TCEQ

April 12, 2006

One Total Maximum Daily Load for Dissolved Oxygen in Lake O' the Pines

For Segment 0403

Prepared by the:
Chief Engineer's Office, Water Programs, TMDL Section

TEXAS COMMISSION ON ENVIRONMENTAL QUALITY

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Table of Contents

Figures

Tables

One Total Maximum Daily Load for Dissolved Oxygen in Lake O' the Pines

Executive Summary

Lake O' the Pines (Segment 0403) is listed on the state's 303(d) list as impaired due to low levels of dissolved oxygen. In accordance with the requirements of Section 303(d) of the federal Clean Water Act, the Texas Commission on Environmental Quality has developed a Total Maximum Daily Load (TMDL) which will allow the segment to attain its designated uses and meet its water quality standards. The TMDL document was prepared in cooperation with the Texas State Soil and Water Conservation Board and the Cypress Creek Basin Clean River Program/Lake O' the Pines TMDL Combined Steering Committee.

The Lake O' the Pines watershed is part of the 2,812 square mile Cypress Creek Basin, a sub-basin of the Red River drainage located in Northeast Texas between the Sulphur River Basin on the north and the Sabine River Basin to the west and south. It is an area vegetated primarily by an oak woodland-prairie mosaic. The watershed includes some of the leading broiler producing counties in the state.

Since 2000, the assessment of water quality has consistently identified low dissolved oxygen concentrations in the upper portion of the reservoir. Samples taken at the lower end of the reservoir show a declining trend in dissolved oxygen concentrations. Analyses of the data determined that low dissolved oxygen concentrations in Lake O' the Pines result from *in situ* photosynthesis and respiration and that the key parameter of concern is phosphorus.

Dissolved oxygen concentrations as defined by the state water quality standards are the final endpoint for the TMDL in Lake O' the Pines. However, concentrations of total phosphorus and chlorophyll-*a* in the reservoir will be used as intermediate water quality targets for the TMDL. The relationship of nutrient input to reservoir metabolism is well known in general. However, nutrient loads do not precisely predict either nutrient levels within the reservoir, or their effects on photosynthesis and respiration. Paired values of chlorophyll-*a* and total phosphorus collected at the same stations and dates were employed to directly test the relationship with nutrient levels in Lake O' the Pines. The results showed that the state screening criterion for chlorophyll-*a* (21.4 μg/l) was exceeded only when corresponding total phosphorus concentrations equaled or exceeded 0.07 mg/l. These values represent the intermediate water quality targets for the TMDL.

Existing loadings of phosphorus to Lake O' the Pines from point sources were determined through field sampling and maximum permitted discharge rates. Existing loadings of phosphorus to Lake O' the Pines from nonpoint sources were determined by adapting the Natural Resource Conservation Service's Soil and Water Assessment Tool (SWAT) model to simulate runoff and watershed loads. The TMDL determined that a 56% reduction in existing phosphorus loads is needed.

Introduction

Section 303(d) of the federal Clean Water Act (CWA) requires all states to identify waters that do not meet, or are not expected to meet, applicable water quality standards. For each listed water body that does not meet a standard, states must develop a total maximum daily load (TMDL) for each pollutant that has been identified as contributing to the impairment of water quality in that water body. The Texas Commission on Environmental Quality (TCEQ) is responsible for ensuring that TMDLs are developed for impaired surface waters in Texas.

In simple terms, a TMDL is a quantitative plan that determines the amount of a particular pollutant that a water body can receive and still attain and maintain its applicable water quality standards. In other words, TMDLs are the best possible estimates of the assimilative capacity of the water body for a pollutant under consideration. A TMDL is commonly expressed as a load, with units of mass per unit of time, but may also be expressed in other ways. TMDLs must also estimate how much the pollutant load needs to be reduced from current levels in order to achieve water quality standards.

The Total Maximum Daily Load Program, a major component of Texas' statewide watershed management approach, addresses impaired or threatened streams, reservoirs, lakes, bays, and estuaries (water bodies) in or bordering the state of Texas. The primary objective of the TMDL Program is to restore and maintain the beneficial uses (such as drinking water, recreation, support of aquatic life, or fishing) of impaired or threatened water bodies.

The ultimate goal of this TMDL is to increase the level of dissolved oxygen concentrations in Lake O' the Pines, allowing the aquatic life uses to be restored to the water body.

Section 303(d) of the CWA and the U.S. Environmental Protection Agency's (EPA) implementing regulations (40 Code of Federal Regulations, Section 130) describe the requirements for acceptable TMDLs. The TCEQ guidance document, *Developing Total Maximum Daily Load Projects in Texas* (GI-250), further refines the process for Texas. Following all these guidelines, this TMDL document has been prepared and is composed of six elements which are summarized in the following sections:

- Problem Definition
- Endpoint Identification
- Source Analysis
- Linkage Between Sources and Receiving Water
- Margin of Safety
- Pollutant Load Allocation

This TMDL document was prepared by:

- the Texas State Soil and Water Conservation Board (TSSWCB) TMDL Team; and

- the TMDL Section in the Water Programs of the Chief Engineer's Office at the TCEQ.

This document was prepared based upon the "Lake O' the Pines Watershed TMDL Project Documentation Report" prepared by Paul Price Associates, Inc. as a subcontractor to the Northeast Texas Municipal Water District (NETMWD), which was under contract with the TCEQ. Additionally, significant assistance in the preparation of this document was provided by the Cypress Creek Basin Clean Rivers Program/Lake O' the Pines TMDL Combined Steering Committee.

The Texas State Soil and Water Conservation Board passed a resolution in support of the TMDL document on March 23, 2006. It was adopted by the Texas Commission on Environmental Quality on April 12, 2006. Upon EPA approval, the TMDL will become an update to the state's Water Quality Management Plan. The TSSWCB and the TCEQ will use the EPA-approved document for managing and abating pollution leading to low dissolved oxygen levels in the Lake O' the Pines watershed.

Background Information

The Lake O' the Pines watershed encompasses Segments 0403 and drainage areas upstream from Lake O' the Pines designated as Segments 0404, 0405, and 0408 in the Cypress Creek Basin, and includes:

- four major impoundments: Lake Cypress Springs (Segment 0405), Lakes Monticello and Bob Sandlin (Segment 0408), and Lake O' the Pines (Segment 0403);
- approximately 50 miles of Big Cypress Creek (Segment 0404); and
- numerous tributary streams (see Figure 1).

The watershed is part of the 2,812-square-mile Cypress Creek Basin, which is a subbasin of the Red River drainage located in Northeast Texas between the Sulphur River Basin on the north and the Sabine River Basin to the west and south. The Lake O' the Pines watershed drains much of the western Cypress Creek Basin, an area vegetated primarily by an oak woodland-prairie mosaic. The watershed tends to be the site of the more intense agricultural activity as compared to the eastern part of the basin (which is more forested), and contains the bulk of the Cypress Creek Basin's urban concentrations, industry, and recreational waters. The primary uses of Lake O' the Pines are recreation and public water supply, and demand for both uses is expected to continue to grow.

Annual rainfall ranges from 35-inches per year at the western extreme of the basin to near 50 inches annually at Ferrels Bridge Dam, which was closed to impound Big Cypress Creek, forming Lake O' the Pines in 1958. Temperatures average near 90 degrees Fahrenheit in the summer and freezes in the winter can be expected each year, but temperatures as low as zero degrees Fahrenheit are rare. The abundant rainfall and low regional slope result in frequent floods that overflow onto floodplains for lengthy periods, leaving water-filled oxbow lakes, sloughs, and other water-filled depressions behind when they recede. These floodplain habitats associated with the waterways are used as important dispersal highways by eastern forest dwelling animals to move beyond the forest limits, into areas such as the Blackland prairies, where upland vegetation types present a barrier to them. Regionally, upland soils tend to be acid sandy loams or sands, while bottomland soils are typically brown-to-dark-gray acid sandy loams to clays. The regional landscape consists of rolling wooded hills with regional elevations of 200 to 800 feet mean sea level, but with limited local relief, gentle slopes, and broad, frequently flooded, densely vegetated stream bottoms.

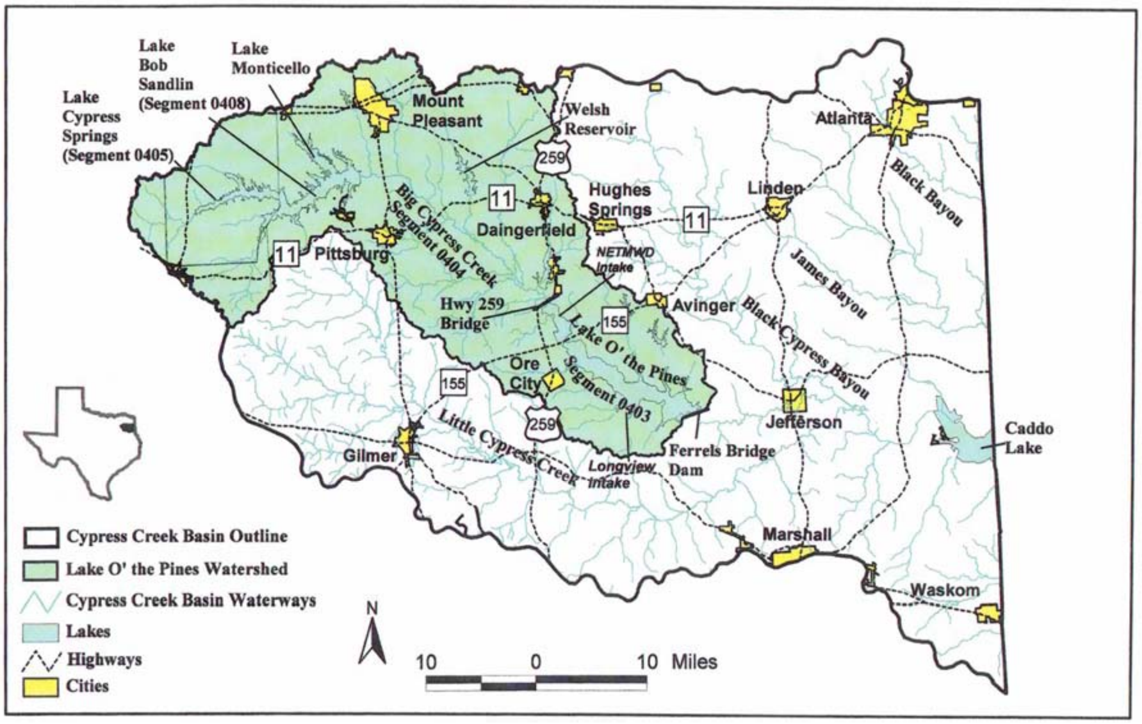

Figure 1. Lake O' the Pines Watershed, Cypress Creek Basin

The Lake O' the Pines watershed is located within the South and East Central Texas Plains Ecoregions (Ecoregions 33 and 35) (Omernik, 1987). The two major vegetational areas corresponding to the South and East Central Texas Plains Ecoregions are, respectively, the post oak savannah and the piney woods. The post oak savannah is a north-south strip in the central part of eastern Texas encompassing most of the subwatersheds draining into Big Cypress Creek. Streams draining directly into Lake O' the Pines are mostly located within the piney woods vegetational region, typically a gently rolling to hilly-forested landscape where rainfall tends to be more abundant and uniformly distributed than in the western portion of the basin. The pine-oak forest characteristic of this region of Texas is an ecotone between the eastern pine forests and the oak-hickory forest of the post oak woodlands to the west. Although post oak and blackjack oak constitute the dominant climax overstory vegetation, loblolly and shortleaf pine are generally common.

The Lake O' the Pines watershed includes some of the leading broiler producing counties in the state. The area around Pittsburg has experienced particularly intense development of poultry production facilities. The Poultry Farm and Litter Application Survey compiled by Pilgrim's Pride Corporation on behalf of the Cypress Basin Clean Rivers Program indicated that poultry production throughout the Cypress Creek Basin totaled approximately 99,000,000 birds, nearly 25% of statewide production. This activity generated 132,720 tons of litter, of which 114,511 tons were disposed of on 42,363 acres of disposal sites within the Cypress Creek watershed at application rates that varied from one to five tons/acre. There is no accounting of the fate of the remaining litter.

Timber sales factor heavily in the regional economy, particularly in the eastern portion of the basin. Truck crops (vegetables, fruit, melons), hay production, and livestock are important throughout the Cypress Creek Basin, but the oak woodland-prairie mosaic characteristic of the western half exhibits the most intense agricultural activity, including confined poultry feeding operations. Lignite and iron ore mining, oil and gas production, and small manufacturing facilities are scattered throughout the basin.

The city of Mount Pleasant, in Titus County, recorded a population of almost 14,000 in the 2000 census, making it the largest urban concentration in the Lake O' the Pines watershed. The cities of Pittsburg, Daingerfield, Lone Star, and Ore City constitute the other major population centers. The total population projected for the Lake O' the Pines watershed in 2050 is 80,808, including estimates of the rural populations in those portions of eleven counties in the watershed, an increase of about 37% (TWDB, 2002). Manufacturing and electric power generation accounts for the majority of water use within the watershed, with municipal water supply a distant third. Although most rural residents still depend on groundwater from the Carrizo-Wilcox and Queen City aquifers, the demand for treated surface water by rural basin residents and by population centers outside the Lake O' the Pines watershed (*e.g.*, Longview) is increasing.

Problem Definition

Since 2000, the TCEQ's assessment of water quality in Lake O' the Pines has consistently identified dissolved oxygen concentrations that are lower than optimal for attainment of the lake's designated High Aquatic Life Use. This assessment was confirmed by additional data collected during the course of the TCEQ's TMDL project for the lake.

State Water Quality Inventory and 303(d) Listing

The final *2000 Texas Water Quality Inventory and 303(d) List* found that approximately 2,000 acres in the upper end of Lake O' the Pines exhibited dissolved oxygen concentrations that were occasionally lower than the 24-hour average criterion (5 milligrams per liter, or mg/l) established to assure optimum conditions for aquatic life. This area, corresponding to the portion of the reservoir upstream from the SH 155 causeway, is a transition zone between the stream-like conditions prevailing in Big Cypress Creek and the more typically lake-like environment of the lower lake basin (Lind, 2002) (see Figure 2).

The final *2002 Texas Water Quality Inventory and 303(d) List* found approximately 3,700 acres in the upper reservoir exhibited dissolved oxygen concentrations below the level established to assure optimum conditions for aquatic life. This area includes the portion of the reservoir above the SH 155 causeway, and an additional area in the upper

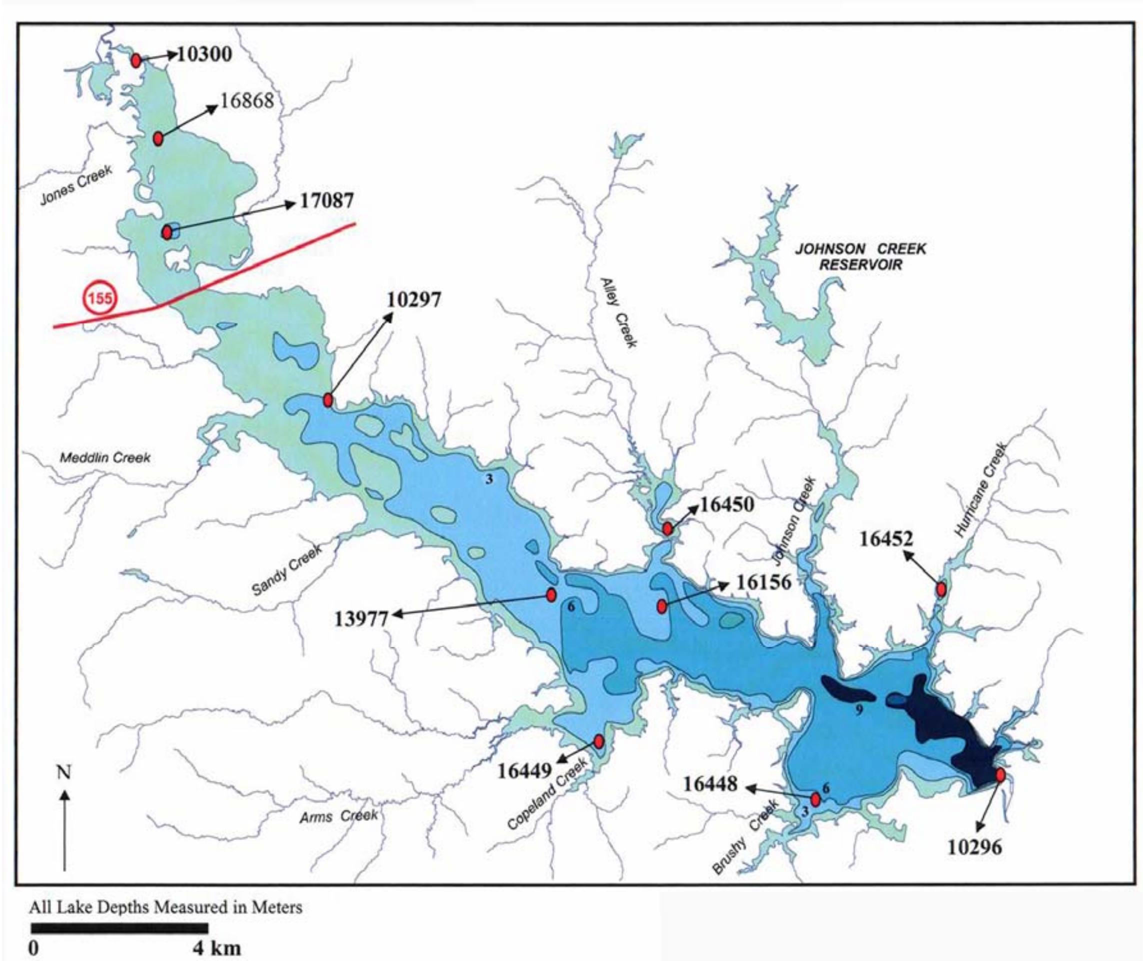

Figure 2. Lake O' the Pines

part of the main basin in the vicinity of the Northeast Texas Municipal Water District raw water intake. The assessment of Lake O' the Pines also indicated that excessive nutrient levels were a cause for concern in the upper 3,700 acres of the reservoir, though they do not result in impairment of any uses. While fishing appears to be the primary use in the reservoir above SH 155, the lower, deeper reach of the reservoir is perhaps of greater concern for water quality and water supply to the Cypress Creek Basin stakeholders, as this typifies the open, well-aerated waters of the lake, and is the location of the major water supply intakes.

The draft *2004 Texas Water Quality Inventory and 303(d) List* describes the upper 3,700 acres of the reservoir as partially supporting its aquatic life use due to low levels of dissolved oxygen. Water quality concerns for Lake O' the Pines identified in the draft 2004 assessment are presented in Table 1.

Table 1. Water Quality Concerns for Lake O' the Pines

Assessment Area	Use or Criterion	Concern Status	Description of Concern
Lower 5000 acres	Aquatic Life Use	Use Concern	Depressed dissolved oxygen
Upper 3700 acres	Aquatic Life Use	Use Concern	Depressed dissolved oxygen
Upper 3700 acres	Nutrient Enrichment	Concern	Nitrate+nitrite nitrogen
Upper 3700 acres	Nutrient Enrichment	Concern	Total phosphorus

Source: *Draft 2004 Texas Water Quality Inventory and 303(d) List*

Texas Parks and Wildlife Fish Kill Data

Data from the Texas Parks and Wildlife Department (TPWD) on fish kills and other pollution incidents records only a single event in Segment 0403 since 1994. That event was a moderately large fish kill (about 9,400 individuals) that began on July 22, 2002, extending from below SH 155 down the reservoir to Ferrels Bridge Dam. The TPWD report indicates that only one species of fish, Gizzard Shad, was affected. Although this kill was attributed to low dissolved oxygen concentrations resulting from "algal respiration," samples collected during the period show that only low to moderate levels of chlorophyll-*a* were present throughout the reservoir, and the dissolved oxygen diurnal cycle measured during the period gave no indications of low concentrations at the stations sampled.

TMDL Data Collection and Assessment

Violations of the dissolved oxygen standard, based on grab sampling, have been documented by the TCEQ in the upper portion of the reservoir. Extensive diurnal dissolved oxygen sampling conducted as part of the TMDL program confirms that exceedences of the dissolved oxygen standard are occurring in the upper- and lower-most stations in the reservoir, as explained further below.

The analysis of profile and surface grab sample data from the upper reach of the reservoir confirmed the presence of high dissolved oxygen deficits and large diurnal excursions, and found that the 3 mg/l instantaneous minimum dissolved oxygen concentration established by the TCEQ to assure attainment of the High Aquatic Life Use (the present designation for Lake O' the Pines) was violated in 10-15% of measurements (Ward, 2000). This violation rate is only slightly higher than the 10% rate identified in the TCEQ guidance for determining that impairment exists. Dissolved oxygen in Lake O' the Pines is strongly affected by seasonal stratification in the middle and lower reaches of the lake, where depths are sufficient to allow the development of the seasonal thermocline. The two stations sampled most frequently suggest that a systematic increase in dissolved oxygen deficit is correlated with position upstream in the system. The uppermost reach, above SH 155, is typically too shallow for thermal stratification and generally exhibits the highest deficits in the lake.

The sampling station at the Ferrels Bridge Dam (Station 10296) shows a declining trend in dissolved oxygen concentration since 1973, statistically discernible at a 95%

confidence level. Violations of the standard and screening criteria have been observed in the lower reservoir in recent years, although not at a rate that would cause this portion of the reservoir to be considered impaired according to the state's water quality screening criteria. This data is shown in Figure 3, and is a compilation of all data available for the station. Moreover, the data show that these degraded dissolved oxygen conditions are associated with seasonal low inflow and late summer seasons. The data record in the upper reservoir extends back only to 1998, but evidences a similar degradation in oxygen, including a marked increase in dissolved oxygen deficit (Ward, 2000).

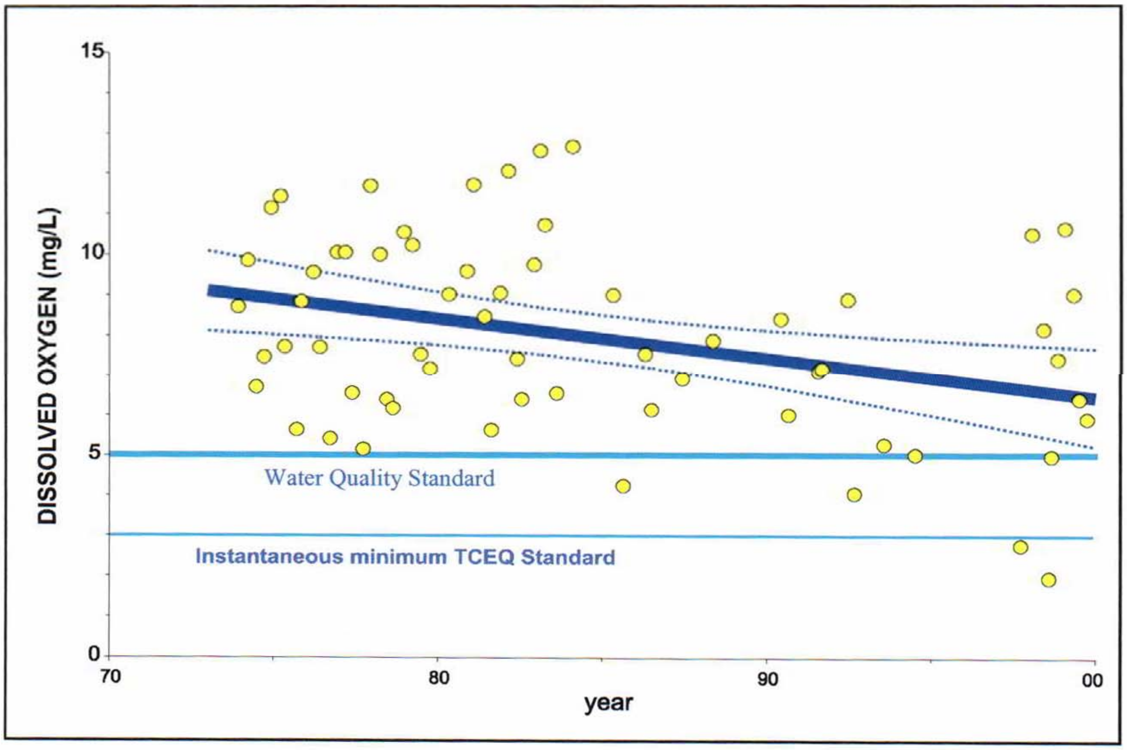

Figure 3. Dissolved Oxygen Concentrations at Ferrels Bridge Dam

That these are not simply a result of the lower saturation at high temperature was established by a companion analysis of dissolved oxygen deficit. These same conditions apply to the violations of dissolved oxygen standard in the upper reach of the reservoir, for which Lake O' the Pines was placed on the 303(d) list. The low-flow, high-temperature stratified condition, typical of late summer, comprises the set of critical conditions under which violations of water quality standard is occurring. The external nutrient loadings that contribute to the observed low dissolved oxygen levels do not correspond in time with this set of critical conditions (Ward, 2001a). The relationship between violations of the nutrient and dissolved oxygen criteria defines the seasonal variability that exists in Lake O' the Pines, and is the basis of the set of critical conditions that are evaluated in this TMDL.

Community primary production and respiration were measured in shallow vegetated and unvegetated habitats upstream from the SH 155 causeway. Large volume respirometers and deployable sondes were employed for this purpose. Respirometers were deployed for 24-hour periods to assess night respiration and daylight oxygen production for the entire community, including planktonic and benthic (or attached) biota. Conventional diurnal dissolved oxygen measurements were taken for comparison at nearby representative locations.

The magnitude of the rates of respiration and gross production implied by the respirometer results are quite high, ranging from 5 to 7 grams of dissolved oxygen per square meter (gO_2/m^2) per day in June, and 4 to 6 gO_2/m^2/day in August 2002. The dissolved oxygen amplitudes observed during the summer of 2002 (in both respirometers and in conventional dissolved oxygen diurnal samples) were only about half of those observed during summer 2001, providing an indication of the interannual range of variation to be expected in this parameter. Diurnal dissolved oxygen data collected during 2001 were used to calculate respiration rates during development of the QUALTX model of Lake O' the Pines. Those calculations gave community respiration rates (*i.e.*, nighttime dissolved oxygen decrease) of 8 – 30g O_2/m^2/day at 20°C, reflecting the more extreme changes occurring on a daily basis during that year.

Evidence that low dissolved oxygen concentrations in Lake O' the Pines result from *in situ* photosynthesis and respiration, rather than, for example, consumption of inflowing, oxygen-demanding materials, or ammonia oxidation, includes:

1) relatively low concentrations of total organic carbon (TOC), and ammonia are the typical condition during critical periods,
2) analysis of results showed that oxygen demand originating in wastewater discharges was assimilated in the tributary streams (Ward, 2002a),
3) exceedences tend to correspond with larger 24-hour dissolved oxygen concentration amplitudes, and
4) the high metabolic rates obtained in the analysis of diel oxygen data and observed in respirometer studies (Ward, 2002b).

Given that they are occurring in the same water body, the magnitude of dissolved oxygen change over a 24-hour period provides an index of biological activity, of community photosynthesis, and respiration. Average 24-hour dissolved oxygen amplitudes tend to vary systematically in Lake O' the Pines, with highest values (averaging about 7 mg/l) in the reach upstream from the SH 155 causeway, intermediate values (about 3 mg/l) in the main basin, and lowest values (about 2 mg/l) at the cove stations.

Analysis of water quality data from the lake indicate that the key parameters of concern to dissolved oxygen levels in Lake O' the Pines are nutrients, notably compounds of nitrogen and phosphorus, and that kinetic processes usually identified with lake eutrophication are probably the primary determinants of reservoir quality. These processes include assimilation of nitrogen (N) and phosphorus (P), and high rates of photosynthesis and respiration that result in large diurnal excursions in dissolved oxygen. Exceedences of the dissolved oxygen criteria appear to result from elevated nutrient concentrations throughout the reservoir, which originate primarily in the Big Cypress Creek drainage.

Analysis of water quality data from the lake further indicates that phosphorus is the limiting nutrient in the reservoir during the critical summer period. Phosphorus may appear to be too abundant in Lake O' the Pines to be exerting limits or control on production and coupled respiration, this is not the case since summer total phosphorus concentrations primarily represent phosphorus tied up in living and dead organic material, phosphorus sorbed to mineral particles, or present as polyphosphate, all of which are of only limited availability for new growth. Dissolved phosphorus was rarely detected in Lake O' the Pines summer baseflow samples. Summer nitrogen likewise consisted almost entirely of total Kjeldahl nitrogen (TKN) and much smaller concentrations of ammonia, indicating that nitrogen was also present primarily as organic matter (biomass and detritus) and not in an immediately available form.

In this condition of general nutrient abundance but limited availability, photosynthesis and respiration rates will tend to depend on the rates of regeneration of nitrogen and phosphorus from sediments or from living populations, given appropriate conditions of temperature, light, and other nutrients. Nutrient regeneration rates at any given time and location may depend on chemical factors, such as sediment redox potential, dissolved oxygen concentrations and pH of overlying water; physical factors, such as mixing events (*e.g.*, wind stress, internal waves), and biological factors, including pathogen-induced lysis of algal cells, grazing by fish and macroinvertebrates, or direct excretion from growing algal populations under otherwise favorable environmental conditions.

The pattern of metabolic activity described above is consistent with a conceptual model of Lake O' the Pines in which photosynthesis and respiration are supported by nutrients that enter the system primarily in Big Cypress Creek inflows, with a decline in community metabolism, and dissolved oxygen criteria violations, at locations successively more isolated from the nutrient supply. Summer chlorophyll-*a* and phosphorus concentrations follow similar patterns; highest values of both parameters tend to be present in the upper reservoir, and lowest in the cove stations. As has been previously shown in Figure 3, there is an indication that dissolved oxygen concentrations may be in long-term decline in the lower reservoir.

Reservoir Transitional Area

The reservoir upstream from the SH 155 causeway is predominantly shallow. Although depths of 3 meters may be found in maintained parts of the inundated Big Cypress Creek channel, most of the area is less than 1.5 meters deep and is covered by a large biomass of rooted vegetation, primarily lotus and hydrilla. The presence of large stands of submerged aquatic vegetation impedes water flow, facilitating sediment deposition, and presumably nutrients associated with soil and organic particles. Perhaps more importantly from the standpoint of the overall lake water quality, the metabolism of the rooted vegetation and its epiphytic community is likely to dominate the dissolved oxygen regime and nutrient budgets of this portion of the reservoir, while the ability of the rooted vegetation to extract nutrients from sediments and return them to the water column in the form of detrital material may be significant in the nutrient dynamics of the entire reservoir.

That nutrient and sediment should accumulate in the reach of the lake that receives the bulk of the inflow and that eutrophic conditions should result are not surprising. Such eutrophic conditions are a natural and largely unavoidable feature of the aging of a reservoir, and Lake O' the Pines is a relatively old lake, approaching 50 years. The primary site of sediment deposition and delta formation in reservoirs typically occurs at the mouths of the major tributaries where organic and mineral solids, maintained in suspension by the turbulent energy of the streams, enter the lower energy environment of the reservoir. The upper reservoir may be best described as a delta rather than as a lake due to these conditions.

Endpoint Identification

TMDL projects must identify a quantifiable water quality endpoint for each constituent that causes a body of water to appear on the state's 303(d) list. These endpoints are indicators of the desired water quality condition and provide a measurable goal for the TMDL. For certain constituents of concern, the primary water quality endpoint for the TMDL is explicitly set forth in the *Texas Surface Water Quality Standards* (Title 30 of the Texas Administrative Code (TAC), Chapter 307). In other cases, the state standards may not establish a numeric criterion for the constituents of concern. In these cases, current scientific literature, cause-and-effect relationships established from scientific studies, or other appropriate means are used to establish the water quality target for the TMDL. The TMDL endpoint serves to focus the technical work to be accomplished during TMDL development and serve as a criterion against which to evaluate future conditions.

The establishment of the endpoint for the TMDL is an integral part of the TMDL process itself, and manifests many of the same complexities as the development of TMDLs. Through the analysis of water quality data and modeling exercises, it becomes possible, at least to some degree, to define quantitative values of various parameters that can serve as target conditions. The TMDL is, by definition, the set of external loadings, which result in a predicted concentration in the water body equal to the target condition. The TMDL determination and the endpoint specification are coordinated, parallel activities. Specification of endpoint conditions implies a corresponding set of critical conditions and there is not necessarily one unique set of these critical conditions. The parameter for which an endpoint condition is defined may not be the parameter that characterizes pollutant loading, and may not be in itself sufficient to ensure attainment of the desired use of the water body.

Lake O' the Pines is listed on the state's 303(d) list because of low dissolved oxygen levels. As discussed in the previous section, dissolved oxygen levels in Lake O' the Pines have been linked to nutrient loading via algae/chlorophyll-*a*/macrophyte photosynthesis and respiration and the resultant large diurnal variations. Modeling and predicting these effects is not very precise. Dissolved oxygen concentrations are affected by many things in addition to nutrients and biological metabolism. Nutrient/biological/dissolved oxygen interactions are very complex and are not well quantified. Several options for defining numerical endpoints were evaluated by the TMDL. There are technical issues involved in the sampling and analysis of particular parameters. There are also problems with linking quantitative measures of water quality impairment (*e.g.*, segment standards) to their immediate biological effectors and the watershed inputs potentially driving them. Therefore, in recognition of the limitation of selecting any single target condition, a multiple parameter approach has been developed to define the target condition for the TMDL in Lake O' the Pines. A final endpoint has been established in addition to intermediate targets for two water quality parameters. Dissolved oxygen concentrations are identified as the final endpoint for the TMDL. Average concentrations of total phosphorous and chlorophyll-*a* have been identified as intermediate water quality targets for the TMDL. These parameters are presented and discussed below in greater detail.

Dissolved Oxygen

The state water quality standards specify criteria for dissolved oxygen levels in Lake O' the Pines, stating that 24-hour average dissolved oxygen levels should not fall below 5 mg/l and minimum dissolved oxygen levels should not fall below 3 mg/l. In this context, dissolved oxygen is not a pollutant but rather an indicator parameter for water quality. The pollutant of concern is the material that exerts a demand upon the instream dissolved oxygen resources. For Lake O' the Pines, nutrients (phosphorus in particular) have been determined to be the primary constituent of concern. Dissolved oxygen concentrations as defined by the state water quality standards are the final endpoint for the TMDL.

Total Phosphorus

As stated in the previous section, analyses of information from Lake O' the Pines indicate that low dissolved oxygen levels result from *in situ* photosynthesis and respiration supported by nutrients that enter the system primarily in Big Cypress Creek inflows. The analysis further concluded that phosphorus is the limiting nutrient in the reservoir. The relationship of nutrient loadings and lake metabolic activity is generally accepted, though the precise effect of nutrient levels on photosynthesis and respiration in the reservoir cannot be established. However, analyses of data from Lake O' the Pines presented in the "Linkage Between Sources and Receiving Waters" section of this report suggest that a concentration of 0.07 mg/l of total phosphorus is needed in the reservoir in order to protect dissolved oxygen levels. This is the concentration that has been demonstrated to be correlated with chlorophyll-*a* concentrations below the state screening level, as described more fully later in this report. Thus, the concentration of total phosphorus in the reservoir is identified as an intermediate water quality target for the TMDL.

Chlorophyll-*a*

Chlorophyll-*a* is an indicator parameter employed as an index to more complex water quality conditions such as reservoir metabolic activity. Chlorophyll-*a* has a long history of use in assessing reservoir hyper-stimulation and algal contamination of drinking water sources. Chlorophyll-*a* is more directly related to nutrient levels and their associated effects than are dissolved oxygen measurements. State water quality standards do not establish a specific water quality criterion for chlorophyll-*a*. However, in the absence of an established criteria, the TCEQ has adopted screening levels for chlorophyll-*a* in order to identify areas where elevated concentrations cause secondary concerns. The screening levels do not represent adopted state criteria.

Waters are classified as having no concerns or concerns based on comparisons of water quality data to screening levels presented in *Guidance for Assessing Texas Surface and*

Finished Drinking Water Quality Data, 2004 (TCEQ, 2004). The screening levels listed for chlorophyll-*a* in the Guidance were statistically derived from long-term TCEQ monitoring data. The 85th percentile value for the parameter in reservoirs is given in the Guidance. The screening level for chlorophyll-*a* in reservoirs in Texas is 21.4 micrograms per liter (μg/l). This represents a second intermediate water quality target for the TMDL.

The subject of the appropriate water quality endpoint for the TMDL program was raised with both regional watershed steering committees. The Lake O' the Pines Watershed Steering Committee and the Cypress Creek Basin Clean Rivers Program/Lake O' the Pines Combined Steering Committee both expressed the importance of protecting the water supply, recreational, and aesthetic uses of Lake O' the Pines. There is a great deal of local concern over preserving these uses, since they are widely perceived to be threatened by activities in the watershed. Although grab sampling has indicated localized violations of the segment standard for dissolved oxygen concentrations, there is presently little direct evidence that those uses are now being impaired. Basin stakeholders are concerned that a declining dissolved oxygen trend has been detected at the lowermost station in the reservoir. The steering committee indicated that the low dissolved oxygen conditions in the upper part of Lake O' the Pines must be addressed. The stakeholders discussed a recommendation to TCEQ to consider sub-dividing the lake into two segments based on the known hydrological differences between the upper reservoir and the main body of the reservoir.

Source Analysis

The permitted discharges in the Lake O' the Pines watershed were catalogued by the TMDL program. While the largest volume discharges are for industrial cooling water, those generally have limited effects on water quality, and little or no effect on Lake O' the Pines, since they are discharged into tributary reservoirs specifically constructed for that purpose (*i.e.*, Johnson Creek, Ellison Creek, Welsh, and Monticello Reservoirs). The remaining discharges are effluents from municipal wastewater treatment facilities (most of which are small) and one industrial discharger. The dischargers most important to water quality in Lake O' the Pines are the relatively large treatment facilities located in Mount Pleasant and Pittsburg. The Pilgrim's Pride Corporation processing facility is the largest of these, discharging its effluent into Tankersley Creek, a tributary of Big Cypress Creek, Segment 0404. Based on the results of field surveys conducted in the watershed, the Pilgrim's Pride plant accounts for approximately 88% of the total phosphorus and 73% of the total nitrogen contributed from permitted dischargers in the watershed. The Mount Pleasant treatment facility and the Pittsburg facilities discharge into Hart Creek, Sparks Branch, and Dry Creeks, respectively, and thence to Big Cypress Creek.

Table 2 presents nutrient loads expected from the major point sources (those with a discharge rate of 0.1 million gallons per day or greater) in the Lake O' the Pines watershed when they are operating at their respective maximum permitted discharge rates. Since none of these facilities currently have nutrient limitations, the concentrations measured during field surveys were used with permitted flows to estimate nutrient loadings. Discharges into tributary impoundments (*e.g.*, Welsh and Ellison Creek Reservoirs) are not included in this tabulation. Several smaller discharges (with flows less than or equal to 0.03 million gallons per day) are also not included in this tabulation. Annual loads coming from the major point source facilities were calculated to be 61,900 kilograms (kg) total phosphorus (TP) per year and 328,800 kg total nitrogen (TN) per year.

Table 2. Major Point Source Nutrient Loadings in Lake O' the Pines Watershed

Permit	**Permit No.**	**Flow**	**Total Phosphorus**		**Total Nitrogen**	
		MGD	**mg/l**	**kg/yr**	**mg/l**	**kg/yr**
Pilgrim's Pride Corporation	03017-000	3.00	13.23	54,900	58.02	241,000
City of Mount Pleasant	10575-004	2.91	0.56	2,300	12.05	48,500
City of Pittsburg - Sparks Branch	10250-001	2.00	0.664	1,800	9.03	25,000
City of Dangerfield	10499-001	0.70	0.54	500	5.72	5,500
City of Lone Star	14365-001	0.44	0.769	500	2.93	1,800
City of Ore City	14389-001	0.22	3.5	1,000	13.66	4,100
City of Omaha	10239-001	0.20	0.98	300	1.7	500
City of Pittsburg - Dry Creek	10250-002	0.20	2.14	600	8.54	2,400
Total		**9.67**	**--**	**61,900**	**--**	**328,800**

The NRCS's Soil and Water Assessment Tool (SWAT) model application was adopted to the simulate runoff and associated watershed loads into Lake O' the Pines. The model's application to the Lake O' the Pines TMDL project is summarized in the technical memoranda for the project: "Rationale for Selection of Watershed Model" (Ward, 2001b): "Validation of Watershed Loading Model" (Ward, 2002c); and "Application of SWAT to Basin Scale Simulation of Lake O' the Pines Watershed" (Ward, 2003). SWAT can simulate multiple subwatersheds with a variety of vegetation, soils, and land-surface characteristics, and includes sophisticated features for biomass simulation, nutrient uptake, sediment mobilization, and erosion. The validation of SWAT for several categories of watersheds from data collected in the Lake O' the Pines watershed was detailed in "Validation of Watershed Loading Model" (Ward. 2002c). Data collection did not include "edge of field studies," but focused on monitoring storm runoff in streams of varying classification in multiple subwatersheds. The version of SWAT employed in all of the modeling work for the Lake O' the Pines project is SWAT2000.

The basic element of SWAT is the hydrological response unit (HRU), defined to be a specific area with uniform soil, vegetation, surface slope, and land surface treatment. A subwatershed is a catchment made up of one or more HRUs, a channel reach, and a vadose zone compartment. The internal drainage network of a subwatershed is characterized as a single tributary length. For these large-scale simulations of the watershed of Lake O' the Pines, a system of 25 subwatersheds was employed. Fifteen subwatersheds were used to depict the complex watershed of the Big Cypress, and ten to depict the other tributaries that flow directly into Lake O' the Pines.

In SWAT, the loads are computed as a land-use source, based upon soils, vegetation, season, precipitation, sunlight, air temperature, and so on, then further altered as a function of movement across the watershed surface, including effects of surface slope, soils, and percolation. These are then combined with the same load calculation for other land uses to determine the load from a subwatershed. It was assumed that there was no further alteration of the load in its travel down the stream channel to Lake O' the Pines.

Application of SWAT to simulate runoff and nutrient transport from the Lake O’ the Pines watershed produced average loading estimates of 113,000 kg TP/year and 197,000 kg TN/year for all categories of nonpoint sources. Background nonpoint source loads (*e.g.*, existing land cover categories but without poultry litter or other fertilizer application) were calculated to average 18,200 kg TP/year and 75,400 kg TN/year. Subtracting the background nonpoint source loadings from the total nonpoint source loading yields loading estimates of 94,800 kg TP/year and 122,000 kg TN/year from anthropogenic nonpoint sources (Ward, 2003).

This work is based on soiled poultry litter application rates provided by Pilgrim’s Pride Corporation. Because of a lack of information on which to base extrapolations, no attempt was made to vary litter application rates through the simulative period, or to account for the application of other (chemical) fertilizers. This information, and most of the monitoring data used in developing the TMDL, was compiled prior to the implementation of management practices intended to reduce the runoff of sediments and nutrients from poultry production facilities and litter application sites. Contributions of on-site sewage treatment facilities to the nutrient loads from the Lake O’ the Pines watershed are included in the SWAT model as a consequence of subwatershed land uses, and are part of the calculated landscape loads.

The SWAT nonpoint source estimates, like the point source loads, are gross loadings deposited from the respective modeled land surfaces into the watercourses draining into Lake O’ the Pines. Unlike the other major biologically active elements (carbon, hydrogen, oxygen, nitrogen, and sulfur), phosphorus has no phases or compounds that are gases at ordinary temperatures and pressures. As a consequence, phosphorus introduced into an aquatic environment will remain there, and be potentially available for use by macrophytes and microbiota, until it is flushed out or buried in sediments beyond the depth of bioturbation. In the context of the Lake O’ the Pines watershed, this implies that any phosphorus reaching the stream network will eventually be transported to the reservoir, assuming Big Cypress Creek is in steady-state equilibrium to the point at which it is affected by Lake O’ the Pines backwater (Gordon, et al, 1992). Although monitoring data appear to indicate that significant biological assimilation and sorption by fine-grained sediments are taking place in Big Cypress Creek, the data is subject to a low-flow sampling bias that does not account for the transport of significant portions of the suspended and bed loads that will carry the particulate phosphorus fraction.

Water samples have generally been collected during periods of low to normal flow, whereas much of the actual transport of water, sediments, and dissolved constituents takes place during high flow periods in response to rainfall events (Allan, 1995). It is expected that phosphorus will accumulate in the stream during low to normal flow periods in Big Cypress Creek, but will be transported downstream during high flow periods. Although the cycle of sequestration and subsequent scour and transport probably occurs on a longer time scale for the entire floodplain as compared to the Big Cypress Creek channel, nutrients in this system can be assumed to eventually reach Lake O' the Pines. The assumption of zero loss of phosphorus in the stream translates to neglecting true sequestration in the bed and floodplain sediments and temporary retention in biomass. The "net" load to the reservoir may therefore be overestimated; this overestimation is part of the implicit margin of safety for this TMDL. These considerations lead to the conclusion that the gross point and nonpoint source phosphorus loads (61,900 kg/year and 113,000 kg/year, respectively) are the appropriate net loads being delivered to Lake O' the Pines.

The nitrogen budget is not such a simple matter, due to the variety of biological transformations it is subject to, and to the circumstance that nitrogen may be both assimilated (nitrogen fixation) and lost (denitrification) as a result of biological processes in direct exchange with the atmosphere. During low and normal flow periods, nitrogen, like phosphorus, will also tend to be assimilated and processed in Big Cypress Creek. The nitrogen, however, will tend to be lost from the system through bacterial denitrification, which proceeds most rapidly in environments containing abundant organic material and having anaerobic and aerobic zones in close physical proximity, such as at a sediment surface (Rheinheimer, 1991). High reported rates of denitrification result in approximately a 20% reduction in the gross loads (Ford, 1993). A 20% reduction factor was used in this report for total nitrogen loadings from point sources.

Table 3. Nutrient Loadings to Lake O' the Pines

Source Category	Totals	Total Phosphorus	Total Nitrogen
		kg/year	kg/year
Point Sources		61,900	263,000
Nonpoint Sources		94,800	122,000
	Anthropogenic Sources	156,700	385,000
Background Nonpoint Sources		18,200	75,400
	All Sources	174,900	460,400

The loads estimated to be entering Lake O' the Pines are summarized in Table 3. Information presented in Table 3 indicates that anthropogenic nonpoint sources are the largest contributor of phosphorus to Lake O' the Pines, comprising approximately 54% of the total loading, with point sources (35%) and background nonpoint sources (11%) contributing smaller fractions. Big Cypress Creek is estimated to contribute about 80% of the total annual inflow to Lake O' the Pines, and about 88% of the total phosphorus load. This estimate of the importance of Big Cypress Creek contributions is consistent with the water quality conditions found to prevail in the upper and main reservoir basins, compared with the cove environments into which the minor tributaries flow.

The atmospheric pathway has been found to be an important source of nitrogen compounds to a watershed. For phosphorus, while there is an atmospheric pathway, it is almost always minor, and negligible. For example, in the USGS's SPARROW project, a thorough, detailed, GIS-based evaluation of constituent loads into the nation's water courses, including atmospheric pathways, Smith *et al.*, state bluntly, "The atmosphere is assumed to be a negligible source of total phosphorus" (Smith, *et al.*, 1997).

This fact notwithstanding, the runoff from Big Cypress watersheds includes any nutrient deposition on the watershed surface. The atmospheric load is therefore included in the nutrient concentrations in runoff samples. The atmospheric load is also included implicitly, but not explicitly, in the model input specification. The SWAT input parameters that characterize surface land use (including vegetation) and soils (including surficial soils) are derived from field data, and implicitly include all normal sources of nutrients to the landscape, one of which is the atmospheric pathway. Thus, validation of the SWAT model implicitly includes validation of the atmospheric loading component. Unless we wished to consider a situation in which the atmospheric load is changed (which is not part of the present TMDL studies), there is no need to separate the atmospheric component and treat it as an independent input.

Nitrogen deposition in precipitation has been reported to average about 100 milligrams per square meter per year (mg/m^2/yr) over the continental United States, and to range up to 350 mg/m^2/yr in the upper Midwest. Dry deposition of ammonium and nitrate salts in the same region were reported to be even more important, bringing maximum observed atmospheric deposition rates up to 1000 mg/m^2/yr (Wetzel, 1983). Other authors have indicated even greater atmospheric deposition potentials for nitrogen, since nitrate concentrations in rainfall are reported to commonly fall into the range 0.4 – 1.3 mg/l (at an annual precipitation rate of 35 inches, deposition would range from 267 to 1156 mg/m^2/yr), but no dry deposition rates were given (Allan, 1995). Assuming a total atmospheric deposition rate for nitrogen compounds of 1500 mg/m^2/yr implies an annual load to Lake O' the Pines of nearly 20% of the Big Cypress Creek loading. Again, only a fraction of this load would seem relevant to excessive nutrient conditions in the upper reservoir, although this magnitude of input is probably significant to the overall mass balance of nitrogen in Lake O' the Pines.

In addition to physical deposition of nitrogen compounds from the atmosphere, biological conversion of molecular nitrogen to ammonium ion (fixation) may be a significant source of nitrogen input to Lake O' the Pines during summer stratification. Nitrogen fixation during the summer may be carried out by blue-green algae (Cyanobacteria) in the aerobic epilimnion, by photosynthetic bacteria concentrated in the metalimnion, by heterotrophic bacteria in the anaerobic hypolimnion, and by benthic algae and bacteria on shallow sediment surfaces within the euphotic zone. Aggregate rates of nitrogen fixation in lakes and reservoirs are reported to range from <100 to 800 mg/m^2/yr, with the extreme value corresponding to an annual load of 54,777 kg added to Lake O' the Pines (Rheinheimer, 1991).

Linkage Between Sources and Receiving Waters

Violations of dissolved oxygen criteria in upper Lake O' the Pines have been revealed to be the result of high levels of community metabolism, that is, excessive levels of photosynthesis and respiration. The levels of production and respiration calculated from the diurnal dissolved oxygen curves in "Calibration and Verification of Lake O' the Pines QUALTX Model" (Ward, 2002b) were used as model input to generate satisfactory simulations of the dissolved oxygen distribution in the reservoir. The resultant levels of metabolic activity and biomass necessary to generate the simulated dissolved oxygen distribution was then employed to derive estimates of the quantities of phosphorus and nitrogen needed to support that metabolic activity.

On a steady-state, whole lake basis, this analysis revealed loadings rates several times larger than the rates estimated from an analysis of watershed sources discussed previously. This discrepancy is explained by the fact that QUALTX is a steady-state model. However, monitoring and analysis of dissolved oxygen in Lake O' the Pines have shown that metabolic activity in the reservoir varies in time and space, and adverse dissolved oxygen conditions occur only occasionally, presumably in response to the development of certain conditions.

The upper reservoir is the direct receiving water for the nutrient loads carried by Big Cypress Creek. Water quality monitoring data from the TCEQ's TRACS database as well as the data collected as part of the TMDL program indicated that phosphorus and nitrogen concentrations at the lower-most station on Big Cypress Creek have varied substantially over time.

Total phosphorus averaged 0.114 mg/l using all data from 1997 through 2002 when values reported as "non-detects" were set to their respective detection limits. The extreme lower bound of average total phosphorus concentration can be estimated by setting "non-detect" values to zero, which yields an average of 0.096 mg/l. For this analysis, we choose a mid-range value of 0.105 mg/l by setting the "non-detect" values to one half of the reported detection limits. This is the standard procedure employed by the TCEQ to evaluate the quality of Texas surface waters.

Total nitrogen data showed higher levels of organic nitrogen were present during the summer periods. Summer ammonia nitrogen concentrations averaged 0.112 mg/l, and nitrate plus nitrate nitrogen averaged 0.092 mg/l over all stations. Unlike total phosphorus or TKN concentrations, which tend to exhibit a gradient along the reservoir axis, little difference, either among reservoir locations or seasons, is evident in inorganic nitrogen concentrations.

A very rough estimate of the summer standing stock of total phosphorus and TKN (approximating total nitrogen) in Lake O' the Pines was developed. Summer (May-September) nutrient concentrations in the epilimnion were based on the TCEQ's TRACS and TMDL surface sample results for all Lake O' the Pines stations. Hypolimnion concentrations were based on summer (May-September) samples collected from the bottom at stations in the main body of the reservoir. The chemical characteristics of sediment were determined from cores collected from Lake O' the Pines. Sediment data is reported on a dry weight basis and includes a percent solids analysis (CRP, 2000).

The estimates of atmospheric deposition and nitrogen fixation are based on the near maximum rates discussed previously (Ford, 1993). Denitrification was assumed to occur at a maximal rate taken from a survey of available literature. These results indicate that phosphorus accumulated in Lake O' the Pines at a rate of 1,938 mg/m^2 annually during the period monitored. The highest surface sediment phosphorus concentrations observed in Lake O' the Pines (circa 37,500 mg/m^3), would require the annual deposition of 3,538,053 m^3 of sediment, a layer 5 centimeters (cm) deep throughout the reservoir. This is equivalent to a sedimentation rate of 874 acre-feet/year, about three times the sedimentation rate estimated by the Texas Water Development Board — a high rate, but not impossibly so (TWDB, 1999). In spite of the large inputs of nitrogen, accumulation in Lake O' the Pines did not take place during the period monitored; instead, the reservoir experienced an average net loss of total nitrogen.

Paired values of total nitrogen and total phosphorus collected during the TMDL project are used to characterize the summer epilimnitic N:P ratios in Lake O' the Pines. Total nitrogen and total phosphorus represent:

1) the entire macronutrient pool of the summer reservoir waters, including the inorganic, immediately available nutrients;
2) nitrogen and phosphorus bound to non-living organic and inorganic particulate material which is more slowly available; and
3) that contained in the living tissue of primary producers and microconsumers, which together are performing the bulk of the observed reservoir metabolism.

The living tissue fraction, particularly from rapidly growing plankton populations, tends to exhibit an N:P ratio of 16:1 on an atom for atom basis, and is expected to take up those nutrients in that ratio for growth. This analysis finds phosphorus to be in short supply in this system; the N:P ratios average 127, ranging from 32 to 203, which is a substantial oversupply of nitrogen relative to the amount of phosphorus present. Considering the values observed at the individual reservoir stations reveals a gradient in the N:P ratio consistent with our hypothesis that phosphorus is being assimilated, driving metabolic activity that results in violations of the dissolved oxygen criteria, and is being deposited through sedimentation during transport through the reservoir. Considering just inorganic nitrogen, N:P ratios average 31. The same pattern emerges, one that reflects the preferential assimilation of phosphorus as the nutrients move down the reservoir axis from their primary source in Big Cypress Creek.

Examination of the N:P (and carbon) ratios in the sediment samples shows that, in contrast to the water column, sediment phosphorus is abundant relative to nitrogen. This is the same situation seen in the external nutrient sources, and represents the endpoint of phosphorus assimilation and sequestration by burial in deep sediment.

It is significant that the phosphorus content of the sediments at stations in the upper part of the reservoir are two to three times the levels in the lower stations, reflecting the more intense assimilation and sedimentation taking place at the locations of the upper stations.

Losses due to denitrification and to net export of nitrogen in dam releases reflect the low N:P ratio of the sediments.

The distribution of dissolved oxygen throughout Lake O' the Pines depends on the interplay of lake physical properties and processes, and on the biological processes of photosynthesis and respiration. The rate of photosynthesis is usually limited either by light or by the rate at which nutrients can be delivered to metabolizing cells, up to a threshold level beyond which the cellular machinery cannot use more light or nutrient. The highest rates of photosynthesis in algae (and plant cells in general) are achieved in actively growing populations that typically exhibit the highest ratios of chlorophyll-*a* to biomass characteristic of the species.

At any point in time, the reservoir will harbor several plant populations with somewhat different distributions, abundances, and physiological states, plus heterotrophic populations, all of which interact with lake physical properties to produce the distribution of dissolved oxygen throughout the lake volume. The magnitude of lake metabolism, and the amount of oxygen produced and respired per unit time (hour, day, or year), is generally proportional to its plant biomass; larger standing crops of algae and rooted vegetation usually support greater levels of oxygen production and uptake than do smaller standing crops. The adverse conditions commonly associated with excess nutrient input (turbid water, episodes of low dissolved oxygen concentration, floating algal blooms, taste and odor problems, fish kills) also tend to be associated with the larger plant standing crops, since it is their metabolism, together with the heterotrophic respiration the plant products support, that causes the problems.

Although the relationship of nutrient input to reservoir metabolism is well known in general, nutrient loads do not precisely predict either nutrient levels within the reservoir, or their effects on photosynthesis and respiration. For example, summer total phosphorus concentrations on the order of 0.04-0.05 mg/l are widely recognized to indicate potentially eutrophic conditions (Carlson, 1977), or to entail a high probability of severe algal blooms (Havens, et al, 2002), but the physical and biological characteristics of a given water body can greatly influence its response to particular levels of a nutrient (Stauffer, 1991).

A number of empirical models have been developed to relate nutrient loads and levels to phytoplankton biomass, photosynthetic rate, and other phenomena such as composition of the plankton community and turbidity. These relate directly to daily fluctuations in dissolved oxygen, but are critically dependent on a host of physical, chemical, and biological factors that are beyond our ability to model in detail; hence steady state models and empirical (*e.g.*, regression) models were developed, which ignore much of the detail, but which are sufficiently accurate to be useful as guidelines for analysis.

Given that larger plant biomass in the reservoir will tend to correspond with greater magnitudes of metabolism and, consequently, larger amplitudes of daily dissolved oxygen concentration change during critical conditions, chlorophyll-*a* concentrations were evaluated as an index of biomass in Lake O' the Pines, and thus of the probability of encountering adverse dissolved oxygen conditions. Chlorophyll-*a* sampling results show that concentrations in the lower reservoir are moderate, never exceeding the state screening level of 21.4 μg/l. This is confirmed by the outflow data collected during 2000 through 2002; the six samples collected ranged from the quantitation limit (3.3 μg/l) to a high value of 16 μg/l in August 2000. Two of the highest chlorophyll-*a* measurements (33 μg/l and 31.2 μg/l) observed at the upper reservoir stations suggested moderate algal blooms, while the highest value of 58.5 μg/l could be indicative of a severe bloom.

In a direct evaluation of the relationship between dissolved oxygen levels and chlorophyll-*a* concentrations in Lake O' the Pines, dissolved oxygen amplitudes measured during diurnal studies were compared with chlorophyll-*a* and pheophytin-*a* concentrations that were measured at the same time. The analysis was limited by a lack of time correspondence between dissolved oxygen diurnals and plant pigment measurements, but a weak ($R^2 = 0.2898$) positive relationship between dissolved oxygen amplitudes and Pheophytin-*a* concentration was present. Although still positive, the relationship with chlorophyll-*a* was much weaker ($R^2 = 0.1097$).

Paired values of chlorophyll-*a* and total phosphorus collected at the same stations and dates were employed to directly test the relationship with nutrient levels in Lake O' the Pines. The 46 paired chlorophyll-*a* / total phosphorus concentrations were inspected, and the results showed that the state screening criterion for chlorophyll-*a* (21.4 μg/l) was exceeded only when corresponding total phosphorus concentrations equaled or exceeded 0.07 mg/l. Chlorophyll-*a* concentrations averaged 6.8 μg/l when corresponding total phosphorus levels were less than 0.07 mg/l, and 16.7 μg/l when total phosphorus exceeded 0.07 mg/l, a statistically significant difference (t-test, unequal variance, P<0.002). The analysis was also performed for chlorophyll-*a* concentrations of 30 μg/l. Figure 4 shows these results as cumulative probabilities for exceeding the two thresholds.

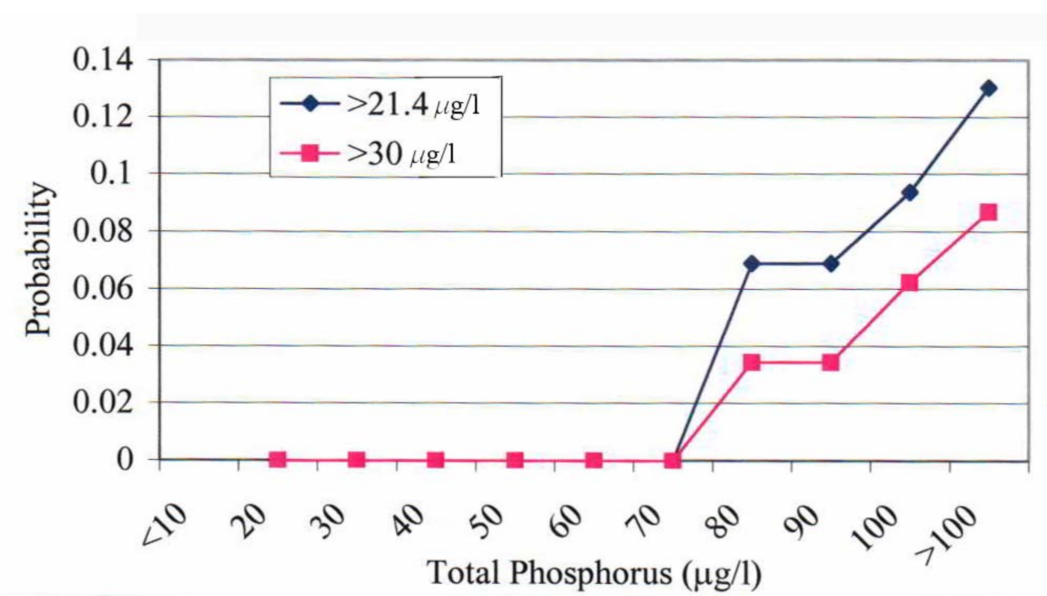

Figure 4. Threshold Frequencies of Chlorophyll-*a* Versus Total Phosphorus Concentrations

For its observed levels of total phosphorus, Lake O' the Pines exhibits a rather small standing crop of chlorophyll-*a*, and in fact, correspondingly infrequent dissolved oxygen problems. TMDL work on Lake Okeechobee (in South Florida), for example, documented total phosphorus concentrations averaging 0.087 mg/l in open waters and 0.056 mg/l in vegetated near shore areas (comparable to, but opposite from the phosphorus distribution in Lake O' the Pines) that corresponded to chlorophyll-*a* averages of 0.025 mg/l and 0.026 mg/l, respectively, about twice the levels in Lake O' the Pines (Havens, 2002).

To establish a quantitative relationship between phosphorus loading and concentrations in Lake O' the Pines, the empirical model developed by Vollenweider is employed to relate landscape loading to lake or reservoir total phosphorus concentration (Cooke, et al, 1993):

$$TP\ (mg/m^3) = \frac{load\ (mgTP/m^2*year)}{Z\ (r + s)}$$

where load refers to areal loading, or the mass of annual total phosphorus loading (from the SWAT simulation plus the point source load, Table 4), divided by reservoir area:

$$= (113{,}000 + 61{,}900\ kgTP/year)*1{,}000{,}000/68{,}471{,}193\ m^2$$
$$= 2554\ mgTP/m^2*year$$

where

Z = average depth (reservoir volume/reservoir area, 4.34 m) (TWDB, 1999),
r = flushing rate (reservoir volume/annual inflow, 1.89), and
s = sedimentation coefficient (10/Z).

$$TP_{total} = 2554/4.34(1.89 + 10/4.34)$$
$$= 140\ mg/m^3 \text{ or } 0.140\ mg/l$$

This estimated load is in general agreement with the observed total phosphorus concentrations in the reservoir, recognizing that the model gives an average value over the phosphorus gradient that is characteristic of Lake O' the Pines.

The SWAT landscape load (18,200 kg/year) can be used to examine the lower limit of average phosphorus concentration potentially achievable in Lake O' the Pines without human activity in the watershed — which is *not* an actual, feasible lower limit:

$$TP_{Natural} = 266/4.34(1.89 + 10/4.34)$$
$$= 14.6\ mg/m^3 \text{ or } 0.015\ mg/l$$

Margin of Safety

EPA guidance on TMDLs requires that a margin of safety be included in the analysis. The guidance states that the margin of safety is to account for uncertainty in the analysis and thus provide a higher level of assurance that the goal of the TMDL will be met. The guidance further states that the margin of safety can be incorporated into the analysis by using conservative assumptions in the analysis, which would produce conservative estimates of sources, constituent loadings, instream dynamics, load allocations, and other technical components of the TMDL. This approach is referred to in the guidance as an “implicit” margin of safety. Alternatively, the guidance states that the margin of safety can be “explicitly” included in the TMDL load allocation. This approach involves specifying a loading amount for the margin of safety in the pollutant load allocation. The explicit load for the margin of safety is frequently specified as a percentage of the allowable load as determined in the TMDL analysis, and is assigned a value which corresponds to the degree of uncertainty believed to be present in the analysis (frequently 10% or 20%).

Analysis of Uncertainty

The underlying need for a margin of safety in TMDL determination stems from the dilemma of specifying water quality control strategies on the basis of imperfect science. This, in turn, is driven by the need to implement controls early enough to arrest water quality degradation and avoid perhaps irreversible impacts of contaminant loads, without affording the time necessary to establish the cause-and-effect linkages to an adequate level of scientific assurance. Quantification of the uncertainty in the science underlying TMDL determination, to the extent possible, is the basis for assigning a margin of safety.

There are two fundamental sources of uncertainty in the various procedures resulting in the TMDL determination for Lake O' the Pines. The first of these are inaccuracies in measurement that arise from limitations of sampling procedures, instrumental imprecision, and variability in the environment itself, all of which may include both random and systematic (non-random or bias) error. Many of these, especially hydrologic and water quality data, can be quantified by the exercise of repeated measurements. Some of these, such as land-use designation, crop coverage, soil characteristics, vegetation cover, and diversion and return flow disposition, have acknowledged uncertainties due to information deficiencies and limits of resolution. However, there is no acceptable procedure for estimating these uncertainties. Still other factors, such as agricultural cropping strategies, fertilizer applications, wastewater treatment overflows, CAFO animal density, and herding practices on rangelands, must be inferred from sparse anecdotal information, the uncertainty of which can only be guessed.

The second fundamental source of uncertainty, and the one which is often of interest to those engaged in predictive modeling of water quality, results from our imperfect understanding of the system under study. This includes approximations of the parameters specified in the model (*e.g.*, rate coefficients, kinetic interactions, etc.), invalid or incorrect premises in the conceptual model on which the system analysis is based (*e.g.*, neglect of benthal fluxes, effects of additional factors such a predation of algae or concentrations of silicates), and the inability to perfectly (or adequately) represent important system features and interactions in the mathematical model chosen to represent it (*e.g.*, approximating horizontal mixing by a dispersion equation). Sometimes these uncertainties may be formally quantified through the use of "sensitivity analyses," in which model input parameters are varied systematically and the corresponding behavior of the model output is determined (USEPA, 1997).

A significant, often compromising, problem with such formal sensitivity analysis is that the variation in the input parameter is not tied to its natural range of variation, but is rather assigned an arbitrary value, *e.g.* ±10%. This leads to erroneous conclusions about the relative importance of the various parameters. In the present project for Lake O' the Pines, the modeling uncertainty is assessed as part of the validation procedure, *i.e.*, by examining the variance of field data about the model prediction. This allows us to include a measure of parameter variation that includes at least a portion of the natural range in our assessment of the reliability and accuracy of the simulations. This uncertainty is addressed, for example, in "Calibration and Verification of Lake O' the Pines QUALTX Water-Quality Model," (August 2002).

In evaluations of future scenarios underlying the TMDL, the specification of conditions for model operation is subject to both types of uncertainty. Errors in measurement may further exacerbate the TMDL projection by forcing the water quality prediction beyond the range of historical measurement. Future scenarios may include land use and population forecasts, which are themselves inaccurate, and subject to both types of uncertainty. The uncertainties of the conceptual model may become even more problematic because of projected changes to the landscape or to the structure of the receiving water.

Margin of Safety for This TMDL

The TMDL for dissolved oxygen in Lake O' the Pines employs an implicit margin of safety. Conservative assumptions used in the TMDL analysis have led to estimations of constituent source loadings, the linkage between sources and instream water quality, and load allocations, which provide a significant level of assurances that the goal of the TMDL will be met. Several of the conservative assumptions used in the TMDL analysis are discussed below.

The TMDL analysis for dissolved oxygen in Lake O' the Pines assumes that all permitted wastewater discharges in the basin are discharging at their maximum permitted level. In reality, there is a very low probability that the wastewater dischargers in the basin would actually discharge at this level. Historically, most municipal wastewater discharges operate well below their maximum permitted value. This mode of operation provides the permitted discharger with a margin of safety in complying with the terms of their permit. Additionally, TCEQ rules require municipal wastewater facilities to expand their facilities when their discharges reach 85% to 90% of their permitted values. This requirement suggests that the municipal permits are currently, in effect, discharging at levels that are at least 15% less than their permitted level.

The TMDL analysis for Lake O' the Pines also assumes that there was no net loss of total phosphorus in the stream channels that deliver the phosphorus loads from their point of origin (either the discharge from wastewater treatment facilities or from agricultural applications of phosphorus-containing materials). Several reasons for this assumption are presented in the TMDL, and the assumption is considered reasonable. However, it is also true that some loss of total phosphorus undoubtedly occurs through deep burial in floodplain sediments and by other mechanisms.

The SWAT model used for estimating nonpoint source loadings is generally conservative. This is evident when comparing the total phosphorus loads estimate from the SWAT model with the monitored phosphorus data from the lowermost station on Big Cypress Creek. The model output tends to predict higher average annual loadings of total phosphorus than those calculated based upon the monitoring data. Also, the data used to calibrate the SWAT model was collected prior to the time that extensive efforts were made to install best management practices on agricultural lands in the watershed. It is reasonable to assume that these practices will reduce the loadings of total phosphorus from these areas. This assumption will probably be a major initial focus of the TMDL implementation plan for Lake O' the Pines.

The TMDL analysis was based on loadings of total phosphorus to the reservoir. As has been discussed previously, significant amounts of total phosphorus are actually present as polyphosphate, sorbed to mineral particles, or are tied up in organic material. These forms of phosphorus are not readily available for new growth and therefore contribute only indirectly to the dissolved oxygen regime in Lake O' the Pines. By controlling total phosphorus, the TMDL seeks to insure that not only the dissolved fraction is limited, but also other forms of phosphorus are limited, including those that could have an indirect or secondary impact on plant growth and dissolved oxygen levels in the reservoir.

Data collected during the TMDL project indicated that the dissolved oxygen criteria were not achieved in about 15% of the measurements conducted at stations located in the upper portion of the reservoir. This observed violation rate is only slightly higher than the rate, which is allowed under state water quality assessment guidelines. The analysis used in the development of the TMDL defines a target total phosphorus concentration that will maintain chlorophyll-*a* concentrations below the state screening level at all times. The large reductions in total phosphorus loadings identified in the TMDL can reasonably be expected to influence biochemical processes in the reservoir to the small degree necessary to bring the reservoir back into compliance with state water quality assessment criteria.

Finally, the TMDL analysis of the dissolved oxygen regime in Lake O' the Pines has identified several water quality parameters to serve as both a final endpoint and intermediate water quality targets for monitoring the TMDL. These parameters provide multiple measures of water quality and address both chemical and biological conditions. Target values have been specified for dissolved oxygen, total phosphorus, and chlorophyll-*a*, which were evaluated during development of the TMDL. These target values can be expected to be consistent with the maintenance of the water quality standards in Lake O' the Pines. This broad-based, multiple parameter approach provides added assurances toward meeting the goal of the TMDL.

Pollutant Load Allocation

Previous discussions have presented the available information that relates dissolved oxygen levels in Lake O' the Pines with nutrient and chlorophyll-*a* levels. Data from Lake O' the Pines has shown a positive correlation between the range of dissolved oxygen concentrations and the concentration of pheophytin-*a*. Further, it was demonstrated with data from Lake O' the Pines that the concentration of chlorophyll-*a* remains below the state's screening level when concentrations of total phosphorus in the reservoir remain below 0.07 mg/l. To minimize the probability of algal blooms (either planktonic or periphytic), it is necessary to reduce the average total phosphorus concentration in the reservoir to below 0.07 mg/l. Solving the Vollenwieder model for the appropriate load gives:

$$\begin{aligned} Load_{desired} &= TP*Z(r + s) \\ &= 70.0\ mg/m^3*4.34(1.89+10/4.34) \\ &= 1{,}274\ mgTP/m^2*year\ \text{or}\ 87{,}200\ kg/year \end{aligned}$$

Thus, the allowable loading of total phosphorus to Lake O' the Pines under the TMDL is calculated to be approximately 87,200 kg/year. Of this amount, 18,200 kg/year is estimated to be the background nonpoint source load. This leaves 69,000 kg/year of total phosphorus (87,200 - 18,200 = 69,000) available to be allocated to anthropogenic point and nonpoint sources in the watershed, an approximate 56% reduction in the existing loadings to the reservoir. Reducing the existing loadings by 56% yields allowable loadings for point sources and nonpoint sources as approximately 27,000 kg/year and 42,000 kg/year respectively.

The TMDL equation as defined in EPA guidance is as follows:

$$TMDL = \sum WLA + \sum LA + MOS$$

where

1) WLA = Load from all point sources;
2) LA = Load from all nonpoint sources (including both background and anthropogenic); and
3) MOS = Margin of safety accounting for uncertainty in the analysis.

As discussed previously, an implicit margin of safety is incorporated into the TMDL for Lake O' the Pines. Therefore, the MOS term is set to zero. The TMDL equation for total phosphorus in Lake O' the Pines then becomes:

$$\begin{aligned} TMDL &= 27{,}000\ kg/year + (18{,}200 + 42{,}000)\ kg/year + 0 \\ &= 27{,}000 + 60{,}200 + 0 \\ &= 87{,}200\ kg/year \end{aligned}$$

Implementation and Reasonable Assurance

The TMDL development process involves the preparation of two documents:

- a TMDL, which determines the amount of pollutant a water body can receive and meet applicable water quality standards, and
- an implementation plan, which is a detailed description and schedule of regulatory and voluntary management measures necessary to achieve the pollutant reductions identified in the TMDL.

It is the policy of the TCEQ to develop implementation plans for all TMDLs adopted by the Commission (TNRCC 1999; TCEQ 2002), and to assure the plans are implemented. During TMDL implementation, the TCEQ works with stakeholders to develop the management strategies needed to restore water quality to an impaired water body. This information is summarized in the TMDL Implementation Plan (IP), which is separate from the TMDL document. Preparation of an implementation plan is critical to ensure water quality standards are restored and maintained.

Preparation of the implementation plan for Lake O' the Pines will be initiated upon Commission approval of the TMDL. The IP will detail any activities such as mitigation measures, permit actions, best management practices, and additional sampling and monitoring determined to be necessary to restore water quality. Additional sampling at appropriate locations and frequencies will allow progress toward the targeted interim and primary endpoints to be tracked and evaluated. These steps will provide reasonable assurances that the regulatory and voluntary activities necessary to achieve the pollutant reductions will be implemented.

Public Participation

The public participation process in TMDL development is described in detail in the TCEQ's *Developing Total Maximum Daily Load Projects in Texas: A Guide for Lead Organizations* (GI-250, June, 1999). More information about the public and stakeholder participation process in TMDL development and implementation can be found on the TCEQ's Web site at: *www.tceq.state.tx.us/implementation/water/tmdl/*.

The focus of public participation efforts in the TMDL program is the encouragement of stakeholder involvement concerning the development and implementation of water quality goals and activities in the basin. The Northeast Texas Municipal Water District (NETMWD) is the regional partner with the TCEQ in the development of the TMDL for Lake O' the Pines. The NETMWD, was the prime contractor to the TCEQ for the TMDL project, and carried out the public participation activities during the project. The public was involved with the project through steering committee meetings, the District's Web site, and other informational materials. The Web site (*www.netmwd.com*) provided the citizens of the basin and other interested parties with a useful tool for focusing on water quality issues in the Cypress Creek Basin and the Lake O' the Pines watershed. Included within the site are TMDL project reports, current information on water monitoring, water data, basin maps, and special study information, in addition to other resources. The goal is to provide a readily available resource of information to the public. It is hoped that this information will, in turn, encourage citizens of the basin to reach out and get involved in the TMDL.

Basin Steering Committee meetings are held at least once a year. The steering committee meeting announcements and minutes are updated regularly on the Web site. Meeting agendas are structured to promote public involvement and serve as a review of achievable water quality objectives and priorities for the basin. Steering Committee meeting minutes are available from the home page or the site map of the District's Web site. Open to the public, Basin Steering Committee meetings are designed to be forums for public comment and input on water quality issues. The committee includes stakeholders who represent government, permitted facilities, agriculture, business, environmental, and community interests in the watershed.

Notice concerning the release of the draft Lake O' the Pines TMDL for public comment and the scheduling of a public meeting was mailed to basin stakeholders in October 2005. Notice was also published in the *Texas Register*, and in the Longview *News-Journal*, the Pittsburg *Gazette*, and the Daingerfield *Bee*. Both the notice and the draft TMDL were posted on the TCEQ's Web site during the comment period. A public meeting to accept oral comments was held in Hughes Springs on November 17, 2005. The 30-day public comment period ended on December 5, 2005. Information about the TMDL project has been posted on the TCEQ's Web site since early in the project development, and will updated regularly throughout implementation. A document called "Response to Public Comment on One TMDL for Lake O' the Pines" will summarize the TCEQ's responses to comments received during the formal comment period, and any modifications made to the TMDL document as a result of the public comment process. The TCEQ's response to public comment and the final TMDL will be submitted to the EPA and posted on the TCEQ's Web site (*www.tceq.state.tx.us/implementation/water/tmdl/*). It will be made available in hard copy by request to all interested parties.

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