BEAVER LAKE SITE-SPECIFIC WATER QUALITY CRITERIA DEVELOPMENT: RECOMMENDED CRITERIA

FEBRUARY 8, 2008

BEAVER LAKE SITE-SPECIFIC WATER QUALITY CRITERIA DEVELOPMENT: RECOMMENDED CRITERIA

Prepared for

The Graduate School
119 Ozark Hall
University of Arkansas
Fayetteville, AR 72701

Prepared by

FTN Associates, Ltd.
3 Innwood Circle, Suite 220
Little Rock, AR 72211

FTN No. 3055-021

February 8, 2008

ACKNOWLEDGEMENTS

The authors wish to thank the Walton Family Foundation for their support of this work. In addition, the authors would like to acknowledge Mr. Alan Fortenberry and Mr. Robert Morgan of the Beaver Water District, Dr. Reed Green and Dr. Joel Galloway of the United States Geological Survey, and Dr. Joe Nix, retired, for their contributions to this work.

EXECUTIVE SUMMARY

Beaver Lake is not only the primary public water supply for over 250,000 Arkansans, it is also a major contributor to the quality of life in Northwest Arkansas. The Arkansas Department of Environmental Quality (ADEQ) is developing site-specific numeric water quality criteria for Arkansas lakes and reservoirs. Because of its importance to all Arkansans, ADEQ selected Beaver Lake as the prototype for developing site-specific, numeric water quality criteria to protect the designated uses of this waterbody and subsequently other lakes and reservoirs throughout Arkansas. The project was supported by funding from the Walton Family Foundation, the United States Environmental Protection Agency (USEPA), and the United States Geological Survey.

A weight of evidence approach was used to develop recommendations for site-specific, numeric water quality criteria, which included considerations of:

1. Surrounding state numeric criteria for chlorophyll, Secchi transparency, total phosphorus, and total nitrogen values;
2. Ecoregion values proposed by USEPA;
3. Percentile values based on both reference lake data and extant data for Beaver Lake;
4. Hydrologic plunge point analyses;
5. Statistical analyses of data from Beaver Lake and the reference lakes;
6. Empirical nutrient loading relationships; and
7. Dynamic modeling results.

Based on this weight of evidence approach, the following site-specific, effects-based numeric water quality criteria are recommended for measurement at the Hickory Creek site in Beaver Lake:

- Growing season geometric mean chlorophyll a concentration: 8 μg/L
- Annual average Secchi transparency: 1.1 meters

Nutrient targets, not criteria, are recommended for total phosphorus (40 µg/L) and total nitrogen (0.4 mg/L).

These recommendations are considered protective and supportive of all designated uses for Beaver Lake.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS i
EXECUTIVE SUMMARY ii
1.0 INTRODUCTION 1-1
1.1 Purpose and Participation 1-1
1.2 Conceptual Model 1-2
1.3 Weight of Evidence 1-3
1.4 Analyses Background 1-3
1.4.1 Beaver Lake System Description 1-3
1.4.2 Reference Lake Systems 1-4
1.4.3 Historical Studies of Beaver Lake 1-4
2.0 DESIGNATED USES 2-1
3.0 LITERATURE AND STATE SOURCES FOR CRITERIA 3-1
3.1 Information Sources 3-1
3.2 Numeric Criteria 3-1
3.3 Additional Considerations 3-3
4.0 DEMOGRAPHIC CHANGES, 1990-2000 4-1
5.0 ORDER OF MAGNITUDE ESTIMATES – SETTING THE STAGE 5-1
5.1 Morphometric Estimates 5-1
5.2 Hydrologic Estimates 5-3
6.0 HYDROLOGIC ANALYSES 6-1
6.1 Hydrologic Characterization 6-1
6.2 Plunge Point Analyses 6-2
6.2.1 Average Condition Plunge Points 6-2
6.2.2 Storm Flow Plunge Points 6-4
6.2.3 Beaver Lake Plunge Points, All Dates 6-5
6.3 Plunge Point Conclusions 6-6
7.0 STATISTICAL ANALYSES 7-1
7.1 Beaver Lake Analyses 7-1
7.1.1 Summary Statistics 7-1

TABLE OF CONTENTS (CONTINUED)

7.1.2 Longitudinal Water Quality Perspective ... 7-2
7.1.3 Trend Analyses ... 7-2
7.1.4 Water Quality Percentile Analyses ... 7-2
7.1.5 Change-Point Analyses ... 7-2
7.2 Reference Conditions ... 7-2
7.2.1 Reference Streams ... 7-2
7.2.2 Reference Reservoirs ... 7-2
7.3 Comparison Between Beaver Lake and Reference Reservoirs ... 7-2
7.3.1 Inputs ... 7-2
7.3.2 Reservoir Water Quality ... 7-2
8.0 MODELING ANALYSES ... 8-2
8.1 Water Quality Modeling for Criteria Development ... 8-2
8.2 Nutrient Loading ... 8-2
8.3 Dynamic Water Quality Modeling ... 8-2
8.4 Modeling Conclusions ... 8-2
9.0 WEIGHT OF EVIDENCE ... 9-2
9.1 Location ... 9-2
9.2 Frequency, Duration, and Magnitude ... 9-2
9.3 Weight of Evidence ... 9-2
9.3.1 Chlorophyll a ... 9-2
9.3.2 Secchi Depth ... 9-2
9.3.3 Total Phosphorus ... 9-2
9.3.4 Total Nitrogen ... 9-2
9.4 Recommended Criteria ... 9-2
9.4.1 Relative Risk of Exceedance ... 9-2
9.4.2 Rationale for Criteria ... 9-2
9.4.3 Sampling Location and Frequency ... 9-2
10.0 REFERENCES ... 10-2

LIST OF TABLES

Table 2.1 Beaver Lake numeric water quality criteria 2-1

Table 2.2 Stream reaches within the Beaver Lake watershed listed on ADEQ's 2004 303(d) list 2-2

Table 3.1 Numeric nutrient-related WQS adopted by southern states and USEPA guidance criteria for Beaver Lake ecoregions. 3-2

Table 4.1 Comparison of historical and current northwest Arkansas county populations 4-1

Table 4.2 Comparison of historical and current Beaver Lake watershed population 4-2

Table 4.3 Estimated increase in housing units in the Beaver Lake watershed 4-2

Table 4.4 Estimated number of people living below the poverty level in Beaver Lake watershed 4-3

Table 5.1 Beaver Lake attributes and OMEs at conservation – water supply pool level 5-2

Table 6.1 Depths at plunge points calculated for monthly average conditions at Lake Ouachita and DeGray Lake 6-3

Table 6.2 Depths at plunge points calculated for monthly average conditions at Beaver Lake inflows 6-3

Table 6.3 Depths at plunge points calculated for selected storm events at DeGray Lake 6-4

Table 6.4 Depths at plunge points calculated for selected storm events at Beaver Lake 6-5

Table 6.5 Depths at plunge points calculated for sampling events at Beaver Lake 6-6

Table 7.1 Annual summary statistics, by location 7-1

Table 7.2 Seasonal Kendall-Tau output indicating trends in War Eagle Creek water quality 7-7

Table 7.3 Comparison of historical Beaver Lake summary statistics 7-8

LIST OF TABLES (CONTINUED)

Table 7.4 Potential criteria determined using USEPA method for selected Beaver Lake stations – raw data ... 7-8

Table 7.5 Potential criteria determined using USEPA method for selected Beaver Lake stations – annual statistics ... 7-9

Table 7.6 Ecoregion least-disturbed streams ... 7-13

Table 7.7 Potential criteria for upper lake stations in reference reservoirs using USEPA method ... 7-15

Table 7.8 Comparison of inflow concentrations for reference reservoirs and Beaver Lake from 1989 to 2006 ... 7-17

Table 7.9 Comparison of nutrient loads to Beaver Lake and the reference systems ... 7-18

Table 8.1 TASTR Beaver Lake Bathtub model inputs and results ... 8-2

Table 8.2 Total phosphorus concentration statistics for White River, Richland Creek, and War Eagle Creek ... 8-3

Table 8.3 TASTR/Bathtub results for Beaver Lake, changing only total phosphorus concentrations in White River, Richland Creek, and War Eagle Creek ... 8-3

Table 8.4 Comparison of observed chlorophyll a data and model results ... 8-5

Table 8.5 Comparison of observed total phosphorus data and model results ... 8-6

Table 9.1 Comparison of growing season geometric chlorophyll means (mg/L) collected by USGS and Beaver Water District at the site near Lowell, Arkansas ... 9-4

Table 9.2 Weight of evidence comparison of analytical approaches for Beaver Lake water quality criteria ... 9-7

Table 9.3 Exceedance/attainment ratios (and relative risk) of exceeding different growing season geometric chlorophyll means and average annual Secchi transparency values at Lowell based on potential water quality targets for Hickory Creek ... 9-20

LIST OF FIGURES

Figure 1.1 Conceptual process for the development of effects-based water quality criteria 1-2

Figure 1.2 Upper White River Basin, Arkansas and Missouri 1-5

Figure 1.3 Beaver Lake Watershed with sub-basins 1-6

Figure 1.4 State map showing ecoregions and location of Beaver, Ouachita, Greeson, and DeGray Lakes 1-7

Figure 6.1 Hydrologic characterization of White River flows 6-7

Figure 6.2 Hydrologic characterization of Fayetteville precipitation 6-8

Figure 6.3 Hydrologic characterization of Ouachita River flows 6-8

Figure 6.4 Plunge point dynamics in reservoirs 6-9

Figure 6.5 Gradients in water quality constituents associated with the plunge point, which defines the location of the transition zone 6-9

Figure 6.6 Locations of plunge points in DeGray Lake for monthly average conditions 6-10

Figure 6.7 Locations of plunge points in Ouachita Lake for monthly average conditions 6-11

Figure 6.8 Locations of plunge points in Beaver Lake for monthly average conditions 6-12

Figure 6.9 Locations of plunge points in DeGray Lake for high-flow storm events 6-13

Figure 6.10 Locations of plunge points in Beaver Lake for high-flow storm events 6-14

Figure 6.11 Locations of plunge points in Beaver Lake for wet, average, and dry year sampling dates 6-15

Figure 7.1 Map of Beaver Lake water quality stations for analyses 7-20

Figure 7.2 Explanation of box and whisker plot 7-21

Figure 7.3 Box and whisker plot of Secchi transparency at selected Beaver Lake locations 7-21

Figure 7.4 Box and whisker plot of turbidity at selected Beaver Lake locations 7-22

Figure 7.5 Box and whisker plot of chlorophyll a at selected Beaver Lake locations 7-22

LIST OF FIGURES (CONTINUED)

Figure 7.6 Box and whisker plot of total nitrogen at selected Beaver Lake locations 7-23

Figure 7.7 Box and whisker plot of total phosphorus at selected Beaver Lake locations 7-23

Figure 7.8 Box and whisker plot of ratios of total nitrogen to total phosphorus at selected Beaver Lake locations 7-24

Figure 7.9 Secchi transparency during wet, average, and dry years at selected Beaver Lake sites 7-24

Figure 7.10 Chlorophyll a concentrations during wet, average, and dry years at selected Beaver Lake sites 7-25

Figure 7.11 Total phosphorus concentrations during wet, average, and dry years at selected Beaver Lake sites 7-25

Figure 7.12 Total nitrogen concentrations during wet, average, and dry years at selected Beaver Lake sites 7-26

Figure 7.13 Turbidity during wet, average, and dry years at selected Beaver Lake sites 7-26

Figure 7.14 Turbidity levels at selected Beaver Lake and tributary sites 7-27

Figure 7.15 Water quality data for White River at Highway 45 7-28

Figure 7.16 Water quality data for Richland Creek at Highway 45 7-29

Figure 7.17 Water quality data for War Eagle Creek at Hindsville 7-30

Figure 7.18 Months when dissolved oxygen data were collected by USGS, COE, and FTN 7-31

Figure 7.19 Days of year when dissolved oxygen data were collected by USGS, COE, and FTN 7-31

Figure 7.20 Days of year when dissolved oxygen values reported by various entities were less than 2 mg/L at Lowell 7-32

Figure 7.21 Decreasing trend evident in date of onset of hypoxia 7-32

Figure 7.22 Tree analysis indicating change in date of onset of hypoxia after 1997 7-33

Figure 7.23 Possible increasing trend evident in number of days of hypoxia per year 7-33

Figure 7.24 Tree analysis indicating change in number of days of hypoxia per year after 1997 7-34

LIST OF FIGURES (CONTINUED)

Figure 7.25 Total organic carbon values near Lowell reported by various entities 7-34

Figure 7.26 Water quality parameters plotted against flow for White River 7-35

Figure 7.27 Water quality parameters plotted against gage height for War Eagle Creek 7-36

Figure 7.28 Tree model output for Beaver Lake chlorophyll a with total nitrogen showing change-point.. 7-37

Figure 7.29 Tree model output for Beaver Lake chlorophyll a with turbidity showing change-point 7-37

Figure 7.30 Tree model output for chlorophyll a with total phosphorus for Beaver Lake at Highway 12.. 7-38

Figure 7.31 Tree model output for chlorophyll a with total phosphorus for Beaver Lake near Lowell 7-38

Figure 7.32 Tree model output for chlorophyll a with turbidity for Beaver Lake near Lowell.. 7-39

Figure 7.33 Tree model output for chlorophyll a with turbidity for Beaver Lake at Highway 412... 7-39

Figure 7.34 Tree model output for Beaver Lake Secchi transparency with all total phosphorus data 7-40

Figure 7.35 Tree model output for Beaver Lake Secchi transparency with reported total phosphorus values greater than detection................................... 7-40

Figure 7.36 Tree model output for Beaver Lake Secchi transparency with total nitrogen data 7-41

Figure 7.37 Tree model output for Beaver Lake Secchi transparency with turbidity data 7-41

Figure 7.38 Flint Creek nutrient data over time 7-42

Figure 7.39 War Eagle Creek nutrient data over time.. 7-43

Figure 7.40 Kings River nutrient data over time.. 7-44

Figure 7.41 Long Creek nutrient data over time 7-45

Figure 7.42 Categorization of DeGray Lake water quality sampling sites 7-46

Figure 7.43 Categorization of Lake Ouachita water quality sampling sites 7-47

Figure 7.44 Categorization of Lake Greeson water quality sampling sites........................... 7-48

Figure 7.45 Secchi transparency at selected locations in reference reservoirs 7-49

LIST OF FIGURES (CONTINUED)

Figure 7.46 Total phosphorus concentrations at selected locations in reference reservoirs 7-49

Figure 7.47 Total nitrogen concentrations at selected locations in reference reservoirs 7-50

Figure 7.48 Turbidity levels at selected locations in reference reservoirs 7-50

Figure 7.49 Chlorophyll a concentrations at selected locations in reference reservoirs 7-51

Figure 7.50 Tree analysis output for chlorophyll a with total phosphorus showing change-point 7-51

Figure 7.51 Tree analysis output for Secchi transparency with total phosphorus showing change-point 7-52

Figure 7.52 Tree analysis output for Secchi transparency with total nitrogen showing change-point 7-52

Figure 7.53 Tree analysis output for Secchi transparency with turbidity showing change-point 7-53

Figure 9.1 Proposed Hickory Creek monitoring site for assessing WQS attainment 9-3

Figure 9.2 Growing season geometric chlorophyll means as a function of hydrologic category at the Highway 412 and Lowell sites 9-5

Figure 9.3 Average annual Secchi transparency values as a function of hydrologic category at the Highway 412 and Lowell sites 9-6

Figure 9.4 Regression relationship with 95% confidence interval between growing season geometric chlorophyll means at Highway 412 and Lowell sites 9-9

Figure 9.5 Long-term growing season geometric chlorophyll mean, with 95% confidence interval, for Highway 412 and Lowell sites 9-11

Figure 9.6 Longitudinal gradient in Beaver Lake game fish biomass 9-12

Figure 9.7 Predicted change in sport fish standing crop resulting from changes in chlorophyll concentrations 9-12

Figure 9.8 Regression relationship, with 95% confidence intervals, between average annual Secchi transparency values at the Highway 412 and Lowell sites 9-13

Figure 9.9 Long-term average annual Secchi transparency, with 95% confidence interval, at the Highway 412 and Lowell sites 9-15

LIST OF FIGURES (CONTINUED)

Figure 9.10 No apparent relationships were observed between annual average total phosphorus means and annual average Secchi or growing season geometric chlorophyll means at either the Highway 412 or Lowell sites 9-16

Figure 9.11 No apparent relationships were observed between annual average total nitrogen means and annual average Secchi or growing season geometric chlorophyll means at either the Highway 412 or Lowell sites 9-18

1.0 INTRODUCTION

1.1 Purpose and Participation

The United States Environmental Protection Agency (USEPA) recently issued a policy requiring all states to develop numeric nutrient criteria to protect the designated uses of waterbodies within each state. These nutrient criteria will be developed and implemented by the state of Arkansas by 2010. As part of this process, the Arkansas Department of Environmental Quality (ADEQ) is developing site-specific numeric water quality criteria for Arkansas lakes and reservoirs. Beaver Lake is a critical water resource for the economy and quality of life of northwest Arkansas, and is the public water supply for over 250,000 people. One out of every eight Arkansans gets his/her drinking water from Beaver Lake. Because of its importance to all Arkansans, ADEQ has selected Beaver Lake as the prototype for developing site-specific, numeric water quality criteria to protect the designated uses of this waterbody and subsequently other large reservoirs.

ADEQ assembled a Scientific Work Group to assist in this effort, including representatives from the University of Arkansas, Fayetteville, and the Arkansas Water Research Center. The purpose of the Scientific Work Group was to review recommendations to ADEQ on numeric water quality criteria for Beaver Lake. It is critical that the numeric water quality criteria be scientifically defensible and protect the designated uses for Beaver Lake. This approach is necessary if Arkansas is to protect the water source for one of the fastest growing areas in the state.

A Technical Subcommittee of the Scientific Work Group developed the scientific approach that was used to recommend water quality criteria for Beaver Lake. This Technical Subcommittee included representatives from ADEQ, the United States Geological Survey (USGS), Beaver Water District, FTN Associates, Ltd. (FTN), and Dr. Joe Nix (retired from Ouachita Baptist University). USGS and Beaver Water District are monitoring Beaver Lake water quality and provided data that were used in the criteria development process. In addition, USGS calibrated a water quality model that also was used to evaluate the ecological effects from different pollutant load scenarios.

1.2 Conceptual Model

Water quality standards (WQS) consist of: 1) the designated use(s) of the waterbody to be protected; 2) numeric water quality criteria that will protect the use(s); and 3) an anti-degradation policy. This project focused on the first two parts of the WQS – designated uses and recommended numeric criteria. USEPA has recently emphasized numeric effects-based criteria instead of criteria for specific physical or chemical parameters. With over 10,000 new chemicals being developed each year, developing chemical-specific criteria for each new chemical would be exceedingly difficult. Stream and lake biological indicators integrate the myriad physical and chemical factors occurring within these waterbodies. These integrated ecological effects, therefore, can provide the basis for water quality criteria. In addition, effects-based criteria, such as changes in water clarity, biological diversity, or fish production, typically can be related more closely to specific designated uses.

By definition, water quality criteria serve to protect the designated uses for the waterbody. The conceptual process for the development of effects-based water quality criteria related to waterbody designated uses as part of this project is illustrated below.

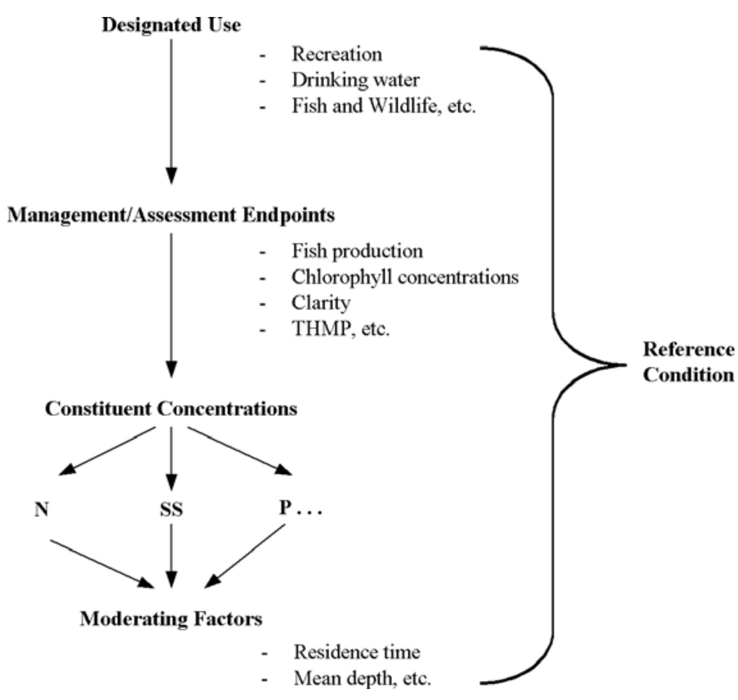


Figure 1.1. Conceptual process for the development of effects-based water quality criteria.

Trihalomethane precursors (THMP), listed in Figure 1.1, are potential carcinogenic compounds formed from chlorinating drinking water that has elevated organic compounds, while nitrogen (N) and phosphorus (P) are nutrients that stimulate nuisance algae blooms, and suspended sediments (SS) decrease water clarity and increase drinking water treatment costs.

1.3 Weight of Evidence

A weight-of-evidence approach was used to arrive at the recommended water quality criteria for Beaver Lake. A weight-of-evidence approach uses multiple lines of evidence, balancing the strengths and weaknesses of each line of evidence, to derive criteria that reflect the concurrence among these multiple lines of evidence, the association between the criterion and the stressors affecting the criterion, and potential risks to the system both from attainment and non-attainment of the criterion. The lines of evidence considered in deriving water quality criteria for Beaver Lake included:

1. Designated uses;
2. Literature review for comparable lakes;
3. Historical perspective, including:
    - Demographic watershed changes,
    - Historical water quality trends, and
    - Land use.
4. Hydrologic and plunge point analyses;
5. Statistical analyses of Beaver Lake water quality;
6. Reference lake water quality and analyses;
7. Nutrient loading model estimates for selected water quality variables; and
8. CE-QUAL-W2 simulations of Beaver Lake water quality.

These multiple lines of evidence were weighted based on their different strengths and used to derive the recommended numeric water quality criterion.

1.4 Analyses Background

1.4.1 Beaver Lake System Description

Beaver Lake is the first of four large impoundments on the White River managed by the United States Army Corps of Engineers (USACE) (Figure 1.2). The other USACE impoundments on the White River are, in downstream order, Table Rock Lake, Bull Shoals Lake, and Norfork Lake. Beaver Lake was created to provide project purposes of flood control, hydroelectric power generation, fish and wildlife propagation, and water supply for northwest Arkansas. Beaver Dam was first authorized by the United States Congress in 1954 under the Flood Control Act of 1944, which granted USACE the authority to propose such projects, and resulted in the construction of many dams and reservoirs throughout the United States.

Beaver Lake covers 11,421 hectares in Washington, Benton, and Carroll counties at its conservation/water supply pool level (341 meters National Geodetic Vertical Datum (NGVD)). Beaver Lake receives drainage from approximately 307,174 hectares in Washington, Benton, Carroll, and Madison counties. The three primary tributaries to Beaver Lake (listed in size order) are the White River, War Eagle Creek, and Richland Creek (Figure 1.3). On average, the White River contributes approximately 30% of the inflow to Beaver Lake.

1.4.2 Reference Lake Systems

Lake Greeson, DeGray Lake, and Lake Ouachita were selected as reference reservoirs (Figure 1.4), because there has been limited development in their watersheds. As such, they were considered to be examples of the best possible water quality for reservoirs in Arkansas. These reservoirs are located in a different, but similar, ecoregion of Arkansas than Beaver Lake.

1.4.3 Historical Studies of Beaver Lake

Beaver Lake has been the subject of numerous water quality studies over the years. Differences in sampling, methodologies, analytical parameters and methodologies, and levels of quality assurance and control associated with all of these studies led us to use primarily long-term routine monitoring data collected by ADEQ and USGS in our analyses. However, data from two previous water quality studies were included in our analyses, the National Eutrophication Survey (NES) and the Beaver Clean Lakes Study (CLS).

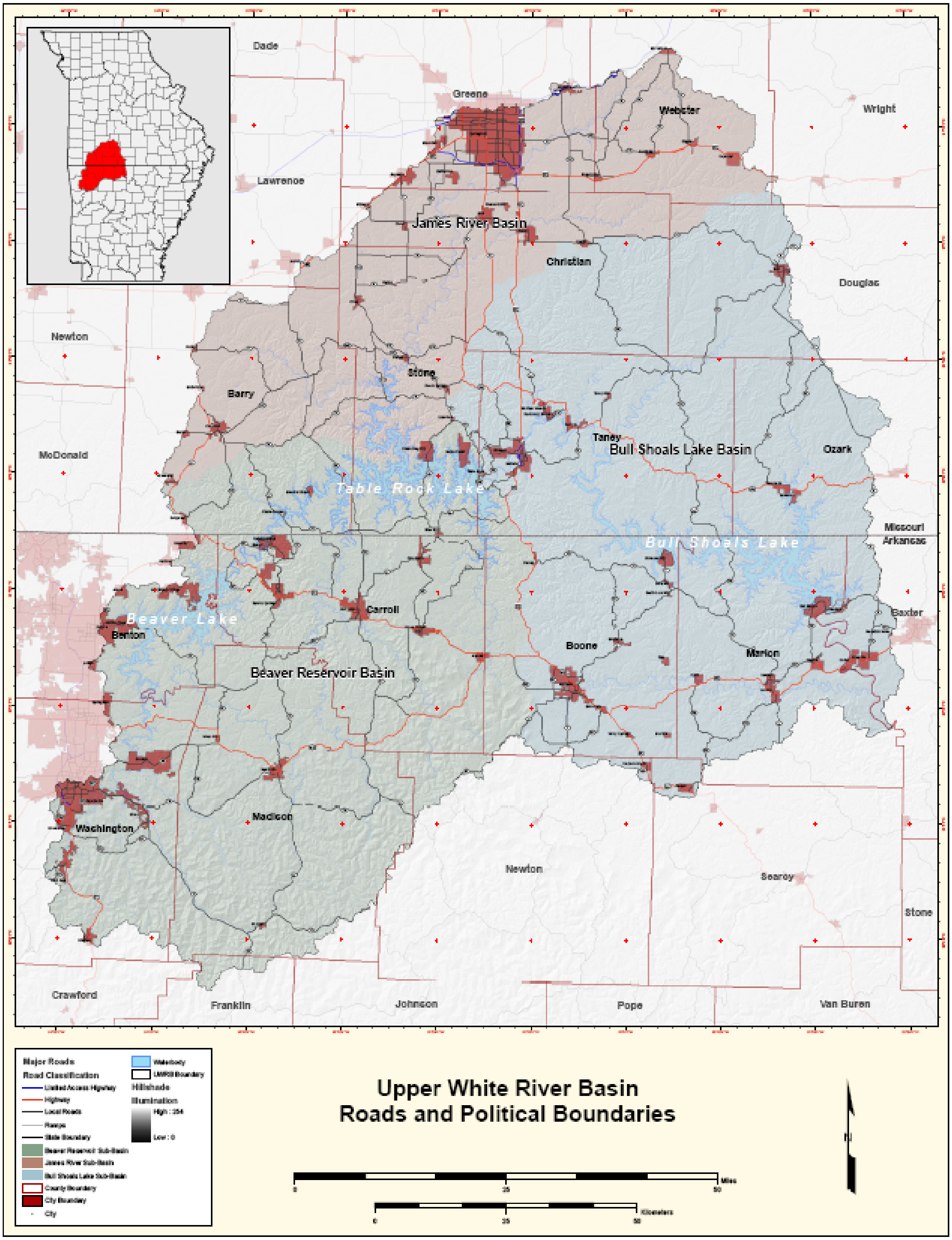


Figure 1.2. Upper White River Basin, Arkansas and Missouri.

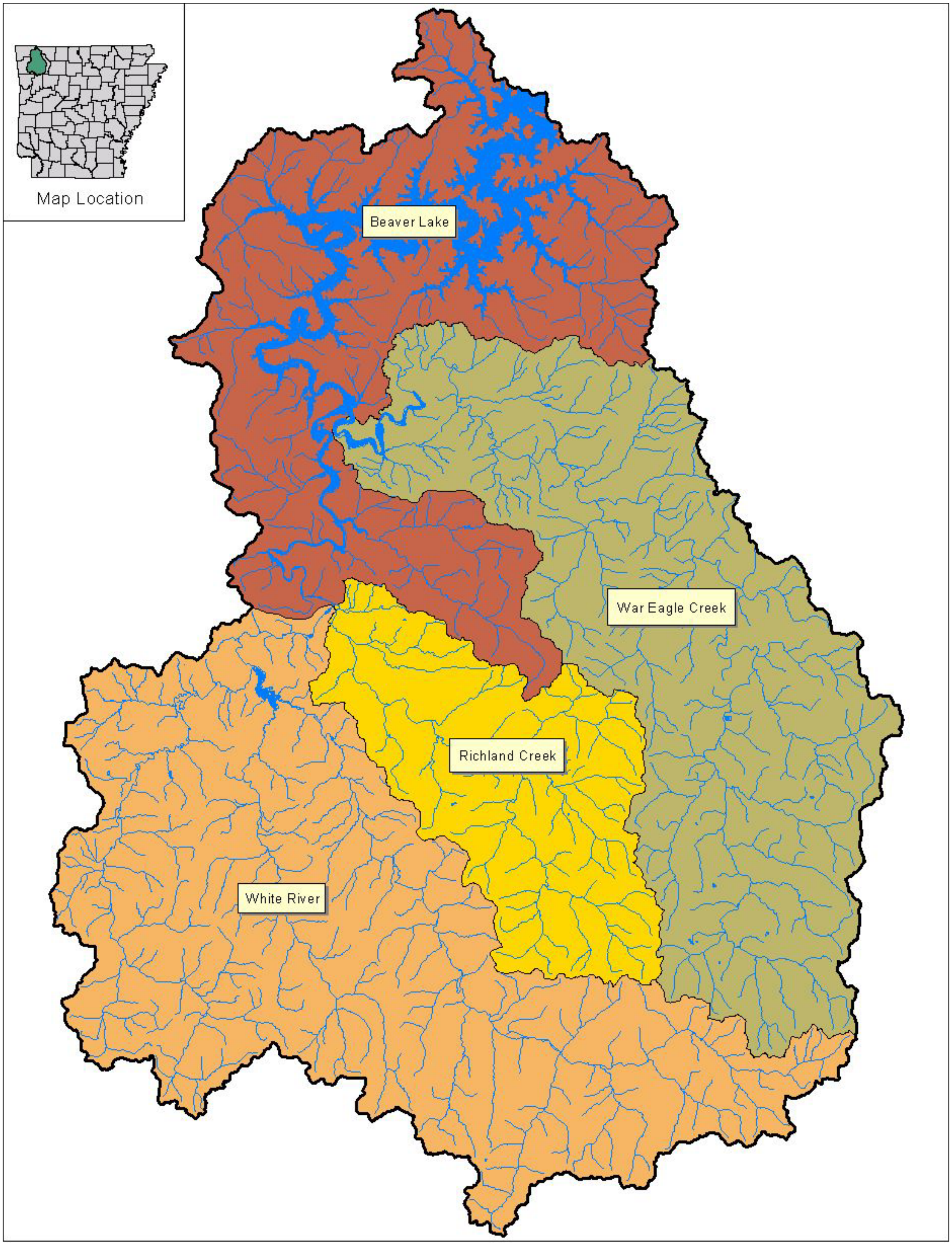


Figure 1.3. Beaver Lake watershed with sub-basins.

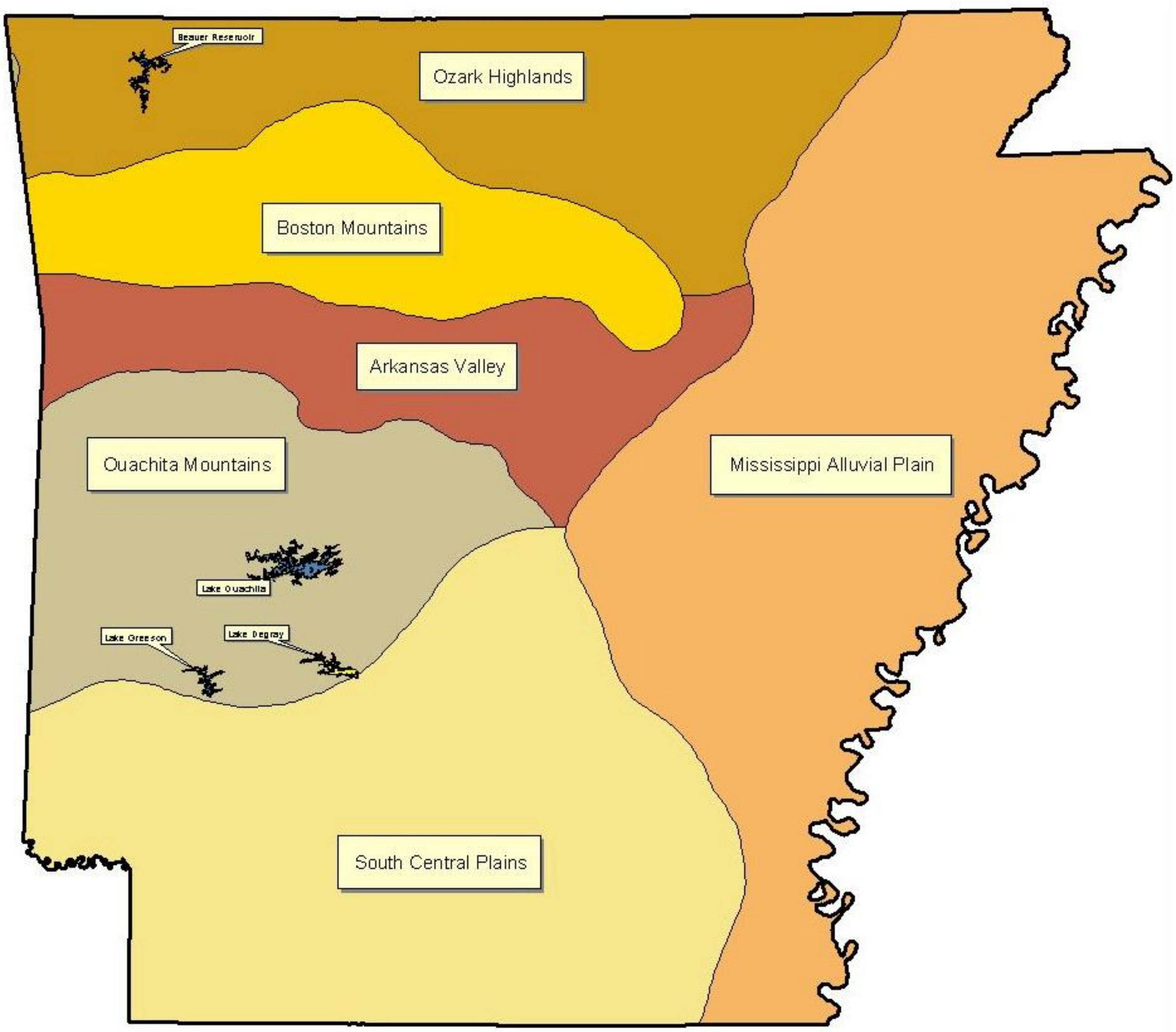


Figure 1.4. State map showing ecoregions and location of Beaver, Ouachita, Greeson, and DeGray Lakes.

1.4.3.1 National Eutrophication Survey

From 1972 until 1976, USEPA conducted the NES to determine the number of lakes in the US that were eutrophic because of nutrient loadings primarily from wastewater treatment facilities. Beaver Lake was sampled in 1974 because the City of Fayetteville wastewater treatment plant discharged into the White River. While nutrient loading from the Fayetteville wastewater treatment plant was significantly decreased in 1987, the NES provides an historical perspective on Beaver Lake water quality in 1974. While the tributaries to Beaver Lake were sampled on a monthly basis, the reservoir was only sampled on three occasions: spring, summer, and fall.

1.4.3.2 Beaver Clean Lakes Study

In 1991, FTN conducted a USEPA CLS on Beaver Lake through Section 314 funding of the USEPA Clean Lakes Program. Reservoir sampling occurred 14 times during the year at multiple locations in Beaver Lake so that seasonal dynamics in chlorophyll concentrations, nutrient concentrations, and Secchi depth could be determined.

2.0 DESIGNATED USES

Under Arkansas WQS specified by Arkansas Pollution Control and Ecology Commission (APCEC) Regulation No. 2, the designated uses for Beaver Lake are:

- Primary contact recreation,
- Propagation of fish, wildlife and aquatic life, and
- Domestic, industrial, and agricultural water supply.

Note the designated uses are not the same as the project purposes. Numeric water quality criteria for Beaver Lake are listed in Table 2.1. Beaver Lake is currently attaining WQS. In general, domestic water supply represents the highest priority use for Beaver Lake and is associated with the most stringent WQS. Therefore, water quality criteria development initially focused on protecting this designated use.

Table 2.1. Beaver Lake numeric water quality criteria.

Constituent	WQS
Turbidity (NTU) Primary/Storm	 25/45
pH (standard units)	6.0 – 9.0
Dissolved Oxygen (mg/L)	5.0
Total Dissolved Solids (mg/L)	160
Numeric Nutrient Criteria	None

Some stream tributary reaches to Beaver Lake, however, are not attaining their designated uses and are listed on the 2004 ADEQ 303(d) list of impaired waterbodies as high priorities for remediation. Specific water quality problems associated with these non-attaining stream reaches are listed in Table 2.2. The Station Identification is specific to individual ADEQ monitoring sites.

Table 2.2. Stream reaches within the Beaver Lake watershed listed on ADEQ's 2004 303(d) list.

River	Reach No.	Length (miles)	Station ID	Impaired Use(s)	Source	Cause
White River near Goshen, AR	023	6.2	WHI 52	Aquatic Life, Agriculture and Industry	Road Construction, Agriculture	Total dissolved solids, sulfates, chlorides
White River near Durham, AR	027	23.8	WHI 106	Aquatic Life	Unknown	Dissolved oxygen
West Fork, east of Fayetteville	024	27.2	WHI 51	Aquatic Life, Agriculture and Industry	Unknown, Road Construction, Agriculture	Sulfates, total dissolved solids
War Eagle Creek	060	28.3	N/A	Drinking Water, Agriculture and Industry	Municipal Point Source	Total dissolved solids, sulfates, chlorides
Holman Creek	059	9.1	WHI 70	Drinking Water, Agriculture and Industry	Municipal Point Source	Total dissolved solids, sulfates, chlorides

3.0 LITERATURE AND STATE SOURCES FOR CRITERIA

3.1 Information Sources

A literature search on nutrients, phosphorus, fish, and THMPs (disinfection byproducts) was initially performed at the University of Arkansas Mullins Library using InfoLinks (University of Arkansas electronic library catalog of books) in 2003. This information search was updated in 2006. In addition, a recent review by Virginia Polytechnic Institute and State University was included in the development of nutrient criteria (Younos et al. 2007). Resources (papers, manuscripts, symposia) were reviewed if the lakes and reservoirs were in the southern tier of states (Arkansas, Alabama, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, and Texas). Over 100 reports and journal articles were reviewed, with over 50 sources containing quantitative relationships between nutrients and biological endpoints. These quantitative relationships were used to estimate chlorophyll, Secchi depth, and THMP concentrations based on different nutrient (nitrogen and phosphorus) scenarios. This is discussed further in Chapter 8.0, Modeling Analyses.

Electronic searches were also conducted to identify state nutrient criteria and aggregate ecoregional criteria developed by USEPA. Particular emphasis was again placed on southern states. A summary document prepared by USEPA (2003) incorporates information on nutrient standards for states, tribes, and territories based on a survey of these entities during 2002 (www.USEPA.gov/waterscience/standards/wqs/library). This document served as a base, which was expanded through literature searches of state, tribe, and territory websites in 2006.

3.2 Numeric Criteria

Table 3.1 lists the numeric nutrient-related WQS that have been adopted by states and numeric criteria proposed by USEPA for ecoregions covering Beaver Lake and its watershed. Some states have also developed lake or site-specific criteria so a range from the lowest criterion value to the highest criterion value for different lakes is shown. Nutrient criteria listed for Mississippi are recommended only, and have not proceeded through the rule-making process to become WQS. Mississippi is currently considering a site-specific approach for nutrient criteria in their lakes and oxbows. USEPA ecoregion criteria are based on the 25th percentile of extant data available over the last decade of lake and reservoir monitoring within the ecoregion. In most cases, the data for Ecoregion 38 (Boston Mountains) are limited. Ecoregion 39 represents the Ozark Highlands (see Figure 1.4).

Table 3.1. Numeric nutrient-related WQS adopted by southern states and USEPA guidance criteria for Beaver Lake ecoregions. For states that have site-specific lake criteria, the range of criteria are shown.

Parameter	Source	State or Ecoregion	Standard of Guidance
Chlorophyll a (µg/L)	State Criteria	Alabama	5 – 17 (site-specific)
		Georgia	5 – 27 (site-specific)
		Mississippi	20 (reservoir)
		North Carolina	10 (trout) 40 (non-trout)
		Oklahoma	10 (drinking water)
		South Carolina	10 or 40 (ecoregion-based)
	USEPA Ecoregion Guidance (XI) (1)	Ecoregion 38	6.6
		Ecoregion 39	6.1
Total phosphorous (µg/L)	State Criteria	Georgia(2)	< 0.25 – 5.5 lb/ac-ft/yr
		Mississippi	90
		Oklahoma	168 (Eucha) 141 (Spavinaw)
		South Carolina	20 – 90 (ecoregion)
	USEPA Ecoregion Guidance (XI) (1)	Ecoregion 38	5.0
		Ecoregion 39	24.4
Total nitrogen (mg/L)	State Criteria	Georgia	< 4.0
		Mississippi	1.0
		South Carolina	0.35 or 1.5 (ecoregion)
	USEPA Ecoregion Guidance (XI) (1)	Ecoregion 38	0.12
		Ecoregion 39	0.5
Secchi (m)	State Criteria	Mississippi	0.45
	USEPA Ecoregion Guidance (XI) (1)	Ecoregion 38	1.8
		Ecoregion 39	2.0

Notes:
(1) USEPA Ecoregion criteria represent the 25^{th} percentile of extant data.
(2) Georgia total phosphorus criteria are based on loading rather than concentration.

3.3 Additional Considerations

Carcinogenic compounds, such as trihalomethanes and haloacetic acids, can be formed from organic matter during disinfection of drinking water when there are even relatively low concentrations of organic matter in the raw water supply (Chapra et al. 1997, Walker 1983). Organic carbon in raw water, including algal cells and the organic compounds released by algae, can react with chlorine during treatment to form these compounds. While there are treatment procedures that can reduce the formation of these carcinogenic compounds, the procedures increase treatment costs.

Because Beaver Lake is a drinking water source for northwest Arkansas, another water quality criteria consideration was to minimize the formation of these disinfection byproducts in the raw water. The Oklahoma Water Resources Board established a chlorophyll a criterion of 10 µg/L for drinking water reservoirs based on a study that demonstrated the risk of THMP increased significantly when chlorophyll a concentrations in the raw water exceeded this criterion (Downing et al. 2001). Other studies have found that when chlorophyll a concentrations or total organic carbon concentrations exceed 1 to 2 µg/L or 2 mg/L, respectively, there was a high likelihood that trihalomethane concentrations would exceed the USEPA drinking water criterion of 80 µg/L.

4.0 DEMOGRAPHIC CHANGES, 1990-2000

The Beaver Lake watershed includes portions of Benton, Carroll, Madison, and Washington counties in northwest Arkansas. Northwest Arkansas has experienced rapid population growth for almost two decades (Table 4.1). Between 1990 and 2006, the total population in this four-county area increased by 76% (from 241,180 to 425,266), compared to the population increase of approximately 20% for the entire state over the same period. While the majority of this growth has occurred outside of the Beaver Lake watershed, it does represent an increase in water supply demand for the area, which is supplied primarily from Beaver Lake, as well as an increase in hydropower demand and recreational users of Beaver Lake.

Table 4.1. Comparison of historical and current northwest Arkansas county populations.

County	1990	2000	2006*
Benton	97499	153406	196,045
Carroll	18654	25357	27,339
Madison	11618	14243	15,361
Washington	113409	157715	186,521
Total	241180	350721	425266
Percent Change		45%	21%

Notes: * = from Table GCT-T1 Population Estimates online at:http://factfinder.census.gov/servlet/GCTTable?_bm=y&-geo_id=04000US05&-_box_head_nbr=GCT-T1&-ds_name=PEP_2006_EST&-_lang=en&-format=ST-2&-_sse=on

Population change within the Beaver Lake watershed was estimated through area proportioning. The Beaver Lake watershed includes one-third of Benton County, one-half of Washington County, and all of Madison County. These proportions of total county population were assumed to reside in the Beaver Lake watershed. The resulting numbers are shown in Table 4.2. Between 1990 and 2006, the estimated watershed population increased approximately 72%. This population increase has the potential to affect Beaver Lake water quality through land use changes.

Table 4.2. Comparison of historical and current Beaver Lake watershed population.

County	1990	2000	2006*
Benton	29250	46022	58814
Madison	11618	14243	15,361
Washington	56704	78858	93260
Total	97572	139123	167435
Percent change		42%	20%

Notes: * = from Table GCT-T1 Population Estimates online at http://factfinder.census.gov/servlet/GCTTable?_bm=y&-geo_id=04000US05&-_box_head_nbr=GCT-T1&-ds_name=PEP_2006_EST&-_lang=en&-format=ST-2&-_sse=on

Housing units in the Beaver Lake watershed were estimated based on the proportions of the county used for estimating population. Housing unit estimates are summarized in Table 4.3. Between 1990 and 2000, the number of housing units in the watershed increased approximately 40%. In 1990, approximately 50% of housing units in Benton County used septic tanks or cesspools for sewage disposal, along with approximately 30% of housing units in Washington County, and 76% of housing units in Madison County (Bureau of the Census 1991). Malfunctioning septic systems can contribute to nutrient enrichment of reservoirs. The Census Bureau stopped collecting household information on water supply and wastewater disposal after 1990, so there are no estimates for 2000.

Table 4.3. Estimated increase in housing units in the Beaver Lake watershed.

County	1990	2000
Benton	12433	19284
Madison	5182	6537
Washington	23674	32165
Watershed Total	41289	57986

Northwest Arkansas is generally considered to be experiencing economic growth. However, not all residents of this area benefit from the strong economy. The number of people living below the poverty level in Beaver Lake watershed is estimated from US Census data (www.census.gov) and shown in Table 4.4. Between 1990 and 2000, the number of people in the Beaver Lake watershed estimated to be living below the poverty level increased by 40%. This was slightly less than the population increase during this period (42%); therefore, the percentage of the estimated watershed population living below poverty level actually decreased by 1%.

In 2000, approximately 18% of the people in Arkansas were living below the poverty level. The economic strength of northwest Arkansas is reflected in the fact that the percentage of people in Beaver Lake watershed living below poverty level (13%) was less than the percentage for the state.

Table 4.4. Estimated number of people living below the poverty level in Beaver Lake watershed.

County	1990	2000
Benton	3079	5067
Madison	2307	2616
Washington	7957	11052
Watershed Total	13343	18735
Percent	14%	13%

5.0 ORDER OF MAGNITUDE ESTIMATES – SETTING THE STAGE

Stream and reservoir water quality information was reviewed and order of magnitude estimates (OMEs) or “back-of-the envelope” estimates (such as relative depth, area erosion, and residence time) were calculated for Beaver Lake. These assist in initial determinations of the relative importance of various reservoir processes in controlling reservoir water quality, such as sedimentation, stratification, mixing, inflow placement, light penetration, and dissolved oxygen (DO) dynamics. These estimates provide initial insight and knowledge about certain reservoir characteristics that can be useful in water quality analyses, model calibration, and development of appropriate management strategies, including water quality criteria.

OMEs provide insight on the potentially important processes and the potential dependence among processes. The estimates are usually within factors of 3 to 5 (or better) of actual values (Fischer et al. 1979). Given the temporal and spatial variability in most environmental variables and characteristics, estimates within a factor of 3 to 5 can be useful. For example, knowing whether summer average chlorophyll a concentrations are estimated to be 3 µg/L or 30 µg/L immediately indicates whether the reservoir is likely to be oligotrophic or eutrophic, respectively. OMEs are the first step, and an integral part, of any water quality analyses and criteria recommendations. Table 5.1 provides the general morphometric characteristics of Beaver Lake and the OMEs calculated from them.

5.1 Morphometric Estimates

Drainage area/surface area (DA/SA) ratios indicate potential area water, sediment, and nutrient loads to a reservoir and the relative usefulness of various watershed best management practices (BMPs) for improvement of reservoir water quality. The DA/SA ratio of Beaver Lake, 27:1, is greater than 10:1 (Table 5.1), which indicates that watershed water, sediment, and nutrient loads could significantly impact reservoir water quality. Because the DA/SA ratio is less than 50:1, even watershed management practices implemented farther up in the watershed can contribute to improved reservoir water quality. Water quality improvements in reservoirs with a large DA/SA ratio (>50:1) typically become a function of where in the watershed the BMPs are implemented. Our observations are that improvements in stream water quality from BMPs implemented near the upstream end of large drainage basins (i.e., DA/SA >50:1) are diminished by downstream loadings to the reservoir.

Table 5.1. Beaver Lake attributes and OMEs at conservation – water supply pool level.

Reservoir Attributes (based on USACE project data)	Value
Volume, $\forall$ (m^3)	2.04×10^9
Surface Area, SA (km^2)	114
Watershed Area, DA (km^2)	3,072
Length (thalweg length from Highway 45 to dam), L (km)	124
Length of shoreline, L_s (km)	723
Mean width, W (km), SA/L	16
Maximum depth, Z_m (m)	62
Mean depth, Z (m), $\forall$/SA	18
OMEs	**Value**
Drainage area/surface area, DA/SA	27
Aspect ratio, L/W	7.5
Shoreline development ratio $L_S/2\sqrt{\pi SA}$	19.1
Relative depth (%) $\frac{88.6Zm}{\sqrt{SA}}$	51%
Residence time, (yr),$\forall/Q$	1.5
Single storm flushing ratio $Q_S\ /\ \forall$	0.2
Photic zone depth (m) $1nZ_{1\%} = 1.352 + 0.745\ 1nZ_s$	8

Note: *Q* = Average annual total outflow = 42.35 m^3/s (NES 1977)
Qs = largest daily total inflow on record (White River + War Eagle) = 4503 m^3/s
Z_s = average Secchi depth of all reservoir stations for 2000-2004 = 2.6 m

The aspect ratio (comparison of length to average width) provides an indication of how important longitudinal versus lateral gradients might be in a waterbody. The aspect ratio in Beaver Lake is 7.5. An aspect ratio (length divided by width) greater than 4.0 indicates that longitudinal gradients are more important than lateral gradients in water quality (Jirka and Harleman 1979). Plug flow models or models that account for longitudinal gradients in these reservoirs will be more appropriate than 1-D or continuously stirred tank reactor (CSTR) models. Because longitudinal gradients are more important than lateral gradients, this also indicates that a 3-D model is probably not warranted for simulating reservoir water quality, unless there are specific issues associated with local inputs and associated lateral gradients.

The shoreline development ratio indicates the degree to which a waterbody may deviate in shape from that of a circle. For example, a perfectly circular reservoir has a shoreline development ratio of 1.0. The greater the ratio is above 1.0, the more dendritic the system is with greater potential for extensive littoral development, macrophytic and benthic production, and organic loading. A highly dendritic reservoir with multiple coves and embayments may have a ratio of 15 or greater (Thornton et al. 1990). The shoreline development ratio in Beaver Lake (19:1) indicates a highly dendritic reservoir with multiple coves and embayments.

Relative depth is the ratio of maximum depth to average diameter of the reservoir surface. The smaller the relative depth (e.g., <1.0), the greater the potential for wind disruption of thermal stratification because of shallow water conditions (Wetzel 1983). The relative depth for Beaver Lake is 0.51, indicating there is the potential for wind to disrupt thermal stratification. However, Beaver Lake is deep and serpentine and has no long fetches for southerly prevailing winds during summer.

5.2 Hydrologic Estimates

Estimates can also be made using hydrologic characteristics. The theoretical hydraulic residence time is defined as reservoir volume divided by total annual inflow. Residence time is one indicator of potential water quality problems. For example, reservoirs with residence times that are less than 100 days typically have stronger longitudinal gradients and greater productivity than reservoirs with residence times that are greater than 100 days (Thornton, unpublished data). Greater productivity in reservoirs with residence times less than 100 days is typically associated with larger DA/SA ratios, greater sediment and nutrient loads in conjunction with greater areal loads, and areas of maximum primary productivity farther down the reservoir. Beaver Lake has a theoretical hydraulic residence time of 1.5 years, which would indicate it has a relatively large volume compared to annual discharge volume from the watershed.

For reservoirs with residence times greater than 100 days, the area of maximum primary productivity is generally in the upper 5 to 10% of the reservoir where inflowing water laden with nutrients plunges below the surface into the metalimnion or hypolimnion before entering the main portion of the reservoir. Primary productivity is relatively low in the lower portion of the reservoir because of low epilimnetic nutrient concentrations (Kimmel et al. 1990; Thornton et al. 1980). Beaver Lake has a theoretical residence time of 1.5 years, so maximum productivity would be expected in the upper part of the reservoir.

The single-storm flushing ratio can indicate the extent to which inflow waters can disrupt stratification, the distance to which inflow waters can move into the reservoir, and the contribution of inflow waters, through nutrient loading, to nutrient supplies in the epilimnion. If the single-storm flushing ratio exceeds 1 (i.e., the inflow in the single storm is greater than the volume in the reservoir), thermal stratification will be disrupted and the reservoir will completely mix. Minimal mixing is associated with ratios less than 0.5 (Mueller et al. 1981). Beaver Lake has a ratio of about 0.2 for a large inflow (White River + War Eagle), so it is highly unlikely that a single, large storm event would result in complete mixing.

The photic zone is defined as the zone from the reservoir surface to the depth at which light is 1% of the surface value. It is within the photic zone that light is assumed to be sufficient for algal growth. The depth of the photic zone can be estimated from Secchi disk depth measurements using an empirical equation developed by Williams et al. (1980). Nutrient-enriched water entering from the tributaries can flow into the metalimnion as an interflow during the summer stratified period and be made available for algal uptake and growth, if light is available. In Beaver Lake, the photic zone depth is estimated as 8 meters.

6.0 HYDROLOGIC ANALYSES

6.1 Hydrologic Characterization

The flow record for the White River near Fayetteville (USGS Gage 07048600) and the Fayetteville precipitation record were analyzed to characterize years as dry, average, or wet. The historical average annual White River flow for the period from 1964 through 2005 was calculated, along with the standard deviation of annual average flow for the same period. The average flow for each year of record (calendar year, not water year) was then calculated. The historical average total precipitation for the period from 1895 through 2005 was calculated, along with the ±1 and ±2 standard deviations from this historical average and the precipitation total for each year from 1960 through 2005. The annual flow and precipitation values were plotted along with lines showing the historical average and its 95% confidence interval, as well as the historical average plus and minus the standard deviation (Figures 6.1 and 6.2; all figures located at the end of Chapter 6).

Those years with an average flow and total precipitation within ± 1 standard deviation of the historical averages were classified as average years (1998, 1999, 2001, 2002). Those years with an average flow and precipitation total that were similar to or greater than the historical average plus one standard deviation were classified as wet years (1984, 1985, 1990, 1993). Those years with an average flow and precipitation total similar to or lower than the historical average minus one standard deviation were classified as dry years (1980, 1983, 2003, 2005). Note that classifications based on flow did not always agree with those based on precipitation (i.e., the precipitation total was not always outside the historical standard deviation when average annual flow was (see Figures 6.1 and 6.2)). Therefore, only those years where there was reasonable agreement between the flow and precipitation-based classifications were assigned a hydrologic classification. To maintain comparable amounts of data for wet, dry, and average years, only the four most recent classified years (listed in parentheses above) were used in subsequent evaluations of conditions during dry, average, and wet years.

The flow record available upstream of the reference reservoirs (DeGray, Greeson, Ouachita) was not as extensive. Long-term data (from 1942 through present) were available only for the Ouachita River (Figure 6.3). The hydrologic classifications of dry, average, and wet years for the Ouachita and White Rivers agreed the majority of the time; therefore, the White River/Beaver Lake hydrologic classification of years was also used for the reference reservoirs.

6.2 Plunge Point Analyses

The plunge point in a reservoir is the location where, during stratified conditions, the buoyant force of a cooler inflow becomes greater than the inertial force, and the inflow moves from the surface to the depth with similar buoyancy (temperature) (Figure 6.4). The greatest productivity in reservoirs typically occurs just downstream of the plunge point, where nutrients from the inflow are readily available and turbidity in the photic zone decreases dramatically as the inflow plunges beneath the surface (Figure 6.5). Knowing the location of the plunge point in a reservoir provides insight into where in the reservoir the greatest response to nutrient inputs would be expected to occur.

6.2.1 Average Condition Plunge Points

6.2.1.1 Lake Ouachita and DeGray Lake

Plunge points were calculated for monthly average conditions for Lake Ouachita and DeGray Lake during the growing season. These plunge points were calculated using monthly average inflow, inflow temperature, and lake surface water temperature for the period 1993 through 2006. The formula used to calculate the plunge points was from Savage and Brimberg (1975). The results of these calculations are shown in Table 6.1. Locations of these plunge points are shown on Figures 6.6 and 6.7. These results show the plunge points generally moving upstream through the growing season. There are two reasons for this phenomenon. First, the stratification, or thermal buoyancy, becomes stronger, and second, the likelihood of high flow events diminishes.

Table 6.1. Depths at plunge points calculated for monthly average conditions at Lake Ouachita and DeGray Lake.

Month	Lake Ouachita (m)	DeGray Lake* (m)
April	NA	
May	17.01	
June	7.63	
July	4.26	1.6
August	2.21	
September	3.85	4.9
October	12.10	0.7

Notes: NA = Does not plunge because inflow temperature is warmer than lake surface temperature.
* = Plunge points for base flows reported by Ford and Johnson (1983)

6.2.1.2 Beaver Lake (White River and War Eagle Inflows)

Plunge points were calculated for monthly average conditions for Beaver Lake (White River and War Eagle inflows) during the growing season. These plunge points were calculated using monthly average inflow, inflow temperature, and lake surface water temperature for the period 1993 through 2006. The formula used to calculate the plunge points was from Savage and Brimberg (1975). The results of these calculations are shown in Table 6.2. Locations of these plunge points are shown on Figure 6.8. These results also show the plunge points generally moving upstream through the growing season.

Table 6.2. Depths at plunge points calculated for monthly average conditions at Beaver Lake inflows.

Month	Beaver Lake - White River (m)	Beaver Lake - War Eagle (m)
April	NA	47.11
May	38.78	7.43
June	NA	7.60
July	4.96	3.71
August	1.67	1.24
September	1.81	0.90
October	NA	1.96

NA = does not plunge because inflow temperature is warmer than lake surface temperature

6.2.2 Storm Flow Plunge Points

Plunge points were also calculated for storm events at DeGray and Beaver Lakes. Inflow and temperature data were not available for storm events during the target years at Lakes Ouachita or Greeson.

6.2.2.1 DeGray Lake Storm Flow Plunge Points

High flow events were identified from USGS flow records for Station 07359610 (Caddo River at Caddo Gap). Plunge points calculated using temperature data collected close to the high flow events are shown in Table 6.3 and on Figure 6.9.

Table 6.3. Depths at plunge points calculated for selected storm events at DeGray Lake.

Storm Flow Date	Caddo River Flow (cms)	Depth at Plunge Point (m)
8/31/1976	6.9	1.8*
10/24/1976	200	6.1*
6/17/1977	370	5.6*
11/14/1978	500	7.6*
5/01/1979	190	6.2*
5/16/1980	103	3.4*
10/16/1980	168	4.7*
5/17/1989	71.4	15.75
5/27/1989	31.1	9.06
7/15/1989	13.2	4.75
7/17/1989	45.3	10.79
9/9/1989	6.7	2.93

*Values reported by Ford and Johnson (1983)

6.2.2.2 Beaver Lake Storm Flow Plunge Points

Plunge points in Beaver Lake were calculated for several storm events in years classified as wet (1990, 1995), dry (1983, 2003, 2005), and average (1999, 2001) (Table 6.4). Storm events were considered if there were increases in White River flow over a couple of days following rainfall events (http://waterdata.usgs.gov/nwis/sw). In the majority of cases, the rainfall events recorded at the White River Gage 07048600 associated with the flow increases had a recurrence interval of less than one year (National Climatic Data Center (NCDC) 1968). The exception is the 5/19/90 storm flow, which was associated with a rainfall event with a recurrence interval of greater than 100 years (NCDC 1968). Note that the data needed to calculate the plunge point were not available for the majority of the storm events identified during the target years, which limited the number of estimates. The locations of these plunge points are shown on Figure 6.10.

Table 6.4. Depths at plunge points calculated for selected storm events at Beaver Lake.

Storm Flow Date	Hydrologic Classification	White River Flow (cms)	Depth at Plunge Point (m)
05/14/1983	Dry	76.2	22.13
05/19/1990	Wet	210.0	NA
05/03/1993	Wet	139.0	NA
08/24/1993	Wet	15.7	6.42
05/04/1999	Average	274.7	59.87
09/12/1999	Average	2.3	1.58
05/30/2001	Average	49.6	16.71
09/09/2001	Average	21.9	6.02
09/17/2001	Average	36.2	13.35
09/01/2003	Dry	15.7	5.53
08/07/2005	Dry	1.2	1.06

Note: Average May White River flow is 20.81 cms, August is 1.56 cms, and September is 2.13 cms.
N/A = does not plunge because inflow temperature is warmer than lake surface temperature.

6.2.3 Beaver Lake Plunge Points, All Dates

Plunge points were calculated for all sample dates (not just storm events) between May and September with all the necessary data during 1993 (wet year), 2002 (average year), and 2003 (dry year). Plunge points were calculated using the method from Savage and Brimberg (1975). The data and calculated plunge points are listed in Table 6.5. Location of these plunge points are shown on Figure 6.11.

Table 6.5. Depths at plunge points calculated for sampling events at Beaver Lake.

Date	Hydrologic Classification	White River Flow (cms)	Depth at Plunge Point (m)
05/04/1993	Wet	32	NA
08/26/1993	Wet	1	0.637
05/14/2002	Average	10.3	6.68
06/20/2002	Average	5.5	6.44
07/10/2002	Average	1.1	0.866
07/23/2002	Average	3.3	2.49
08/22/2002	Average	2.3	1.37
09/04/2002	Average	0.4	0.476
05/07/2003	Dry	10.7	12.4
07/30/2003	Dry	3.4	1.30
09/09/2003	Dry	0.8	0.782

Notes: N/A = does not plunge because inflow temperature is warmer than lake surface temperature.

NA means a plunge point could not be calculated because the inflow temperature was warmer than the lake surface temperature. Therefore the inflow would be expected to travel along the surface as an overflow (see Figure 6.4).

6.3 Plunge Point Conclusions

During stratification, the plunge point determines the relative location of the transition zone in reservoirs. The transition zone typically is characterized by higher phytoplankton productivity and biomass and can be the most fertile area in the reservoir (Kimmel et al. 1990). Silt and clay particles settle or sediment in this zone, which increases light penetration (Figure 6.5). Nutrient concentrations, although lower than in the riverine zone, are still relatively high and sufficient to stimulate phytoplankton production and blooms because light is available as water clarity increases. During stratification, this transition zone extends down-reservoir from the plunge point until nutrient limitation occurs and phytoplankton biomass and production decrease. The area in the lower portion of the reservoir near the dam typically has the best water quality.

The transition zone is dynamic, as evidenced by the location of the plunge point. Its location is determined both by thermal stratification and inflow. During storm events, the plunge point moves further into the reservoir and then retreats back, upstream as storm flow returns to base flow. In Beaver Lake, the location of this transition zone, based on satellite images and empirical equation estimates, appears to extend from upstream of Highway 412 to the Beaver Water District intake near Lowell. If WQS are attained within the transition zone, then, in general, water quality further downstream in the reservoir should also attain WQS. The plunge point analyses provide insight into possible locations for monitoring water quality to determine if WQS are attained for Beaver Lake.

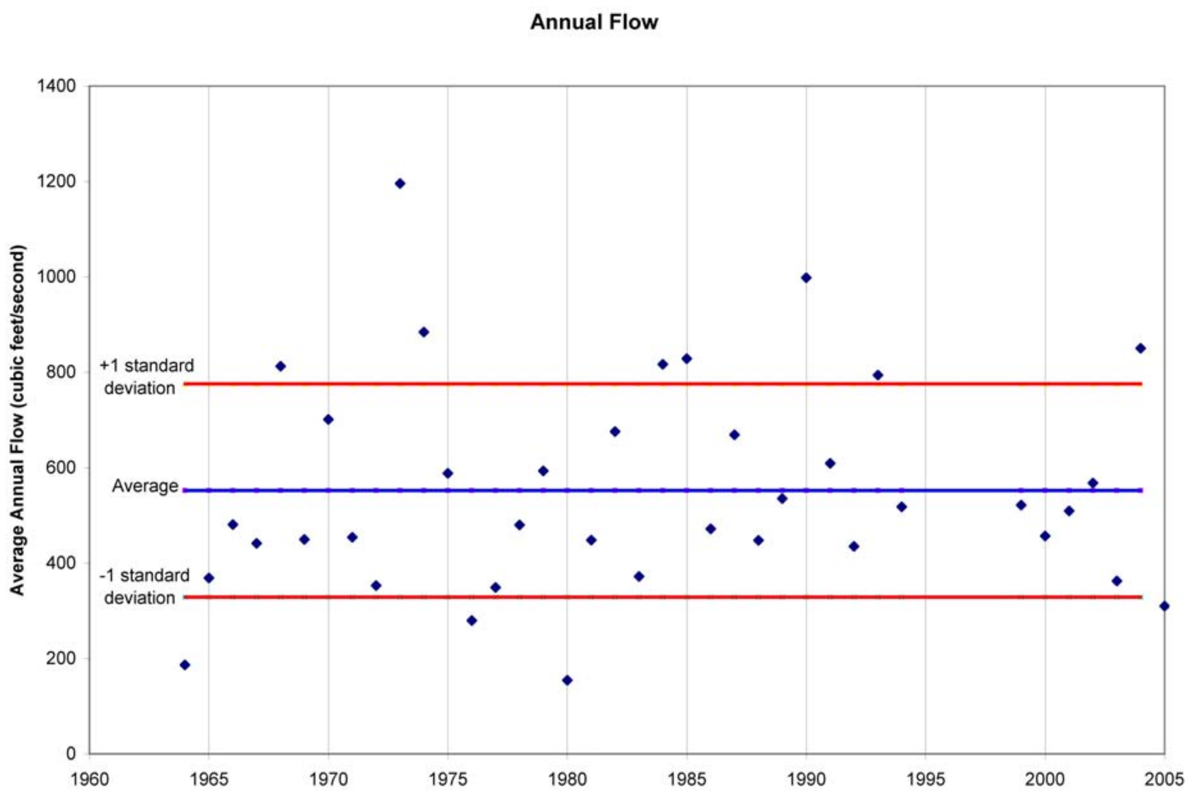


Figure 6.1. Hydrologic characterization of White River flows.

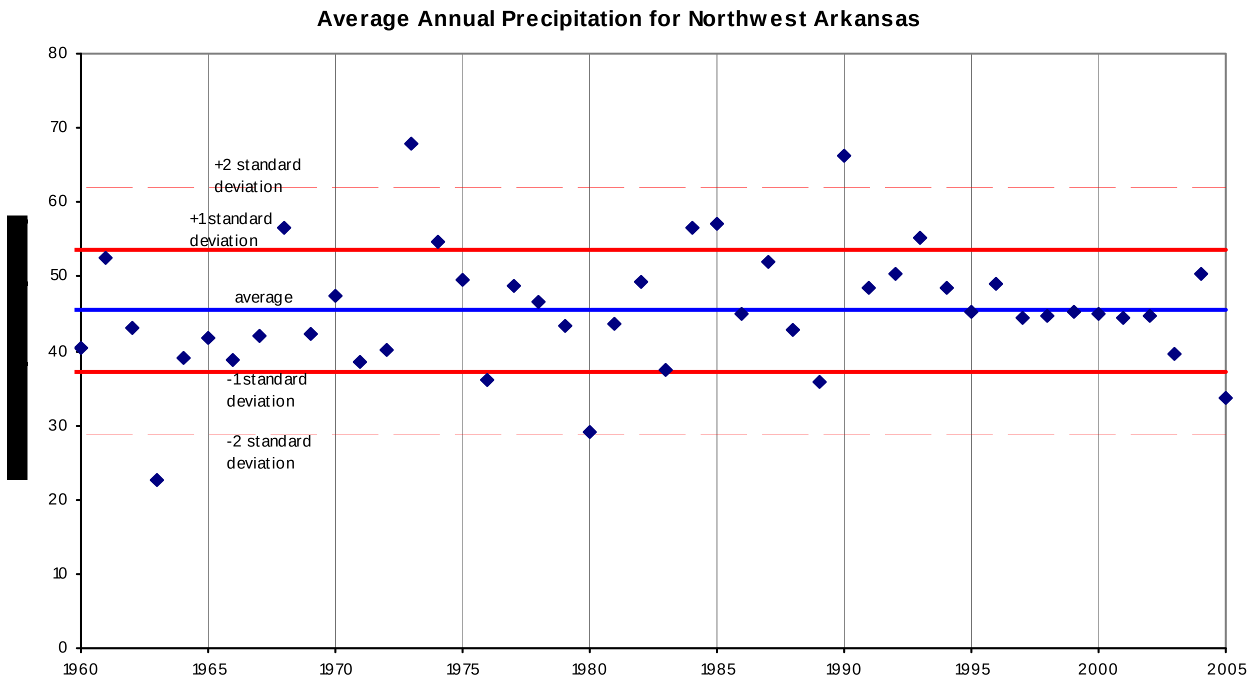


Figure 6.2. Hydrologic characterization of Fayetteville precipitation.

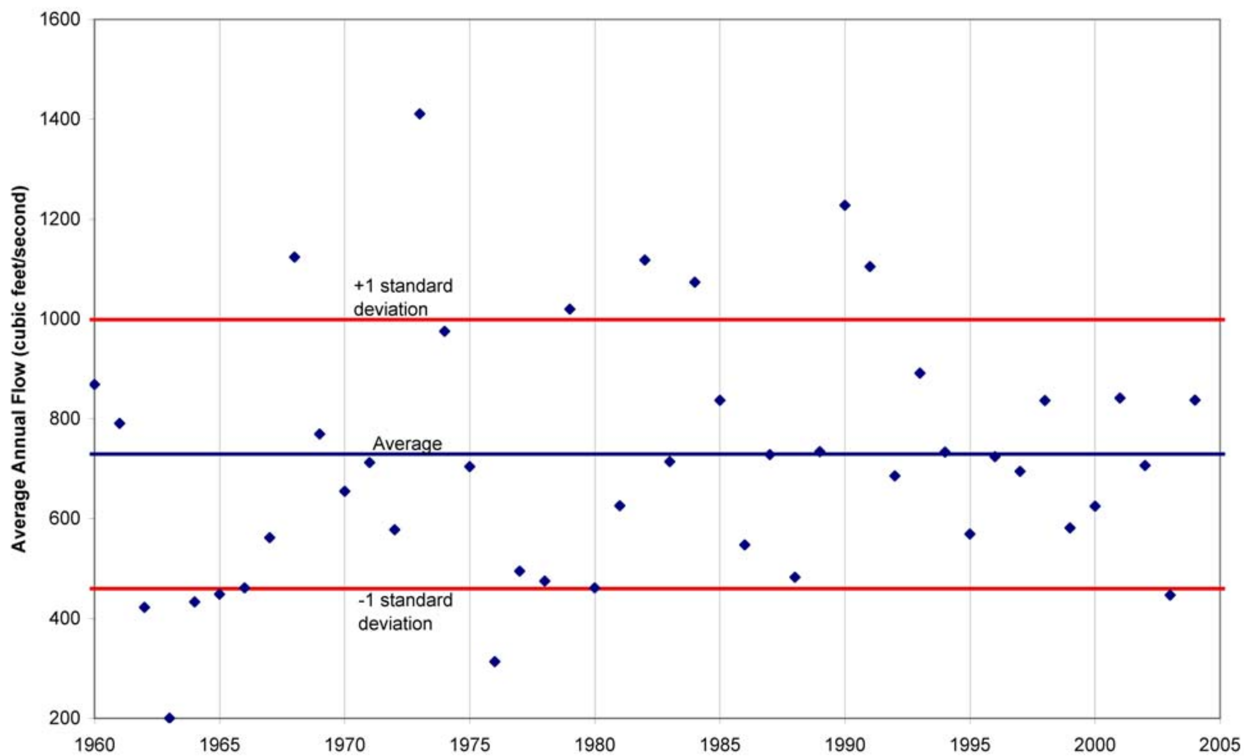


Figure 6.3. Hydrologic characterization of Ouachita River flows.

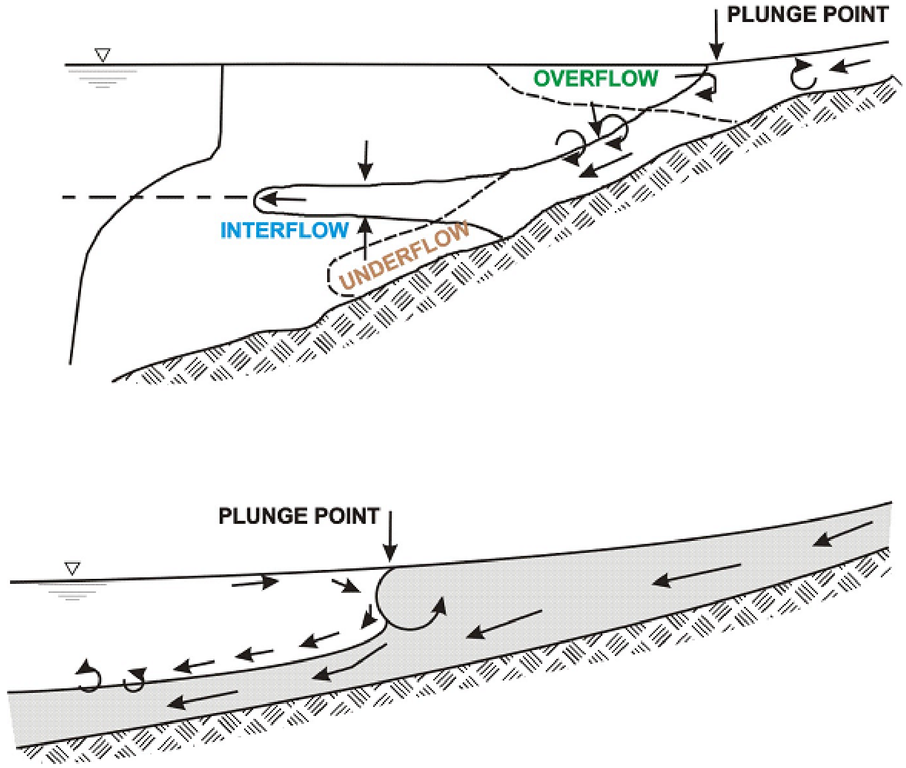


Figure 6.4. Plunge point dynamics in reservoirs.

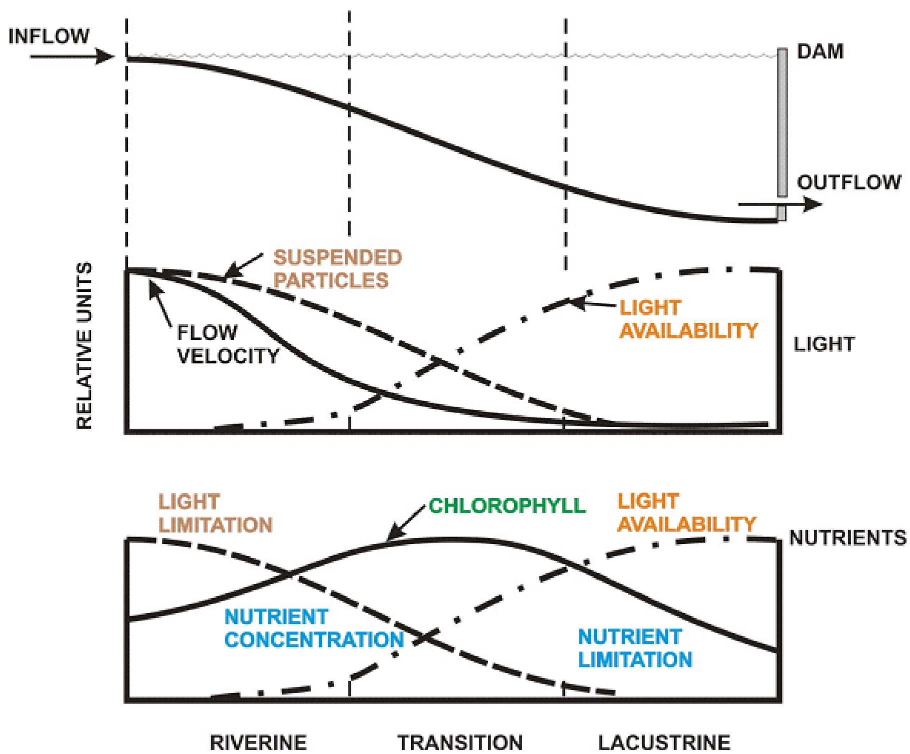


Figure 6.5. Gradients in water quality constituents associated with the plunge point, which defines the location of the transition zone.

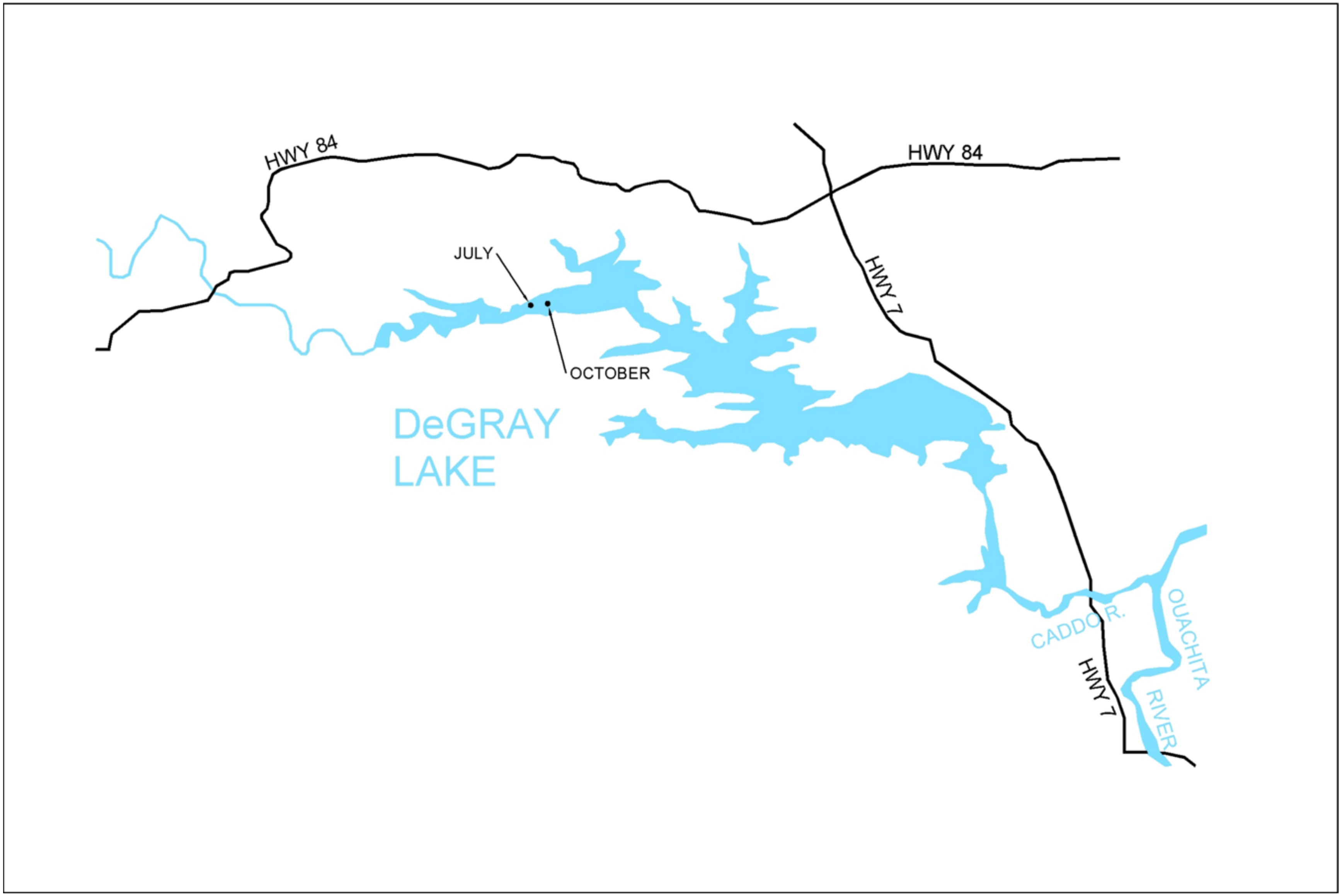


Figure 6.6. Locations of plunge points in DeGray Lake for monthly average conditions.

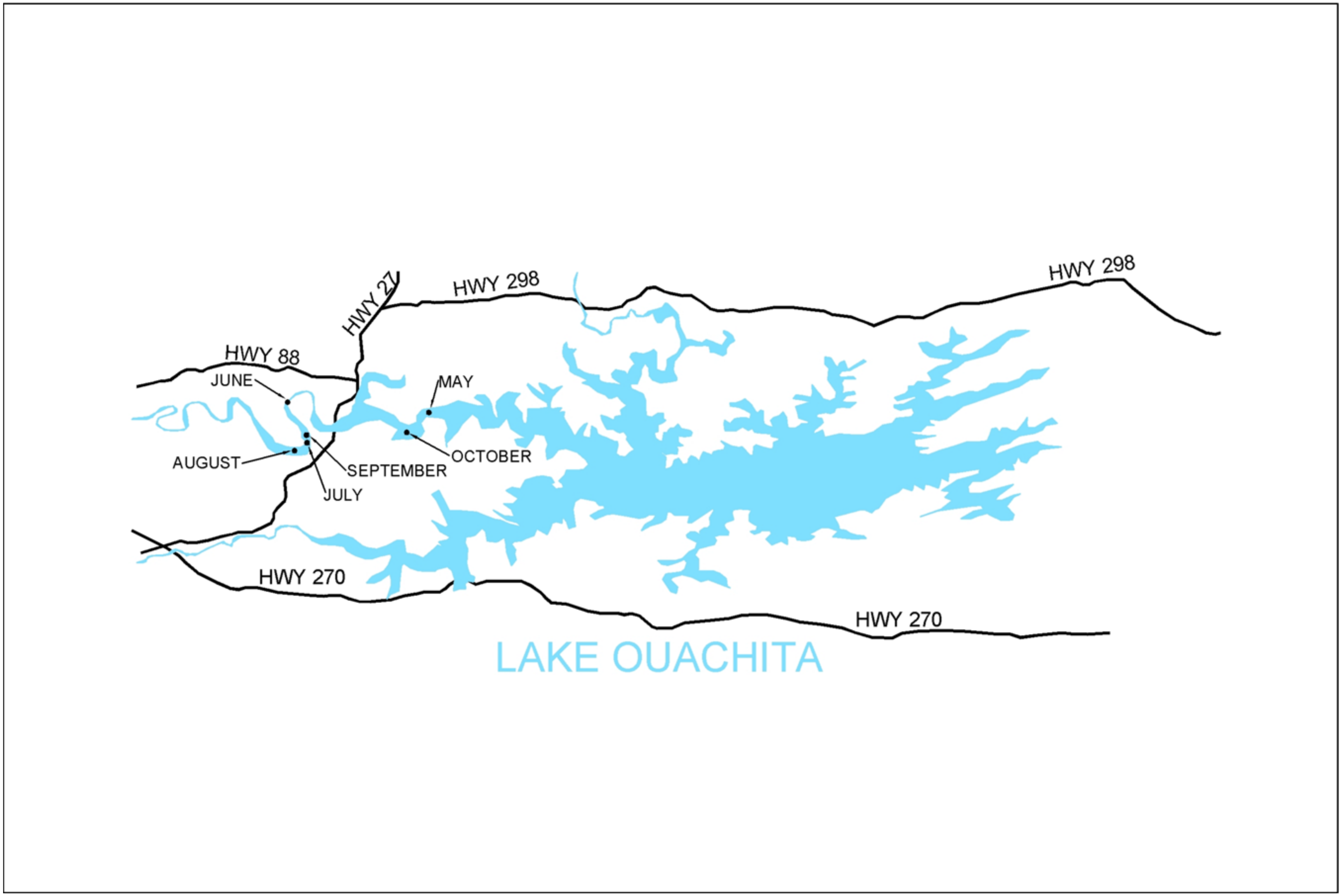


Figure 6.7. Locations of plunge points in Ouachita Lake for monthly average conditions.

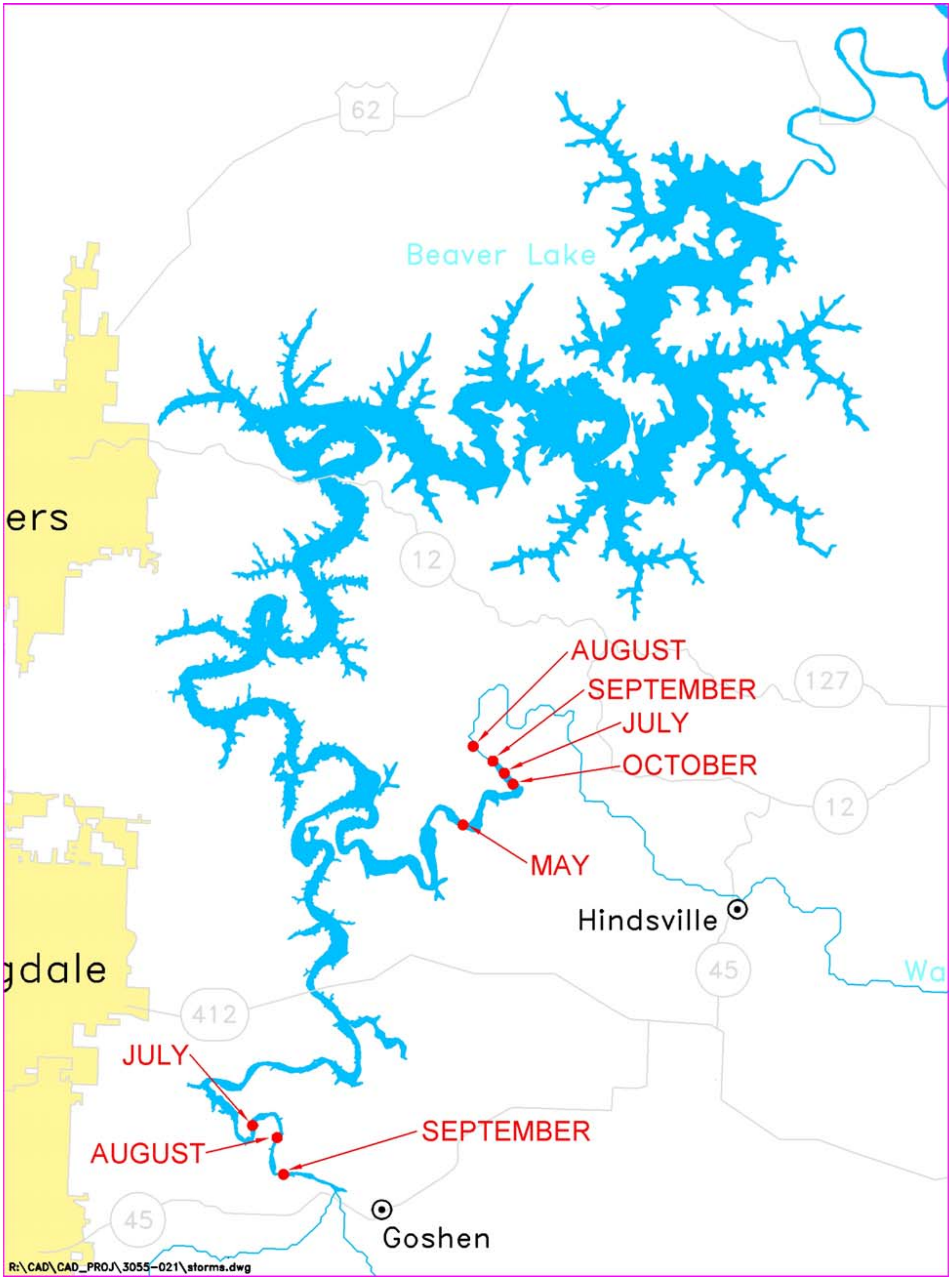


Figure 6.8. Locations of plunge points in Beaver Lake for monthly average conditions.

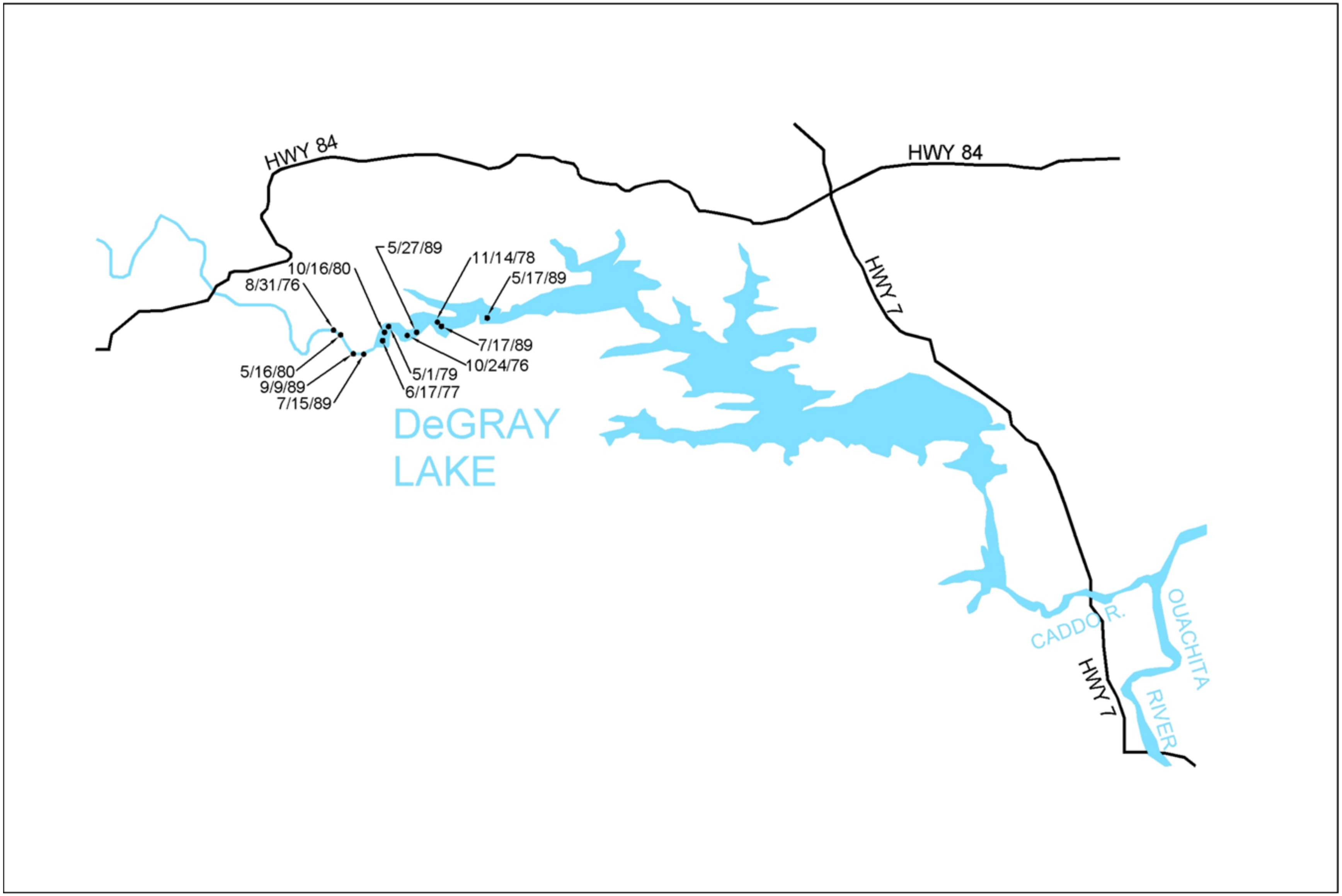


Figure 6.9. Locations of plunge points in DeGray Lake for high-flow storm events.

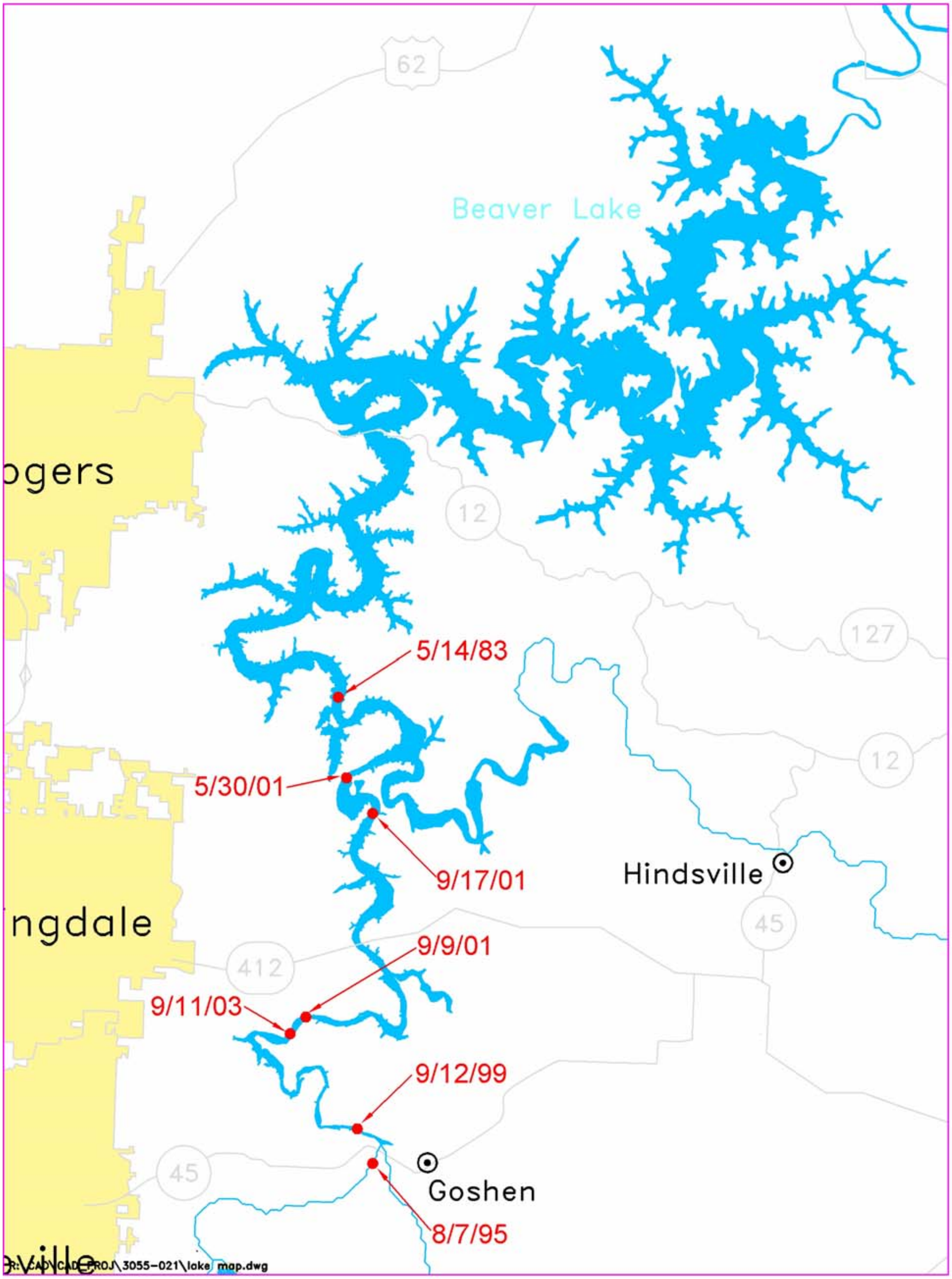


Figure 6.10. Locations of plunge points in Beaver Lake for high-flow storm events.

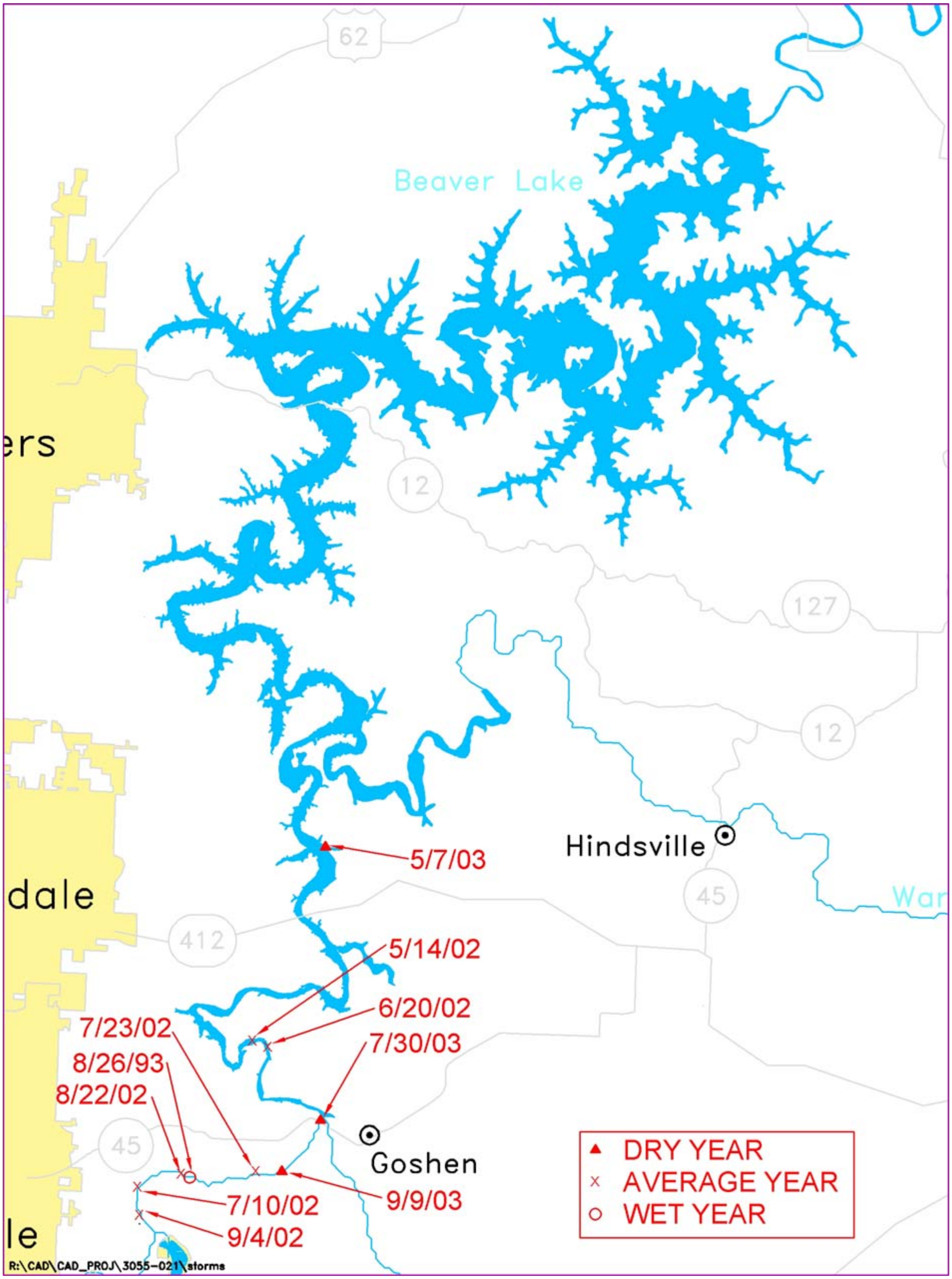


Figure 6.11. Locations of plunge points in Beaver Lake for wet, average, and dry year sampling dates.

7.0 STATISTICAL ANALYSES

7.1 Beaver Lake Analyses

Water quality data collected in Beaver Lake and its tributaries were compiled into a single database. Included in the database are water quality data from USEPA's NES, the Beaver Lake CLS, ADEQ/Arkansas Department of Pollution Control and Ecology (ADPCE) sampling programs, and USGS and USACE sampling programs. Data from the Beaver Water District sampling program for 1993 through 2006 were compiled in a separate database.

7.1.1 Summary Statistics

Summary statistics were calculated for Secchi transparency, DO, chlorophyll a, total phosphorus, and various nitrogen species, as well as ratios of nitrogen to phosphorus. These statistics were calculated for the photic zone by location (Table 7.1). These statistics indicated that there are longitudinal gradients in Beaver Lake water quality. With the exception of chlorophyll concentrations, mean and median values for other water quality constituents were similar at all stations. Mean concentrations of chlorophyll, however, were significantly different than median chlorophyll concentrations, which indicates that each station had chlorophyll blooms and greater chlorophyll concentrations than indicated only by median values

Table 7.1. Annual summary statistics, by location.

Parameter	Annual	Highway 412	Lowell	Dam
Secchi transparency (m)	mean	1.2	1.8	5.0
	median	1.1	1.7	4.9
Chlorophyll a (µg/L)	mean	32.6	12.1	11.0
	median	7.2	4.2	1.1
Total Nitrogen (mg/L)	mean	0.42	0.29	0.22
	median	0.40	0.30	0.18
Total Phosphorus (µg/L)	mean	35	21	14
	median	30	20	10

7.1.2 Longitudinal Water Quality Perspective

Water quality stations in Beaver Lake and its tributaries were ordered based on their distance from the dam (Figure 7.1; all figures are located at the end of this chapter). Box and whisker plots indicate the distribution of a data set as shown in Figure 7.2. Box and whisker plots of historical Secchi transparency, turbidity, chlorophyll a, total nitrogen, and total phosphorus measurements, as well as nitrogen to phosphorus ratios, were developed for all data (Figures 7.3 through 7.8), and for the wet, dry, and average years together (Figures 7.9 through 7.13). These plots exhibited expected longitudinal patterns of water quality.

Ratios of historical total nitrogen to total phosphorus in the photic zone of Beaver Lake (Figure 7.8) generally indicated phosphorus limitation (i.e., were greater than 10). At the upper reservoir station (Site 4), all of the ratios were greater than 10. In the downstream portions of Beaver Lake, there were some ratios that were less than 10, and at the dam there was at least one ratio that was less than 4, indicating nitrogen limitation. However, at all of the Beaver Lake stations, at least 75% of the ratios were greater than 10. At the inflow station (Site 5) over 25% of the ratios were less than 10, and a little less than 25% of the ratios were less than 4, indicating nitrogen limitation.

The box and whisker plots comparing water quality in Beaver Lake under different hydrologic conditions (dry, average, wet) indicated that in the reservoir, Secchi transparency tends to be highest during average hydrologic years and lowest during wet years (Figure 7.9). Except at the dam, Secchi transparency during dry, average, and wet hydrologic years was not statistically different. At the dam, Secchi transparency during wet years was statistically different from transparencies during dry and average years. In general, Secchi transparency was highest at the dam and decreased upstream in the reservoir, with the lowest values at the inflow station.

Beaver Lake chlorophyll a concentrations also tended to be highest during average hydrologic years and lowest during wet years (Figure 7.10). Overall, chlorophyll a concentrations were lowest at the dam and tended to be highest at the upper reservoir station. Typically, chlorophyll a concentrations are highest in the transition zone or the upper portions of the reservoir just downstream of the plunge point (Thornton et al. 1990).

Total phosphorus concentrations in Beaver Lake tended to be less than detection levels in the photic zone, so there was no indication that total phosphorus concentrations in the photic zone differed under different hydrologic conditions, except at the inflow station (Figure 7.11). At the inflow station, total phosphorus concentrations were highest during wet years and lowest during dry and average years. Total phosphorus concentrations during the dry and average years were not statistically different; however, wet year concentrations were statistically different from concentrations in average years. Overall, the highest total phosphorus concentrations occurred at the inflow station and were statistically lower at the downstream stations.

A box and whisker plot of turbidity data available for the Beaver Lake (Figure 7.14) exhibited the expected decreasing trend within Beaver Lake (Sites 1 through 4). The plot also indicated that the White River site (Site 5), and particularly the West Fork site (Site 7), accounted for the majority of the turbidity entering Beaver Lake. Turbidity levels in Richland Creek (Site 6) and War Eagle Creek (Site 10) were significantly lower than White River levels.

7.1.3 Trend Analyses

7.1.3.1 Tributary Water Quality

Long-term water quality data collected from the three major Beaver Lake tributaries (White River, Richland Creek, and War Eagle Creek) were examined for evidence of trends. Initial plots of nutrient, conductivity, turbidity, total suspended sediment, and total organic carbon data over time suggested that water quality in all three tributaries had changed (Figures 7.15 through 7.17).

Water quality data for the White River at Highway 45 were available from 1980 to the present (Figure 7.15). The plots of total phosphorus and ammonia exhibit significant drops in concentration levels in late 1989 or early 1990. This change was due to the new Fayetteville wastewater treatment system that came online (1987). Nitrate + nitrite concentrations, however, appear to have increased since the Fayetteville wastewater treatment system came online. Conductivity also appears to exhibit and increasing trend. Increasing conductivity in streams has been correlated with increasing urbanization of the stream watershed (Paul and Meyer 2001;

Roy et al. 2003). Total organic carbon and total kjeldahl nitrogen concentrations appear to have downward trends over time.

Water quality data for some parameters measured in Richland Creek were available from 1980 to the present. Plots of total phosphorus, total kjeldahl nitrogen, total organic carbon, and turbidity appear to indicate decreasing trends in concentration levels. The plot of nitrate + nitrite appears to indicate an increasing trend over time.

Water quality data for War Eagle Creek were generally available from the early 1990s to the present. The plots of total phosphorus, turbidity, and conductivity suggest increasing trends for these parameters. The plots of total suspended sediment, ammonia, and total organic carbon indicate concentrations of these parameters have decreased over time. The plot of nitrate + nitrite appears to show concentrations increasing between about 1991 and 2000, and then decreasing since 2000 or 2001.

Water quality trends in the White River and War Eagle Creek were examined more closely using Seasonal Kendall-Tau trend analysis (see Sections 7.1.3.3 and 7.1.3.4).

7.1.3.2 Onset and Duration of Anoxia

Initially, DO data collected near Lowell in Beaver Lake by USGS, USACE, and FTN (CLS) were used to determine the earliest date (Julian day) when DO less than 2 mg/L occurred. Since there were gaps in this data during the 1990s, DO data collected by Beaver Water District at their intake were added to the analyses. Examination of the USGS and USACE data revealed that most of the DO data collected by these agencies prior to 2001 were not adequate for estimating date of onset and duration of hypoxic conditions. Most of these years USGS and USACE sampled only three to four times a year (Figures 7.18 and 7.19). A minimum sampling frequency of once per month is necessary to provide a reasonable estimate of date of onset of hypoxic conditions. Beaver Water District sampling frequency ranged from monthly to every 2 weeks.

Examination of the useable data revealed several years where data were available from more than one source. Slightly different start and end dates for hypoxic conditions (DO less than 2 mg/L) were exhibited by the data from different sources (Figure 7.20). New duration values were calculated for these years using the earliest start date and latest end date from available sources. The earliest start date from available sources was also used for these years in the analyses described below.

The earliest Julian day with measured DO less than 2 mg/L was plotted versus year with a linear regression line (Figure 7.21). This plot indicated that there could be a decreasing trend in the Julian day when hypoxic conditions occur, i.e., hypoxic conditions could be occurring earlier. Linear regression analysis of these data did not indicate a significant relationship ($R^2 = 0.08$, $P = 0.38$). Tree analysis (see Section 7.1.5) indicated that there was a statistically significant difference in the day of the year when hypoxia began before and after 1997 (Figure 7.22).

The number of days between the first and last Julian days with measured DO less than 2 mg/L was plotted versus year with a linear regression line (Figure 7.23). This plot indicated that there could be an increasing trend in the duration of hypoxic conditions near the Beaver Water District intake, i.e., hypoxic conditions could be lasting longer. Linear regression analysis of these data did not indicate a significant relationship ($R^2 = 0.13$, $P = 0.24$). Tree analysis (see Section 7.1.5) indicated that there was a statistically significant difference in the duration of hypoxic conditions before and after 1997 (Figure 7.24).

7.1.3.3 Seasonal Kendall-Tau Trend Analyses of Water Quality – Analyses

Water quality data at War Eagle Creek (USGS Gage 0749000), White River (USGS 07048700), Beaver Lake at Highway 412 (USGS Gage 07048910), and Beaver Lake near Lowell (USGS Gage 07049200) collected between 1990 and 2005 were analyzed for long-term trends using Seasonal Kendall-Tau. The parameters analyzed were nitrate + nitrite N, nitrate N, total nitrogen, total phosphorus, turbidity, conductivity, and total organic carbon. The majority of the data used for the analyses were collected by USGS, ADEQ, and USACE. Where it was available, data collected by Beaver Water District were also included in the analyses. Analyses were performed using the USGS-developed program for Kendall trend analyses (USGS 2006).

The lake stations data were adjusted for variability related to sample depth by performing the Seasonal Kendall-Tau analysis on the residuals from LOWESS smoothing of the water quality data versus sample depth. Nutrients in particular usually display characteristic gradients with depth. Total organic carbon at the Lowell station was not adjusted for depth so the Beaver Water District raw water total organic carbon data could be included to increase the size of the data set. Sample depth information was not really available for the Beaver Water District values, so it could not be adjusted. A plot of the Beaver Water District raw water data and total organic carbon data from other sources indicated that reported values were similar, and did not vary much with depth (Figure 7.25). As a result, combining the total organic carbon data and not adjusting them was deemed appropriate.

Plots of the White River data versus the natural log of White River flow at USGS Gage 07048600 indicated relationships between water quality concentrations and flow rate (Figure 7.26). Therefore, the White River data were adjusted for variability related to flow rate by performing the Seasonal Kendall-Tau analysis on residuals from LOWESS smoothing of the water quality data versus the natural log of the reported flow rate. Long-term flow data were not available for War Eagle Creek between 1990 and 1998. Gage height data were available for most of the period between 1990 and 2005, but plots of War Eagle Creek data versus gage height did not indicate relationships between them (Figure 7.27). Plots of the War Eagle Creek data versus the natural log of War Eagle Creek flow for 1998 through 2005 indicated effects of flow on total phosphorus, turbidity, and conductivity. Therefore, these parameters from War Eagle Creek were adjusted for variability related to flow rate by performing the Seasonal Kendall-Tau analysis on residuals from LOWESS smoothing of the parameters versus the natural log of the reported flow rate.

7.1.3.4 Seasonal Kendall-Tau Trend Analyses of Water Quality – Results

Seasonal Kendall-Tau analyses of War Eagle Creek data indicated the most statistically significant ($p \leq 0.05$) water quality trends. Output from the Seasonal Kendall-Tau analyses that indicated trends is summarized in Table 7.2.

Table 7.2. Seasonal Kendall-Tau output indicating trends in War Eagle Creek water quality.

Parameter	Tau Correlation Coefficient	P	Trend Direction	Kendall Line Equation
Nitrate	-0.284	0.0549	Decreasing	NO_3 = 0.92 – (0.02667 * time)
Total Organic Carbon	-0.421	0.0034	Decreasing	TOC = 2.695 – (0.1 * time)
Conductivity	0.325	0.0278	Increasing	Conductivity = 4.295 * time

Notes: Time = decimal year – 1991.75 (beginning of first water year with data)
Conductivity was adjusted for flow prior to analysis.

Seasonal Kendall-Tau analyses of White River data indicated a statistically significant trend only in total phosphorus ($p = 0.0238$). The analysis indicated a decreasing trend in total phosphorus (TP = -0.002106 * time). Seasonal Kendall-Tau analyses of the selected water quality parameters from the Beaver Lake station at Highway 412 did not indicate any statistically significant ($p < 0.05$) trends. Seasonal Kendall-Tau analyses of the selected water quality parameters from the Beaver Lake station near Lowell did not indicate any statistically significant ($p < 0.05$) trends.

7.1.3.5 NES to Present

The only common monitoring station among the 1974 NES, 1991 CLS, and 2001 through 2002 USGS study was the dam station (Table 7.3). In general, there were no significant differences in any of the water quality constituent means or medians.

The monitoring station near Lowell, Arkansas, was a common site between the 1991 CLS and the 2001 through 2002 USGS study. Although there were no significant differences among constituent mean and median values, chlorophyll and total nitrogen concentrations were higher in 2001 through 2002 compared with 1991, but water clarity was better in 2001 through 2002 compared with 1991.

Table 7.3. Comparison of historical Beaver Lake summary statistics.

Parameter		Dam			Lowell	
		NES	CLS	2001-2002	CLS	2001-2002
Chlorophyll a (μg/L)	mean	2.8 (4) [(b)]	1.1 (13)	2.0	2.6 (14)	5.8 (27)
	median	2.7	0.8	1.9	3.8	5.9
Secchi depth (m)	mean	4.5	4.7	5.5	1.8	2.0
	median	4.2	5.2	5.7	1.7	2.0
Total phosphorus (μg/L)	mean	10 (14) [(c)]	4 (78)	20 (50) [(a)]	13 (47)	20 (26) [(a)]
	median	11	5	20	17	20
Total nitrogen (mg/L)	mean	0.38	0.48	0.37	0.44	0.56
	median	0.35	0.49	0.35	0.59	0.68

Notes:
(a) TP values are affected by minimum detection level of 20 μg/L.
(b) Number in parentheses is sample number for chlorophyll and Secchi variables.
(c) Number in parentheses is sample number for total phosphorus and total nitrogen.

7.1.4 Water Quality Percentile Analyses

In its guidance document on developing nutrient criteria for lakes and reservoirs (USEPA 2000), USEPA recommends setting nutrient criteria based on the 25th percentile of existing data for a system (75th percentile for Secchi transparency). Therefore, for Beaver Lake, the 25th percentile of chlorophyll a and trophic zone total phosphorus and total nitrogen, as well as the 75th percentile Secchi transparency, were determined for the available Highway 412 data and the Lowell data. These values are summarized in Table 7.4. In addition, the 25th percentiles of annual average total phosphorus and total nitrogen, and geometric average chlorophyll a for the growing season, along with the 75th percentile of annual average Secchi transparency, were determined for Highway 412 and Lowell sites (Table 7.5). The values in Tables 7.4 and 7.5 are very similar.

Table 7.4. Potential criteria determined using USEPA method for selected Beaver Lake stations – raw data.

Site	25th Percentile Chlorophyll a (μg/L)	75th Percentile Secchi Transparency (m)	25th Percentile Total Phosphorus (mg/L)	25th Percentile Total Nitrogen (mg/L)
Highway 412	2.6	0.76	0.020	0.65
Lowell	2.35	1.1	0.013	0.39

Table 7.5. Potential criteria determined using USEPA method for selected Beaver Lake stations – annual statistics.

Site	25th Percentile Growing Season Geometric Mean Chlorophyll a (μg/L)	75th Percentile Annual Average Secchi Transparency (m)	25th Percentile Annual Average Total Phosphorus (mg/L)	25th Percentile Annual Average Total Nitrogen (mg/L)
Highway 412	2.9	0.77	0.025	0.705
Lowell	2.4	1.35	0.020	0.38

7.1.5 Change-Point Analyses

Change-point statistical analysis is a procedure for identifying natural changes in variance of a constituent. This nonparametric procedure is based on a series of rules for partitioning variance into classes or categories, each with a more homogeneous variance structure. These rules are incorporated into classification and regression tree (CART) analyses.

Qian et al. (2003) noted that the change-point nonparametric deviance reduction approach for identifying water quality change points "is consistent with the tree-based modeling (i.e., CART) approach," and that "the change point is the first split of a tree model when *x* is used as the single predictor variable. As a result, the commonly available tree model software … can be used." We used the tree model in the Systat version 9.0 statistical software program to identify change points in Beaver Lake data from 1979 through 2005 collected in the photic zone.

7.1.5.1 Chlorophyll a

Change-point analyses of chlorophyll a concentrations paired with total phosphorus, total nitrogen, and turbidity were conducted. The analysis did not identify a significant change in chlorophyll a concentrations associated with total phosphorus concentrations. A significant change in the chlorophyll a data was identified at 0.5 mg/L total nitrogen (Figure 7.28). There were 100 chlorophyll a measurements associated with total nitrogen concentrations less than 0.5 mg/L, with a mean value of 2.71 mg/L chlorophyll a. There were 95 chlorophyll a measurements associated with total nitrogen concentrations greater than 0.5 mg/L, with a mean value of 5.85 mg/L chlorophyll a. A significant change in the chlorophyll a data was also identified at 0.26 nephelometric turbidity units (NTU) turbidity (Figure 7.29). There were five chlorophyll a measurements associated with turbidities less than 0.26 NTU with an average value of 38 µg/L. There were 290 chlorophyll a measurements associated with turbidities greater than 0.26 NTU, with an average value of 4.8 µg/L.

Change-point analyses pairing chlorophyll a concentrations and location in the reservoir indicated a significant difference in chlorophyll a concentrations at Highway 412 and at stations downstream of Highway 412. At Highway 412 there were 92 chlorophyll a measurements with a mean value of 11.3 µg/L. Downstream of the Highway 412 station there were 305 measurements with a mean value of 3.1 µg/L. This indicates that the highest chlorophyll a concentrations occur in the upper reservoir, as would be expected.

Change-point analyses pairing total phosphorus concentrations and location in the reservoir indicated a significant difference in total phosphorus concentrations upstream and downstream of the station near Lowell. At the Lowell and Highway 412 stations there were 127 total phosphorus measurements with a mean value of 0.023 mg/L. Downstream of the Lowell station there were 373 measurements with a mean value of 0.013 mg/L. The location of the highest total phosphorus concentrations was similar to the location of the highest chlorophyll a concentrations, as would be expected.

Additional tree modeling for individual locations in the reservoir identified total phosphorus and turbidity thresholds associated with change points in chlorophyll a concentrations. Chlorophyll a change points associated with total phosphorus were identified at only two of the Beaver Lake stations. At Site 2 (see Figure 7.1), chlorophyll a was statistically different (less) when total phosphorus concentrations were less than 0.010 mg/L (Figure 7.30), and at Lowell (Site 3), chlorophyll a was statistically different (greater) when total phosphorus concentrations were less than 0.040 mg/L (Figure 7.31). Also at Lowell, chlorophyll a was statistically different (greater) when turbidity was less than 2.6 NTU (Figure 7.32). At Site 4 (Highway 412), chlorophyll a was statistically different (greater) when turbidity was less than 26 NTU (Figure 7.33).

7.1.5.2 Secchi depth

Change-point analyses of Secchi depth paired with total phosphorus, total nitrogen, and turbidity were conducted. For these analyses, all total phosphorus, total nitrogen, and turbidity values reported for the photic zone were associated with the sample day Secchi transparency. Analyses with total phosphorus were conducted both including and excluding total phosphorus reported as less than detection (less than detection values were set to the detection level in the data set). Results of these analysis are summarized as follows:

1. When cases with total phosphorus less than detection values were included, a Secchi depth change point was identified at 0.007 mg/L total phosphorus (Figure 7.34). There were 112 Secchi measurements associated with total phosphorus less than 0.007 mg/L, with a mean value of 4.9 meters. There were 541 Secchi measurements associated with total phosphorus greater than 0.007 mg/L, with a mean value of 3.0 meters;
2. When cases with total phosphorus less than detection values were excluded, the Secchi depth change point was at 0.011 mg/L total phosphorus (Figure 7.35). There were 187 Secchi measurements associated with total phosphorus less than 0.011 mg/L, with a mean value of 4.2 meters. There were 231 Secchi measurements associated with total phosphorus greater than 0.011 mg/L, with a mean value of 2.1 meters;
3. For Secchi measurements associated with total nitrogen data, a Secchi depth change-point was identified at 0.75 mg/L total nitrogen (Figure 7.36). There were 320 Secchi measurements associated with total nitrogen less than 0.75 mg/L, with a mean value of 4.1 meters. There were 109 Secchi measurements associated with total nitrogen greater than 0.75 mg/L, with a mean value of 2.4 meters; and
4. For Secchi measurements associated with turbidity data, a Secchi depth change point was identified at 1.8 NTU turbidity (Figure 7.37). There were 324 Secchi measurements associated with turbidity less than 1.8 NTU, with a mean value of 4.2 meters. There were 334 Secchi measurements associated with turbidity greater than 1.8 NTU, with a mean value of 2.0 meters.

Change-point analyses pairing Secchi transparency and location in the reservoir indicated a significant difference in Secchi transparency upstream and downstream of Highway 12. At the dam and Highway 12 stations there were 313 Secchi transparency measurements with a mean value of 5.0 meters. Upstream of Highway 12 there were 314 measurements with a mean value of 1.7 meters.

Additional tree modeling identified total phosphorus thresholds associated with change points in Secchi depth at different locations in the reservoir. These analyses showed that Secchi transparency was statistically different (greater) when total phosphorus concentrations were less than 0.011 to 0.008 mg/L at stations downstream of Lowell. At Lowell, Secchi transparency was statistically different (greater) when total phosphorus concentrations were less than 0.031 mg/L, and at the upper reservoir station, Secchi transparency was statistically different (greater) when total phosphorus concentrations were less than 0.040 mg/L.

7.2 Reference Conditions

7.2.1 Reference Streams

In the late 1980s, ADEQ identified least-disturbed streams in the Ozark Highlands and Boston Mountains Ecoregions of the state for development of ecoregion water quality standards (ADPCE 1987). These streams are listed in Table 7.6. Nutrient concentrations in these streams can also contribute to development of nutrient water quality criteria for Beaver Lake. Average nutrient concentrations from the ecoregion water quality study are included in Table 7.6. Note that these data were collected between 1984 and 1986, and consist of three samples collected on each sample date. Nutrient concentrations in the least-disturbed streams in the Ozark Highlands Ecoregion are higher than in the Boston Mountain Ecoregion. Since the majority of the Beaver Lake watershed is located in the Ozark Highlands Ecoregion, data from this ecoregion will be used for comparison to Beaver Lake tributaries.

Water quality data are currently collected from only four of the Ozark Highlands least-disturbed streams: Flint Creek, Long Creek, War Eagle Creek, and Kings River. Analysis of historical and current measurements of total phosphorus, phosphate phosphorus, and nitrate + nitrite indicate that for Flint Creek, War Eagle Creek, and Kings River (near Berryville), current levels of these nutrients are similar to the levels in the early 1990s (Figures 7.38 through 7.40). Current nutrient concentrations in Long Creek, especially phosphorus, appear significantly higher than occurred historically (Figure 7.41).

Table 7.6. Ecoregion least-disturbed streams (ADPCE 1987).

	Total Phosphorus (mg/L)		**PO_4 P (mg/L)**		**NO_2+NO_3 (mg/L)**		**NH_3-N (mg/L)**	
	Spring	**Summer**	**Spring**	**Summer**	**Spring**	**Summer**	**Spring**	**Summer**
Ozark Highlands Ecoregion								
South Fork Spavinaw Creek	0.01	0.01	0.01	0.01	1.51	0.92	0.04	0.01
Flint Creek	0.15	0.08	0.09	0.01	1.86	0.92	0.10	0.04
Yocum Creek	0.07	0.03	0.03	0.02	1.52	0.72	<0.01	<0.02
Long Creek	0.04	0.03	0.03	0.01	0.95	1.03	0.03	0.04
War Eagle Creek	0.03	0.05	0.02	0.03	0.62	1.15	0.07	<0.01
Kings River	0.02	0.09	0.02	0.07	0.19	0.38	0.08	0.01
Average	0.05	0.04	0.03	0.02	0.95	0.73	<0.05	<0.02
Boston Mountains Ecoregion								
Indian Creek	0.01	0.01	<0.01	0.01	<0.01	<0.01	0.04	0.02
Hurricane Creek	0.01	0.02	<0.01	<0.01	<0.01	<0.01	0.03	0.01
Archey Fork Creek	0.02	0.03	0.02	0.01	0.02	0.03	0.03	<0.01
Illinois Bayou	0.01	0.03	0.01	0.02	0.04	0.05	0.03	0.02
Lee Creek	0.05	0.02	0.02	<0.01	0.05	0.03	0.02	0.01
Mulberry River	0.05	0.03	0.01	<0.01	0.05	0.01	0.01	<0.01
Average	0.02	0.02	<0.01	<0.01	<0.03	<0.02	0.02	<0.01

7.2.2 Reference Reservoirs

Data were compiled for Lake Greeson, DeGray Lake, and Lake Ouachita. These data sets included data from ADEQ/ADPCE, USACE, and USGS sampling programs. Very little water quality data were available for Lake Greeson, so it was eventually dropped from the analyses. Water quality in DeGray Lake and Lake Ouachita was characterized using longitudinal plots of data, plunge point estimates, and change-point analysis.

7.2.2.1 Longitudinal Water Quality Plots

Water quality stations in DeGray Lake, Lake Ouachita, Lake Greeson and their tributaries were ordered based on their distance from the dam (Figures 7.42 through 7.44). Box and whisker plots (see Figure 7.2) of historical Secchi transparency, turbidity, chlorophyll a, total nitrogen, and total phosphorus measurements versus location in the reservoir were developed for all three reservoirs. Plots of total phosphorus, total nitrogen, and turbidity used only data from samples taken from near the surface of the reservoirs. Analyses of these parameters were restricted to the photic zone because that is the part of the water column where the response of algal productivity and Secchi transparency has been strongest in reservoirs. Most of the data available for DeGray Lake were not categorized by depth (i.e., TOP, MID, BOTTOM). For DeGray Lake, all data collected from depths less than 20 ft were categorized as TOP samples. This depth was an estimate of the depth of the photic zone (2 * Secchi transparency) for DeGray Lake. Secchi transparency data were not available for the majority of the DeGray Lake samples; therefore, it was not possible to calculate the depth of the photic zone for each sample date. The overall historical average Secchi transparency of DeGray Lake was 2.6 meters. This Secchi transparency suggests a photic zone approximately 17 ft deep, which was rounded up to 20 ft.

Water quality in reservoirs typically varies longitudinally. The box and whisker plots helped us characterize and compare the water quality variability at different locations in the reservoirs. These plots also showed us that useable amounts of data at all locations in the reservoir were available only for DeGray Lake. For the most part, water quality data for Lake Ouachita and Lake Greeson were available only near the dam and for the primary tributaries. Therefore, DeGray Lake was the only reservoir for which longitudinal variability could be characterized. The longitudinal variability of DeGray Lake is summarized below:

1. Secchi depths exhibited an increasing trend from the lake headwaters to the dam, with Secchi depths near the dam statistically different (greater) from those in the upper lake (Figure 7.45);
2. Total phosphorus concentrations exhibited a decreasing trend from the lake headwaters to the dam. Total phosphorus concentrations near the dam were statistically different (less) from those in the upper lake and tributaries. The greatest maximum total phosphorus concentration was measured in the upper lake, 19.5 miles upstream of the dam (Figure 7.46);
3. Total nitrogen concentrations exhibited a decreasing trend from the lake headwater to the dam (Figure 7.47). The median at each lake sampling site was statistically different (less) from the upstream station;
4. Turbidity measurements exhibited a decreasing trend from the lake inflows to the dam (Figure 7.48). Turbidity values near the dam were statistically different (less) from those in the upper lake and tributaries; and
5. Chlorophyll a concentrations also exhibited a decreasing trend from the upper lake to the dam (Figure 7.49). Chlorophyll a concentrations near the dam were statistically different (less) from those in the upper lake. The greatest maximum

chlorophyll a concentration was measured in the upper lake, 19.5 miles upstream of the dam (the same location as the maximum phosphorus and nitrogen concentrations).

7.2.2.2 Percentile

In its guidance document on developing nutrient criteria for lakes and reservoirs (USEPA 2000), USEPA recommends setting nutrient criteria based on the 75th percentile of existing data from a reference system. Therefore, for DeGray Lake and Lake Ouachita, the 75th percentile of chlorophyll a, trophic zone total phosphorus and total nitrogen, and the 25th percentile of Secchi transparency were determined for the data for the upper lakes. These values are summarized in Table 7.7.

Table 7.7. Potential criteria for upper lake stations in reference reservoirs using USEPA method.

Reservoir	75th Chlorophyll a (µg/L)	25th Secchi Transparency (m)	75th Total Phosphorus (mg/L)	75th Total Nitrogen (mg/L)
DeGray Lake	9.0	0.9	0.038	0.765
Ouachita Lake	--	1.4	0.016	0.33

7.2.2.3 Change-Point Analyses

Change-point analyses (see Section 7.1.5) were conducted on DeGray Lake water quality data sampled from less than 20 ft deep (except chlorophyll a, which was assumed to be collected only in the photic zone).

7.2.2.3.1 Chlorophyll a

Change-point analyses were conducted on chlorophyll a concentrations paired with total phosphorus, total nitrogen, and turbidity. The analyses did not identify a significant change in the chlorophyll a distributions when associated with total nitrogen or turbidity. A significant change in the chlorophyll a distributions was identified at 17 µg/L total phosphorus (Figure 7.50). There were 543 chlorophyll a measurements associated with total phosphorus measurements less than 17 µg/L, with a mean value of 2.83 µg/L chlorophyll a. There were 150 chlorophyll a measurements associated with total phosphorus concentrations greater than 17 µg/L, with a mean value of 4.89 µg/L chlorophyll a.

7.2.2.3.2 Secchi Depth

Change-point analyses were conducted on Secchi depth paired with total phosphorus, total nitrogen, and turbidity. Results of these analyses are summarized below.

1. In Secchi measurements associated with total phosphorus (Figure 7.51), a Secchi depth change point was identified at 14 µg/L total phosphorus. There were 1,247 Secchi measurements associated with total phosphorus concentrations less than 14 µg/L, with a mean value of 2.71 meters. There were 1,155 Secchi measurements associated with total phosphorus concentrations greater than 14 µg/L, with a mean value of 1.68 meters;
2. In Secchi measurements associated with total nitrogen, a Secchi depth change point was identified at 0.46 mg/L total nitrogen (Figure 7.52). There were 767 Secchi measurements associated with total nitrogen concentrations less than 0.46 mg/L, with a mean value of 2.43 meters. There were 695 Secchi measurements associated with total nitrogen concentrations greater than 0.46 mg/L, with a mean value of 1.68 meters; and
3. In Secchi measurements associated with turbidity, a Secchi depth change point was identified at 3.7 NTU turbidity (Figure 7.53). There were 1,568 Secchi measurements associated with turbidity measurements less than 3.7 NTU, with a mean value of 2.63 meters. There were 1,013 Secchi measurements associated with turbidity measurements greater than 3.7 NTU, with a mean value of 1.60 meters.

The mean and standard deviations of the Secchi measurements above and below the total phosphorus and turbidity change points were very similar. The means of the Secchi measurements above and below the total nitrogen change point were similar to the means above and below the total phosphorus and turbidity change points, but the standard deviations were different.

7.3 Comparison Between Beaver Lake and Reference Reservoirs

7.3.1 Inputs

The average nutrient concentrations reported for inflows to the reference reservoirs and Beaver Lake during the period from 1989 through 2006 are listed in Table 7.8. Average nutrient concentrations reported for the inflows to the reference reservoirs are all less than the Ozark Highlands Ecoregion average concentrations (these streams are not located in the Ozark Highlands Ecoregion). Average nutrient concentrations reported for the White River (at Highway 45) are greater than the averages for the ecoregion. Average nutrient concentrations reported for Richland Creek are all less than the ecoregion averages. Average recent nutrient concentrations reported for War Eagle Creek are similar to or greater than the ecoregion averages.

Table 7.8. Comparison of inflow concentrations for reference reservoirs and Beaver Lake from 1989 to 2006.

	Total P (mg/L)	PO_4 P (mg/L)	NO_2+NO_3 (mg/L)	NH_3-N (mg/L)
Ozark Highlands Ecoregion (1984 – 1986)				
Average	0.045	0.025	0.84	<0.035
Reservoir Inflows (1989 – 2006)				
Self Creek (Greeson)	0.019	0.009	0.251	0.013
Little Missouri River (Greeson)*	0.019	0.002	0.147	0.019
Caddo River (DeGray)*	0.045	0.013	0.170	-
Iron Fork (Ouachita)	0.019	0.002	0.039	0.015
Ouachita River (Ouachita)	0.039	0.009	0.171	0.017
South Fork River (Ouachita)*	0.021	0.011	0.122	0.018
White River (Beaver)	0.081		1.03	0.052
Richland Creek (Beaver)	0.045		0.387	0.036
War Eagle Creek (Beaver)*	0.054		1.37	0.029

* These are least-disturbed reference streams from ADEQ 1987.

Table 7.9 shows a comparison of nutrient loads to Beaver Lake and the reference reservoirs. These loads are calculated from the average flows recorded by USGS gages on tributaries and the average concentrations of nutrients measured in the tributaries. The least-disturbed Beaver Lake load is calculated using the average flows recorded by USGS gages on the tributaries, and the lower of the measured concentration or the Ozark Highlands

Ecoregion least-disturbed average concentration. Nutrient loads for the reference reservoirs are less than half the Beaver Lake existing and least-disturbed loads. In part, this is because inflows to the reference lakes are lower than for Beaver Lake. Lake Ouachita has almost as much inflow as Beaver Lake, but still has a significantly lower load because the inflow concentrations are so much lower for Lake Ouachita than for Beaver Lake.

Table 7.9. Comparison of nutrient loads to Beaver Lake and the reference systems.

Waterbody	Inflow (cfs)	Total P (kg/day)	NO_x (kg/day)	NH_3 (kg/day)
Beaver Lake (existing)	964	161	2443	102
Beaver Lake (least-disturbed)	964	106	1830	78
DeGray Lake	594	65	247	
Lake Ouachita	814	74	330	34
Lake Greeson	131	6.1	47	6.1

7.3.2 Reservoir Water Quality

Water quality in Beaver Lake was compared to water quality in DeGray Lake by comparing the longitudinal box and whisker plots for these two reservoirs (plots of Beaver Lake data are shown in Figures 7.3 through 7.8; DeGray Lake plots are shown in Figures 7.42 through 7.44). Secchi transparencies measured at the dam in Beaver Lake tended to be greater than those measured at the dam in DeGray Lake. This is likely a result of the fact that Beaver Lake is longer than DeGray Lake, so more material has settled out of the water column by the time water reaches Beaver Dam. Chlorophyll a concentrations at all Beaver Lake sites were similar to those reported for DeGray Lake. Total phosphorus concentrations at all Beaver Lake sites except the dam (Site 1) were greater than (statistically significant) total phosphorus concentrations reported in DeGray Lake. Total nitrogen concentrations at all Beaver Lake sites were greater than (statistically significant) total nitrogen concentrations reported for similar locations in DeGray Lake. Turbidity values at the mid and upper DeGray Lake stations were greater than (statistically significant) Beaver Lake turbidity values for similar locations. However, Beaver Lake inflow (White River) turbidity was greater than (statistically significant) for DeGray Lake (Caddo River). Overall, it does appear that Beaver Lake is more nutrient-rich than DeGray Lake. However, Secchi transparency and chlorophyll a concentrations in Beaver Lake do not appear to be significantly different.

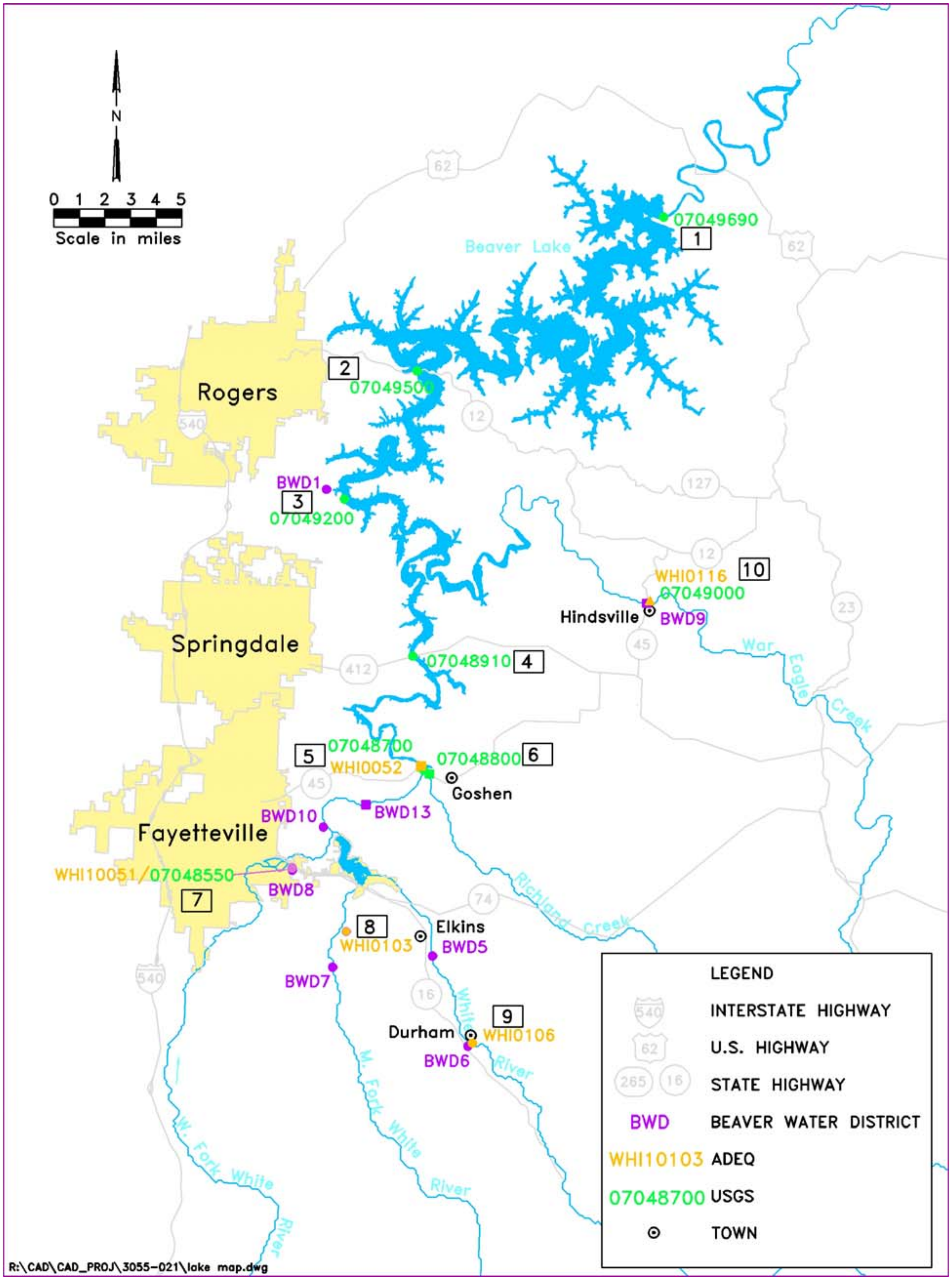


Figure 7.1. Map of Beaver Lake water quality stations for analyses.

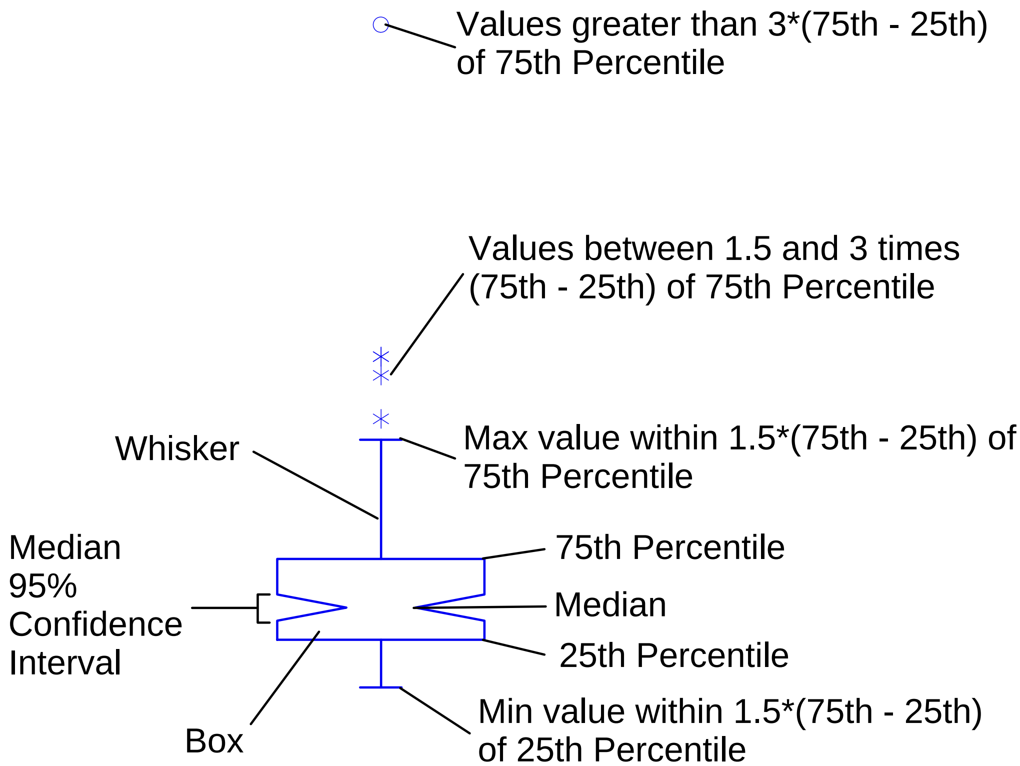


Figure 7.2. Explanation of box and whisker plot.

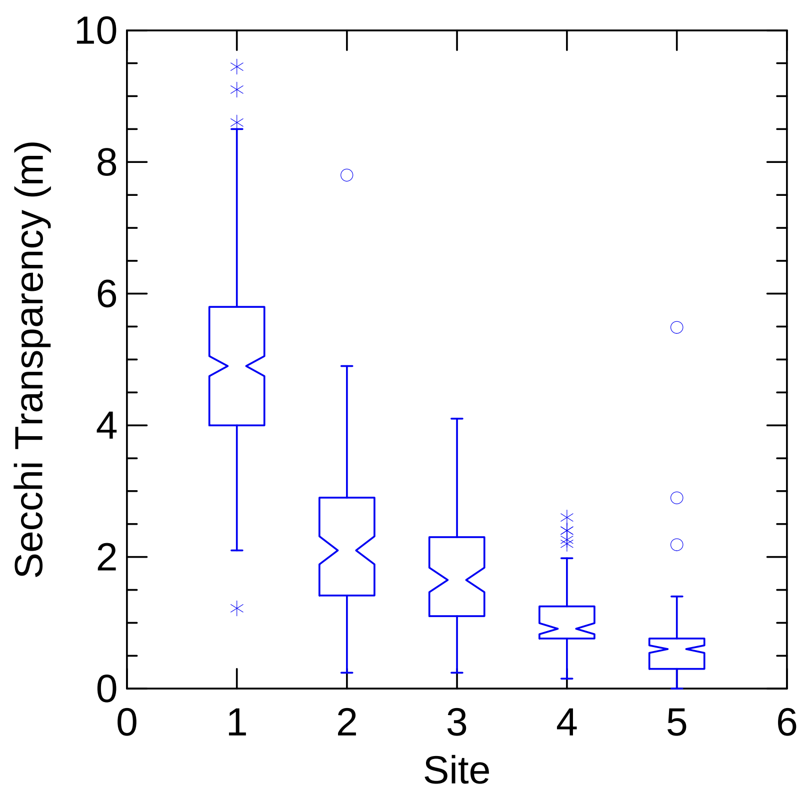


Figure 7.3. Box and whisker plot of Secchi transparency at selected Beaver Lake locations.

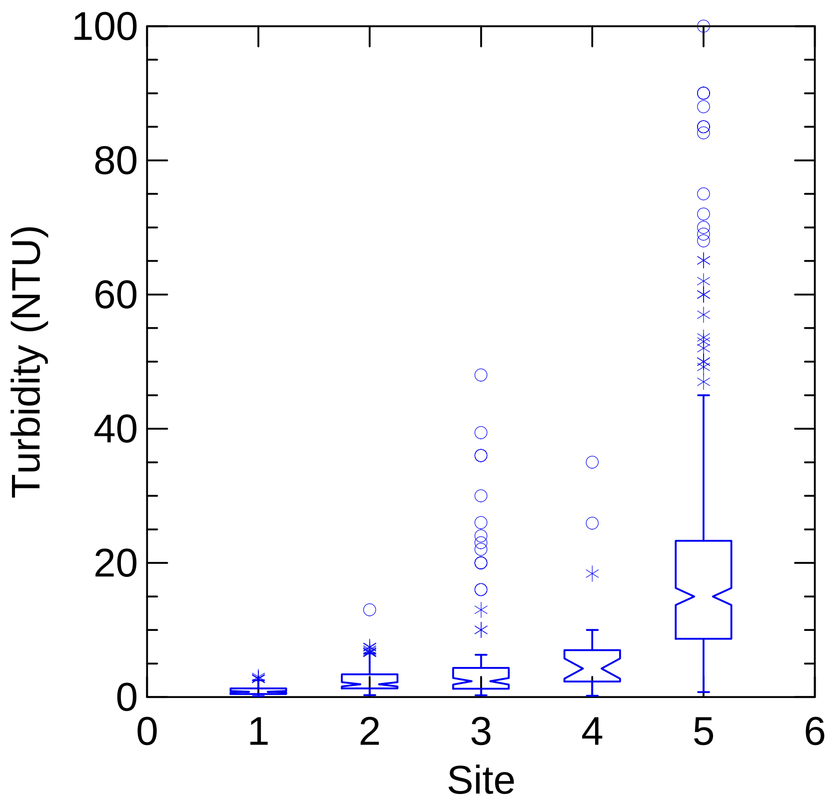


Figure 7.4. Box and whisker plot of turbidity at selected Beaver Lake locations.

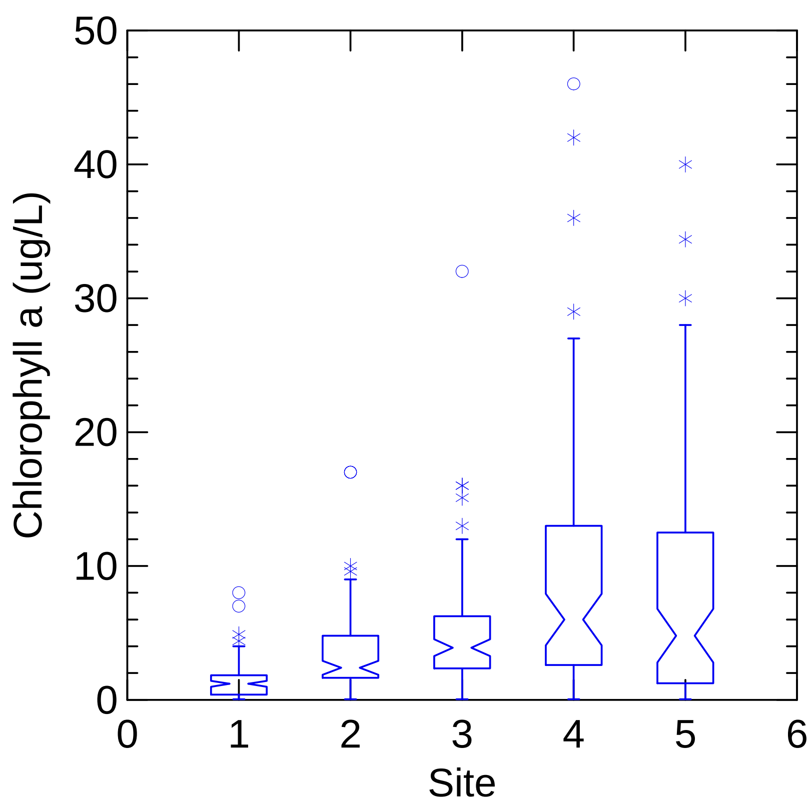


Figure 7.5. Box and whisker plot of chlorophyll a at selected Beaver Lake locations.

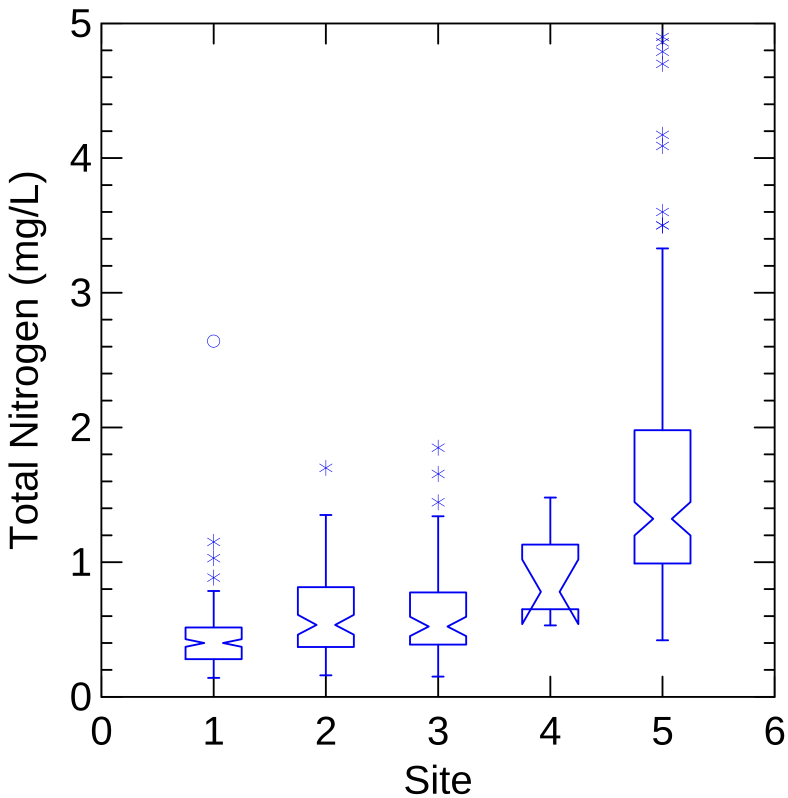


Figure 7.6. Box and whisker plot of total nitrogen at selected Beaver Lake locations.

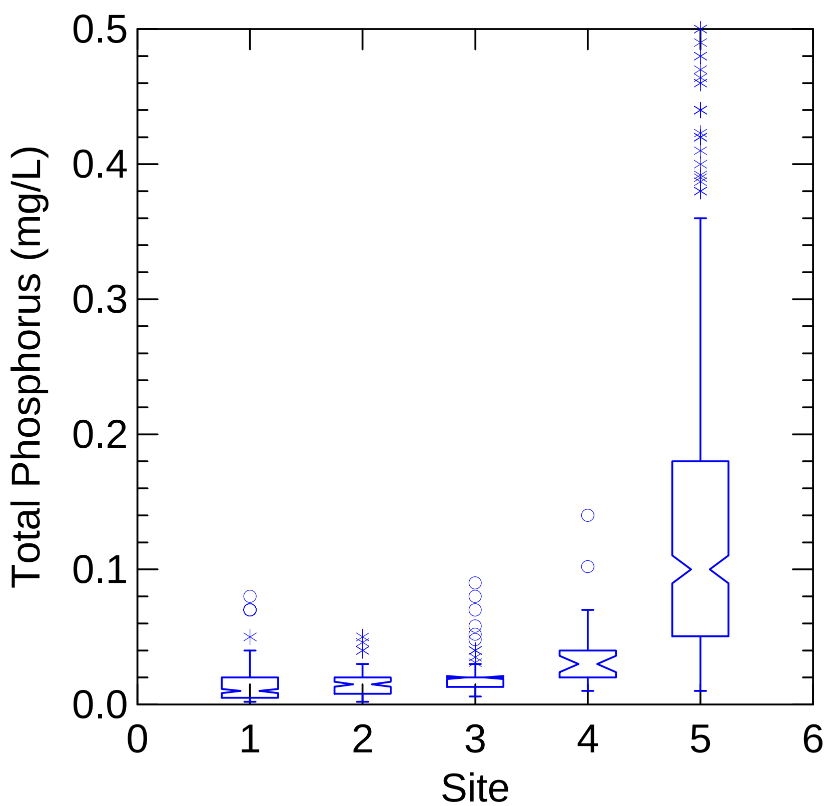


Figure 7.7. Box and whisker plot of total phosphorus at selected Beaver Lake locations.

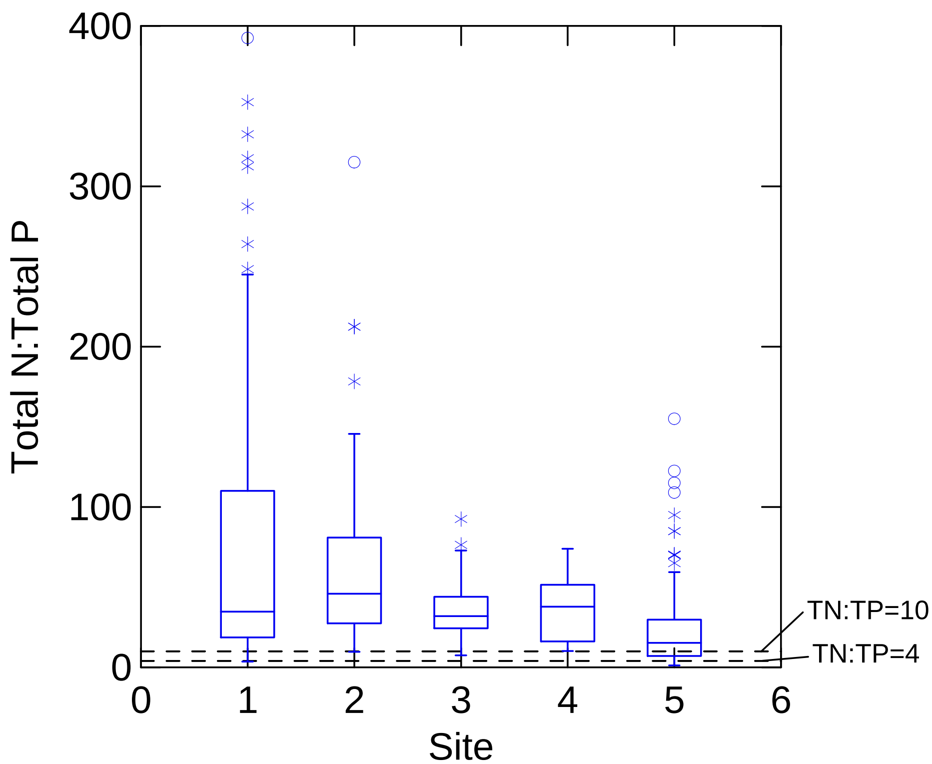


Figure 7.8. Box and whisker plot of ratios of total nitrogen to total phosphorus at selected Beaver Lake locations.

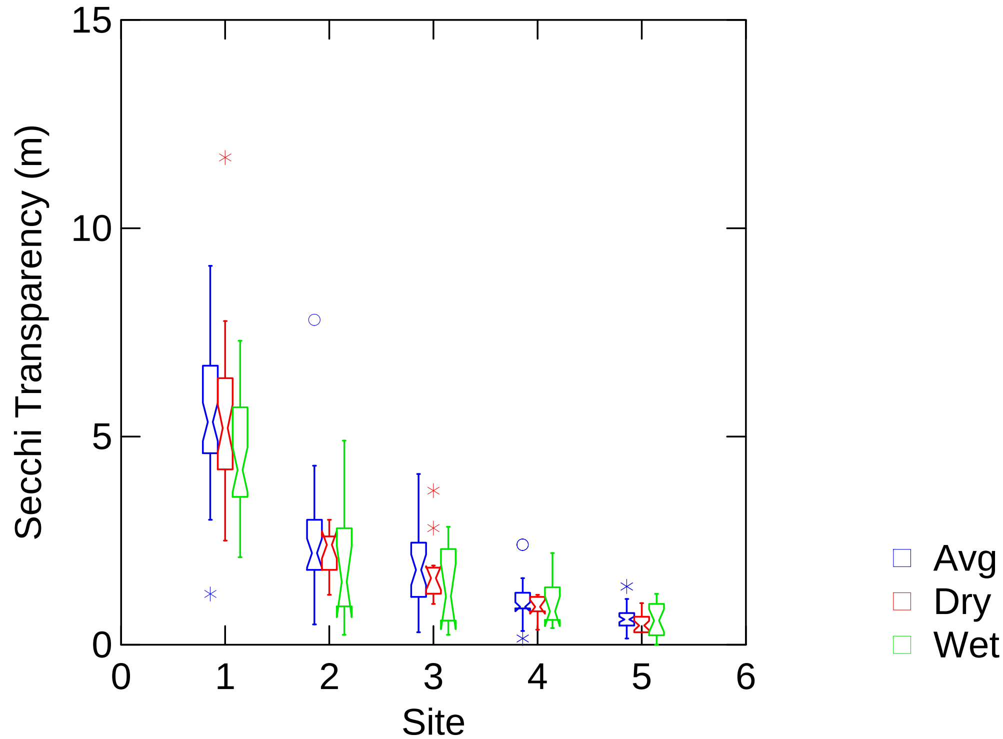


Figure 7.9. Secchi transparency during wet, average, and dry years at selected Beaver Lake sites.

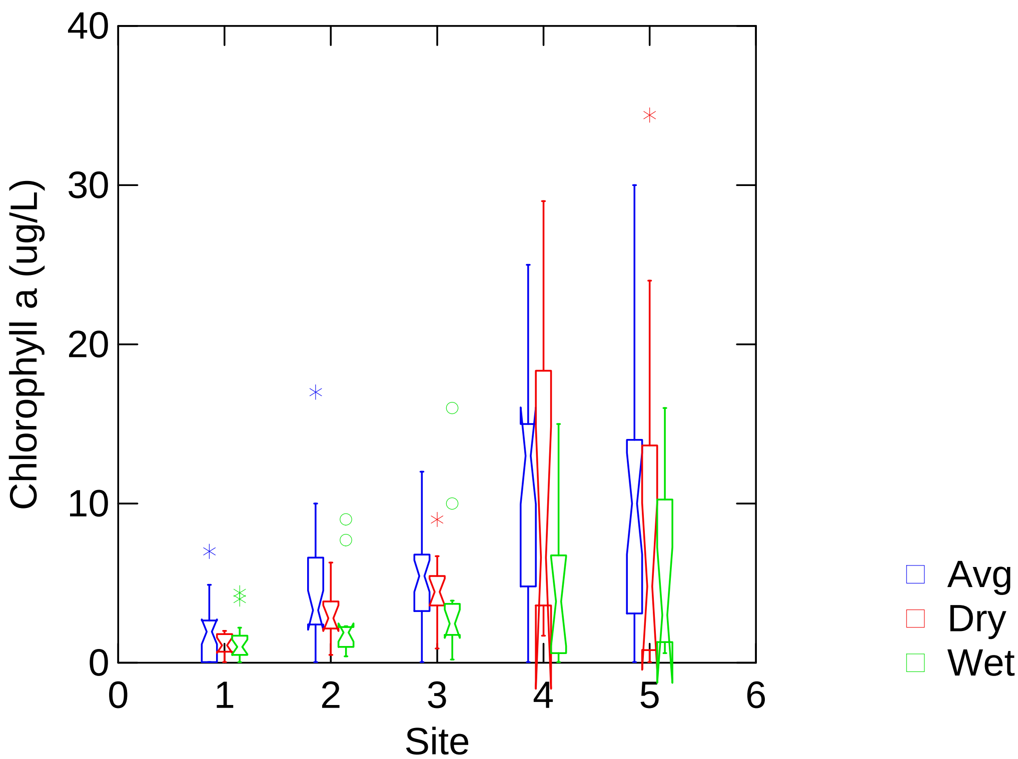


Figure 7.10. Chlorophyll a concentrations during wet, average, and dry years at selected Beaver Lake sites.

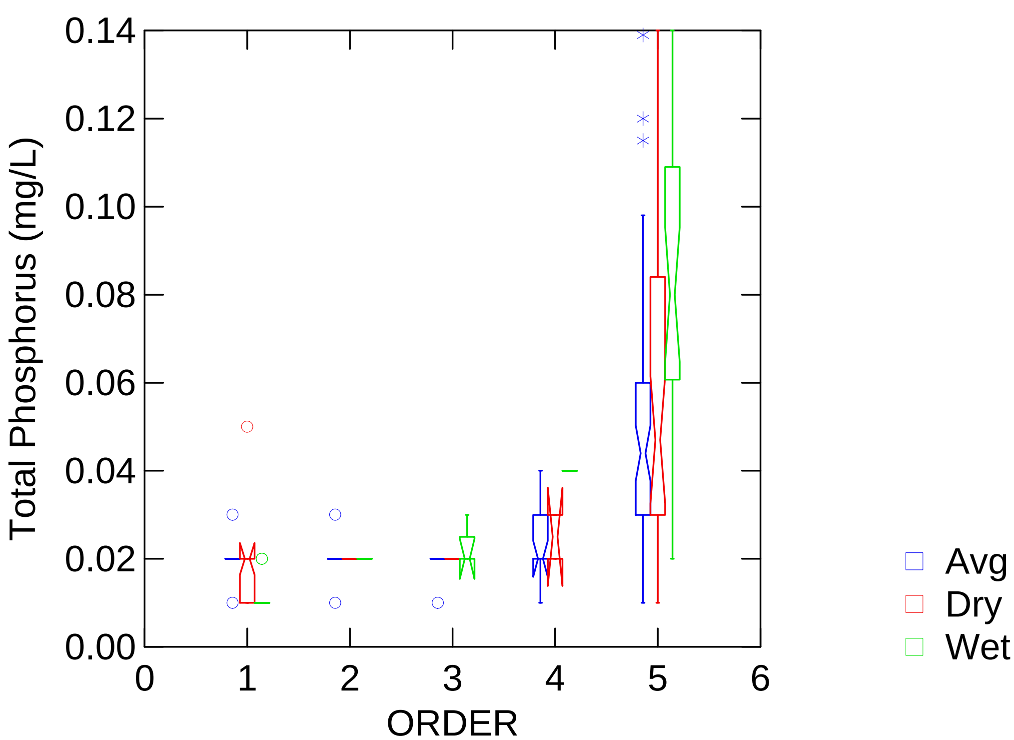


Figure 7.11. Total phosphorus concentrations during wet, average, and dry years at selected Beaver Lake sites.

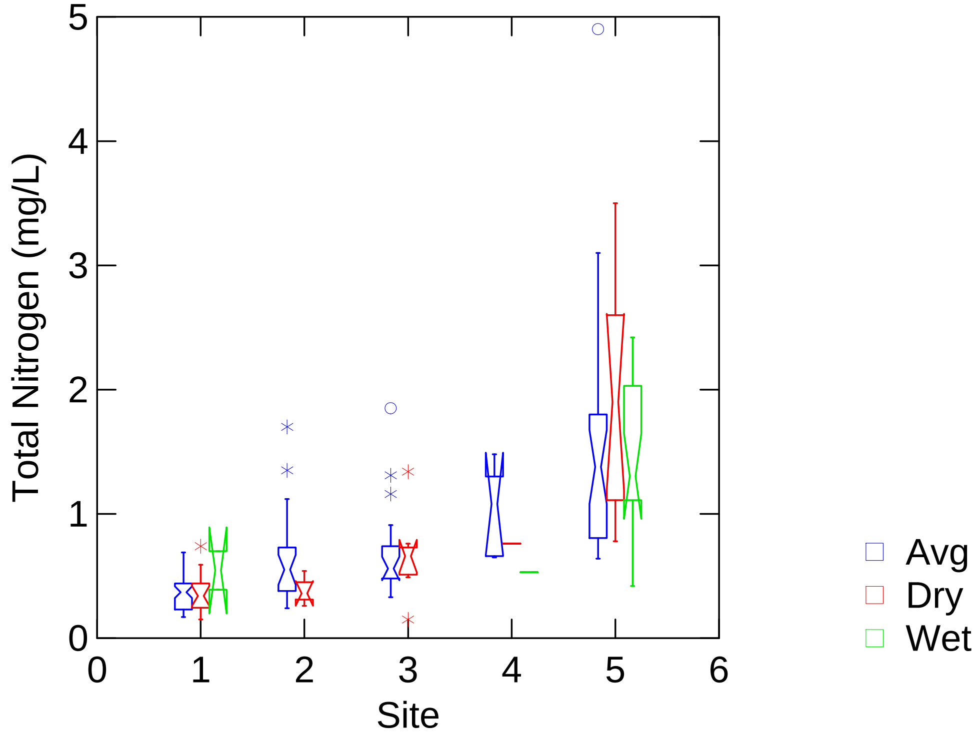


Figure 7.12. Total nitrogen concentrations during wet, average, and dry years at selected Beaver Lake sites.

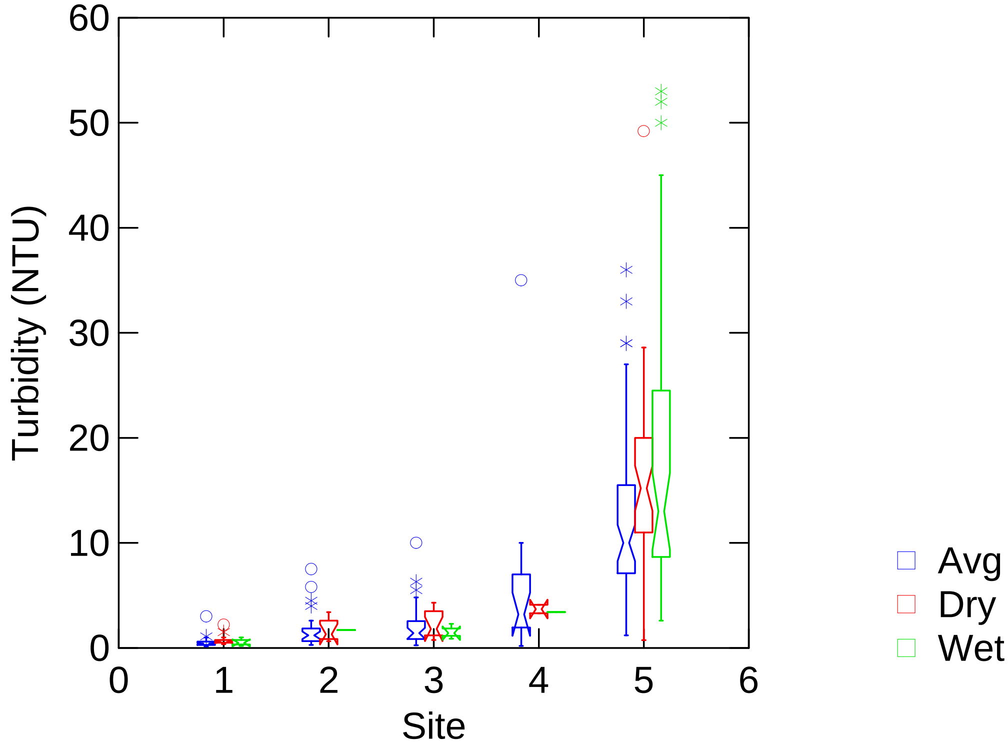


Figure 7.13. Turbidity during wet, average, and dry years at selected Beaver Lake sites.

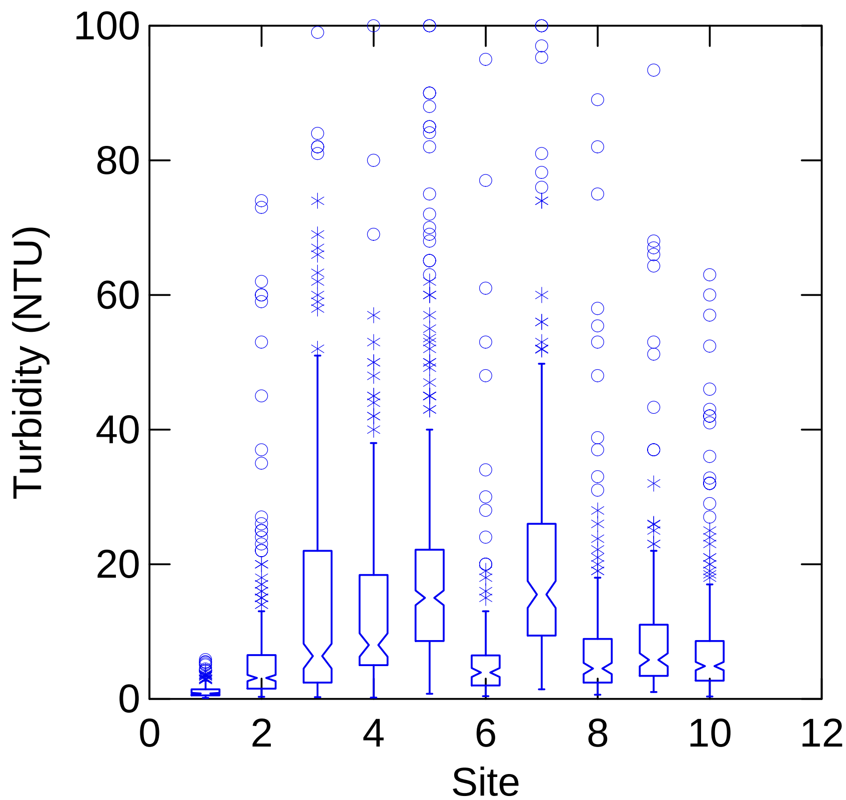


Figure 7.14. Turbidity levels at selected Beaver Lake and tributary sites.

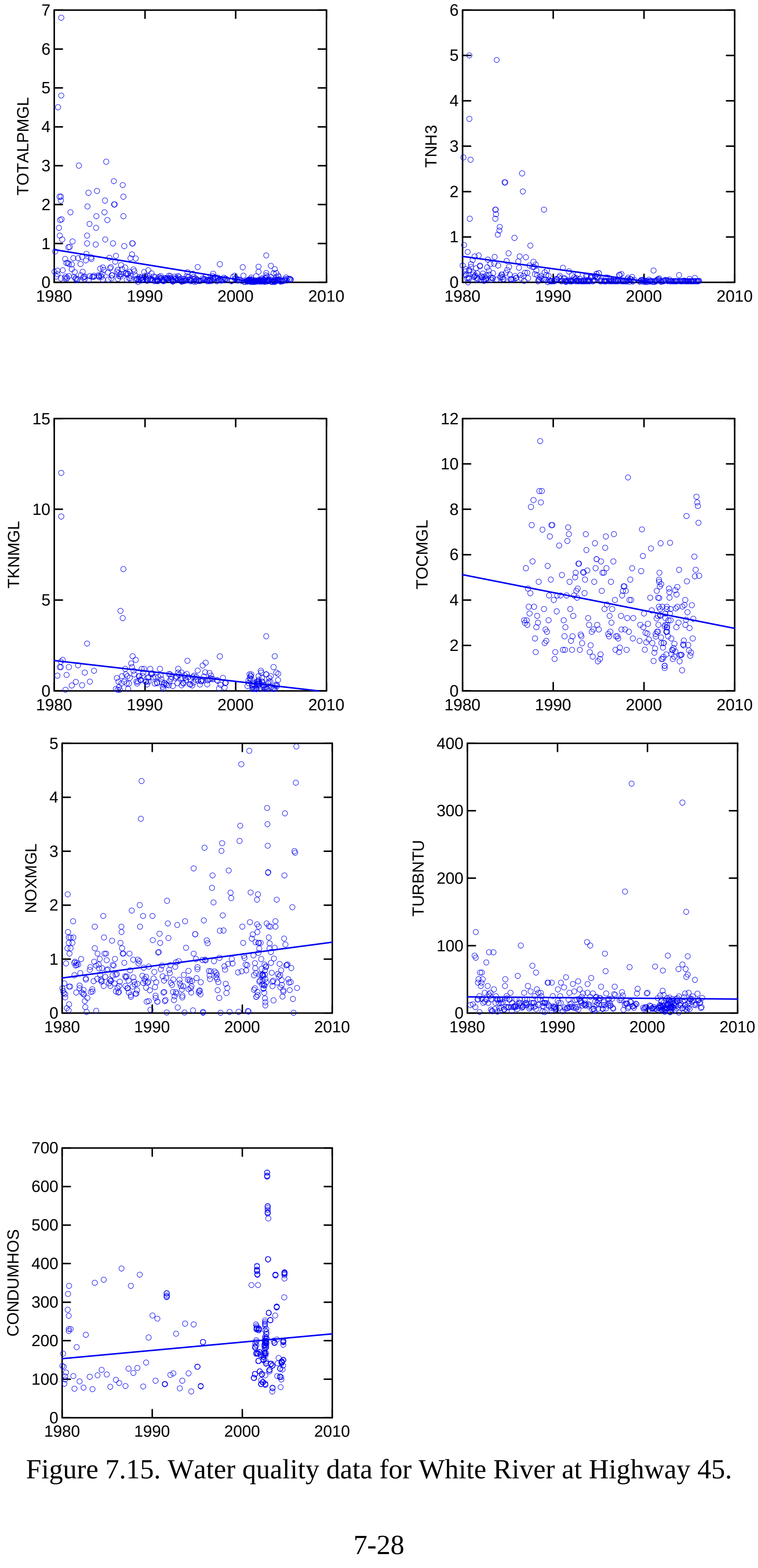


Figure 7.15. Water quality data for White River at Highway 45.

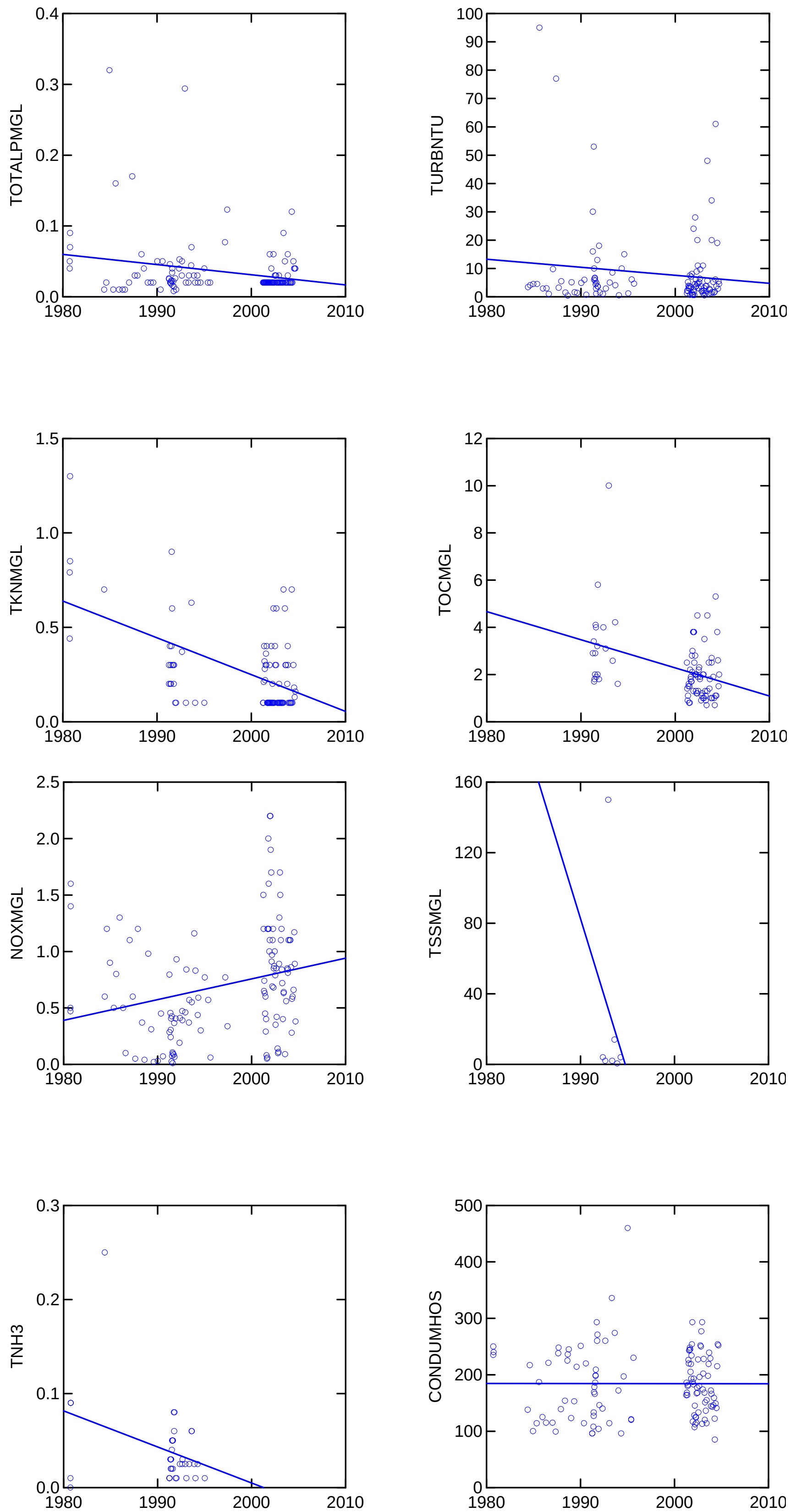


Figure 7.16. Water quality data for Richland Creek at Highway 45.

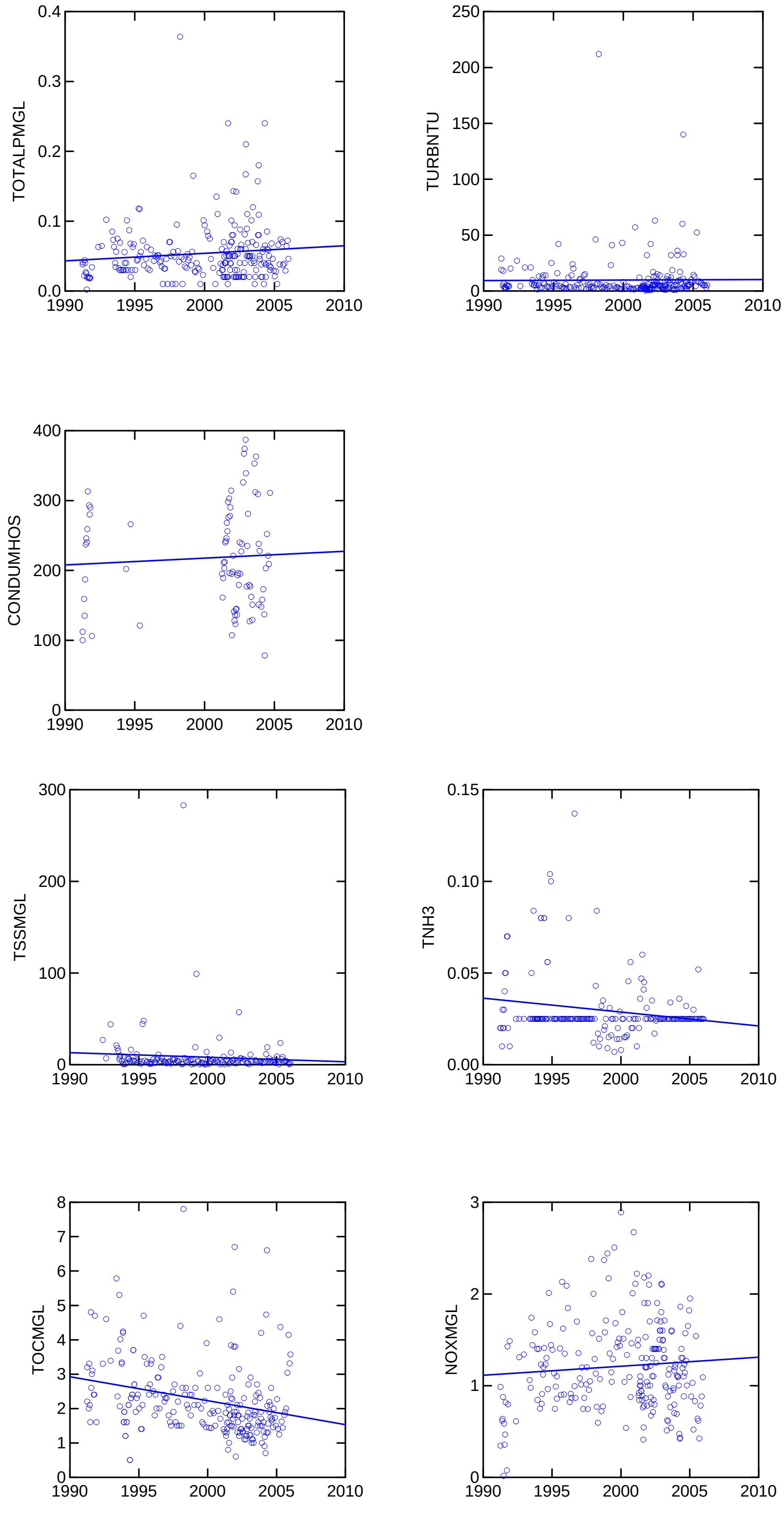


Figure 7.17. Water quality data for War Eagle Creek at Hindsville.

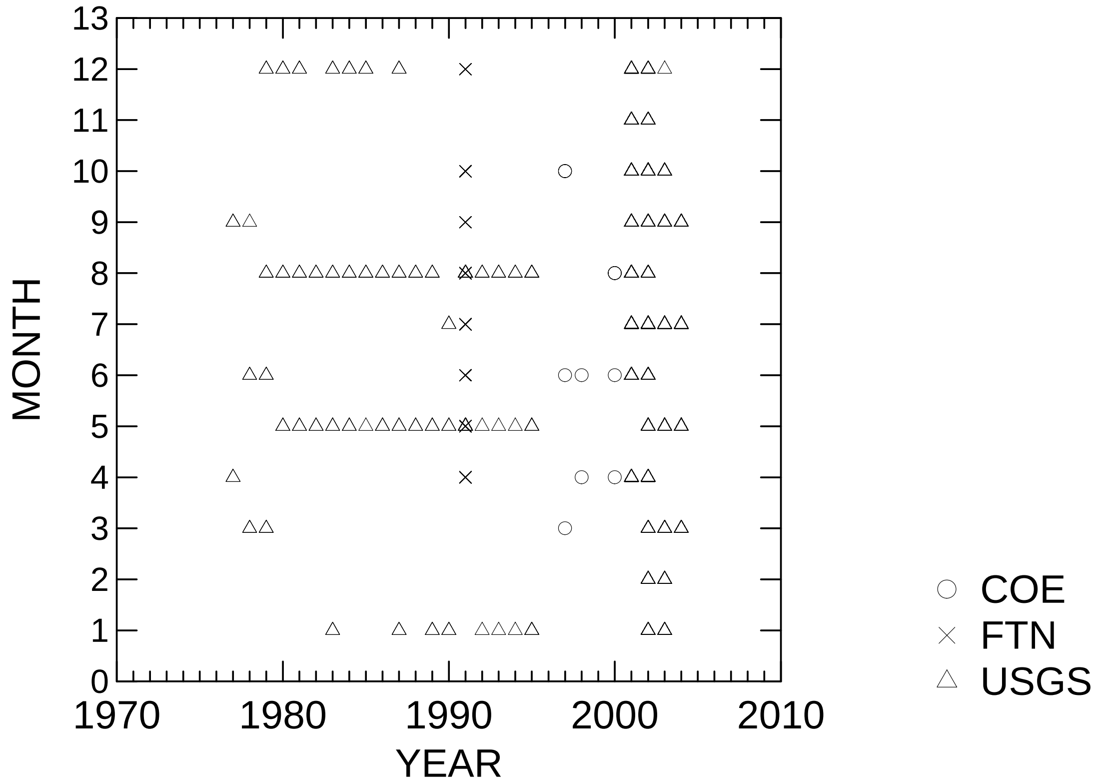


Figure 7.18. Months when dissolved oxygen data were collected by USGS, COE, and FTN.

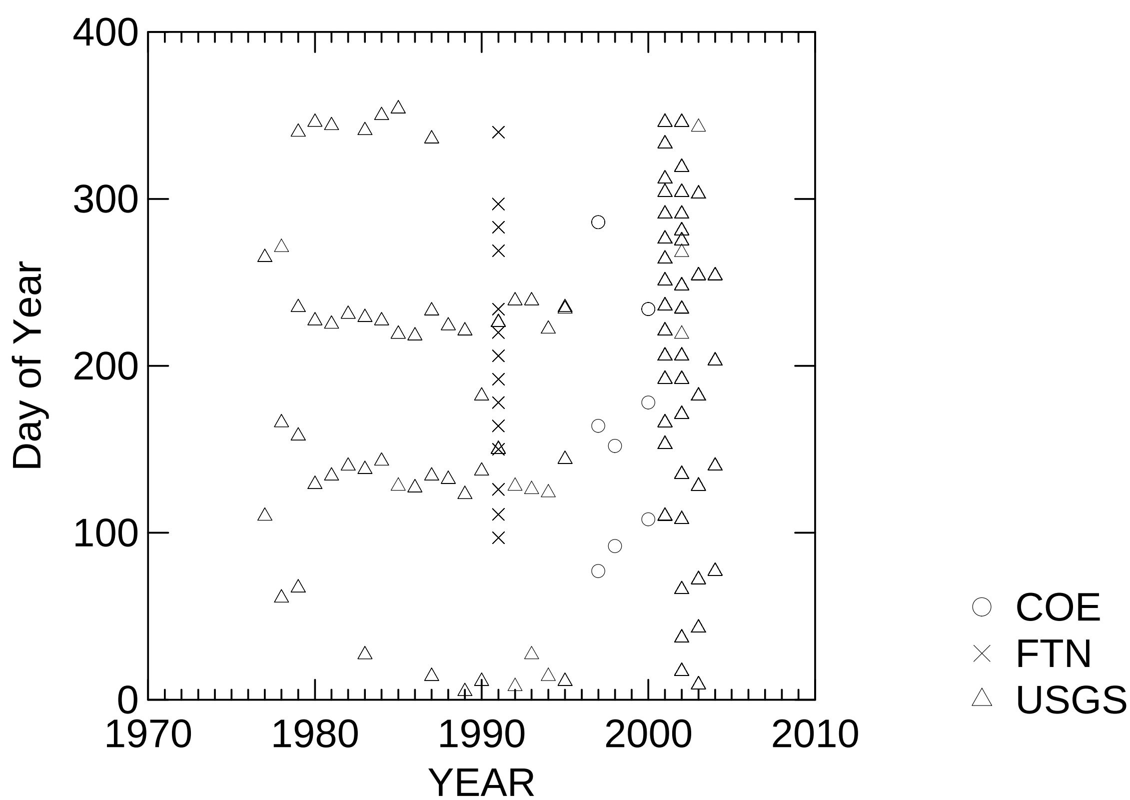


Figure 7.19. Days of year when dissolved oxygen data were collected by USGS, COE, and FTN.

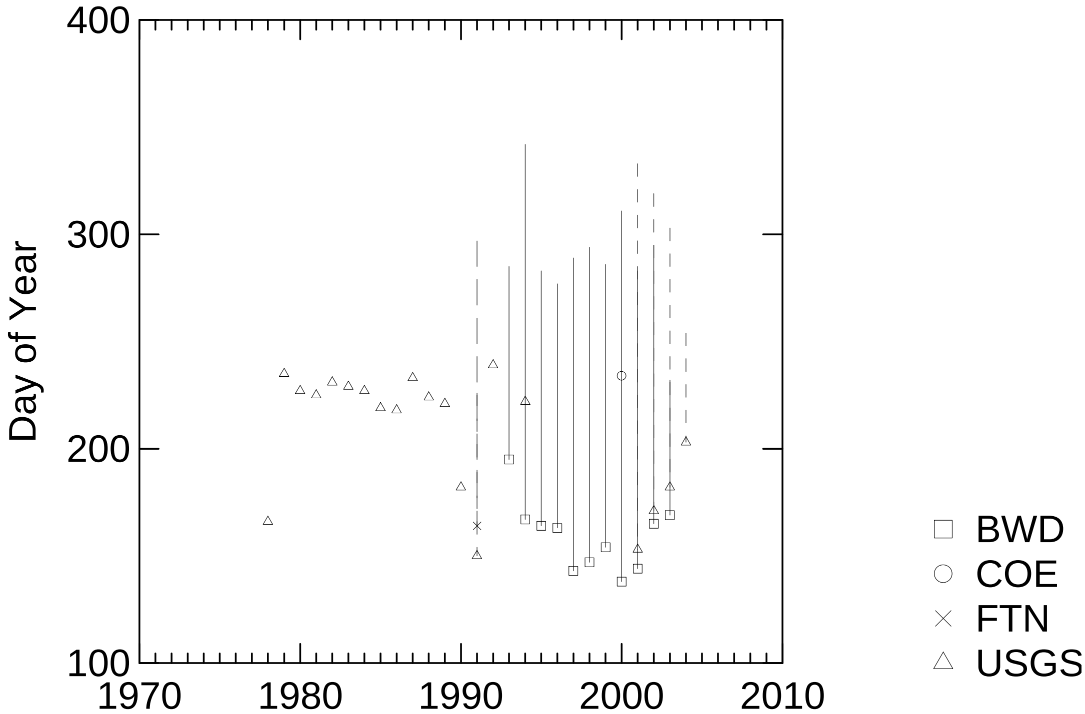


Figure 7.20. Days of year when dissolved oxygen values reported by various entities were less than 2 mg/L at Lowell.

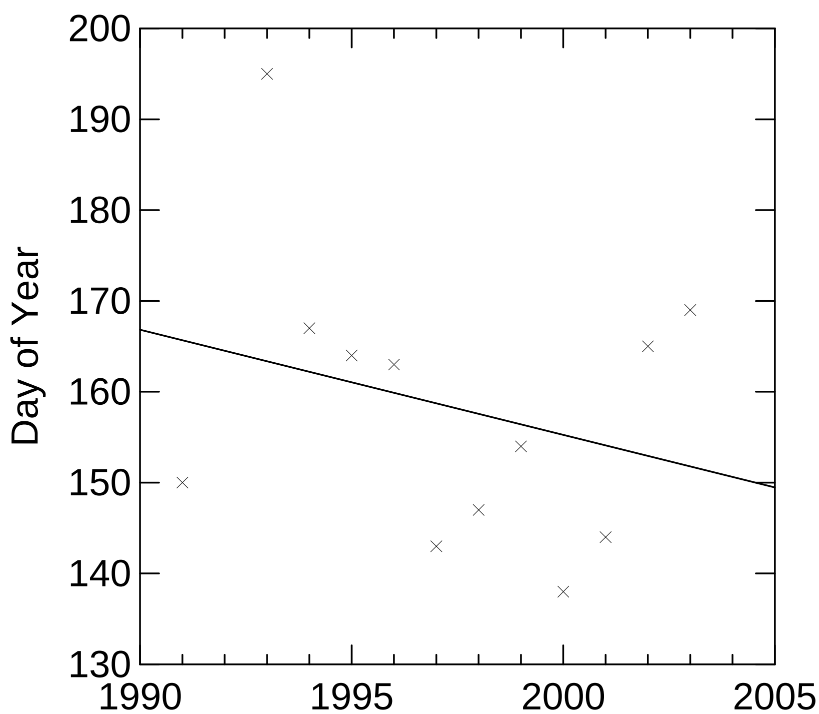


Figure 7.21. Decreasing trend evident in date of onset of hypoxia.

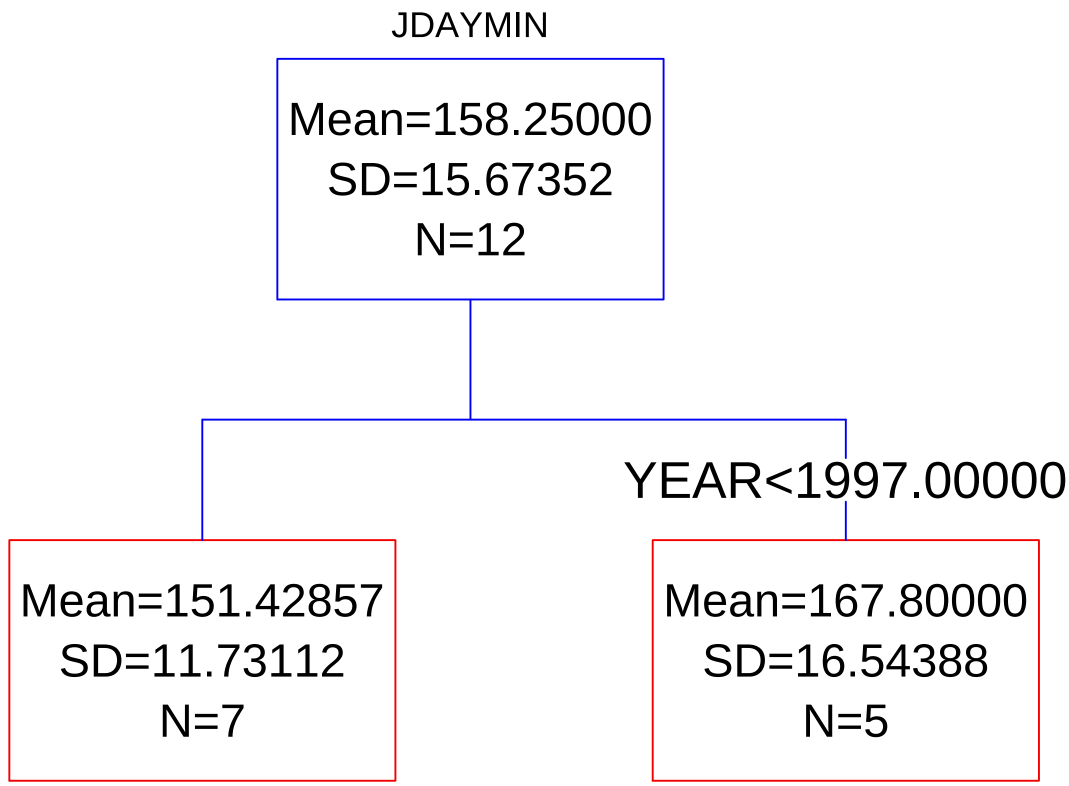


Figure 7.22. Tree analysis indicating change in date of onset of hypoxia after 1997.

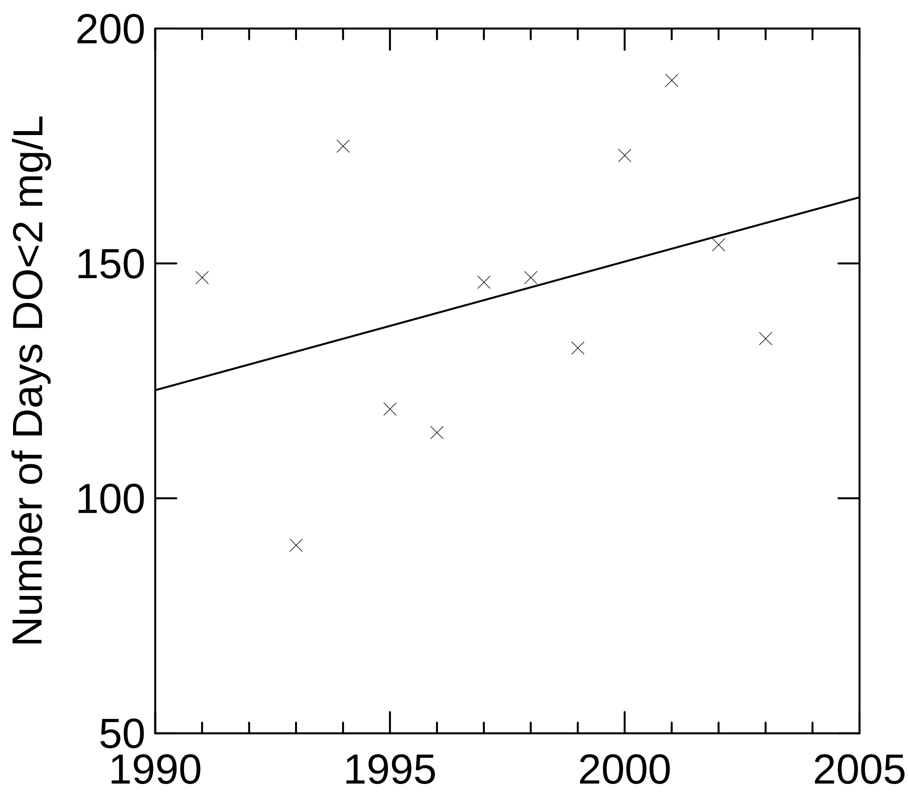


Figure 7.23. Possible increasing trend evident in number of days of hypoxia per year.

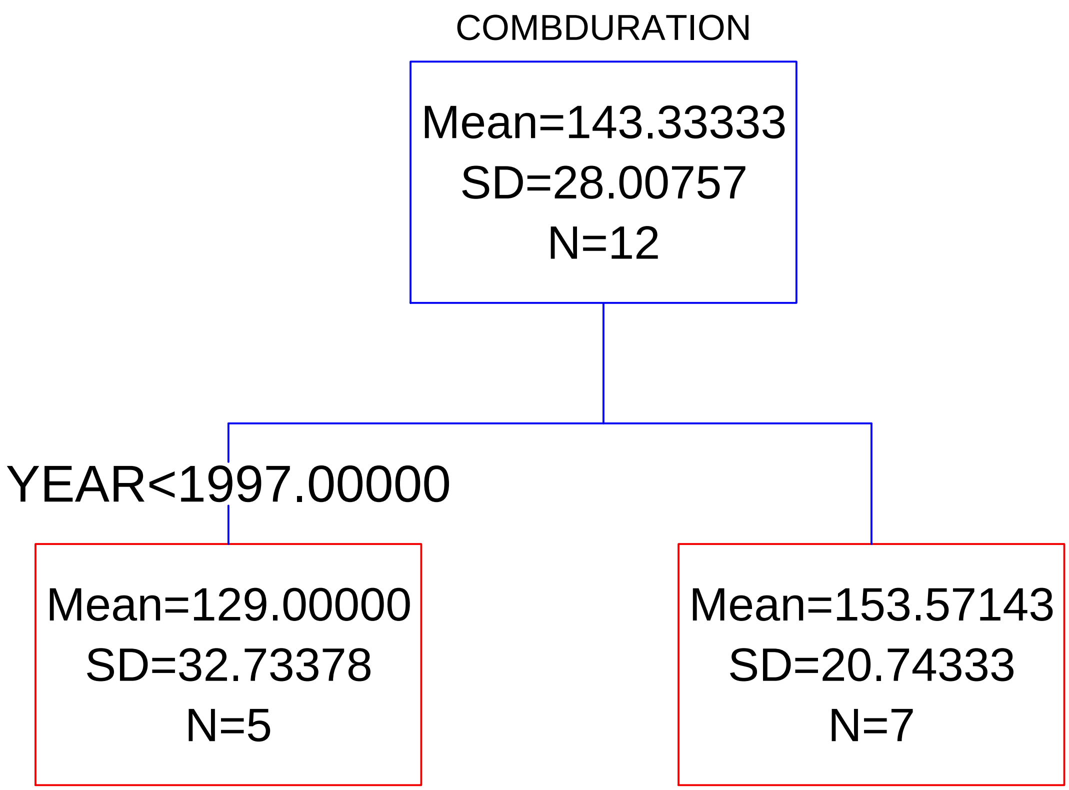


Figure 7.24. Tree analysis indicating change in number of days of hypoxia per year after 1997.

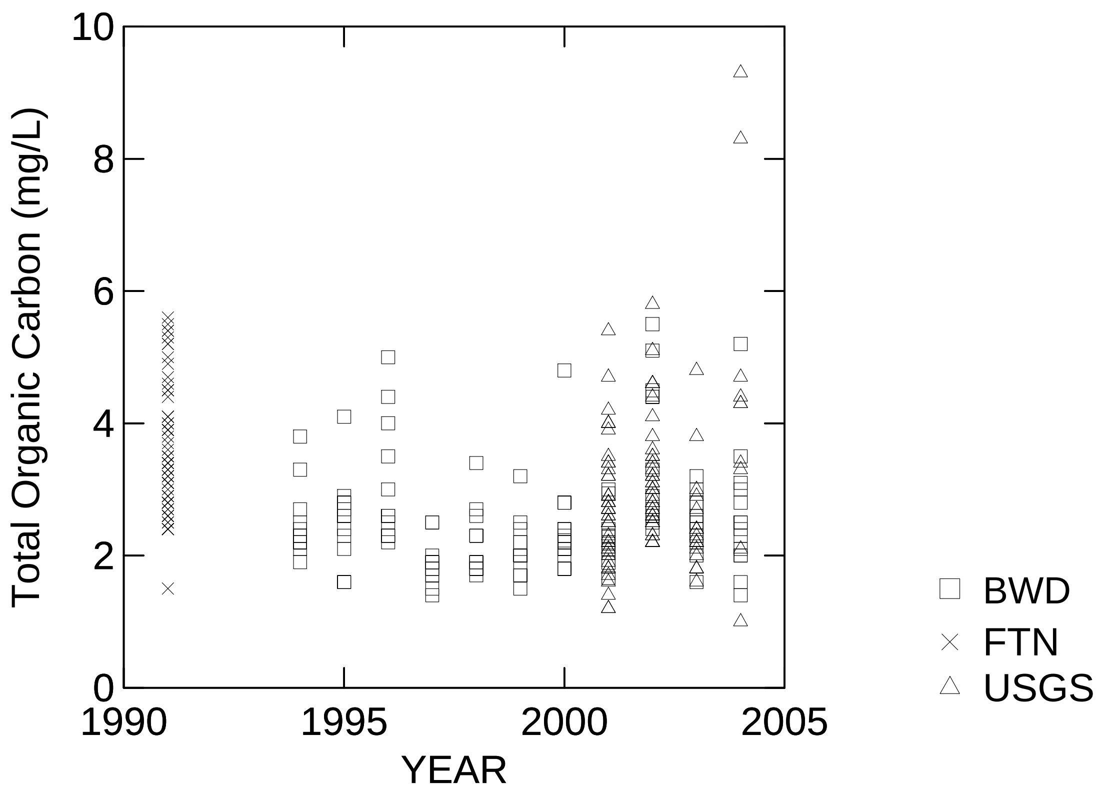


Figure 7.25. Total organic carbon values near Lowell reported by various entities.

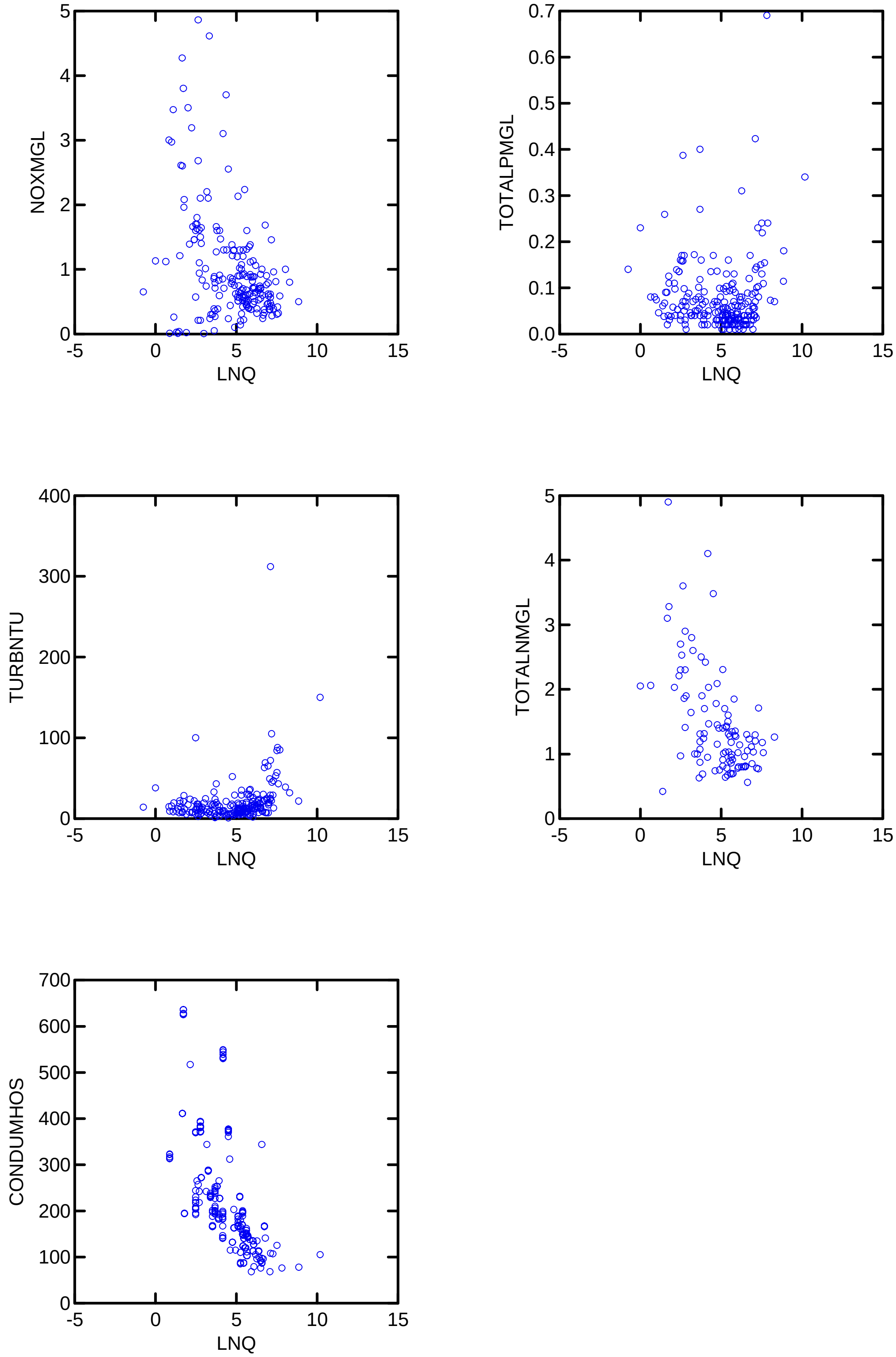


Figure 7.26. Water quality parameters plotted against flow for White River.

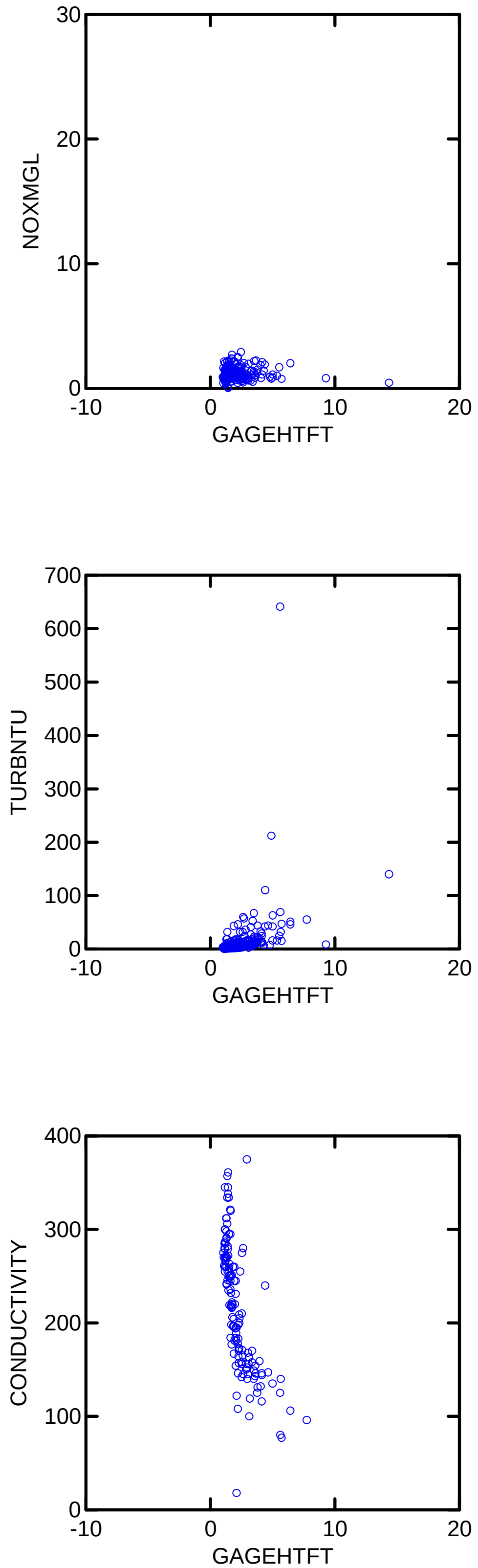


Figure 7.27. Water quality parameters plotted against gage height for War Eagle Creek.

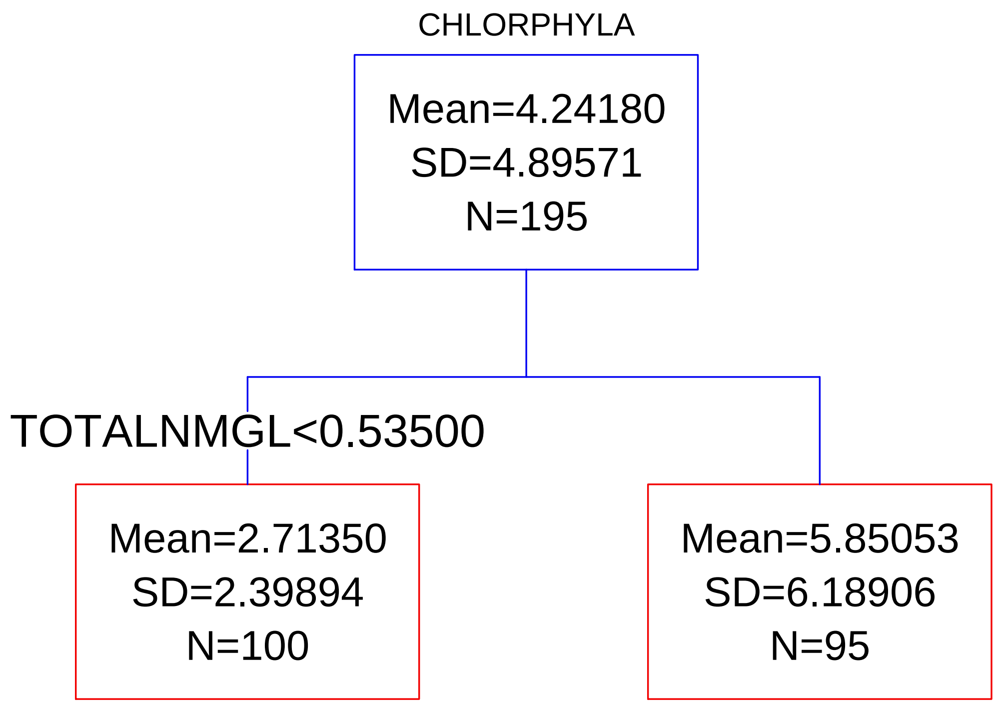


Figure 7.28. Tree model output for Beaver Lake chlorophyll a with total nitrogen showing change-point.

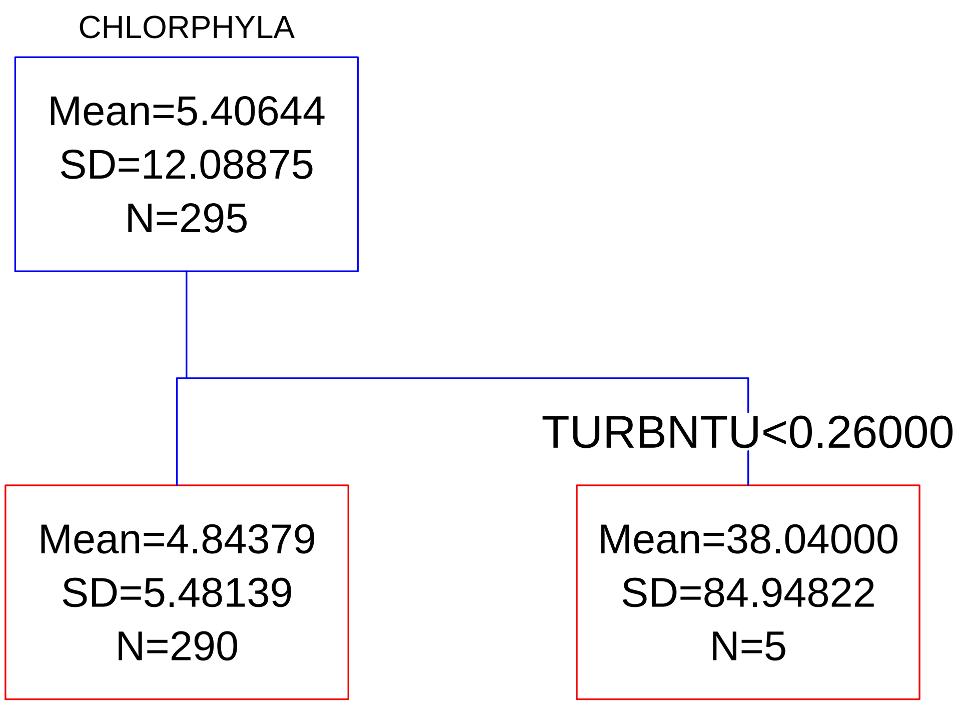


Figure 7.29. Tree model output for Beaver Lake chlorophyll a with turbidity showing change-point.

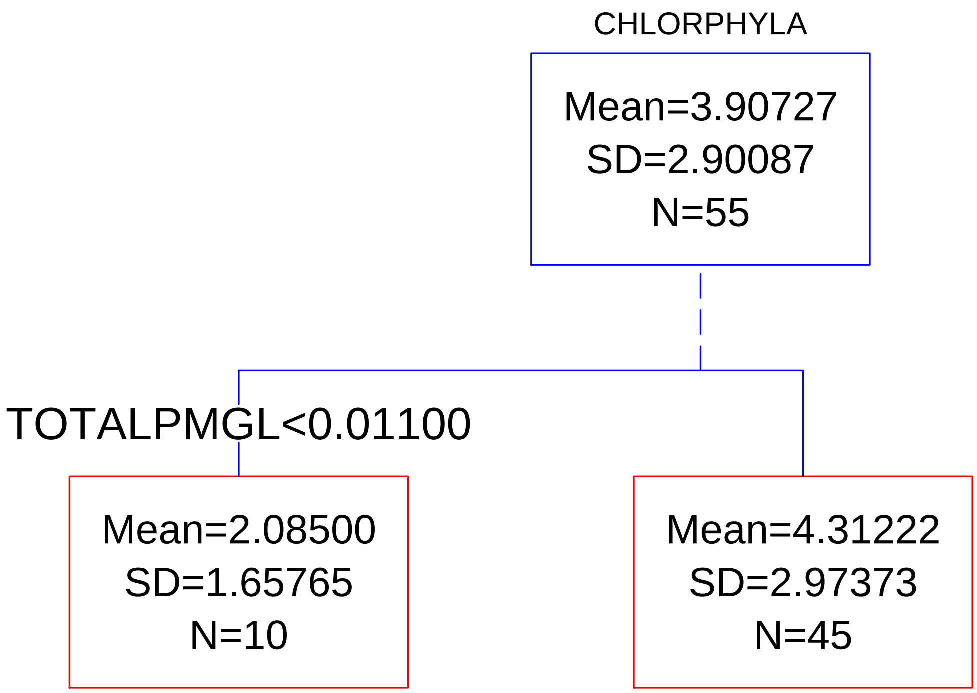


Figure 7.30. Tree model output for chlorophyll a with total phosphorus for Beaver Lake at Highway 12.

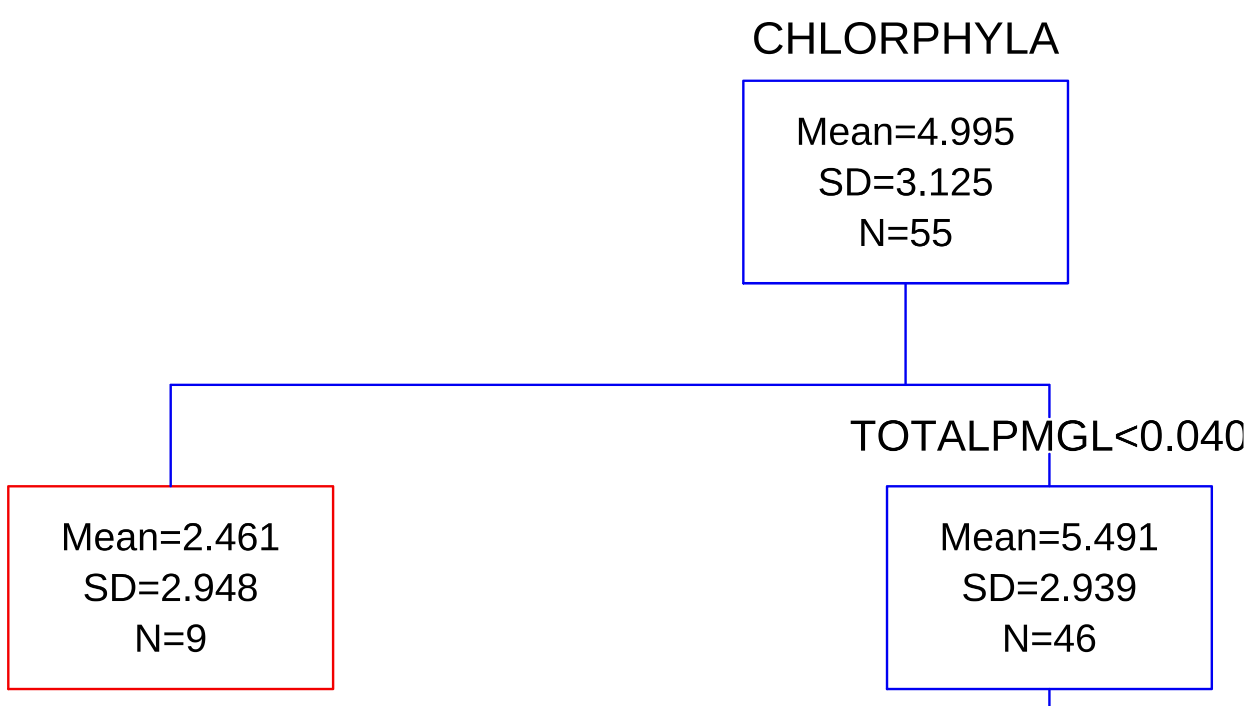


Figure 7.31. Tree model output for chlorophyll a with total phosphorus for Beaver Lake near Lowell.

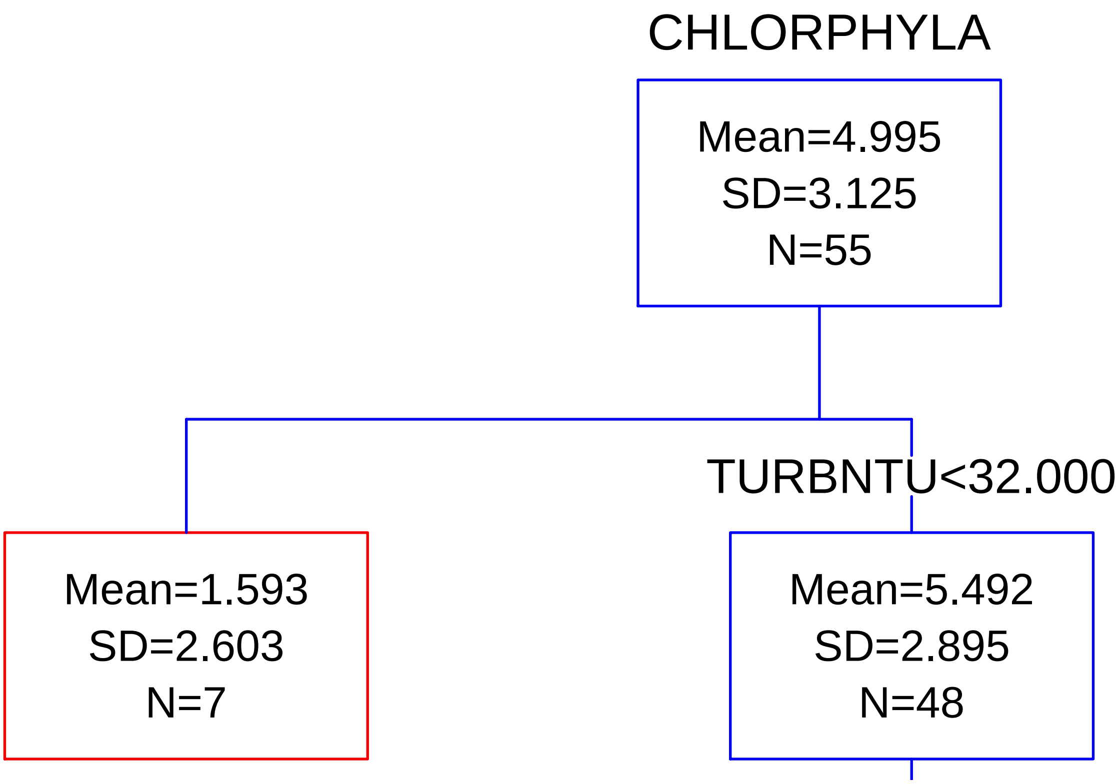


Figure 7.32. Tree model output for chlorophyll a with turbidity for Beaver Lake near Lowell.

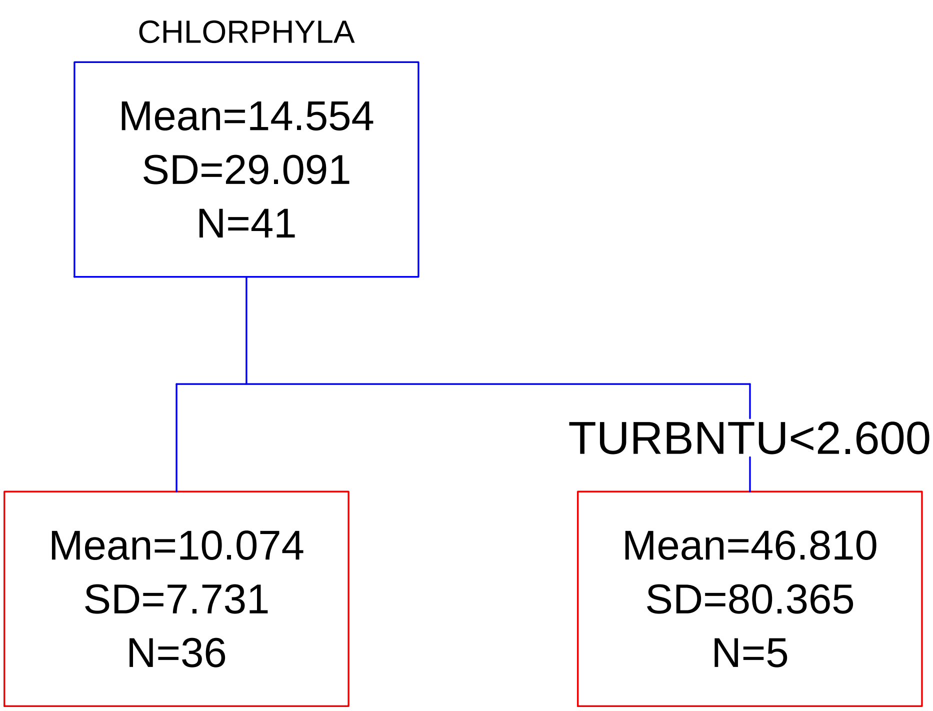


Figure 7.33. Tree model output for chlorophyll a with turbidity for Beaver Lake at Highway 412.

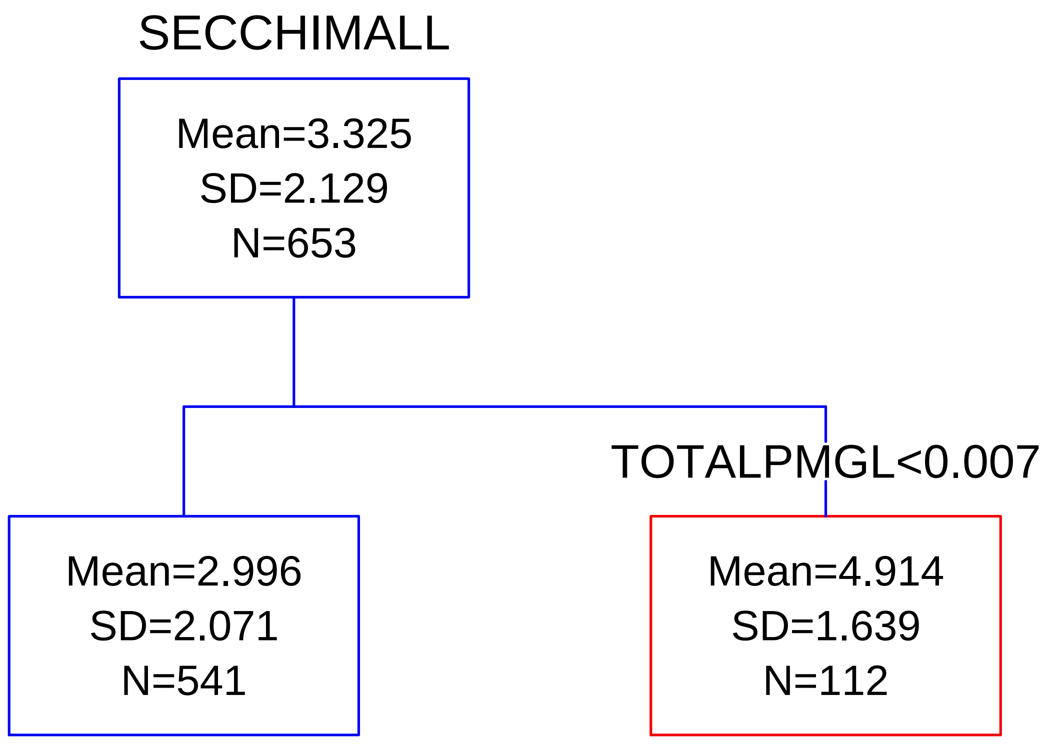


Figure 7.34. Tree model output for Beaver Lake Secchi transparency with all total phosphorus data.

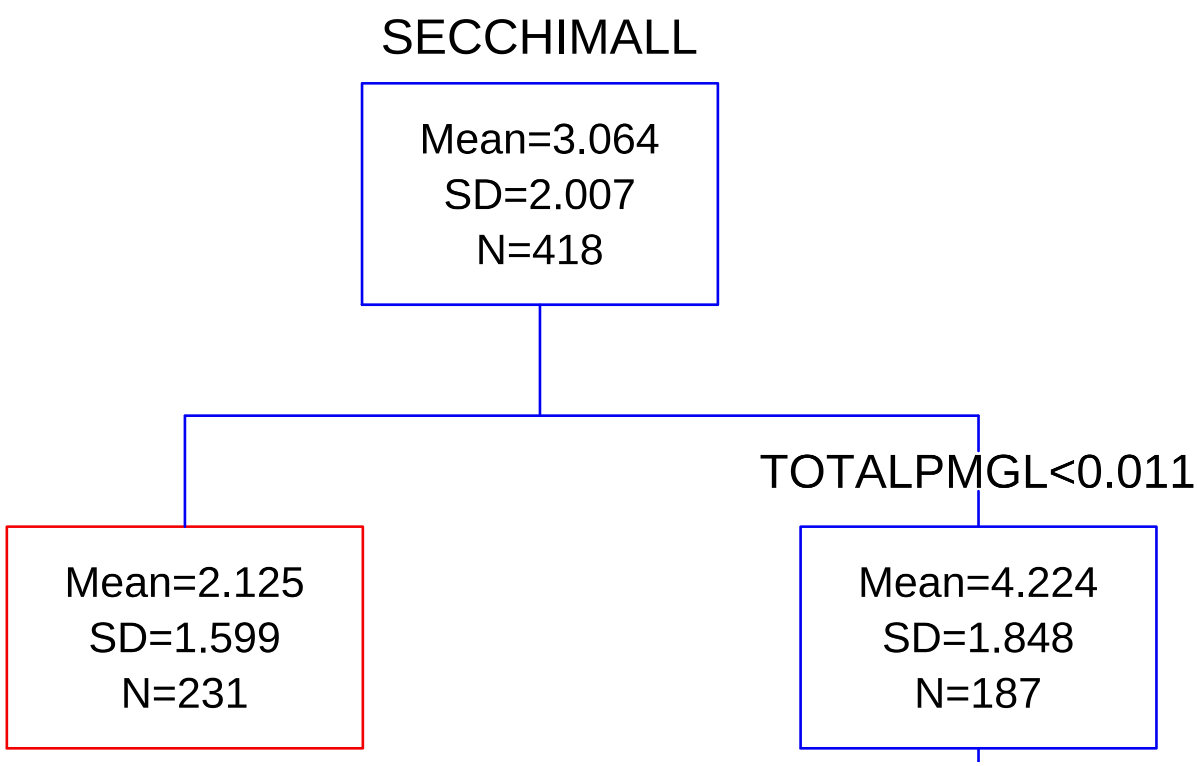


Figure 7.35. Tree model output for Beaver Lake Secchi transparency with reported total phosphorus values greater than detection.

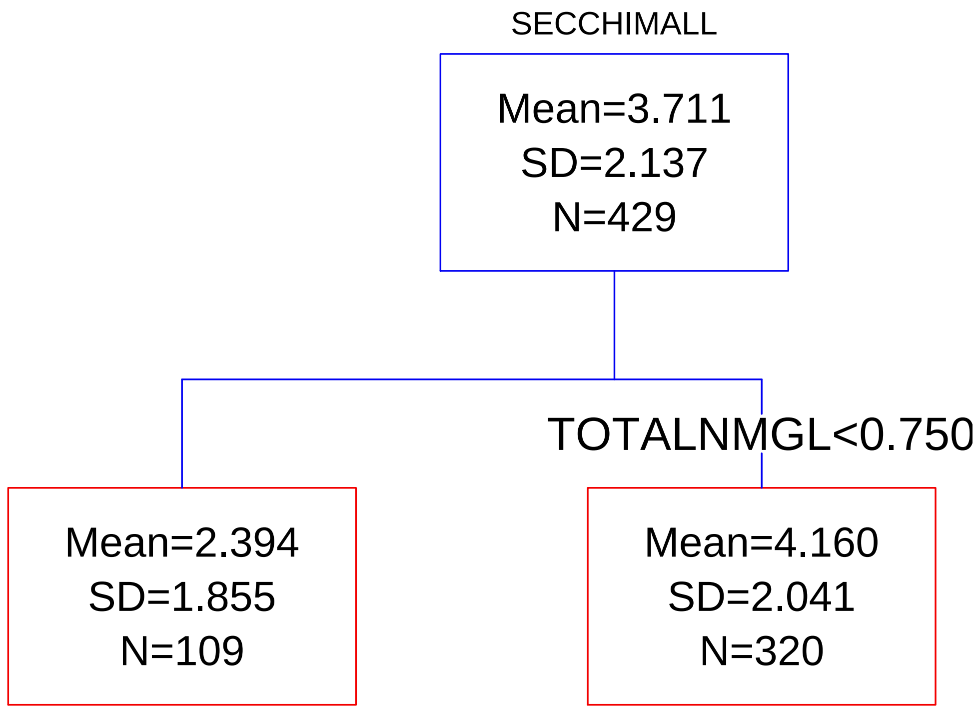


Figure 7.36. Tree model output for Beaver Lake Secchi transparency with total nitrogen data.

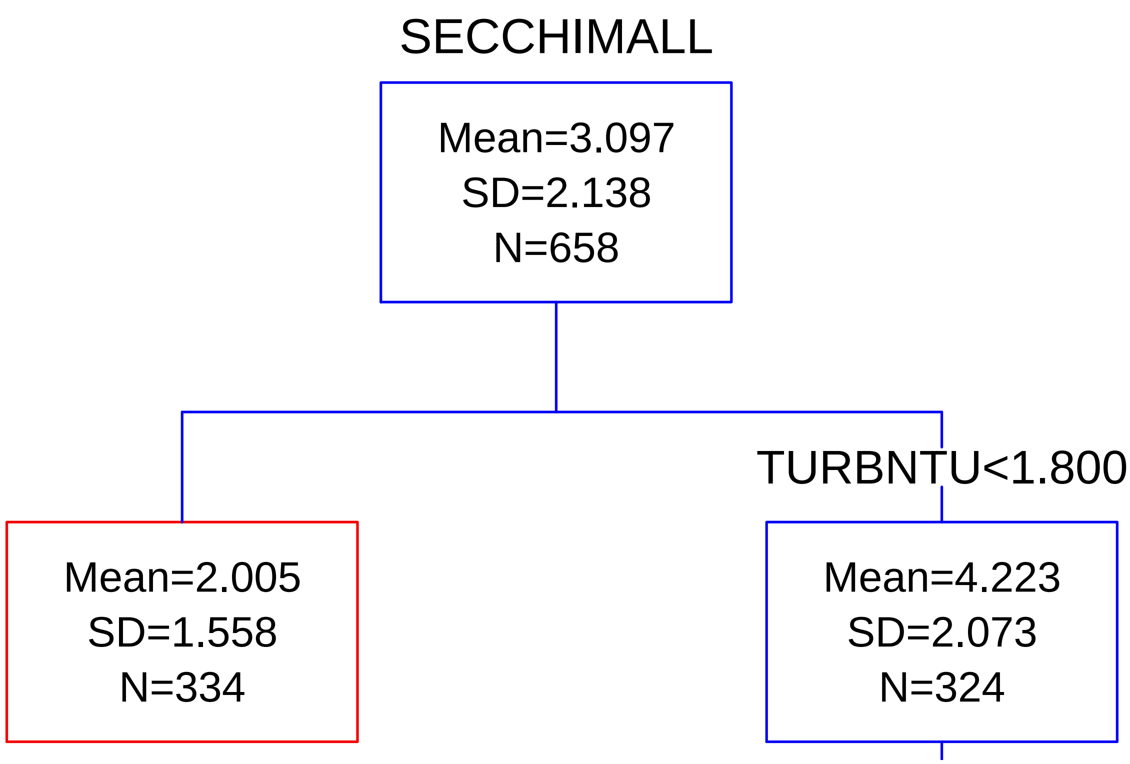


Figure 7.37. Tree model output for Beaver Lake Secchi transparency with turbidity data.

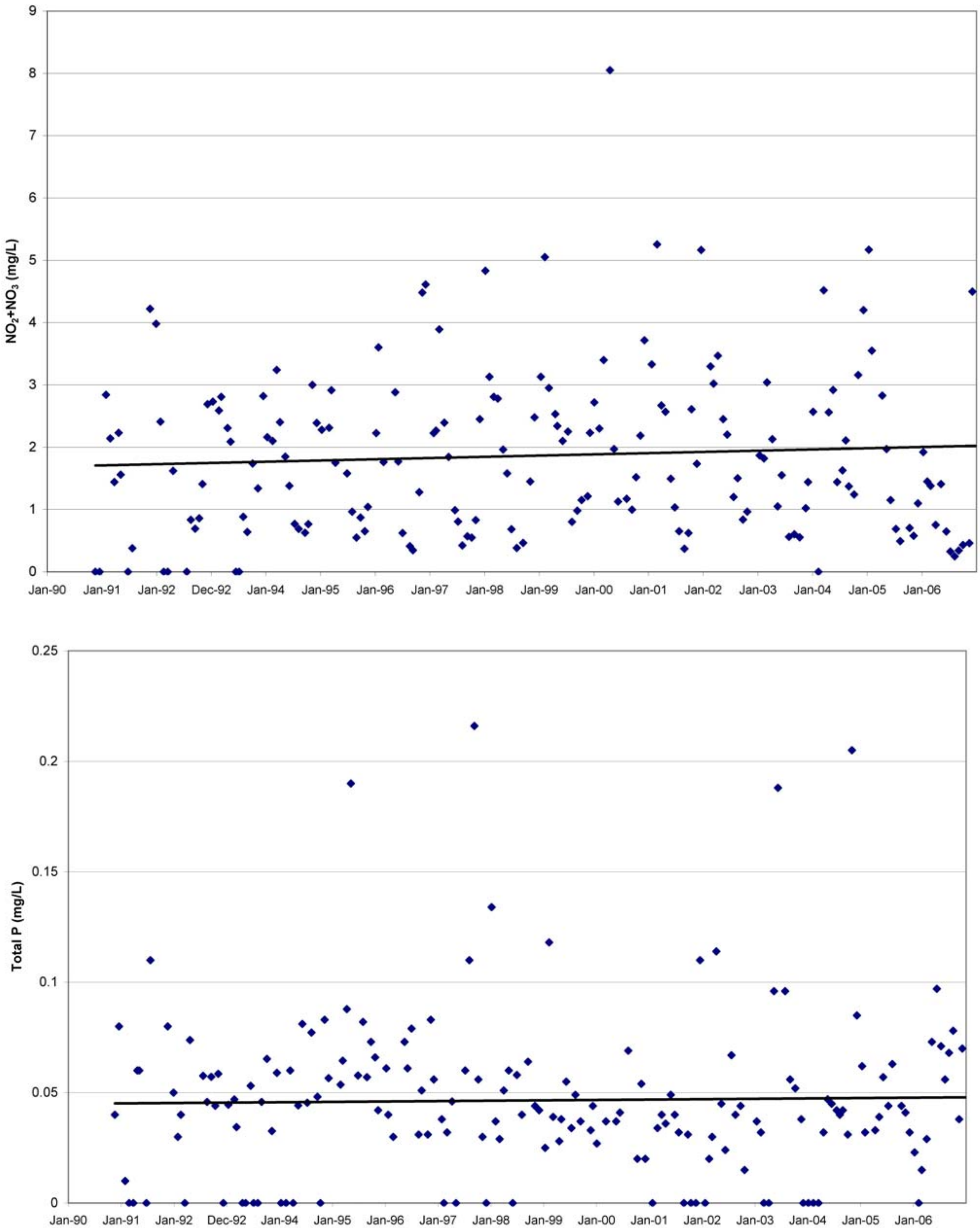


Figure 7.38. Flint Creek nutrient data over time.

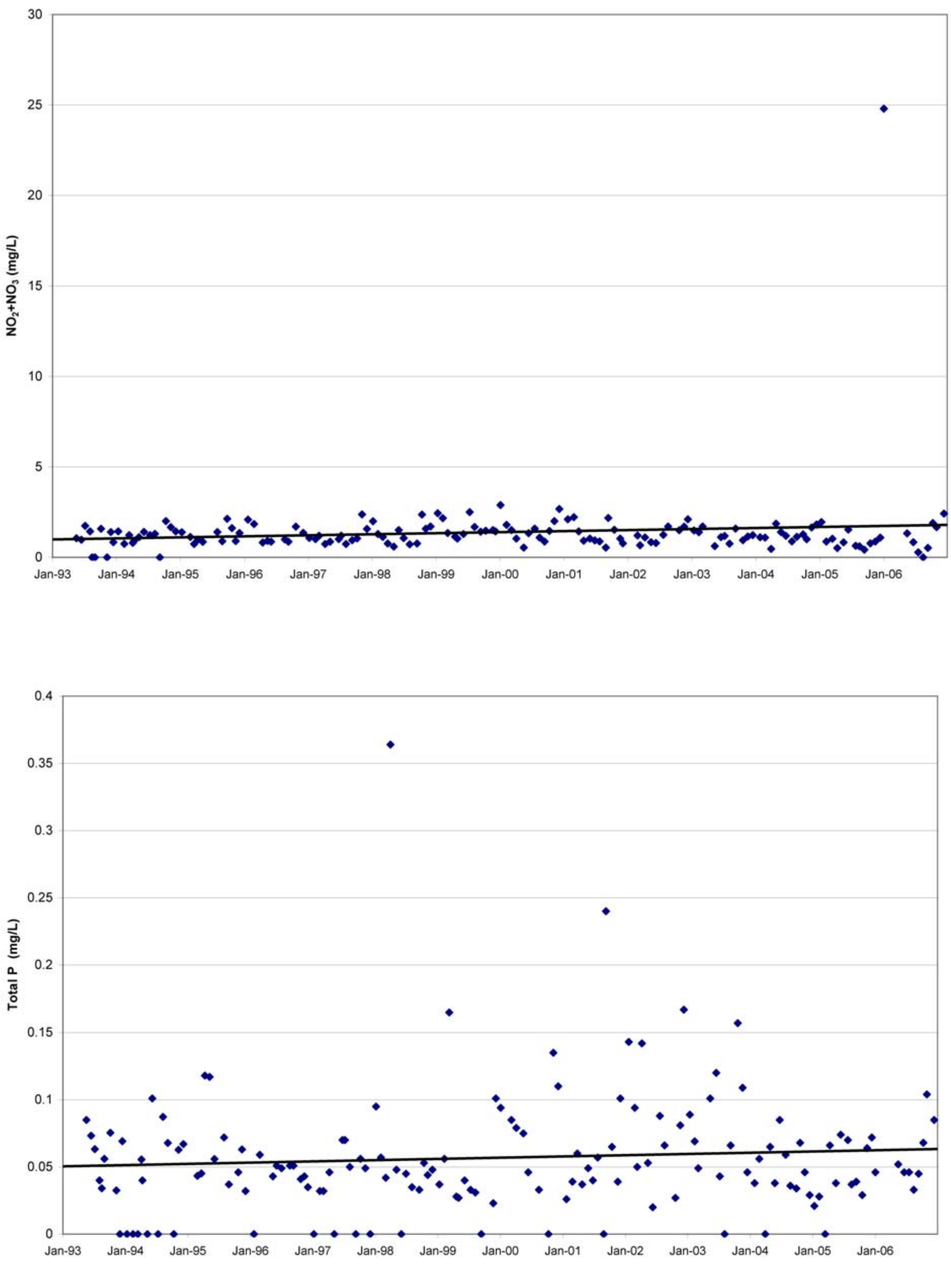


Figure 7.39. War Eagle Creek nutrient data over time.

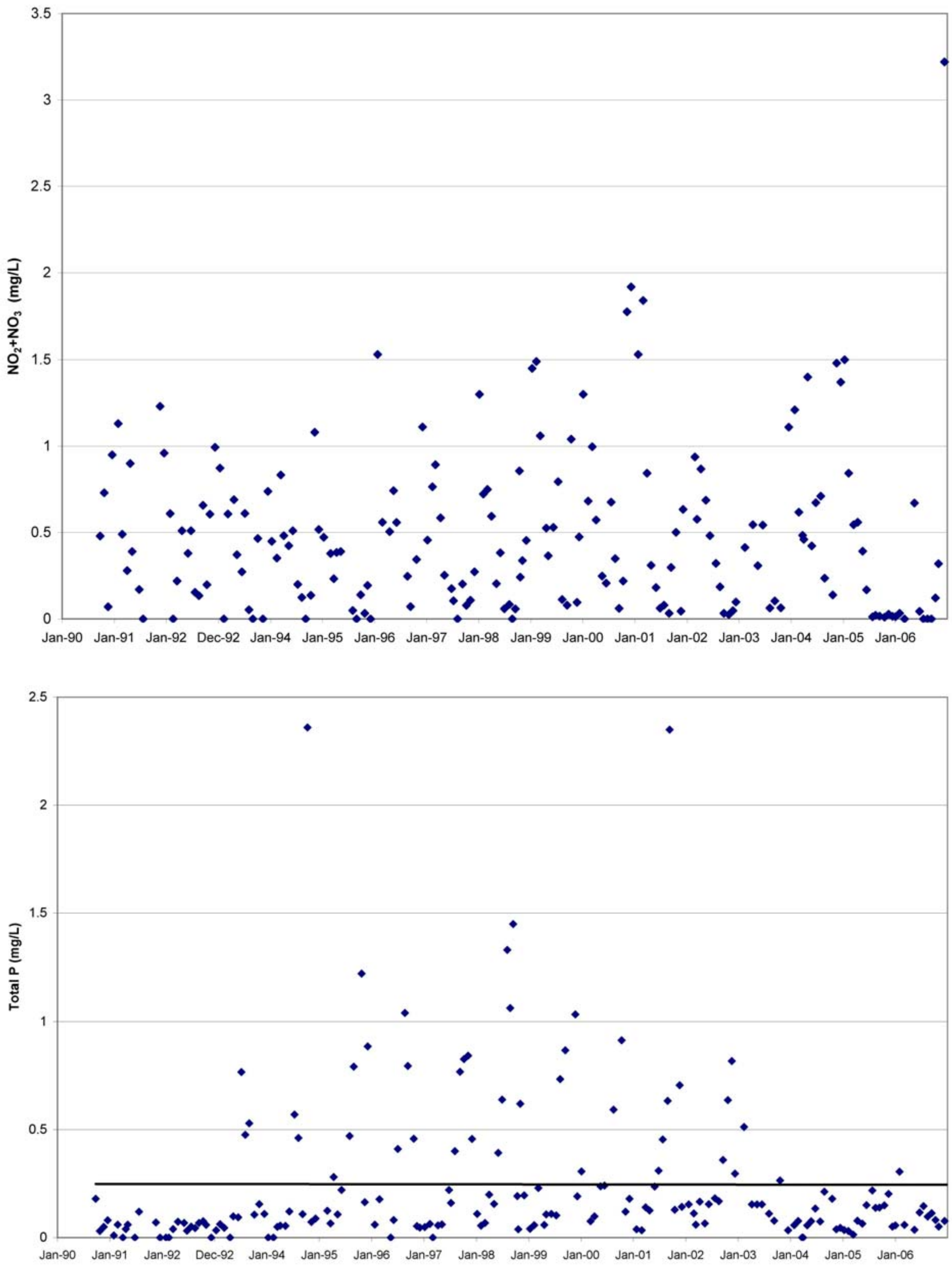
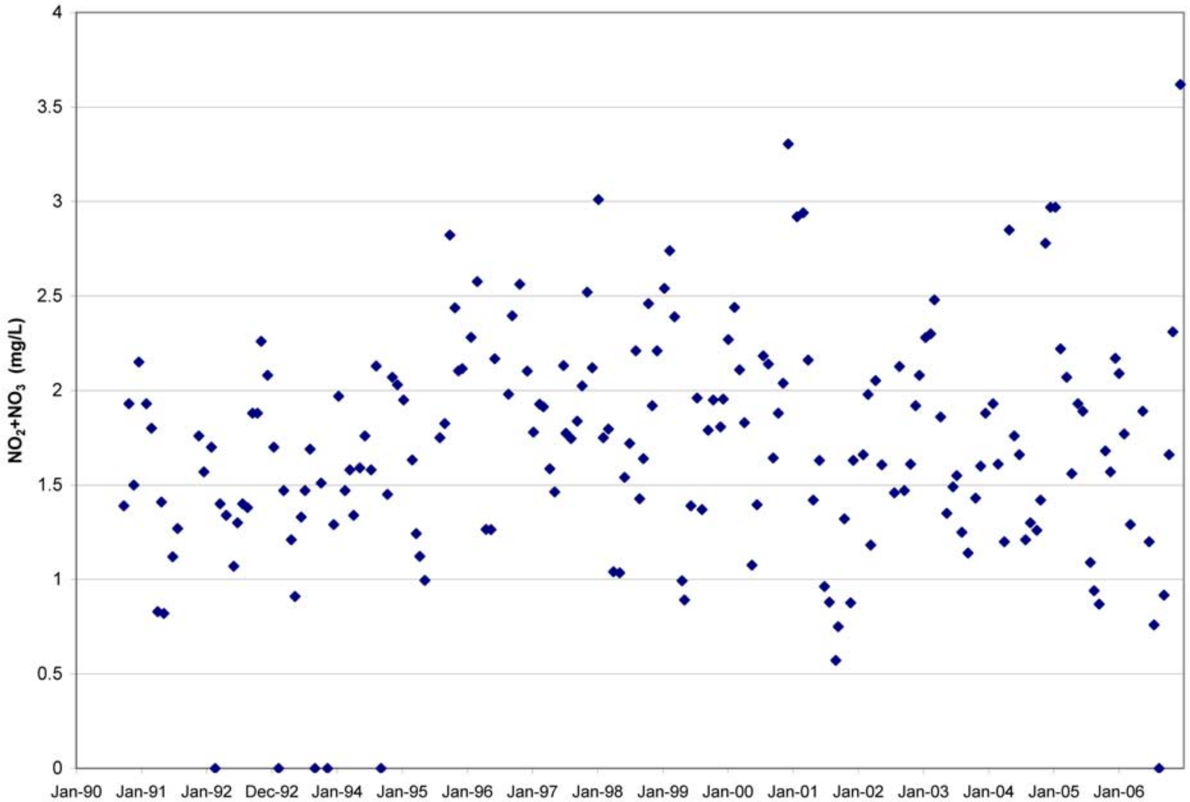


Figure 7.40. Kings River nutrient data over time.



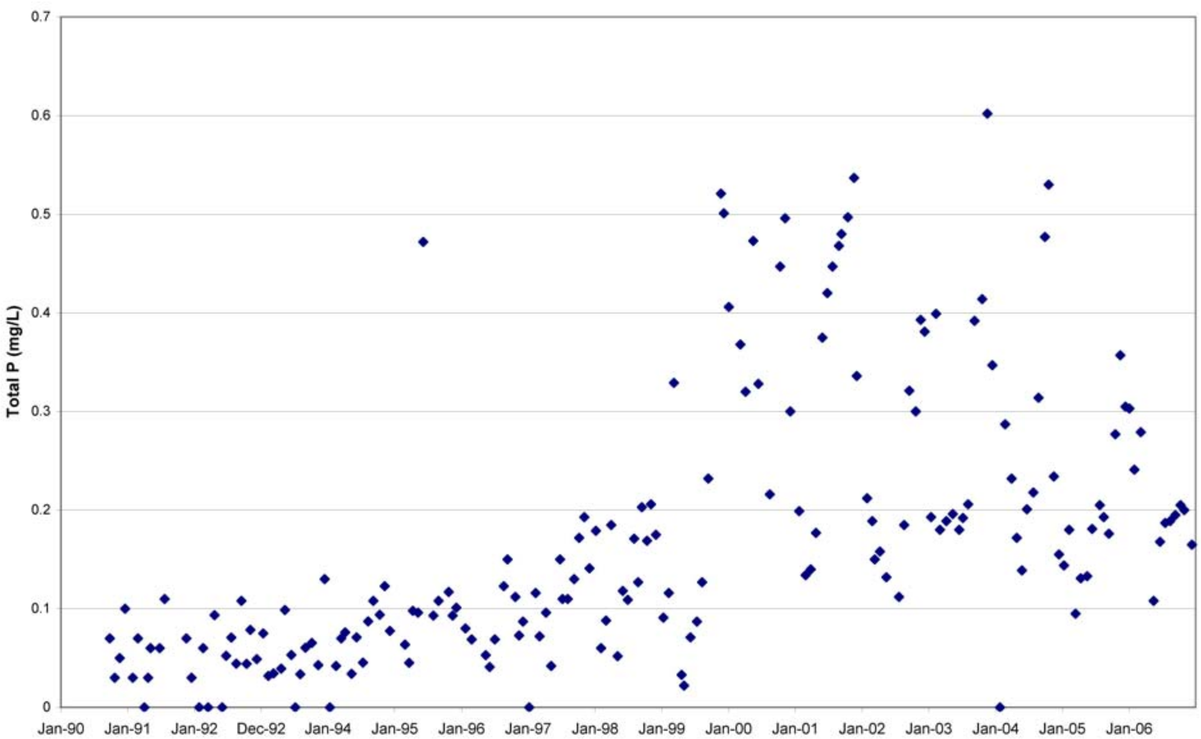


Figure 7.41. Long Creek nutrient data over time.

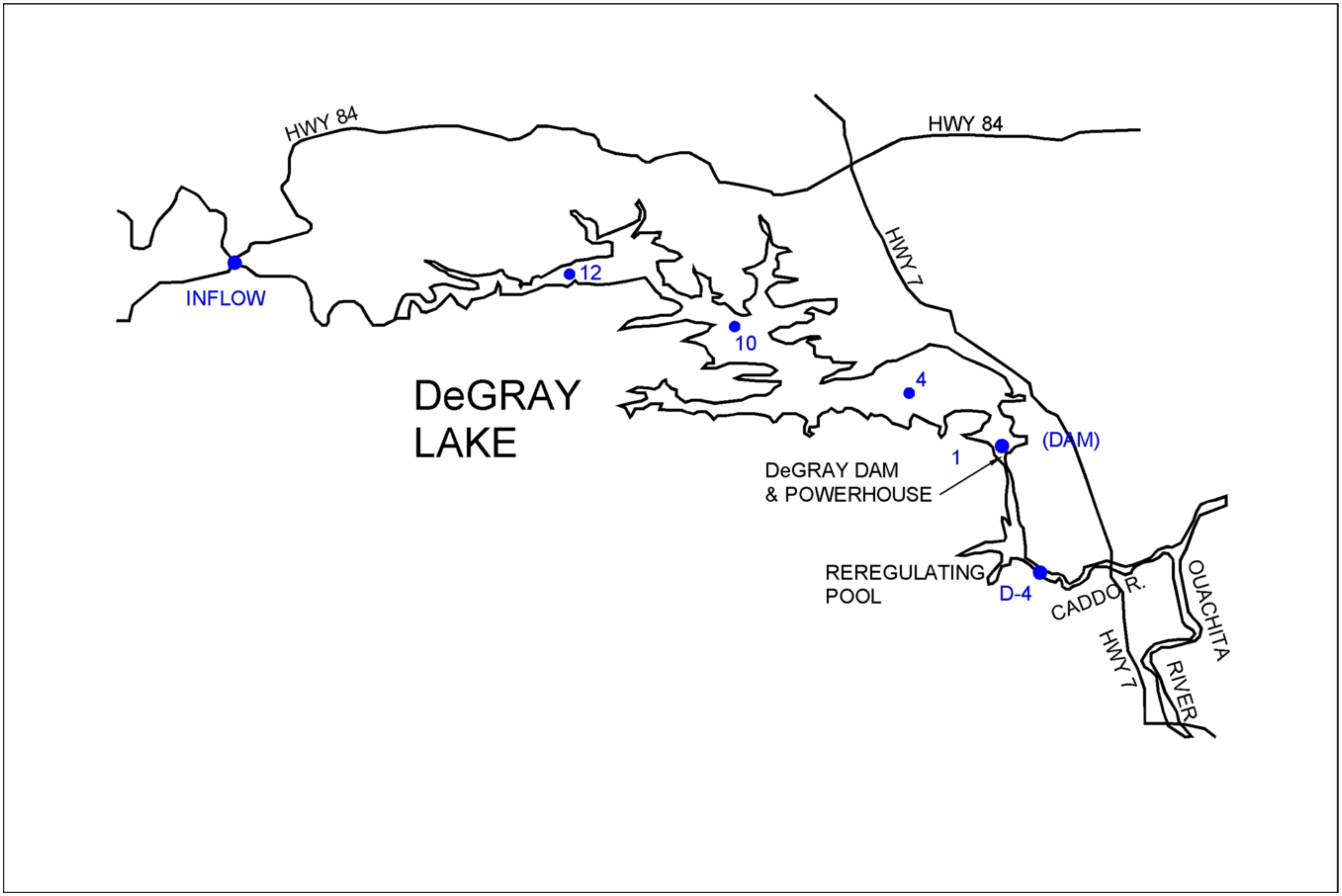


Figure 7.42. Categorization of DeGray Lake water quality sampling sites.

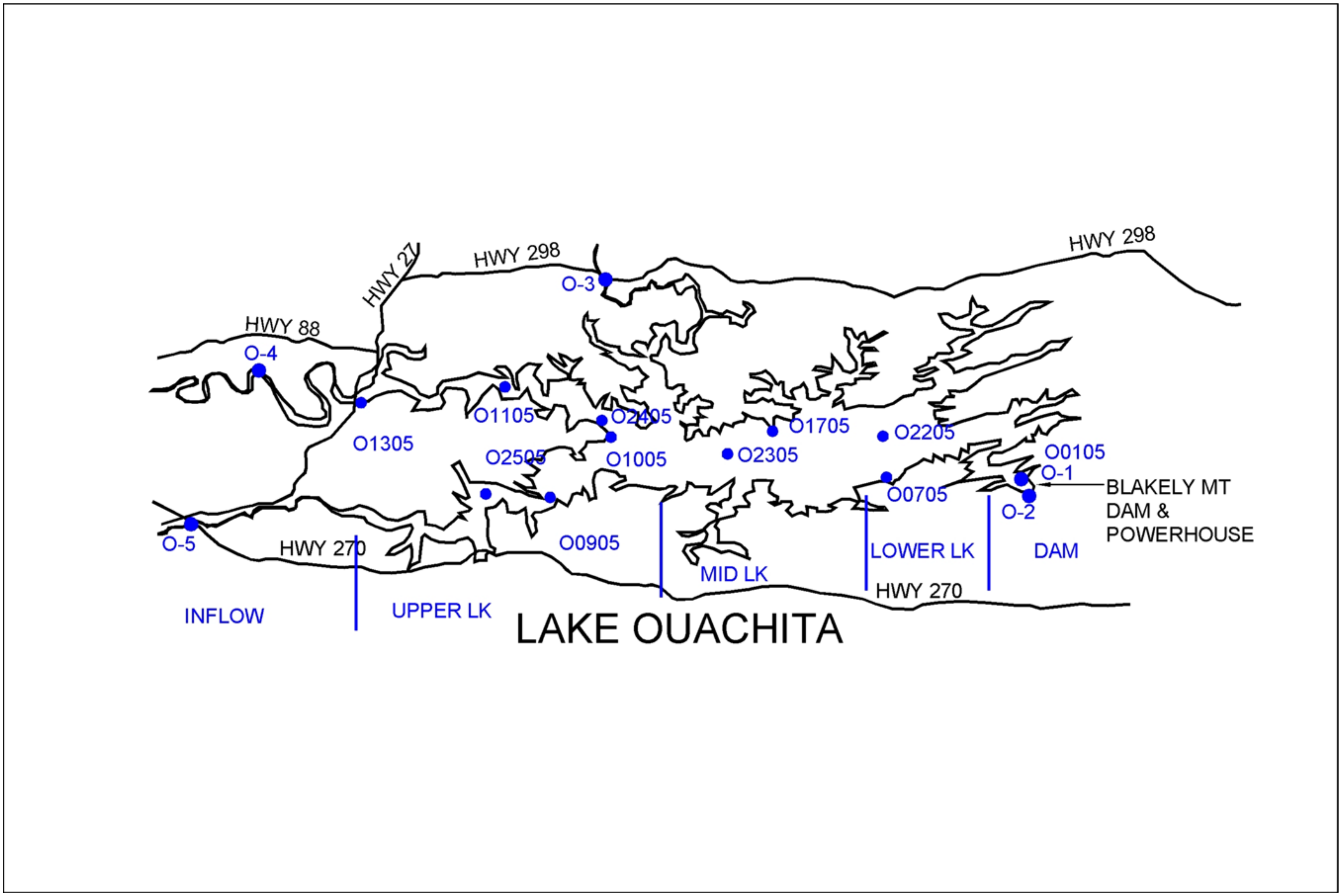


Figure 7.43. Categorization of Lake Ouachita water quality sampling sites.

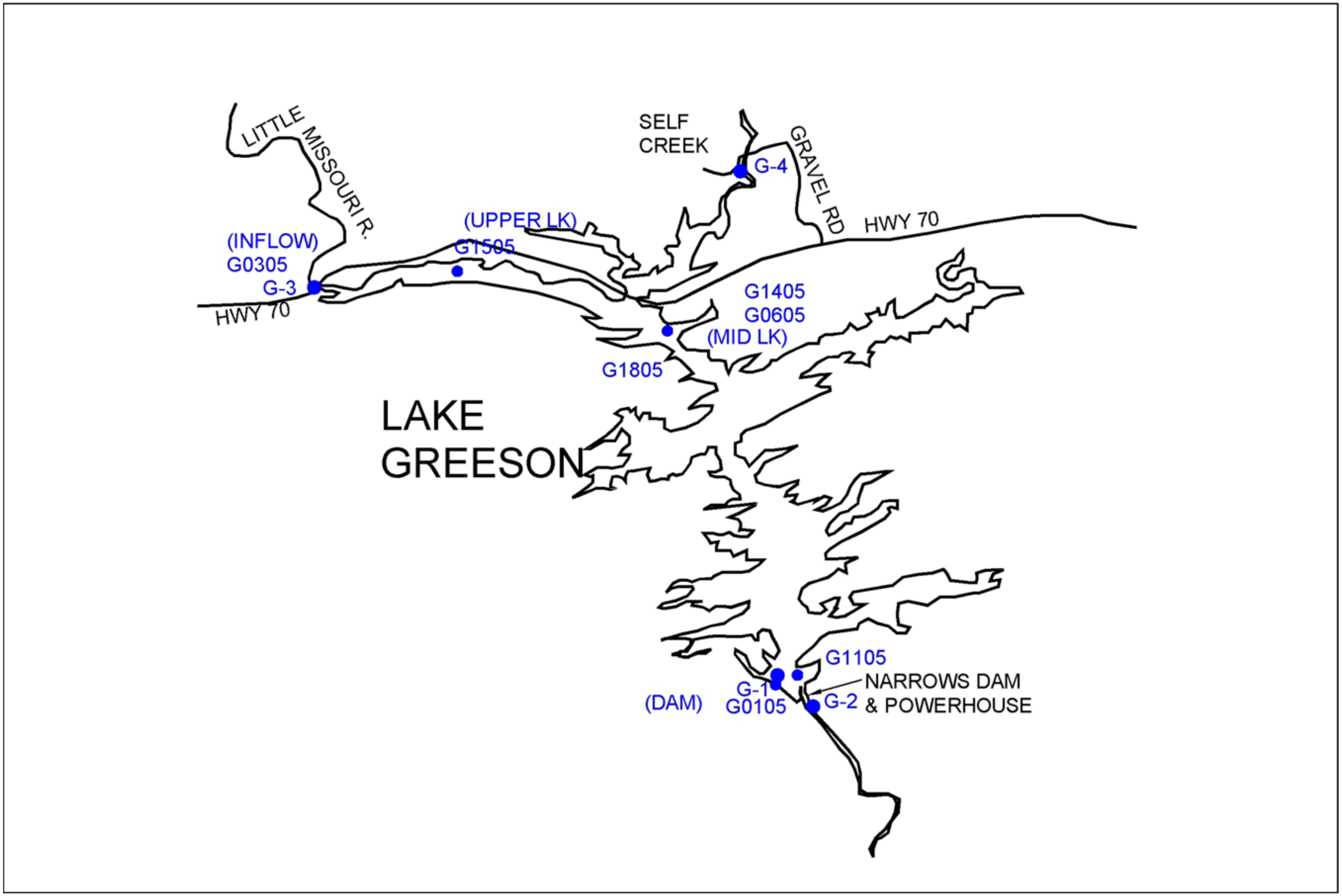


Figure 7.44. Categorization of Lake Greeson water quality sampling sites.

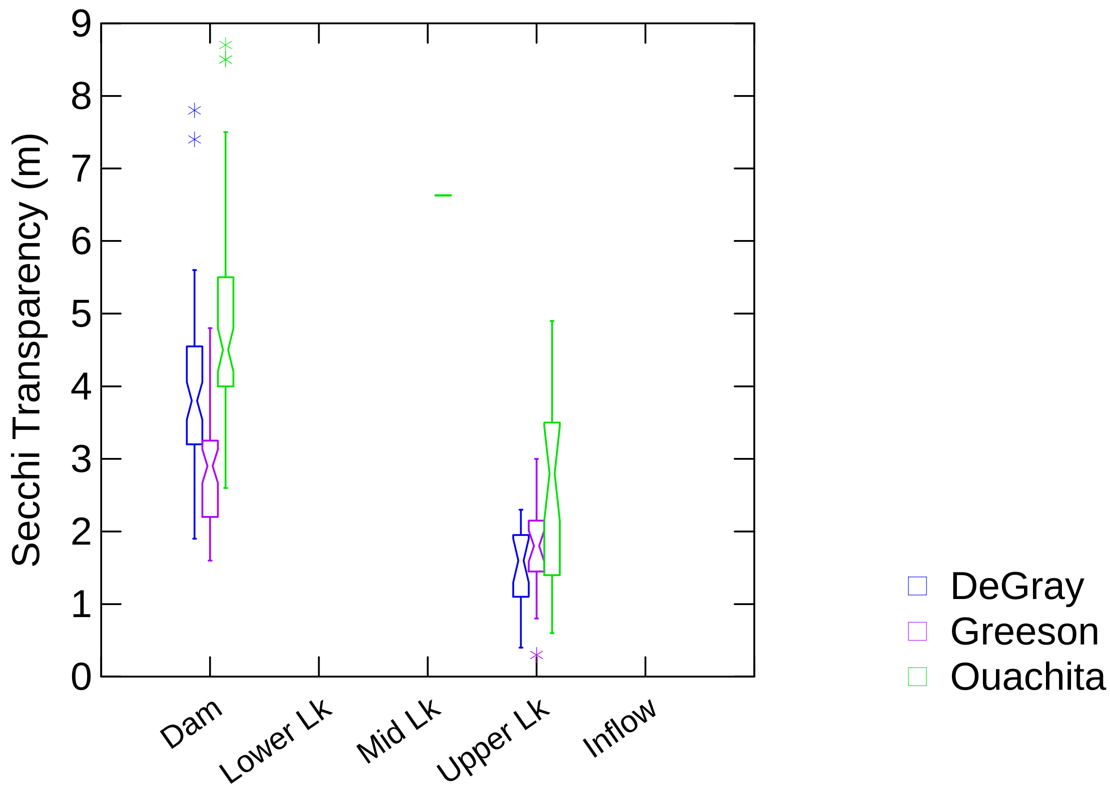


Figure 7.45. Secchi transparency at selected locations in reference reservoirs.

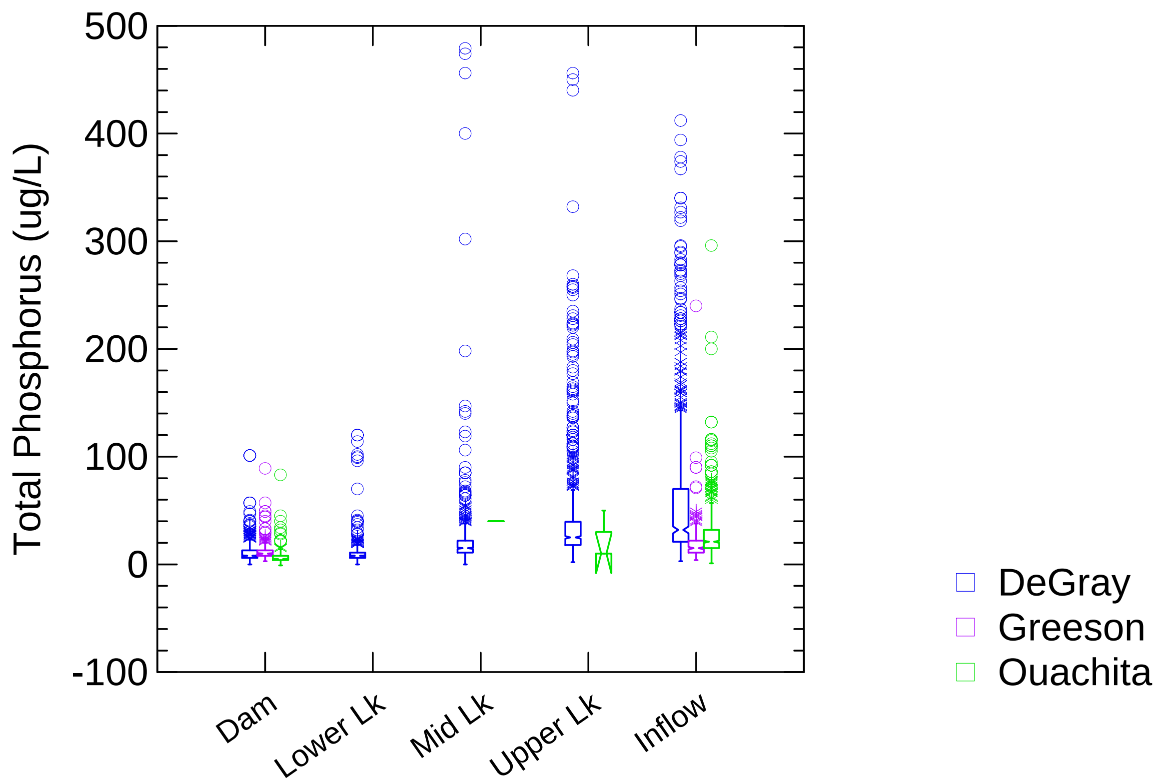


Figure 7.46. Total phosphorus concentrations at selected locations in reference reservoirs.

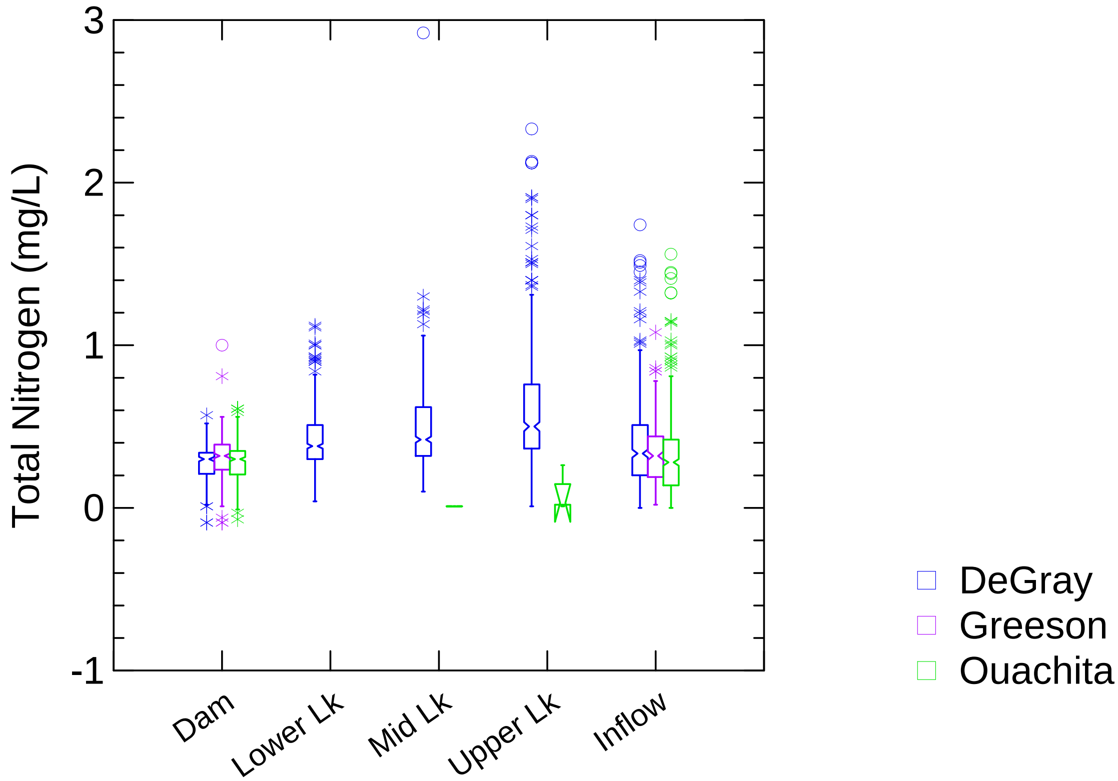


Figure 7.47. Total nitrogen concentrations at selected locations in reference reservoirs.

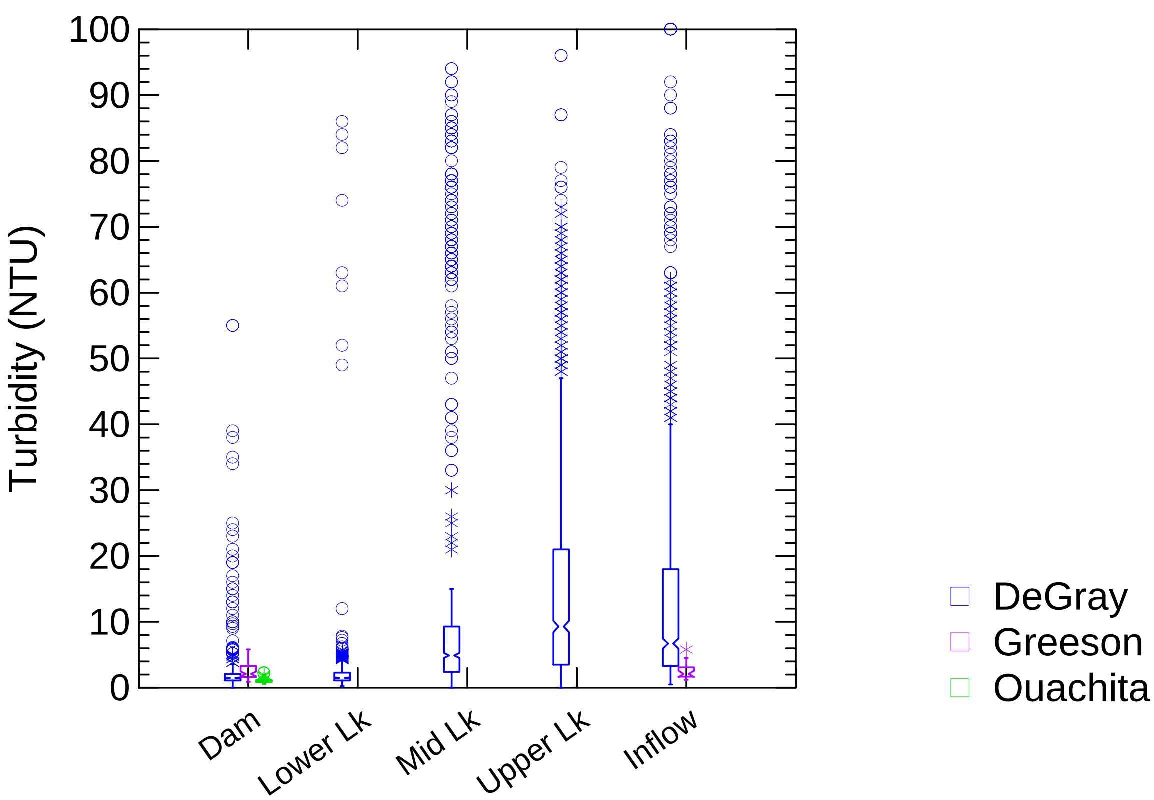


Figure 7.48. Turbidity levels at selected locations in reference reservoirs.

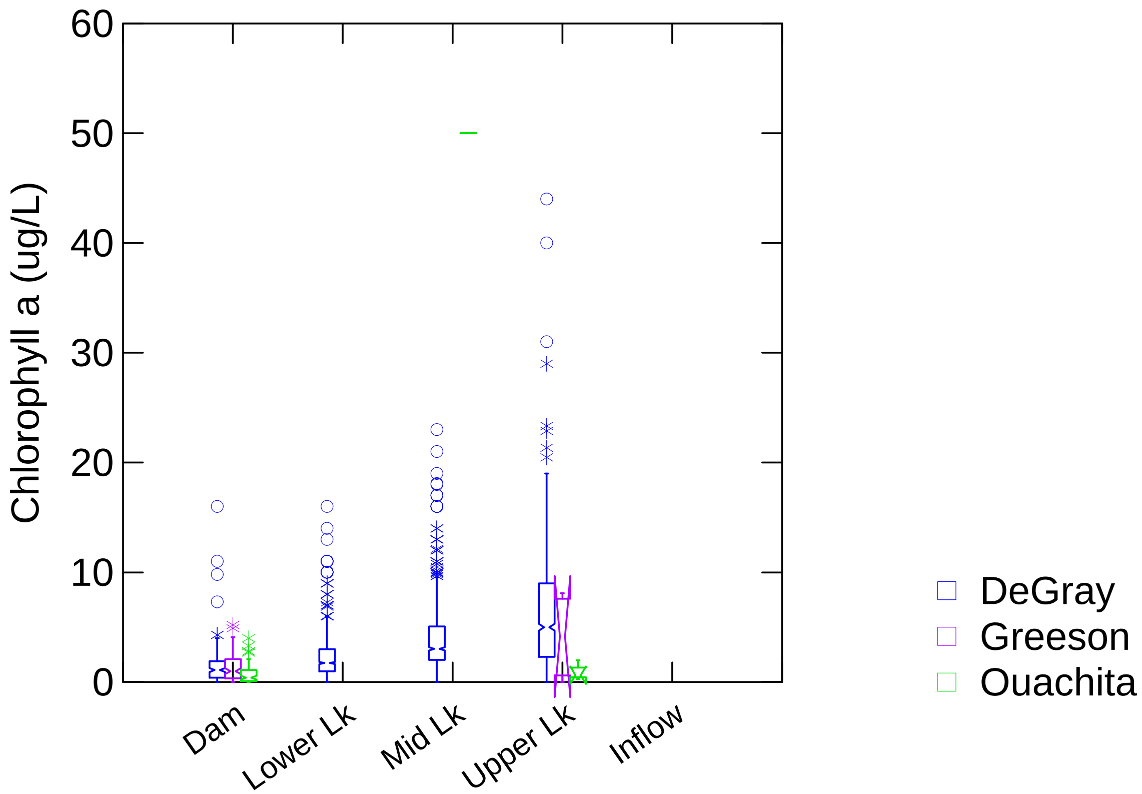


Figure 7.49. Chlorophyll a concentrations at selected locations in reference reservoirs.

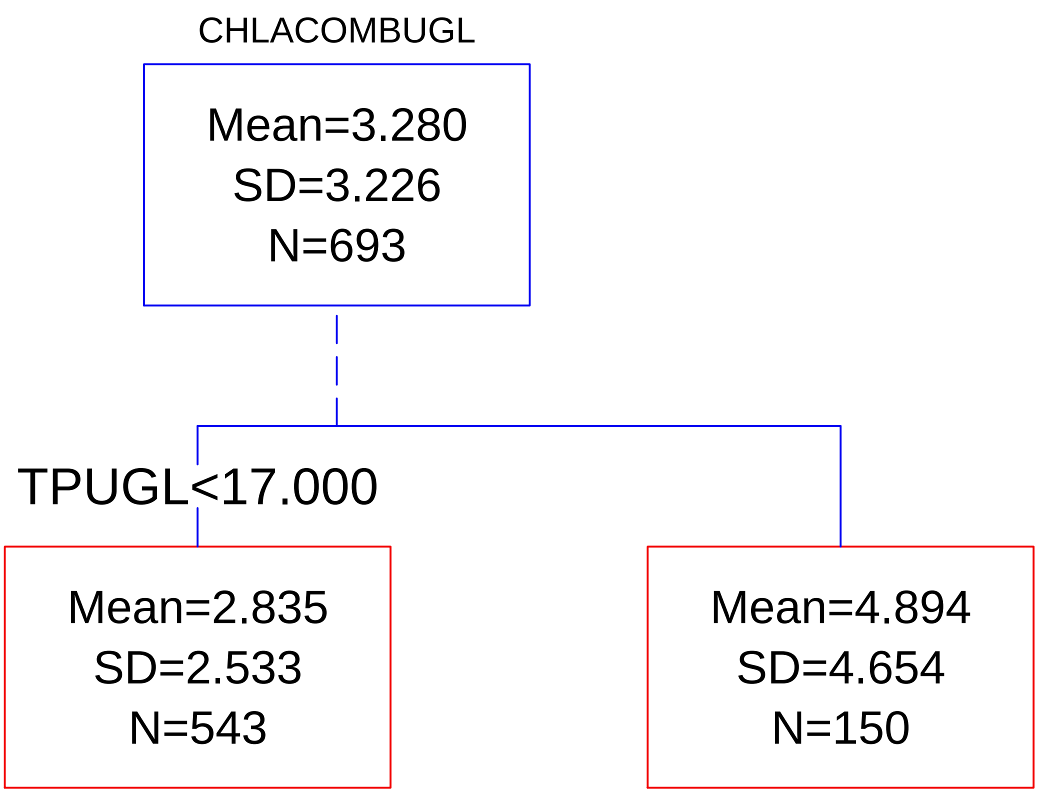


Figure 7.50. Tree analysis output for chlorophyll a with total phosphorus showing change-point.

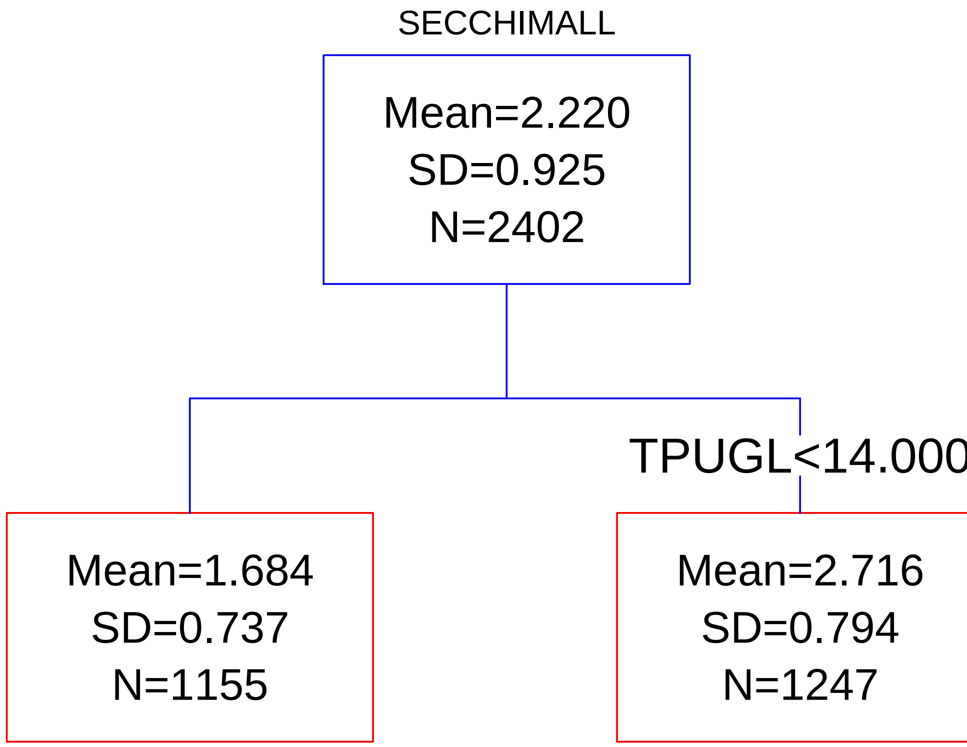


Figure 7.51. Tree analysis output for Secchi transparency with total phosphorus showing change-point.

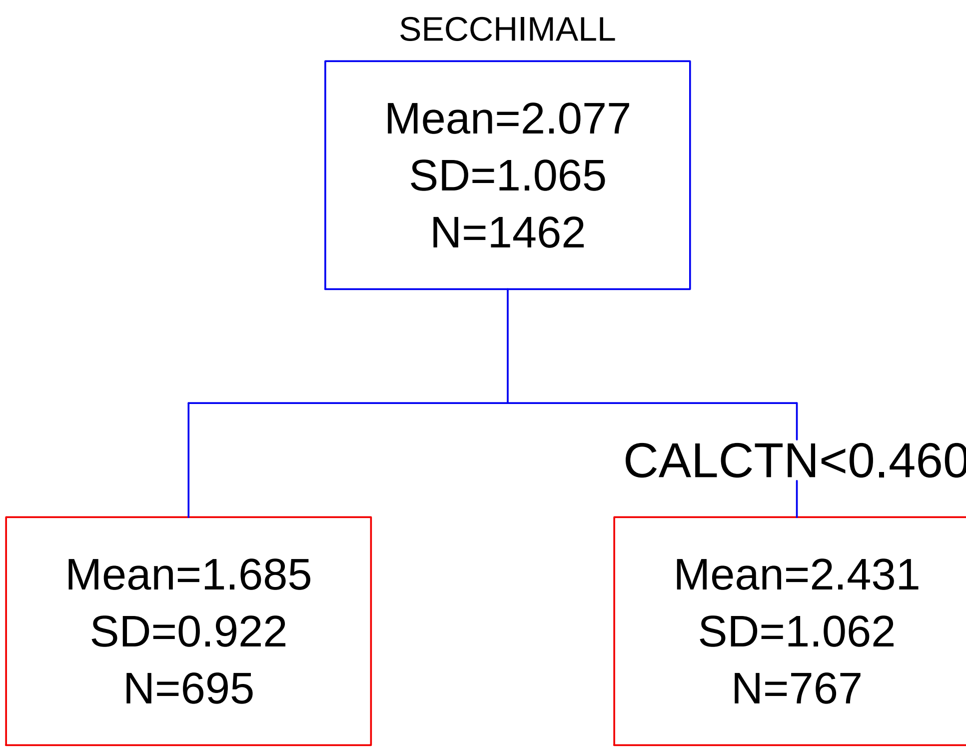


Figure 7.52. Tree analysis output for Secchi transparency with total nitrogen showing change-point.

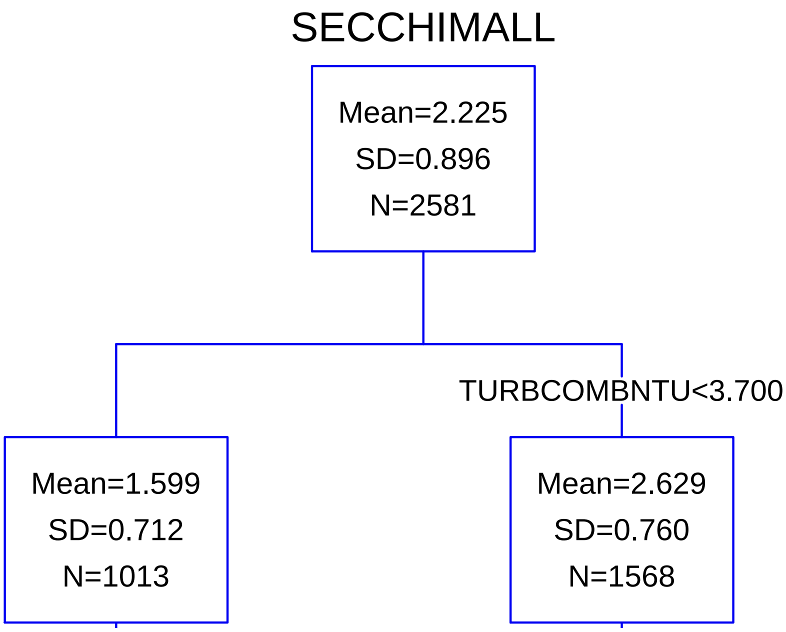


Figure 7.53. Tree analysis output for Secchi transparency with turbidity showing change-point.

8.0 MODELING ANALYSES

8.1 Water Quality Modeling for Criteria Development

Both empirical and dynamic water quality models were used to evaluate the response of Beaver Lake to different nutrient scenarios under different flow regimes. While monitoring information provides the strongest base for evaluating water quality responses, modeling exercises provide information on possible water quality responses to different nutrient concentrations and for different lake locations than those monitored (e.g., Hickory Creek confluence). Nutrient responses were modeled using empirical relationships incorporated in a modeling platform developed for CE reservoirs and through the use of a dynamic model, CE-QUAL-W2, calibrated to Beaver Lake.

8.2 Nutrient Loading

TASTR is a modeling platform developed by the USACE Environmental Research and Development Center (ERDC) for simulating reservoir water quality using empirical relationships (ERDC 2007). TASTR uses Bathtub, a previously developed empirical modeling framework (Walker 1995), to estimate potential changes in reservoir water quality because of nutrient loading. The base case for Beaver Lake TASTR represents conditions observed during the NES. Changing total phosphorus inflow concentrations in the Beaver Lake Bathtub model resulted in the greatest changes in water quality in the upper reservoir (Table 8.1). While the current White River total phosphorus concentrations are greater than the TASTR baseline concentration, lower total phosphorus concentrations in Richland and War Eagle Creeks resulted in an overall lower average total phosphorus load under existing conditions. The TASTR Bathtub model of Beaver Lake predicted that this reduced phosphorus load would result in lower total phosphorus and chlorophyll a concentrations in the reservoir. The reduced phosphorus load did not result in any change in model predicted Secchi transparencies. Reducing the total phosphorus load also resulted in reductions in predicted Carlson’s Trophic State Indices (TSI). The Beaver Lake Bathtub model predicted maximum total phosphorus concentrations in Beaver Lake headwaters (the upper 10 km of the reservoir), with baseline and existing total phosphorus inputs. The

Beaver Lake Bathtub model predicted maximum chlorophyll a concentrations between 20 km and 30 km downstream of Highway 45. These predictions are consistent with results from the water quality monitoring program.

Table 8.1. TASTR Beaver Lake Bathtub model inputs and results.

Run	Baseline	Existing	Least-disturbed
White River, total phosphorus (µg/L)	73	81	45
Richland Creek, total phosphorus (µg/L)	181	45	45
War Eagle Creek, total phosphorus (µg/L)	76	54	45
Predicted Inflow Available Phosphorus Load (kg/yr)	116,307	106,425	95,451
Predicted Mean Headwater total phosphorus (µg/L)	49.4	44.1	37.1
Predicted Maximum Segment chlorophyll a (µg/L)	8.7	8.4	7.9
Predicted Minimum Segment Secchi transparency (m)	0.7	0.7	0.7
Area-weighted Mean Carlson TSI-P	48.1	47.5	46.7
Area-weighted Mean Carlson TSI-Chla	46.4	46.2	45.9
Area-weighted Mean Carlson TSI-Secchi	50.4	50.3	50.2

Mean total phosphorus concentrations for the four most recent years classified as dry, average, and wet were calculated for Richland and War Eagle Creeks (Table 8.2), and used in the TASTR Bathtub model of Beaver Lake. For the White River, only those years since 1989 classified as dry, average, and wet were used to calculate mean total phosphorus, because total phosphorus concentrations in the White River prior to 1990 were statistically different from mean total phosphorus concentrations after 1990. Treatment was upgraded in the Fayetteville wastewater treatment plant in 1987, which significantly decreased phosphorus point source discharges and loads to the White River. In addition, mean total phosphorus concentrations were also calculated from the data collected by USGS from 2001 through 2003 for their CE-QUAL-W2 modeling (Table 8.2). These phosphorus concentrations were also used in the TASTR Bathtub. The results of the TASTR Bathtub runs using these mean concentrations are shown in Table 8.3.

Table 8.2. Total phosphorus concentration statistics for White River, Richland Creek, and War Eagle Creek.

Condition	Statistic	White River at Hwy 45 (mg/L)	Richland Creek at Hwy 45 (mg/L)	War Eagle Creek at Hwy 45 (mg/L)
Dry	N	38	20	39
	Mean	0.090	0.036	0.061
	Median	0.046	0.020	0.050
Average	N	80	41	87
	Mean	0.062	0.023	0.056
	Median	0.040	0.020	0.040
Wet	N	29	15	10
	Mean	0.102	0.057	0.056
	Median	0.080	0.030	0.060
CE-QUAL-W2	N	56	57	57
	Mean	0.065	0.025	0.048
	Median	0.030	0.020	0.040

Table 8.3. TASTR/Bathtub results for Beaver Lake, changing only total phosphorus concentrations in White River, Richland Creek, and War Eagle Creek.

Run	TASTR Baseline	Dry	Average	Wet	CE-QUAL-W2
White River, total phosphorus (µg/L)	73	90	62	102	65
Richland Creek, total phosphorus (µg/L)	181	36	23	57	25
War Eagle Creek, total phosphorus (µg/L)	76	61	56	56	48
Predicted Inflow Available Phosphorus Load (kg/yr)	111,691.9	104,739.8	95,705.4	108,450.0	95,362.2
Predicted Mean Headwater, total phosphorus (µg/L)	49.4	45.6	38.9 (20-30 km)	49.3	39.4
Predicted Maximum Segment, chlorophyll a (µg/L)	8.7 (20-30 km)	8.5 (20-30 km)	8.2 (20-30 km)	8.6 (20-30 km)	8.1 (20-30 km)
Area-weighted Mean Carlson TSI-P	48.1	47.6	47.0	47.9	47.0
Area-weighted Mean Carlson TSI-Chla	46.4	46.3	46.0	46.4	46.0
Area-weighted Mean Carlson TSI-Secchi	50.4	50.3	50.2	50.3	50.2

The maximum chlorophyll concentrations were predicted to occur 20 to 30 km downstream of Highway 45. The Highway 412 monitoring site is 18 to 20 km downstream of Highway 45. This is consistent with the longitudinal profiles of chlorophyll observed from the monitoring program. The CE-QUAL-W2 loads also resulted in maximum chlorophyll concentrations in the same area. The predicted maximum segment chlorophyll concentration was 8.1 µg/L while the median chlorophyll concentrations observed during 2001-2003 at the

Highway 412 site were 12.5 µg/L. The observed median chlorophyll concentrations, however, were within the error for predicted chlorophyll concentrations (± 7 µg/L).

8.3 Dynamic Water Quality Modeling

In addition to using empirical modeling relationships, USGS calibrated a two-dimensional, laterally-averaged, hydrodynamic and water quality model, CE-QUAL-W2, to Beaver Lake. The model was calibrated at four sites in the reservoir for the period from April 2001 through April 2003 (Galloway and Green 2006). The four sites were based on location of monitoring stations in Beaver Lake: Highway 412 station near Sonora, the station near Lowell, Highway 12 site near Rogers, and at the dam station near Eureka Springs. Following calibration, the model was used to evaluate the effects of different nutrient loading scenarios on Beaver Lake water quality.

Nitrogen and phosphorus loadings were decreased by half, and increased two, four, and ten times the calibrated daily input concentrations in the three tributaries simultaneously and for each individual tributary (Galloway and Reed 2007). In addition, nitrogen and phosphorus concentrations were increased simultaneously as well as independently. In general, the chlorophyll response to increased phosphorus or nitrogen was not as great as when both nitrogen and phosphorus were increased.

The greatest response to nutrient load changes was in the upper portions of the Beaver Lake (Galloway and Green 2007). For example, a ten-fold increase in nitrogen and phosphorus concentrations in the three major tributaries (White River, Richland Creek, and War Eagle Creek) resulted in a four-fold increase in total nitrogen at the Highway 412 station and a two-fold increase at the dam station. The ten-fold increase in both nitrogen and phosphorus in the three major tributaries resulted in a total phosphorus concentration increase of about nine-fold at the station near Lowell. A ten-fold increase in nitrogen and phosphorus in the three major tributaries also resulted in about a 10 µg/L increase in chlorophyll concentrations at the station near Lowell. A doubling of the nitrogen/phosphorus daily concentrations in the three major tributaries resulted in about a 2 µg/L increase in chlorophyll concentrations at the Highway 12 station and less than a 1 µg/L increase in chlorophyll concentration at the dam station.

Decreasing both nitrogen and phosphorus daily concentrations in the three major tributaries by half resulted in about a 1 µg/L decrease in chlorophyll concentrations at the Highway 412 station and about a 0.5 µg/L decrease at the dam station.

8.4 Modeling Conclusions

Both empirical and dynamic modeling results indicated that the greatest change to increased or decreased nutrient loading would occur in the upper portions of the reservoir, with significantly lower responses in the lower portion of the reservoir, consistent with monitoring results. The mean of observed chlorophyll concentrations in Beaver Lake during 2001 to 2003 were 15.6 µg/L at Highway 412 and 5.4 µg/L at the station near Lowell. The empirically predicted chlorophyll concentrations near the Highway 412 station were 9.8 µg/L compared with dynamic model mean chlorophyll concentration predictions of 5.8 µg/L at the Highway 412 station during 2001 to 2003. Dynamic model chlorophyll concentrations at the station near Lowell averaged 5.4 µg/L compared with monitored concentrations of 5.4 µg/L and the empirical model mean concentration of 7.0 µg/L. The root mean square error (RMSE) associated with dynamic model predictions of chlorophyll concentrations for the Highway 412 station was 7.3 µg/L, and 3.3 µg/L for the station near Lowell. This means that the mean concentration predicted by the model could be ± RMSE, as shown in Table 8.4. Chlorophyll concentrations predicted by the empirical model at Highway 412 and the station near Lowell varied by 40% to 37% about the estimated mean chlorophyll concentrations of 10 and 7.0 µg/L, respectively.

Table 8.4. Comparison of observed chlorophyll a data and model results.

Location	**Observed 2001 – 2003 (µg/L)**	**Bathtub (µg/L)**	**CE-QUAL-W2 (µg/L)**
Highway 412	15.6	9.8	5.8 ± 7.3
Lowell	5.4	7.0	5.4 ± 3.3

The mean of observed total phosphorus concentrations in Beaver Lake during 2001 to 2003 were 26 µg/L at Highway 412 and <20 µg/L (the detection limit) at the station near Lowell. The mean empirically predicted total phosphorus concentration near the Highway 412 station was 59 µg/L compared with dynamic model mean total phosphorus concentration prediction of 61 µg/L at the Highway 412 station during 2001 to 2003. Dynamic model total phosphorus concentrations at the station near Lowell averaged 36 µg/L compared with monitored concentrations of <20 µg/L and the empirical model mean concentration of 35 µg/L. The RMSE associated with dynamic model predictions of total phosphorus concentrations for the stations at Highway 412 near Lowell was 40 µg/L for both stations. This means that the mean concentration predicted by the model could be ± RMSE, as shown in Table 8.5. Total phosphorus concentrations predicted by the empirical model at Highway 412 and the station near Lowell varied by 41% and 37%, respectively, about the estimated mean total phosphorus concentrations of 61 and 36 µg/L.

Table 8.5. Comparison of observed total phosphorus data and model results.

Location	**Observed 2001 – 2003 (µg/L)**	**Bathtub (µg/L)**	**CE-QUAL-W2 (µg/L)**
Highway 412	26	58.8	61 ± 40
Lowell	<20	34.6	36 ± 40

9.0 WEIGHT OF EVIDENCE

9.1 Location

Some WQS are established to be applicable any time, anywhere in the waterbody. It is recommended that reservoir WQS be established for a specific location or locations within the waterbody because of the complexity and dynamic processes in these ecosystems. Previous chapters have described the distinct longitudinal gradients in water quality constituents with most constituent concentrations decreasing from the headwater to the dam (Secchi depth, or water clarity, increases from the headwater to the dam). If water quality criteria were established for a location in the upper portion of the reservoir, then, designated uses downstream from this location should be protected, and numeric water quality criteria should be attained. There are two primary considerations for establishing this location: plunge point and dominant tributary inflow.

Because the area or zone downstream from the plunge point is typically the most dynamic region in the reservoir for most water quality constituents, including chlorophyll, this zone might be considered for establishment of the location to monitor and assess the attainment of the water quality criteria. The riverine zone typically does not exhibit the greatest chlorophyll concentrations because of light limitation, and chlorophyll and other constituent concentrations are significantly lower downstream from the plunge point. Although dynamic, the plunge point typically occurs just upstream from the Highway 412 monitoring site (See Table 6.4 and Figure 6.11).

Loading from major tributaries is the second consideration in establishing a location for monitoring and assessing water quality attainment. If there are several major inflows to a reservoir, multiple locations might be established below the plunge point for each major tributary. Alternatively, a single location below the confluence of all major tributaries might be established. The Highway 412 location integrates the inflows from the White River and Richland Creek, but is upstream from the confluence of War Eagle Creek inflows. The location at Lowell integrates the inflow from all three major tributaries. One of the disadvantages of the Lowell monitoring site location is that it provides limited buffer for episodic excursions above the water quality criterion to protect the drinking water designated use.

An alternative location, which is not currently a monitoring site, but does have access and is below the confluence of all three major inflows, is a site near Hickory Creek. Advantages of the Hickory Creek site include: 1) there is a boat ramp at this location; 2) it is below the confluence of all three major tributaries and should integrate the loadings from these three tributaries; and 3) it is upstream from the location of a major drinking water intake, so it should provide protection from episodic excursions of chlorophyll and suspended sediment in the transition zone.

The proposed location for the monitoring and assessment site, therefore, is over the thalweg at the Hickory Creek site in Beaver Lake, between the current Highway 412 and Lowell monitoring sites (Figure 9.1). Rationale includes:

1. It integrates the loadings from all three major tributaries – White River, Richland and War Eagle Creeks;
2. It is typically below the plunge point in the transition zone of the reservoir, which has the greatest water quality dynamics;
3. It provides some buffer from episodic excursions for the downstream drinking water intake, which represents one of the highest designated uses for Beaver Lake;
4. Water quality typically improves significantly for all constituents downstream from this location so downstream designated uses should be protected;
5. Subsequent tributary numeric WQS for nutrients and other constituents should protect Beaver Lake designated uses from minor tributary loadings downstream of the site;
6. Water quality constituent concentrations can be extrapolated from the Highway 412 and Lowell sites to estimate concentrations at the Hickory Creek site until sufficient data can be established at the Hickory Creek site to assess water quality status and trends; and
7. The Beaver Lake Watershed Management Plan should assist in moving toward restoration of tributaries that are currently not meeting WQS and provide protection of both upstream and downstream areas from degradation. The DA/SA ratio described in Chapter 5 indicated that best management practices implemented anywhere in the watershed should result in improved water quality conditions in Beaver Lake.

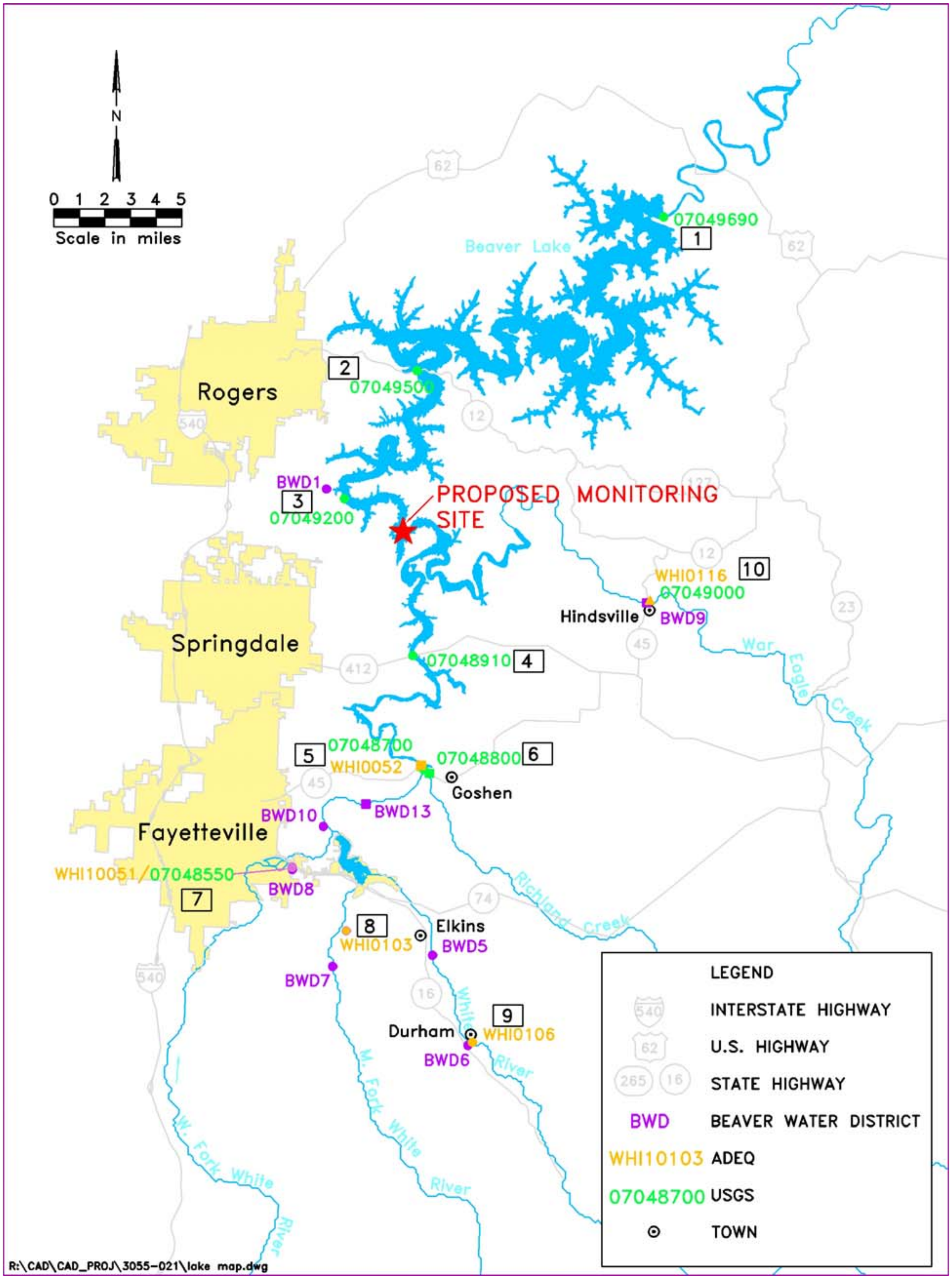


Figure 9.1. Proposed Hickory Creek monitoring site for assessing WQS attainment.

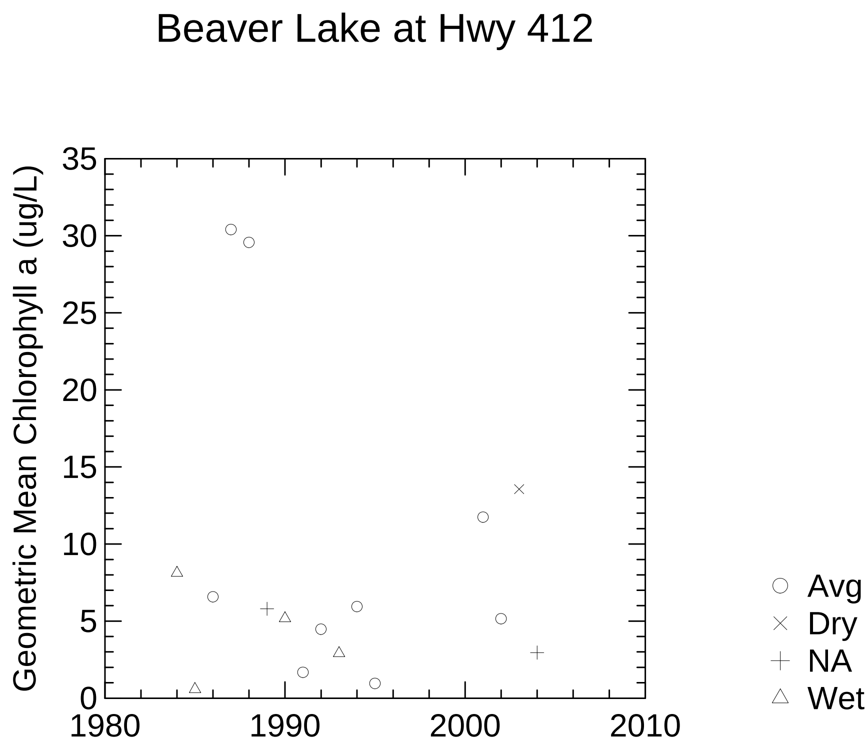
9.2 Frequency, Duration, and Magnitude

The emphasis has been on developing effects-based criteria that can be directly related to the designated uses for Beaver Lake. The two effects-based criteria are chlorophyll a (aquatic life, drinking water, recreation designated uses), and Secchi transparency or water clarity (drinking water, recreation designated uses). Both of these constituents are dynamic and vary episodically, seasonally, and annually, based on hydrology and in-lake processes. Therefore, the development of water quality criteria needs to consider not only magnitude, but also frequency and duration in constituent concentrations.

Chlorophyll data are traditionally quite variable with time scales of about a week. A comparison of seasonal means for chlorophyll collected at the same site by Beaver Water District and USGS for 2001-2005 illustrates this variability (Table 9.1) Because Secchi transparency is an indicator of water clarity, it also is affected by algal biomass as well as inorganic particulate concentrations. Geometric means are typically used to estimate conditions for constituents with highly variable concentrations. Geometric means of growing season (May – October) chlorophyll concentrations and annual average Secchi depth values in Beaver Lake at the Highway 412 and Lowell stations, along with hydrologic year classification, are shown in Figures 9.2 and 9.3.

Table 9.1. Comparison of growing season geometric chlorophyll means (μg/L) collected by USGS and Beaver Water District at the site near Lowell, Arkansas.

Agency	Growing Season Geometric Chlorophyll Mean (μg/L)				
	2002	2003	2004	2005	2006
USGS	4.6	4.9	1.1	3.4	4.2
BWD	5.3	4.8	7.2	3.8	1.3



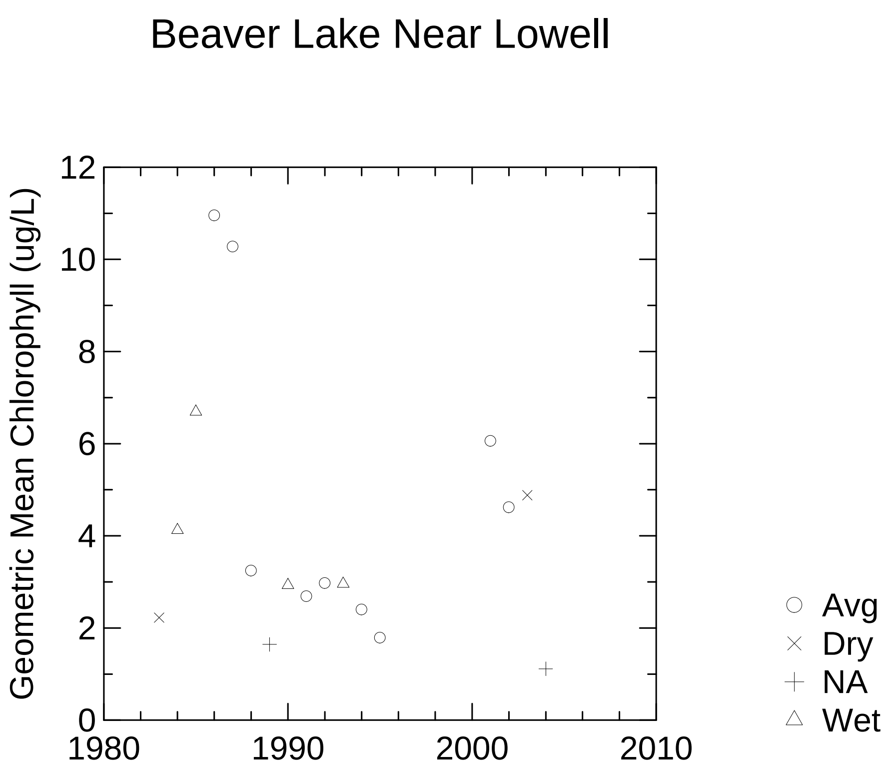


Figure 9.2. Growing season geometric chlorophyll means as a function of hydrologic category at the Highway 412 (top graph) and Lowell (bottom graph) sites. No apparent hydrologic patterns were noted. NA indicates that hydrologic classification based on precipitation was different from the classification based on flow.

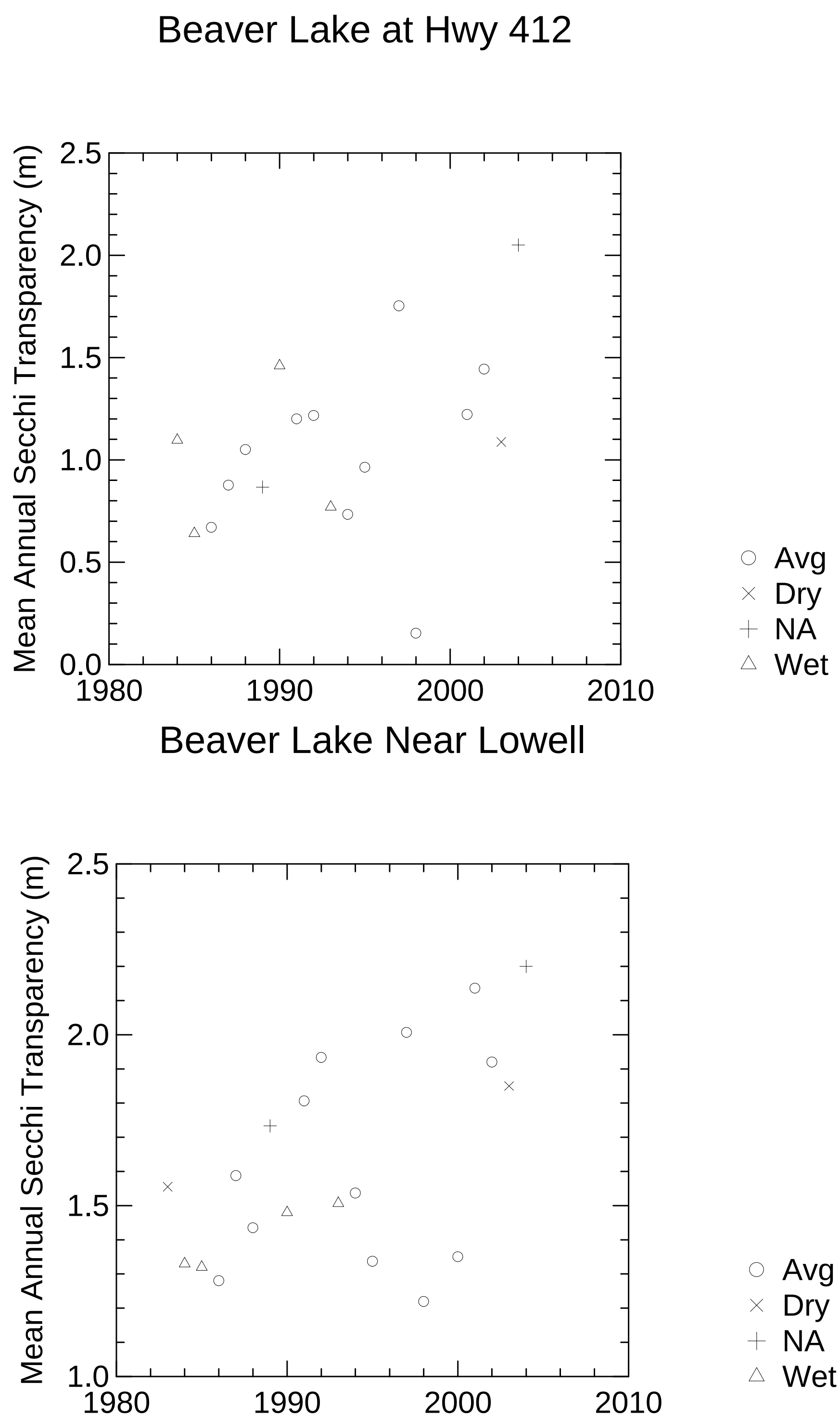


Figure 9.3. Average annual Secchi transparency values as a function of hydrologic category at the Highway 412 (top graph) and Lowell (bottom graph) sites. No apparent hydrologic patterns were noted, but there has been an increasing trend in water clarity at both sites over time. NA indicates that hydrologic classification based on precipitation was different from the classification based on flow.

9.3 Weight of Evidence

A weight of evidence approach was used to develop and derive numeric water quality criteria for Beaver Lake. This included considerations of:

1. Surrounding state numeric criteria for chlorophyll, Secchi transparency, total phosphorus, and total nitrogen values;
2. Ecoregion values;
3. Percentile values based on both reference lakes and extant values for Beaver Lake;
4. Statistical analyses of Beaver Lake and reference lake data;
5. Empirical nutrient loading relationships; and
6. Dynamic modeling results.

Results from these various lines of evidence are shown in Table 9.2 for chlorophyll a, Secchi depth, total phosphorus, and total nitrogen. Each of these constituents are discussed below.

Table 9.2. Weight of evidence comparison of analytical approaches for Beaver Lake water quality criteria.

Constituent	Station Standards	Percentile Distributions					
		75th Percentile		25th Percentile			
		DeGray	Ouachita	Highway 412	Lowell	Ecoregion 38	Ecoregion 39
Chlorophyll a (µg/L)	10	9	--	2.6	2.4	6.6	6.1
Secchi depth (m)	0.45 [(a)]	0.9	1.7	2.0	2.4	1.8	2.0
Total phosphorus (µg/L)	90 [(a)]	38	17	20	13	5	24
Total nitrogen (mg/L)	1.0 [(a)]	0.76	0.33	0.65	0.39	0.12	0.5

Constituent	Change-Point Analyses						Historical				
	Chlorophyll			Secchi Transparency			Lowell		Dam		
	DeGray	Hwy 412	Lowell	DeGray	Hwy 412	Lowell	CLS	2001/2	NES	CLS	2001/2
Chlorophyll a (µg/L)	--	--	--	--	--	--	3.9	5.9	2.7	0.8	1.9
Secchi depth (m)	--	--	--	--	--	--	1.7	2.0	4.2	5.2	5.7
Total phosphorus (µg/L)	28	60	15	21	40	48	17	20	11	5	20
Total nitrogen (mg/L)	0.42	0.5	0.31	0.52	0.5	--	0.59	0.68	0.35	0.49	0.35

Notes: [(a)] Recommended criteria for MS reservoirs, not WQS.

9.3.1 Chlorophyll a

The drinking water criterion for chlorophyll adopted by Oklahoma Water Resources Board (OWRB) is 10 μg/L, which is the chlorophyll concentration associated with increased risk of blue-green bacteria blooms for drinking water supplies. None of the other lines of evidence resulted in concentrations that exceeded this criterion value. DeGray was the only reference lake for which distributional (75th percentile) analysis could be performed for a station in the upper portion of the reservoir (see Figure 7.42). The distributional concentration for DeGray Lake at this upper reservoir station was 9 μg/L (Table 9.2). Distributional analyses on extant data for Beaver Lake (25th percentile) at both the Highway 412 and Lowell sites were similar – 2.4 to 2.6 μg/L (Table 9.2). Distributional analyses on extant data for Ecoregions 38 and 39 (see Section 3.2) ranged from 6.6 to 6.1 μg/L (Table 9.2). The approach recommended by USEPA (2000) was to use distributional analyses for reference lakes, when possible. Therefore, greater weight was given to the DeGray Lake chlorophyll concentration. There was no significant change in historic chlorophyll concentrations at either the Lowell station or dam station in Beaver Lake, although there was an apparent increase in chlorophyll concentrations at the Lowell station after 1991 (Figure 9.2).

Geometric mean chlorophyll concentrations were computed for the Highway 412 and Lowell stations for the period from the early 1980s through 2004 (Figure 9.2). The long-term growing season geometric means at the Highway 412 and Lowell sites were 5.2 and 3.5 μg/L, respectively. While the highest chlorophyll means occurred in the 1980s, several means greater than the long-term average have also occurred since 2000 at both sites. There was a statistical relationship, albeit a weak relationship, between growing season geometric mean chlorophyll concentrations at the Highway 412 and Lowell stations ($R^2 = 0.11$, $p < 0.1$). Increased chlorophyll concentrations at Lowell were generally associated with increased chlorophyll concentrations at the Highway 412 station (Figure 9.4). The War Eagle confluence with Beaver Lake downstream from the Highway 412 station likely confounds this relationship. If the Hickory Creek site was established in Beaver Lake, it might be expected that chlorophyll concentrations at the Hickory Creek site would be correlated with similar, but lower chlorophyll concentrations at the downstream Lowell station.

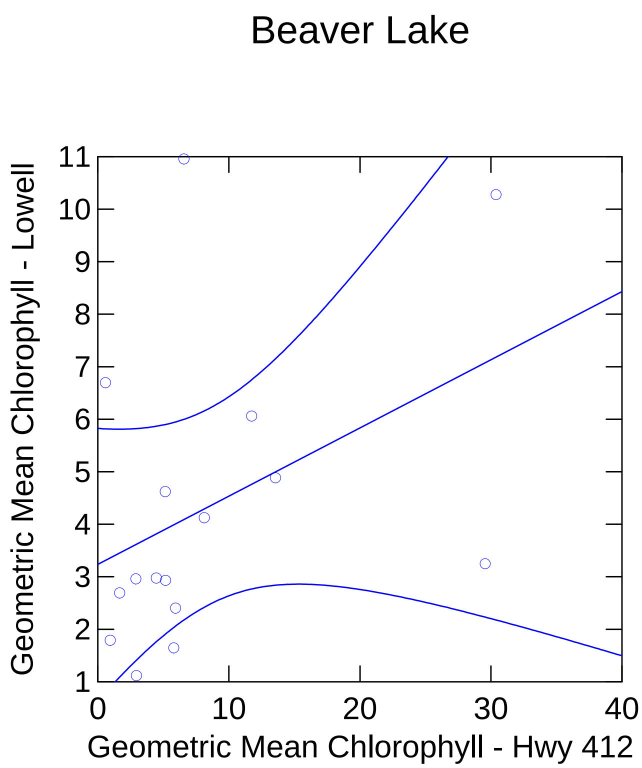


Figure 9.4. Regression relationship with 95% confidence interval between growing season geometric chlorophyll means at Highway 412 and Lowell sites (gmchl Lowell = 0.13 * gmchl 412 + 3.23; $R^2 = 0.11$, $p \leq 0.1$).

The likelihood of exceeding various geometric mean chlorophyll concentrations at the Highway 412 and Lowell sites was evaluated by considering hydrologic frequency and probability of exceedance. Initially, it was assumed there might be a direct relationship between increased nutrient loading during wet years and chlorophyll concentrations. However, there was no apparent relationship between hydrology (i.e., wet, dry, and average years) and geometric chlorophyll means or annual Secchi depth means at either the Highway 412 or Lowell stations (Figure 9.2). In some cases, chlorophyll concentrations were higher during dry years than during wet years.

A long-term geometric chlorophyll mean, with a 95% confidence interval, was determined for both the Highway 412 and Lowell stations. Geometric means and confidence interval, as log values, are shown on Figure 9.5. Variance or confidence intervals cannot be transformed into arithmetic values because of nonlinear relations in the variance estimates. The growing season geometric chlorophyll mean associated with the 95% confidence interval at the Highway 412 and Lowell stations are 9.2 and 4.8 μg/L, respectively.

The chlorophyll regression equation was used to estimate concentrations at Lowell, and subsequently at the Hickory Creek site by averaging the values from the Highway 412 and Lowell sites. The Hickory Creek site is located about half the way between Highway 412 and Lowell. A growing season geometric mean chlorophyll concentration of 10 and 12 μg/L at Highway 412 results in a predicted geometric chlorophyll mean of 4.5 and 4.8 μg/L at Lowell, with the upper 95% geometric means at Lowell estimated as 6.5 and 6.9 μg/L, respectively. The associated Hickory Creek growing season geometric chlorophyll means estimated for the Hickory Creek site were 7.5 and 8.5 μg/L, respectively. The DeGray reference lake chlorophyll concentration was 9 μg/L, which is consistent with this estimated value.

Drinking water supply is one designated use, but aquatic life and fishable are also designated uses for Beaver Lake. Chlorophyll, as an indicator of productivity, relates not only to the drinking water use, but also to Beaver Lake sport fisheries. In general, greater productivity in a reservoir results in greater sport fish standing stocks. Game fish biomass is greatest in the upper reservoir and lowest near the dam (data from AGFC 2004) (Figure 9.6). This longitudinal pattern is similar to the longitudinal patterns of nutrients and chlorophyll a in Beaver Lake. Arkansas Game and Fish Commission uses regression equations to describe relationships between fishery condition and water quality metrics. Information for Beaver Lake was used to estimate changes in sport fish standing stock that might result if chlorophyll concentrations were decreased from 7 μg/L to 3 μg/L. Sport fish standing stock would be expected to decline as chlorophyll a concentrations decrease (Figure 9.7).

There are potential conflicts between criterion values that protect drinking water while increasing fish support/recreational fishing uses of Beaver Lake. Lower chlorophyll and nutrient levels, which would be preferable for the drinking water use, can reduce productivity and the sport fishery use. There are trade-offs that must be acknowledged and considered.

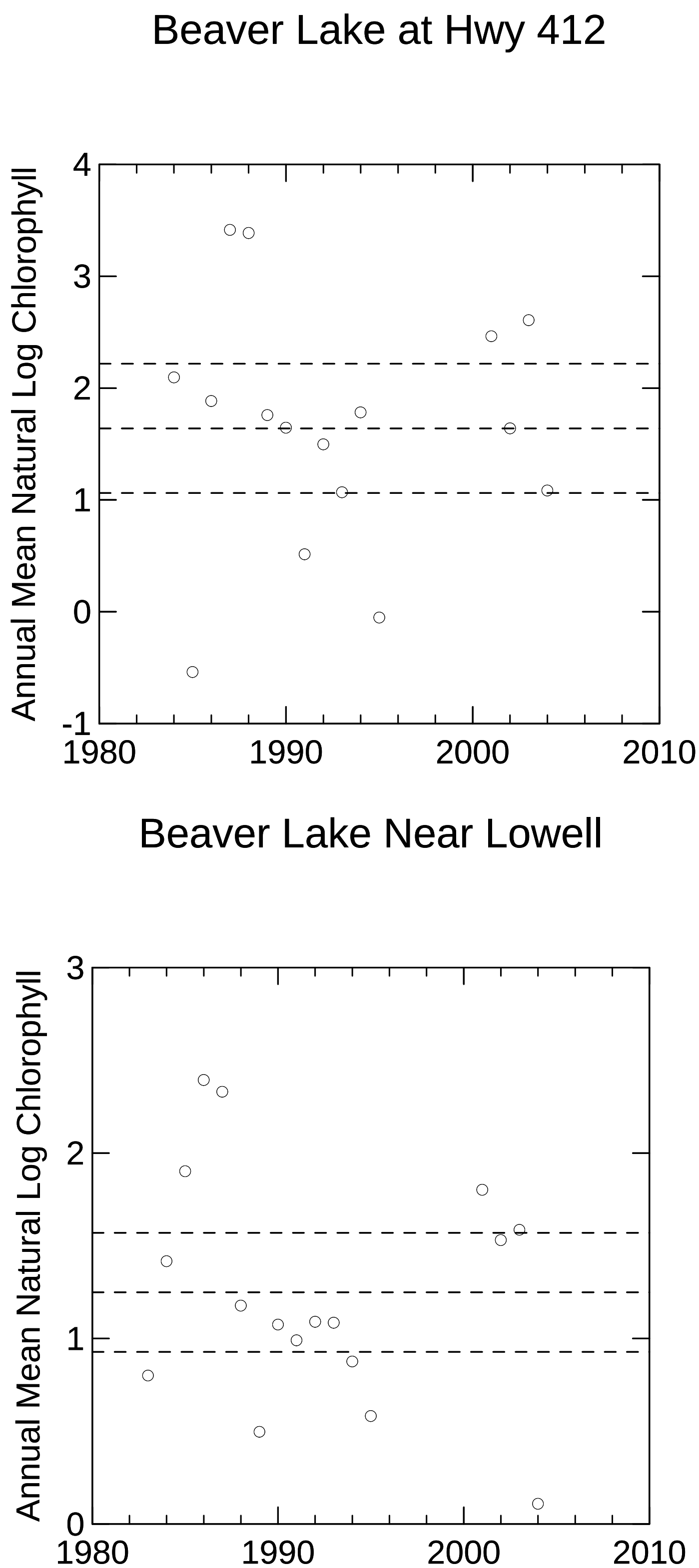


Figure 9.5. Long-term growing season geometric chlorophyll mean, with 95% confidence interval, for Highway 412 (top graph) and Lowell (bottom graph) sites.

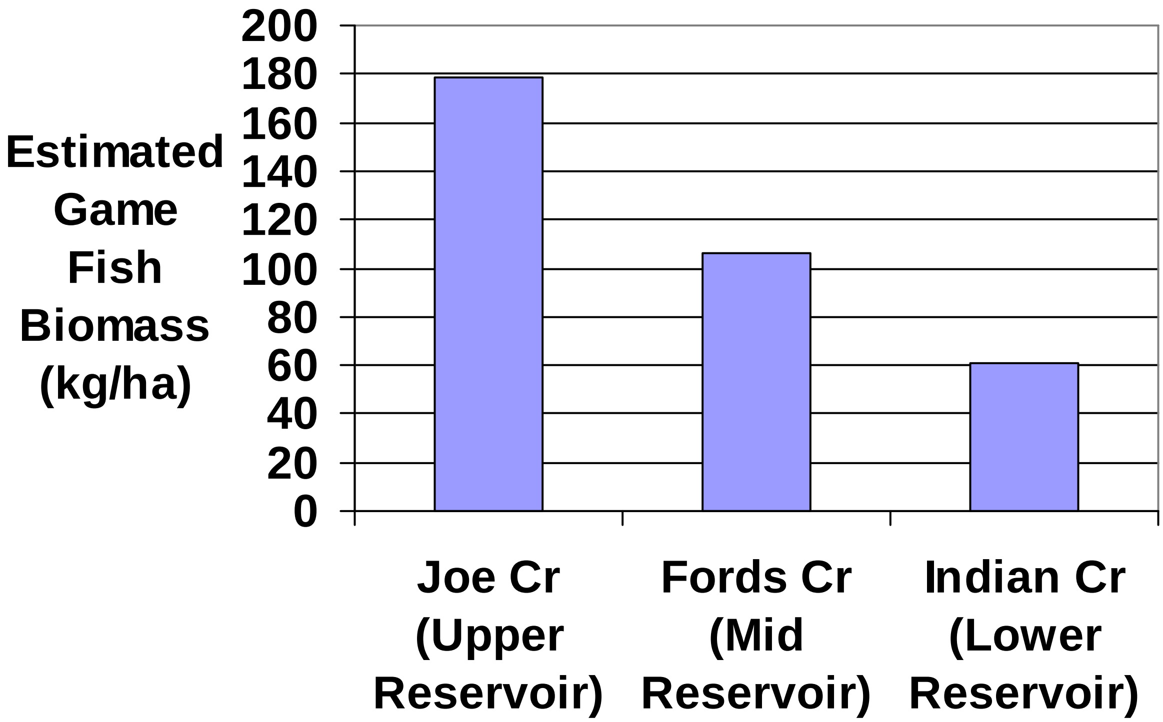


Figure 9.6. Longitudinal gradient in Beaver Lake game fish biomass.

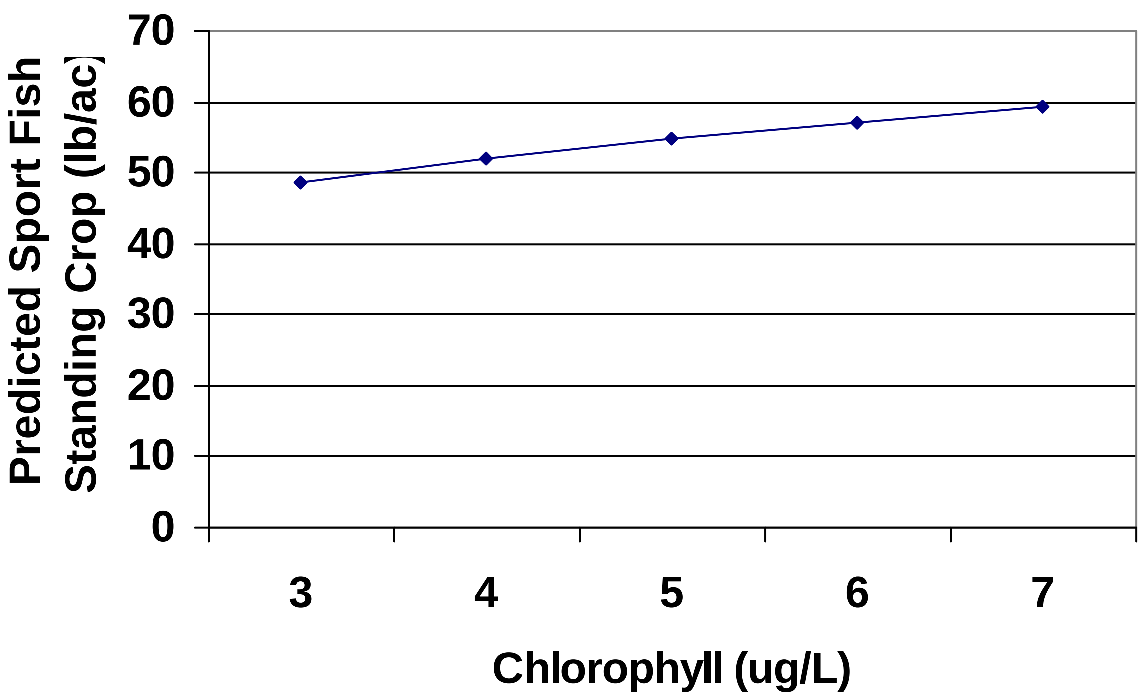


Figure 9.7. Predicted change in sport fish standing crop resulting from changes in chlorophyll concentrations.

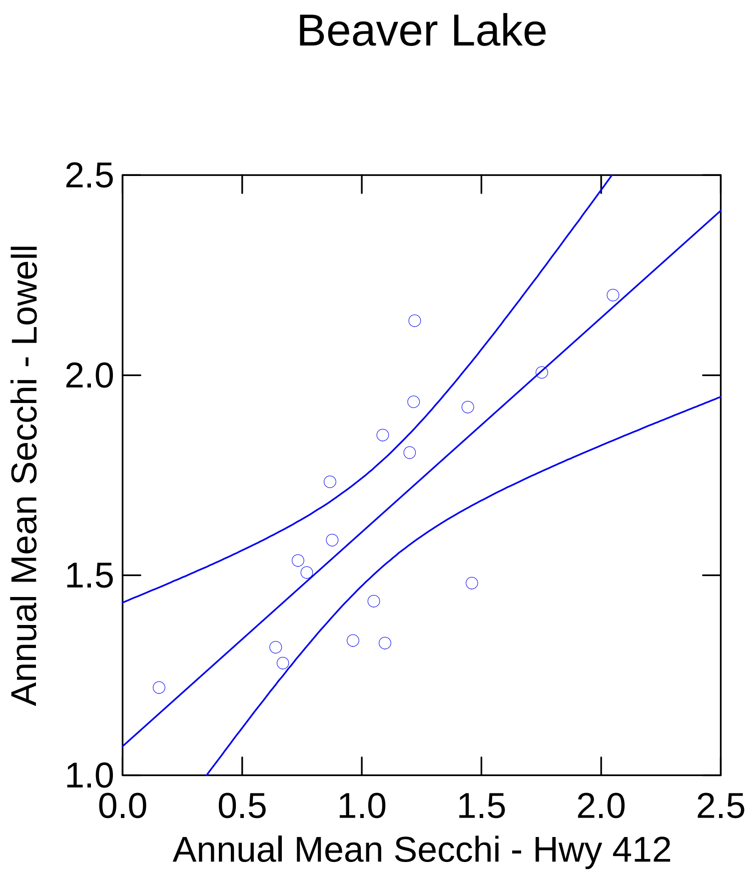


Figure 9.8. Regression relationship, with 95% confidence intervals, between average annual Secchi transparency values at the Highway 412 and Lowell sites (AM Secchi Lowell = 0.54 * AM Secchi 412 + 1.07; $R^2 = 0.55$, $p < 0.001$).

9.3.2 Secchi Depth

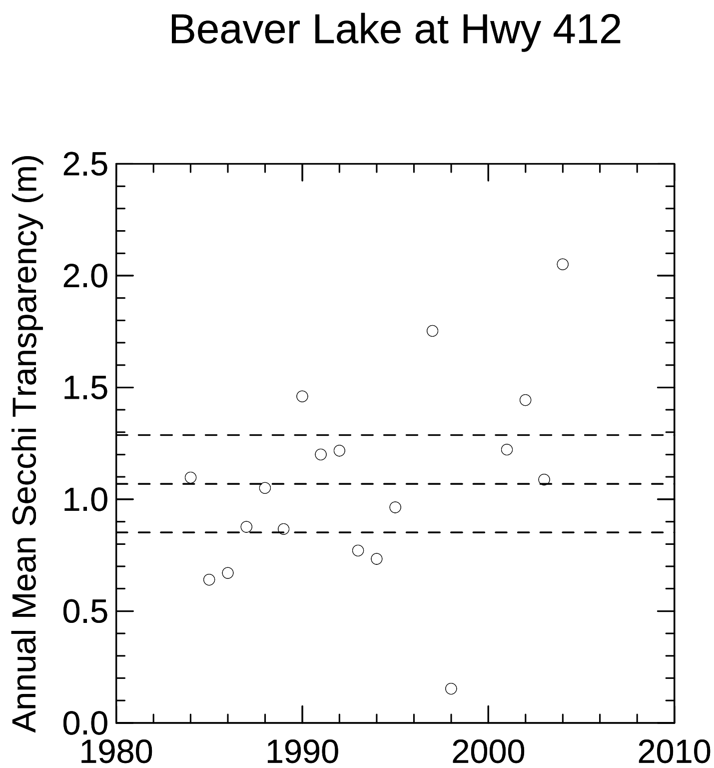
Secchi depth values ranged from 0.9 to 2.4 meters for upstream reservoir site locations (Table 9.2). The highest upstream reservoir Secchi values were noted at the Lowell station. DeGray Lake and Lake Ouachita Secchi depth values for upstream sites (see Figures 7.42 and 7.43) were 0.9 and 1.7 meters, respectively. Because these are reference systems, greater weight was given to these values. There has been a statistically significant increase in Secchi transparency since the 1980s at both the Lowell and Highway 412 stations (Figure 9.3). In addition, there is a statistically significant relationship between Secchi depth values are Highway 412 and the Lowell stations (Figure 9.8; $R^2 = 0.55$, $p < 0.001$).

The long-term annual average Secchi transparency values for both the Highway 412 and Lowell stations, with 95% confidence interval, are shown on Figure 9.9. The annual average Secchi transparency value associated with the lower 95% confidence interval at the Highway 412 and Lowell stations are 0.85 and 1.5 meters, respectively.

The Secchi transparency regression equation was used to estimate Secchi transparencies at Lowell, and subsequently at the Hickory Creek site. Secchi transparency values of 0.8 and 1.0 meters at the Highway 412 site resulted in predicted Secchi transparency values of 1.5 and 1.6 meters at Lowell, with the 95% estimate at Lowell of 1.3 and 1.5 meters, respectively. The estimated values at Hickory Creek were 1.15 and 1.3 meters, respectively. The DeGray Lake and Lake Ouachita Secchi transparency values ranged from 0.9 to 1.7 meters, with an average value of 1.3 meters, which is consistent with the estimated values at Hickory Creek.

9.3.3 Total Phosphorus

Total phosphorus concentrations for upstream stations in Arkansas reservoirs ranged from 13 to 60 μg/L (Table 9.2). Total phosphorus concentrations at the two upstream stations in the reference lakes were 17 μg/L and 38 μg/L (Table 9.2). Change-point analyses for total phosphorus using either the chlorophyll or Secchi depth response variable ranged from 15 to 48 μg/L at the Lowell site and 40 to 60 μg/L at the Highway 412 site (Table 9.2). No apparent patterns were revealed in bivariate plots of annual average total phosphorus concentrations with growing season geometric chlorophyll means and annual Secchi depth means (Figure 9.10). Computation of nitrogen to phosphorus ratios for Beaver Lake indicate that it is typically phosphorus-limited, with nitrogen limitation during late summer. However, the limited relationship between total phosphorus and chlorophyll or Secchi depth indicates that increased or decreased total phosphorus loads might or might not elicit an associated response in chlorophyll concentrations or Secchi depth. Therefore, establishing a total phosphorus criterion might not be warranted and should be approached with caution.



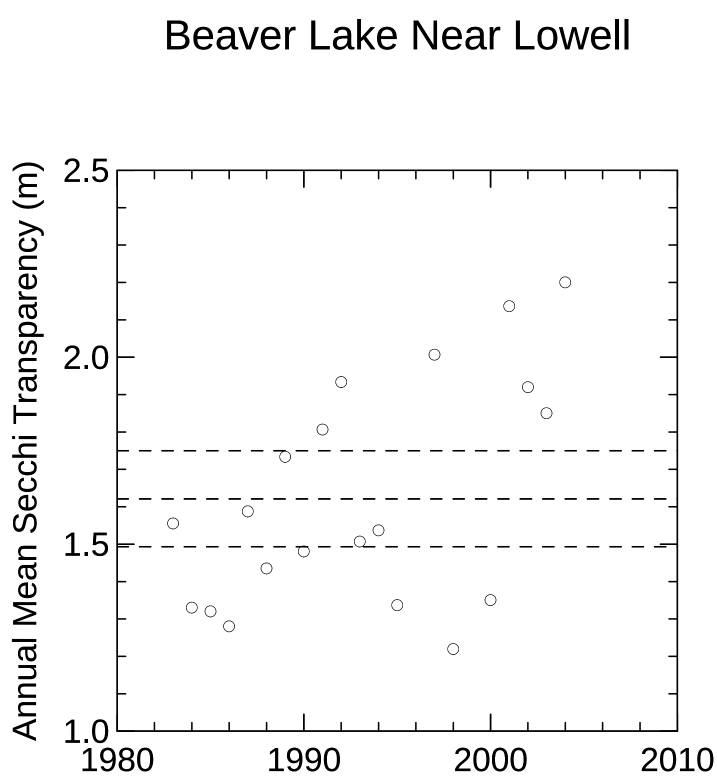


Figure 9.9. Long-term average annual Secchi transparency, with 95% confidence interval, at the Highway 412 (top graph) and Lowell (bottom graph) sites.

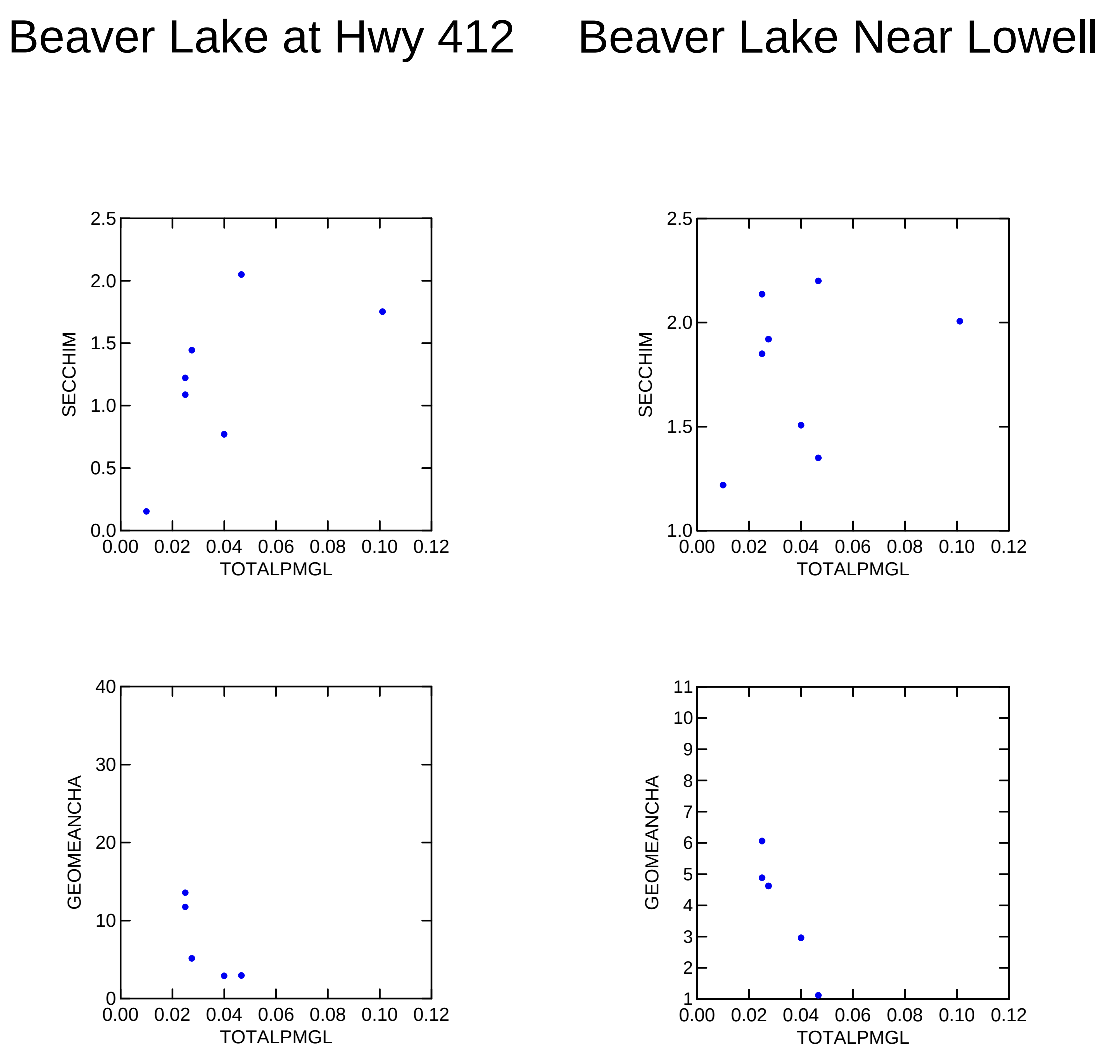


Figure 9.10. No apparent relationships were observed between annual average total phosphorus means and annual average Secchi or growing season geometric chlorophyll means at either the Highway 412 (left column) or Lowell (right column) sites.

Nutrient-loading relationships for chlorophyll and Secchi transparency were used to back-calculate the total phosphorus concentration associated with a chlorophyll value of 8 μg/L and a Secchi transparency value of 1.1 meters. These annual average total phosphorus concentrations were 40 and 30 μg/L, respectively.

9.3.4 Total Nitrogen

Total nitrogen concentrations ranged from 0.31 to 0.76 mg/L for upstream stations in Arkansas reservoirs (Table 9.2). Total nitrogen concentrations in the two reference reservoirs were 0.33 and 0.76 mg/L (Table 9.2). Based on nitrogen to phosphorus ratios, nitrogen limitation does appear to occur in late summer in Beaver Lake. There was no pattern revealed in bivariate plots of annual average total nitrogen concentrations with growing season geometric chlorophyll means and annual Secchi depth means (Figure 9.11). Increased or decreased total nitrogen loads might or might not elicit an associated response in chlorophyll concentrations or Secchi depth. Therefore, establishing a total nitrogen criterion might not be warranted and should be approached with caution.

There are few nutrient loading relationships between total nitrogen and chlorophyll or Secchi transparency. Therefore, an upper estimate of the optimal Redfield ratio (10:1 based on mass) was used to estimate a total nitrogen concentration of 0.4 and 0.3 mg/L at the Hickory Creek site.

9.4 Recommended Criteria

The site-specific effects-based numeric water quality criteria recommended for the Hickory Creek site in Beaver Lake are:

- Growing season geometric chlorophyll a concentration: 8 μg/L; and
- Secchi transparency: 1.1 meters

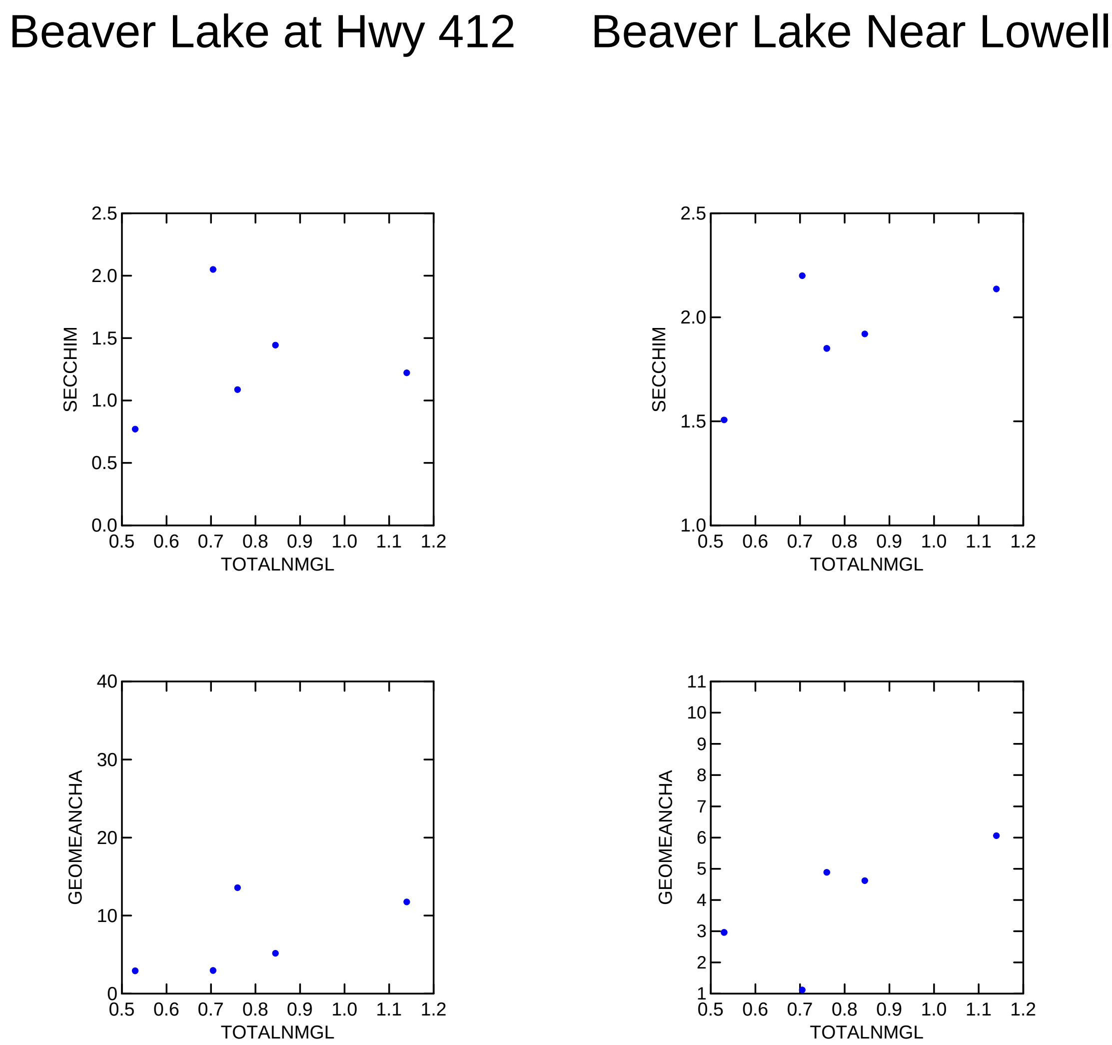


Figure 9.11. No apparent relationships were observed between annual average total nitrogen means and annual average Secchi or growing season geometric chlorophyll means at either the Highway 412 (left column) or Lowell (right column) sites.

Total phosphorus and total nitrogen criteria are not recommended because the effects-based criteria above integrate the total phosphorus, total nitrogen, and other contributing factors in their response. Total phosphorus and total nitrogen targets for the Hickory Creek site in Beaver Lake might be:

- Total phosphorus nutrient target: 40 μg/L; and
- Total nitrogen nutrient target: 0.4 mg/L.

A relative risk analysis was conducted using the proposed effects-based criteria and the nutrient targets to estimate the likelihood of exceedances based on these criteria.

9.4.1 Relative Risk of Exceedance

Relative risk analyses were used to estimate possible exceedance/attainment ratios for growing season geometric chlorophyll and annual Secchi means at Lowell based on possible chlorophyll and Secchi criteria values at the Hickory Creek site (Table 9.3). Because monitoring has not occurred at the Hickory Creek site, it is not possible to directly evaluate attainment of the recommended water quality criteria. However, using the regression equations showing on Figures 9.4 and 9.8, and assuming that Hickory Creek values were equivalent to the average of Highway 412 and Lowell values, chlorophyll and Secchi values at Hickory Creek were used to estimate corresponding values at Highway 412 and the Lowell site. The 95th percentile for the growing season geometric chlorophyll (i.e., 11 μg/L) and average annual Secchi mean (i.e., 0.8 meter) calculated for the Highway 412 site were used to derive the Lowell chlorophyll (6.7 μg/L) and Secchi means (1.5 meters) corresponding to the Hickory Creek targets.

A range of target values were evaluated to determine the relative risk of exceeding these values. The intent was to protect the designated resource uses without overly stringent water quality criteria. The relative risk of exceeding the 95th percentile value at Lowell associated with the recommended criteria at Hickory Creek (chlorophyll = 8 μg/L and Secchi = 1.1 meters) was about 10%. More stringent chlorophyll and Secchi criteria at Hickory Creek resulted in exceedances ranging from 20% for chlorophyll to 40% for Secchi at the downstream Lowell station, based on historical means for these constituents (Figures 9.4 and 9.8).

Table 9.3. Exceedance/attainment ratios (and relative risk) of exceeding different growing season geometric chlorophyll means and average annual Secchi transparency values at Lowell based on potential water quality targets for Hickory Creek.

Parameter	Station			
	Hickory Creek	Highway 412	Lowell	
	Targets	Targets	Targets	Exceedances
Chlorophyll a (µg/L)	9	12	7	2/17 (0.12)
	8	11	6.7	2/17 (0.12)
	7.5	10	6.5	3/17 (0.18)
	7	9.5	6.3	3/17 (0.18)
	6	7.8	6.1	3/17 (0.18)
Secchi transparency (m)	0.8	0.3	1.0	0
	1.0	0.6	1.2	0
	1.1	0.8	1.3	2/22 (0.09)
	1.2	0.9	1.4	6/22 (0.27)
	1.25	1.0	1.5	9/22 (0.41)
	1.4	1.1	1.5	9/22 (0.41)

The recommended chlorophyll and Secchi mean criteria at Hickory Creek are considered sufficient to protect the downstream designated resource uses without being overly restrictive for current and historical watershed activities.

9.4.2 Rationale for Criteria

Rationale for the recommended criteria are:

1. The growing season geometric chlorophyll mean of 8 µg/L at Hickory Creek provides protection for the downstream drinking water supply intakes in Beaver Lake;
2. The growing season geometric chlorophyll mean is less than the OWRB 10 µg/L criterion established to protect drinking water sources;
3. The chlorophyll and Secchi transparency mean values are considered conservative and protective of the designated uses, but should not result in frequent non-attainment assessments;
4. The recommended criteria are consistent with concentrations and values found in the reference lakes, change point and other statistical analyses and were developed through a weight of evidence approach;
5. The criteria can be related directly to the designated uses of the waterbody;

6. The criteria can be related to nutrient targets if nutrient TMDLs might be required at some future date because of non-attainment;
7. The location within the plunge point represents a dynamic area of the reservoir where attainment of the WQS should result in attainment of downstream designated uses in Beaver Lake; and
8. The criteria provide a reference frame for subsequent development of tributary numeric WQS and for discussion of watershed management practices that will protect upstream and downstream designated uses in Beaver Lake.

9.4.3 Sampling Location and Frequency

The sampling location for monitoring is recommended as the **Hickory Creek site over the old thalweg**, below the confluence of War Eagle Creek and the White River. **Monthly sampling,** including nutrient sampling in the photic zone, is recommended because it is consistent with the current ADEQ monitoring program, and it provides sufficient information for estimating growing season chlorophyll geometric means and annual Secchi transparency means.

10.0 REFERENCES

Arkansas Department of Pollution Control and Ecology. 1987. Physical, Chemical, and Biological Characteristics of Least-Disturbed Streams in Arkansas' Ecoregions: Volume 1 – Data Compilation. WQ87-06-1. Arkansas Department of Pollution Control and Ecology. Little Rock, AR.

Bureau of the Census. 1991. Census of Population and Housing, 1990: Summary Tape File 3A, Arkansas. US Department of Commerce Bureau of the Census. Washington, DC.

Bureau of the Census. 2002. Census 2000 SF3 Demographic Profiles, Arkansas. US Department of Commerce Bureau of the Census. Washington, DC.

Chapra, S.C., R.P. Canale, and G.L. Amy. 1997. Empirical models for disinfection by-products in lakes and reservoirs. Journal of Environmental Engineering. 123(7):714-715.

Downing, J.A., S.B. Watson, and E. McCauley. 2001. Predicting cyanobacteria dominance in lakes. Can. J. Fish. Aquat. Sci. 58: 1905-1908.

Fischer, H.B., E.J. List, R.C.Y. Koh, J. Imberger, and N.H. Brooks. 1979. Mixing in inland and coastal waters. Academic Press. New York.

Ford, D.E., and M.C. Johnson. 1983. An Assessment of Reservoir Density Currents and Inflow Processes. Technical Report E-83-7. U.S. Army Corps of Engineers Waterways Experiment Station. Vicksburg, MS.

FTN Associates, Ltd. 2005. Compilation of Lake and Reservoir Nutrient Criteria and Nutrient-Endpoint Relationships. Mississippi Department of Environmental Quality. Jackson, MS.

Häkanson, L. 1982. Lake bottom dynamics and morphometry: the dynamic ratio. Water Resour. Res. 18:1444–1450.

Jirka, B.H., and D.R.F. Harleman. 1979. Cooling impoundments: Classification and analyses. ASCE Jour. Hyd. Div. 106:701–715.

Kimmel, B.L., O.T. Lind, and L.J. Paulson. 1990. Chapter 6: Reservoir primary productivity. In Cole, T.M. and H.H. Hannah (eds).

Mueller, K.K., D.C. Croft, R.L. George, P.L. Johnson, and R.A. Robine. 1981. Guidelines for studies of potential eutrophication. Water Quality Planning Technical Memorandum. Bureau of Reclamation. Denver, CO.

National Climatic Data Center. 1968. Climate Atlas of the United States.

Paul, M.J., and J.L. Meyer. 2001. Streams in the urban landscape. Annual Review of Ecology and Systematics. 32:333-365.

Qian, S.S., R.S. King, and C.J. Richardson. 2003. Two statistical methods for the detection of environmental thresholds. Ecological Modeling 166:87-97.

Roy, A.H., A.D. Rosemond, M.J. Paul, D.S. Leigh, and J.B. Wallace. 2003. Stream macroinvertebrate response to catchment urbanization. Freshwater Biology 48(2): 329-346.

Savage, S.B., and J. Brimberg. 1975. Analysis of plunging phenomena in water reservoirs. J. Hydraulic Research. 13(2):187-204.

Thornton, K.W., R.H. Kennedy, J.H. Carroll, W.W. Walker, R.C. Gunkel, and S. Ashby. 1980. Reservoir sedimentation and water quality—an heuristic model in Proceedings of the Symposium on Surface Water Impoundments. ASCE. Vol. I. pp. 654–661.

Thornton, K.W., B.L. Kimmel, and F.E. Payne, eds. 1990. Reservoir limnology: Ecological perspectives. John Wiley & Sons, Inc. New York.

Walker, W.W. 1983. Significance of eutrophication in water supply reservoirs. Journal AWWA. 75(1): 38-42.

Wetzel, R.G. 1983. Limnology, 2nd edition. Saunders College Publishing. Chicago, IL.

Williams, D.T., G.R. Drummond, D.E. Ford, and D.L. Robey. 1980. Determination of light extinction coefficients in lakes and reservoirs. In H.G. Stefan, Ed. ASCE Proc. Surface Water Impoundments. II:1329–1335.

Younos, T., J.L. Walker, and C.E. Zipper. 2007. Nutrients in Lakes and Reservoirs – A Literature Review for Use in Nutrient Criteria Development. Special Report SR34-2007. Virginia Polytechnic Institute and State University. Blacksburg, VA.