Lake Wister Water Quality, Bathymetry, and Restoration Alternatives

Final Draft Report
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Prepared for:

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Cover: Aerial photo taken in August 1998 showing lake wide algae bloom at the opening of Quarry Island Bay, Wister Lake, Oklahoma.

AUTHORITY: This study was conducted under authority of the Flood Control Act, Approved 28 June 1938, Committee Document No. 1, 75th Congress, 1st Session.

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BACKGROUND: Wister Lake is a large, relatively shallow flood storage and water supply impoundment in eastern Oklahoma. It is highly eutrophic with a burgeoning poultry industry in the watershed. Lake Wister also exhibits some of the horizontal variability characteristic of a large river impoundment (i.e., turbidity decreases and Secchi depth increases from tributary inflows to the dam) suggesting potential for in-lake management to ameliorate the impacts of eutrophy. This study will be the first complete assessment of Wister Lake since the raising of the conservation pool to 478 feet. It is hoped that by obtaining a complete assessment at the new conservation pool elevation management alternatives may be identified to improve conditions at Wister Lake. Successful restoration and management of Wister Lake will involve both watershed improvements (reducing external loads of nutrients, sediments, and contaminants) and in-lake techniques. In-lake management techniques can control the adverse consequences of external loads.

STUDY OBJECTIVES:
Three objectives are outlined:

- Determine whether lake water quality has changed since the 1996 Clean Lakes Study.
- Identify the most feasible in-lake management option to mitigate the observed low dissolved oxygen in Wister Lake.
- Develop a detailed shoreline erosion control plan.

Accomplishment of these objectives has been partitioned into five tasks:

1. Aeration Evaluation
2. Shoreline Erosion Control
3. Water Quality Sampling and Evaluation
4. Bathymetric Mapping
5. Reporting

Executive Summary

Study objectives were achieved through intensive water quality sampling from 22 May 2001 through 30 October 2001, consultation of experts regarding in-lake processes, and construction of a bathymetric map. Data was used to yield an updated view of Lake Wister since the raising of the conservation pool elevation to 478 Mean Sea Level (MSL). In-lake methods are available to improve the water quality impacts to Lake Wister. Dissolved oxygen can be increased in the water column during the critical summer months while suspended solids can be reduced in the extensive lake shallows. Elevated dissolved oxygen in Lake Wister will serve to reduce internal nutrient concentrations but will not control external loading. Comprehensive control of suspended solids should not be implemented prior to reductions of in-lake nutrient concentrations. Decreased suspended solids without decreased nutrients will likely stimulate excessive or hypereutrophic algae growth.

Water Quality

Past problems in Lake Wister include accelerated eutrophication and excessive turbidity. These were noted as early as 1974 during the United States Environmental Protection Agency's National Eutrophication Study. Wister is listed in the Oklahoma Water Quality Standards (OWQS) as a nutrient-limited watershed threatened by nutrient enrichment. Applying Use Support Attainment Protocols (USAP) in the OWQS to the 2001 lake data concludes beneficial uses for Fish and Wildlife Propagation are not supported due to excessive turbidity, low pH and low dissolved oxygen. In the major tributaries all assessed beneficial uses were supported except Warm Water Aquatic Community – Fish and Wildlife and Primary Body Contact – Recreation in the Fourche Maline Creek. Low dissolved oxygen, high lead and high bacteria concentrations contributed to the loss of these beneficial uses.

Major changes in water quality over time include increased turbidity, increased chlorophyll-a concentrations, and increased magnitude of anoxic hypolimnetic duration and volume. Nutrient concentrations appear to be fairly consistent with historical data although internal loading of nutrients from the sediment will increase with increased hypolimnetic anoxia. Light and nitrogen were the limiting nutrient for algae growth during the study period. This switch is likely the result of in-lake dynamics coupled with watershed loading. Since the 1996 Clean Lakes study, differences in water quality include higher nutrient concentrations (both nitrogen and phosphorus), increased sediment and suspended solids, increased sulfate concentrations, and decreased alkalinity. Increased productivity (algae growth) concurrent with increased turbidity is a disturbing trend for Wister Lake and bodes ill for beneficial uses of Wister Lake.

Aeration Evaluation

Increasing oxygenation of the water column through in-lake management strategies would increase habitat for fish and wildlife, decrease offensive odors, improve water quality for water supply, and enhance the recreational value of Lake Wister. Multiple restoration alternatives were examined for their relative ability to oxygenate Lake Wister. Two alternatives, depth-selective flow-routed outflow and aeration techniques, directly addressed the problem of low dissolved oxygen in the reservoir and were examined in detail.

Close examination of the release structure revealed the deepest section of the lake stagnates during the summer months. Routing of release water to discharge the lowest quality water (from the anoxic hypolimnion) rather than epilimnetic water would increase oxygenation of the lake water. From a long-term perspective the method of depth selective flow-routed outflow shows the best promise to alleviate the excessive anoxia in Lake Wister. Although this innovative method may initially cost as much as $400,000, the nominal cost for annual operation and maintenance (O&M) make it an attractive option.

Erosion Control

Two types of erosive processes were identified in Lake Wister: shoreline erosion and sediment resuspension. Methods to mitigate these processes emphasized bioengineering methods due to cost effectiveness and benefit to fish and wildlife.

Shoreline erosion is extensive in Lake Wister with many miles of shoreline in need of treatment. Control of shoreline erosion at the four primary recreational areas, Quarry Island, Ward's Landing, Victor Campground and Pocahontas Slough require various levels of treatment, depending on the magnitude of erosion. Cost per area is likewise variable. Options for the four recreational sites were developed and detailed treatments for each area are given. Cost for treating these areas total $225,000, ranging from a low of $22,000 at Ward's Landing to $120,000 at Quarry Island.

The unique morphology of Lake Wister, namely the extensive shallow mud flats, reveals several areas of sediment suspension within the Poteau River arm to the south and Fourche Maline and Lewis Creek arms to the west. Creation of breakwaters with wetlands to provide a wave barrier and a sediment trap in the shallow flats is recommended. Three breakwaters are proposed for a total length of 1.5 miles. The most cost-effective method, using brush bundles, would cost approximately $600,000. Implementation of a breakwater would reduce suspended solids by increasing the sedimentation rate in the shallowest portion of the lake. Consequently sedimentation within the conservation pool should be expected to increase.

Bathymetry

Field surveying occurred in the winter of 2001 using state of the art data collection and interpretation methods for the lake at 478 MSL. No attempt was made to determine areas or capacities above the conservation pool elevation (478 MSL). Data collection methodology was patterned after that developed by the Tulsa District USACE for sedimentation surveys. Post processing used GIS technology combined with limnological methods to yield the most accurate area and capacity possible. A map of the lake bottom contours was constructed. The 2001 Lake Wister bathymetric survey indicates a 6,077-acre lake with a shoreline length of 76.34 miles and a pool volume of 46,848 acre-feet at 478 MSL.

Data generated from the mapping effort were used to compare against previous sedimentation surveys. Comparison of 2001 data to the 1985 USACE sedimentation survey for the 478 MSL elevation showed surface area decreased by 1,309 acres (–17.7 %), storage capacity decreased by 14,858 acre feet (–23.7%) and maximum depth decreasing 4.16 feet (–9.5%). The annualized 1985 – 2001 sedimentation rate for the conservation pool yielded a much higher rate, 875 acre-feet per year, than seen before. The higher sedimentation rate closely brackets the major legislated changes in pool operation: 3-foot rise (to 474.6) in 1983 and an additional 3.4 feet rise in 1993. These indicate that the recent rise in pool elevation has increased erosive processes in the shallowest portion of the lake and that net sedimentation has increased. Future sedimentation surveys should be planned to track sedimentation in Lake Wister over time.

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Introduction

Lake Wister and its surrounding watershed have a unique and varied history. When Wister was impounded in the 1940s, the watershed consisted primarily of small farms, orchards, forests and pastures spreading across the watershed from Arkansas to Oklahoma. Pine and oak forests still blanket the surrounding mountains, making Wister a prime spot for camping, hiking and other outdoor recreation. In recent years, however, the poultry industry has become synonymous with the region. Thousands of chicken houses dot the landscape. In addition, point source discharges, abandoned strip mines, forestry practices, residential development, and other non-point pollution sources have resulted in high levels of nutrients and sediments flowing into the lake.

While this study was undertaken primarily to illustrate and recommend, respectively, in-lake problems and solutions to Wister's continued habitat deficiencies, it is worth noting that the Oklahoma Water Resources Board has placed Wister's watershed on the Nutrient Limited Watershed (NLW) list. Lake Wister's watershed is also on the State's 303 (d) list. This requires a TMDL by the Oklahoma Department of Environmental Quality (ODEQ). Lake Wister is a high priority watershed for the state of Oklahoma. To effect environmental solutions, greater emphasis must be placed on widespread and long-term changes in policy and management within the watershed. Low dissolved oxygen, suspended solids, turbidity, shoreline erosion, sedimentation and pollution from runoff make Wister a desirable candidate for a collaborative approach to helping this lake function as a healthy, vibrant ecosystem.

Lake Wister was built primarily as a flood-control reservoir, catching and pooling waters from the Poteau River from the east and the Fourche Maline Creek from the west. Wister also supplies over 40,000 residents in the area with drinking water. Other uses include recreation and fish habitat. Over the years Wister has been under varying pool elevation plans, ranging from 471.6 ft to its current conservation pool elevation of 478 ft. Another impetus for undertaking this study stems from a desire to understand how this changing pool elevation has affected the lake, both in bathymetry and water quality.

The current narrative is the result of a yearlong partnership with the United States Army Corps of Engineers (USACE) to investigate ecosystem restoration options for Wister. The OWRB has investigated several possibilities for remedial action in Wister and they will be outlined in detail in this report. Lake Wister is on the threshold between eutrophic and hypereutrophic, with many water quality parameters solidly in the hypereutrophic category. Low dissolved oxygen, high-suspended solids and excessive turbidity are the primary focal points for action. Alternatives to increase dissolved oxygen levels in Lake Wister are discussed in Task 1. Task 2 utilizes the unique features of Lake Wister in outlining a plan to reduce the excessive turbidity through shoreline stabilization and minimizing re-suspension of sediment. Unfortunately the perils of reducing turbidity without nutrient reduction are a serious concern. Task 3 discusses the comprehensive water quality-monitoring phase of this investigation, and Task 4 is devoted to bathymetry.

Many thanks goes out to the dedicated staff of the Poteau Valley Improvement Authority (PVIA), the Lake Wister Corps of Engineers staff, USACE Tulsa District personnel, and the Lake Wister Park employees for their kind assistance during this study. OWRB staff has relied on their knowledge and willingness to help us during this project.

Task 1: Aeration Evaluation

This task examined in-lake management strategies to alleviate the impact of watershed loading on Lake Wister. In-lake management is not intended as a substitute for action in the Lake Wister watershed. Real, on-the-ground action is needed to reduce the inflow of nutrients, sediment and other contaminants from the watershed. The extreme anoxic event of June 23, 1993 (< 2 mg/L at depths 2 meters and greater), which was the worst seen during OWRB sampling, illustrates the need for immediate short-term relief for Lake Wister. Attenuation of the severe anoxia would increase habitat for fish and wildlife, decrease odor, improve water quality for water supply, and enhance the recreational value of Lake Wister. Because of these multiple benefits the goal of providing oxygenation to Lake Wister was selected as the first task. Alternatives to ensure an oxygenated Lake Wister were evaluated from a restoration point of view to optimize realized benefits from oxygenation.

The contract for this task was awarded to Ecosystem Consulting Service, Inc (ECS). A report has been prepared by ECS discussing conceptual alternative methods of oxygenating Lake Wister (Kortmann, 2002). The following alternatives were examined to address several objectives:

- Improve overall ecosystem quality aesthetically (visual and odor) and increase habitat for fish and wildlife
- Maintain the primary function of flood storage for Lake Wister
- Optimize cost-effectiveness of long-term in-lake management

Multiple restoration alternatives were examined for their relative ability to oxygenate Lake Wister. Methods examined were nutrient inactivation, depth-selective flow-routed outflow, aeration techniques and finally biomanipulation/trophic level management. Of these four alternatives, two, depth-selective flow-routed outflow and aeration techniques, directly addressed the problem of low dissolved oxygen in the reservoir and were examined in detail. Reservoir morphometry, spillway design, water supply withdrawal structures, maximum area and volume of anoxia, hydraulic budget, thermal budget and oxygen consumption were used to carefully examine both potential restoration techniques. The following discussion is taken from the report prepared by ECS. The report is available for technical details as Appendix B.

Discussion

Depth-selective flow routed outflow appears to be the most appropriate method for Lake Wister. Expected benefits of this method are increased oxygen content, reduced sediment-mediated nutrient load, decreased dissolved metal content and, potentially, reduced algae growth. The spillway floor is at elevation 450 while a significant portion of the reservoir and river bottom is below 450 elevation. By routing through the river channel (deepest portion) prior to release, the lowest quality water from the lake bottom can be flushed out of the lake. To effect this flow routing, a barrier would need to be placed in front of the spillway channel from 450 ft to 478 ft or 480 ft. The cross sectional area below 450 ft elevation would need to be great enough to keep flow velocities relatively low and be resistant to wave action, fluctuating pool levels and other forces.

An attractive feature of depth-selective flow routing is its zero operation and low annual maintenance costs. The barrier could be fabricated as a solid structure (fiberglass partition), scrim-reinforced curtain or similar structure. General estimate for the construction and installation of a flow routing barrier is approximately $400,000. Although this method would increase the potential for oxygenation of the main lake body, this method cannot guarantee complete oxygenation of both the main body and nearby embayment (Quarry Island).

Three direct aeration methods were also examined as independent oxygenation measures: artificial circulation, hypolimnetic aeration and controlled mixing. The following summarizes the assessment of each method.

Artificial Circulation prevents thermal stratification and increases the re-aeration coefficient at the lake surface. This allows oxygenated surface water to mix throughout the water column. Specifically, pneumatic devices are installed in the deep areas of the lake that utilize a diffused release of compressed air. The energy generated by rising air bubbles is designed to overcome the relative thermal resistance to mixing (RTRM) by stratification. The specific shape of Lake Wister, with deeper “borrow” areas excavated during dam construction, suggests that several devices would need to be deployed. Designs for artificial aeration were examined for conservation pool only and not flood pool. The criterion requires a minimum compressor size of 175-hp and flow-rate of approximately 700 SCFM (Standard cubic feet per minute). This design should allow for complete mixing of the water column in the main lake body and consequently oxygenation. Potential negative impacts of this system are suspension of sediment particles from the lake bottom and elevation of lake temperatures. Suspension of sediment would increase turbidity while elevated temperature would lower oxygen solubility. Loss of stratification would also eliminate depth-selective withdrawal potential.

Hypolimnetic Aeration and layer aeration utilize structures that draw water from lower depths and aerate it within the structure itself. Hypolimnetic aerators draw water from the bottom and release it below the thermocline. Water is aerated within the structure and dispersed, creating a temperature differential between the layers and maintaining stratification. Layer aerators have a modified design that in deeper lakes allows several intake valves to draw water from two or more depths, blend and aerate the water, and release it between the two intakes. Both methods would have similar applications at Lake Wister. A pneumatic device releases air within a submerged chamber located within the deeper areas of the lake. The rising air bubbles lift the water while oxygen diffuses in as it rises. The chamber is designed to vent the air bubbles toward the surface as the oxygenated water is shunted back toward a designated depth. Potential negative impacts of this method include a slight temperature increase on the bottom of the lake, weakening stratification and causing turnover to occur earlier. This is important to note because the function of hypolimnetic aerators is to maintain stratification.

Controlled Mixing, a simplified version of hypolimnetic aeration, withdraws water from the bottom, aerates it, and expels it horizontally at a designated depth. The diffuser chamber then releases excess air vertically to encourage mixing from the diffuser to the surface of the water. The shape of the lake, intensity of thermal stratification and magnitude of hypolimnetic oxygen demand suggest that controlled mixing is the best strategy for Lake Wister. This design uses the released air from the lift chamber to enhance aeration of the epilimnion. **Table 1.1** summarizes implementation and operation costs for each assessed aeration alternative.

Table 1.1: Preliminary cost estimate for purposes of comparing aeration methods.

Aeration Method	Cost estimate in dollars	
	Implementation	Operation
Artificial Circulation	$ 200,000	$ 45,000
Hypolimnetic Aeration	$ 375,000	$ 45,000
Layer Aeration	$ 375,000	$ 45,000
Controlled Mixing	$ 175,000	$ 30,000

Recommendations

From a long-term perspective the method of depth selective flow-routed outflow shows the best promise to alleviate the excessive anoxia in Lake Wister. Although this innovative method may cost as much as $400,000, the nominal cost for annual operation and maintenance (O&M) make it an attractive option. Flow routing would release water with the lowest quality first using a passive device installed in the lake.

The next best method to oxygenate Lake Wister would be "controlled mixing". Installation of a device to produce "controlled mixing" would cost approximately $175,000 with an estimated annual O&M cost of $30,000. Although cheaper initially, O&M costs would be required every year to maintain an airlift chamber and active diffuser in Lake Wister. Oxygenation during the summer months will greatly increase the available habitat for fish and wildlife in Lake Wister as well as decrease dissolved metal concentrations, reduce dissolved nutrient concentrations, decrease odors and potentially decrease algae growth.

Both methods are designed to address anoxic events at or near conservation pool elevation. No attempt was made to fit a device for flood-pooled waters. Although both methods would alleviate water quality concerns in the lake main body at conservation pool elevation problems may persist within the Quarry Island embayment. For this reason a separate "controlled mixing" device may be appropriate for Quarry Island bay.

Task 2: Evaluation of Options for Erosion Control

This task evaluated in-lake management options to alleviate the excessive turbidity of Lake Wister. Traditionally, inorganic suspended solids have been the primary cause of high turbidity in Lake Wister. The documentation of algae scum formation since 1996 and the massive algae bloom of August 1998 (pictured on the front cover) suggests that organic or biotic suspended solids also contribute to turbidity. The massive algae bloom also underscores the need for nutrient reductions prior to or concurrent with suspended solids control. Solids control without nutrient control would only increase the frequency of algae scum and bloom formation. It is also important to note that recommended methods address suspended solids within the lake but not the primary source of suspended solids, the watershed. In-lake management will reduce the impacts of watershed inputs but is no substitute for action in the Lake Wister watershed. While overland erosion and wind-driven wave action cause much of the loss of shoreline around Wister, the unique morphology of Lake Wister reveals several zones of sediment suspension under the water surface. Thus, methods to control suspended solids below the waterline are also examined to control erosive processes. Bioengineering methods are recommended to control erosion both at and below the waterline.

Bioengineering methods are emphasized for two reasons, cost effectiveness and benefit to fish and wildlife. The USACE (1984) and USEPA (1993) have recognized the cost-effectiveness of bioengineering methods in lower energy areas. Recent work by the OWRB in Lake Wister to demonstrate in-lake non-point source control has led to the development of lake-specific techniques to establish aquatic plants (OWRB, 2001a). The establishment of aquatic plants in Lake Wister shows promise not only to improve water quality but greatly increase the available habitat for fish and wildlife (**Figure 2.1**).

Figure 2.1: Wildlife utilizing new habitat (emergent aquatic plants) in Lake Wister, September 2001.

Completion of Task 2 has been partitioned into three sections, *In-lake Non-point Pollutant Sources*, *Controlling Shoreline Erosion* and *Controlling Suspended Solids*, to outline the scope of turbidity problems in-lake and recommend the most cost effective means to reduce excessive turbidity in Lake Wister. Two reports, completed by Mr. Hollis Allen of the Environmental Laboratory of the USACE Research and Development Center, were used as primary information sources. Mr. Allen’s first report, completed for the OWRB, categorized shoreline erosion in Lake Thunderbird and listed bioengineering treatment options for each category

(2001a). Mr. Allen also performed a site-specific assessment of recreational areas and generic suspended solids recommendations for the Tulsa District USACE in Lake Wister (2001b). OWRB staff has taken narrative and conceptual work performed by Mr. Allen in both reports and expanded them to include a comprehensive assessment and recommendation for Lake Wister. Work completed through the Tulsa District USACE through the Planning Assistance to the States (PAS) program has also been incorporated into this report. The Tulsa District USACE completed three PAS studies for the OWRB regarding Lake Wister. Two addressed the feasibility of establishing native aquatic plants in the reservoir (USACE, 1998a and 1998b) and one addressed suspended solids reduction through the installation of wave barriers (fetch reduction) (USACE, 1998c).

In-Lake Non-Point Source Pollution

When first impounded the top of the conservation pool was set at 471.6 feet mean sea level (MSL). Currently, the top of active conservation pool at Lake Wister is 478 MSL. This conservation pool, 478 MSL, is the target for USACE staff to maintain the lake pool elevation. Because of the drainage basin and climatic factors significant variation of the actual pool elevation is expected throughout the year. For example, the lake pool occasionally drops down 3 - 4 ft below conservation pool level in the fall and winter while in the spring, the pool level often rises 17 feet or more, up to 495 feet or higher. The rise in pool level can be held for up to a month or longer. An elevated springtime pool has the combined effect of producing longer fetches than normal and thus bigger waves because the water inundates peninsulas and islands that would otherwise block the wind at lower pool elevations. This prolonged flooding can also kill vegetation intolerant to flooding. Consequently, this high flooding level causes escarpments to appear shoreward of a terrace, bench, or steep slope and may be close to a camping area, such as that observed at the west side of Victor Camping Area (Allen, 2001b).

Shoreline geometry plays a substantial part in determining the degree of erosion at a particular shoreline site, and both have changed with the subsequent raising of the conservation pool elevation. Maximum north-south and east-west fetch has doubled since the conservation pool was raised from 471.6 to 478 MSL. Fetch, the distance across a body of water producing a wind-driven wave, ranges from less than one-half mile to over five miles in some cases, primarily from the west and northwest. Sites with straight shorelines or headlands that are exposed to long wind fetches from prevailing wind directions are particularly vulnerable to more frequent and higher waves. Conversely, sites within coves or behind peninsulas or islands that block the wind are more protected from waves.

According to Oklahoma Climatological Survey Mesonet records for the Wister station (OCS, 2002a), winds in the Wister area are predominantly from the south and northeast with some high gusts from the northwest as shown in the wind rose of daily maximum wind speeds for Wister, Oklahoma (**Figure 2.2)**. In the figure, wind speeds are relative; the average daily gust speed for Wister is around 20 miles per hour, though gusts reach up to 68 miles per hour. The blue wedge in the wind rose shows the wind frequency distribution, or how often the wind blows from a particular direction. The black wedge shows the frequency multiplied by the wind speed from each direction, which indicates how much each sector contributes to the overall average wind speed. The red wedge shows the frequency multiplied by the cube of the wind speed from each direction, which indicates how much each sector contributes to the energy content of the wind. The red wedges are most important here, as the highest energy of the wind is most likely to produce the largest wave heights.

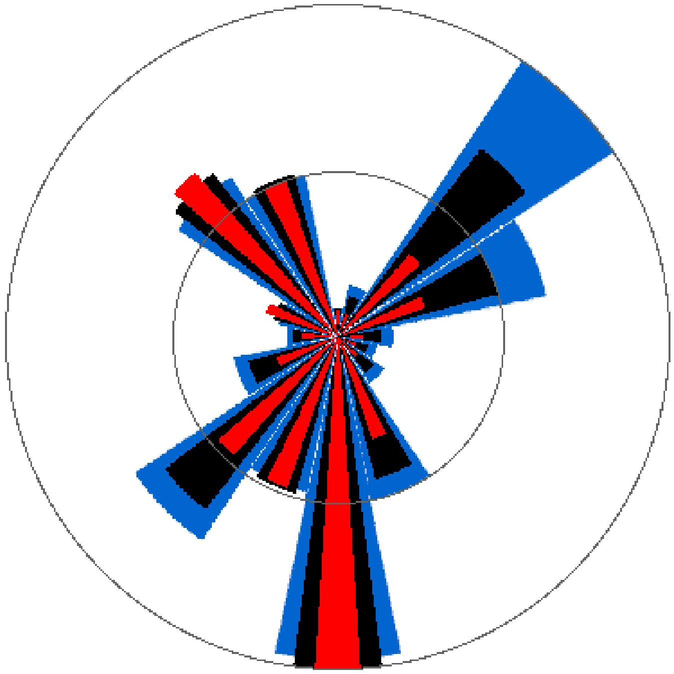

Figure 2.2: Wind rose of relative wind speed and intensity for Wister, Oklahoma based on Oklahoma Mesonet data Jan. 1994 – May 2002 (OCS, 2002a).

Assuming that there are sustained wind speeds of 35 miles per hour for 5 minutes or more, waves could be produced that are between 1.5- and 2-ft high as a general rule (Fuller 1997). Generally speaking, the longer the fetch, the higher the wave. **Table 2.1** portrays a general relationship between fetch and wave height.

Table 2.1: Simplified chart to estimate significant wave heights for different conditions of wind speed and fetch (modified from Allen, 2001a).

	Average Sustained Over-Water Wind Speed (mph)			
Fetch (mi.)	**10**	**20**	**35**	**50**
1.0	0.30	0.60	1.05	1.50
2.0	0.40	0.85	1.45	2.15
5.0	0.70	1.35	2.35	3.30
10.0	0.90	1.90	3.30	4.75
15.0	1.20	2.35	4.10	5.80
20.0	1.35	2.70	4.70	6.75

Bathymetry, like geometry, also plays a large part in the degree of wave action. The shallower and wider the near shore underwater bench, for instance, the more drag or resistance to waves there will be. Waves will subsequently be smaller in these areas in contrast to those where the water deepens abruptly and there is less resistance or bottom roughness to influence the wave (Allen, 2001b).

Bathymetry is shallow in places due to lake-bottom features. Examination of the 1-meter contour interval for Lake Wister indicates extensive shallow flats facing the eastern shoreline of the Fourche Maline arm of Lake Wister and southern shoreline of the Poteau arm (**Figure 2.3**). These mud flats serve as an extremely long bench, minimizing wave height. In contrast, the north shore shows considerable relief with little bench to attenuate wave height. Although the large fetch and shallow mud flats seen in the Fourche Maline arm of Lake Wister minimize wave height and consequently shoreline erosion, suspension of fine sediments occurs on these shallow flats. Because of dual action of in-lake non-point source pollutants in Lake Wister, the scouring feature of Lake Wister's shallow mud flats must also be addressed in addition to shoreline erosion to reduce excessive turbidities (Allen, 2001b).

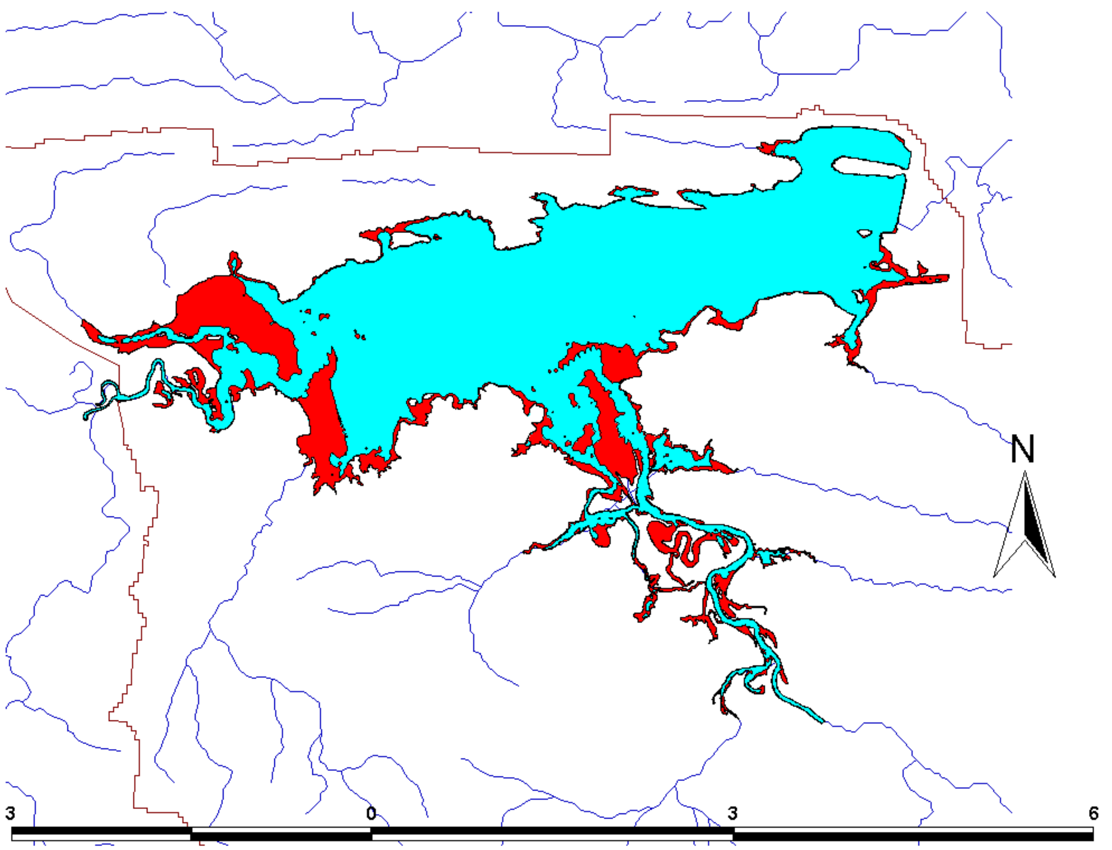

Figure 2.3: Lake Wister 2001 showing the 1-meter depth contour level.

Note: Large shallow areas (seen in red) in the upper arms. Shallow depths will attenuate wave height but also serve as zones of sediment suspension.

The physical attributes of the surrounding soils factor into the magnitude of shoreline erosion. In the case of Lake Wister, soils along the shoreline are predominantly in the Bengal, Octavia, Pirum, Clebit, Stigler, Neff, and Cupco associations (USDA 1981). Bengal, Octavia, Pirum, and Clebit soils have topsoil ranging from stony fine sandy loam to sandy loam to an average of 9 inches in depth. Subsoils are mostly clay to shaly clay, and the underlying material is soft shale or clay at around 30 inches below the surface. Stigler, Neff, and Cupco soils are found mainly along the inflows and are mostly silty loam to about 20 inches over silty clay to loam below. In general, Stigler, Neff, and Cupco soils are medium in fertility and organic matter content, are highly erodible, and have low droughtiness. Bengal, Octavia, Pirum, and Clebit soils have low fertility and organic matter, medium droughtiness, and moderately high erodibility (USDA 1983). In severely eroded reaches of Wister Lake shoreline the topsoil has eroded away leaving only the subsoil or parent materials such as clays and shale or sandstone exposed. These characteristics together make these soils very difficult to revegetate without man's assistance.

Land use also influences the degree of erosion at a site. If the site is adjacent to a public use area where a lot of people walk to and from the shoreline, vegetation is often mowed and/or trampled leaving very little, if any, vegetation to control erosion. Subsequent paths from foot-traffic are created and serve to channelize water flow, creating rills and gullies from the above terrain (Allen, 2001b). Examples like this were seen at the Quarry Island and the Pocahontas Camping Areas.

The findings suggest that a combination of the above factors such as infertile and non-cohesive soils, long fetches, and high winds that produce significant wave heights can cause erosion. These factors combined with an occasional fluctuating pool level that rises almost 20 feet and remains above conservation pool for several weeks can exacerbate the erosion by killing non-flood tolerant plants. Also, exposed shorelines with abrupt and deep lake depths adjacent to them, and heavy foot traffic and mowing at public use areas all contribute to substantial shoreline erosion in certain reaches of the reservoir.

Figure 2.4: Stand of mud plantain in Lake Wister.

Prior to USACE and OWRB investigations into establishing native aquatic plants in Lake Wister (USACE, 1998a), buttonbush represented nearly the entire aquatic plant community. Although beneficial, the single-species dominance illustrates Wister's depauperate aquatic plant community. Further investigation by the USACE and OWRB highlighted a suite of native aquatic plants that could be established in Lake Wister (USACE 1998b). Application of this technology by the OWRB resulted in the establishment of small stands of a mud plantain, *Echinodorus rostratum*, such as the one seen in **Figure 2.4**, and water willow, *Justicia americana* (**Figure 2.5**).

Figure 2.5: Stand of water willow established through dispersal of sprigs.

Additional species such as soft-stem bulrush, *Scirpus validus*, and arrowhead, *Sagittaria graminea* were established over the course of the study. Success of these plant species however, depended entirely on the degree of herbivore control (caging) provided (Figure 2.6). Species-specific recommendations to establish an aquatic plant community are outlined by the OWRB (2001a). The establishment of a diverse aquatic plant community in Lake Wister would be a major step toward solving the problem of soil loss and suspended solids in the littoral zone.

Figure 2.6: Aquatic plant community transplanted into Lake Wister.

Shoreline Bioengineering Treatments

Bioengineering is the use of vegetation either alone or in combination with engineered structures and materials to achieve erosion control of soil on slopes, shorelines, and streambanks. When vegetation is used alone, it is used in such a way that its physical attributes along with its biology of stems and roots increase the shear and tensile strengths of soils. Bioengineering often incorporates hard structures into the design (such as wave deflection structures or rock toes) to achieve its purposes. Allen (2001a) gives detailed descriptions of the available shoreline erosion methods.

Only the most cost-effective method has been recommended. For example, vegetative anchoring systems might be more beneficial to fish and wildlife and aesthetically pleasing to the public. But a branchbox breakwater system is less expensive to implement and provides the same level of erosion control. Since shoreline erosion is the primary purpose of this task, branchbox breakwaters, for example, would be recommended instead of a vegetative anchoring system. Treatment costs are extrapolated from the material and labor estimates given by Allen (2001a). A labor rate of $9.00/hour was assumed for each cost estimate. Three general levels of treatment are described based on the amount of energy impinging on the shoreline. First, a general description for each level is given. Then specific recreation areas are discussed with a recommended treatment and cost estimate.

Use of Vegetation Alone

This treatment relies solely on using sprigs of emergent aquatic plants, such as water willow, bulrush, spike-rushes or other grass-like plants, and unrooted cuttings or poles of dormant woody plants such as willow. Willow or some other similar type of adventitious plant can be placed in the ground and oriented in such a way as to provide physical benefits of increasing soil strengths and/or intercepting runoff. Combinations of both emergent aquatic plants and wetland facultative woody plants, such as willow, are preferred when implementing vegetative treatments to category type 1 and 2 areas. Vegetative treatments alone are applicable to areas with small escarpments with a fetch of 1 mile or less, or if the shoreline has a large bench (mudflat) to attenuate wave height (Allen, 2001a). **Table 2.2** presents cost estimates for applicable treatments.

Table 2.2: Costs of Vegetative Shoreline Erosion Control Treatments (Allen, 2001a).

Method of Stabilization	Material Cost	Labor required (in man hours)
Sprigging emergent aquatic plants (assumes 0.5 m^2 center spacing)	$0.00 if harvested from wild; $0.25 - $0.50/plant if purchased from nursery	4.0 – 20 m^2/hr
Live cuttings (willow, etc) (spacing will vary- usually placed on 0.5 - 1.0 m centers)	$0.00 if harvested from wild	45 - 50 cuttings/hr
Dormant live poles (willow, etc) (spacing will vary - usually placed on 1.0 - 3.0 m centers)	$0.00 if harvested from wild	10 - 20 poles/hr
Brush layering	$0.00 if harvested from wild	2 -5 m/hr

Vegetative Anchoring Systems

The next level of treatment protection focuses on using vegetation in combination with materials such as geotextile fabrics or mats. Stakes and wire are used to anchor mats containing plant cuttings into the ground. Where sediment movement can be faster than plant growth, anchoring will hold the plant in place long enough for it to become secure. These treatments are needed when wave action is intense enough to preclude vegetative treatments alone. Details for each vegetative anchoring treatment can be found in Allen (2001a). **Table 2.3** presents cost estimates for applicable treatments.

Table 2.3: Costs of Vegetative Anchoring Erosion Control Treatments (Allen, 2001a).

Method of Stabilization	Material Cost	Labor required (in man hours)
Plant roll	ca \$3.00/m (assumes plant clumps harvested from wild)	6 m/hr
Erosion control mat with sprigs inserted into mat (not pre-grown)	\$6.65/m^2 (assumes plants harvested from wild)	3 - 5 m^2/hr
Wattling or fascine with erosion control fabric	\$.50/m for stakes, twine, and \$3.00/m^2 for erosion control fabric	2 - 5 m/hr
Brush matting	\$3.00 - \$5.00/m^2 for construction materials (stakes, wire, etc.)	2 – 6 m^2/hr

Vegetation with Breakwater Systems

When fetches in combination with wind produce waves greater than 1 foot in height, it is advisable to consider the use of some type of breakwater system, either floating or fixed/attached to the lake bottom. For Lake Wister, breakwaters with vegetation shoreward of them should be used in most open-water situations. Conceptually breakwaters only need to be in place long enough to obtain a sufficient vegetative community that will control erosion and heal the bank. The breakwaters mentioned below, for the most part, can be installed using hand labor and a backhoe with auger, hoe with shovel, and front-end bucket attachments. A hydraulic jet pump could be used in lieu of an auger if the soil conditions permit (Allen, 2001a). **Table 2.4** presents cost estimates for applicable treatments.

Table 2.4: Costs of Vegetation and Breakwater Shoreline Erosion Control Treatments (Allen, 2001a).

Method of Stabilization	Material Cost	Labor required (in man hours)
Coir Geotextile Roll (CGR) Breakwater with emergent aquatic plants (sprigs) shoreward of breakwater on 0.5 m^2 centers	ca $30.00 - $60.00 per meter depending on diameter of roll, i.e., 12", 16", 20"	1.5 m/hr of CGR, 4.0 - 20 m^2/hr of sprigs
CGR Breakwater with sprigs on 0.5m^2 centers in erosion control mats shoreward of breakwater	CGR costs as above; add $6.65/$m^2$ for erosion control mats	1.5 m/hr for CGR, 3 - 5 m^2/hr for mats
Branchbox Breakwater (bw) with emergent aquatic plants shoreward	$23.00/m	1.3 m/hr for bw, 4.0 - 20 m^2/hr for sprigs
Log/tree Breakwater with emergent aquatic plants shoreward	$30.00/m	0.5 m/hr for bw, 4.0 - 20 m^2/hr for sprigs

Quarry Island Public Use Area
($120,000 using cellular concrete mat)

Quarry Island Public Use Area is located on a long peninsula in the northeast corner of the lake. It has several recreational facilities including a boat launch area with adjacent dock as well as picnic, camping, and swimming facilities. Because of erosion, the adjacent shoreline around the boat launch and dock had been treated with non-graded stone for a riprap revetment. The rock revetment is somewhat effective in controlling erosion although it is rather poorly constructed. The stone was not uniformly placed and the revetment was not installed with a filter underneath. As a result, water is scouring portions of the shore beneath the revetment (**Figure 2.7**). The rocks do not allow easy access to the shore and are unsightly. This situation will require future maintenance.

The peninsula has a swimming area farther to the west of the boat dock that has eroding banks and is fairly unattractive (**Figure 2.8)**. A 1-ft high escarpment characterizes this area. The boat-launch and swimming areas are apparently subjected to boat-generated waves although the whole bay is a no-wake zone. Fetch is not great enough in the bay to produce a large wind-driven wave (Allen, 2001b).

Figure 2.7: Boat dock at Quarry Island Public Use Area.

Figure 2.8: Swimming area at Quarry Island showing noticeable erosion by the small escarpment and lake ward bench.

An alternative to control erosion at both areas, the boat launch and swimming areas, could should be a cellular concrete mat (CCM) installed in a thirty-foot swath of shoreline. A CCM is a concrete block mat with blocks connected with or without cables. The interstices of the blocks can be planted with vegetation such as grasses (**Figure 2.9**) to improve erosion control potential and to provide a pleasing appearance with easy access to the shore. There are several manufacturers who make these CCMs, such as Armorflex®, Petraflex®, Hydropave®, and Channel-Lock®, to name a few. The interstices of the blocks could be planted with buffalo grass (*Buchloe dactyloides*) which is fairly flood tolerant and does not require much mowing (Allen, 2001b). Installation of a 30' by 750' CCM would cost approximately $120,000 with $96,000 for materials and $27,000 labor.

Figure 2.9: Cellular Concrete Mat (CCM) at Rainbow Lake, Wisconsin (photo taken in winter).

Note: Bottom 3 rows of blocks are covered when the reservoir water level is at normal pool.

Ward's Landing Reach

($22,000 using Coir Rolls)

Ward's Landing is a recreation and boat-launch area on the north shore of the reservoir in the north central area of the main lake body. Just to the east of the boat launch is a reach of shoreline with 1- to 2-ft escarpments (**Figure 2.10**). It is suspected that even though the area is protected most of the time from westerly winds by a peninsula of land to its west, there is occasionally enough wind from the south or southwest to produce some substantial waves. They would be driven by a wind with a 1-1/2 to 2-1/2 mile fetch (Allen, 2001b).

Figure 2.10: Reach of shoreline near Ward's Landing with 2-ft. high escarpments.

For an eroded shoreline such as this with only 1- to 2-ft. escarpments, it is suggested that coir geotextile rolls (CGRs) be used with willow (*Salix*) and buttonbush (*Cephalanthus occidentalis*) cuttings inserted between them and above them as illustrated in **Figure 2.11**. The CGRs are made from coconut husks and will biodegrade, but over time, the vegetation will form a solid mass of roots and stems that will hold the bank together and control erosion. **Figure 2.12**, **Figure 2.13**, and **Figure 2.14** illustrate the use of this method on a reservoir shoreline in Wisconsin where the bank was being undercut. The CGRs were installed in front of the pine tree shown in **Figure 2.12** and then backfilled with soil and planted with willow cuttings as shown in **Figure 2.13**. **Figure 2.14** shows the healed bank 2-1/2 years later. Installation of 16" diameter coir geotextile rolls along 750' of shoreline would cost approximately $22,000 with $20,500 in materials and $1,500 labor.

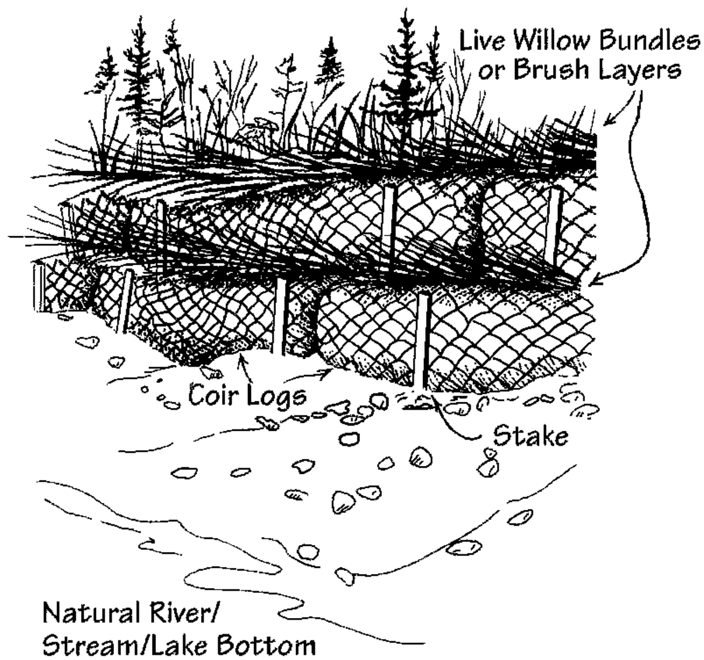

Figure 2.11: Drawing showing coir geotextile rolls (CGRs) with live willow cuttings inserted between and above the CGRs.

Figure 2.12: Undercut tree and escarpment, Rice Reservoir, Wisconsin (Allen 2001b).

Figure 2.13: CGRs and willow used to restore bank in figure above (Allen 2001b).

Figure 2.14: Restored bank at same location as shown in figure above (Allen 2001b).

Victor Campground Area

($48,000 using branchbox breakwater, wetland plants & upland controls)

Bioengineering treatments at Victor Campground Area were installed during a USACE workshop demonstration in 2000 and have been successful. Erosion of the shore south of the workshop demonstration area was assessed as part of this task. This shore lies adjacent to a steep and rocky slope directly subjected to wind-driven waves from the west and as such experiences considerable erosion (**Figure 2.15**). When the lake level rises 15 to 20 ft. above normal pool, waves create escarpments higher up the shore. This can be noted around the undercut tree at the top of **Figure 2.15**. Retreating waters with associated waves at different elevation levels scour the shore and take good soil away with it, leaving rock and poor subsoils. This type of eroded shore needs a combination of treatments that will both break waves from the west and assist in building up sediment. The energy-reduced zone along with built-up sediment will be more conducive for growing vegetation that will in turn aid in controlling erosion (Allen, 2001b).

Figure 2.15: West-facing shore at Victor Campground showing notable upland erosion due to elevated pool levels and wind driven waves.

The shore must be treated at its toe to prevent undercutting waves and up and down its width to reduce the slope length and minimize erosion from overland flow. It is recommended that a branchbox breakwater be constructed just lake ward of the normal pool elevation. This will leave room for a swath of emergent aquatic vegetation (EAV) such as water willow, spikerush (*Eleocharis quadrangulata)* and various bulrush species (**Figure 2.16**). **Figure 2.17** shows the branchbox breakwater that was constructed in April 2000 at the workshop. **Figure 2.18** shows the same breakwater with vegetation behind it in September 2001, 1-1/2 years later. As shown in the picture, the breakwater area breaks up waves and leads to sediment accumulation behind it (Allen, 2001b). Cost to install these erosion controls along 1,200’ of shoreline at the Victor Site is $12,000 with $8,500 in materials and $3,500 labor.

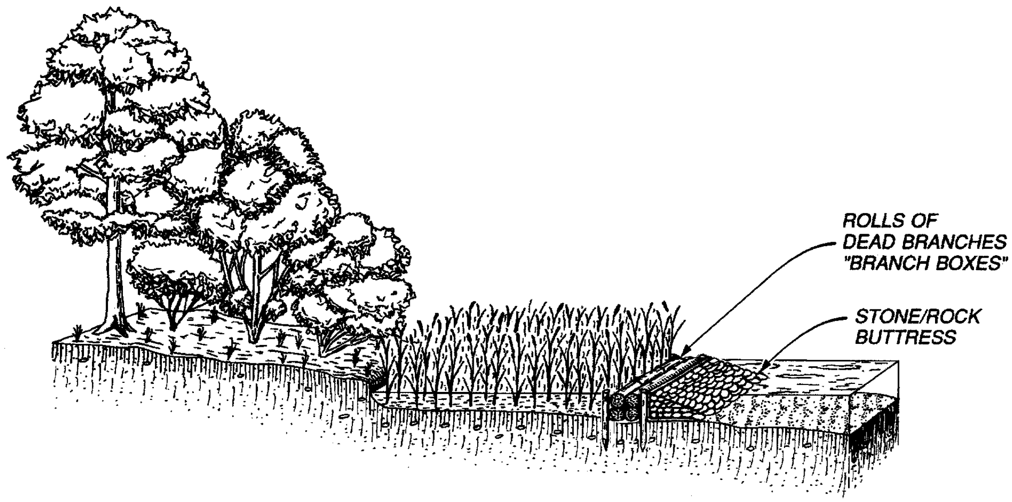

Figure 2.16: Schematic of branchbox breakwater with emergent aquatic vegetation (EAV) shoreward of it.

Figure 2.17: Branchbox breakwater being constructed in April 2000.

Figure 2.18: Branchbox breakwater with vegetation behind, September 2001.

The shore landward of the EAV zone should be treated with a series of contoured wattling or fascines with an erosion control fabric in between the fascines (**Figure 2.19**). Wattling or fascines are bundles of sprouting willow or other woody species that sprout adventitiously. They are usually 8-10 inches in diameter in the center and can be various lengths. They are buried along slope contours in trenches up to about ¾ of their diameter and then backfilled with soil.

When used successively up and down slopes, they break up slope lengths and create small check dams that slow overland flow velocities. They are often used landward and upward on slopes from such treatments as breakwaters with wetlands. Often, they have erosion control fabric, such as that made from coconut husks called coir, placed in the trenches below the wattling or fascines and in between the successive fascines on contours. Other erosion control fabrics exist, such as wood excelsior fabrics, which would also work nicely. Grasses are seeded before the erosion control fabric is laid down. A combination of grasses, such as switch grass (*Panicum virgatum*, Alamo variety), buffalo grass, and wild rye (*Elymus triticoides*) are planted to serve as a nurse crop. **Figure 2.20** shows an example of a fascine installation on a very sandy slope next to the Atlantic Intracoastal Waterway in South Carolina. Such an installation could be used at Victor and possibly at other shore areas landward of the lake shoreline itself where overland wash is creating rills and gullies (Allen, 2001b).

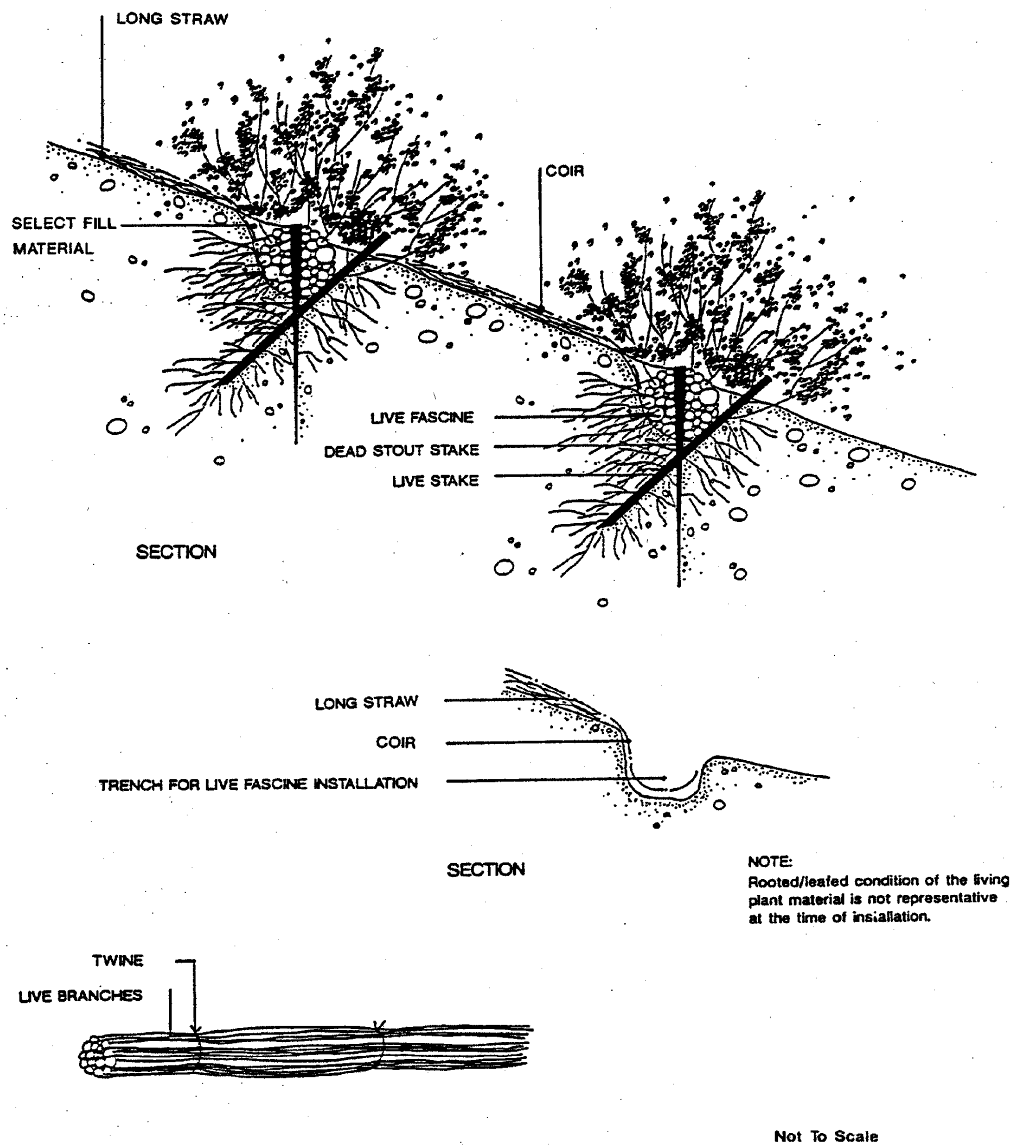

Figure 2.19: Drawing of fascines with erosion control fabric (coir) in between

Figure 2.20: Fascines with erosion control fabric on a slope along the Atlantic Intracoastal Waterway.

Note: Grasses were seeded under the erosion control fabric between the fascine rows.

Pocahontas Campground

($35,000 using branchbox breakwater, wetland plants & upland controls)

Pocahontas Campground area is on the north shore toward the western end of the lake. The area has a southeastern facing slope and shore that is exposed to southeasterly winds that have over a 2-1/2-mi. fetch. The southeastern slope resembles the westerly slope described above for the Victor area and includes a lot of rock and exposed thin layers of subsoil (**Figure 2.21**). Rills and gullies from overland flow were also noted. On the shore farther to the west of that shown in **Figure 2.21** is a boat launch with a less steep slope. The shoreline adjacent to and west of the boat launch is covered, in part, with some buttonbush at the edge of the water. The shoreline also has a fairly low gradient path leading to it that would easily accommodate handicapped access if it were improved (Allen, 2001b).

Figure 2.21: Southeastern shore of Pocahontas Campground with notable upland erosion due to elevated pool levels and wind-driven waves.

It is suggested that the southeast shoreline along with the southwestern shoreline just west of the boat launch receive a branchbox breakwater treatment with EAV behind the breakwater similar to what was discussed and illustrated for the Victor area above. Also, the southwestern shore could also be treated with fascines and erosion control fabric just like the treatment discussed above for the Victor area. The area west of the boat launch would only need a branchbox breakwater with EAV. These treatments, along with construction of a handicapped walkway, would lend themselves to a waterfowl hunting area for both handicapped and non-handicapped hunters. The campground would have easy access to accommodate construction and hunting (Allen, 2001b). Total estimated cost for installation (without handicapped access provisions) is $32,750. Approximately 1,200' of shoreline would require branchbox breakwaters with aquatic plants at a cost of $12,250 with $9,000 in materials and $3,750 labor. Upslope treatment with a 750' of fascine blanket would cost $22,500 with $20,250 in materials and $2,250 labor.

Non-Recreational Areas

So far control measures for specific recreational sites have been detailed. Unfortunately these are not the only areas on the lake experiencing shoreline erosion. Lake-wide erosion not only affects recreational value but also degrades water quality and wildlife habitat. Three categories of erosion were noted on Lake Wister at 478 MSL. These categories are discussed with a recommended treatment system and cost estimate.

Category 1 areas encompass those stretches of shoreline experiencing little to no erosion (**Figure 2.22**) characterized by a high level of protection. These areas are coves or open shores with a wide underwater bench. These areas are relatively isolated from human activity and boat traffic. Generally, Category 1 areas require no shoreline treatment.

Figure 2.22: Category 1 of erosion – no shoreline treatment necessary.

Note: Photo was taken on northeastern end of Lewis Creek arm September 1,1999 while the lake was 1 ¾ feet below conservation pool. Cages exclude herbivores from newly planted bulrush. Buttonbush, seen to the right and background, is found within the first 6 inches of depth below conservation pool.

Category 2 shores are noted by small (<1 to 2 ft) escarpments with a shallow bench lakeward. Fetch in these areas is less than one mile. The area may or may not be covered with emergent aquatic plants such as water willow or other wetland facultative plants. Treatments range from vegetation alone to erosion control mats and other measures given in Allen (2001a). The swimming area at Quarry Island in **Figure 2.8** is an example of Category 2 erosion.

Approximately 19.6 miles of Lake Wister could use vegetative treatments alone to combat shoreline erosion. These lengths are distributed as follows: approximately 6.25 miles of the main lake body, 6.44 miles of the Fourche Maline arm and 6.92 miles in the Poteau River arm. Emergent aquatic plants are placed in a zone lake ward of the woody zone in water depths extending from conservation pool level to depths up to 1.5 ft normally. Herbivore protection is normally employed to allow for establishment of emergent plants such as bulrush and arrowhead. Protection is only needed for a few years to allow establishment. Specific protection measures should vary depending on the magnitude of plantings. For example establishing a bounty on beaver and muskrat may be more cost effective to protect transplants for a few years as opposed to installing a large amount of fencing. When smaller areas are planted plastic coated fencing around the target area (to exclude herbivores) may be more cost effective than a bounty. Total cost to vegetate 19.6 miles of shoreline is $85,000 with $15,000 used to establish a local sustainable plant nursery, $8,000 for herbivore control and $62,000 labor. This planting could be accomplished in a 4-5 year time frame depending on climatic factors (due to the variable summer pool elevation).

Category 3 areas are highly eroded shores indicated by either by high escarpments or extensive overland and wave erosion. Typical examples of Category 3 erosion can be found near the Victor demonstration site (**Figure 2.15**) and at Pocahontas (**Figure 2.21**). Multiple levels of bank erosion can be noted. These areas generally have a fetch greater than one mile. Rising waters and fetch length cause waves to break against the shore at multiple elevations, while upland scour threatens trees high up on the bank. Waves and overland runoff also wash sediment away, taking soil while leaving rocks and creating gullies and rills. Breakwaters are necessary to trap organic matter to allow establishment of aquatic vegetation. Several types of breakwaters will assist in restoring these banks with vegetative cover while slope treatments will require erosion control blankets and seeding. Comparison of cost per unit distance showed that the branchbox breakwater was the least expensive to install.

A branchbox breakwater with vegetation behind has been used successfully at several different lakes in the United States. In fact, one was used at Lake Wister as part of a workshop and demonstration in April 2000. The breakwater was installed on a reach of shoreline that is exposed to greater than a 2-mile fetch from the southwest (**Figure 2.17**). The area shoreward of the breakwater was planted with both emergent aquatics, e.g., water willow, bulrush, sedges, and willow cuttings farther up on shore. The area was examined in September 2001 and was found to be functioning very well in terms of controlling erosion and providing habitat benefits (**Figure 2.18**) (Allen, 2001b).

Approximately 3.6 miles of shoreline have erosion similar to that characterized at the Pocahontas Slough and Victor Campground areas. These areas are associated with steep slope, small to no bench, large fetch with little soil left and were mostly noted in the main body and Fourche Maline Arm of Lake Wister. Of the 3.6 miles approximately 1.63 miles are in the Fourche Maline arm and 1.97 miles in the main body of Lake Wister. Cost to treat 3.6 miles of shoreline with a branchbox breakwater, aquatic plants and upland installation of fascines totals $754,000, $340,000 for the Fourche Maline arm and $414,000 for the main lake body.

Suspended Solids Control for Water Quality

Since its impoundment in 1949 Congress has raised the conservation pool elevation from its initial pool level of 471.6 MSL. In 1983 it was raised to 474.6 MSL while in 1996 it was raised to 478 MSL. These changes had a profound effect on in-lake dynamics of algae growth and sediment movement. The effect of increased fetch has already been discussed as it relates to shoreline erosion. Raising the pool elevation has also had the effect of concentrating the lake shallows into several localized areas (**Figure 2.3**). The formation of these large shallow flats has exacerbated algae growth and suspended solids in Lake Wister.

Although turbidity is high year-round and normally limits algae growth, these shallow flats allow algae cells to be suspended in the photic zone for much of the day, nullifying the light limitation. The elimination of light limitation combined with hypereutrophic levels of nutrients allows exponential algae growth and consequently scum formation. Scums are found annually in coves and in the large shallow reaches of the lake. Nutrient reductions to Lake Wister are necessary to reduce scums. While these scums represent organic suspended solids, these same areas periodically experience elevated inorganic suspended solids as well.

During periods of relative calm inorganic particles will settle out of the water column lake wide. In deeper areas of the lake these particles will be lost from the water column to the lake bottom as sediment. In shallow areas the settled fine particles are prone to re-suspension during periods of wave action. High, sustained winds are the primary originator of waves in Lake Wister. Field observations have noted that swells and wind-driven waves reaching shallow zones can suspend solids in these areas.

Allowing settled particles to stay on the lake bottom and become incorporated with the sediment will reduce the excessive turbidity in Lake Wister. Usually stabilization of shoreline erosion using bioengineering methods minimizes sediment suspension in the shallow reaches. The unique shape of Lake Wister indicates implementation of shoreline control measures will provide adequate suspended solids control. Even with shoreline erosion eliminated, the large shallow benches noted in the Fourche Maline arm and Poteau River Arm of the lake would store fine particles on a short-term basis and resuspend these with wave action.

Placement of breakwaters across the large shallow flats and encouraging wetland development behind the breakwaters will decrease suspended solids in Lake Wister. To some extent these breakwaters will partition off algae scums from the main lake body. Breakwater placement targets the protection of water less than 1 meter deep (**Figure 2.23**). These breakwaters and associated wetlands would break up wind-driven waves from the northwest in the Fourche Maline and Lewis Creek arms of the lake and from the south in the Poteau River arm.

Breakwaters could be constructed from several materials. Many locally available materials were discussed in the PAS report contracted by the OWRB to the Tulsa District USACE (1998c). Sample drawings and detailed cost estimates were furnished for four different construction methods as well as for various lengths. In short, brush bundles and brush piles cost the least per unit length with decreasing per unit cost as the structure lengthened.

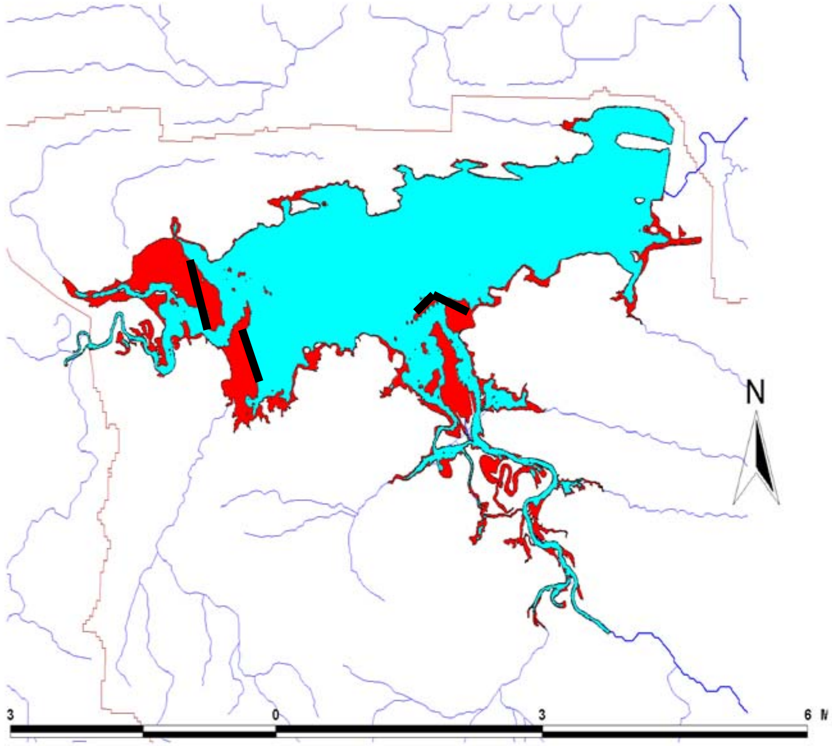

Figure 2.23: Proposed placement of breakwaters to reduce wave action and suspended solids in Lake Wister.

Note: Red areas represent less than 1-meter depth.

Since the time of the PAS report additional materials have been developed that could achieve the same results. For example, a breakwater using geotextile bags filled with sand is a viable option. Other geotextile breakwaters and wetlands can be made from a continuous geotube, as shown in **Figure 2.24**, with wetlands planted on the leeward side. Dredging sand from the reservoir and filling the tube directly from the dredge pipe as illustrated in **Figure 2.25** may be the most feasible method. A geobag or geotube breakwater can be tailored to the height and length needed. Geobags and tubes come in various sizes and can be stacked in a pyramid fashion (Allen, 2001b). A single bag would suffice to break fetch at conservation pool elevation (**Figure 2.26**).

In addition to reducing fetch and protecting the southeastern shore from wind-driven waves, the breakwater and wetland combination would likely help with the turbidity of water to the east of the system (Allen, 2001b). The wetland system would trap sediments and confine them to the marsh. The proposed breakwater design targets greater than 50% of the lake surface area. It is important to note that decreases in turbidity translate into a higher sedimentation rate behind the breakwaters and consequently significant loss of reservoir capacity is expected. A benefit of this wetland would be the creation of waterfowl habitat. It is likely that waterfowl hunting organizations, such as Ducks Unlimited, would be more than willing to cooperate in such a venture.

Figure 2.66: Geobags being filled to form a breakwater for planting wetlands behind it.

Figure 2.24: Geotube breakwater with planted wetlands.

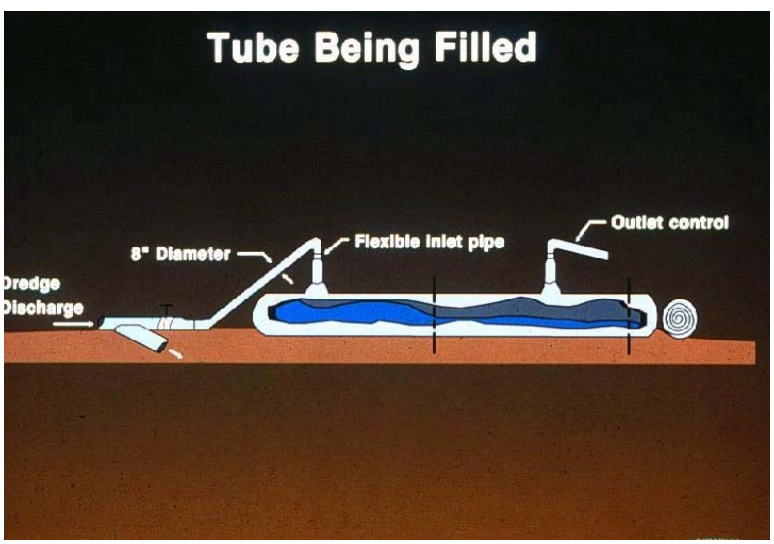

Figure 2.25: Drawing illustrating a geotube being filled from a dredge pipe.

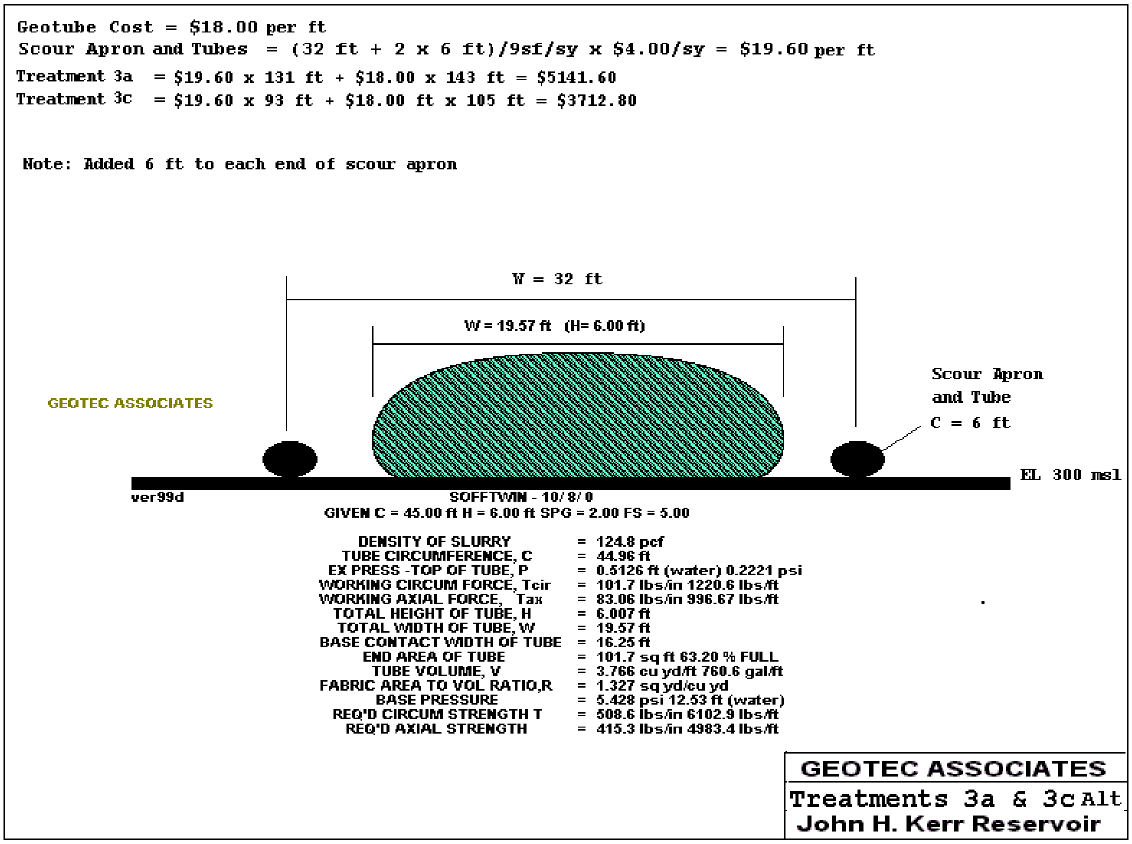

Figure 2.26: Minimum sized geotube for breakwater construction in Lake Wister with associated material cost.

Costs for geotube treatment run $36 in 2000 dollars per linear foot for material plus dredging costs to fill the tube. Cost estimates for brush bundle and brush pile are $72 per linear foot and $82 per linear foot in 1998 dollars (Allen, 2001b & USACE 1998c). An estimate cost of $15/yd^3 for dredge material was used to complete the estimate for geotube installation (**Table 2.5**).

Table 2.5: Cost estimate to implement breakwaters for water quality improvements.

Method	Description	Linear distance	Cost
Geotube*	goetextile material	8300	$ 298,800
	dredging cost ($15/yd^3)	8300	$ 468,867
		total	**$ 767,667**
Brush bundle**	materials and labor	8300	$ 597,600
Brush pile**	materials and labor	8300	$ 680,600

* 2000 dollars
**1998 dollars

Prioritization

Implementation of shoreline erosion control practices should be immediately implemented while placement of breakwaters on the large mud flats should be delayed. Since erosion is so extensive, sites should be prioritized, segregating recreational and non-recreational areas. Higher priority should go to sites where structures or facilities, such as picnic tables and campgrounds, are threatened. It is suggested that one start with less severe sites first to illustrate success and then proceed to more difficult reaches of shoreline. Of course, one such site has already been addressed through a workshop at Lake Wister and can be shown to various parties to illustrate success. Most of the recommended treatments can be fairly easily applied by volunteer labor assuming they can be trained through a 1- to 2-day workshop.

Treatments that meet water quality and aquatic habitat objectives should focus on non-recreational sites. Several methods of prioritization can be employed for prioritizing non-recreational treatments, most shoreline per dollar, most habitat per dollar or most water quality improvement per dollar. In general vegetative treatments will yield the greatest shoreline treatment and habitat per dollar spent. However, because these treatments are at or near the waterline the water quality improvements will not be as great as that expected from installation of the breakwaters. Three areas are recommended for these breakwaters: on the north and south end of the Fourche Maline arm and on the South end of the Poteau arm.

Since bioengineering is a relatively new field for most, some education and convincing may need to be done through a workshop and demonstration in order to garner needed support and monies for future work. To keep costs minimal, it is recommended that cooperation be sought from such groups as boat, fishing, and wildlife clubs or organizations, which could probably volunteer some labor. Other labor could be acquired through the OWRB, Oklahoma Department of Tourism and Recreation (ODTR), Poteau Valley Improvement Authority (PVIA) or the Kerr Center for Sustainable Agriculture.

Implementation of suspended solids control through the installation of large breakwaters should not proceed until nutrient controls are also implemented. Significant reductions of inorganic turbidity are likely to stimulate algae growth without prior or concomitant nutrient reductions. This possibility of stimulating algae production in the main lake body outweighs potential gains by partitioning off the shallow mud flats (**Figure 2.23**). Should comprehensive suspended solids control be contemplated without nutrient reductions, a detailed feasibility study should be performed to assess and predict the lake response to such actions.

Task 3: Water Quality Monitoring

The OWRB collected a total of twelve samples on a biweekly basis from Lake Wister between May 22, 2001, and October 17, 2001 (**Table 3.1**). Equipment calibrations, sample collections, preparation, and analyses were made in accordance with the Quality Assurance Project Plan (QAPP) for the 2001 Lake Wister Study.

Table 3.1: Sample Dates.

5-22-01	6-5-01	6-20-01	7-3-01
7-10-01	7-24-01	8-7-01	8-22-01
9-5-01	9-19-01	10-3-01	10-17-01

Methods

Vertical profiles of the water column measuring temperature, dissolved oxygen, pH, oxidation-reduction potential, total dissolved solids, salinity, and specific conductance were taken with a Hydrolab Surveyor 4a. All of the readings were taken at one-meter intervals from surface to bottom. Visibility was measured at each site using a 20-cm black and white Secchi disk.

Water quality samples were collected in two ½ gallon polyethylene bottles, one preserved with sulfuric acid (H_2SO_4), and stored on ice prior to delivery to the Oklahoma Department of Environmental Quality (ODEQ) Environmental Laboratory for analyses. General chemistry water quality samples were preserved for analysis for the following parameters: ammonia (NH_4^+), nitrate nitrogen (NO_3), nitrite nitrogen (NO_2), kjeldahl nitrogen, ortho-phosphorus, total phosphorus, suspended solids, settable solids, total hardness, alkalinity, apparent color, true color and sulfate. **Table 3.2** lists all parameters sampled for this study.

Table 3.2: Water Quality Parameters.

Temperature	Dissolved Oxygen	Percent oxygen saturation
pH	Oxidation-reduction potential	Alkalinity
Hardness	Specific Conductance	Salinity
Total dissolved solids	Total settleable solids	Total suspended solids
Secchi disk visibility	Turbidity	True & Apparent Color
Total & dissolved Iron	Total & dissolved Manganese	Sulfate
Ammonia-nitrogen	Nitrate-nitrogen	Nitrite-nitrogen
Total Kjeldahl Nitrogen	Ortho-phosphorous	Total phosphorous
Chlorophyll-a	Pheophytin-a	Chemical Oxygen Demand
Zooplankton density	Algae density	Fecal coliform
E. coil	Enterococci	

General chemistry and metals samples were collected at the lake surface and 0.5 m from the bottom at all sites. Lake surface samples were collected by submersing primed bottles approximately one half meter under the surface. Careful consideration was taken not to introduce air into the sample. A 6.2-liter beta bottle was used to collect samples 0.5 meters from the lake bottom. **Figure 3.1** shows a map of lake sampling sites. Numbered map sites are referenced in this report as (1) Dam, (2) Quarry Island, (3) Mid-Lake, (4) Fourche Maline, and (5) Poteau River. The latitude and longitude for the sample sites are listed below in **Table 3.3**.

Table 3.3: Lake Wister sampling site locations.

Site #	Site Name	Latitude	Longitude
1	Dam	34° 56' 13.4772" N	-94° 43' 16.6524" W
2	Quarry Island	34° 56' 46.8261" N	-94° 43' 22.0256" W
3	Mid-Lake	34° 56' 21.4034" N	-94° 44' 48.6232" W
4	Fourche Maline Arm	34° 55' 33.546" N	-94° 48' 22.8138" W
5	Poteau River Arm	34° 54' 29.8642" N	-94° 45' 24.0285" W

At the Dam, three additional interval depth samples were also collected using the beta bottle. A replicate sample labeled “site 6” was split from surface water at the Dam site with a churn splitter for Quality Assurance purposes. A blank sample, labeled “site 7,” was also submitted to the lab for this purpose. Total and dissolved iron and manganese samples were collected at each site using the same procedure as the general chemistry samples (in one-liter polyethylene bottles), iced, and sent to the ODEQ laboratory for nitric acid preservation and analyses.

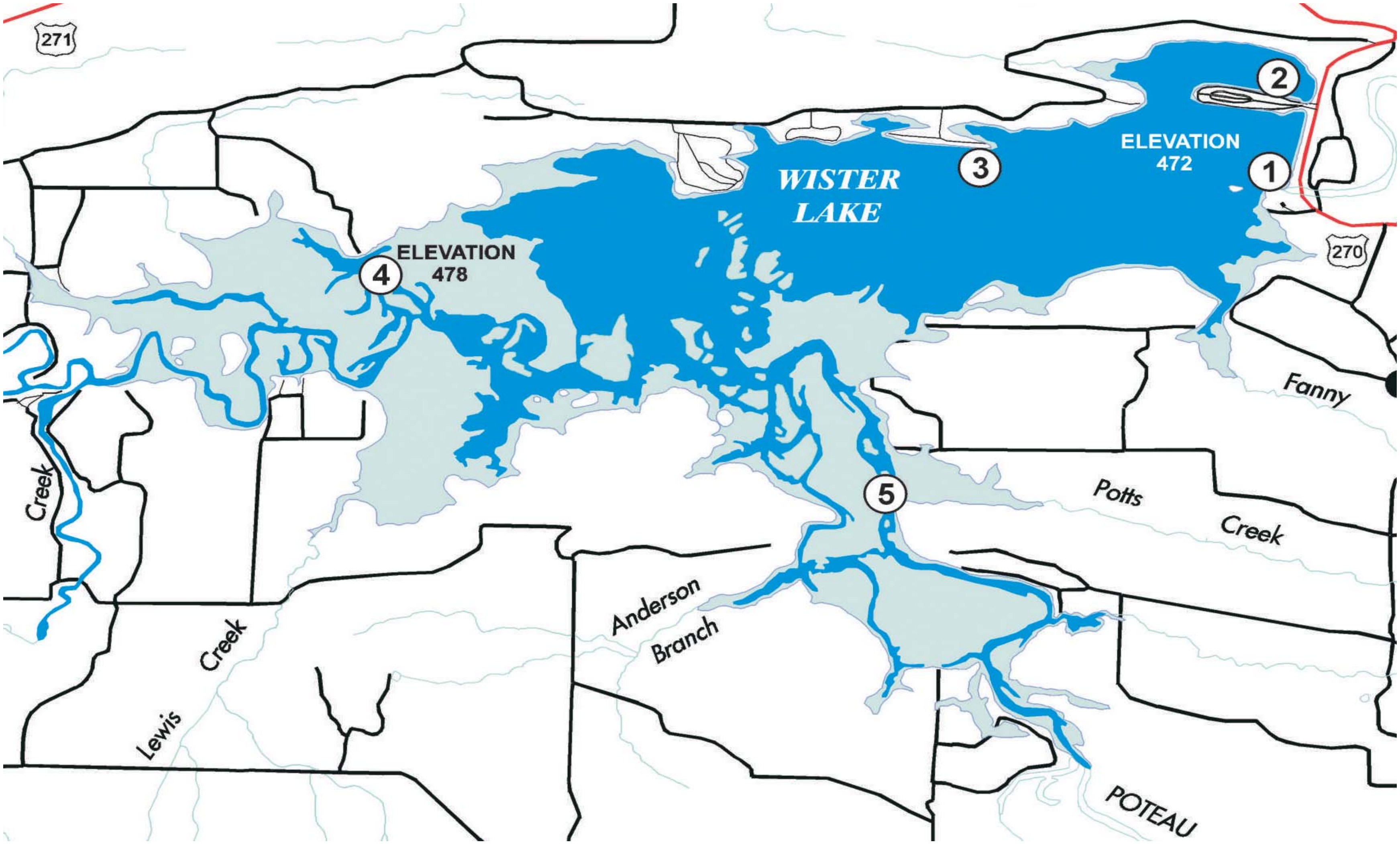

Figure 3.1: Lake Wister Sample Sites.

Biological samples of zooplankton identification and enumeration and phytoplankton (algae) cell density and biovolume were also taken at each sampling site. Phytoplankton samples were preserved with gluteraldehyde and zooplankton samples were preserved using Lugol's solution. Untimely receipt of data from the contractor, Phycotech, Inc., prevented

Samples for chlorophyll-a and turbidity analyses were collected at the surface from all sites. Samples were collected in 1-liter polyethylene bottles and stored on ice and in darkness until return to the OWRB laboratory. At least 300 ml of sample water was filtered through a glass fiber filter using a hand-operated pump. The filter paper and filtrate were ground with a mortar and pestle, preserved with magnesium buffered acetone in a test tube and stored at 4ºC until delivery to the Oklahoma Department of Environmental Quality (ODEQ) for analysis. Turbidity values were expressed as nephelometric turbidity units (NTU) using a HACH 2100P field turbidimeter.

Quality control procedures were followed as noted in the Lake Wister QAPP (OWRB, 2001b). Quality control of field-measured parameters consists of checking instrument calibration with a standard measure prior to each field trip. When a field measured parameter reads out of calibration, the event is recorded in the data notebook, and recording of data for that parameter is discontinued.

Field quality control of laboratory-measured parameters consists of the submittal of replicate and blank samples to the laboratory for analysis as if the samples were part of the data set. A replicate sample is submitted to the laboratory for analysis every sample trip at a 10% frequency per sample event. Submittal of a sample consisting of reagent grade water is considered a "blank" sample. Preparation of the "blank" sample consists of transferring reagent grade distilled, de-ionized water into a sample container. Laboratory quality control sample results are tracked and compared to the laboratory's QC criteria.

Data used for diagnosis must be considered complete. Data must pass the QC acceptance criteria stated in the executed QAPP to be considered complete. Acceptance for a given sample event is based on the comparison of replicate sample values for each sample event. When replicate samples meet the acceptance criteria for a given parameter those reports for the sample event are concluded complete. When replicate sample do not meet the criteria for a given parameter those reports for the sample event are concluded incomplete. Acceptance criterion for replicate samples is less than two laboratory-reported accuracy standard deviations for the parameter evaluated. In this manner the completeness of all laboratory-reported values can be assessed. **Appendix A** lists the data analyzed according to the QC criteria.

A data completeness goal for the entire data set of 85% was adopted and is stated in the QAPP. The drawback to missing the % completeness goal is lost statistical power to evaluate study data. Completeness is calculated for each parameter on an event basis. In the case of this study 12 sample events occurred. The number of events concluded to be complete are divided by the total number of sample events (12) and expressed as a percentage to yield percent completeness.

Most monitored parameters were 100% complete. Parameters that fell short of 100% are listed with their associated percentage (**Table 3.4**). Percent completeness goals were not met for 5 of the 31 analytical parameters in this study. Small sample size, sample error, laboratory error and stringent QC criteria are probable factors for low completeness of chemical oxygen demand, chlorophyll-a, total suspended solids, nitrates and total phosphorus. The relatively small sample size (12 events) could account for total phosphorus and nitrate missing the completeness goal. Had one more successful event occurred the percent completeness for those parameters would have been 11 of 13 or 85%. Chlorophyll-a, which lost one sample event due to laboratory error, may have suffered from small sample size as well as laboratory error. Chemical oxygen demand and total suspended solids failed acceptance criteria for 4 of the 12 sample events. It is likely that the acceptance criteria were too stringent for these parameters due to their variable nature and analytical procedures. All data assessed as acceptable were used in this report, whether their overall completeness goal was met or not.

Table 3.4: Percent completeness of laboratory data.

	Non-Usable Data	Usable Data	Total Data Received	% Completeness	Comments
Chemical Oxygen Demand (mg/L)	4	8	12	67	
Hardness (mg/L)	1	11	12	92	
Chlorophyll-a (mg/m^3)	3	9	12	75	Lab spilled one sample
Total Suspended Solids (mg/L)	4	8	12	67	
Nitrate (mg/L)	2	10	12	83	
Manganese (mg/L)	1	11	12	92	No sample taken 5/22/01
Iron (mg/L)	1	11	12	92	No sample taken 5/22/01
Total Phosphorus (mg/L)	2	10	12	83	
Apparent Color (Pt-Co units)	1	11	12	92	
True Color (Pt-Co units)	1	11	12	92	

Water Quality Results

Table 3.5 summarizes water quality data collected from all five sites on Lake Wister during monitoring. In calculating summary statistics, values below the detection limit were given a value of half the detection limit. Data reflect samples taken from the epilimnion (E) and hypolimnion (H) while stratified. For selected parameters that were only collected at the surface (S), data from the entire sampling period was used.

Table 3.5: Data Summary for Lake Wister.

Parameter	Layer	Mean	Median	Std. Dev.	Min	Max	n
Total Dissolved Solids (g/L)	E	0.019	0.019	0.004	0.012	0.027	30
	H	0.031	0.030	0.009	0.012	0.050	30
Total Settleable Solids (mg/L)	E	0.074	0.05	0.064	<0.1	0.4	35
	H	0.094	0.05	0.106	<0.1	0.45	35
Total Suspended Solids (mg/L)	E	20.83	19	15.96	<5	64	20
	H	89.92	81.5	57.86	10	232	20
Specific Conductance (µS/cm)	E	30.03	29.4	6.31	19.5	41.5	30
	H	47.85	46.15	13.97	19.1	78.6	30
Secchi Depth (cm)	S	30.22	30	11.47	8	59	54
Turbidity (NTU's)	S	36.75	31	27.06	11	185	60
Total Alkalinity (mg/L)	E	12.46	10.3	11.75	<10	67.7	35
	H	13.69	5	16.91	<10	75.3	35
Total Hardness (mg/L)	E	22.36	22.65	4.73	14.8	30.3	30
	H	34.45	35.6	10.64	16.8	58.2	30
pH	E	7.32	7.15	0.632	6.38	8.74	30
	H	6.54	6.55	0.220	6.08	6.91	30
Oxidation-Reduction Potential (mV)	E	286.23	283	108.07	97	519	30
	H	173.58	155.5	218.42	-115	608	30
Total Iron (mg/L)	E	1.60	1.533	0.74	0.522	3.667	33
	H	6.41	4.228	5.51	1.338	29.68	33
Total Mn (mg/L)	E	0.28	0.256	0.18	0.043	0.736	33
	H	2.62	2.347	1.60	0.258	5.428	33

Parameter	Layer	Mean	Median	Std. Dev.	Min	Max	n
Sulfate (mg/L)	E	17.92	16.15	6.41	9.7	36.4	35
	H	35.58	29.6	27.63	17	181	35
Ammonia (mg/L)	E	0.034	0.025	0.018	<0.05	0.09	35
	H	0.512	0.36	0.421	<0.05	2.05	35
Nitrite (mg/L)	E	0.041	0.05	0.016	<0.05	0.09	35
	H	0.082	0.08	0.038	<0.05	0.19	35
Nitrate (mg/L)	E	0.027	0.025	0.008	<0.05	0.07	30
	H	0.029	0.025	0.012	<0.05	0.08	30
Total Kjeldahl Nitrogen (mg/L)	E	0.699	0.67	0.205	0.34	1.6	35
	H	1.42	1.28	0.680	0.67	3.38	35
Total Phosphorus (mg/L)	E	0.094	0.087	0.031	0.033	0.154	25
	H	0.287	0.195	0.188	0.099	0.833	25
Ortho-phosphorus (mg/L)	E	0.026	0.022	0.013	0.011	0.066	35
	H	0.096	0.09	0.051	0.037	0.271	35
Chemical Oxygen Demand (mg/L)	E	29.40	23.5	23.10	10	106	25
	H	31.28	25	26.24	4.5	112	25
Chlorophyll-a (mg/m^3)	S	18.55	17.6	12.79	0.6	75.7	43
Pheophytin-a (mg/m^3)	S	9.77	6.45	10.16	0.05	50.5	43
TSI SD	S	78.36	77.35	5.80	67.60	96.40	54
TSI Chl-a	S	56.63	58.73	8.70	25.59	73.05	43
TSI TP	E	68.93	68.55	5.08	54.57	76.78	25
E. coli (# colonies/100 ml)	S	100.02	5	481.30	<10	3076	57
Fecal coliform (# colonies/100 ml)	S	155.70	5	932.23	<10	7000	57
Enterococci (# colonies/100 ml)	S	1893.86	5	9864.93	<10	57000	57

Parameters in this report are listed as mg/L as N for nitrogen series, mg/L as P for phosphorus series, mg/L as Fe for iron, mg/L as Mn for manganese, mg/L as SO_4 for sulfate, and mg/L as $CaCO_3$ for alkalinity and hardness. Standard methods used for each of the lab parameters are given in **Table 3.6**.

Table 3.6: Analytical methods for laboratory parameters.

Parameter	Analytical Method
Total Settleable Solids (mg/L)	EPA 160.5
Total Suspended Solids (mg/L)	EPA 160.2
Total Alkalinity (mg/L)	EPA 310.1
Total Hardness (mg/L)	EPA 130.1
Total Iron (mg/L)	EPA 200.7/6010
Total Mn (mg/L)	EPA 200.7/6010
Sulfate (mg/L)	EPA 375.4
Ammonia (mg/L)	EPA 350.1
Nitrite (mg/L)	EPA 353.2
Nitrate (mg/L)	EPA 353.2
Total Kjeldahl Nitrogen (mg/L)	EPA 351.3
Total Phosphorus (mg/L)	SM 4500 P-B-E
Ortho-phosphorus (mg/L)	SM 4500 P-E
Chemical Oxygen Demand (mg/L)	EPA 410.1
Chlorophyll-a (mg/m^3)	SM 10200H2
Pheophytin-a (mg/m^3)	SM 10200H2
E. coli	SM 9223
Fecal coliform	SM 9222D
Enterococci	EPA 1600
Apparent color (Pt-Co units)	EPA 110.2
True color (Pt-Co units)	EPA 110.2

In the following graphs, box and whisker plots are used to represent conditions at each site in the epilimnion and hypolimnion when stratified. For parameters measured only at the surface, the box and whisker plots use data from the entire period of record. In each box and whisker plot (**Figure 3.2**), the central line in each box represents the median. The top of the shaded box is the upper quartile, which is the middle value between the median and the maximum number rounded to the nearest whole number. The bottom of the shaded box is the lower quartile, which is the middle value between the median and the minimum number rounded to the nearest whole number. The “whiskers” show the maximum and minimum values.

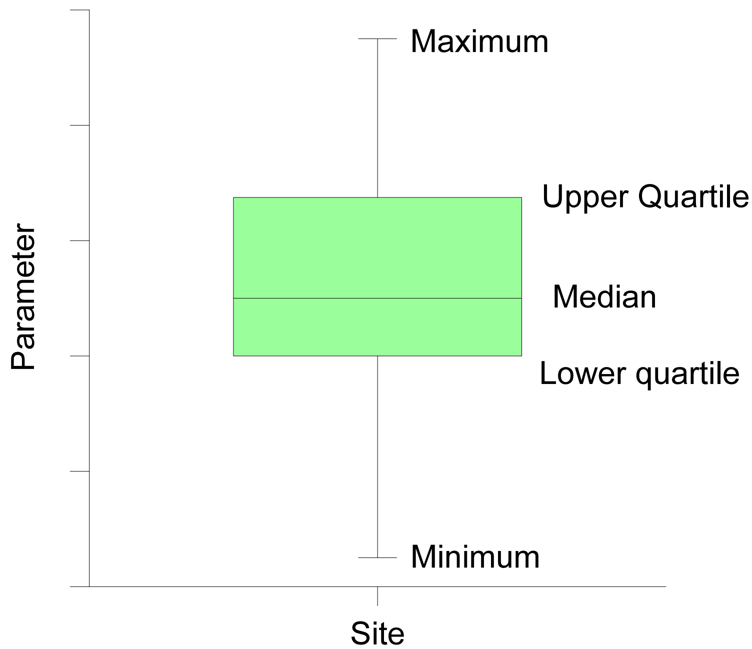

Figure 3.2: Example of a box and whisker plot.

Isopleths were also used to show profiles at a single site for parameters that vary with depth. Isopleths are read as time vs. depth, with the contour lines representing the value of the parameter at that particular depth and time. When the contour line is vertical, the value of the parameter does not change with depth, and the water column is completely mixed. Horizontal lines indicate stratification.

For each parameter at each site, a grid was created using the raw values for the parameter versus depth at each reading. Isopleths were plotted using Surfer® software set at the Nearest Neighbor gridding with a grid spacing of 14 days on the x-axis and 1 m on the y-axis and contour smoothing factor set to high. This method was showed to best represent the raw data in the final illustration. The following narrative describes the water quality data using figures to graphically represent Lake Wister.

Hydrology

In interpreting the results of water quality sampling, knowledge of some of a lake's hydrologic characteristics is essential. Lake hydrology, including changes in the lake's elevation and inflow, has a major impact on the chemical and biological processes that occur within the lake. Stormflow events influence nutrient and sediment loading into the lake, resuspension of lake sediments, and stratification patterns. Changes in lake elevation and nutrient loading can also affect the extent of anoxia in the water column and the hypolimnetic oxidation-reduction potential, which in turn affects solubilization of nutrients and metals from the hypolimnetic sediment.

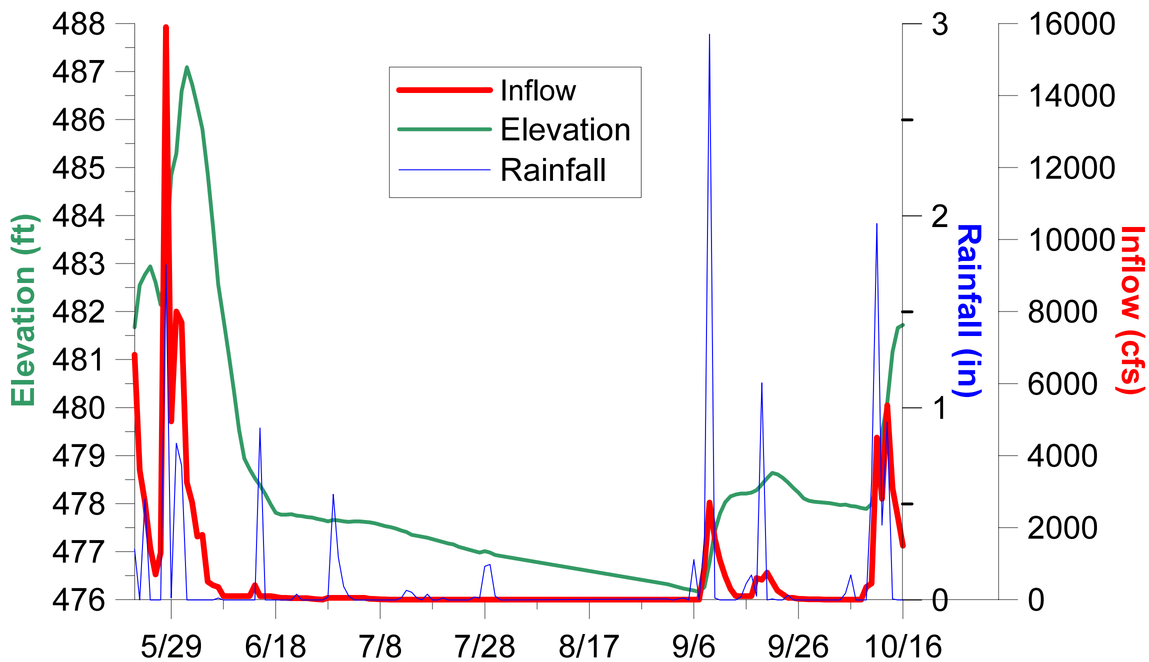

Figure 3.3: Lake Basin Rainfall in inches, Elevation in feet, and Inflow in cubic feet per second (cfs), (Data from USACE).

Figure 3.3 shows Wister's inflow, elevation, and rainfall for the May 22 – October 17, 2001 reporting period. Lake elevations on sampling dates are shown in **Table 3.7**. In general, rainfall in the watershed produces runoff and increased inflow into the lake. In the spring, when the soil of the drainage basin is saturated, a large portion of rainfall becomes runoff and reaches the lake. The lake level can rise several feet due to a single storm or series of storms. In the summer, rainfall events are usually smaller and little of the rain reaches the lake due to increased evaporation and infiltration in the drainage basin. Evaporation and lack of inflow in the summer also causes the lake level to decrease. In 2001, the lake was stratified from May 22 until between the end of August and beginning of September. Baseflow conditions to Wister reservoir were noted from June through July with a few interruptions in August. This resulted in 8 of the 12 sample events occurring within a falling or dropping pool elevation. .

Lake levels can vary considerably with area rainfall patterns. Consulting Oklahoma Climatological Survey data showed that in 2001 southeast Oklahoma had a normal rainfall year, with 103% of the normal amount of precipitation. Rainfall by season was less typical, with 147% of the normal rainfall for the winter, 90% in the spring, 77% in the summer, and 84% in the fall (OCS, 2002b).

Table 3.7: Lake Wister elevations in feet on water quality sampling events.

Sampling date	Lake elevation (ft)
5/22/01	481.67
6/05/01	484.88
6/19/01	477.77
7/03/01	477.63
7/10/01	477.51
7/24/01	477.07
8/07/01	476.68
8/22/01	476.62
9/05/01	476.21
9/16/01	478.4
10/03/01	477.99
10/17/01	481.54

Physical Properties

Temperature

Surface temperatures of the lake ranged from 18-35 °C during the reporting period from May-October 2001. In the winter, temperatures reach as low as 5-6 °C. The lake stratified from around April-May to August-September, and is classified as a warm monomictic lake.

Numerous factors influence a lake's stratification patterns, including climate conditions and wind patterns, lake basin shape and depth, and inflow to volume relationships (Wetzel, 1983). Because of Wister's physical properties, it does not fully stratify with a distinct epilimnion, metalimnion, and hypolimnion. Wister often has a fairly well mixed epilimnion, but a metalimnion is not often observed. Typically, the temperature simply decreases gradually with depth below the epilimnion.

In May, when sampling began, the lake had begun to stratify at the Main Lake and Quarry Island sites. By the beginning of June, the entire lake was stratified. Stratification lasted throughout the summer until the lake mixed between the end of August and the beginning of September (**Figure 3.4**). This is consistent with stratification observed between 1992 and 1994 (OWRB, 1996). Quarry Island did show onset of stratification earlier than all other monitored sites. This indicates that the Quarry Island site is partitioned from the main lake body. Thermal stratification was also noted to be the weakest at the Fourche Maline site. This is likely due to the shallow depth and large available fetch of the area. These differences between the Fourche Maline, Quarry Island and other sites indicate additional water quality differences will be noted.

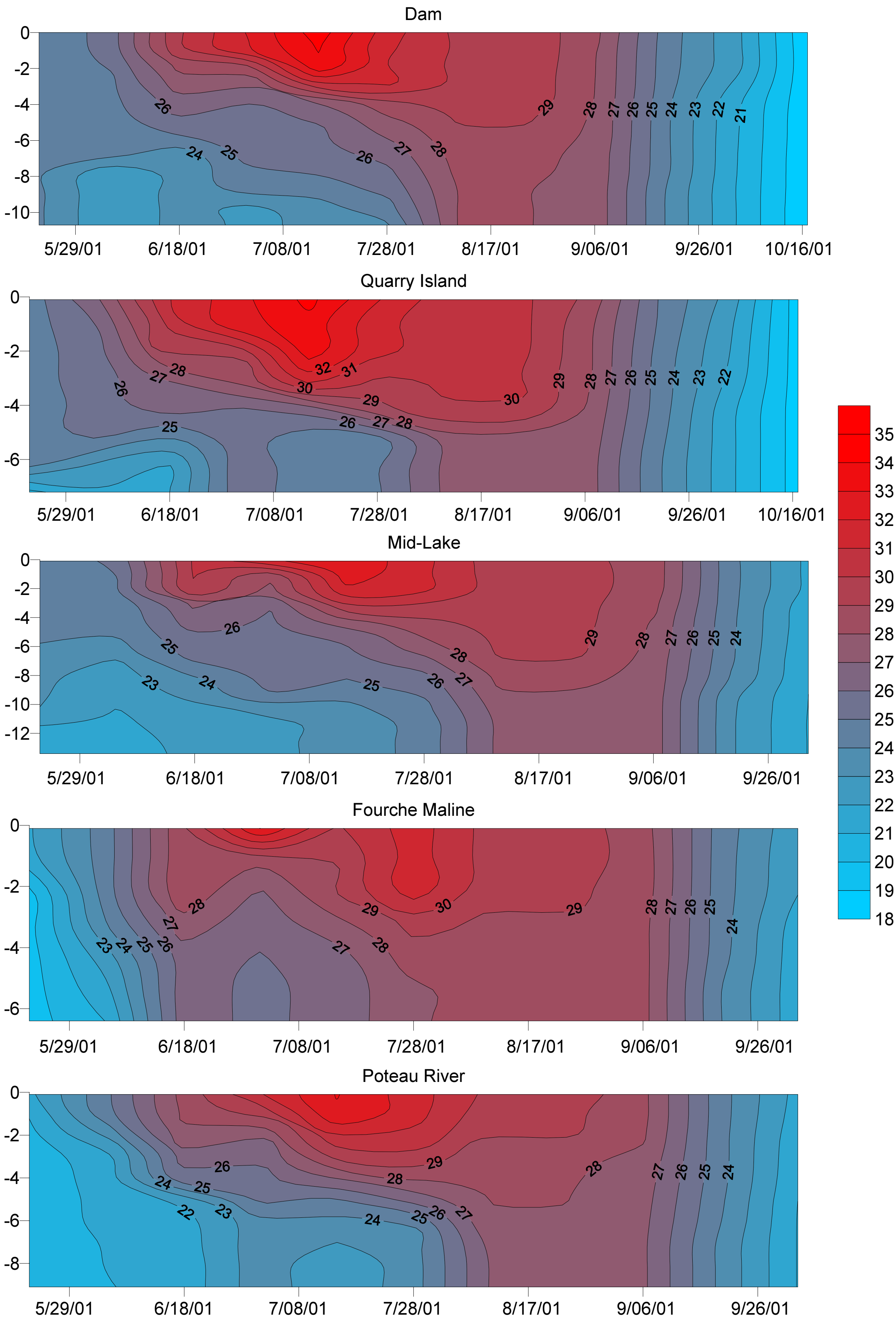

Figure 3.4: Temperature profiles in °C, May 22 – October 17, 2001.

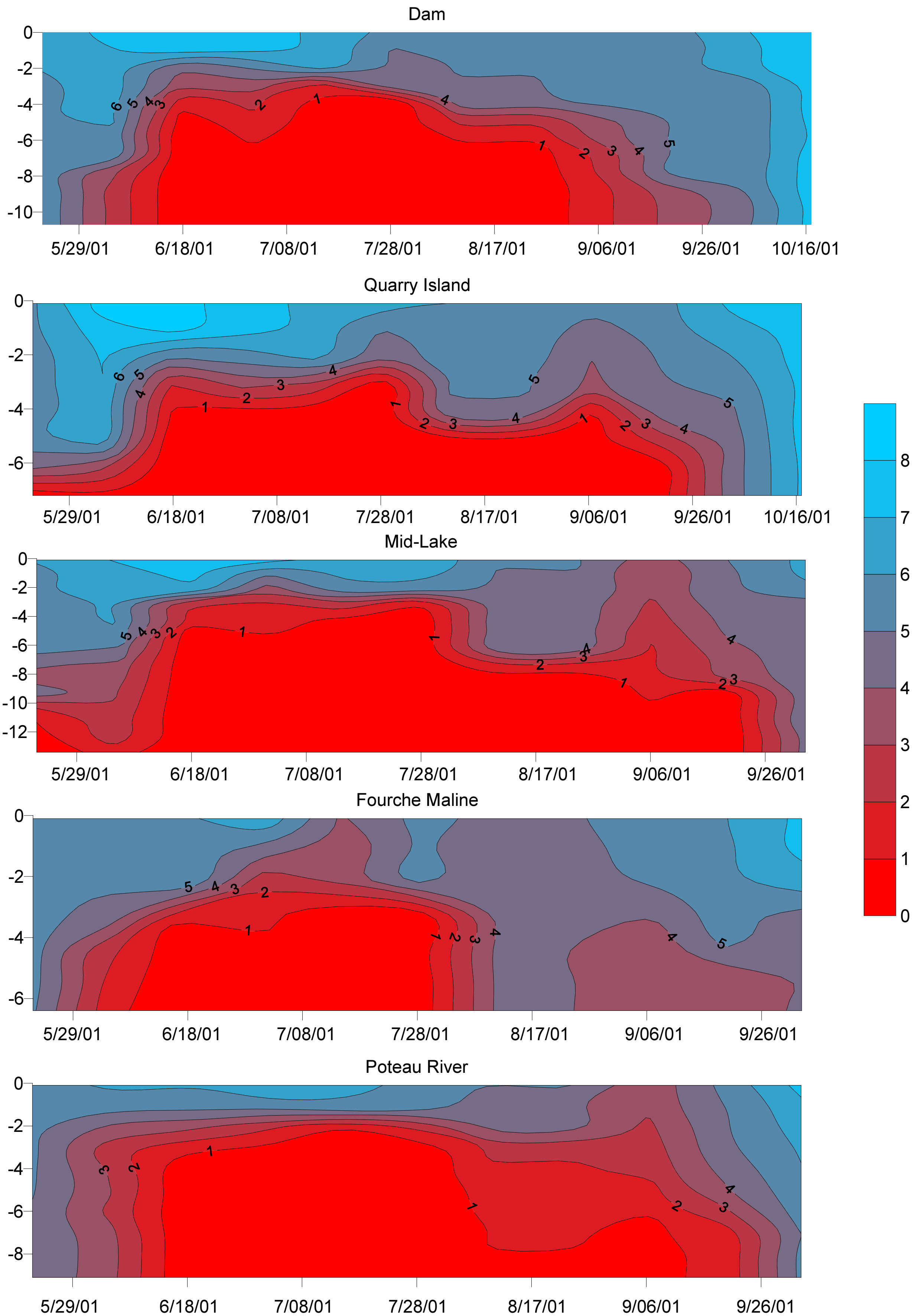

Figure 3.5: Dissolved Oxygen profiles in mg/L, May 22 – October 17, 2001.

Dissolved Oxygen

Wister shows dissolved oxygen dynamics typical for a eutrophic lake. Due to high organic levels in the system, oxygen consumption due to respiration and bacterial decomposition of organic matter are high. When part of the water column becomes partitioned off and no longer receives an external input of oxygen from photosynthesis or solubilization of atmospheric oxygen, dissolved oxygen levels rapidly drop. This means that typically, the onset of thermal stratification is shortly followed by anoxic conditions developing in the hypolimnion (Wetzel, 1983).

Anoxia, defined here as dissolved oxygen of less than 2 mg/L, was found above the lake-sediment interface at the two stratified sites, Mid-Lake and Quarry Island, as soon as sampling began in late May (**Figure 3.5**). At the other sites, hypolimnetic anoxia was observed either as soon as thermal stratification developed at the beginning of June, or at the next sampling event 2 weeks later. If not anoxic at the onset of stratification, the maximum dissolved oxygen concentration was 3 mg/L.

Throughout the summer, hypolimnetic anoxia was seen beginning at 2-4 m below the surface and extending to the lake bottom. The resumption of lake circulation at the end of August to September dropped the depth at which anoxia was measured, but all sites were not oxygenated again until the end of September, several weeks following the end of stratification.

Periods of dissolved oxygen supersaturation, indicating intense photosynthetic activity, occurred from mid-June to July at the surface of the main lake sites, Dam, Mid-Lake, and Quarry Island (**Figure 3.6**). Supersaturation was not observed in the Fourche Maline or Poteau River arms, most likely due to dilution from the inflows or light limitation of photosynthesis.

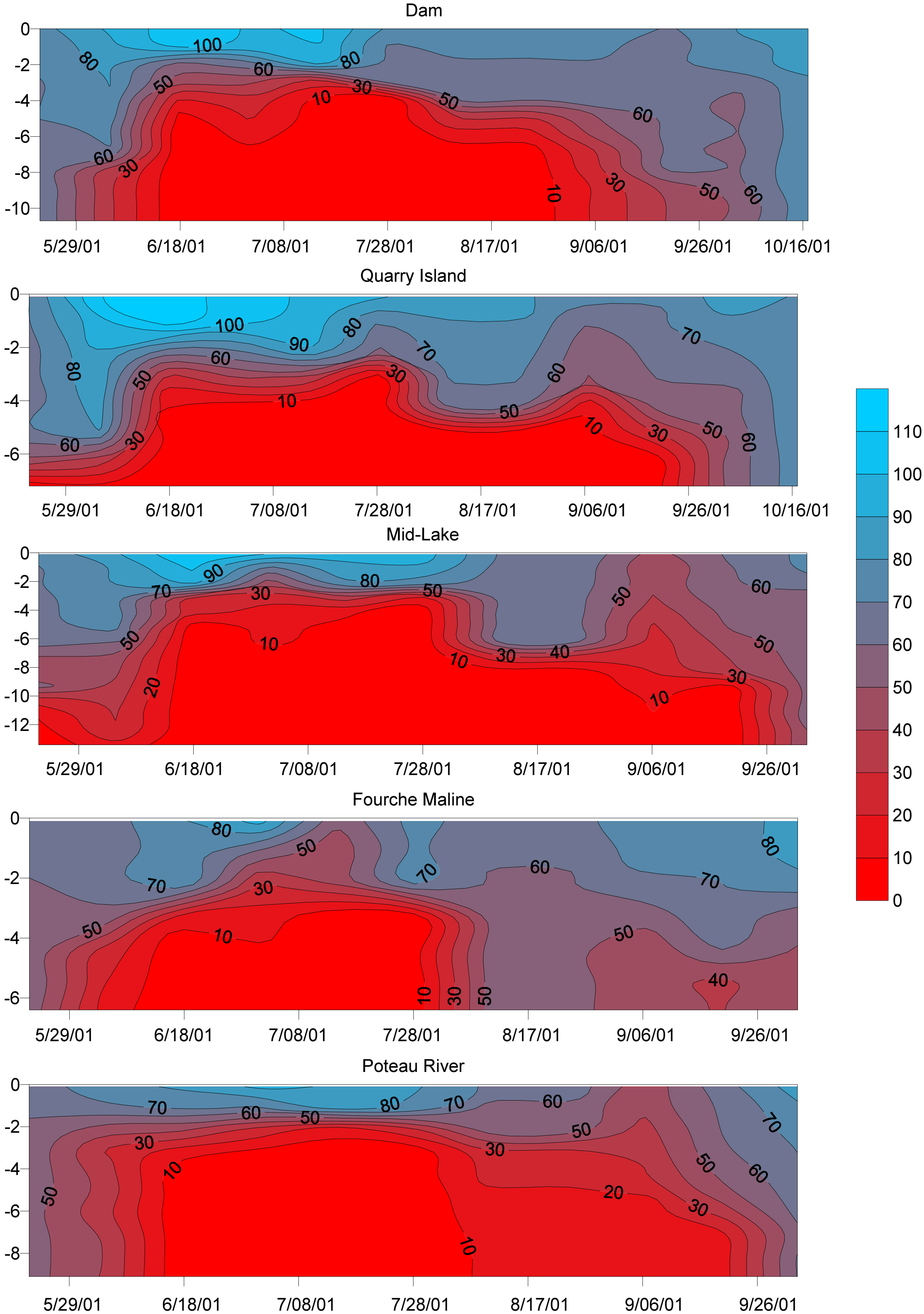

Figure 3.6: Dissolved Oxygen % Saturation profiles, May 22 – October 17, 2001.

pH

The pH of water defines the relative hydrogen ion activity of the water. Where the acid- or base-neutralizing capacity of water defines absolute acidity or alkalinity, pH only describes the relative difference between the two factors. pH values generally range from 6 to 9 in calcium carbonate-containing water (Wetzel, 1983).

The pH is influenced by the dissolved species and many chemical reactions that occur in the water. Of interest here are the reactions that occur differentially through the water column. The major reactions that affect pH are photosynthesis and respiration. Other reactions occur differentially with the presence of oxygen, and can slightly change the magnitude of pH changes. Generally, pH increases in the epilimnion where photosynthesis outweighs respiration and oxidation reactions, and pH decreases in the hypolimnion where respiration is the driving factor and is limited by reducing reactions (Wetzel, 1983; Stumm and Morgan, 1981).

All sites showed decreasing pH values from the surface to the bottom of the water column (**Figure 3.8**). The highest pH values at the surface were recorded in mid-July. This is attributable to increased photosynthesis due to an algal bloom.

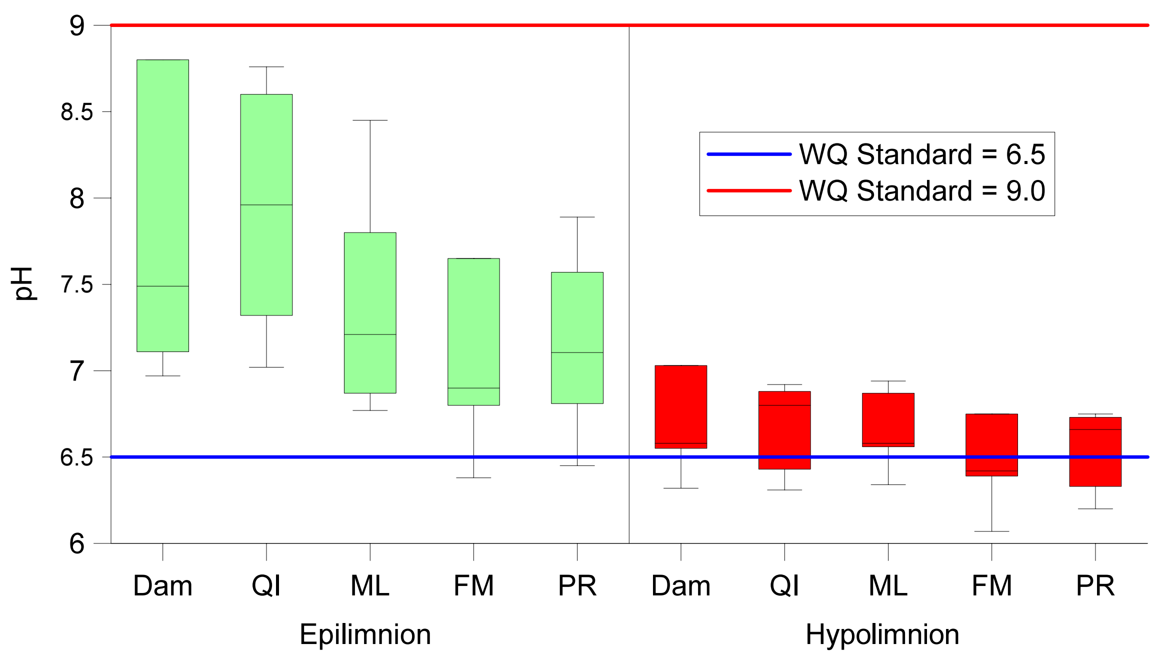

Figure 3.7: Epilimnetic and Hypolimnetic pH, May 22 – August 22, 2001.

Median pH values ranged from 6.9 to 7.96 in the epilimnion (**Figure 3.7**). The Fourche Maline arm had the lowest recorded value, with the high value reported for the Quarry Island site. Hypolimnetic pH values ranged from 6.42 to 6.8, with the low value recorded at the Fourche Maline and the high value at the Quarry Island site.

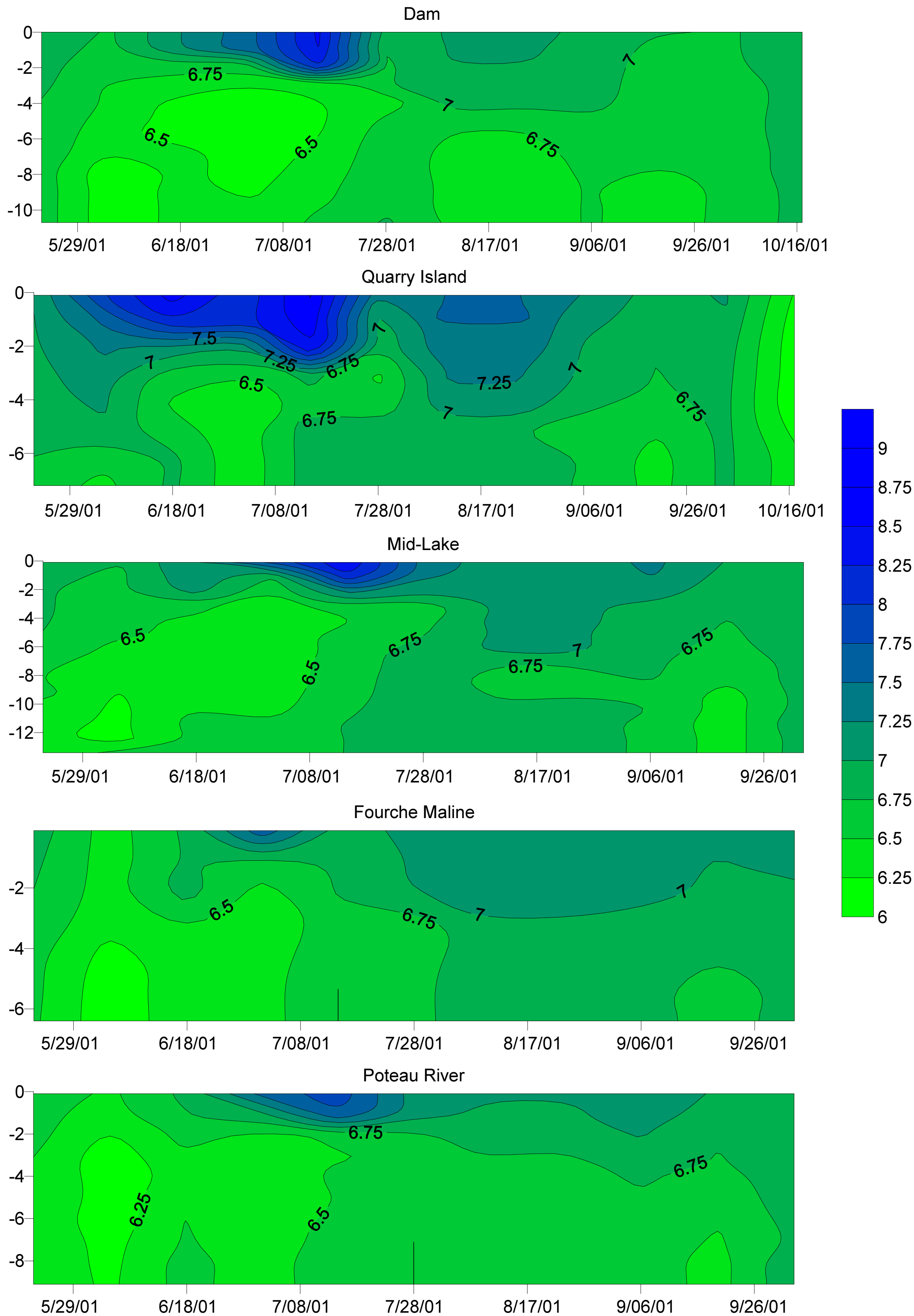

Figure 3.8: pH profiles, May 22 – October 17, 2001.

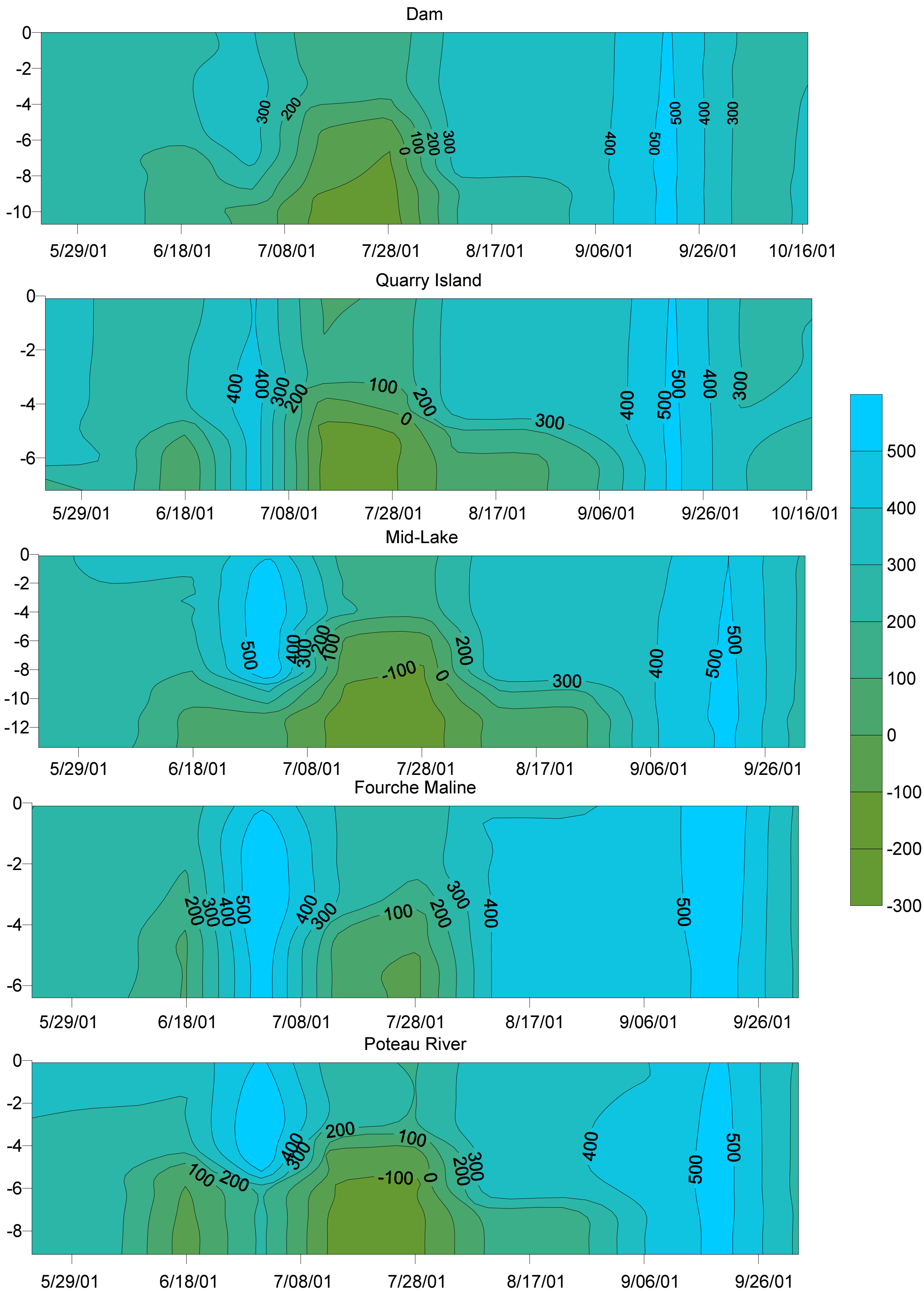

Figure 3.9: Oxidation-Reduction Potential profiles in mV, May 22 – October 17, 2001

Oxidation-Reduction Potential

Oxidation-reduction or redox potential is a measure of the oxidizing or reducing condition of a solution of water. At high values, oxidation reactions occur and at low values, reduction reactions occur. In lakes, redox potential can be regulated by photosynthesis and bacterial metabolism and is largely dependent on the presence of oxygen and other oxidants such as nitrates. Redox potential is also dependent on pH and temperature to a small degree. Redox potential decreases by around 58 mV with a decrease of 1 pH unit, and only extreme temperature fluctuations change redox potential, e.g. an increase from 0 º C to 30 º C decreases redox by 60 mV (Wetzel, 1983).

In natural waters, redox potential will have a maximum of around 300-500 mV at the fully oxygenated surface of a pH-neutral lake. The redox potential will then decrease slightly until all oxidant sources are depleted and then drop to reducing conditions (Wetzel, 1983).

Reduction reactions begin to occur at around 100-200 mV, depending on the pH of the water (Stumm and Baccini, 1978). Under reducing conditions, sediment-bound nutrients and metals become soluble and are released into the hypolimnion. When turbulence partially mixes the nutrient-rich hypolimnion with the epilimnion or the fall mixing of the lake occurs, these nutrients can stimulate the lake's primary productivity as well as elevate dissolved metals concentrations. One net effect of this is increased water treatment costs.

Redox potentials in Lake Wister closely follow dissolved oxygen patterns. Reducing conditions (below 200 mV) were recorded through most of late June to August at the bottom of the deeper sites (**Figure 3.9**). At the shallower sites or on sampling events taken when the lake was down, the redox potential was higher, but still was lowest during June and July when photosynthesis at the surface was highest, and respiration in the hypolimnion was also highest.

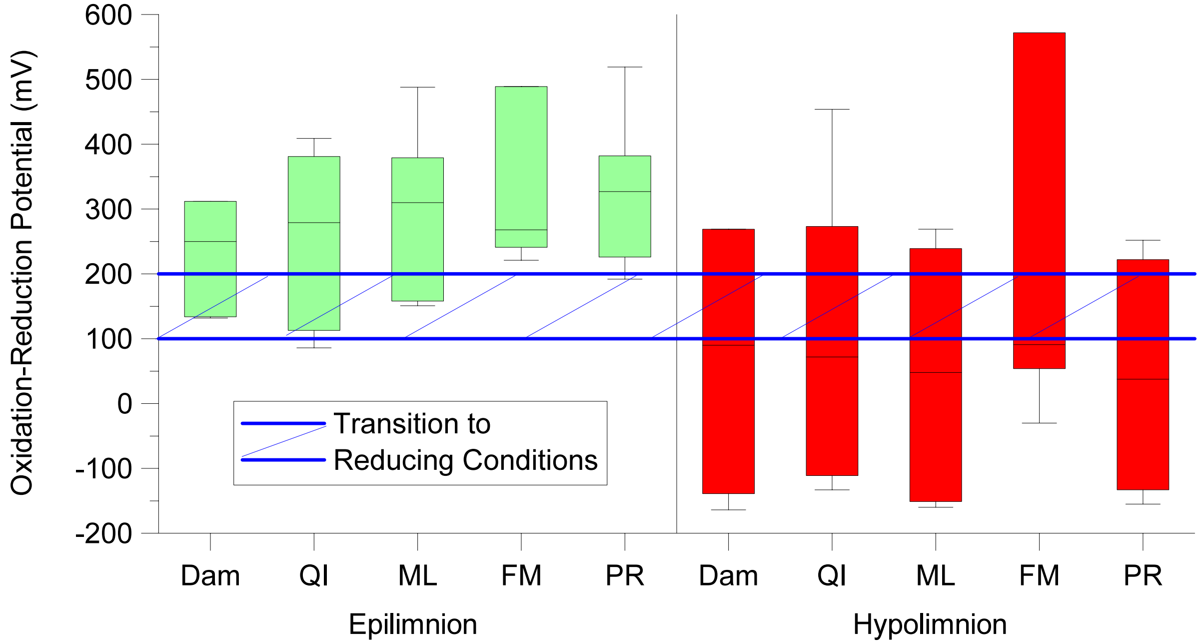

Figure 3.10: Epilimnetic and Hypolimnetic Oxidation-Reduction Potential in mV, May 22 – August 22, 2001.

Median epilimnetic redox potentials ranged from 250 to 327 mV (**Figure 3.10**). Median hypolimnetic redox potentials ranged from 38 to 91 mV, indicating reducing conditions. Reducing conditions (below 200 mV) were also measured at the surface at all sites except the Fourche Maline site during July. The low readings near the surface in July could have been due to the crash of an algal bloom. The lowest surface redox values coincide with the highest measured pheophytin-a (degraded chlorophyll-a or dead algae) compared to chlorophyll-a (actively photosynthesizing algae). Stratification was also the strongest at this period. The most likely explanation for these measurements is a die-off from an epilimnetic algae bloom.

Alkalinity and Hardness

Total alkalinity, a measure of water's total concentration of negatively charged ions, can also be thought of as the waterbody's acid neutralizing capacity. Alkalinity is usually attributed to carbonate species, but other anions such as sulfates and chlorides sometimes are major contributors also, especially in lower pH systems such as Lake Wister. The contribution of chlorides to pH is not known in Lake Wister as chlorides were not a parameter analyzed. Measurement of pH compares the relative amounts of cations to anions, but alkalinity gives a quantitative measure (Wetzel, 1983). Alkalinity also can be an indicator of high photosynthetic rate, as the net result of photosynthesis is to raise alkalinity through uptake of dissolved carbonates, nutrients, and protons (Morel and Hering, 1993).

The profile at the Dam site (**Figure 3.11**) indicates an increase in alkalinity around July – August. The other sites showed similar results, with their maximum values recorded in July – August, except for the Fourche Maline site, which had its maximum in May.

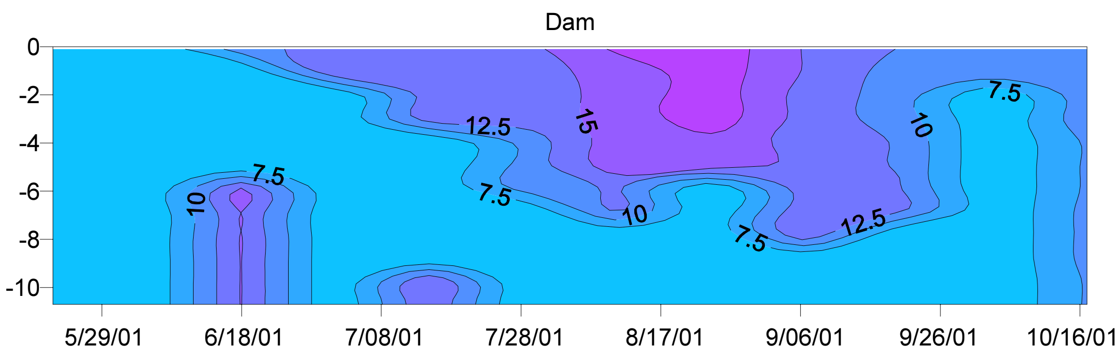

Figure 3.11: Total Alkalinity profile in mg/L at Dam site, May 22 – October 17, 2001.

Median alkalinity values ranged from 5 to 14 mg/L in the epilimnion and 5 to 12 mg/L in the hypolimnion (**Figure 3.12**), with maximum values seen at the Quarry Island site for both the epilimnion and hypolimnion. Wister has a low alkalinity and is not well buffered against pH fluctuations caused by minor changes in water chemistry. Alkalinity values and their timing are consistent with increased photosynthesis in the summer and nutrient releases in the anoxic hypolimnion, as noted by the supersaturation of oxygen in **Figure 3.6**.

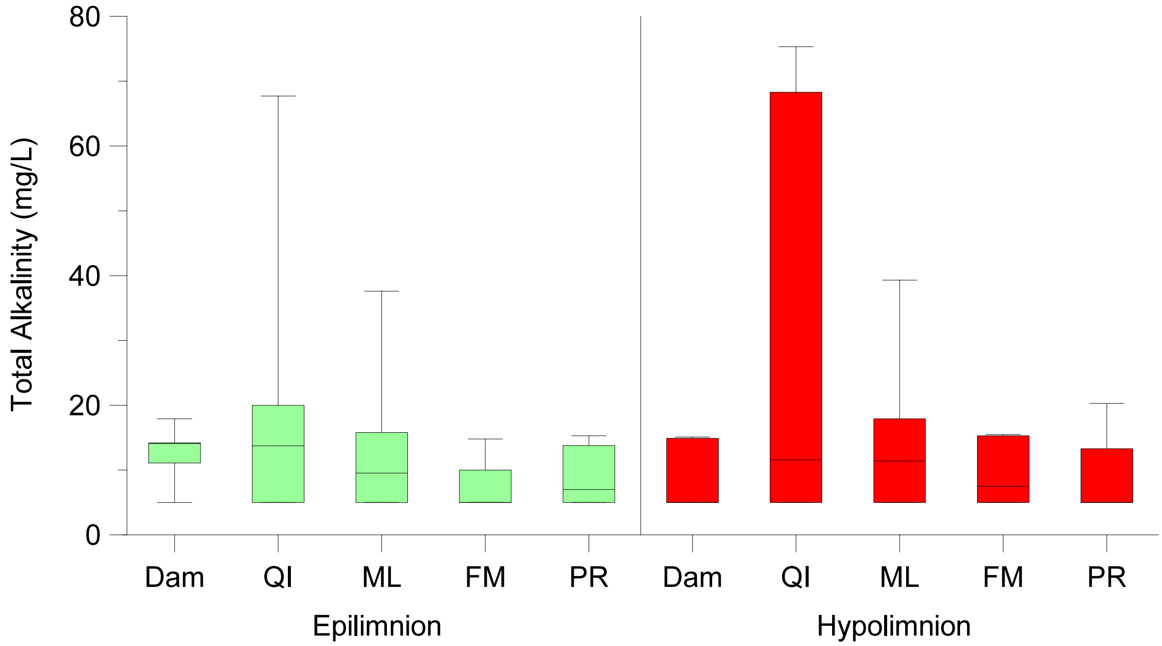

Figure 3.12: Epilimnetic and Hypolimnetic Total Alkalinity in mg/L, May 22 – August 22, 2001.

Total hardness is a measure of the water's concentration of positively charged ions and is mostly made up of calcium and magnesium, although a few metals such as iron can also make a major contribution to hardness in lower pH systems such as Wister. Hardness is a measure of the mineral content of water and is mainly used to assess the quality of a water supply as a drinking water source (Wetzel, 1983). Changes in hardness reflect change in dissolved water constituents due to water chemistry changes. Decreased hardness values in the epilimnion can be due to loss of calcium through a rapid increase in photosynthesis or precipitation of dissolved metals (Wetzel, 1983).

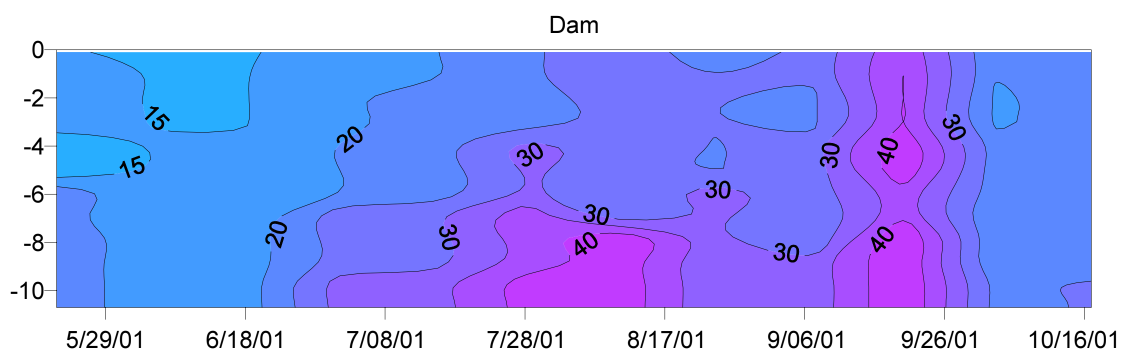

Figure 3.13: Total Hardness profile in mg/L at Dam site, May 22 – October 17, 2001.

The hardness profile at the Dam site (**Figure 3.13**) indicates an increase while the water column is stratified in the hypolimnetic water. All the other sites show the same results; while stratified, the hypolimnion has a higher hardness value than the epilimnion. A low hardness concentration was observed at the Dam site in June, when presumably the rate of photosynthesis was high. The other sites also had their lowest hardness values in June.

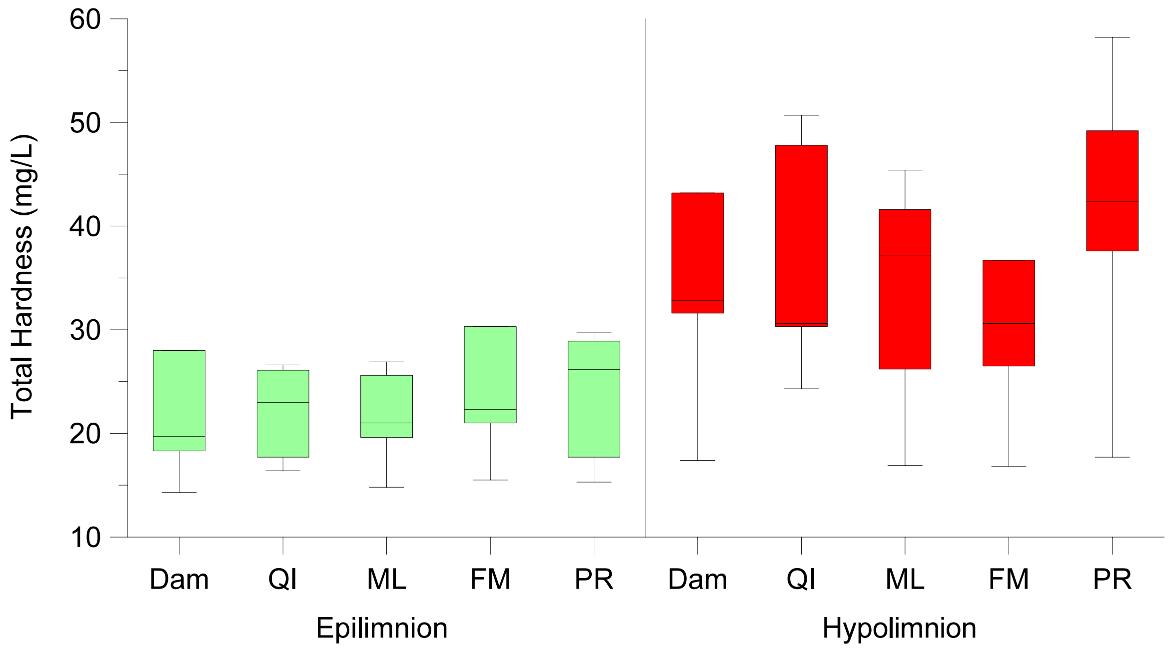

Figure 3.14: Epilimnetic and Hypolimnetic Total Hardness in mg/L, May 22 – August 22, 2001.

Median hardness values (**Figure 3.14**) ranged from 19 to 26 mg/L in the epilimnion, with very little difference in ranges or values between sites. In the hypolimnion, medians ranged from 30 to 42 mg/L. Lake Wister has very low hardness and is classified as a soft water lake (Sawyer and McCarty, 1978).

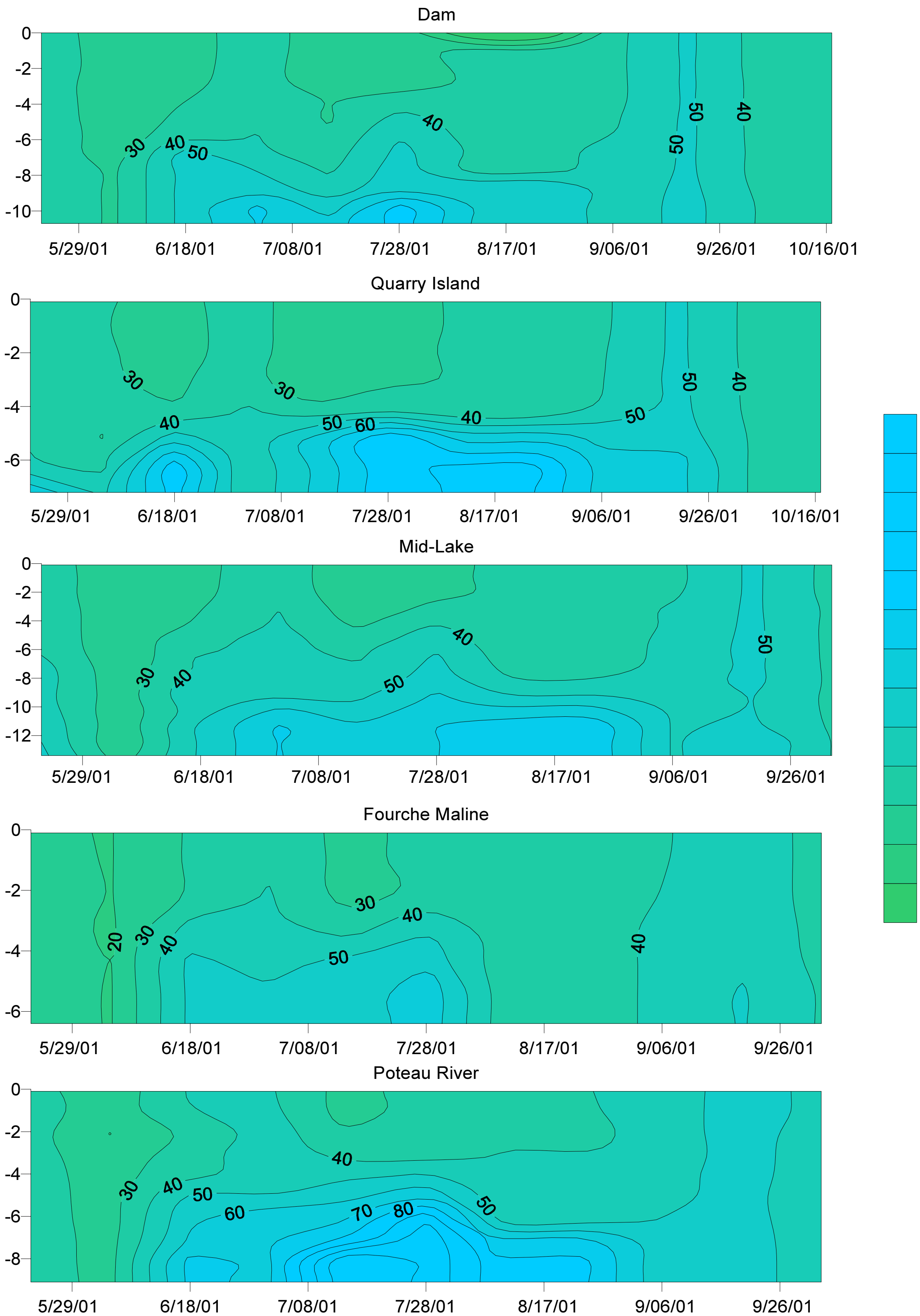

Figure 3.15: Specific Conductance profiles in μS/cm, May 22 – October 17, 2001.

Conductivity

The specific conductance of a solution is a measure of its ability to conduct an electric current or its resistance to electron flow. Resistance to current flow decreases with increasing ionic content (Wetzel, 1983). Just as a lake can stratify thermally, it can also exhibit chemical stratification. Chemical stratification might occur when parcels of water with different chemical compositions meet or when parcels of water are partitioned from each other under different physical conditions, causing their ionic components to change. This might or might not coincide with thermal stratification, depending on the source (Wetzel, 1983). In the case of Wister, any chemical stratification would most likely be due to bacterial decomposition of organic matter and desorption of sediment-bound ions in the anoxic hypolimnion.

All sites exhibited some chemical stratification extending from June to September (**Figure 3.15**). Chemical stratification coincided fairly well with thermal stratification and was seen because of the lack of mixing and directly followed hypolimnetic dissolved oxygen patterns.

Specific conductivity ranged from 26-37 µS/cm in the epilimnion and 52-77 µS/cm in the hypolimnion (**Figure 3.16**). Both epilimnetic and hypolimnetic conductivities were highest at the Poteau River site.

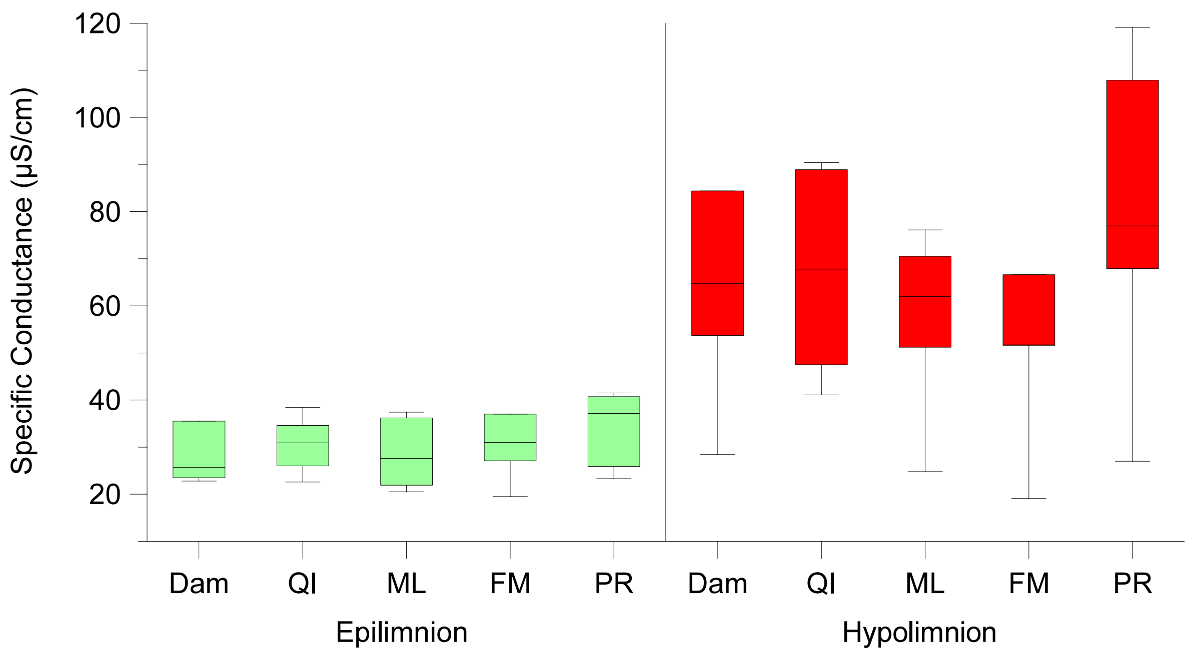

Figure 3.16: Epilimnetic and Hypolimnetic Specific Conductance in µS/cm, May 22 – August 22, 2001.

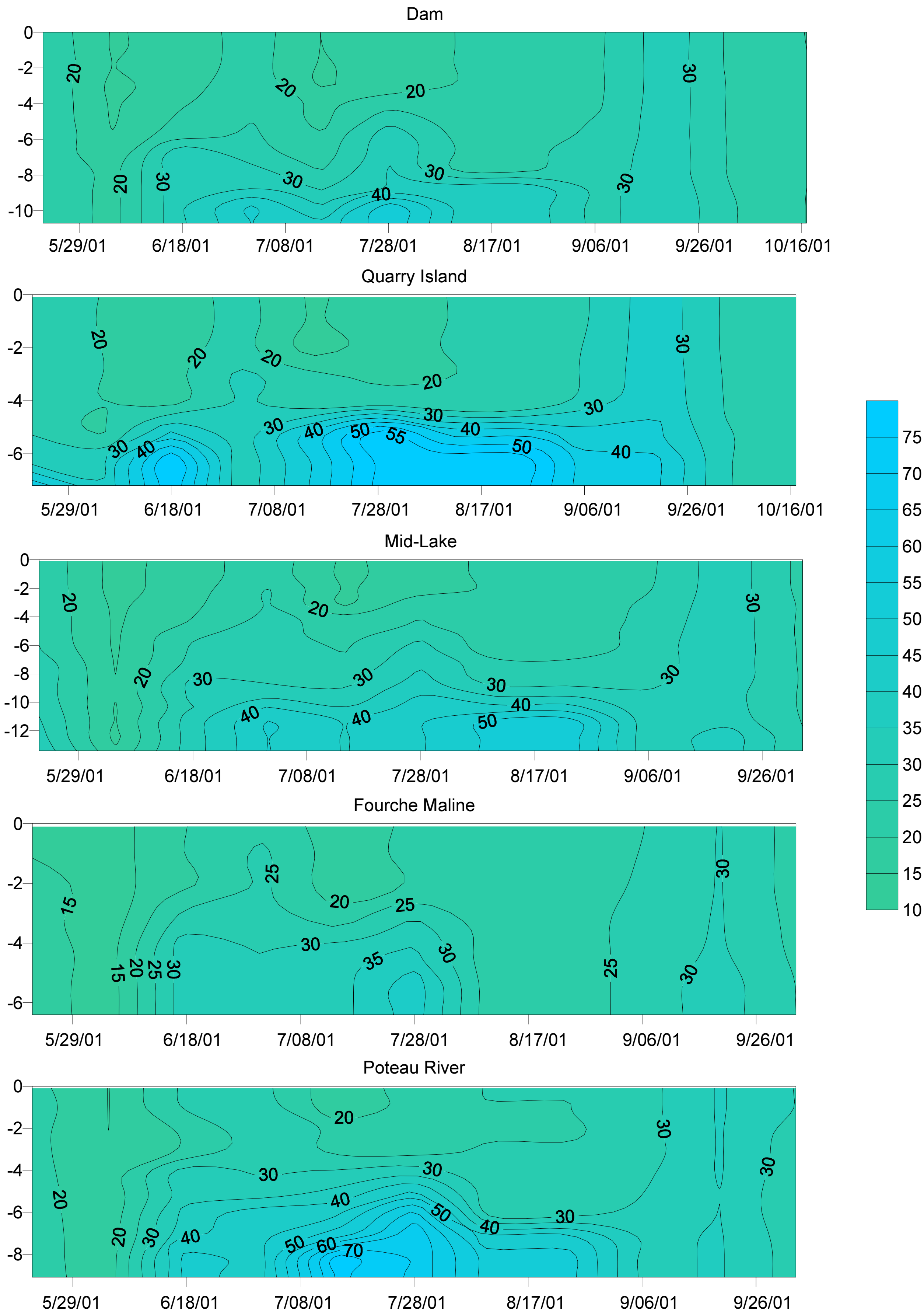

Figure 3.17: Total Dissolved Solids profile in mg/L, May 22 – October 17, 2001.

Total Solids

Total dissolved solids (**Figure 3.17**, **Figure 3.18**) are directly related to conductivity measures and mirrored that seen for conductivity (**Figure 3.15**, **Figure 3.16**). Like conductivity, higher total dissolved solids concentrations were measured at the bottom of the lake from June to September. Median values ranged from 16-24 mg/L at the surface, and 33-49 mg/L at the bottom, with both of the high values reported for the Poteau River site.

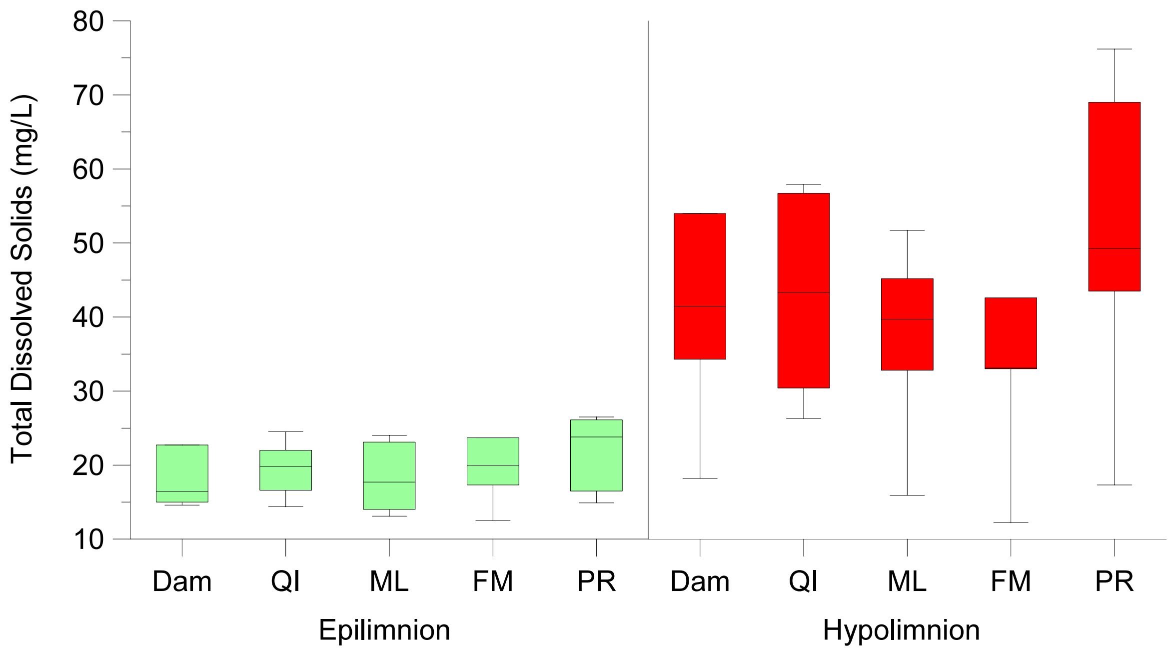

Figure 3.18: Epilimnetic and Hypolimnetic Total Dissolved Solids in mg/L, May 22 – August 22, 2001.

Total settleable solids were rarely measured above the detection level and are not displayed here. Median values for total suspended solids (**Figure 3.19**) in the epilimnion ranged from 6 to 36 mg/L and were highest at the Fourche Maline and Poteau River sites. In the hypolimnetic samples, median values ranged from 39 to 137 mg/L. Use of this data is limited, because of the low sample size from May to October.

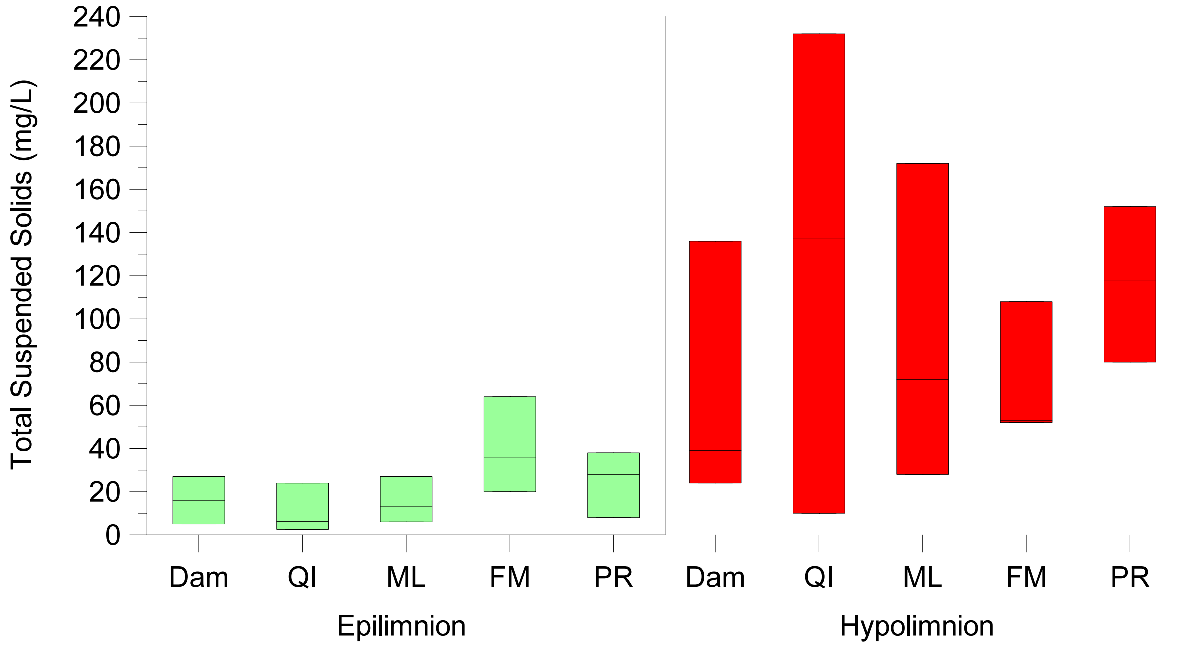

Figure 3.19: Epilimnetic and Hypolimnetic Total Suspended Solids in mg/L, May 22 – August 22, 2001.

Turbidity and Secchi Depth

General water clarity measures indicate the amount of debris in the water column that limits the passage of light. Here two separate measures are used: Secchi disk depth, a direct field measure of transparency, and turbidity, a laboratory measure of light scattering. In Lake Wister, Secchi disk depth and turbidity measurements were taken at the surface. Secchi disk depths (**Figure 3.20**) ranged from 17 to 35 cm. The lowest median value was recorded at the Fourche Maline, and the Poteau River site also had a lower median value and range than the other three sites.

Turbidity measurements (**Figure 3.21**) ranged from 22 to 65 NTU, with the two highest median values reported for the Fourche Maline (65 NTU) and Poteau River (33 NTU) and the highest maximum values at the Fourche Maline (185 NTU) and Poteau River (95 NTU). Comparing turbidity values to the water quality standard, only at the Quarry Island site did the median turbidity fall below 25 NTU.

The Fourche Maline site had by far the highest turbidity and lowest Secchi disk depth. For turbidity, 75% of the data range for Fourche Maline site was above that at all the other sites. For Secchi depth, greater than 50% of the data range was below that for all the other sites.

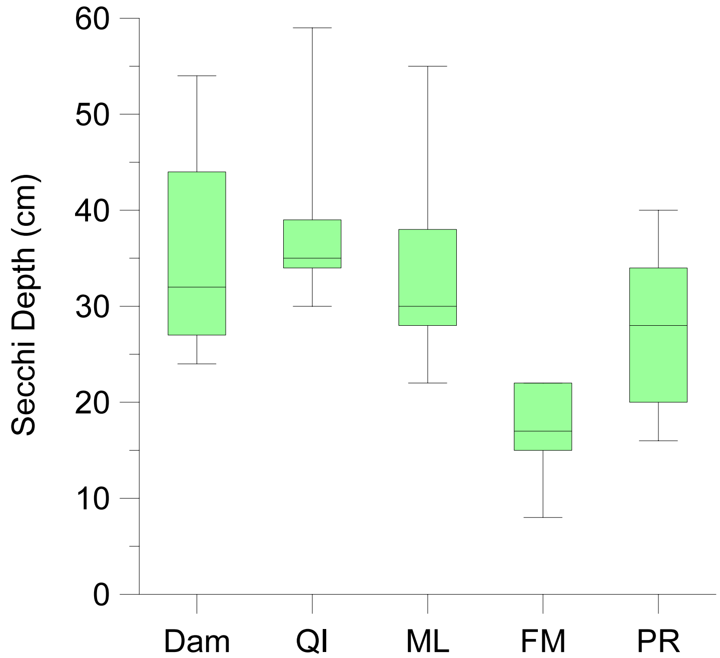

Figure 3.20: Secchi Disk Depth in cm, May 22 – October 17, 2001.

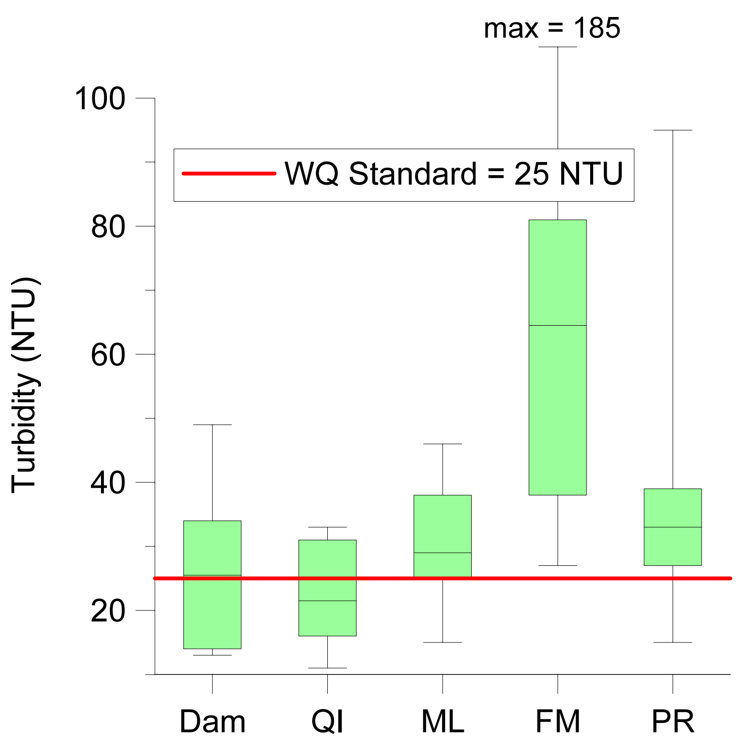

Figure 3.21: Surface Turbidity in NTU, May 22 – October 17, 2001.

Comparison of whole-lake median Secchi depth and turbidity to inflow rates (**Figure 3.22**) indicates dependence of water clarity on stormwater runoff. Each spike of the inflow line on the graph represents a rainfall event that enters the lake and causes turbidity to increase and Secchi depth to decrease. At times when the lake received no inflow, such as the month of July, Secchi depths and turbidity were more dependent on the maximum wind speed on the lake (**Figure 3.23**).

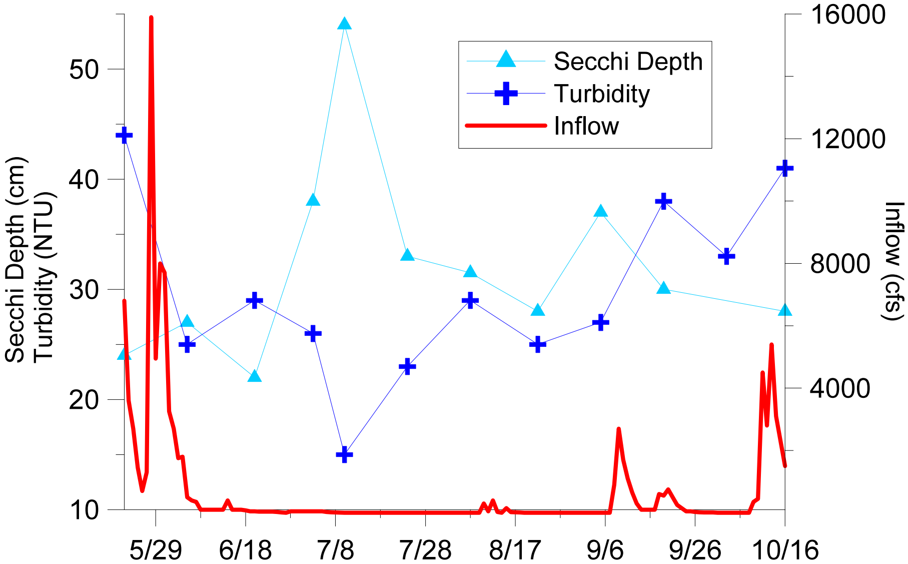

Figure 3.22: Secchi Disk Depth and Turbidity (whole-lake median) compared to Inflow from tributaries in cfs, May 22 – October 17, 2001, (Inflow data from USACE).

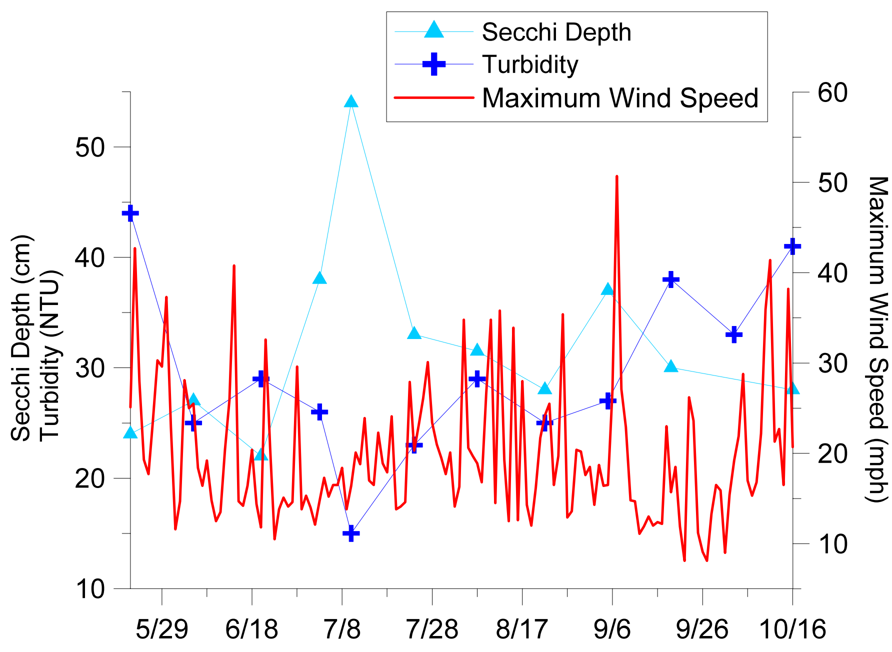

Figure 3.23: Secchi Disk Depth and Turbidity (whole-lake median) compared to maximum wind speed in mph, May 22 – October 17, 2001, (Wind data from OCS, 2002a).

It seems that during periods of calm (low wind speed and little inflow) water clarity increases. The increase would primarily be through increased settling or sedimentation in the lake itself. The apparent increase of water clarity in August suggests in-lake dynamics contribute toward the excessive turbidity in Wister Lake. Although it is possible to pint to one primary contributor to the excessive turbidity in particular intervals, it is clear that both internal and external forces contribute significantly to the present condition.

Chemical Properties

Iron and Manganese

Metals are mostly present in the water column in a solid form, either as part of the substrate or as metal oxides or hydroxides or other complexes likely to precipitate out of the water column. In surface water with a pH range of 5-8, typical total iron concentrations range from 0.05 to 0.2 mg/L and the average concentration of manganese is 0.035 mg/L (Wetzel, 1983). At the surface, you expect to see almost no dissolved metals. In hypolimnetic water, decreased pH and redox potential make it possible for insoluble metal compounds and complexes in the water and bottom sediments to dissolve back into the water column.

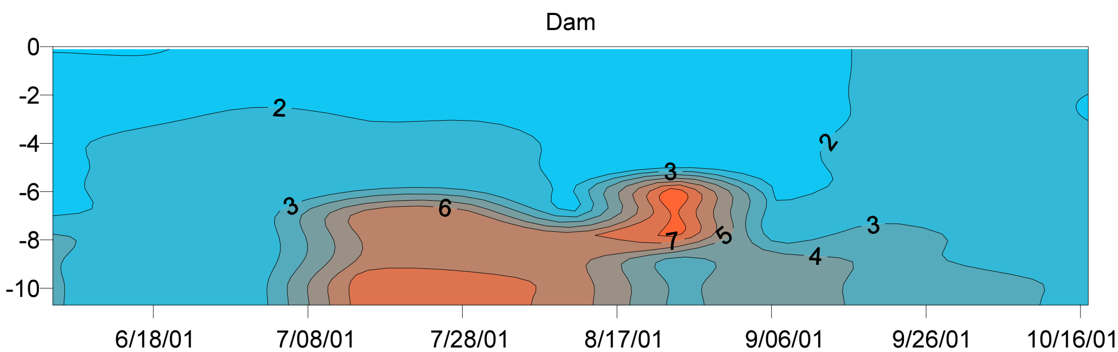

Figure 3.24: Total Iron profile in mg/L at Dam site, June 5 – October 17, 2001.

At the Dam site (**Figure 3.24)**, total iron concentrations were lowest in the epilimnion and when the lake was not stratified. During July – August bottom concentrations increased either due to increased solubilization of iron or resuspension of the bottom sediments. The contours closely follow the redox potential and oxygen content (an inverse relationship), so it is likely due to increased concentrations of dissolved iron.

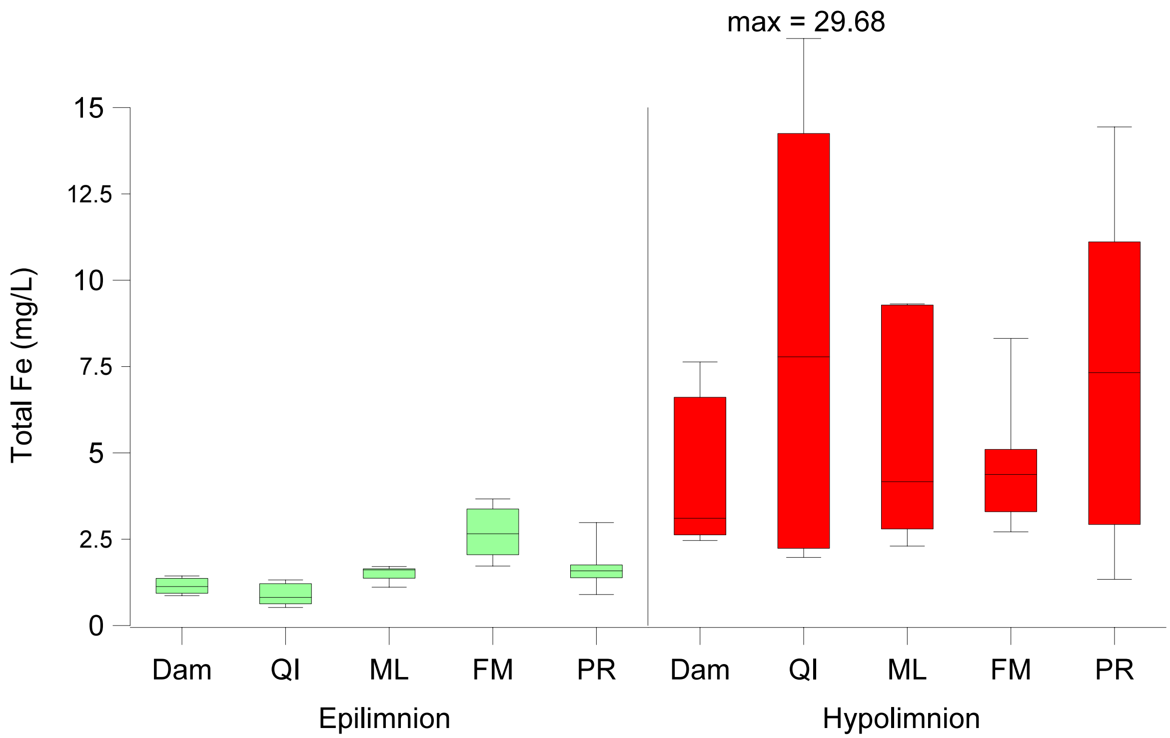

Figure 3.25: Epilimnetic and Hypolimnetic Total Iron concentrations in mg/L, June 5 – August 22, 2001.

Median epilimnetic iron concentrations ranged from 0.8 to 2.7 mg/L, with the highest value recorded at the Fourche Maline site (**Figure 3.25**). Median hypolimnetic iron concentrations ranged from 3.1 to 7.8 mg/L. Higher hypolimnetic concentrations are consistent with resuspension of sediment from the bottom and solubilization of iron from the sediments.

Manganese concentrations followed the same trends as iron concentrations with the manganese profile also following redox potential and dissolved oxygen (**Figure 3.26**).

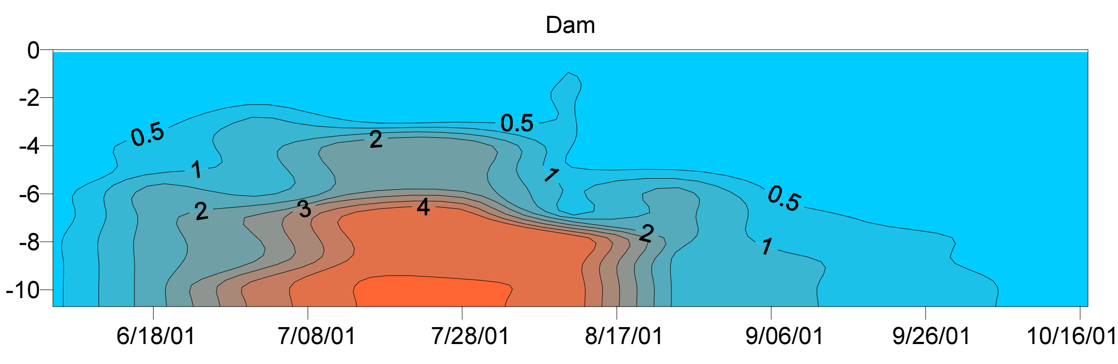

Figure 3.26: Total Manganese profile in mg/L at Dam site, June 5 – October 17, 2001.

Median epilimnetic values ranged from 0.16 to 0.50 mg/L, and hypolimnetic values ranged from 1.8 to 4.0 mg/L (**Figure 3.27**). The high epilimnetic value was at the Fourche Maline site, and the deeper sites—Quarry Island, Mid-Lake, and the Dam—had the highest hypolimnetic values.

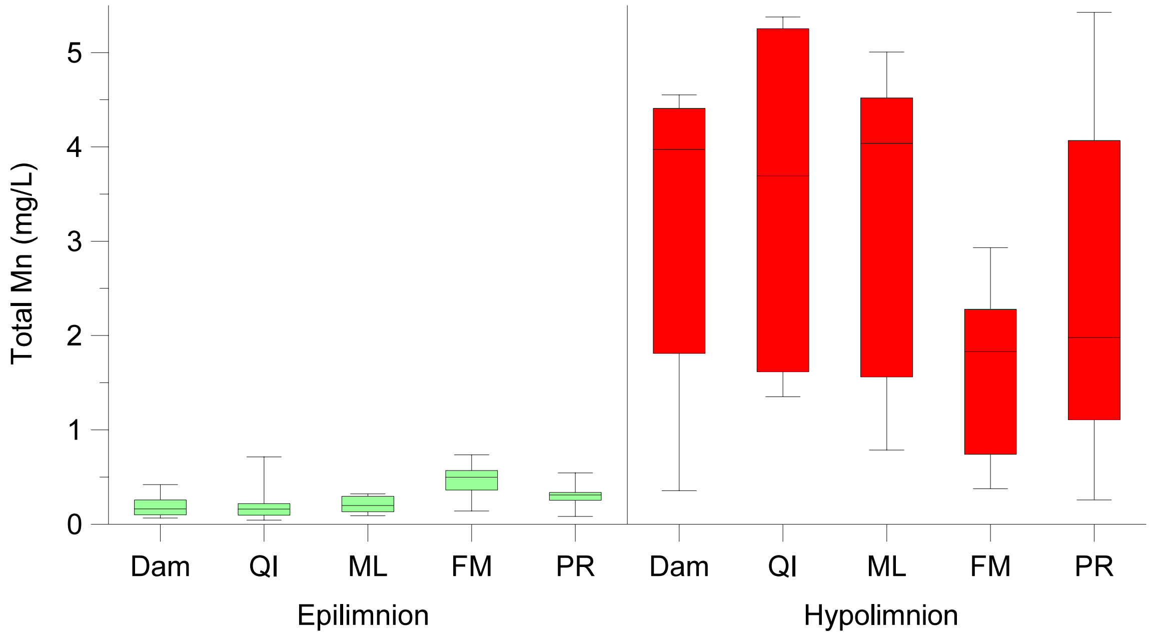

Figure 3.27: Epilimnetic and Hypolimnetic Total Manganese concentrations in mg/L, June 5 – August 22, 2001.

Both iron and manganese were present at the surface at much higher concentrations than expected in a typical lake, probably due to Wister's high turbidity levels.

Sulfate

The predominant form of sulfur in the oxygenated water column is sulfate. In anoxic hypolimnetic water, redox chemistry determines the forms of abiotic sulfur. A small amount of sulfate is released from the sediments, which in eutrophic systems can yield elevated levels of sulfate in the hypolimnion. This usually only occurs briefly at the onset of summer stratification, after which the sulfate is reduced to hydrogen sulfide (Wetzel, 1983). In very low redox conditions (< 100 mV or less, depending on pH), most of the sulfur should be present as hydrogen sulfide, mediated by bacterial decomposition. Sulfate reduction is typically one of the last reduction reactions to occur as redox potential decreases. After depletion of oxygen, denitrification reactions typically follow with nitrate reduction followed by nitrite reduction. Reduction of manganese oxides occurs at about the same redox potential as nitrate reduction, followed by reduction of iron oxides. When the redox potential is low enough, fermentation and sulfate reduction occur at about the same time. This progression of reactions is seen if the redox potential is low enough in the vertical profile of a eutrophic lake and over time if the system remains closed (Stumm and Morgan, 1981). Such is the case with Wister Lake.

At the Dam site (**Figure 3.28**), sulfate concentrations were higher in the hypolimnion than at the surface throughout the anoxic period. This was most likely due to increased sediment release of sulfates due to reducing conditions. Here redox potential was high enough that nitrites were still detected in the bottom samples and therefore sulfate reduction was not occurring. The hypolimnetic sulfate low in the first few weeks of July corresponds with extremely low redox potential. This suggests that sulfate was reduced to sulfide during this time.

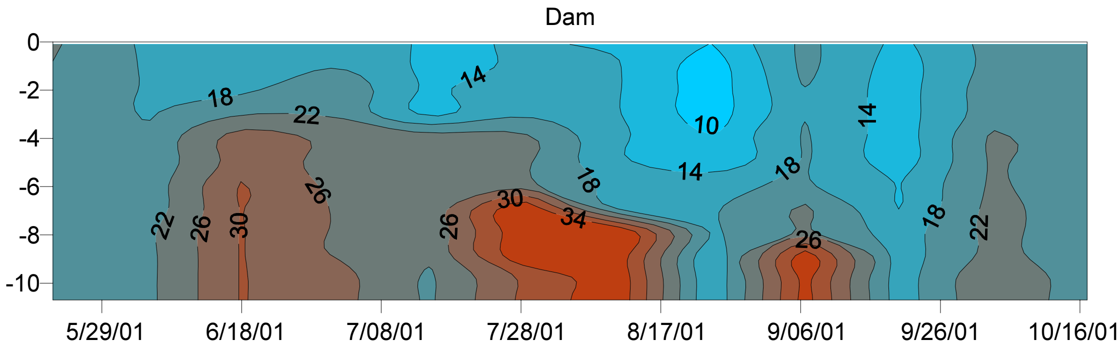

Figure 3.28: Sulfate profile in mg/L at Dam site, May 22 – October 17, 2001.

Median epilimnetic sulfate concentrations ranged from 14 to 26 mg/L, with the high value reported at the Fourche Maline site (**Figure 3.29**). These values were within the typical range of 5 to 30 mg/L of sulfate reported for oxygenated surface water, though Wister had higher than the average typical value of 11 mg/L (Wetzel, 1983). Median hypolimnetic concentrations ranged from 26 to 41 mg/L, with the high value reported at the Quarry Island site. At all sites except the Fourche Maline, a greater concentration of sulfate was measured in the hypolimnion than the epilimnion.

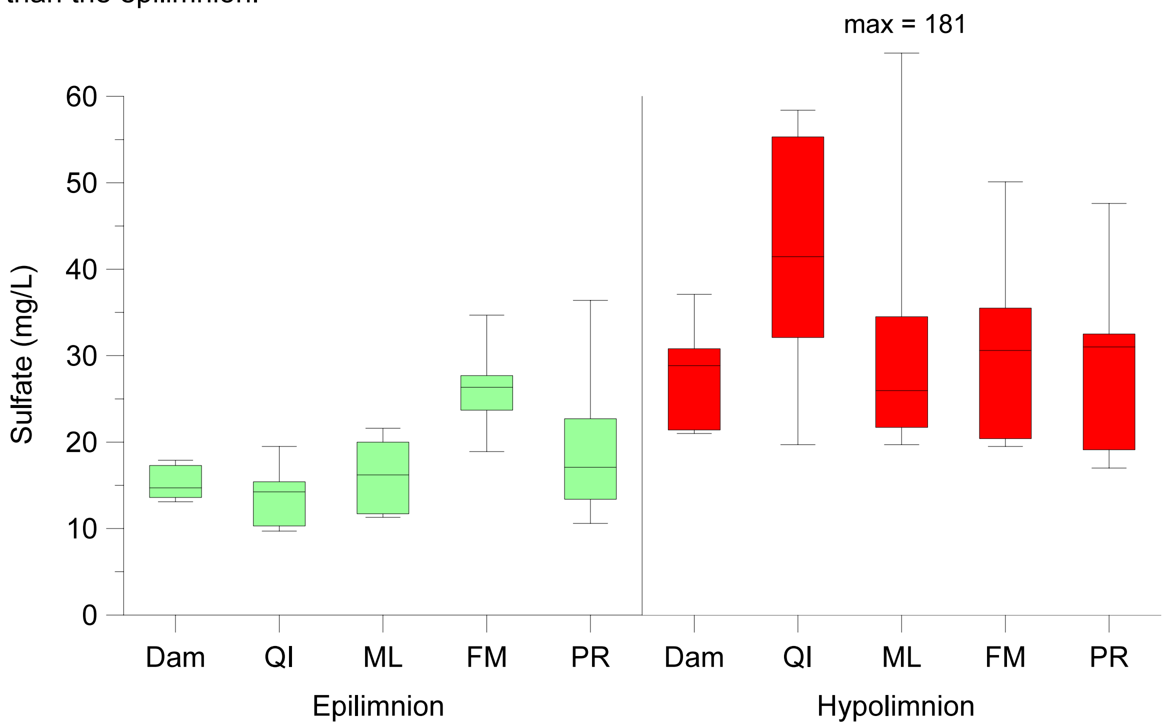

Figure 3.29: Epilimnetic and Hypolimnetic Sulfate concentrations in mg/L, May 22 – August 22, 2001.

Nitrogen

Nitrogen enters a lake through atmospheric deposition, nitrogen fixation and as dissolved organic and inorganic components and organic matter in the influent streams. Atmospheric deposition is generally assumed to be minor when no major industrial source is nearby. Nitrogen fixation, which is carried out mainly by blue-green algae and some bacteria, is light dependent and occurs when algal growth is nitrogen-limited. Nitrogen fixation involves the fixation of dissolved atmospheric N_2 into a dissolved inorganic form, which can then be assimilated by phytoplankton. In an agricultural watershed, the majority of nitrogen in the lake will likely come from the influent streams, which receive runoff from the watershed (Wetzel, 1983). Nitrogen in the lake is measured as organic nitrogen or as dissolved inorganic species, the predominant forms of which are ammonia, nitrate, and nitrite. In agriculturally impacted systems, nitrate is normally found in the highest concentration.

Nitrogen is released as ammonia as a metabolic waste product, through decomposition of organic matter, and sediment release of inorganic nitrogen occurs as ammonia. When oxygen is present, bacterial nitrification will convert ammonia to nitrite and nitrate. Ammonia is also lost in the photic zone of the epilimnion through assimilation by algae and macrophytes. Plants only uptake nitrogen as ammonia; nitrate and nitrite have to be reduced to ammonia before they can be utilized. Because of bacterial nitrification and plant uptake occurring in the epilimnion, ammonia is expected to be measured in the epilimnion at very small concentrations if at all (Wetzel, 1983).

In the hypolimnion, ammonia has three sources. Under anoxic conditions, the adsorptive capacity of the sediments decreases, releasing ammonia from the sediments. Ammonia is also released through bacterial decomposition of organic matter when the redox potential is low enough. Ammonia is also produced through reduction of nitrate. While the lake is mixing and the water column is oxygenated, ammonia concentrations are expected to decrease to epilimnetic levels (Wetzel, 1983).

At the Dam site (**Figure 3.30**), surface ammonia concentrations and concentrations when the lake was mixing were measured at about 0.1 mg/L or less. The ammonia concentration increased in the hypolimnion and was highest around July to August at up to 0.5 to 0.9 mg/L, which corresponds with the lower redox potentials measured in July to August.

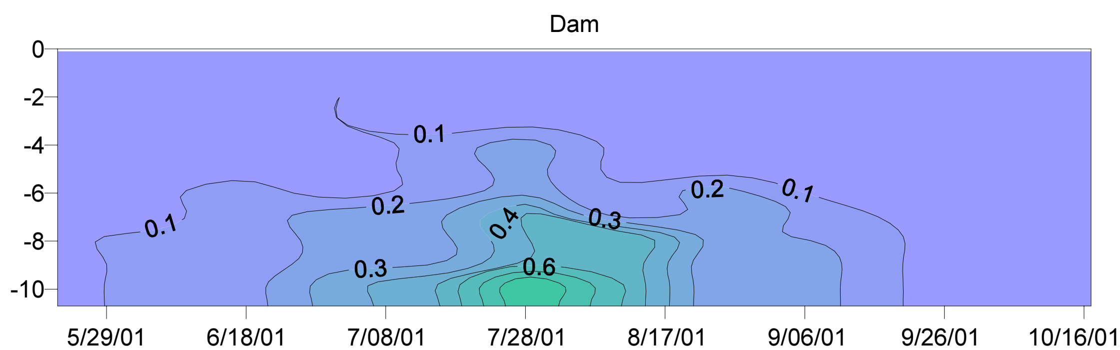

Figure 3.30: Ammonia profile in mg/L at Dam site, May 22 – October 17, 2001.

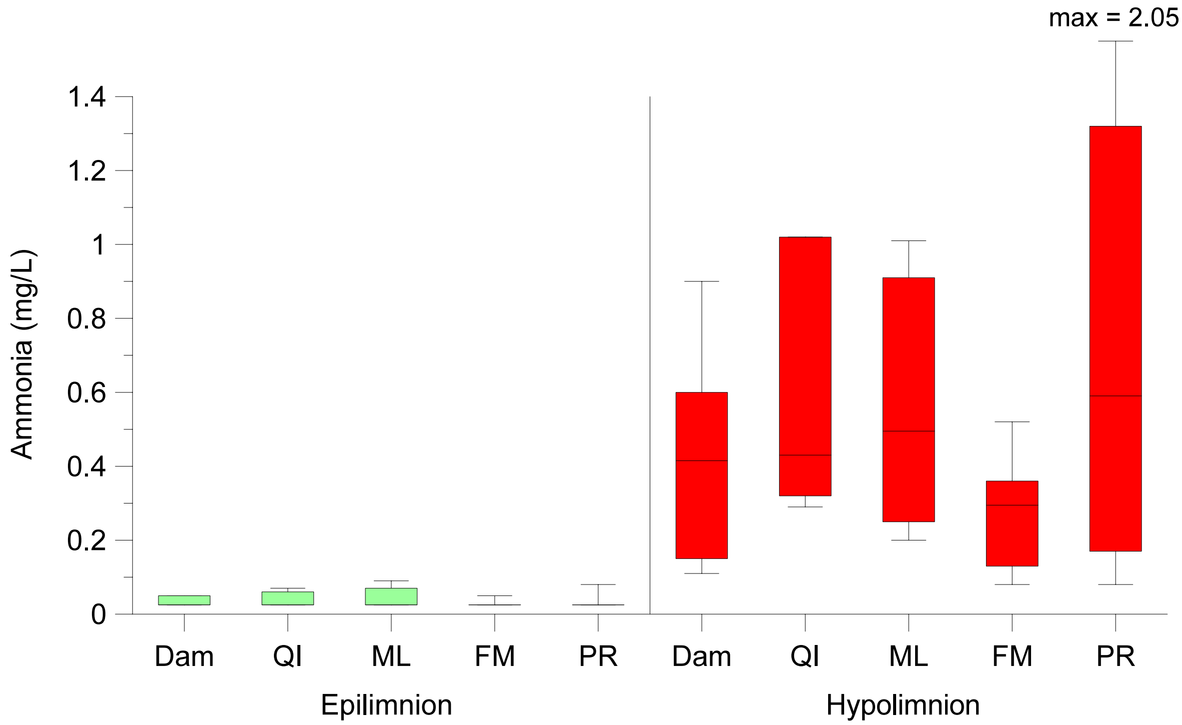

Figure 3.31: Epilimnetic and Hypolimnetic Ammonia concentrations in mg/L, May 22 – August 22, 2001.

Median epilimnetic ammonia concentrations were all below the method detection limit of 0.05 mg/L. When measured above detection limit, maximum concentrations were below 0.1 mg/L. Median hypolimnetic ammonia concentrations ranged from 0.30 mg/L at the Fourche Maline site to 0.60 mg/L at the Poteau River site (**Figure 3.31**). The minimum at the Fourche Maline site reflects the shallower site depth, ranging from around 3 to 6 m during stratification.

Inorganic nitrogen in the epilimnion should be measured as nitrate or nitrite due to bacterial nitrification of ammonia in oxygenated water. Nitrate is usually the major inorganic nitrogen constituent in the epilimnion since nitrite is only an intermediate product of nitrification. Plant uptake might change the relative amounts of nitrate and nitrite because nitrate is utilized before nitrite for plant growth (Wetzel, 1983). In the hypolimnion, concentrations of nitrate and nitrite generally decrease as denitrification to atmospheric N_2 and reduction of nitrate to ammonia occur (Stumm and Morgan, 1981). In some cases, the concentration of nitrite increases in the hypolimnion under reducing conditions and when the amount of organic matter is high (Wetzel, 1983).

Epilimnetic nitrite concentrations at the Dam site (**Figure 3.32**) were low but measurable at less than 0.1 mg/L while the lake was stratified. In July – August hypolimnetic nitrite concentrations increased up to slightly above 0.1 mg/L. The higher concentrations correspond to the lower redox potentials measured in July to August.

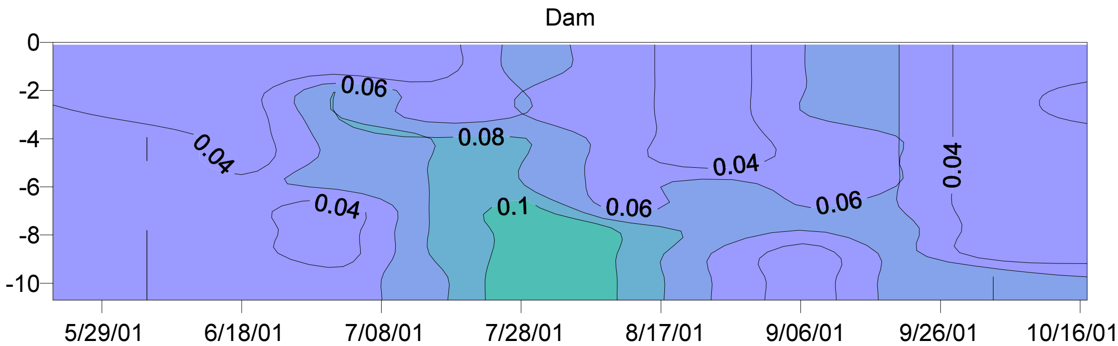

Figure 3.32: Nitrite profile in mg/L at Dam site, May 22 – October 17, 2001.

Median epilimnetic nitrite concentrations (**Figure 3.33**) were at or below detection the detection limit of 0.05 mg/L, except at the Fourche Maline and Poteau River sites, where the median concentrations were around 0.05 mg/L. In the hypolimnion, median concentrations ranged from 0.07 to 0.11 mg/L. At the Dam site, nitrate concentrations were not measured at or above the detection limit of 0.05 mg/L in the epilimnion or hypolimnion until after stratification ended in September. The detection of nitrite and nominal number of nitrate detections indicate active uptake and utilization of nitrates.

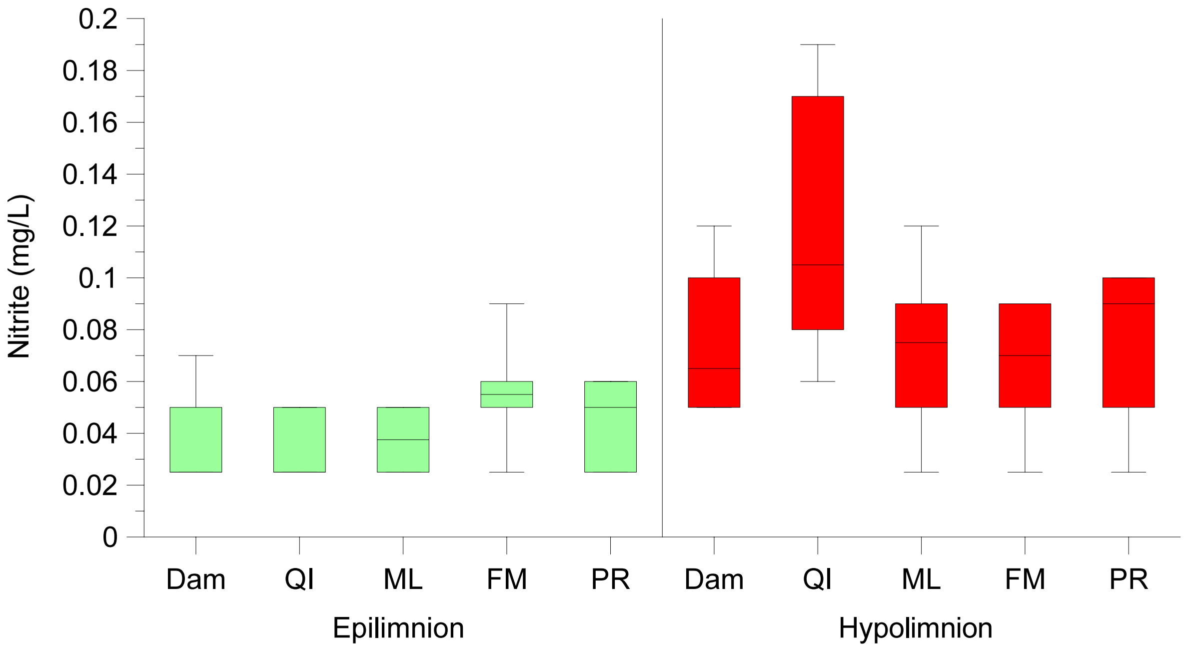

Figure 3.33: Epilimnetic and Hypolimnetic Nitrite concentrations in mg/L, May 22 – August 22, 2001.

Total Kjeldahl nitrogen includes ammonia and organic nitrogen. Organic nitrogen in the water is mostly a product of photosynthesis, and to a lesser extent comes from animal excretion and bacterial decomposition of organic matter. Organic nitrogen generally accounts for about 50% of the total dissolved nitrogen for a lake and does not always show a strong vertical gradient.

This results from nitrogenous compounds being released both in the photic zone due to photosynthesis and in the hypolimnion due to bacterial metabolism and desorption of sediment-bound nitrogenous compounds (Wetzel, 1983).

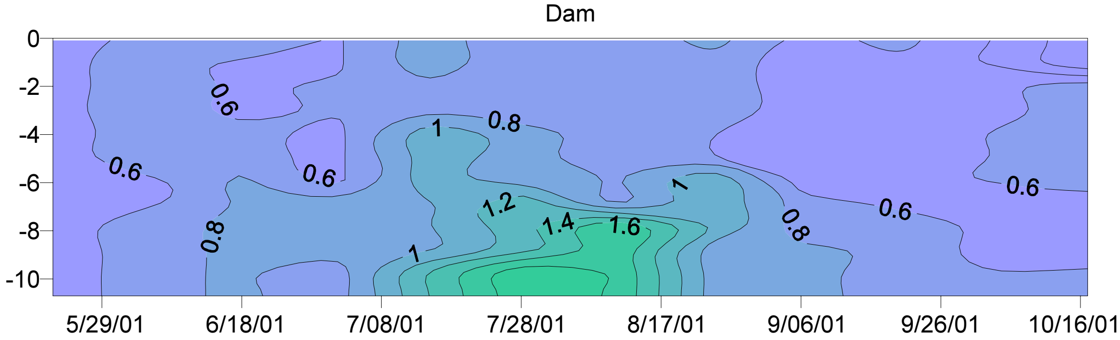

Figure 3.34: Total Kjeldahl Nitrogen profile in mg/L at Dam site, May 22 – October 17, 2001.

At the Dam site (**Figure 3.34**), Kjeldahl nitrogen showed the same July – August peak as the other nutrient parameters and metals and showed a hypolimnetic high concentration. When the ammonia concentration is deleted to give an estimate of organic nitrogen, the same trend is seen (**Figure 3.35**).

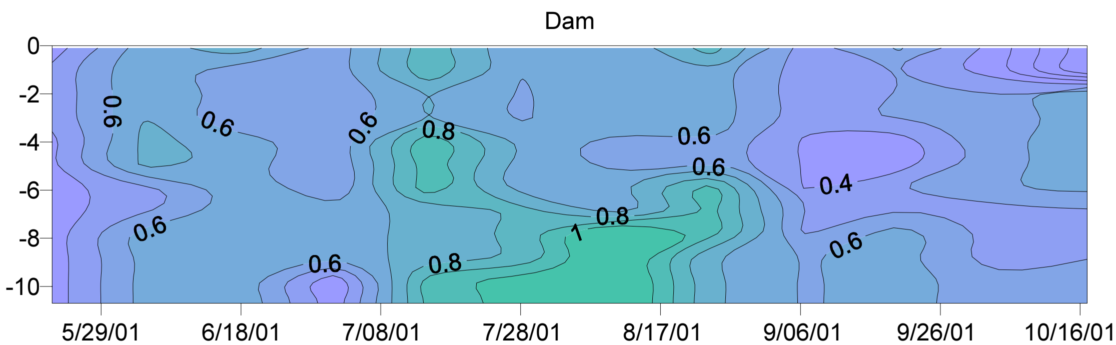

Figure 3.35: Organic Nitrogen profile (calculated) in mg/L at Dam site, May 22 to October 17, 2001.

Median epilimnetic total Kjeldahl concentrations (**Figure 3.36**) ranged from 0.63 to 0.76 mg/L and hypolimnetic values ranged from 1.12 to 1.60 mg/L. Median epilimnetic organic nitrogen concentrations (**Figure 3.37**) ranged from 0.58 to 0.73 mg/L and hypolimnetic values ranged from 0.81 to 1.03 mg/L. The organic fraction made up 56% to 93% of the total nitrogen measured in the epilimnion, indicating high productivity in the lake.

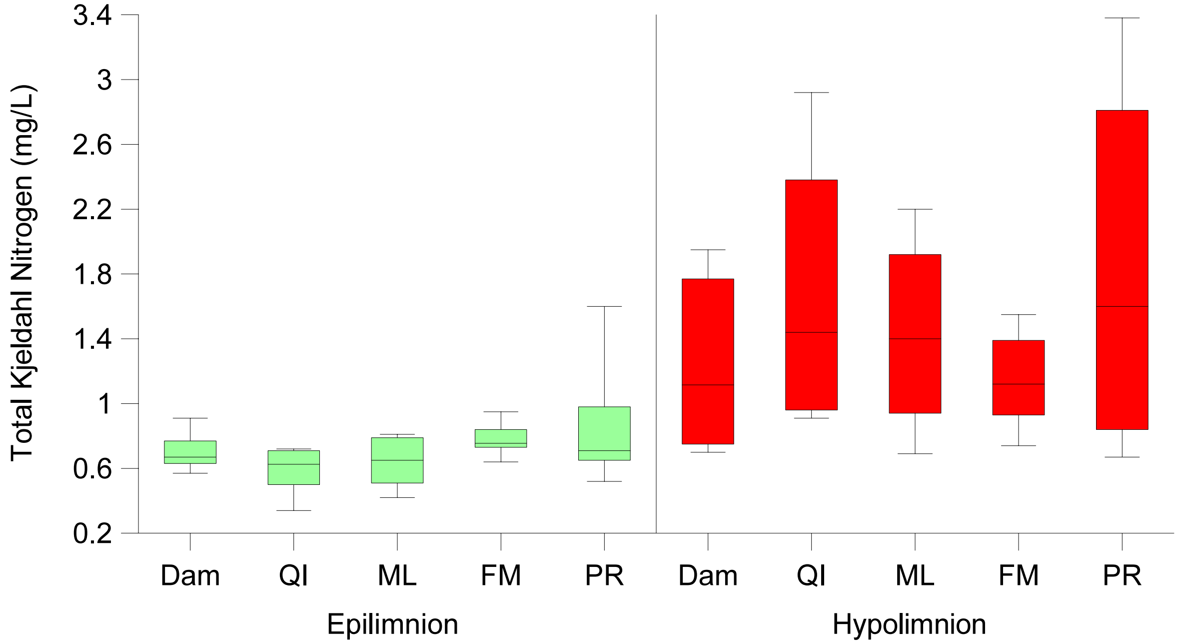

Figure 3.36: Epilimnetic and Hypolimnetic Total Kjeldahl Nitrogen concentrations in mg/L, May 22 – August 22, 2001.

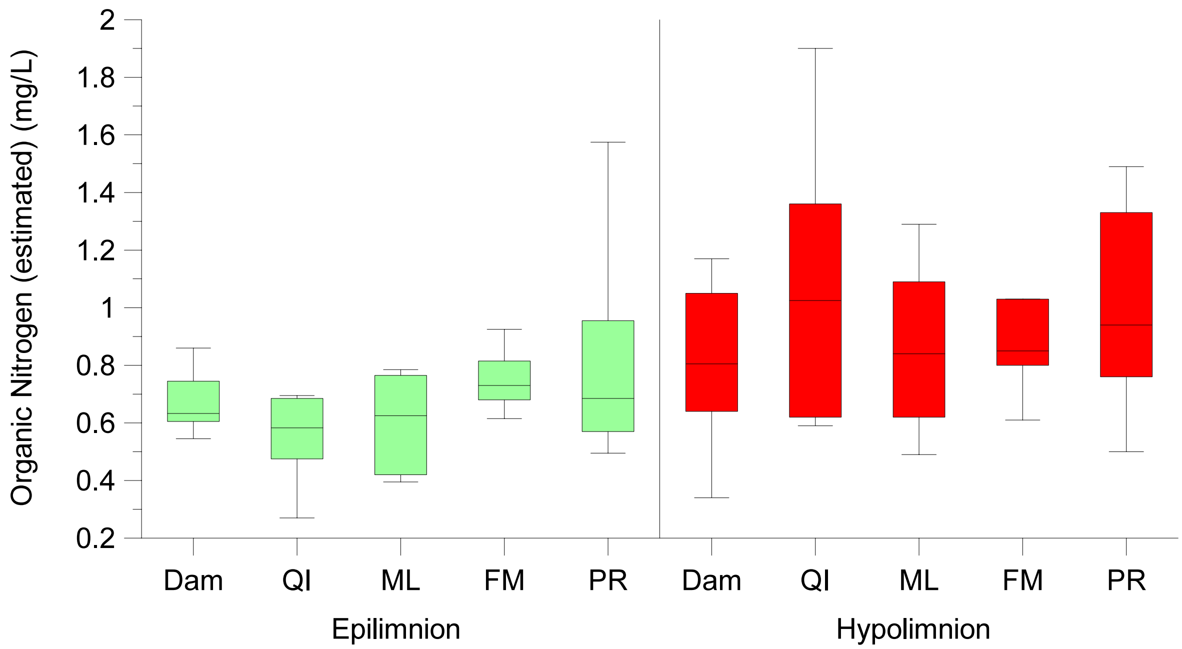

Figure 3.37: Epilimnetic and Hypolimnetic Organic Nitrogen concentrations (calculated) in mg/L, May 22 – August 22, 2001.

The average whole-lake total nitrogen, using all sampling events with complete data, was 1.04 mg/L with a maximum concentration of 3.5 mg/L.

Phosphorus

Phosphorus enters a lake through surface runoff from organic- and fertilizer-rich land and from solubilization of natural deposits of phosphate-bearing rock and soil. In lakes that stratify, transport of phosphorus to and from hypolimnetic sediments can play a major part in phosphorus cycling. In oxygenated lakes the sediment is a major sink for phosphorus, which is lost as part of organic particles or adsorbed to inorganic particles or organic matter. When the sediment-water boundary becomes anoxic, the phosphorus stored in the sediments are released due to a shift in chemical equilibria (Wetzel, 1983).

The most biologically important form of phosphorus is ortho-phosphate. Ortho-phosphate is the major dissolved species and is the form most easily utilized for bacterial and plant metabolism. Attached algae and macrophytes can also uptake phosphorus from the substrate and algae can extract dissolved inorganic phosphate from particulate inorganic complexes and organic phosphate compounds using phosphatase enzymatic breakdown (Wetzel, 1983). Measurement of total phosphorus is useful for quantifying the total loading of phosphorus into the system.

In most unpolluted fresh surface waters, the total phosphorus concentration ranges from 0.01 to 0.05 mg/L, with the higher concentrations seen in lowland areas with sedimentary rock formations and clays. Generally, most of the phosphorus present is organic, though lakes with high non-algal turbidity might have a greater fraction of particulate mineral phosphorus. The fraction of ortho-phosphate is generally 5% of the total phosphorus or less. In typical eutrophic reservoirs, total phosphorus concentrations can reach 0.4 mg/L, and in hypereutrophic reservoirs total phosphorus might reach greater than 1.0 mg/L (Wetzel, 1983).

Phosphorus concentrations in a vertical profile of a lake are variable depending on the form and source of the phosphorus compound. The epilimnion of a stratified lake receives phosphorus from its inflows, from sediment when the lake mixes, and from senescent littoral vegetation (Wetzel, 1983). Algae uptake will decrease the concentration of ortho-phosphate, and the settling out of particulate and organic matter should decrease the total phosphorus measured in the epilimnion. In the hypolimnion, phosphorus can accumulate with the decomposition of organic matter and release of sediment-bound compounds and complexed phosphates.

At the Dam site (**Figure 3.38**), epilimnetic ortho-phosphate concentrations were around 0.02 to 0.04 mg/L. Concentrations in the hypolimnion increased as it became anoxic to a July – August high, following anoxic conditions.

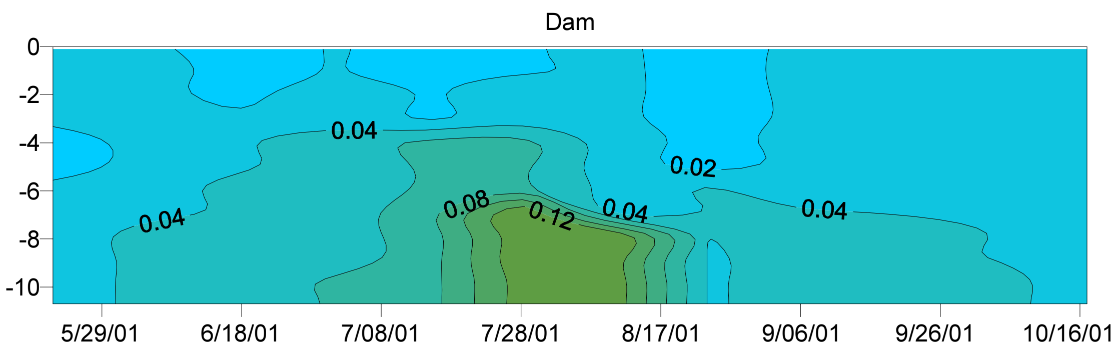

Figure 3.38: Ortho-Phosphate profile in mg/L at Dam site, May 22 – October 17, 2001.

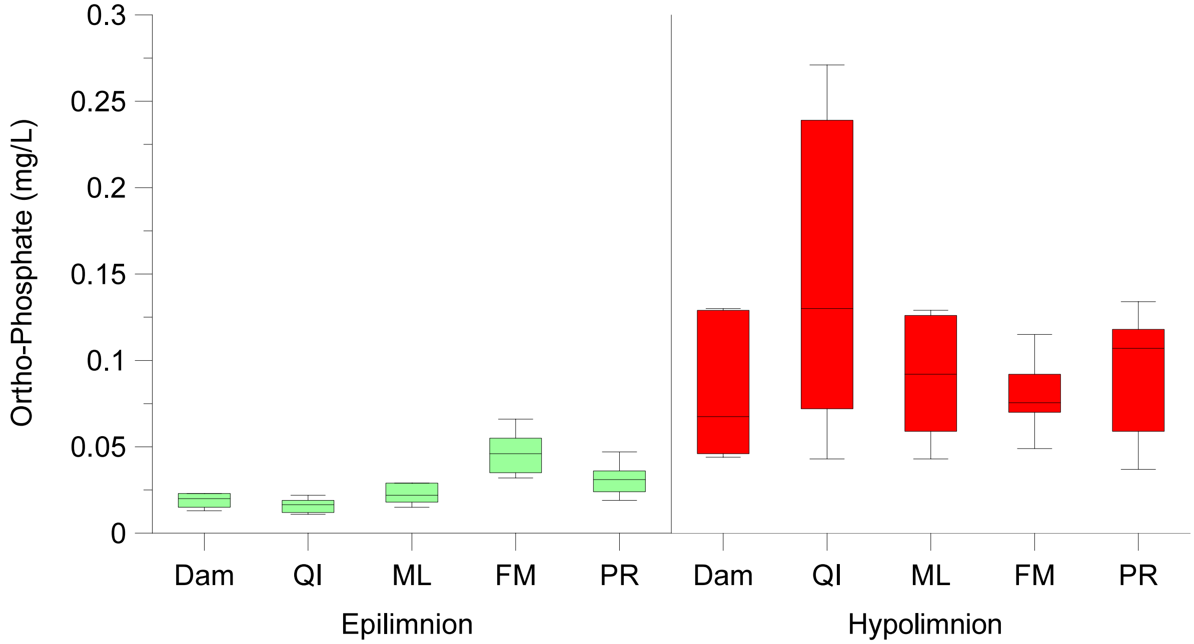

Figure 3.39: Epilimnetic and Hypolimnetic Ortho-Phosphate concentrations in mg/L, May 22 – August 22, 2001.

Median epilimnetic concentrations ranged from 0.02 to 0.05 mg/L, with the highest concentrations measured at the Fourche Maline site (**Figure 3.39**). Median hypolimnetic concentrations ranged from 0.07 to 0.13 mg/L.

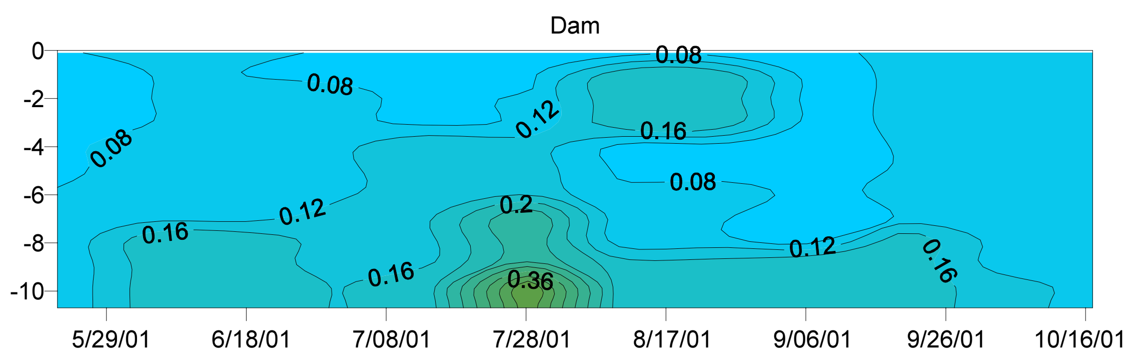

Figure 3.40: Total Phosphorus profile in mg/L at Dam site, May 22 – October 17, 2001.

At the Dam site (**Figure 3.40**), total phosphorus concentrations mirrored ortho-phosphate concentrations with a larger magnitude. In the hypolimnion, total phosphorus reached 0.47 mg/L at the July – August maximum. Epilimnetic concentrations were around 0.06 to 0.08 mg/L during stratification.

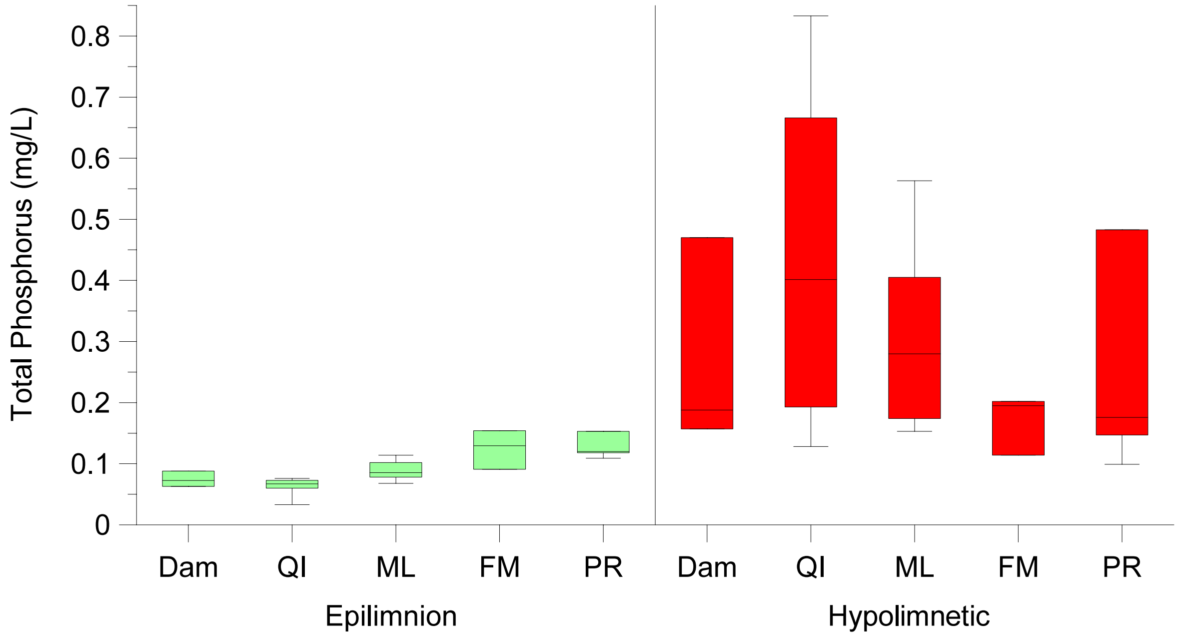

Figure 3.41: Epilimnetic and Hypolimnetic Total Phosphorus concentrations in mg/L, May 22 – August 22, 2001.

Median epilimnetic concentrations (**Figure 3.41**) ranged from 0.07 to 0.13 mg/L with the higher values at the Fourche Maline and Poteau River sites, the sections of the lake nearest the two major inflows. Hypolimnetic medians ranged from 0.18 to 0.4 mg/L. The average whole-lake total phosphorus, using all sampling events with complete data, was 0.15 mg/L with a maximum concentration of 0.83 mg/L.

Limiting Nutrient

Turbidity and Secchi depth data indicate light as the limiting nutrient for Lake Wister. Excessive levels (greater than 20 µg/L) of chlorophyll-a were noted in the data set indicating that light is not the only limiting nutrient. In clearer water systems nitrogen and phosphorus are the elements which most commonly limit algal growth (Vollenweider, 1968). Because different concentrations of each element are required, the ratio of total nitrogen to total phosphorus (TN:TP) is as important as the relative concentrations of each element in consideration of algal productivity. The ratio is commonly used to estimate which factor, N or P, could limit algal growth (Schindler, 1977). The ratio may also provide insight into which types of algae may prevail within the lake (USEPA, 1986). Sakamoto (1966) suggested nitrogen limitation could occur when TN:TP ratios were <15-17:1. Nitrogen-fixing blue green algae often dominate nitrogen limited systems. Blue greens are undesirable because of their propensity to form massive blooms which often cause taste, odor, and oxygen demand problems.

Wister had an average TN:TP of 8 indicating nitrogen was the limiting chemical nutrient. The quick utilization of nitrate and high levels of dissolved phosphorus in the water column noted in the report earlier support nitrogen limitation during the summer of 2001.

Biological Properties

Chlorophyll-a

Chlorophyll-a is the major photosynthetic pigment found in all live algal cells. Measuring chlorophyll-a provides an indirect indicator of the algal population size, and thus the primary productivity of the lake. Based on Vollenweider's (1979) classification of reservoirs, the mean chlorophyll-a concentration of reservoirs that were considered eutrophic was around 14 mg/m^3 with an average peak or concentration reflecting an algal bloom of about 43 mg/m^3. Chlorophyll-a concentrations of 7.2 and 20 mg/m^3 represent the lower boundaries for eutrophic and hypereutrophic trophic status, respectively (OWRB, 2002).

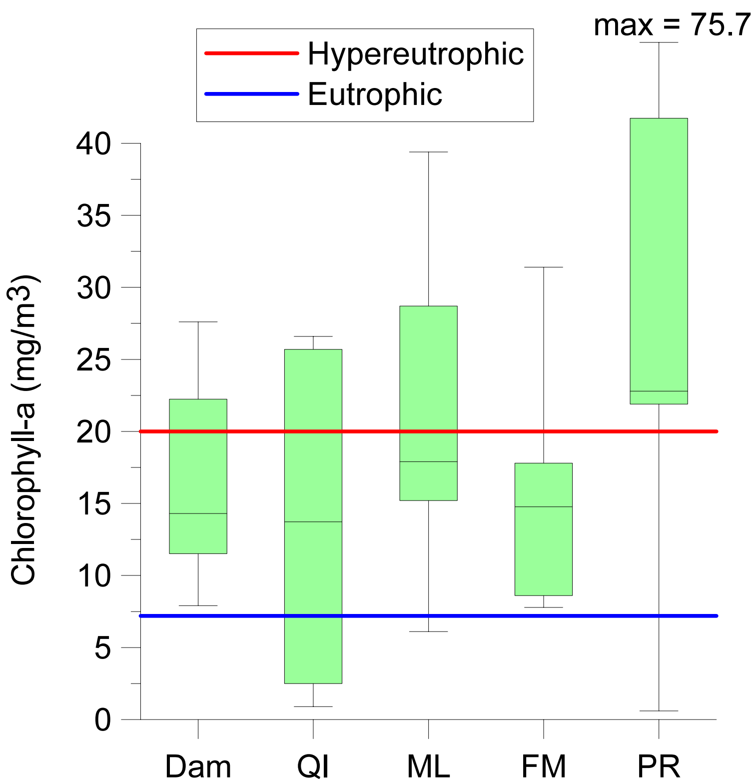

Figure 3.42: Surface Chlorophyll-a concentrations in mg/m^3, May 22 – October 17, 2001.

In Lake Wister, median chlorophyll-a concentrations ranged from 14 mg/m^3 at Quarry Island to 23 mg/m^3 at the Poteau River site (**Figure 3.42**). The whole-lake median was 18 mg/m^3. The peak concentration was 75.7 mg/m^3 at the Poteau River site. The median concentration is very close to the average conditions of reported eutrophic lakes (Vollenweider, 1979). At the Poteau River site, chlorophyll-a concentrations were into the hypereutrophic range above 20 mg/m^3. At all the other sites, concentrations were between eutrophic and hypereutrophic for the bulk of the data ranges. For the whole lake, only 11.6% of samples were in the mesotrophic range, 55.8% of the samples indicate eutrophy and 32.6% indicate hypereutrophy. Over 88% of the sample were in the eutrophic category. This is surprising since Wister Lake also suffers from excessive turbidity.

Temporal examination of chlorophyll-a showed the biggest peak associated with the highest Secchi disk depth and lowest turbidity noted on July 8, 2001 (**Figure 3.44**). The magnitudes of peaks were generally in the hypereutrophic range.

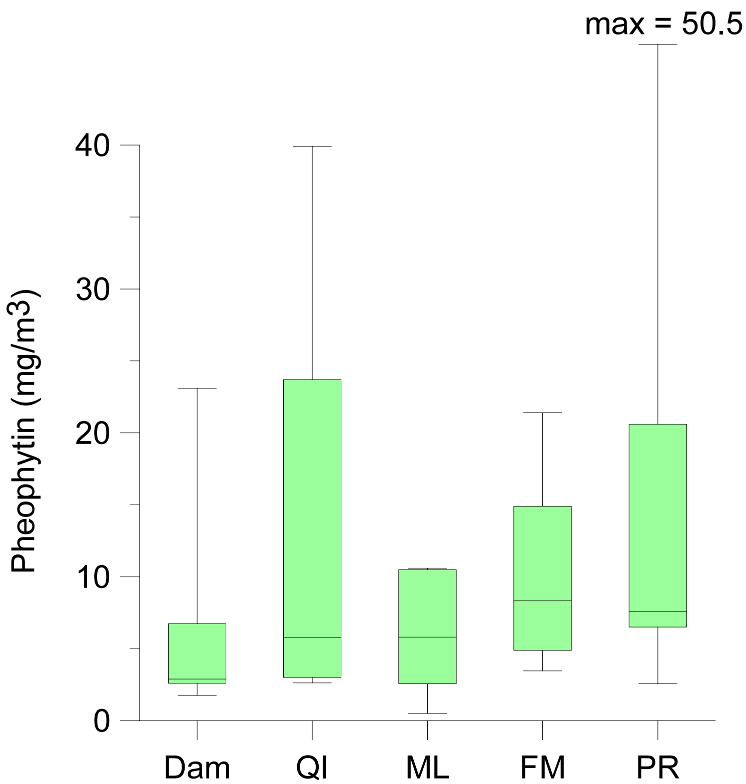

Figure 3.43: Surface Pheophytin-a concentrations in mg/m^3, May 22 – October 17, 2001.

Pheophytin-a, or degraded chlorophyll-a, provides an indicator of past algal growth and indicate when an algal bloom has recently occurred and passed. Pheophytin-a is usually measured in very small concentrations, often below the detection limit of 0.1 mg/m^3. In Lake Wister, median pheophytin-a concentrations ranged from 3 to 8 mg/m^3, with a peak value of 50.5 mg/m^3 (**Figure 3.43**). Pheophytin-a concentrations were often in the eutrophic range, if it were treated like its precursor chlorophyll-a. When very low chlorophyll-a concentrations were measured, high concentrations of pheophytin-a were measured, indicating a recent algal die-off and possibly light limitation of productivity by algal turbidity (**Figure 3.45**). The fact that pheophytin-a concentrations were high, sometimes greater than the chlorophyll-a concentration, is an important observation. High pheophytin-a concentrations are consistent with rapid phytoplankton growth and turnover. The largest pheophytin-a concentrations were measured in June – August, when algal turnover rates were highest.

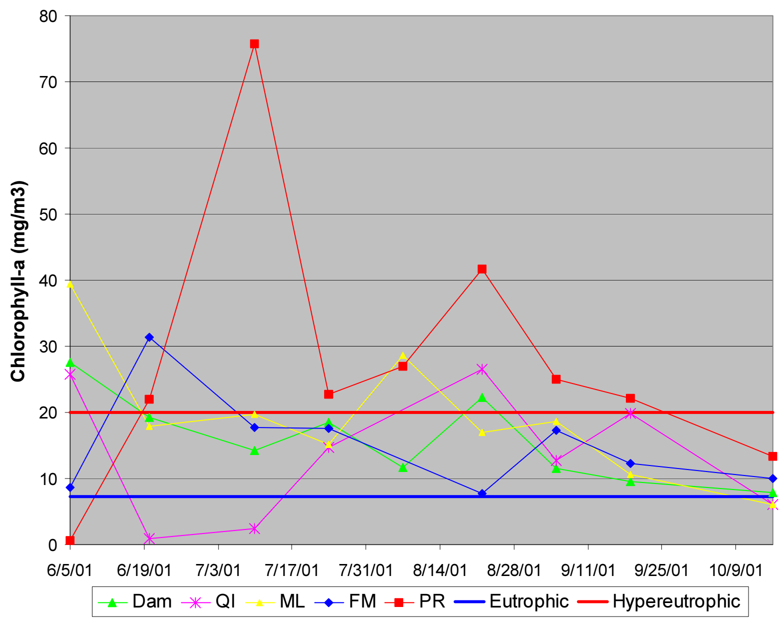

Figure 3.44: Chlorophyll-a time series plot, May 22 – October 17, 2001.

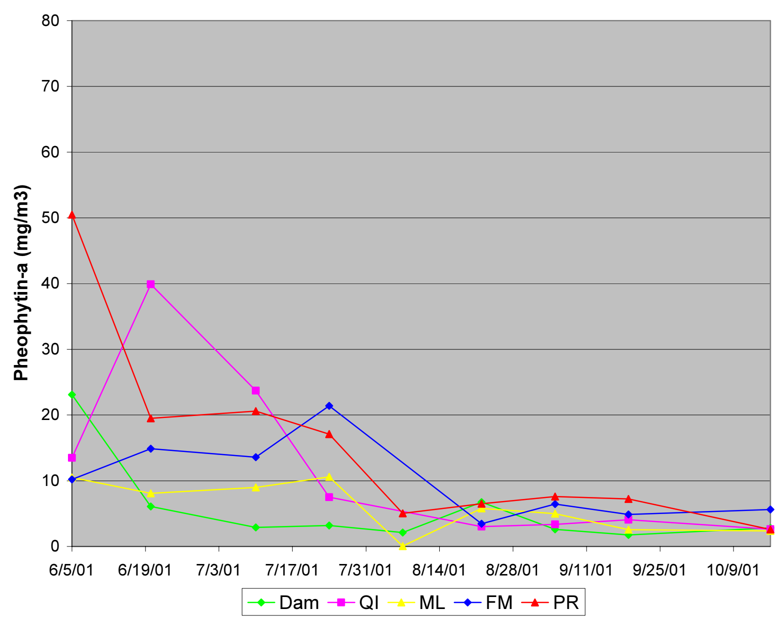

Figure 3.45: Pheophytin-a time series plot, May 22 – October 17, 2001.

The September 19 and October 17 decreases in chlorophyll-a and pheophytin-a can be attributed to storm events with resulting dilution occurring on or just before the sampling dates. Otherwise, concentrations were consistently high and could not be easily traced to nutrient loading from storm runoff. The release of light limitation or internal loading (of nitrogen) are the remaining explanations for the high productivity noted throughout the summer season.

Trophic State Index

Carlson's (1977) trophic state index is one of the most commonly used measurements to compare lake trophic status, which is based on algal biomass. The biological condition of the waterbody indicates the lake's level of nutrient enrichment or eutrophication. Carlson's TSI uses Secchi disk depth, total phosphorus, and chlorophyll-a concentrations to define level of eutrophication on a scale of 1 to 100. A lake is considered oligotrophic below 40, mesotrophic from 41-50, eutrophic 51-60, and hypereutrophic when greater than 60 (OWRB, 2002).

The limitations of Carlson's trophic state indices must be noted. TSI Secchi depth is not appropriate in lakes with high non-algal turbidity, since the high turbidity is assumed to be due to algal growth. The high non-algal turbidity can then decrease water clarity, which leads to more of an overestimate in actual biomass, as in this case of Lake Wister. The high non-algal turbidity can also lead to an overestimate using total phosphorus, as phosphorus will not be the limiting chemical nutrient. TSI total phosphorus is accurate when phosphorus is the factor limiting algal growth. Lake Wister is likely limited by nitrogen as opposed to phosphorus. Chlorophyll-a is the best measure of trophic state for Wister Lake.

Median TSI chlorophyll-a values were between 56 and 61 (**Figure 3.46**), ranging from eutrophic to hypereutrophic. Median TSI Secchi depth values were between 75 and 85 (**Figure 3.47**), and TSI total phosphorus values were between 70 and 77 (**Figure 3.48**) both in the hypereutrophic range.

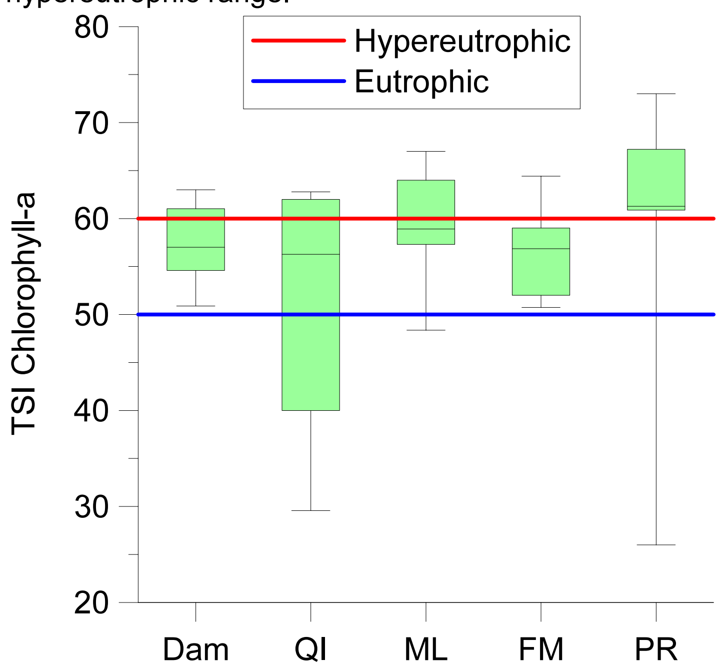

Figure 3.46: Carlson's Trophic State Index Chlorophyll-a, May 22 – October 17, 2001.

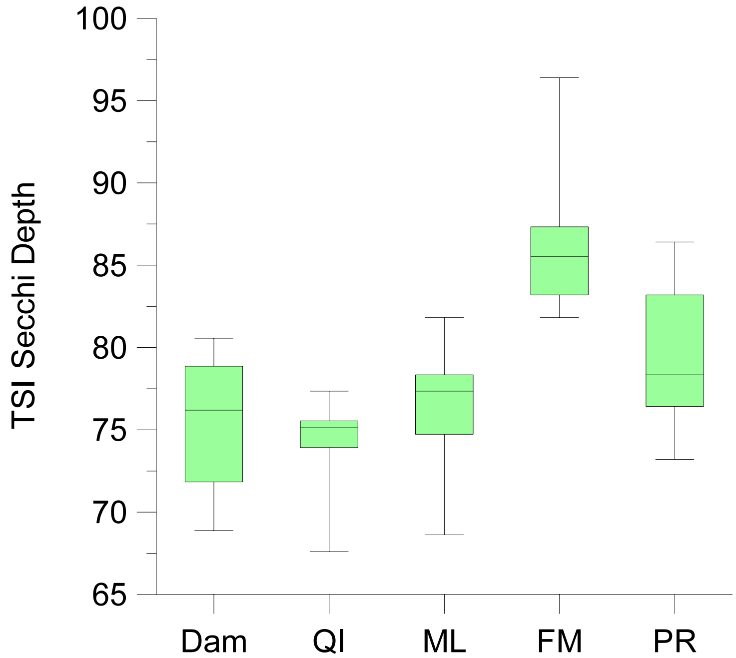

Figure 3.47: Carlson's Trophic State Index Secchi Disk Depth, May 22 – October 17, 2001.

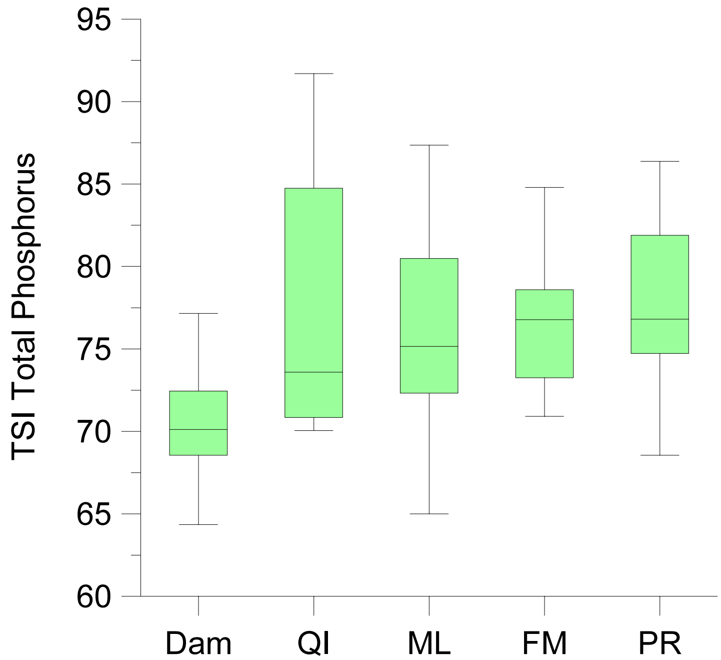

Figure 3.48: Carlson's Trophic State Index Total Phosphorus, May 22 – October 17, 2001.

In Lake Wister, TSI total phosphorus and TSI Secchi disk depth were both in the 70-80 range with TSI chlorophyll-a values falling below the 60 hypereutrophic boundary. It is likely that algae growth is limited by water clarity and the lake's trophic state is somewhere on the eutrophic/hypereutrophic boundary. This is supported by the higher TSI chlorophyll-a at the Poteau River site while TSI total phosphorus was greatest at the Fourche Maline site. The high TSI Secchi depth at the Fourche Maline site provides a plausible explanation (light limitation) why the Fourche Maline TSI chlorophyll-a is not closer to the Poteau River's TSI. The hypereutrophic values of phosphorus TSI underscore the need for immediate nutrient reductions in Wister.

Bacteria

Lake Wister fecal bacterial levels were extremely sensitive to rainfall events in the watershed with resulting increases in lake elevation. Whole-lake geometric means of bacterial samples (**Figure 3.49**) indicate that every occurrence of high bacterial content was associated with an inflow event.

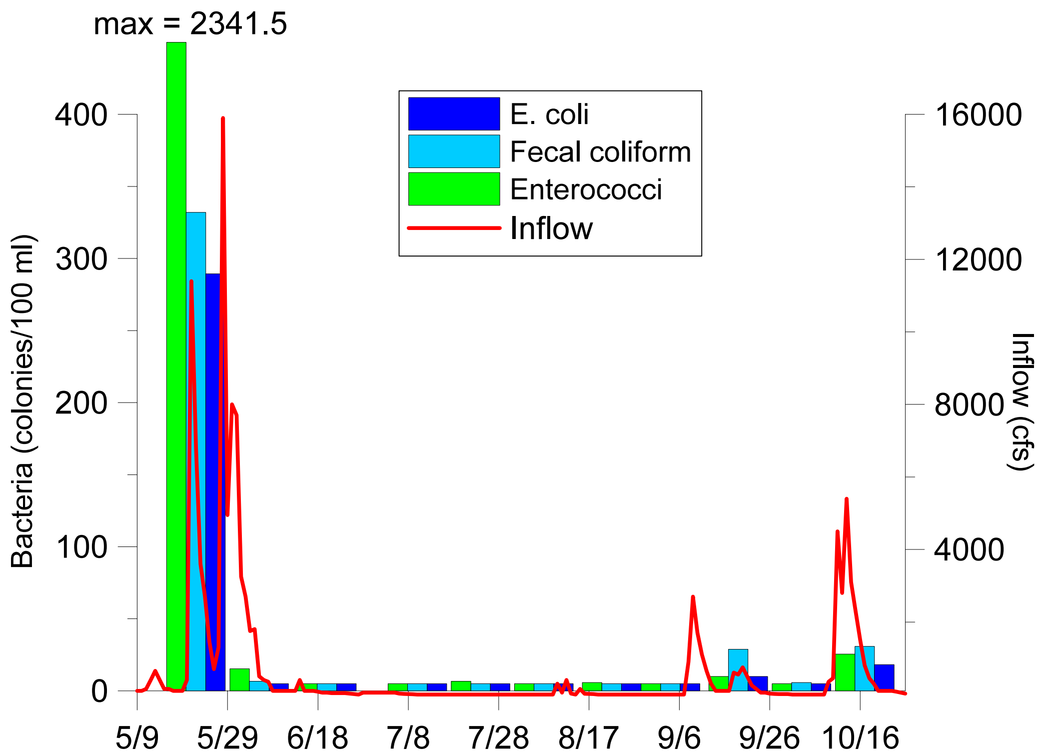

Figure 3.49: Geometric means of Surface Bacteriological samples in # colonies/100 ml compared to lake inflow in cubic feet/second, May 22 – October 17, 2001, (Inflow data from USACE).

Also, the larger the inflow and increase in lake elevation, the greater the bacterial content of the water. Under baseflow conditions, the number of bacterial colonies was usually below the detection limit of 10 colonies/100 ml of sample water. Following the largest stormflow event on May 22, the bacterial levels increased to a maximum of 57,000 colonies/100 ml.

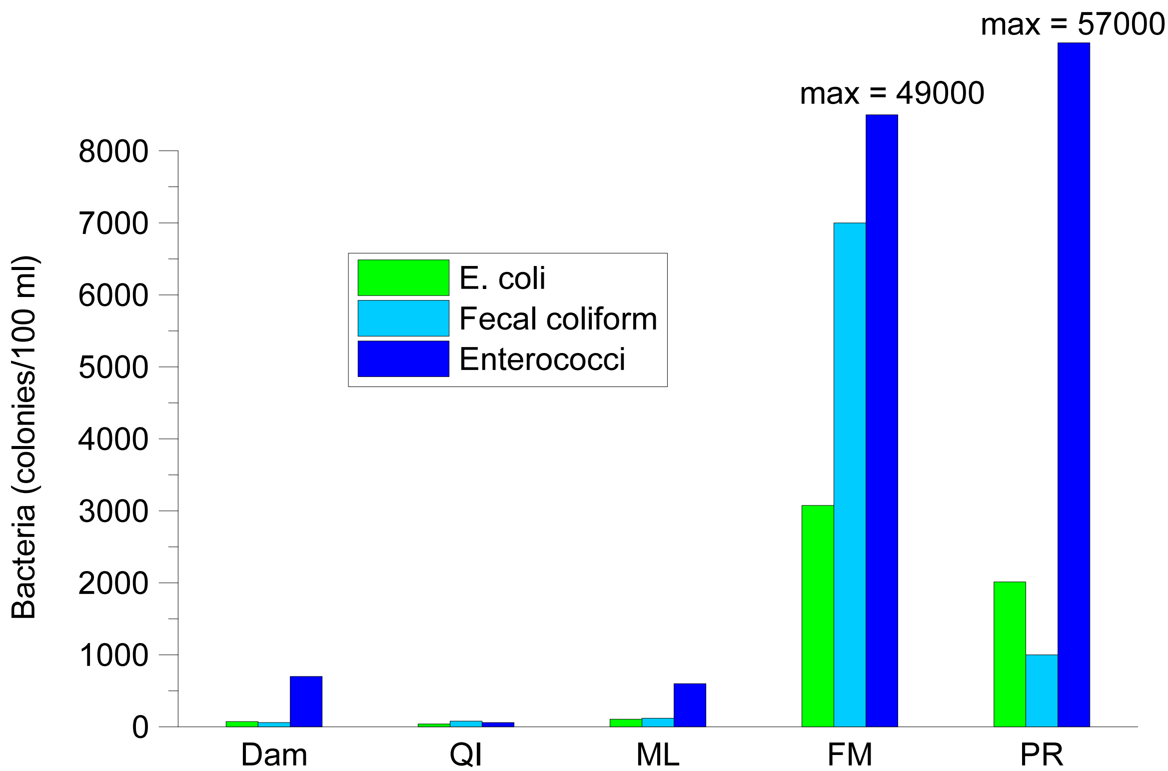

Figure 3.50: Bacteriological samples in #colonies/100 ml associated with May 21 storm event, sampled May 22, 2001.

Figure 3.50 shows the May 22 distribution of bacteria among lake sites, which was typical of stormflow events. The greatest number of bacterial colonies were found in the Poteau River and Fourche Maline arms of the lake, with much smaller concentrations at the main body sites of the lake. This substantiates that bacteria are washing from the watershed into the lake. Specific counts recommend that people refrain from primary body contact in the upper end s of the lake following significant inflow events.

Historical Data Comparison

Comparison of historical to current data allows for the examination of long-term water quality trends. In Lake Wister, water quality changes might also be associated with the change in conservation pool elevation in 1983 from 471.6 to 474.6 ft and in 1996 from 474.6 to 478 ft. Beginning in 1974 the conservation pool was maintained at 478 ft from June 15 to August 1 when inflows permitted. Historical data sources include the National Eutrophication Survey (NES) performed by the U.S. Environmental Protection Agency in 1974 (USEPA, 1977), the Surface Water Quality Assessment for Oklahoma, Water Year 1977 (305b) Report (OSDH, 1977), Williams Brothers Engineering's 1982 investigation of Lake Wister water quality (WBE, 1982), the U.S. Army Corps of Engineers (USACE) Water Quality Report for Lake Wister (USACE, 1994), and the OWRB's 1996 Clean Lakes Phase I: Diagnostic and Feasibility Study of Lake Wister (OWRB, 1996).

Sample sites for each of the studies were in the same areas as in the current data set, though not all the studies used all the sites. For the earlier four studies, the data was reported as annual whole-lake medians, as there was no statistical difference found between sites. The four earlier studies will be used to show long-term trends. From the OWRB's 1996 Phase I study, data from 5/12/93 to 10/13/93 was used to give a direct comparison to the 2001 seasonal data and allow direct comparison of water quality before and after the most recent elevation change.

During these studies, data was limited either as to number of sites or time period and frequency of sampling, particularly before 1989. Also, measurement and laboratory analysis methods were more variable, and the quality of some of the older data may be questionable. Due to these constraints, only a very general comparison of past water quality can be made. A summary of historical data for the major physical and chemical parameters follows.

Temperature

Historical thermal stratification patterns are similar to those seen in the current data set. There was some summer stratification, with no distinct layers present but a gradual decrease in temperature with depth, and possibly with a shorter duration of stratification. Prior to 1989, thermal stratification was present at the Dam site in August but not in June 1974 (USEPA, 1977; WBE, 1982). Stratification was observed at the deeper sites through June – August in 1989 and 1990 (OWRB, 1990; USACE, 1994).

In 1993, stratification also covered three months in the summer (OWRB, 1996). The Dam, Mid-Lake, Fourche Maline, and Poteau River sites were stratified from late May to late August (**Figure 3.51**). The Quarry Island site did not stratify at all because the site depth was less than 3 m throughout most of the May – October time frame.

As early as 1989 Lake Wister has stratified in the summer from around May/June to August/September in the deeper parts of the lake. This stratification was the same as was seen in 2001. Although the conservation pool elevation had changed from 471.6 and 474.6 ft actual pool elevations were higher than the conservation pool for portions of the monitored summers. Change in legislated pool elevation may not have changed the duration of thermal stratification since the late 1980's.

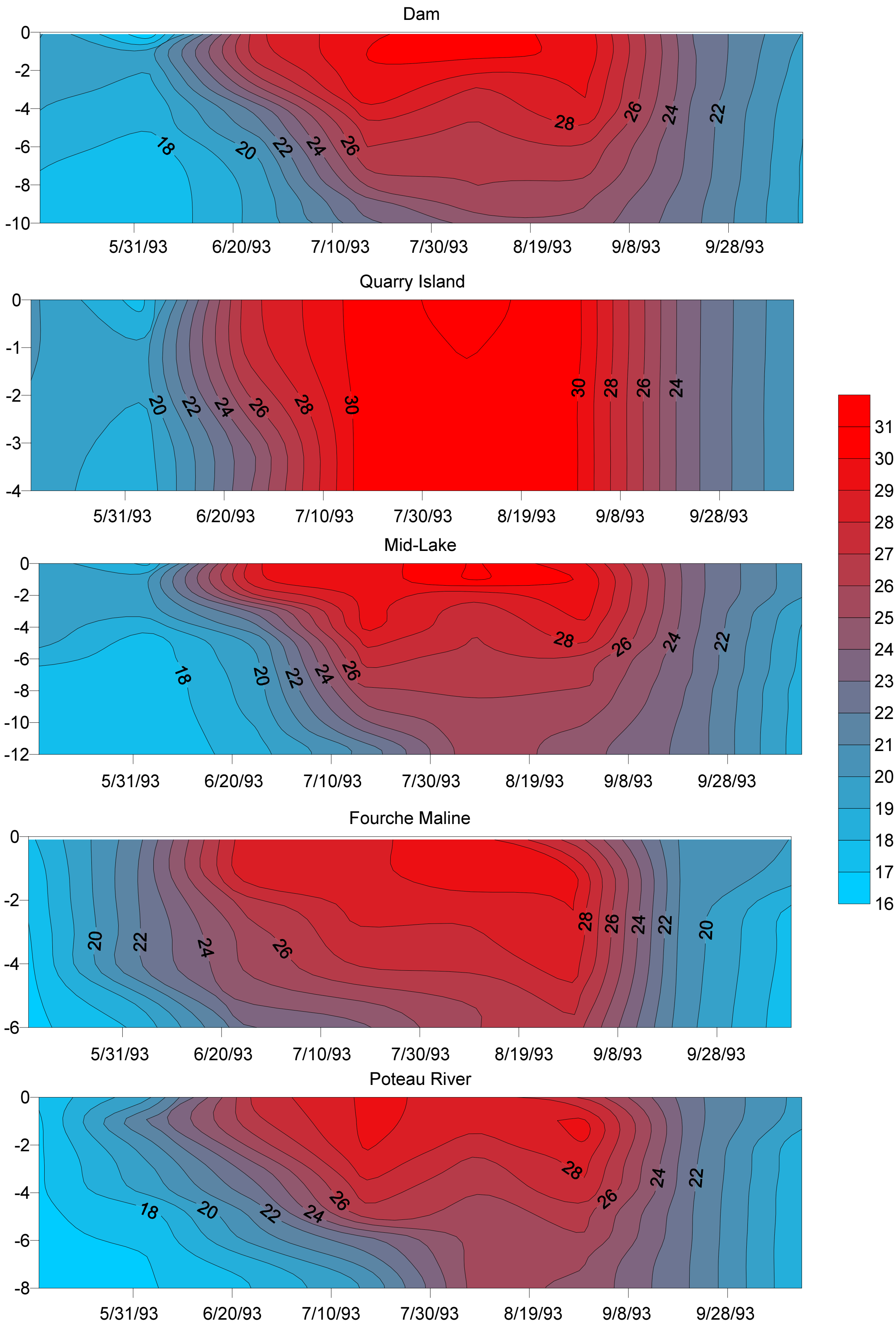

Figure 3.51: Temperature profiles in °C, May 12 – October 13, 1993.

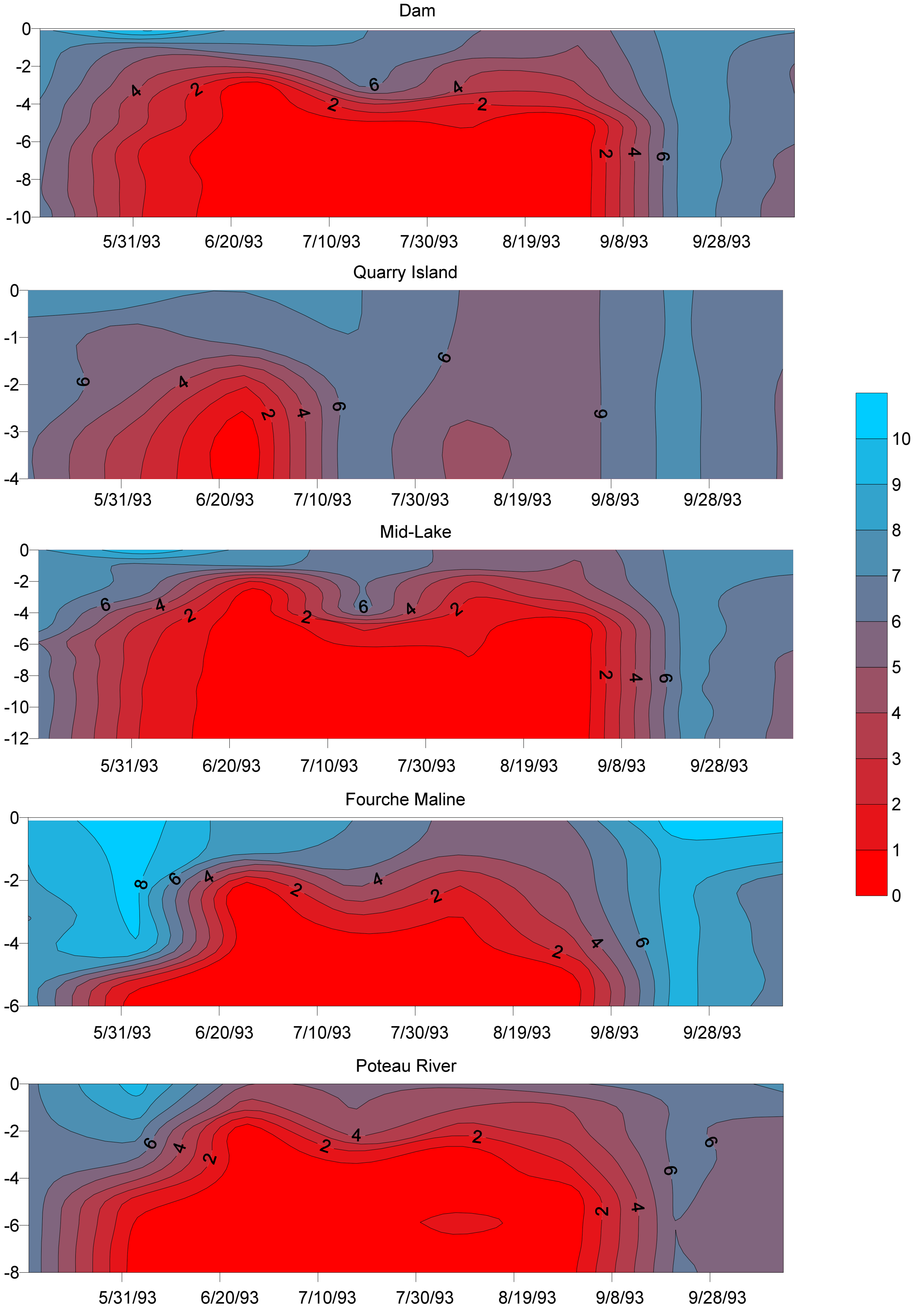

Figure 3.52: Dissolved Oxygen profiles in mg/L, May 12 – October 13, 1993.

Dissolved Oxygen

Hypolimnetic anoxia was observed at the Dam site in August below 4 m in 1974 and below 6 m in 1982 (USEPA, 1977; WBE, 1982). In July and August 1989 – 1990, hypolimnetic anoxia was present intermittently at the Dam site (OWRB, 1990; USACE, 1994). The depth below the surface at which anoxia began was variable, ranging from below 2-3 m on one sampling date to 6-8 m through the rest of the summer.

During 1993 OWRB sampling (**Figure 3.52**), hypolimnetic anoxia began in May at the deeper sites when thermal stratification developed or 2-3 weeks later at the shallower sites. When the lake mixed at the end of August, anoxic conditions were no longer found (OWRB, 1996). Anoxia was consistently found at 2-4 m below the surface while the lake was stratified. Surface dissolved oxygen concentrations were above 5 mg/L, and supersaturation was observed at the same sites in the same time period as in 2001.

In 1974 and 1982, hypolimnetic anoxia was only observed in August below 4-6 m. In 1989 – 1990, dissolved oxygen was below 2 mg/L in July and August at around an average of 6 m below the surface. In 1993, hypolimnetic anoxia was found at around 2-4 m below the surface while the lake was stratified, which was comparable to 2001 data.

In addition to volume of anoxia water, duration of anoxia does also appear to have increased. Prior to 1990, anoxia was only measured in July-August. During 1993 and 2001 sampling, anoxia was present from May/June to August/September.

pH

The 1974 study showed no evidence of pH differences between the epilimnion and hypolimnion, and the pH was between 6.0 and 7.0 on all dates except in the spring with surface values below 6.5 in August and October (USEPA, 1977). In 1982 and 1989 – 1990, evidence of an August epilimnetic high pH value was seen, indicating excessive photosynthetic activity (WBE, 1982; OWRB, 1990; USACE, 1994). 1982 to 1989 pH values were almost entirely below 7.0, though not below 6.5 at the surface.

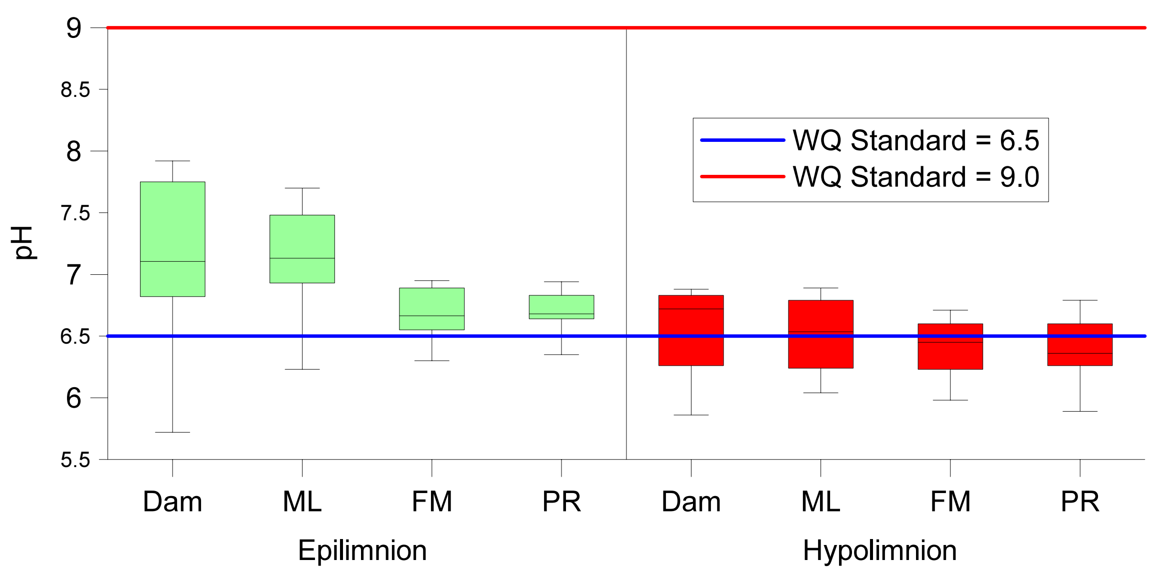

Figure 3.53: Epilimnetic and Hypolimnetic pH, May 12 – August 25, 1993.

OWRB 1993 sampling showed a pronounced difference between epilimnetic and hypolimnetic pH values (**Figure 3.53**). Hypolimnetic values were near 6.5 and epilimnetic values were between 6.5 and 7.25, with low values in the Poteau River and Fourche Maline arms of the lake. Surface pH values at all sites were below the water quality standard at some time. Epilimnetic high pH values, indicating excessive photosynthesis, was also found at the Dam, Quarry Island, and Mid-Lake sites (**Figure 3.54**) around the beginning of August, though not at the Poteau River or Fourche Maline sites.

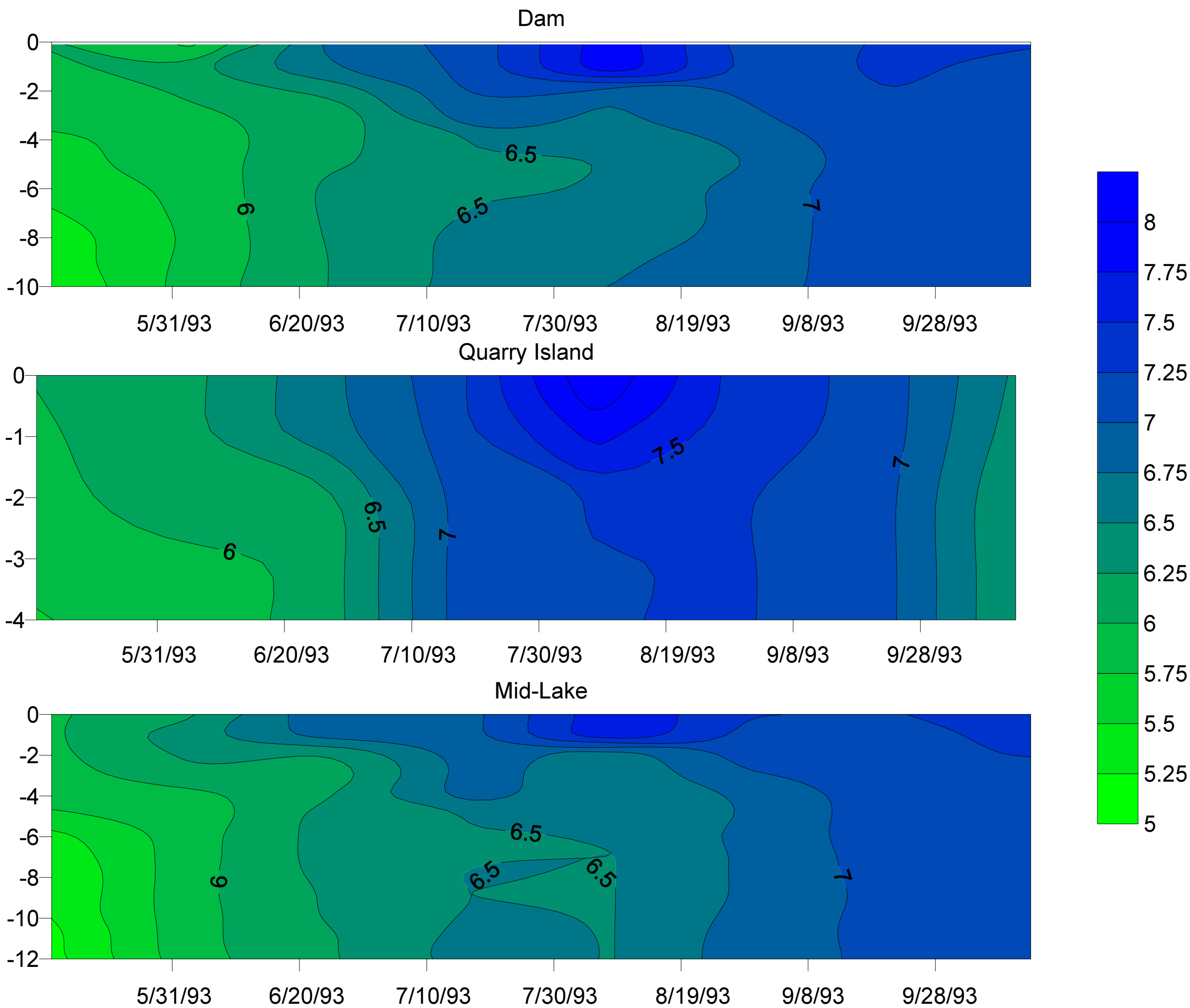

Figure 3.54: pH profiles at the Wister main body sites, May 12 – October 13, 1993.

In general, Wister has had slightly acidic pH values throughout water quality sampling. All sampling periods since 1974 showed increased surface pH, evidence of high productivity, in August. In 1993 surface pH values were generally lower than in 2001. In 2001 an extended period of higher pH values were seen that appear to be associated with high productivity. Hypolimnetic values were in the same range in 1993 and 2001.

Turbidity and Secchi Depth

Turbidity data before 1989 was limited. In 1982, two turbidity samples were taken at the Dam and Quarry Island sites, and both were below 15 NTU (WBE, 1982). In 1989 – 1990 the whole-lake median for turbidity was below 15 NTU, with 75% of the data below 20 NTU and a maximum of 55 NTU (USACE, 1994; OWRB, 1990).

During the summer of 1993 (OWRB, 1996), median turbidity values were 35 NTU in the Fourche Maline arm and around 10 – 15 NTU at all the other sites (**Figure 3.55**). Turbidity was below the water quality standard of 25 NTU for 75% to 100% of the data ranges at all sites except the Fourche Maline site. Median turbidity values for the entire 1992 – 1994 sampling period were slightly higher at around 45 NTU at the Fourche Maline site and 20 – 25 NTU for the rest of the sites.

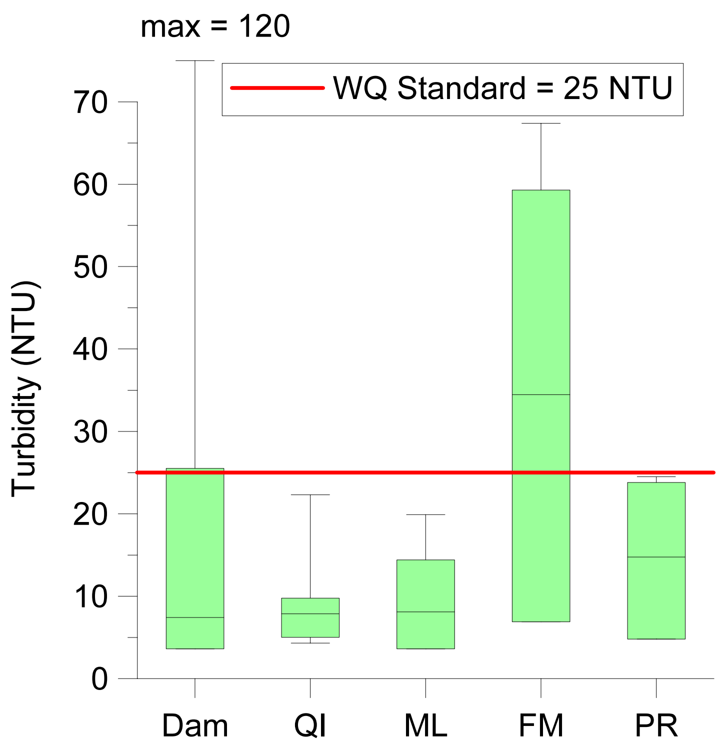

Figure 3.55: Surface Turbidity in NTU, May 12 – October 13, 1993.

In 2001, median turbidity values were 65 in the Fourche Maline arm and 22 – 33 NTU in the rest of the lake, with a maximum of 185 NTU at the Fourche Maline site. Only at the Quarry Island site was the turbidity below the 25 NTU standard.

Median Secchi disk depths were in the 30 – 45 cm range from 1974 to 1990. In 1974, 1977, and 1982, these data come from the Dam and Quarry Island sites only, with summer whole-lake medians given for the 1989 –1990 data (USEPA, 1977; OSDH, 1977; WBE, 1982; USACE, 1994).

In 1993 (OWRB, 1996), median summer Secchi disk depths ranged from 25 – 80 cm, with the low in the Fourche Maline arm of the lake (**Figure 3.56**). Using annual medians, the range lowered to 23 – 53 cm.

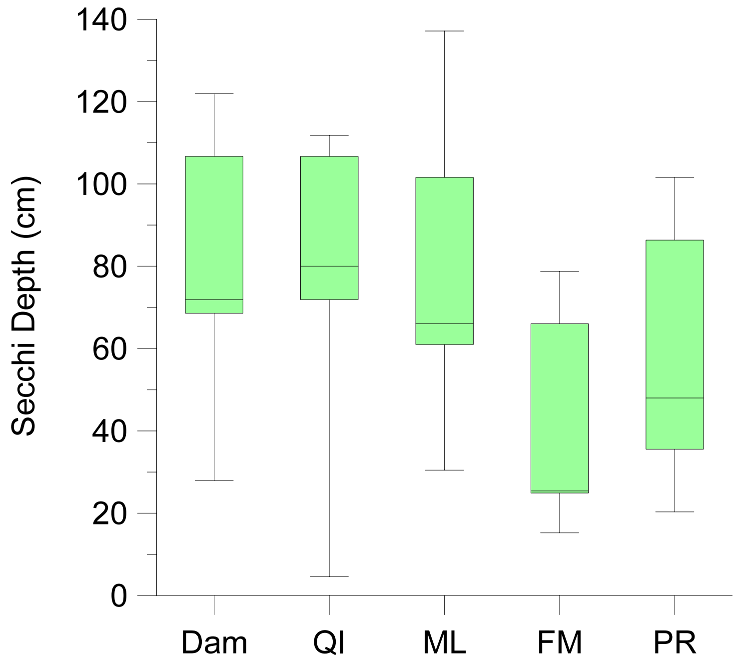

Figure 3.56: Secchi Disk Depth in cm, May 12 – October 13, 1993.

2001 summer sampling showed median Secchi depths of 17 – 35 cm, with the low at the Fourche Maline site.

Metals

Metals analyses of epilimnetic and hypolimnetic water were taken in some of the historical studies. **Table 3.8** shows the whole-lake median concentrations of total iron and manganese.

Table 3.8: Historical Metals Median Concentrations.

Data source	Total Iron (mg/L)		Total Manganese (mg/L)	
	Epilimnion	Hypolimnion	Epilimnion	Hypolimnion
1977 305b	1.1	NA	0.4	NA
1982 WBE	0.7	10	0.4	11
1989-90 USACE	2.1	5.1	0.3	1.5
1992-94 OWRB	1.8	2.6	NA	NA
2001 OWRB	1.4	4.5	0.3	2.3

The number of samples was five or less, making data comparisons difficult. Generally, total iron ranged from 1-2 mg/L in the epilimnion to 2.5-10 mg/L in the hypolimnion. Total manganese ranged from 0.4 mg/L in the epilimnion to 1.5-11 in the hypolimnion.

In 2001 with a much greater sample size, total iron ranged from 1.4 mg/L in the epilimnion to 4.5 in the hypolimnion. Total manganese ranged from 0.3 mg/L in the epilimnion to 2.3 mg/L in the hypolimnion.

Nutrients

Historical data is reported as total Kjeldahl nitrogen and total phosphorus, the major parameters that were available from all the data sets. **Table 3.9** shows whole-lake median concentrations for the nutrient parameters.

Table 3.9: Historical Nutrient Median Concentrations.

Data source	Total Kjeldahl Nitrogen (mg/L)		Total Phosphorus (mg/L)	
	Epilimnion	Hypolimnion	Epilimnion	Hypolimnion
1974 NES	0.5	1.6	0.12	0.18
1977 305b	1.52	2.25	0.12	0.15
1982 WBE	NA	NA	0.1	0.14
1989-90 USACE	0.5	0.5	0.08	0.2
1992-94 OWRB	0.5	1.4	0.07	0.2
2001 OWRB	0.7	1.4	0.09	0.3

Total phosphorus concentrations were consistent across all of the studies, with around 0.1 mg/L in the epilimnion and 0.15 – 0.2 mg/L in the hypolimnion. In 2001, median total phosphorus ranged from 0.09 mg/L in the epilimnion to 0.3 mg/L in the hypolimnion, with maxima of 0.15 mg/L and 0.83 mg/L in the epilimnion and hypolimnion, respectively.

Epilimnetic median Kjeldahl nitrogen was around 0.5 mg/L in all the studies except for the 1977 305b report. In the hypolimnion, Kjeldahl nitrogen ranged from 0.5 to 2.25, probably depending on anoxia above the lake's sediment, which would increase the measured Kjeldahl nitrogen by increasing ammonia releases. In 2001, median total Kjeldahl nitrogen was around 0.7 mg/L in the epilimnion and 1.4 in the hypolimnion, with maxima of 1.6 and 3.4 mg/L in the epilimnion and hypolimnion, respectively.

Chlorophyll-a

Sampling of Lake Wister water for chlorophyll-a occurred in 1974, 1989-90, and 1992-94. In 1974, chlorophyll-a concentrations from four samples taken in March, June, August, and October were all around 5 mg/m^3, with a maximum of 8 mg/m^3 (USEPA, 1977). In 1989-90 USACE sampling, the median chlorophyll-a concentration was around 15 mg/m^3, with 75% of the data at or below 20 mg/m^3 and a maximum concentration of 40 mg/m^3 (USACE, 1994).

During 1993 OWRB sampling (**Figure 3.57**), chlorophyll-a concentrations were in the eutrophic range at the Dam, Quarry Island, and Mid-Lake sites, with median concentrations of 10 – 15 mg/m^3. Median concentrations in the Poteau River and Fourche Maline arms of the lake were around 20 mg/m^3, the boundary for hypereutrophy. The whole-lake median was 15 mg/m^3. High pheophytin-a concentrations were also documented (**Figure 3.58**) at up to 18 mg/m^3, indicating a high algal turnover rate.

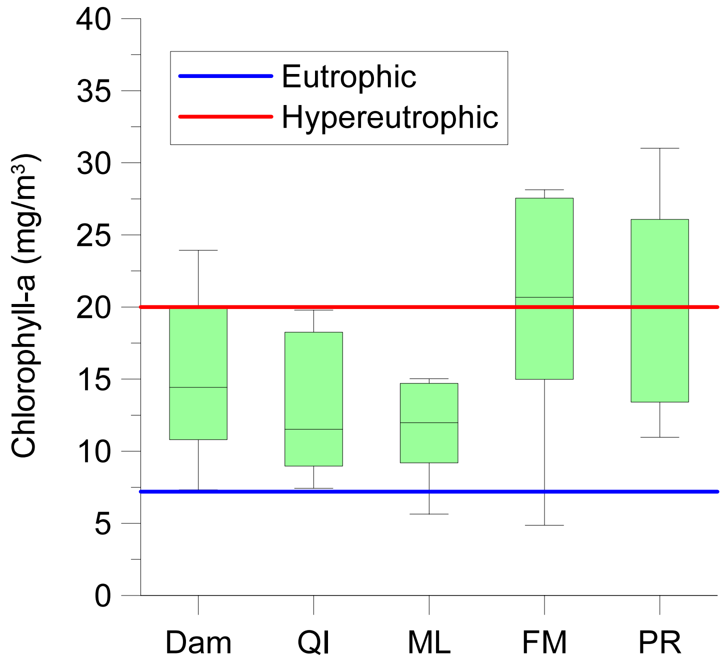

Figure 3.57: Surface Chlorophyll-a concentrations in mg/m^3, May 26 – October 13, 1993.

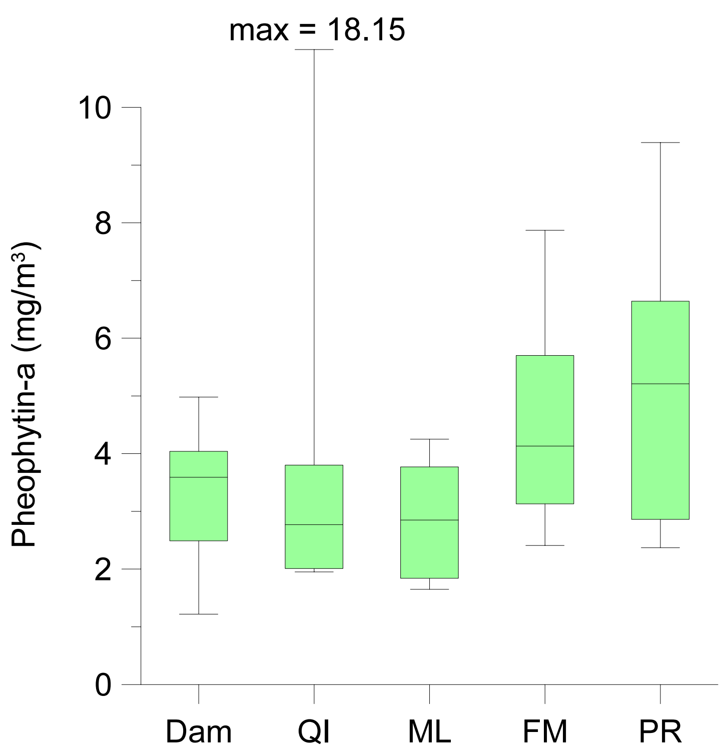

Figure 3.58: Surface Pheophytin-a Concentrations in mg/m^3, May 26 - October 13, 1993.

27% of chlorophyll-a samples for the whole lake were in the hypereutrophic range and 69% were eutrophic in 1993. In 2001, 55.8% of the samples were eutrophic and 32.6% were hypereutrophic.

In 2001, the whole-lake median chlorophyll-a concentration was 18 mg/m^3, with a median concentration above 20 mg/m^3 only at the Poteau River site. Median pheophytin-a concentrations were very similar with a range of 3 to 5 mg/m^3 in 1993 and 3 to 8 mg/m^3 in 2001.

Trophic State Index

In the historical studies (**Table 3.10**), whole-lake median TSI total phosphorus were consistently in the hypereutrophic range with little variation over time. TSI Secchi depth and TSI chlorophyll-a seemed to generally increase over time. TSI Secchi depth were above the 60 hypereutrophic boundary while TSI chlorophyll-a values were at the eutrophic/hypereutrophic boundary. The fact that nutrient concentrations were high, Secchi depth was low, and chlorophyll-a concentrations were high makes it likely that algal growth is light-limited. These trophic state indices are not conducive toward predicting nitrogen limitation.

Table 3.10: Historical median Trophic State Index values.

Data source	TSI total phosphorus	TSI Secchi depth	TSI chlorophyll-a
1974 NES	76	72	46
1977 305b	75	77	NA
1982 WBE	73	71	NA
1989-90 USACE	75	73	57
1992-94 OWRB	75	66	57
2001 OWRB	75	77	59

Statistical Comparison

A statistical comparison was made between 1993 and 2001 Lake Wister data to determine if temporal water quality changes in nutrient and sediment-related parameters were evident. Data was used from the stratified period between May and September for both data sets. Only surface and bottom samples were used to compare epilimnetic and hypolimnetic water quality, and only sites sampled during both time periods were used.

Normality tests indicated that the data were not normally distributed for every parameter during one or both years. Therefore we used a Mann-Whitney or 2-sample rank test, a nonparametric alternative to the 2-sample t test. Test results for parameters that showed a statistical difference between the two sampling periods are shown in **Table 3.11**.

Table 3.11: Statistical differences between 2001 and 1993 data.

	Epilimnion		Hypolimnion	
Parameter	**Change from 1993**	**p**	**Change from 1993**	**p**
Secchi depth	Lower	<0.01	NA	
Turbidity	Higher	<0.01	NA	
Kjeldahl Nitrogen	Higher	<0.01	Not Significant	
Total Phosphorus	Higher	<0.01	Higher	0.03
Ortho Phosphorus	Higher	<0.01	Higher	<0.01
Alkalinity	Lower	<0.01	Lower	<0.01
Sulfate	Higher	<0.01	Higher	<0.01
Suspended solids	Higher	0.01	Higher	<0.01
Settleable solids	Not Significant		Lower	<0.01

The magnitude of differences in the parameters with statistical differences on a lake-wide scale is summarized in **Table 3.12** below. For the nitrogen parameters of ammonia, nitrate, and nitrite, a statistical difference was also observed. These statistical conclusions were not reported because the difference between the reported detection limits for each sampling period was sufficient to explain the statistical significance. This explanation precluded inferences to ambient environmental conditions.

Table 3.12: Statistical Summary for 2001 and 1993.

Year	Parameter	Layer	Mean	Median	Std. Dev.	Min	Max	n
1993	Secchi Depth (cm)	S	63.47	66.00	30.74	4.6	137.2	45
2001	Secchi Depth (cm)	S	30.22	30.00	11.47	8	59	54
1993	Turbidity (NTU's)	S	18.23	9.10	22.42	3.6	120	40
2001	Turbidity (NTU's)	S	36.75	31.00	27.06	11	185	60
1993	Total Kjeldahl Nitrogen (mg/L)	E	0.58	0.55	0.18	0.37	1.04	16
2001	Total Kjeldahl Nitrogen (mg/L)	E	0.76	0.72	0.23	0.42	1.6	32
1993	Total Phosphorus (mg/L)	E	0.06	0.05	0.03	0.02	0.15	24
		H	0.18	0.15	0.12	0.05	0.49	24
2001	Total Phosphorus (mg/L)	E	0.12	0.11	0.06	0.06	0.29	24
		H	0.24	0.20	0.13	0.08	0.56	24
1993	Ortho-phosphorus (mg/L)	E	0.01	0.01	0.01	0.004	0.04	28
		H	0.05	0.04	0.04	0.004	0.13	28

Year	Parameter	Layer	Mean	Median	Std. Dev.	Min	Max	n
2001	Ortho-phosphorus (mg/L)	E	0.04	0.03	0.03	0.01	0.13	32
		H	0.08	0.08	0.04	0.03	0.17	32
1993	Total Alkalinity (mg/L)	E	18.28	19.58	5.29	7.5	25.5	28
		H	31.16	29.25	14.85	7.5	61	28
2001	Total Alkalinity (mg/L)	E	11.04	8.50	8.01	5	37.6	32
		H	10.43	5.00	8.98	5	39.3	32
1993	Sulfate (mg/L)	E	7.45	6.25	1.77	6.25	10	28
		H	8.06	6.25	3.75	6.25	25.1	28
2001	Sulfate (mg/L)	E	20.00	18.35	8.34	9.9	47.6	32
		H	33.10	27.25	28.61	14.4	181	32
1993	Total Suspended Solids (mg/L)	E	15.36	10.50	17.23	1	68	20
		H	36.92	24.00	34.66	8	160	20
2001	Total Suspended Solids (mg/L)	E	23.81	21.00	16.20	5	64	16
		H	82.25	67.00	48.07	24	172	16
1993	Total Settleable Solids (mg/L)	H	0.62	0.53	0.44	0.05	1.485	28
2001	Total Settleable Solids (mg/L)	H	0.10	0.05	0.11	0.05	0.45	32

Lake Wister Use Support Assessment Protocols (USAP)

Lake Wister and watershed are listed on the State's 303(d) list requiring completion of a Total Maximum Daily Load (TMDL). Oklahoma's Water Quality Standards (OWQS) are used as the benchmark to establish TMDL goals for waterbodies in Oklahoma. Wister and its watershed has also been identified as a Nutrient-Limited Watershed (NLW) in Appendix A of the Oklahoma Administrative Code (OAC) 785:45. One consequence of a NLW designation is the requirement to determine whether nutrient enrichment has impaired beneficial use or will impair beneficial use in the following two years. The OWRB worked in close concert with other state environmental agencies and other concerned parties to develop Use Support Assessment Protocols (USAP) to answer this need. The USAP has both temporal and spatial coverage requirements for lake assessment and is memorialized as Subchapter 16 of OAC 785:46. Data must be less than 10 years old to fulfill the temporal requirement. Tributary inflow, pollution sources and professional best judgement are the primary mitigating factors for site selection (spatial coverage element). A minimum of 20 samples is necessary to assess beneficial use support of water quality parameters such as dissolved oxygen and pH. The data reported for Wister Lake, May to October of 2001, fulfill many required elements for assessment under the USAP. Data collected through the Beneficial Use Monitoring Program (BUMP) were used to assess uses in the major tributaries to Wister Lake; the Poteau River and Fourche Maline Creek.

Lake Wister has five designated beneficial uses: 1) Fish & Wildlife Propagation/ Warm Water Aquatic Community, 2) Public/ Private Water Supply, 3) Agriculture, 4) Primary Body Contact Recreation and 5) Aesthetics. While beneficial uses are assessed this data set is not large enough to address whether the lake is impaired from nutrient inputs.

Fish & Wildlife Propagation

Three of the project parameters are used to assess Fish and Wildlife Propagation: dissolved oxygen, turbidity, and pH. Fish and Wildlife Propagation use support protocols are outlined in the Oklahoma Water Quality Standards (OWQS) 785:45-5-12. Screening levels and support tests are found in the OWQS 785:46-15-5. Failure of any one parameter results in an impaired assessment. In Wister Lake, Fish and Wildlife beneficial use is impaired due to low dissolved oxygen, low pH and excessive turbidity.

The Fish and Wildlife Propagation beneficial use is not supported for dissolved oxygen (DO). On July 24, 2001 greater than 63% of the water column was less than 0.2 mg/L-dissolved oxygen. To be concluded impaired, greater than 50% of the water column must be below 2 mg/L DO.

The Fish and Wildlife Propagation beneficial use was also is not supported for turbidity. Median turbidity in Lake Wister is 31 nephelometric turbidity units (NTU). The standard for the Fish and Wildlife Propagation beneficial use is 25 NTU. While turbidity is expected to elevate after a runoff event, the median value of 31 quantifies an overall impairment for turbidity.

Fish and Wildlife Propagation is partially supported for pH. 16% of pH values were outside of the allowable range of 6.5 to 9.0 units. To fully support Fish and Wildlife Propagation, no more than 10% of samples may fall outside the prescribed range. Based on vertical water profiles taken with the Hydrolab Surveyor® 4a, the average pH of Lake Wister is 7.2. Low pH values are associated with low alkalinity and pH of surrounding soils. It is likely that the low pH is exacerbated by bacterial decomposition of organic matter in the lake.

Primary Body Contact Recreation

Primary Body Contact Recreation (PBCR) beneficial use protocols are outlined in OWQS 785:45-5-16. PBCR beneficial use is a designation only during the recreational season, May 1 – September 30. Screening levels for bacteria are outlined in the Oklahoma Water Quality Standards 785:46-15-6. The PBCR beneficial use in Lake Wister is fully supported for fecal coliform, *Escherichia coli* and enterococci. The screening level for fecal coliform is the geometric mean of 400 colonies per 100 mL with no more than 25% of the values exceeding the screening level. *E. coli* values support the PBCR beneficial use. The screening level for *E. coli* is the geometric mean of 126 colonies per 100 mL with no values exceeding the screening level. The PBCR beneficial use is fully supported for enterococci since the geometric mean of 33 colonies per 100 ml is met, and no sample taken during the recreation season exceeded the screening level. Mean bacteria values for the sampling period are shown in
Table 3.13.

Table 3.13: Bacterial geometric means.

Site	Escherichia coli (Colonies/100 ml)	Fecal coliform (Colonies/100 ml)	Enterococci (Colonies/100 ml)
Dam	6.80	9.04	10.08
QI	8.11	7.77	8.37
ML	7.99	9.15	9.33
FM	10.85	17.74	19.29
PR	10.18	11.32	19.41
Total	**8.66**	**10.52**	**12.41**

Public and Private Water Supply

For the purposes of this study, only the coliform bacteria standard for Public and Private Water Supply beneficial use is applicable (OWQS 785:45-5-10(3)(D)): in cases where both public and private water supply and primary body contact recreation uses are designated, the primary body contact criteria will apply. Lake Wister does meet the standard for fecal coliform thus the beneficial use is supported.

Agriculture

Table 3.14 shows the guidelines for total dissolved solids (TDS), sulfate and chloride from Appendix F in OWQS 785:45. The Oklahoma Department of Environmental Quality (ODEQ) Laboratory analyzed at least 500 ml of each Lake Wister sample for TDS and sulfate. The TDS sample average was 25.99 mg/L. No standard has been set for total dissolved solids, however, and agricultural use support for TDS cannot be determined. The sulfate sample average through 10/17/01 was 23.54 mg/L. 7.69% of the samples were above 36 mg/L, the sample standard. Agriculture beneficial use is fully supported for sulfate because the average sulfate sample was less than the 36-mg/L sample standard and less than 10% of the samples exceeded the prescribed standard. Chloride was not a parameter sampled for this phase of the Lake Wister project.

Table 3.14: Appendix F from OWQS 785:45 for Lake Wister (all units mg/L).

Monitoring Station	Chloride Yearly Mean Standard	Chloride Sample Standard	Sulfate Yearly Mean Standard	Sulfate Sample Standard	TDS Yearly Mean Standard	TDS Sample Standard
247535	12	16	21	28	157	199
2485	12	15	22	29	157	199
24944	60	100	58	84	-	-
Average	20	31	28	36	-	-

Poteau River near Heavener

This station on the Poteau River (**Figure 3.59**) has been active for all water quality variables since November of 1998. The following assessment of beneficial uses is based on data collected from December of 1998 through September of 2001. For purposes of reporting, this station is representative of the Poteau River from its entrance into Oklahoma near Loving, Oklahoma downstream to the confluence of the Poteau River with Lake Wister. Appendix A of OAC 785:45 assigns the following designated beneficial uses to this segment of the river: 1) Public and Private Water Supply (PPWS), 2) Warm Water Aquatic Community—Fish and Wildlife Propagation (WWAC), 3) Agriculture—Class I Irrigation (AG), and 4) Primary Body Contact—Recreation (PBCR).

Figure 3.59: Poteau River near Heavener.

PPWS has two criteria, toxicants and bacteria. WWAC has five: dissolved oxygen, toxicants, pH, biological criteria such as degraded fish population, and turbidity. AG use assessment is based on chlorides, sulfates and total dissolved solids. Finally, PBCR assessment is dependent on levels of fecal coliform, *E. coli* and enterococci bacteria in the water.

The PPWS beneficial use is supported. The WWAC beneficial use is supported. Dissolved oxygen (**Figure 3.60**), pH (**Figure 3.61**), turbidity (**Figure 3.62**), and toxicant samples met the criteria prescribed in the WWAC beneficial use. The AG beneficial use is supported for total dissolved solids (**Figure 3.63**), chlorides, and sulfates (**Figure 3.64**). Although 13% of the TDS concentrations exceeded the sample standard of 199.0 mg/L, the values are below the minimum standard of 750 mg/L. Although 28% of the sulfate concentrations exceeded the sample standard of 36.0 mg/L, the values are below the minimum standard of 250 mg/L. The PBCR beneficial use is supported for fecal coliform, enterococci, and *E. coli*. This segment of the Poteau River is not nutrient-threatened. The total phosphorus and nitrate/nitrite median values were below the threshold medians of 0.36 mg/L and 5.0 mg/L, respectively (**Figure 3.65**).

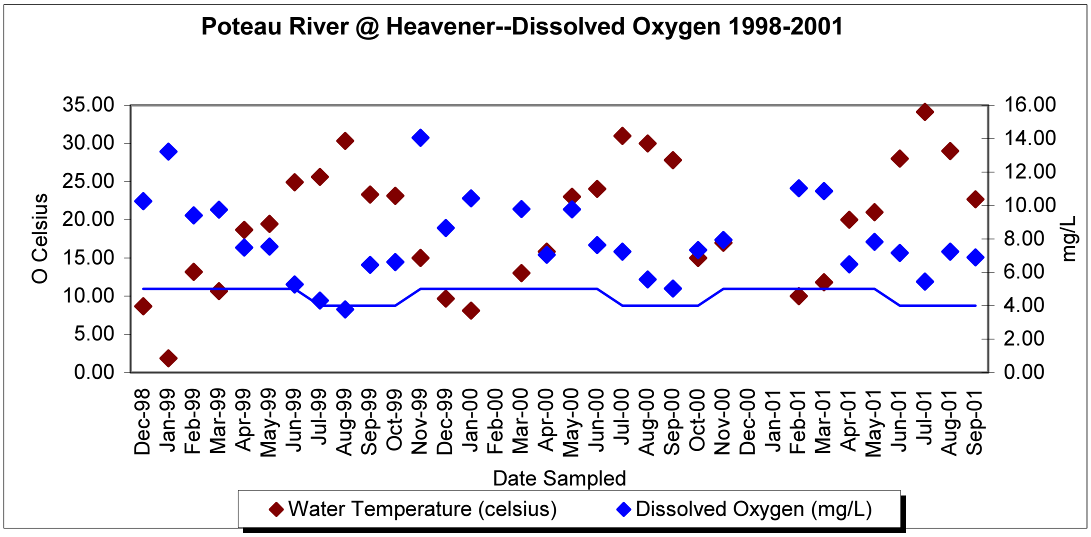

Figure 3.60: Dissolved Oxygen data for Poteau River station, 1998-2001.

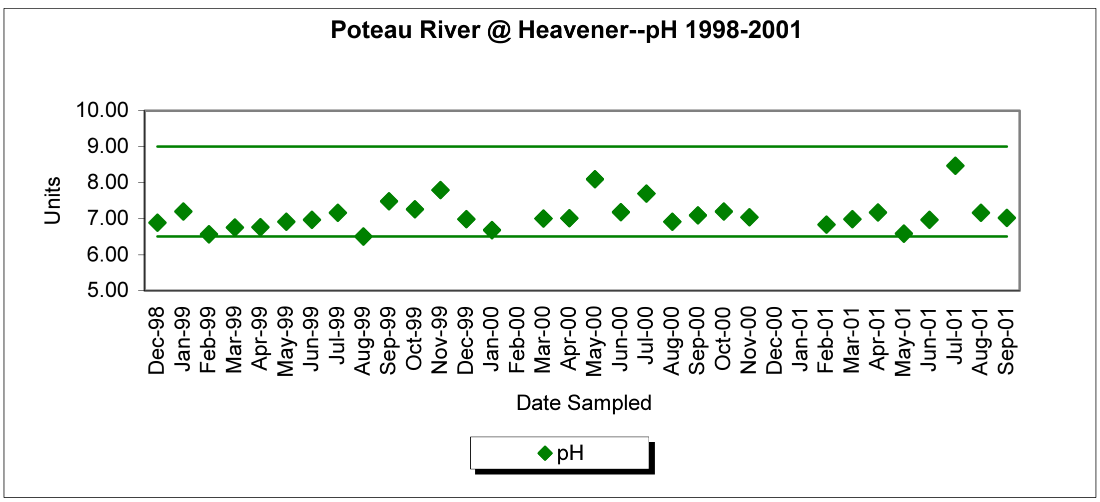

Figure 3.61: pH data for Poteau River station, 1998-2001.

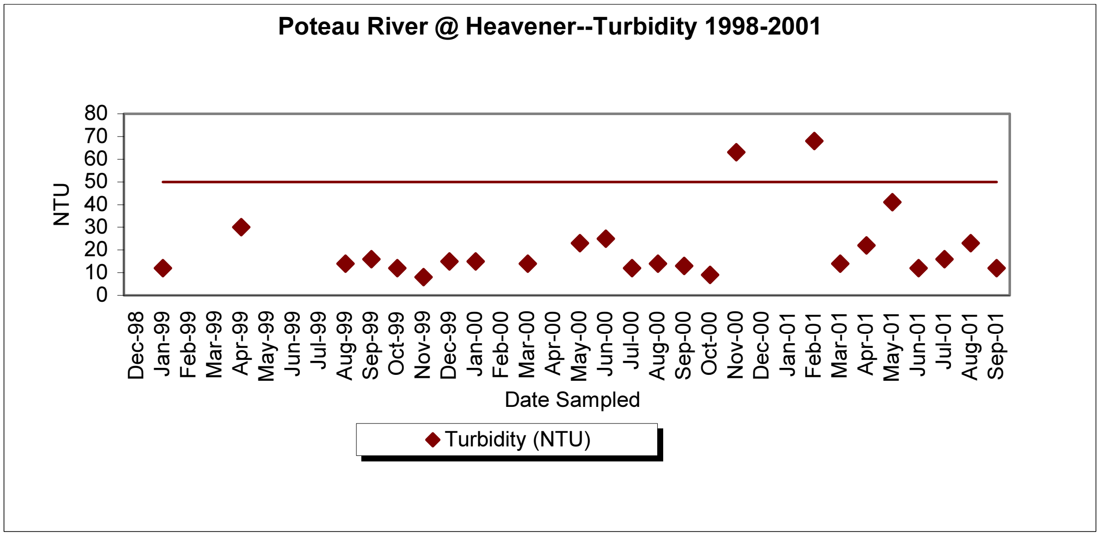

Figure 3.62: Turbidity data for Poteau River station, 1998-2001.

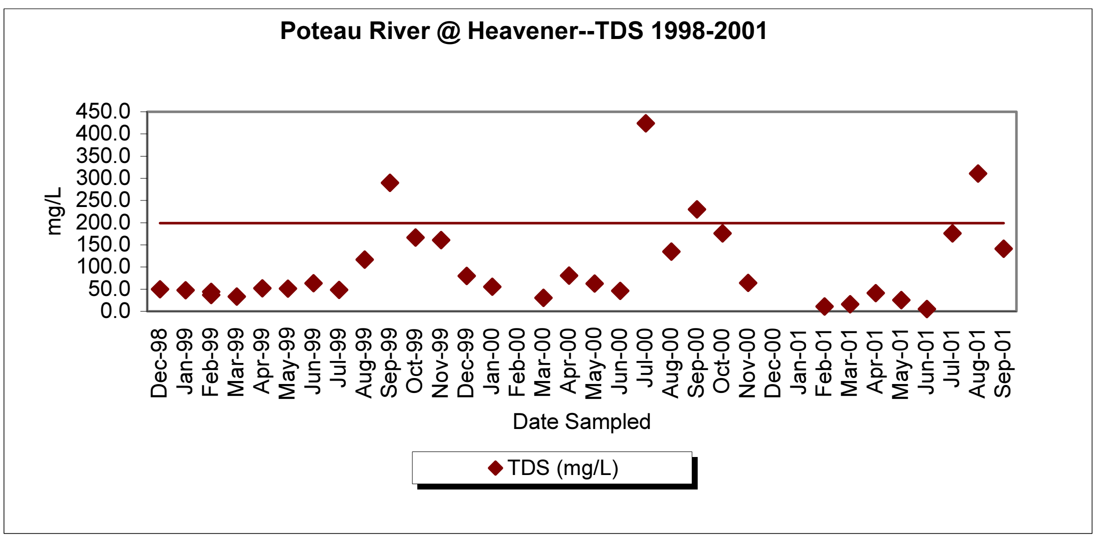

Figure 3.63: Total Dissolved Solids data for Poteau River station, 1998-2001.

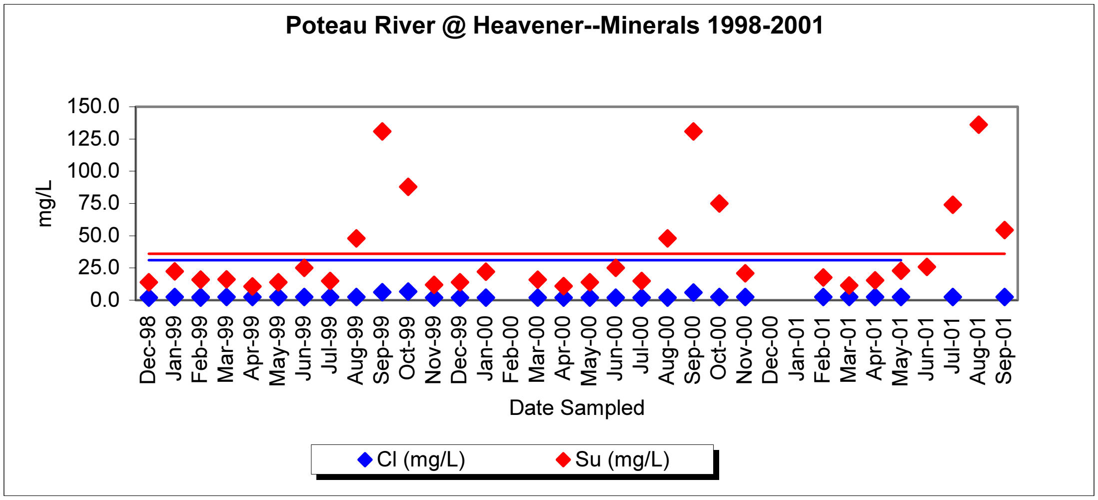

Figure 3.64: Chloride and Sulfate data for Poteau River station, 1998-2001.

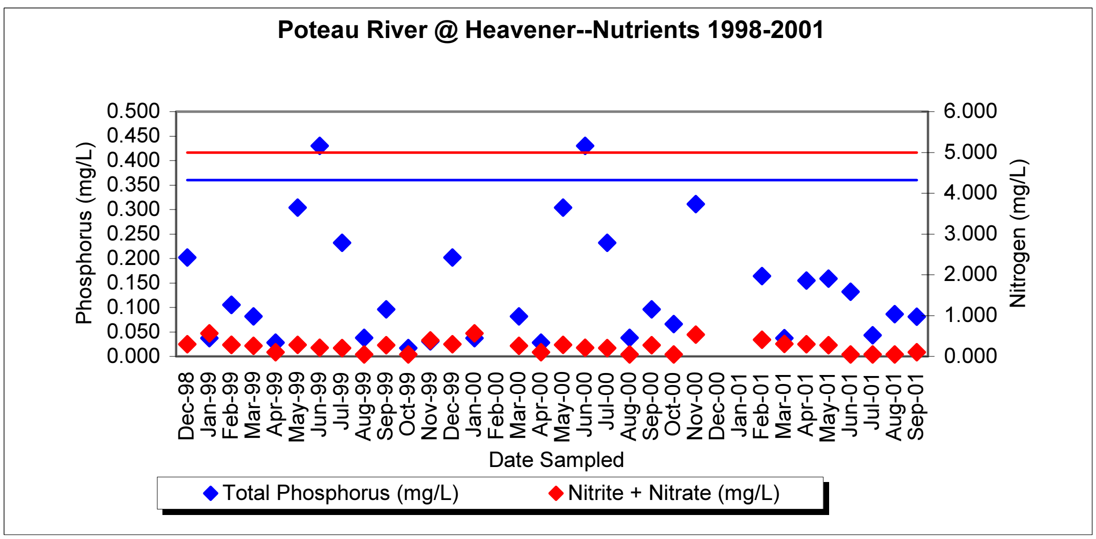

Figure 3.65: Nutrient data for Poteau River station, 1998-2001.

Fourche-Maline Creek near Red Oak

Figure 3.66: Fourche Maline Creek near Red Oak.

This station on Fourche-Maline Creek (**Figure 3.66**) has been active for all water quality variables since November of 1998. The following assessment of beneficial uses is based on data collected from December of 1998 through September of 2001. For purposes of reporting, this station is representative of Fourche-Maline Creek from the confluence of Coon Creek downstream to confluence of Spring Creek with Fourche-Maline Creek. Appendix A of OAC 785:45 assigns this segment the following designated beneficial uses: 1) Public and Private Water Supply (PPWS), 2) Warm Water Aquatic Community—Fish and Wildlife Propagation (WWAC), 3) Agriculture—Class I Irrigation (AG), and 4) Primary Body Contact—Recreation (PBCR).

PPWS has two criteria, toxicants and bacteria. WWAC has five: dissolved oxygen, toxicants, pH, biological criteria such as degraded fish population (not assessed here), and turbidity. AG use assessment is based on chlorides, sulfates and total dissolved solids. Finally, PBCR assessment is dependent on levels of fecal coliform, *E. coli* and enterococci bacteria in the water.

The PPWS beneficial use is supported for toxicants and bacteria. The WWAC beneficial use is not supported. Of the thirty (30) dissolved oxygen concentrations (**Figure 3.67**), fourteen (14) samples (or 47%) were below the screening level. Of the seven (7) toxicant samples collected, two (2) of the lead concentrations (or 29%) exceeded the prescribed hardness-dependant chronic criteria of 1.16 µg/L. The pH (**Figure 3.68**) samples met the criteria prescribed in the WWAC beneficial use. Of the twenty-one (21) turbidity samples (**Figure 3.69**), three (3) samples (or 14%) exceeded the numerical criteria of 50. The AG beneficial use is supported for total dissolved solids (**Figure 3.70**), chlorides, and sulfates (**Figure 3.71**). Although 13% of the sulfate concentrations exceeded the sample standard of 36.0 mg/L, the values are below the minimum standard of 250 mg/L. The PBCR beneficial use is not supported. Of the twelve (12) fecal coliform concentrations, four (4) samples (or 33%) exceeded the prescribed screening level of 400 cfu/mL. Of the 12 enterococci concentrations, 4 samples exceeded the prescribed screening level of 406 cfu/mL, and the geometric mean (224.0 cfu/mL) exceeded the prescribed mean standard of 33 cfu/mL. Of the 12 *E. coli* concentrations, 5 samples exceeded the prescribed screening level of 406 cfu/mL, and the geometric mean (183.9 cfu/mL) exceeded the prescribed mean standard of 126 cfu/mL. This segment of Fourche-Maline Creek is not nutrient-threatened. The total phosphorus and nitrate/nitrite median values were below the threshold medians of 0.36 mg/L and 5.0 mg/L, respectively (**Figure 3.72**).

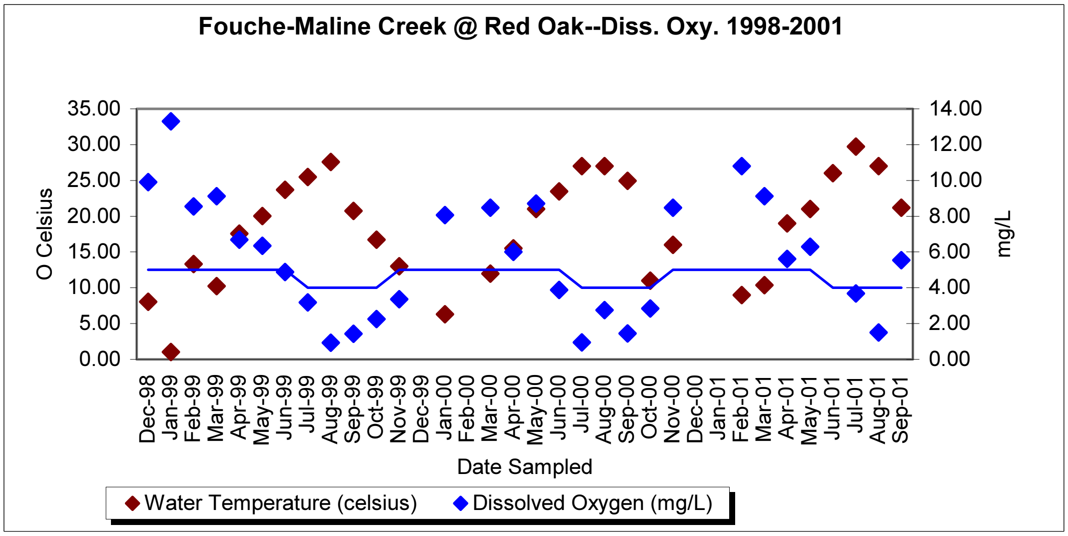

Figure 3.67: Dissolved Oxygen data for Fourche Maline Creek station, 1998-2001.

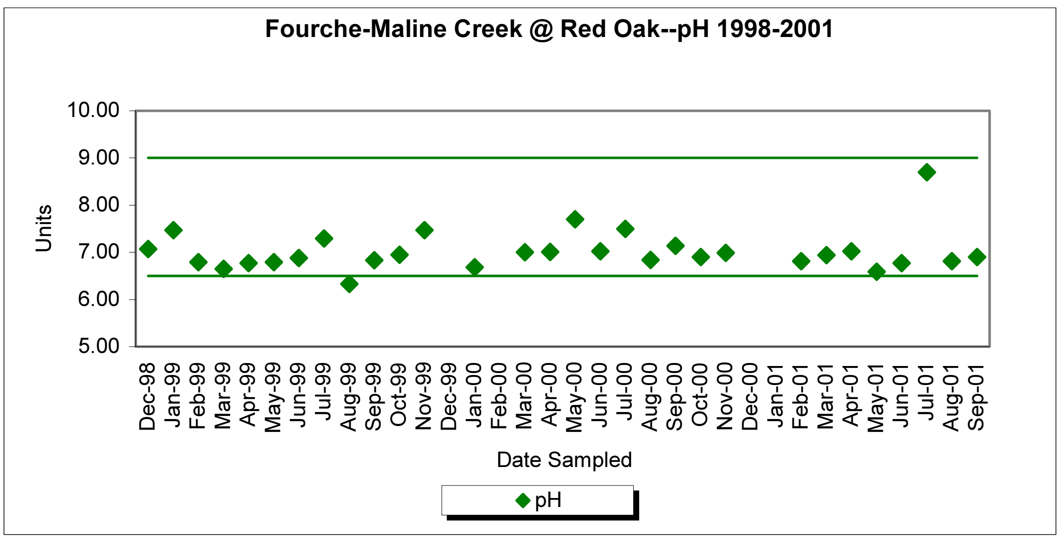

Figure 3.68: pH data for Fourche Maline Creek station, 1998-2001.

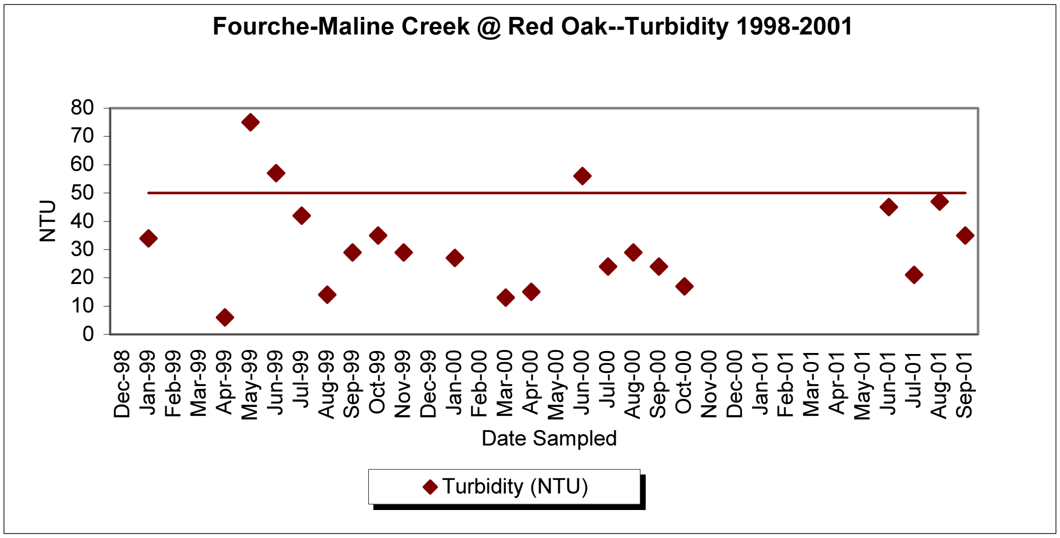

Figure 3.69: Turbidity data for Fourche Maline Creek station, 1998-2001.

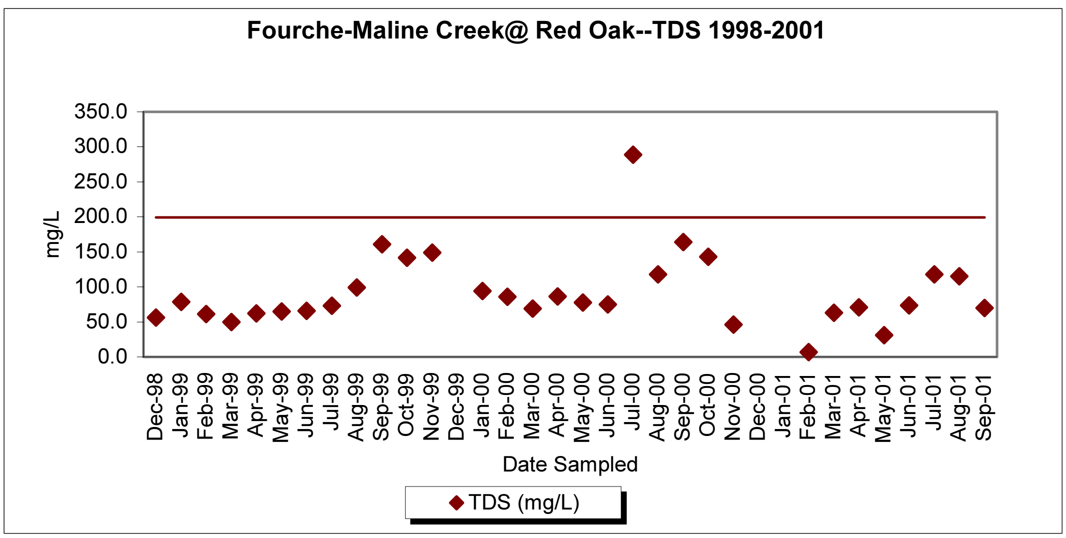

Figure 3.70: Total Dissolved Solids data for Fourche Maline Creek station, 1998-2001.

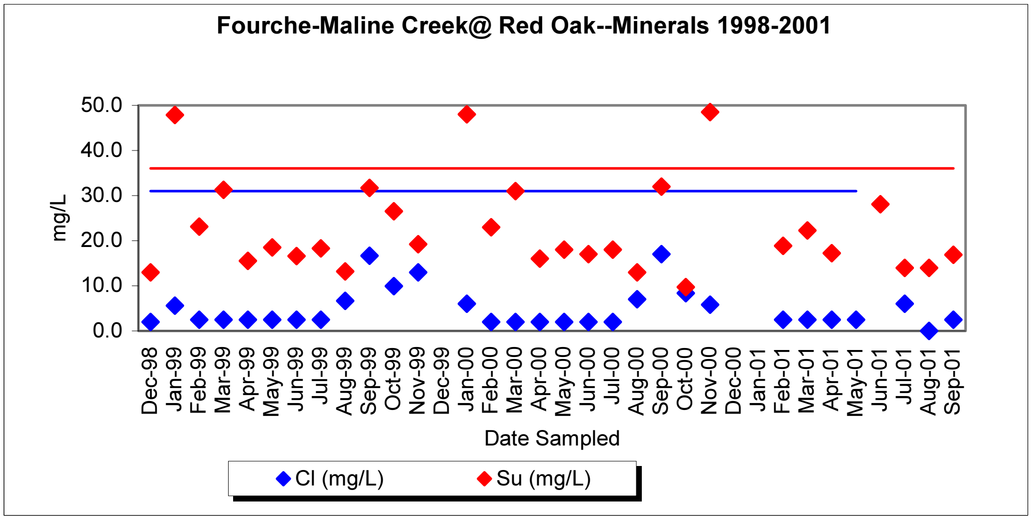

Figure 3.71: Chloride and Sulfate data for Fourche Maline Creek station, 1998-2001.

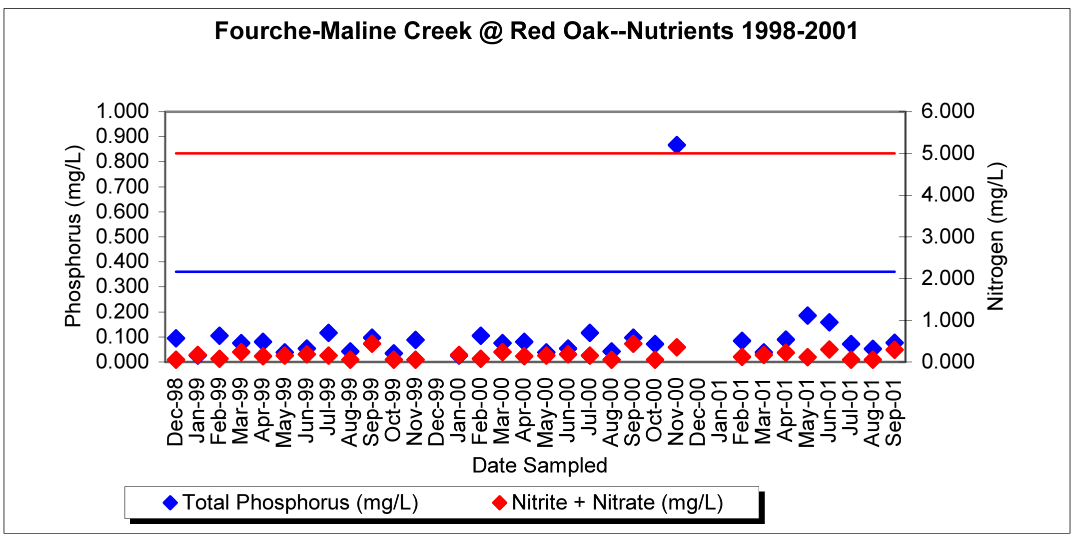

Figure 3.72: Nutrient data for Fourche Maline Creek station, 1998-2001.

Discussion

Oklahoma Water Quality Standards

Past problems in Lake Wister include accelerated eutrophication and excessive turbidity. These problems were stated in almost every report dealing with water quality in Lake Wister, as early as 1974. Wister is listed in the OWQS as a nutrient-limited watershed threatened by nutrient enrichment. Applying USAP to the 2001 lake data concludes beneficial uses for Fish and Wildlife Propagation are not supported due to excessive turbidity, low pH and low dissolved oxygen. In the major tributaries all assessed beneficial uses were supported but Warm Water Aquatic Community – Fish and Wildlife and Primary Body Contact – Recreation in the Fourche Maline Creek. Low dissolved oxygen, high lead and high bacteria concentrations contributed to the loss of these beneficial uses.

Data Comparisons

Historical median Secchi depths ranged from 25-50 cm. 2001 median Secchi depths were much lower, with a range of 17 – 35 cm, and a whole-lake median of 30 cm. Historical median turbidity values were below 15 NTU, whether considered annually or in the summer months. In 2001, turbidity was much higher, with site-specific medians of 22 – 65 NTU and a whole-lake median of 31 NTU. The maximum turbidity associated with baseflow conditions was 89 NTU. 72% of all samples were above the WQS criteria of 25 NTU.

Anaerobic hypolimnetic conditions have been observed since 1974 and have increased in recent years in duration and capacity (proximity to the lake's surface). Before 1992, the average depth below the surface at which anoxia began ranged from 4 – 6 m and did not last all summer. In 1992 – 1994 and 2001 sampling, anoxia was measured 2 – 4 m below the surface for 2 ½ to 3 months. The magnitude of anoxia is such that Fish and Wildlife propagation is threatened. Low dissolved oxygen also has a chemical impact to the lake. Under anoxic conditions nutrients and metals from the sediment solubilize into the water column. These nutrients add to the load from the watershed to stimulate algae growth. Dissolved metals from the sediment threaten water supply use through increased treatment costs by local water suppliers (City of Heavener and Poteau Valley Improvement Authority). Legislative changes of the conservation pool elevation, physical changes in lake size, can not account for these noted differences. Therefore, biological processes are an important factor towards the noted increase in duration and magnitude of anoxia.

High nutrient concentrations have been reported for Lake Wister consistently throughout historical sampling. In 2001 Wister had a whole-lake total nitrogen average of 1.04 mg/L and a total phosphorus average of 0.15 mg/L. Compared to trophic states and values reported by Vollenweider (1979), Lake Wister has a total nitrogen concentration similar to that reported for meso-eutrophic to eutrophic reservoirs and a total phosphorus concentration similar to that reported for eutrophic to hypereutrophic reservoirs. Nitrogen was the predicted limiting chemical nutrient for Wister Lake during the summer months of 2001. Implications of nitrogen limitation are an algae community dominated by nitrogen fixing blue-green algae and higher probability and occurrences of taste and odor events in the finished drinking water produced from Wister Lake.

Chlorophyll-a was measured in 2001 at eutrophic to hypereutrophic levels of up to 75.7 mg/m^3, indicating excessive algae growth. The whole-lake median for 2001 was 18 mg/m^3, corresponding to a TSI of 59, where a TSI of 60 is hypereutrophic. As sampled in the EPA's National Eutrophication Survey, chlorophyll-a concentrations in 1974 were around 5 mg/m^3, with a maximum of 8 mg/m^3. In 1989-90 and 1992-94, whole-lake median chlorophyll-a concentrations were around 15 mg/m^3, with maxima of 31 and 40 mg/m^3. 55.8% of 2001 summer samples were in the eutrophic range and 32.6% were hypereutrophic, and 69% of 1993 summer samples were in the eutrophic range and 27% were hypereutrophic showing Lake Wister sustains a high level of algae growth. In addition, pheophytin-a was measured at high concentrations of up to 50.5 mg/m^3 in 2001 and 18 mg/m^3 in 1993. Median pheophytin-a concentrations ranged from 3 to 8 mg/m^3 in 2001 and 3 to 5 mg/m^3 in 1993. These high pheophytin-a concentrations indicate high algal growth and turnover rates. Algae blooms and die-offs substantiate the NLW designation of Lake Wister.

Statistical comparisons between 2001 and 1993 data showed total kjeldahl nitrogen at the surface, and total and ortho-phosphorus throughout the water column were significantly higher in 2001. Sulfate throughout the water column also increased, accompanied by a decrease in alkalinity. Regarding sediment-related parameters, 2001 samples had significantly higher turbidity and lower Secchi depths than 1993, and suspended solids throughout the water column increased, and settleable solids in the hypolimnion decreased. Although nitrogen was the chemical-limiting nutrient, there is also evidence for light limitation of algae growth in Wister Lake.

Summary

High turbidity and low Secchi depths, along with high phosphorus concentrations in the lake, indicate that light and nitrogen limited algal growth in Lake Wister. Release of light limitation was noted (with concurrent algae bloom indicators) during calm periods. These calm periods were also concurrent with no storm runoff rather than or in addition to when nutrients are added to the system. This indicates the need to reduce in-lake nutrient concentrations. Examination of nutrient ratios and amounts of dissolved nutrients indicate that nitrogen was the limiting chemical nutrient during most of the monitoring period (June – September). Major changes in water quality over time include increased turbidity, increased chlorophyll-a concentrations, and the increased magnitude of anoxic hypolimnetic duration and volume. Nutrient concentrations appear to be fairly consistent with historical data although internal loading of nutrients from the sediment will increase with increased hypolimnetic anoxia. Since the 1992-94 OWRB study, differences in water quality include higher nutrient concentrations, increased sediment and suspended solids, increased sulfate concentrations, and decreased alkalinity. Increased productivity (algae growth) concurrent with increased turbidity is a disturbing trend for Wister Lake and bodes ill for beneficial uses of Wister Lake.

Task 4: Bathymetry

Lake Wister has a history of varied and increasing conservation pool elevations. Most of these conservation pool changes have occurred relatively recently in the life of Lake Wister. The pool elevation for Lake Wister from 1949 to 1982 was 471.6 mean sea level (MSL). In 1983 Public Law 98-63 permanently raised the pool elevation to 474.6 MSL. That law also required that the previous, discretionary seasonal pool operation, which raised the conservation pool to 478.0 from June through December, be continued indefinitely. After the completion of a reconnaissance study in September 1993, Public Law 103-126 directed that a minimum conservation pool of 475.5 at Lake Wister be maintained during FY 1994. Additional legislation in FY 1995, FY 1996, and FY1997 continued the temporary 1-foot increase to elevation 475.5. Subsequently, the Water Resources Development Act (WRDA, 1996) permanently raised the conservation pool to 478.0 feet in 1996. These legislated changes in conservation pool elevation have modified lake hydrology.

To exhibit changes in lake hydrology, annual hydraulic residence times were computed for Wister at the three different annual pool elevations: 471.6, 474.6, and 478 MSL. Residence times (**Table 4.1**) were calculated using annual lake outflow statistics from 1994 to 2001and capacity for each elevation using the 2001 bathymetric data (dividing by discharge volume). Lake Wister a short annual residence time of 22 days at the current 478 MSL pool elevation. At past pool elevations, the residence time was even shorter, with 8 days at an elevation of 471.4 feet and 14 days at 474.6 feet using the same release scheme. Increasing conservation pool elevation from 471.6 MSL to 474.6 MSL had the theoretical effect of increasing the residence by a factor of 1.75. Increasing the conservation pool to 478 had the potential to increase residence time by a factor of 2.75. Changing residence time for a reservoir should affect the rate and location of sedimentation within Wister Lake. Associated factors such as sediment suspension and algae growth may also be effected.

Table 4.1: Lake Wister estimated annual hydraulic residence times with variable conservation pool elevations.

Pool elevation (ft)	Hydraulic residence time (days)		
	Mean	Median	Standard deviation
478	21.94	21.76	6.86
474.6	13.57	13.46	4.24
471.6	8.17	8.10	2.55

The purpose of this task was to create a bathymetric map of Lake Wister. Information obtained was compared to previous sedimentation surveys and assisted in the development of a suspended solids control plan. The 2001 Lake Wister bathymetric survey indicates a 6,077-acre lake with a shoreline length of 76.34 miles and a pool volume of 46,848 acre-feet at 478 MSL.

OWRB Surveying History

The Oklahoma Water Resources Board (OWRB) bathymetric mapping program began in 1999 when the agency contracted with the City of Oklahoma City to map their water supply reservoirs. This project included Lakes Atoka, Hefner, McGee Creek, Overholser, and Stanley Draper. The OWRB also completed bathymetric studies for the City of Tulsa on Lakes Eucha and Spavinaw, and for the City of Fredrick on their water supply reservoir. Bathymetric studies were also performed on Lakes Sardis and Hugo for the Kiamichi River Development Project. The OWRB has just recently completed surveys on Lakes Murray and Thunderbird.

Hydrographic Surveying Technology

Equipment Used in Mapping:

- Trimble Global Positioning System AG122 (GPS) (sub meter accuracy)
- Bathy 1500 Survey Echo Sounder with 10 degree transducer (±2.5 cm accuracy)
- Coastal Oceanographics, Inc. Hypack Software
- Rocky Ruggedized Field Notebook Computer
- Survey Vessel

Trimble Global Position System AG122 (GPS)

GPS is a relatively new technology that uses a network of satellites, maintained in precise orbits around the earth, to determine exact locations on the earth's surface. GPS receivers continuously monitor broadcasts from satellites to determine the position of the receiver. During OWRB's surveys approximately five to seven satellites are locked in on the receiver at one time to ensure the greatest level of accuracy.

The accuracy of the positions recorded is dependent on the number of transponders (satellites) used, the geographical arrangement of the transponders, positional accuracy of the transponder location, and the quality of the signals received. A twelve-channel GPS system that can achieve differential GPS was used for the survey of Lake Wister. The increased number of channels provides for better tracking of satellites under conditions of signal interference. Potential errors are reduced with differential GPS because additional data from a reference GPS receiver at a known position is used to correct positions obtained during the survey. The reference station used in the Wister survey is located near Sallisaw, Oklahoma. The reference beacon system transmitted corrected signals in real time, so no post-processing corrections were needed for the position data that was collected throughout the survey.

Bathy 1500 Survey Echo Sounder

Figure 4.1: Mud flats in Poteau River arm of Lake Wister.

Wister's shallow flats and submersed islands (**Figure 4.1**) made the purchase of a new, more precise depth sounder essential to the production of this task. A Bathy 1500 Survey Echo Sounder was obtained in summer of 2001. The new depth sounder allowed for shallow-water surveying to take place. Depths of .5 ft with an accuracy of ±2.5 cm can be recorded in optimal conditions. The display on the depth sounder shows both an acoustic rendering of the lake bottom and a digitized depth reading. With the sounding equipment on, the speed of sound can be adjusted until the digitized depth equals the measured (acoustic) water depth for quality assurance purposes.

Coastal Oceanographics, Inc. Hypack Software

Hypack 8.9 was the hydrographic survey software used to map Lake Wister. The computer software merges the calculated position with the digitized depth sounding obtained from the sounder. Hypack software improves the efficiency of data collection by allowing the boat operator to display shoreline, virtual track lines, heading, speed, depth, and position while collecting data.

Rocky Ruggedized Field Notebook Computer

Position data as well as depth are recorded and stored on an Amrel Rocky field notebook computer. Depth is exported from the depth sounder to the notebook via a RS232 serial port. Position data is taken from the GPS and recorded to the notebook by a USB serial port adapter.

Survey Vessel

A 1989 Predator 180 with a 90 hp, 4-stroke outboard engine was the survey vessel used. The vessel has a restricted depth of ≤ 2 feet.

Methods

As the boat travels across the lake surface, the depth sounder gathers approximately one reading every 300 milliseconds (ms), or 0.3 seconds (s), from the lake bottom. The depth readings are stored on the survey vessel's on-board computer along with the corrected positional data generated from the boat's GPS receiver. The daily data files collected are downloaded from the computer and brought to the office for editing after the survey is completed. During editing, data "noise" is removed or corrected, and average depths are converted to elevation readings based on the daily-recorded lake elevation on the day the survey was performed. Accurate estimates of the lake volume can be quickly determined by building a 3-D model of the reservoir from the collected data. The level of accuracy of the new technology allows for better determinations of lake volume.

The Bathymetric survey conducted consisted of four successive procedures.

1.) Setup
2.) Field Survey
3.) Post-processing collected data
4.) Exportation of data into GIS format

1.) Setup

Creating a reservoir boundary (shoreline) is one of the primary steps involved in conducting a bathymetric survey. A total of 6 digital orthophoto quadrangles (DOQQ) were used for a complete coverage of Lake Wister. All 6 were taken on March 23rd 1995 near pool elevation 475.7 feet MSL . This lake elevation was considerably lower (by 2.3 feet) than the boundary file requirement of 478 MSL. To compensate for this difference, field staff was consulted by the digitizing staff for identifying patterns for the 478 MSL boundary in the existing DOQQ. In this manner a digitized boundary of Lake Wister was produced from the 6 digital orthophoto quarter quadrangles at a scale of 1:3000. The reservoir boundary was digitized in Universal Transverse Mercator (UTM) zone 15 projection, then reprojected to State Plane Coordinates (Oklahoma South). This conversion from UTM to State Plane is necessary for map units to be transformed from meters to feet. The conversion is a requirement of the survey software used. OWRB staff noted that lake surface area could be under estimated because of the DOQQs used and the lack of a standard to measure the prepared boundary file.

Hypack Max version 00.5B software from Coastal Oceanographics, Inc., is used to create virtual track lines that are laid across a digital rendering of the reservoir with GPS (XY) coordinates. These virtual track lines are spaced according to the accuracy required for each project. The virtual track lines for Lake Wister were at 300-foot increments and ran perpendicular to the shoreline. Approximately 198 virtual track lines were created for the Wister project. Closely spaced virtual track lines result in the collection of a large number of data points.

2.) Field Surveying

Field Surveying consists of equipment calibration and data collection. Calibration is the process of testing the accuracy of depth readings and adjusting the speed of sound accordingly (Rogala,1999). Distance (depth) determinations are based on the travel time of a reflected pulse from the transducer. Inconsistencies in readings due to certain water quality parameters must be adjusted for before setting out to survey. Salinity and water temperature account for most of the variability. A 2’X3’X1/4” sheet of aluminum was used for calibration. This method involves lowering the sheet of aluminum to precisely 5 feet below the transducer. The speed of sound is then adjusted so that the digitized reading equals the acoustic reading (5 feet) on the depth sounder. This calibration was performed daily prior to surveying Wister.

To start data collection the survey vessel is steered to follow the virtual track lines (displayed on the field computer screen) across the lake. Shoreline data is also collected two or three feet (or as close as the boat allows) offshore where applicable. Distances off the virtual transect line (offsets) and distances along the track line are displayed on the computer to guide the boat operator (Rogala,1999). To map a cove, or the backwaters of the Poteau River and Fourche Maline Creek, data lines are recorded in a zigzag method and along the thalweg of the channel.

This method is a way to record data when maneuverability is an issue. Areas with depths less than the minimum depth limit of the boat are avoided. The zigzag method of collecting lines will also allow for the best representation of the river channels, which will be misrepresented on 300 ft-increment track lines. Only increased data collection will accurately identify such small areas.

Hypack Max software coordinates the GPS (XY) point and the depth reading (Z) collected every 300 ms while navigating each virtual track line. Point data density is dependent on boat speed. The raw data is collected in Oklahoma South State Plane Coordinate System. In this mode the XYZ coordinates are collected in feet. The method used to interpolate the contours from XYZ point data was the CONTOUR WIZARD in ARCINFO's Arc Toolbox under Analysis Tools. The Contour Wizard runs the Arc LATTICECONTOUR command if the input surface is a grid. In our case we used a grid, which was created from the data points we collected on the lake, and the points generated from the boundary file. Hypack software was used to display the map of the reservoir, the virtual track lines, and store all data points.

3.) Post processing collected data

Data is first downloaded from the field notebook to one of the desktop Hypack Max version 00.5B programs. After download, reviewing of data for accuracy and completeness using the Hypack Single Beam Editing program begins. This editing program displays each virtual line and the profile of the data collected for that line. Collected points on each line that are inaccurate ("noise") are integrated with adjacent accurate points. Fluctuations in lake levels during the data collection process are also adjusted during this phase. This is done by recording the lake elevations for each date that the surveying took place and then adjusting the raw depth (Z) values. Once the raw data is corrected it is then sorted on a five foot radius, saved, and exported as an *.XYZ file. The XYZ data file was then imported into Excel where it is saved as a *.XLS which can then be brought into ArcView 3.2x.

4.) Exportation of data into GIS format

In ArcView 3.2x the data is rendered into a map, such as a contour map, or some other form of graphical representation to satisfy the needs of the project. Volume calculations can then be made and compared to original volumes and/or projected volumes to determine current reliable yield.

Results and Discussion

Data collection occurred in 2001 on October 17-19, 23, November 5-7, 14-16, and December 3-4. A total of two hundred fifty nine transect lines were collected during this period. **Figure 4.2** shows the data points recorded during the survey. These points were then used to create a bathymetric map.

181,247 data points were used to create the Wister bathymetric map. The majority of the points (156,805) were collected/edited/sorted from the data collected by the survey vessel. Another 23,342 points came from the digitized boundary of Lake Wister while the remaining 1,100 points were added in. The points added in were due to shallow water areas as well as stumpy areas where the survey vessel was not capable of navigation.

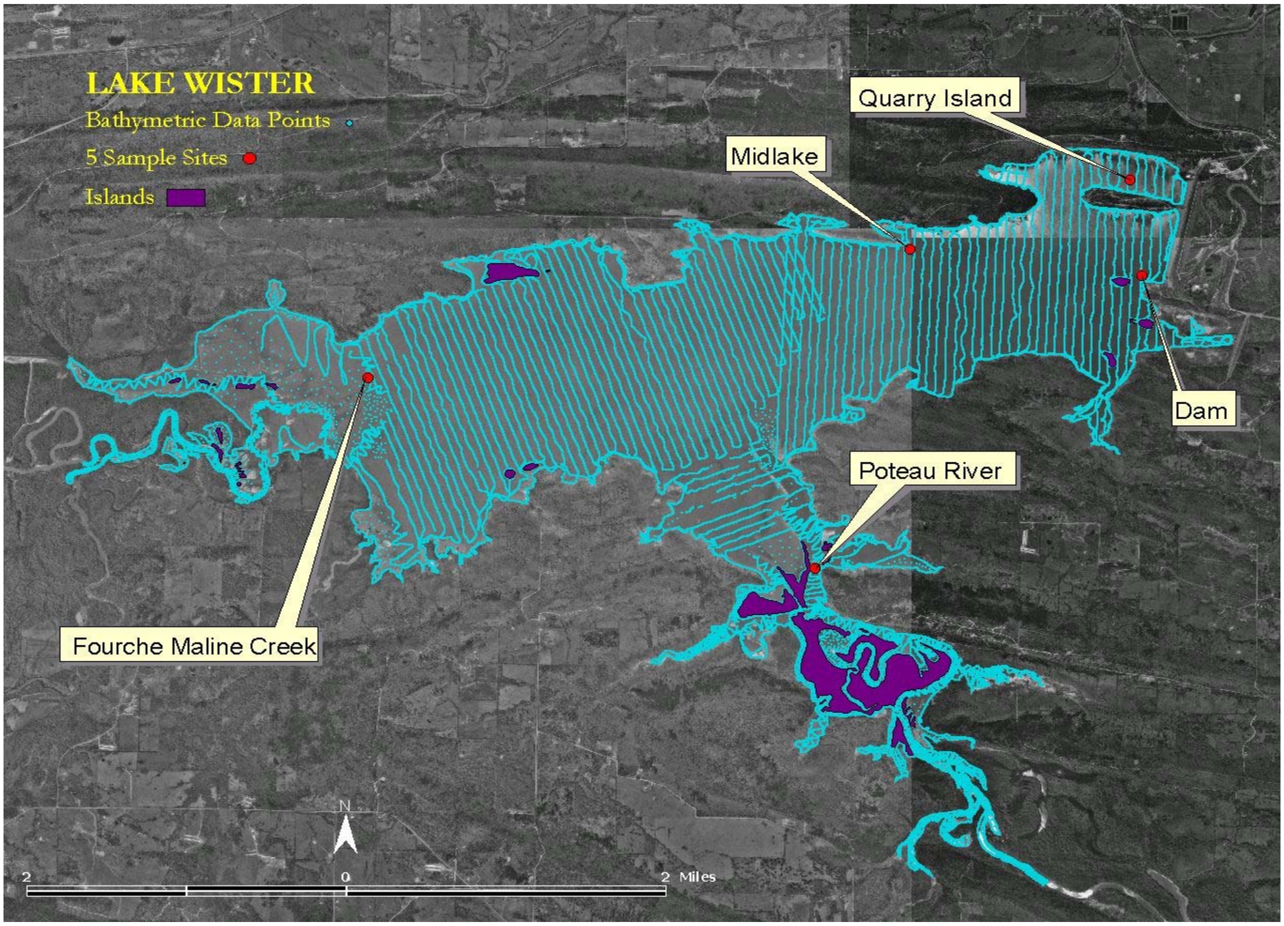

Figure 4.2: Data points collected along virtual transect lines, 2001.

The total number of points was then used to interpolate a lake bottom surface grid comprised of 10-foot by 10-foot cells. Each cell has a single depth value. These cells were used to compute the lake volume, maximum and average depths (**Table 4.2**).

Table 4.2: GIS calculated statistics of Lake Wister 2001.

Lake Wister GRID Calculations (10 ft. cells)		
Volume	47,414.471 ac-ft	
Maximum Depth	-39.038 ft	
Average Depth	-7.401 ft	
Depth Range (m)	**Count**	**Area (acres/range)**
0-1	1	1357.31
1-2	54	1678.63
2-3	114	1246.819
3-4	66	826.252
4-5	86	457.491
5-6	147	247.437
6-7	132	142.274

7-8	133	75.471
8-9	90	26.654
9-10	66	12.368
10-11	44	5.508
11-12	28	1.643
		6077.308

A contour map for Lake Wister was produced by integrating area measurements with depth and allowed for capacity to be broken into intervals **Figure 4.3**. This map gives contours appropriate to the lake bottom morphometry. The areas covered by each depth contour are given in the map key. Islands within Lake Wister are listed on the map as well.

GIS results from the 2001 OWRB bathymetric survey indicates Lake Wister encompasses 6,077 surface acres and contains a volume of 47,414 acre-feet at the conservation pool elevation of 478.0 feet. The shoreline was calculated from the digitized reservoir boundary to be 76.34 miles at conservation pool elevation. The maximum depth of -39.84 was collected approximately 3,209 feet WNW from the primary spillway. The maximum depth recorded from the GRID calculations was -39.038 feet with an average depth of -7.4 feet. Metadata is available upon request through the Information Services Section at the Oklahoma Water Resources Board. Although these GIS applications are considered accurate additional morphometric methods were applied to ensure the precision of morphometric estimates.

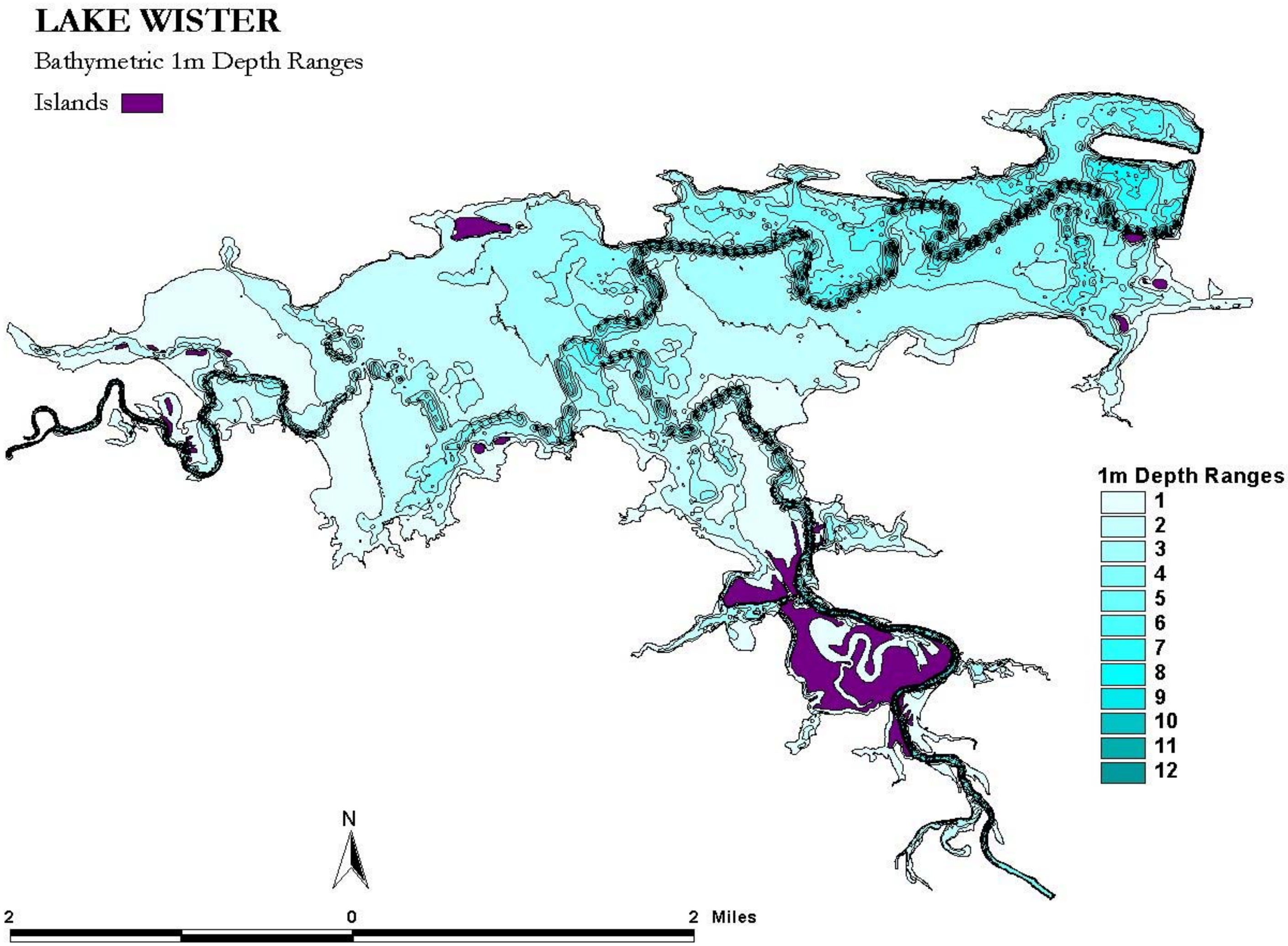

Figure 4.3: 1-Meter interval bathymetric map of Lake Wister 2001.

A graphical display was produced to show area distribution in Lake Wister. Methods outlined by Håkanson (1981) were used to provide the most accurate capacity possible following GIS applications with additional morphometric features calculated. (**Table 4.3**). In short, GIS generated areas were used to construct a cumulative area table dictated by a Håkanson model that predicted the optimal contour interval (**Figure 4.4**). Additional Håkanson models determined the appropriate method to integrate areas into capacity as well as yielding an estimate of capacity error. Once cumulative capacity had been corrected the percent cumulative capacity curve generated from Håkanson's initial determination was used to distribute the total corrected capacity with depth (**Figure 4.5**). The relative percent error for capacity, our correction factor, was –1.23%. The percent error in area determinations for Lake Wister was 5.6%. **Table 4. 4** shows the tabular summary of area and corrected capacity broken by depth intervals. Once capacity corrections were completed comparisons to previous surveys were possible.

Table 4.3: Lake Wister morphometric parameters, 2001.

Morphometric feature	Measurement
Max depth (ft)	39.80
Max depth (m)	12.13
Capacity (acre-feet)	46,838
Capacity (m^3)	57,774,468
Perimeter (ft)	403,073
Perimeter (km)	122.9
Area (ft^2)	264,716,478
Area (m^2)	24,601,903
Area (acres)	6077
Area (km^2)	24.59
Mean Depth (ft)	7.71
Mean Depth (m)	2.35

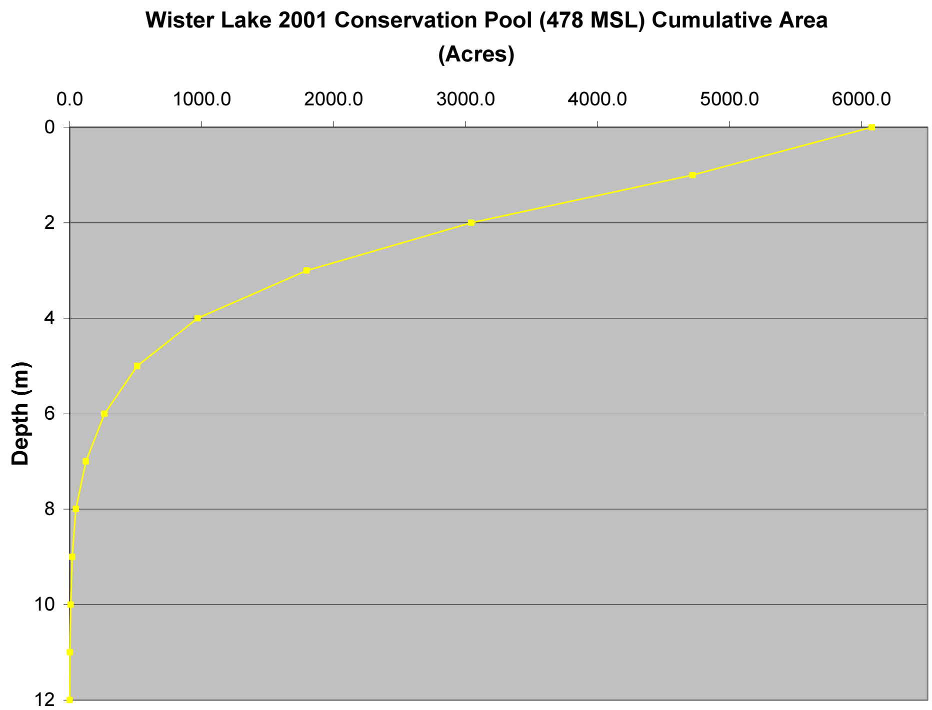

Figure 4.4: Lake Wister 2001 GIS generated cumulative area using Håkanson predicted (1 meter) contour intervals.

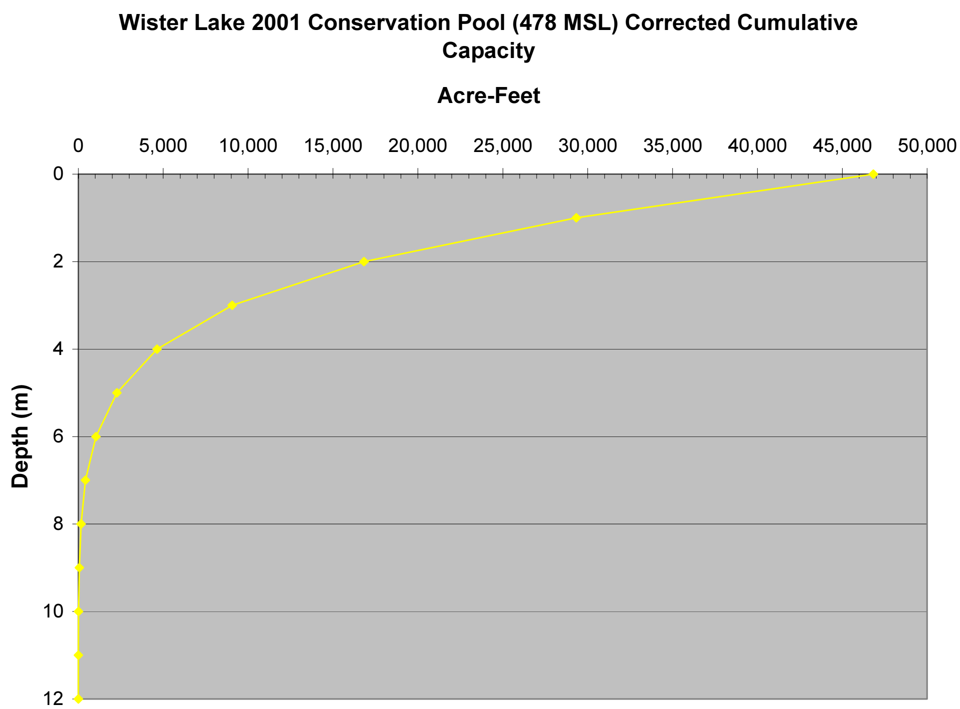

Figure 4.5: Wister Lake 2001 Corrected Cumulative Capacity Curve.

Table 4.4: Tabular summary of area and capacity versus depth of Lake Wister 2001.

Depth (meters)	Cumulative Area (acres)	Cumulative Volume (acre-feet)
0-1	6077.9	46838
1-2	4720.5	29341
2-3	3041.9	16830
3-4	1795.1	9060
4-5	968.8	4638
5-6	511.4	2273
6-7	263.9	1035
7-8	121.6	423
8-9	46.2	160
9-10	19.5	57
10-11	7.2	15
11-12	1.6	2
12-13	0.0	0

U.S. Army Corps of Engineers (USACE) sedimentation data for the years 1949, 1972, and 1985 was obtained and compared to the 2001 data set for purposes of bathymetric evaluation **(USACE 1990)**. No data were collected above 478 MSL eliminating the ability to evaluate sedimentation in the flood pool (above 478 MSL). Comparing 1985 to 2001 Lake Wister 478 MSL data for surface area, capacity, and maximum depth showed surface area decreased by 1,309 acres (–17.7 %), storage capacity decreased by 14,858 acre feet (–23.7%) and maximum depth decreasing 4.16 feet (–9.5%). **Table 4.5** summarizes the combined data for 478-pool elevation. During the first 23 years of reservoir operation (1949-1972), maximum depth reduced 11 feet, mean depth decreased 1 foot, and 4,500 acre-feet of sediment was deposited. From 1972 to 1985, there was no significant change in maximum or mean depth showing decreased sedimentation within Wister Reservoir. This most recent time interval suggests increased sedimentation over time.

Table 4.5: Selected morphometric features as they relate to sedimentation.

MORPHOMETRIC MEASURE AT 478 MSL	SURVEY YEAR			
	1949	1972	1985	2001
Area (acres)	7,342	7,532	7,386	6,078
Cumulative Volume (acre-feet)	66,887	61,274	61,423	46,838
Maximum Depth (feet)	55	44	44	39.5
Mean Depth (feet)	9.1	8.1	8.3	7.7
Net volume change (acre-feet) *		-5,613	149	-14,585
Annualized net sedimentation rate (acre-feet) *		-66	11	-875

* Volume change and rate calculations are between survey periods.

Reporting from the 1985 survey data showed sedimentation below 478 MSL to be negligible while sedimentation above 478 was significant (OWRB, 1996). This disparate distribution of sedimentation was explained by deposition in the flood pool elevations by pooling floodwaters with a low residence time while in the conservation pool. No evaluation of the flood pool elevation above 478 MSL was possible this last survey period. The annualized 1985 – 2001 sedimentation rate for the conservation pool yielded a much higher rate than seen before, 875 acre-feet per year. The higher sedimentation rate closely brackets the major legislated changes in pool operation: 3-foot rise (to 474.6) in 1983 and an additional 3.4 feet rise in 1993. These indicate that although recent raise of pool elevation has increased erosive processes in the shallowest portion of the lake, while net sedimentation has increased.

Summary

From the data collected, future surveys will be able to determine the location and rates of sediment deposition in the conservation pool over time. Due to the fluctuation in conservation pool elevations over the years, determining the rate of sedimentation has proven difficult. However, the preliminary data from this study if applicable can be compared to original design capacity to yield an estimated sedimentation rate for the conservation, inactive, and dead pools. Current estimates indicate an accelerated sedimentation rate since the increases in conservation pool. Previous sedimentation surveys noted sedimentation occurring in the flood pool and relatively little sedimentation in the conservation pool. This shift in sedimentation should be tracked in future years.

The OWRB considers the 2001 survey to be a significant improvement over previous survey endeavors and recommends that the same methodology be used in five years or after major flood events to monitor changes to the lake's storage capacity. The new volume calculation of 46,838 acre-feet will serve as a more accurate number for future comparisons.

An error analysis of the reservoir boundary could increase map accuracy and reduce the potential for negative bias of the lake boundary at 478 MSL. Methods to verify and or modify the generated 2001 boundary should be developed for Wister Lake.

References

Allen, Hollis. 2001a. "Lake Thunderbird Shoreline Erosion Control Using Bioengineering Methods." Environmental Laboratory, US Army Engineer Research and Development Center, Vicksburg, MS.

Allen, Hollis. 2001b. "Lake Wister Shoreline Erosion Control Using Bioengineering Methods." Environmental Laboratory, US Army Engineer Research and Development Center, Vicksburg, MS.

Carlson, R.E. 1977. A Trophic State Index for Lakes. Limnology and Oceanography. 22:361-369.

Fuller, Douglas R. 1997. "Understanding, Living with, and Controlling Shoreline Erosion: a Guidebook for Shoreline Property Owners (2nd Edition)," Tip of the Mitt Watershed Council, Conway, Michigan 49722.

Håkanson, Lars, 1981. A Manual of Lake Morphometry. Springer-Verlag, Berlin, Heidelberg. 78 pp.

Kortmann, Robert W. 2002. Feasibility of Alternative In-Lake Restoration Methods, Wister Lake, Oklahoma. Prepared for OWRB.

Morel, F. M.M., and J.G. Hering. 1993. Principles and Applications of Aquatic Chemistry. J. Wiley & Sons, New York. 588 pp.

Oklahoma Climatological Survey (OCS). 2002a. Monthly Summaries, Wister station, Oklahoma Mesonet, http://www.mesonet.ou.edu/premium/summary.html

Oklahoma Climatological Survey (OCS). 2002b. Summary Precipitation Statistics, Southeastern Oklahoma, 2001, Oklahoma Mesonet, http://climate.ocs.ou.edu/rainfall-update.html

Oklahoma State Department of Health (OSDH). 1977. Surface water quality assessment for Oklahoma, water year 1977: 305b report. State Water Quality Laboratory Water Quality Service Environmental Health Services, Oklahoma City, OK.

Oklahoma Water Resources Board (OWRB). 1990. Oklahoma Water Atlas. OWRB, Oklahoma City, OK. Publication 135.

Oklahoma Water Resources Board (OWRB). 1996. Diagnostic and Feasibility Study of Lake Wister: Phase I of a Clean Lakes Project.

Oklahoma Water Resources Board (OWRB). 2001a. Implementation of Non-point Source BMPs in the Fourche Maline Arm of Lake Wister: Task 700. Oklahoma City, OK.

Oklahoma Water Resources Board (OWRB). 2001b. Quality Assurance Project Plan: 2001 Lake Wister Study. Oklahoma City, OK.

Oklahoma Water Resources Board (OWRB). 2002. Oklahoma's Beneficial Use Monitoring Program 2001 Report. Oklahoma City, OK.

Public Law 98-63. 98th Congress. 1983.

Public Law 103-126. 103rd Congress. 1993.

Rogala, James T. 1999. Chapter 2: Methodologies employed for bathymetric mapping and sediment characterization as part of the Upper Mississippi River System Navigation Feasibility Study. ENV Report 13. Interim Report for the Upper Mississippi River-Illinois Water way System Navigation Study; prepared for US Army Corps of Engineers District, Rock Island, US Army Corps of Engineers District, St. Louis, and US Army Corps of Engineers District, St. Paul.

Sakamoto, M. 1966. Primary production by phytoplankton community in some Japanese lakes and its dependence upon lake depth. Arch. Hydrobiol. 62:1-28

Sawyer, C.N. and P.L. McCarty. 1978. Chemistry for environmental engineering. McGraw-Hill, Inc., New York, NY. 532 pp.

Schindler, D.W. 1977. Evolution of Phosphorous Limitation in Lakes. Science 179:382-384.

Stumm, W., and P. Baccini. 1978. Man-made Chemical Perturbation of Lakes. In A. Lerman (Ed.), Lakes—Chemistry, Geology, Physics (pp. 91-126). Springer-Verlag, New York.

Stumm, W., and J.J. Morgan. 1981. Aquatic Chemistry. An Introduction Emphasizing Chemical Equilibria in Natural Waters. 2nd Edition. J. Wiley & Sons, New York. 780 pp.

Texas Water Development Board. 1998. Benbrook Lake Hydrographic Survey Report Prepared for U.S. Army Corps of Engineers, Fort Worth District.

US Army Corps of Engineers (USACE). 1984. Shoreline Protection Manual. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS. 2 vols.

US Army Corps of Engineers (USACE). 1994. Water Quality Report. Lake Wister, Oklahoma, 1989-1990. U.S. Army Corps of Engineers, Tulsa District, Tulsa, OK.

US Army Corps of Engineers (USACE). 1998a. Planning Assistance to States Lake Wister Native Plant Establishment Study Phase I Report. U.S. Army Corps of Engineers, Tulsa District, Tulsa, OK.

US Army Corps of Engineers (USACE). 1998b. Planning Assistance To States Lake Wister Native Plant Establishment Study Phase II Report. U.S. Army Corps of Engineers, Tulsa District, Tulsa, OK.

US Army Corps of Engineers (USACE). 1998c. Planning Assistance to States Fetch Reduction in Fourche Maline Arm of Lake Wister, Oklahoma. U.S. Army Corps of Engineers, Tulsa District, Tulsa, OK.

US Army Corps of Engineers (USACE). 2001. "Monthly Charts for Lake Wister, http://www.swt-wc.usace.army.mil/WISTcharts.html

US Department of Agriculture Soil Conservation Service. 1981. Soil Survey of LeFlore County Oklahoma, National Cooperative Soil Survey.

US Environmental Protection Agency (USEPA). 1977. Wister Reservoir, LeFlore County, Oklahoma, National Eutrophication Survey, Working Paper No. 595, Corvallis Environmental Research Laboratory, Corvallis, OR.

United States Environmental Protection Agency. 1986. National Quality Criteria for Water. Office of Water Regulations and Standards, Washington, D.C. EPA 440/5-86-001.

US Environmental Protection Agency (USEPA). 1993. Guidance Specifying Management Measures for Sources of Non-point Pollution in Coastal Waters. EPA-840-B-93-001c.

Vollenweider, R. 1968. Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters, with Particular Reference to Nitrogen and Phosphorus as Factors in Eutrophication. Organization for Economic Cooperation and Development, DAS/CSIO/68.27, Paris, France, 192 pp.

Vollenweider, R.A. 1979. Das Nährstoffbelastundskonzept als Grundlage für den externen Eingriff in den Eutrophierungsprozess stehender Gewässer und Talsperren. Z. Hydrol. 37:53-84.

Water Resources Development Act of 1996, Public Law 104-303.

Wetzel, R.G. 1983. Limnology. 2nd Edition. Saunders College Publishing, Philadelphia. 767 pp.

William Brothers Engineering (WBE). 1982. Investigation of Water Quality Problems at Lake Wister. Contract No. DACW56-82-D-0083. Tulsa, OK

Appendix A

Lake Wister Total Manganese							
Routine replicate samples are sites 1 with site 6							
The criterion for manganese rejection is >60%							
Date	**Sample #**	**Site #**	**Depth**	**Manganese**	**Range**	**60% Rejection**	
05/22/2001	294885	1	0.1	229			
05/22/2001	No sample	6					
06/05/2001	295260	1	0.1	65	1	39.6	accept
06/05/2001	295273	6	0.1	66			
06/19/2001	296228	1	0.1	99	6	59.4	accept
06/19/2001	296241	6	0.1	93			
07/03/2001	296906	1	0.1	258	2	154.8	accept
07/03/2001	296919	6	0.1	256			
07/10/2001	297166	1	0.1	124	62	74.4	accept
07/10/2001	297179	6	0.1	62			
07/24/2001	297948	1	0.1	198	0	118.8	accept
07/24/2001	297961	6	0.1	198			
08/07/2001	298573	1	0.1	420	2	253.2	accept
08/07/2001	298586	6	0.1	422			
08/22/2001	299695	1	0.1	246	4	147.6	accept
08/22/2001	299708	6	0.1	242			
09/04/2001	300509	1	0.1	254	0	152.4	accept
09/04/2001	300522	6	0.1	254			
09/19/2001	301452	1	0.1	341	1	204.6	accept
09/19/2001	301459	6	0.1	340			
10/03/2001	302382	1	0.1	290	0	174	accept
10/03/2001	302395	6	0.1	290			
10/17/2001	302884	1	0.1	137	0	82.2	accept
10/17/2001	302897	6	0.1	137			

Lake Wister Total Iron

Routine replicate samples are sites 1 with site 6

The criterion for iron rejection is >60%

Date	Sample #	Site #	Depth	Iron	Range	60% Rejection	
05/22/2001	294897	1	0.1	4282			
05/22/2001	No sample	6					
06/05/2001	295260	1	0.1	935	429	818.4	accept
06/05/2001	295273	6	0.1	1364			
06/19/2001	296228	1	0.1	959	388	575.4	accept
06/19/2001	296241	6	0.1	571			
07/03/2001	296906	1	0.1	1298	23	792.6	accept
07/03/2001	296919	6	0.1	1321			
07/10/2001	297166	1	0.1	864	485	518.4	accept
07/10/2001	297179	6	0.1	379			
07/24/2001	297948	1	0.1	1365	80	819	accept
07/24/2001	297961	6	0.1	1285			
08/07/2001	298573	1	0.1	1435	36	882.6	accept
08/07/2001	298586	6	0.1	1471			
08/22/2001	299695	1	0.1	1064	68	638.4	accept
08/22/2001	299708	6	0.1	996			
09/04/2001	300509	1	0.1	1396	49	837.6	accept
09/04/2001	300522	6	0.1	1347			
09/19/2001	301452	1	0.1	2240	47	1372.2	accept
09/19/2001	301459	6	0.1	2287			
10/03/2001	302382	1	0.1	2419	167	1451.4	accept
10/03/2001	302395	6	0.1	2252			
10/17/2001	302884	1	0.1	2223	19	1345.2	accept
10/17/2001	302897	6	0.1	2242			

Lake Wister Chlorophyll-a						
Routine replicate samples are sites 1 with site 6						
The criterion for chlorophyll-a rejection is >40%.						
Date	**Sample #**	**Site**	**Chl-a**	**Range**	**40% rejection**	
05/22/2001	295925	1	5.4	4.3	2.16	reject
05/22/2001	297647	6	1.1			
06/05/2001	297653	1	27.6	11.1	15.48	accept
06/05/2001	297653	6	38.7			
06/20/2001	297661	1	19.2	1	8.08	accept
06/20/2001	297666	6	20.2			
07/02/2001	297667	1	8.7	8.6	3.48	reject
07/02/2001	297672	6	0.10			
07/10/2001	297715	1	14.30	7.9	8.88	accept
07/10/2001	297720	6	22.20			
07/24/2001	298861	1	18.50	0.2	7.48	accept
07/24/2001	298866	6	18.7			
08/07/2001	301101	1	11.73	5.75	6.992	accept
08/07/2001	301105	6	17.48			
08/22/2001	301141	1	22.25	0.85	8.9	accept
08/22/2001	301146	6	21.4			
09/05/2001	301174	1	11.52	1.29	5.124	accept
09/05/2001	301179	6	12.81			
09/18/2001	303645	1	9.56	0.15	3.884	accept
09/18/2001	303650	6	9.71			
10/03/2001	303652	1	16.35		6.54	reject
10/03/2001	303657	6	Laboratory Spilled Sample, no data available			
10/17/2001	303659	1	7.91	0.04	3.18	accept
10/17/2001	303665	6	7.95			

Lake Wister Nutrients and General Chemistry					
The criterion for rejection is >40%					
Date Collected: 5/22/2001					
Sample # 294885 = Site 1, 0.1 M					
Sample # 294898 = Site 6, 0.1 M					
	Split Sample Results				
	Report Values		Range	40%	
Parameter	294885	294898			
Chem. Oxy demand	129	106	23	51.6	accept
Total Alkalinity	10	10	0	4	accept
Settleable Solids	1	1	0	0.4	accept
Total Sus. Solids	16	5	11	6.4	reject
Ammonia as N	0.08	0.07	0.01	0.032	accept
Nitrite as N	0.05	0.05	0	0.02	accept
Nitrate as N	0.05	0.05	0	0.02	accept
Kjeldahl as N	0.43	0.51	0.08	0.204	accept
Total phosphorus	0.077	0.071	0.006	0.0308	accept
Ortho-phosphorus	0.029	0.028	0.001	0.0116	accept
Apparent Color	225	201	24	90	accept
True Color	131	114	17	52.4	accept
Total Hardness	15.4	23	7.6	9.2	accept
Sulfate	22.5	23.9	1.4	9.56	accept
Date Collected: 6/5/2001					
Sample # 295260 = Site 1, 0.1 M					
Sample # 295274 = Site 6, 0.1 M					
	Split Sample Results				
	Report Values		Range	40%	
Parameter	295260	295273			
Chem. Oxy demand	6	17	11	6.8	reject
Total Alkalinity	10	10	0	4	accept
Settleable Solids	1	1	0	0.4	accept
Total Sus. Solids	15	8	7	6	reject
Ammonia as N	0.05	0.05	0	0.02	accept
Nitrite as N	0.05	0.05	0	0.02	accept
Nitrate as N	0.05	0.09	0.04	0.036	reject
Kjeldahl as N	0.71	0.67	0.04	0.284	accept
Total phosphorus	0.088	0.098	0.01	0.0392	accept
Ortho-phosphorus	0.023	0.023	0	0.0092	accept
Apparent Color	242	240	2	96.8	accept
True Color	175	199	24	79.6	accept
Total Hardness	14.3	15.2	0.9	6.08	accept
Sulfate	17.3	16.7	0.6	6.92	accept

Date Collected: 6/19/2001					
Sample # 296228 = Site 1, 0.1 M					
Sample # 296241 = Site 6, 0.1 M					
	Sample Results				
	Report Values		**Range**	**40%**	
Parameter	296228	296241			
Chem. Oxy demand	32	22	10	12.8	accept
Total Alkalinity	11.1	10	1.1	4.44	accept
Settleable Solids	1	1	0	0.4	accept
Total Sus. Solids	5	18	13	7.2	reject
Ammonia as N	0.05	0.05	0	0.02	accept
Nitrite as N	0.05	0.05	0	0.02	accept
Nitrate as N	0.05	0.05	0	0.02	accept
Kjeldahl as N	0.77	0.64	0.13	0.308	accept
Total phosphorus	0.059	0.213	0.154	0.0852	reject
Ortho-phosphorus	0.013	0.013	0	0.0052	accept
Apparent Color	174	135	39	69.6	accept
True Color	130	78	52	52	accept
Total Hardness	5	10.5	5.5	4.2	reject
Sulfate	15	15.3	0.3	6.12	accept
Date Collected: 7/3/2001					
Sample # 296906 = Site 1, 0.1 M					
Sample # 296919 = Site 6, 0.1 M					
	Sample Results				
	Report Values		**Range**	**40%**	
Parameter	296906	296919			
Chem. Oxy demand	30	25	5	12	accept
Total Alkalinity	14.1	10	4.1	5.64	accept
Settleable Solids	1	1	0	0.4	accept
Total Sus. Solids	16	12	4	6.4	accept
Ammonia as N	0.05	0.05	0	0.02	accept
Nitrite as N	0.05	0.05	0	0.02	accept
Nitrate as N	0.05	0.05	0	0.02	accept
Kjeldahl as N	0.57	0.6	0.03	0.24	accept
Total phosphorus	0.075	0.076	0.001	0.0304	accept
Ortho-phosphorus	0.021	0.02	0.001	0.0084	accept
Apparent Color	130	111	19	52	accept
True Color	61	42	19	24.4	accept
Total Hardness	18.3	18.4	0.1	7.36	accept
Sulfate	17.9	17.4	0.5	7.16	accept

Date Collected: 7/10/2001					
Sample # 297166 = Site 1, 0.1 M					
Sample # 297179 = Site 6, 0.1 M					
	Sample Results				
	Report Values		**Range**	**40%**	
Parameter	297166	297179			
Chem. Oxy demand	25	24	1	10	accept
Total Alkalinity	14.2	15.8	1.6	6.32	accept
Settleable Solids	1	1	0	0.4	accept
Total Sus. Solids	5	6	1	2.4	accept
Ammonia as N	0.05	0.05	0	0.02	accept
Nitrite as N	0.05	0.05	0	0.02	accept
Nitrate as N	0.05	0.05	0	0.02	accept
Kjeldahl as N	0.91	0.67	0.24	0.364	accept
Total phosphorus	0.063	0.072	0.009	0.0288	accept
Ortho-phosphorus	0.015	0.015	0	0.006	accept
Apparent Color	245	160	85	98	accept
True Color	140	113	27	56	accept
Total Hardness	19.7	20.5	0.8	8.2	accept
Sulfate	13.1	11.1	2	5.24	accept
Date Collected: 7/24/2001					
Sample # 297948 = Site 1, 0.1 M					
Sample # 297961 = Site 6, 0.1 M					
	Sample Results				
	Report Values		**Range**	**40%**	
Parameter	297948	297961			
Chem. Oxy demand	24	44	20	17.6	reject
Total Alkalinity	14.1	14.9	0.8	5.96	accept
Settleable Solids	1	1	0	0.4	accept
Total Sus. Solids	16	20	4	8	accept
Ammonia as N	0.05	0.05	0	0.02	accept
Nitrite as N	0.07	0.07	0	0.028	accept
Nitrate as N	0.05	0.05	0	0.02	accept
Kjeldahl as N	0.63	0.45	0.18	0.252	accept
Total phosphorus	0.07	0.069	0.001	0.028	accept
Ortho-phosphorus	0.019	0.019	0	0.0076	accept
Apparent Color	152	247	95	98.8	accept
True Color	71	141	70	56.4	reject
Total Hardness	24.3	23	1.3	9.72	accept
Sulfate	14.4	14.4	0	5.76	accept

Date Collected: 8/7/2001					
Sample # 298573 = Site 1, 0.1 M					
Sample # 298586 = Site 6, 0.1 M					
	Sample Results				
	Report Values		Range	40%	
Parameter	298573	298586			
Chem. Oxy demand	19	19	0	7.6	accept
Total Alkalinity	17.9	16.6	1.3	7.16	accept
Settleable Solids	1	1	0	0.4	accept
Total Sus. Solids	27	24	3	10.8	accept
Ammonia as N	0.05	0.05	0	0.02	accept
Nitrite as N	0.05	0.05	0	0.02	accept
Nitrate as N	0.05	0.05	0	0.02	accept
Kjeldahl as N	0.63	0.71	0.08	0.284	accept
Total phosphorus	0.047	0.098	0.051	0.0392	reject
Ortho-phosphorus	0.023	0.023	0	0.0092	accept
Apparent Color	135	140	5	56	accept
True Color	70	80	10	32	accept
Total Hardness	28	26.2	1.8	11.2	accept
Sulfate	13.6	15.1	1.5	6.04	accept
Date Collected: 8/22/2001					
Sample # 299695 = Site 1, 0.1 M					
Sample # 299708 = Site 6, 0.1 M					
	Sample Results				
	Report Values		Range	40%	
Parameter	299695	299708			
Chem. Oxy demand	17.7	23.5	5.8	9.4	accept
Total Alkalinity	19.4	17.9	1.5	7.76	accept
Settleable Solids	1	1	0	0.4	accept
Total Sus. Solids	22	84	62	33.6	reject
Ammonia as N	0.05	0.05	0	0.02	accept
Nitrite as N	0.05	0.05	0	0.02	accept
Nitrate as N	0.05	0.05	0	0.02	accept
Kjeldahl as N	0.87	0.62	0.25	0.348	accept
Total phosphorus	0.063	0.074	0.011	0.0296	accept
Ortho-phosphorus	0.012	0.014	0.002	0.0056	accept
Apparent Color	118	200	82	80	reject
True Color	94	88	6	37.6	accept
Total Hardness	22.2	25.9	3.7	10.36	accept
Sulfate	9.9	10.5	0.6	4.2	accept

Date Collected: 9/4/2001					
Sample # 300509 = Site 1, 0.1 M					
Sample # 300522 = Site 6, 0.1 M					
	Sample Results				
	Report Values		**Range**	**40%**	
Parameter	300509	300522			
Chem. Oxy demand	22.2	17.8	4.4	8.88	accept
Total Alkalinity	14.8	15.7	0.9	6.28	accept
Settleable Solids	1	1	0	0.4	accept
Total Sus. Solids	35	24	11	14	accept
Ammonia as N	0.07	0.08	0.01	0.032	accept
Nitrite as N	0.06	0.05	0.01	0.024	accept
Nitrate as N	0.05	0.05	0	0.02	accept
Kjeldahl as N	0.52	0.54	0.02	0.216	accept
Total phosphorus	0.064	0.079	0.015	0.0316	accept
Ortho-phosphorus	0.025	0.024	0.001	0.01	accept
Apparent Color	133	145	12	58	accept
True Color	65	46	19	26	accept
Total Hardness	26.2	25.7	0.5	10.48	accept
Sulfate	19	17.8	1.2	7.6	accept

Date Collected: 9/19/2001					
Sample # 301432 = Site 1, 0.1 M					
Sample # 301445 = Site 6, 0.1 M					
	Sample Results				
	Report Values		**Range**	**40%**	
Parameter	301432	301445			
Chem. Oxy demand	24.4	40.6	16.2	16.24	accept
Total Alkalinity	12.4	12.9	0.5	5.16	accept
Settleable Solids	1	1	0	0.4	accept
Total Sus. Solids	18	26	8	10.4	accept
Ammonia as N	0.05	0.05	0	0.02	accept
Nitrite as N	0.06	0.06	0	0.024	accept
Nitrate as N	0.2	0.2	0	0.08	accept
Kjeldahl as N	0.66	0.4	0.26	0.264	accept
Total phosphorus	0.095	0.089	0.006	0.038	accept
Ortho-phosphorus	0.031	0.032	0.001	0.0128	accept
Apparent Color	156	158	2	63.2	accept
True Color	48	50	2	20	accept
Total Hardness	28.9	39.5	10.6	15.8	accept
Sulfate	13	19.7	6.7	7.88	accept

Date Collected: 10/3/2001					
Sample # 302382 = Site 1, 0.1 M					
Sample # 302395 = Site 6, 0.1 M					
	Split Sample Results				
	Report Values		**Range**	**40%**	
Parameter	302382	302395			
Chem. Oxy demand	39.9	12	27.9	15.96	reject
Total Alkalinity	12	10	2	4.8	accept
Settleable Solids	1	1	0	0.4	accept
Total Sus. Solids	32	24	8	12.8	accept
Ammonia as N	0.05	0.05	0	0.02	accept
Nitrite as N	0.05	0.05	0	0.02	accept
Nitrate as N	0.19	0.2	0.01	0.08	accept
Kjeldahl as N	0.39	0.66	0.27	0.264	reject
Total phosphorus	0.11	0.102	0.008	0.044	accept
Ortho-phosphorus	0.027	0.025	0.002	0.0108	accept
Apparent Color	306	318	12	127.2	accept
True Color	153	149	4	61.2	accept
Total Hardness	20.4	19.3	1.1	8.16	accept
Sulfate	19.4	17.2	2.2	7.76	accept
Date Collected: 10/17/2001					
Sample # 302884 = Site 1, 0.1 M					
Sample # 302897 = Site 6, 0.1 M					
	Split Sample Results				
	Report Values		**Range**	**40%**	
Parameter	302884	302897			
Chem. Oxy demand	16	5	11	6.4	reject
Total Alkalinity	11.3	10.1	1.2	4.52	accept
Settleable Solids	1	1	0	0.4	accept
Total Sus. Solids	18	14	4	7.2	accept
Ammonia as N	0.05	0.05	0	0.02	accept
Nitrite as N	0.05	0.05	0	0.02	accept
Nitrate as N	0.11	0.06	0.05	0.044	reject
Kjeldahl as N	0.59	0.63	0.04	0.252	accept
Total phosphorus	0.098	0.102	0.004	0.0408	accept
Ortho-phosphorus	0.026	0.025	0.001	0.0104	accept
Apparent Color	145	121	24	58	accept
True Color	60	45	15	24	accept
Total Hardness	22.9	20.9	2	9.16	accept
Sulfate	19.3	18.2	1.1	7.72	accept

Appendix B