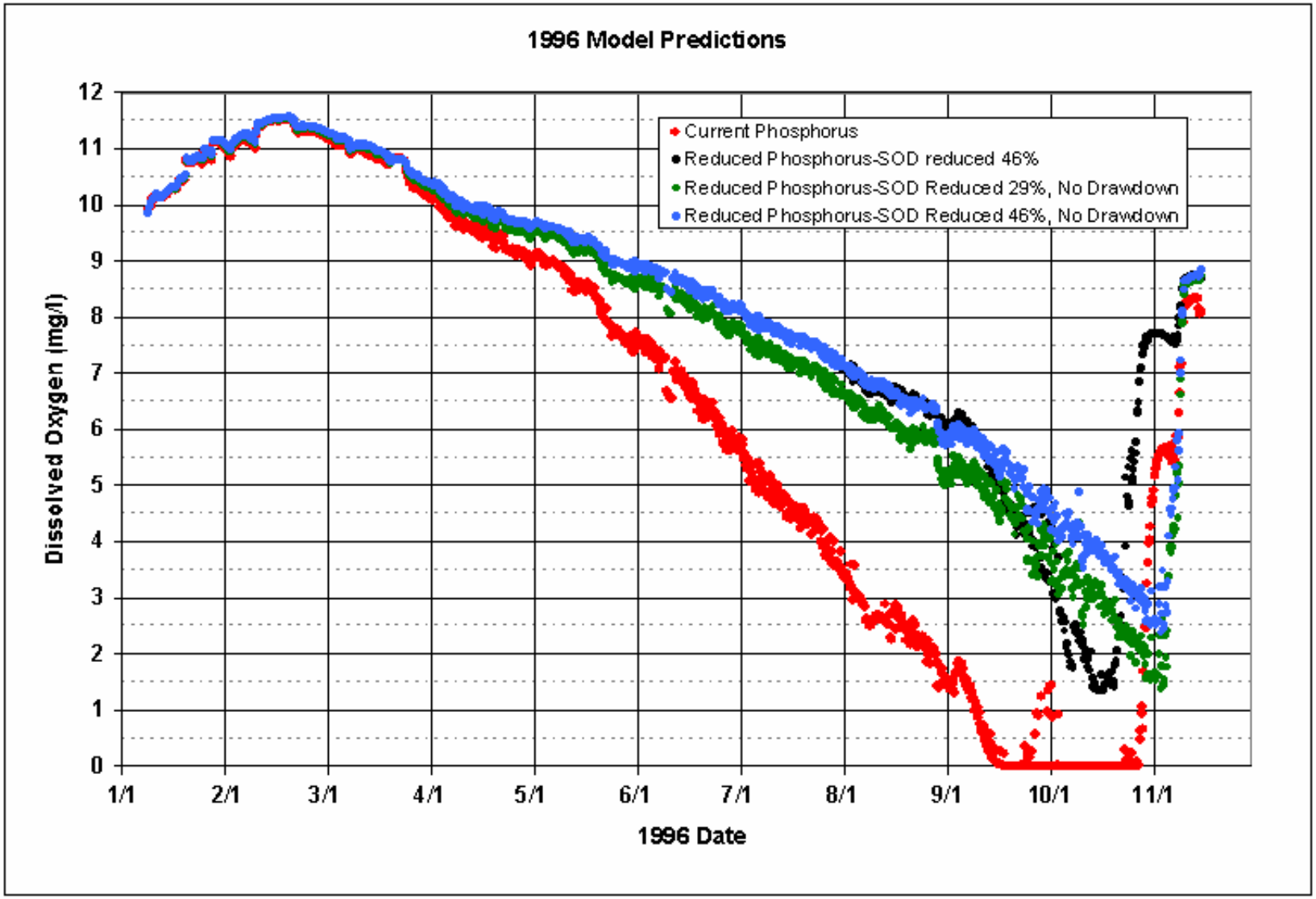
Animation

Current vs. Reduced Phosphorus

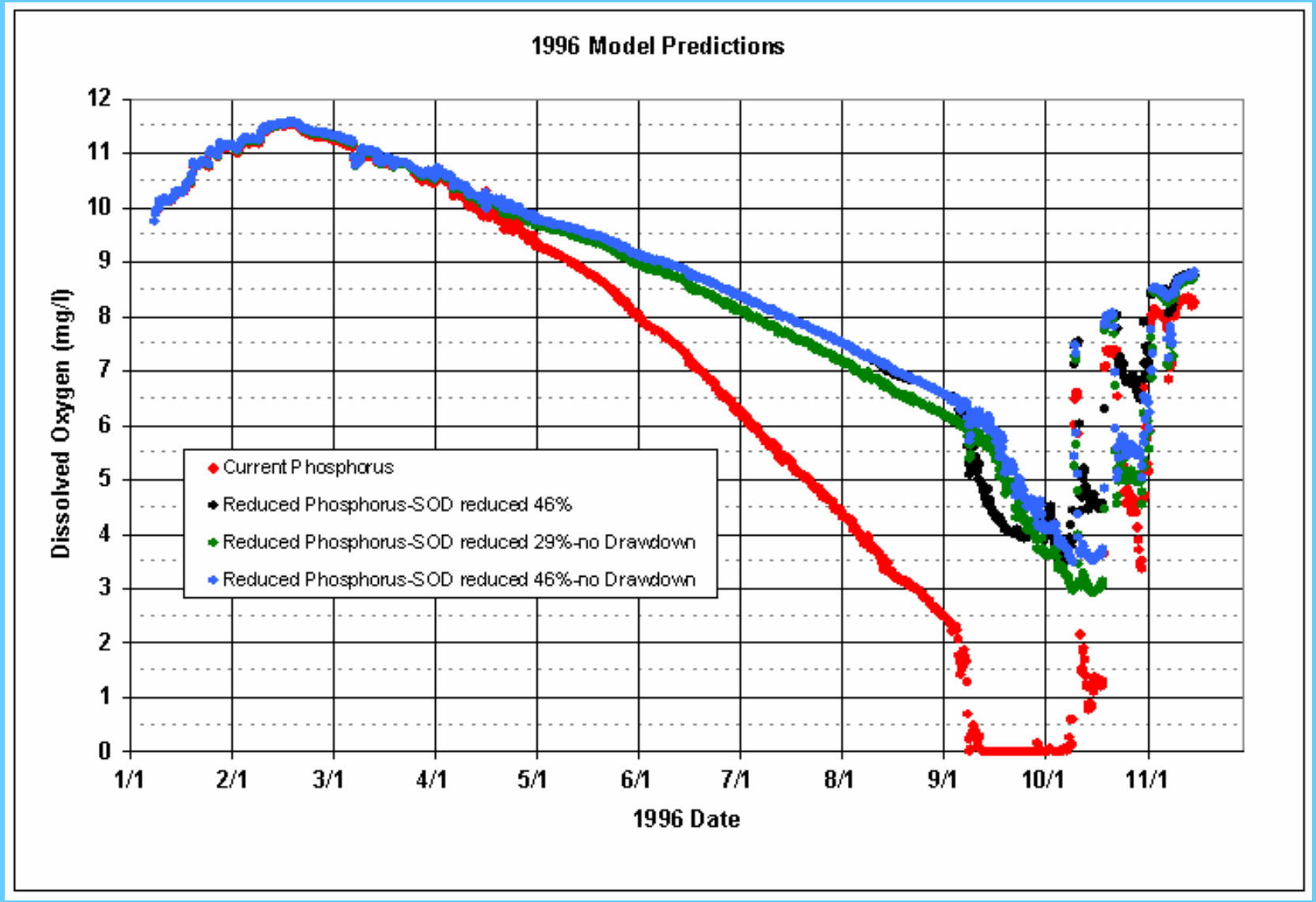
Comparison of Water Surface Elevations for Various Years at Lake Murray



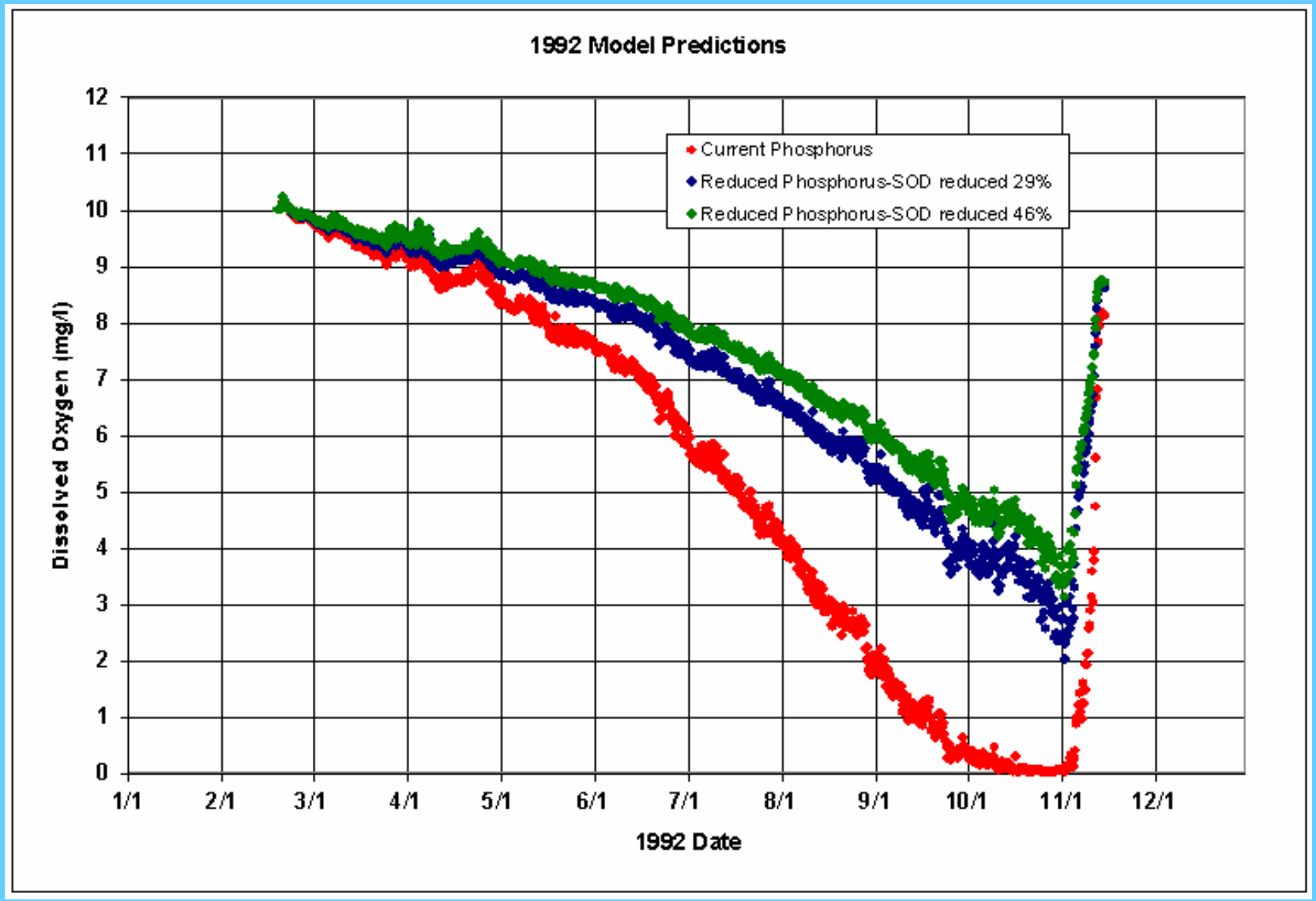
1996 Discharge DO for Current and Reduced Phosphorus, and without the Special Drawdown



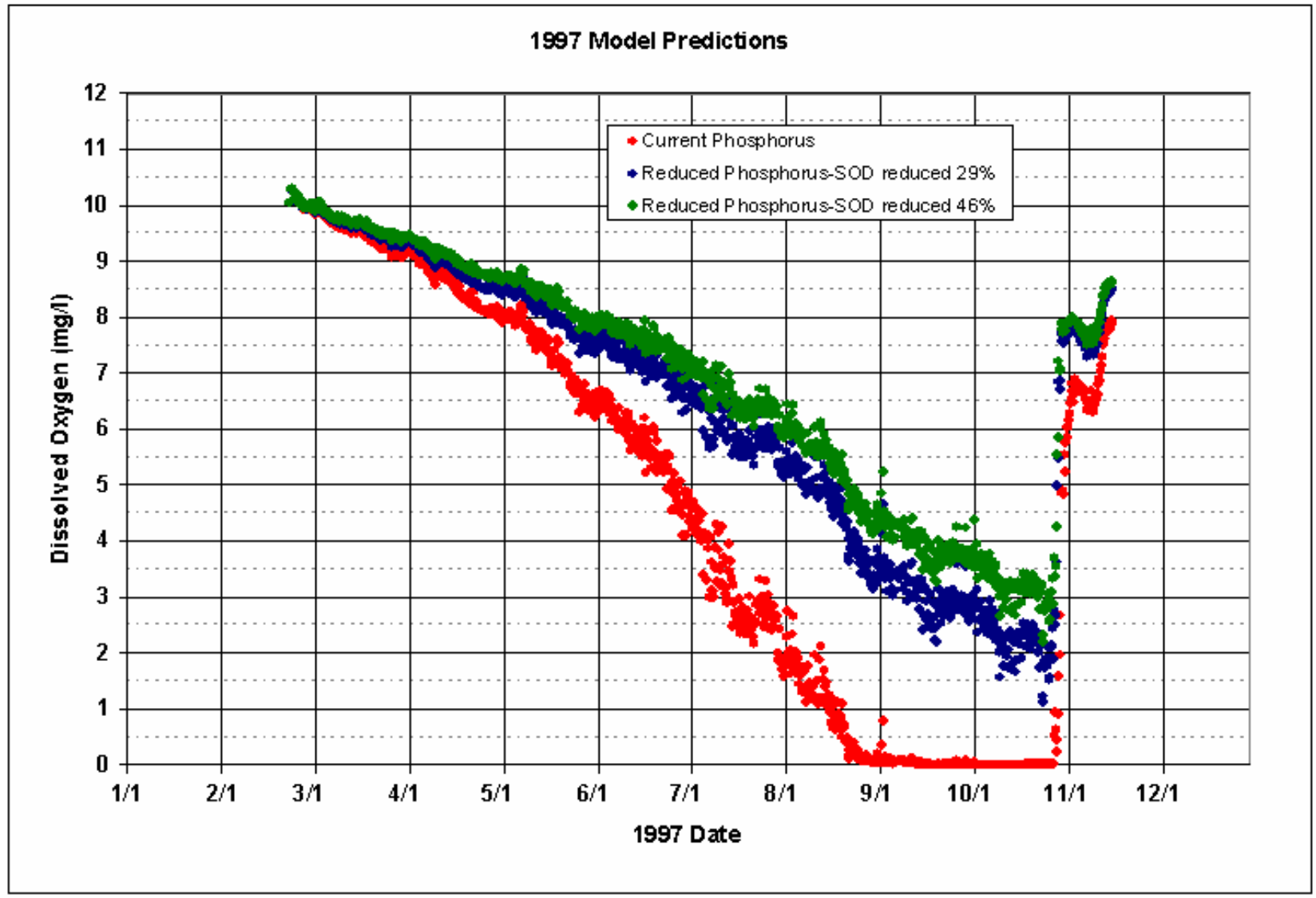
1996 DO at the Elevation of the Unit 5 Intake for Current and Reduced Phosphorus, and without the Special Drawdown



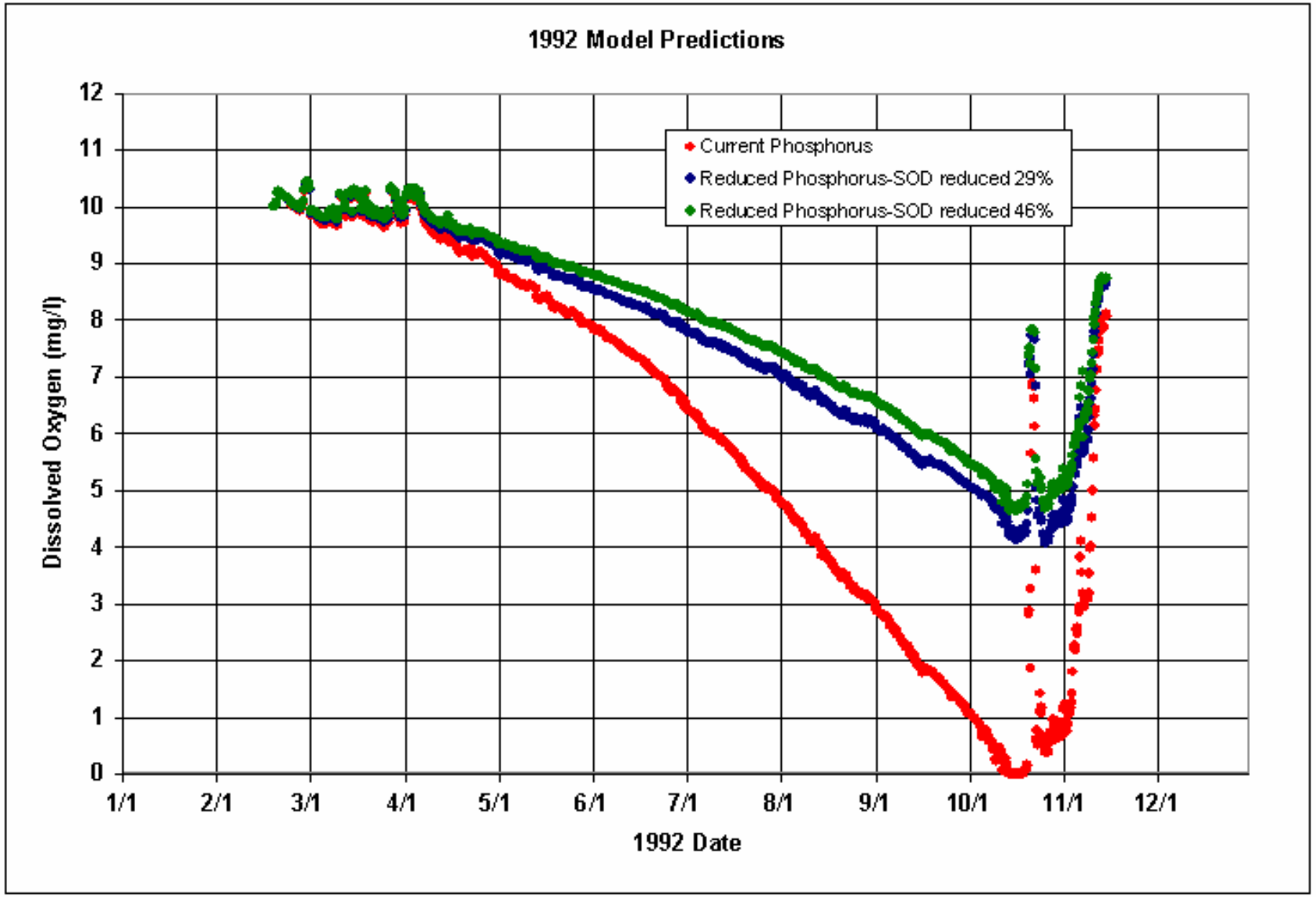
1992 Discharge DO for Current and Reduced Phosphorus



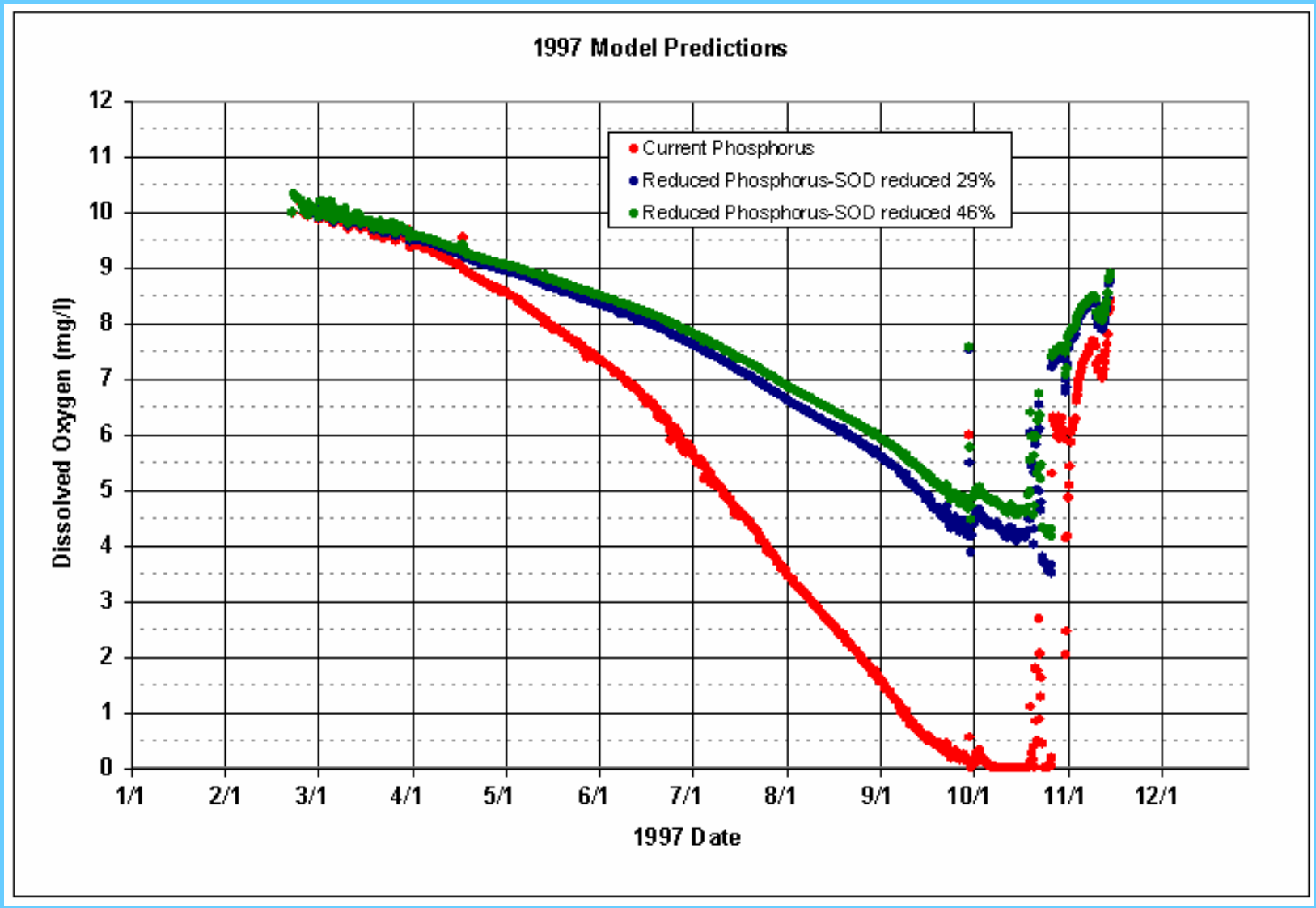
1997 Discharge DO for Current and Reduced Phosphorus



1992 DO at the Level of the Unit 5 Intake for Current and Reduced Phosphorus



1997 DO at the Level of the Unit 5 Intake for Current and Reduced Phosphorus



Animation

Striped Bass Habitat Highlighted

End