Revised Draft Nutrient Thresholds to Protect Aquatic Life Uses in Mississippi Lakes and Reservoirs

Photos: Mississippi Department of Wildlife, Fisheries, and Parks

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Acknowledgements

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Executive Summary

In response to the threat posed by nutrients, EPA requested that states develop criteria to protect designated uses from impairment due to excessive nutrients. The State of Mississippi implemented this project to support development of nutrient criteria for lakes and reservoirs within the State. EPA recommended three methods to establish nutrient criteria (USEPA 2000): a frequency distribution reference-based approach, a stressor-response approach, and literature-derived values. In the original report (MDEQ 2007a), MDEQ recommended criteria primarily based on a reference approach using the quality of sports fisheries as indicators of aquatic life use condition. The original report was reviewed by the Mississippi Department of Environmental Quality (MDEQ) Nutrient Criteria Technical Advisory Group (TAG). They provided feedback and suggested additional analysis based on dissolved oxygen endpoints. In addition, MDEQ had collected additional data since the original report was written. This report incorporated the new data and incorporated the new DO based analyses. The intent is not to supplant the original report, but to supplement that report with this new one. Readers are encouraged, therefore, to consider both reports as complementary and relevant.

We compiled data collected by MDEQ for lakes in Mississippi. These datasets included nutrients and other related water quality parameters. Appropriate QA/QC was further performed to assess the quality of the data and condense the data one overall dataset. We also obtained diel DO data for Janous Pond from a member of the MDEQ nutrient TAG (Paul Rodrigue, USDA NRCS) to validate some assumptions of the DO based analysis.

The novel analysis presented in this report is the use of minimum DO values to identify chlorophyll concentrations associated, based on empirical models, with a likelihood of violating the state instantaneous DO criterion of 4 mg/L promulgated to protect aquatic life. Oxygen is vital to aquatic life and existing DO criteria exist to protect aquatic life uses. Use of DO, therefore provided a way to directly link nutrient endpoints to aquatic life use protection.

Minimum DO was estimated using a simple model that assumes that, relative to DO saturation, nighttime DO deficits are equivalent to diurnal DO surpluses. Using diurnal DO data, we estimated nighttime deficits and, therefore, minima and then related this to chlorophyll *a* concentrations. The symmetrical assumption of diurnal and nocturnal DO around saturation was validated using continuous DO data from Janous Pond. The empirical models of DO minima versus chlorophyll *a* resulted in recommended thresholds of 20 ppb for both reservoirs and oxbows, a value consistent with chlorophyll *a* derived based on the original MSFish based analysis but lower the that value derived for oxbows (MDEQ 2007a). TP and TN concentrations were then evaluated using empirical models of chlorophyll a versus TN and TP using MDEQ data and estimating lower quartile and average predictions based on the 20 ppb chlorophyll value.

Overall, the novel DO based analysis resulted in a lower recommended threshold for chlorophyll *a* in oxbows, and confirmed that the recommended threshold for reservoirs from the original analysis would not likely result in DO criterion violations (MDEQ 2007a). The new analysis also confirmed that the TP and TN values recommended based on the original analysis were consistent with TP and TN values to protect the chlorophyll endpoints generated using the DO based analysis.

This novel analysis provides true stressor-response based recommended nutrient thresholds that are directly linked to an aquatic life use measure, dissolved oxygen criteria.

The summary of thresholds derived from different lines of evidence in both reports (MDEQ 2007a and this one) are as follows:

	Chl a (ug/L)					
	Distribution Based (Ranges based on reservoir size)			**Stressor-Response**		**Other Literature**
	EPA Values	**25th Percentile (MDEQ)**	**MBISQ Reference Streams into Reservoirs**	**MSFish**	**DO Based**	
Reservoirs	3.0 – 5.0	7.6 – 9.5	N/A	19	20	5-40
Oxbows		25		46 – 68	20-25	

	TP (mg/L)					
	Distribution Based (Ranges based on reservoir size)			**Stressor-Response**		**Other Literature**
	EPA Values	**25th Percentile (MDEQ)**	**MBISQ Reference Streams into Reservoirs**	**MSFish**	**DO Based**	
Reservoirs	0.010-0.020	0.020-0.040	0.060	0.080	0.040 – 0.250	0.020-2.00
Oxbows		0.070	N/A	0.090-0.150	0.040 – 0.250	

	TN (mg/L)					
	Distribution Based (Ranges based on reservoir size)			**Stressor-Response**		**Other Literature**
	EPA Values	**25th Percentile (MDEQ)**	**MBISQ Reference Streams into Reservoirs**	**MSFish**	**DO Based**	
Reservoirs	0.360-0.600	0.450-0.570	0.600	0.990	0.562 – 2.50	0.350 – 4.00
Oxbows		1.030	N/A	1.250-1.620	0.562 – 2.50	

1 Introduction

Nutrients are a natural component of healthy ecosystems. In natural concentrations, essential nutrients help maintain the structure and function of ecosystems. However, in excessive quantities, nutrients can destabilize natural ecosystems leading to a variety of problems including nuisance plant growth, hypoxia and anoxia, species loss, and risks to human health.

Nutrients affect aquatic systems in diverse ways. The direct effects are on the primary producers, namely, algal and macrophyte production and species composition. The effects on most non-primary producer aquatic life are indirect (Figure 1.1).

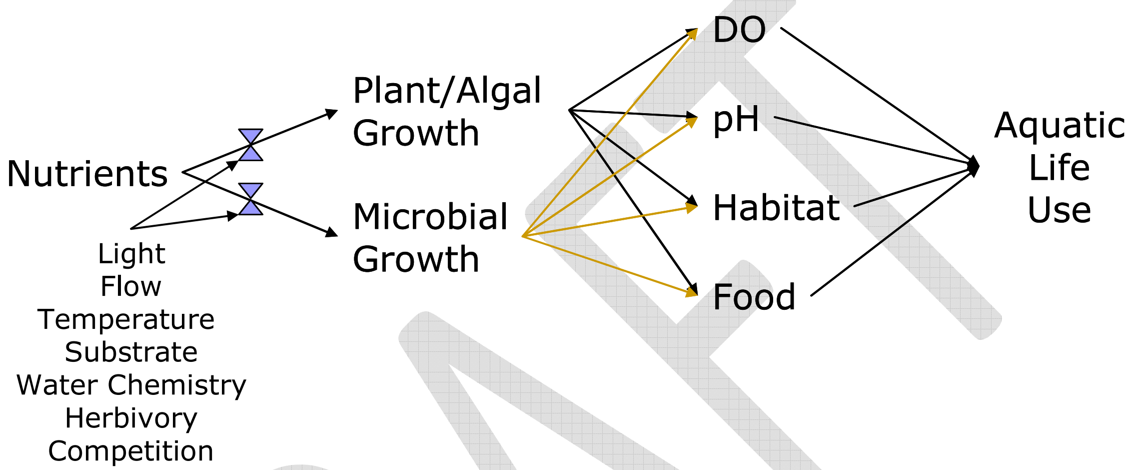

Figure 1-1 Simplified diagram illustrating the causal pathway between nutrients and aquatic life use impacts. Nutrients enrich both plant/algal as well as microbial assemblages, which lead to changes in the physical/chemical habitat and food quality of lakes. These effects directly impact insect and fish assemblages. The effects of nutrients are influenced by a number of other factors as well, such as light, flow, and temperature.

Nutrients increase the growth of primary producers and decomposers which lead to changes in the physical and chemical lake environment (e.g., reduced oxygen, loss of reproductive habitat, alteration of the food base for aquatic animals, reduced clarity, etc.). It is these effects which result in changes to the lake biological community (e.g., loss of oxygen sensitive fishes), and ultimately impair the use of a lake for aquatic life.

In response to the threat by nutrients, EPA has requested that states develop nutrient criteria to protect designated uses from impairment due to excessive nutrients. Nutrient criteria are developed to protect designated uses and, as such, the applicable designated uses are integral to guiding the appropriate criteria. Nutrients principally threaten aquatic life, recreational, and drinking water uses. Aquatic life uses are threatened when nutrients actually impact plant assemblages and enrich microbial assemblages, resulting in the proliferation of nuisance or invasive taxa or causing excessive growth of algae, which alters the habitat (physical habitat, dissolved oxygen, etc.) for other aquatic life. Recreational uses are threatened when nutrients cause excess growth of primary producer taxa that interfere with fishing, swimming, or other recreational uses of streams and rivers. Lastly, drinking water uses are impaired when nutrients cause the proliferation of nuisance primary producer taxa that generate taste and odor problems in drinking water, produce toxic compounds, or, potentially, overwhelm filtration systems.

EPA has developed recommended regional nutrient criteria, but encouraged states to pursue their own nutrient criteria development programs. The state of Mississippi has committed to the development of scientifically defensible nutrient criteria to protect designated uses in its waterbodies. As such, MDEQ developed nutrient thresholds for streams as part of an earlier effort (MDEQ 2007a). In response to additional data collection and feedback from the MDEQ nutrient Technical Advisory Group (TAG), additional data incorporation and analyses were recommended. This brief report summarizes those additional efforts. Readers are directed to the original report for the core of the lake and reservoir analyses.

The original report outlined a series of analyses based on USEPA nutrient criteria guidance (USEPA 2000). First, the report demonstrated, through classification analysis, that the most parsimonious classification was based on splitting reservoirs and oxbows, but did not recommend additional classification although explorations of reservoir size and oxbow location relative to the Delta were considered. The report then considered a variety of analyses for deriving nutrient thresholds related to use protection, again based principally on USEPA guidance (USEPA 2000). These were primarily reference distribution based approaches using EPA recommended criteria and the 25th percentile of MS specific data, as well as distributions of reference stream concentrations tributary to reservoirs and lakes. Scientific literature was also used to generate candidate nutrient thresholds for consideration. The final approach was based on a response indicator using fish assemblage information (MSFish), the one biological assemblage in lakes for which there was information.

The MSFish index, developed by MS Department of Wildlife, Fisheries, and Parks to rate the quality of expected fishing experience in MS lakes and reservoirs, was essentially used to generate a reference site population with acceptable biological conditions. The MSFish index is derived from a mix of qualitative and quantitative information on the abundance, size distribution, and condition of bass, crappie, and bream species. A series of metrics derived from the data on these species were calculated and overall score generated for lakes and reservoirs. These scores were re-scaled to 100 and trisected to generate low, medium, and high MSFish index categories. For reservoirs, the 75th percentile of nutrient concentrations from waterbodies scoring in the high MSFish index category was used to generate nutrient thresholds, whereas for oxbows, the 25th percentile of the low fish index category was used. The differences in which category and which percentile was used were based on the nature of the MSFish index response to nutrients in the two waterbody types. This approach is akin to the biologically healthy condition (BHC) reference site approach used for streams (MDEQ 2009a). More detail on the approach is provided in MDEQ (2007a).

The MDEQ Nutrient Criteria Technical Advisory Group (TAG) expressed reservations with the MSFish index approach and was principally concerned with the degree to which the index reflected the entire aquatic life use of lakes and the lack of a distinct stressor-response relationship. As part of that feedback, it was recommended that MDEQ consider the range of possible response indicators and generate potential response relationships that could be related to aquatic life use. Chlorophyll *a* had been investigated in the original report (MDEQ 2007a) and while relationships between nutrients and chlorophyll were largely consistent with a global review of nutrient-chlorophyll responses, there was no information on what an appropriate chlorophyll concentration should be. Trophic State Index (TSI) thresholds for chlorophyll were considered and reviewed (Carlson 1977); however, the strong effect of non-algal turbidity cast doubt on the applicability of that approach in MS and, therefore, on the appropriateness of the chlorophyll thresholds used. The general trophic concept is useful, but it was recognized that reservoirs and oxbows in MS have likely different trophic expectations than those in northern temperate regions (MDEQ 2007a). Dissolved oxygen was another potential response indicator related to aquatic life and for which there were existing aquatic life use criteria and available data. We report here on nutrient thresholds derived using stressor-response analyses based on relating chlorophyll concentrations to dissolved oxygen levels. Chlorophyll concentrations were identified that were related to probabilities of dissolve oxygen criteria exceedances. These resultant chlorophyll concentration thresholds were then related to nutrient concentrations using the nutrient-chlorophyll empirical models consistent with the MDEQ (2007a) report to generate nutrient thresholds. This approach provides an additional line of evidence for nutrient thresholds based on stressor-response models that are related to aquatic life use.

2 Stressor-Response Analysis: Dissolved Oxygen

Dissolved oxygen (DO) is of vital importance to aquatic life in aquatic ecosystems including lentic waterbodies (Kalff 2001). Aquatic organisms rely on sufficient oxygen to survive and grow, and USEPA and states have developed oxygen criteria to protect aquatic life (USEPA 1986). Mississippi has dissolved oxygen criteria as well, to protect aquatic life (MDEQ 2007b):

> Dissolved Oxygen: Dissolved oxygen concentrations shall be maintained at a daily average of not less than 5.0 mg/l with an instantaneous minimum of not less than 4.0 mg/l.
>
> When possible, samples should be taken from ambient sites according to the following guidelines:
>
>> For waters that are not thermally stratified, such as unstratified lakes, lakes during turnover, streams, and rivers:
>>
>>> At mid-depth if the total water column depth is 10 feet or less.
>>> At 5 feet from the water surface if the total water column depth is greater than 10 feet.
>>
>> For waters that are thermally stratified such as lakes, estuaries, and impounded streams:
>>
>>> At mid-depth of the epilimnion if the epilimnion depth is 10 feet or less.
>>> At 5 feet from the water surface if the epilimnion depth is greater than 10 feet.

Dissolved oxygen is affected by nutrients through causal pathways that include increased primary production resulting in increased internal organic matter loading that, in turn, increases the amount of reduced carbon available to decomposers (Kalff 2001). In addition nutrient enrichment increases decomposition itself by enriching the microbes that decompose organic matter. The decomposition of primary production then reduces oxygen in the lake. This can be especially pronounced during stratification in lower lake strata which may remain hypoxic or anoxic. The reduction in oxygen has deleterious effects on biota, as described above. Therefore, MDEQ investigated DO endpoints in stressor-response models to derive nutrient criteria.

Nutrient enrichment is expected to decrease oxygen concentrations in lakes as chlorophyll increases and results in the response described above. A plot of oxygen versus chlorophyll from the MDEQ lake sampling dataset, however, indicates the opposite (Figure 2.1).

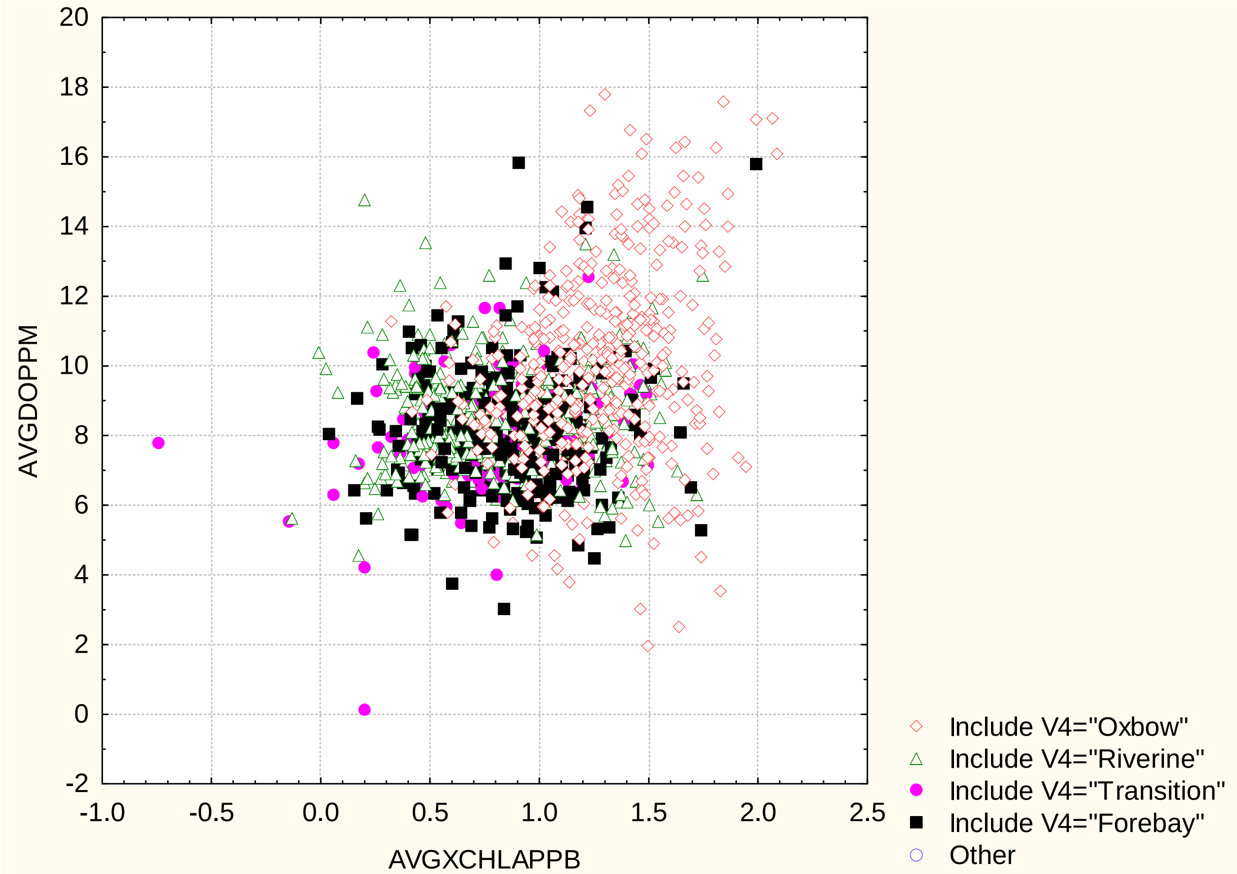

Figure 2-1 Average dissolved oxygen (ppm, AVGDOPPM) versus $\log_{10}$average chlorophyll (ppb, AVGXCHLPPB) from samples in the MDEQ lake monitoring dataset.

MDEQ routinely collects grab sample dissolved oxygen as part of its monitoring program. However, grab samples are only a snapshot of oxygen dynamics in lakes. DO typically follows a sinusoidal pattern as photosynthesis increases DO during light hours and respiration removes DO during dark hours, when photosynthesis does not occur. The cycle is also affected by reaeration, which is the abiotic movement of oxygen into and out of surface water depending on oxygen concentration relative to the saturation concentration of DO concentration (the equilibrium concentration of oxygen in water), which is primarily determined by temperature, but also influenced by barometric pressure and salinity. If water is under-saturated, oxygen will dissolve in from the atmosphere, if super-saturated, it will dissolve out of the water into the atmosphere. Typically, water quality modelers assume DO varies symmetrically around the saturation DO concentration (the equilibrium concentration of oxygen in water), which is primarily determined by temperature, but also influenced by barometric pressure and salinity (APHA 1985, Thomann and Mueller 1987).

Ideally, we would have used diel DO data for each sampling date to relate nutrient enrichment to DO minima which DO criteria address, but MDEQ does not routinely collect diel DO data; rather, MDEQ collects grab sample DO along a vertical profile in lakes during the day. DO samples are typically collected around midday and later (Figure 2.2), when dissolved oxygen is typically above saturation and closer to its diel maximum.

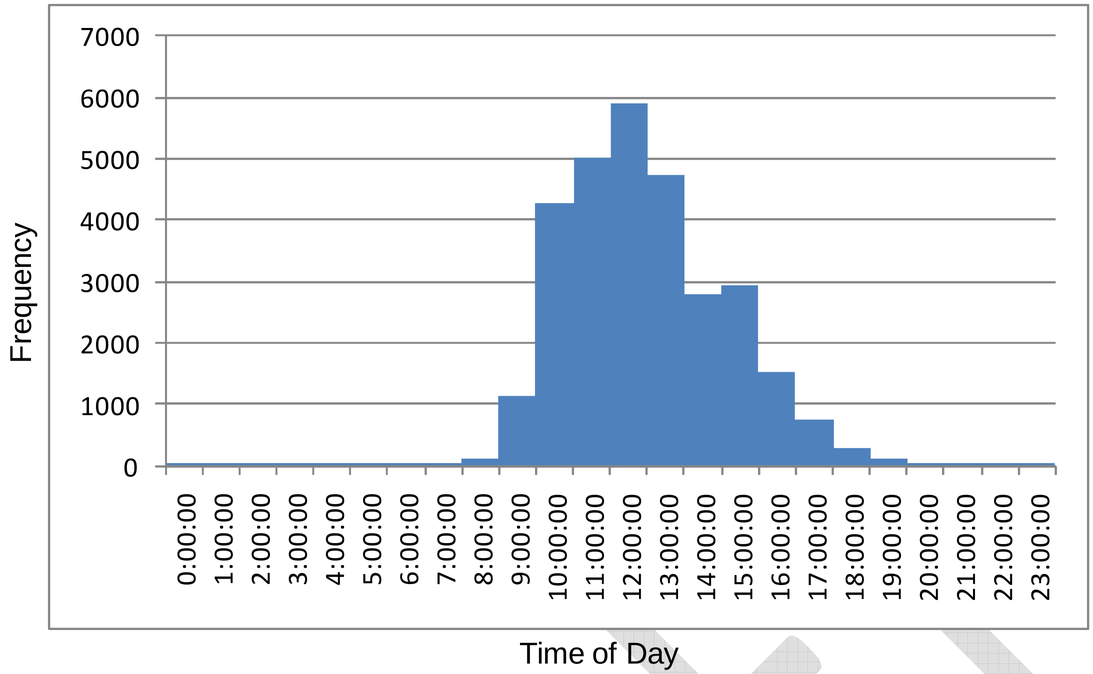

Figure 2-2 Histogram of times of the day when DO grab samples are taken as part of MDEQ lake monitoring.

The fact that DO was actually sampled during the midday and later explains Figure 2.1, since nutrients enrich primary production which is expected to result in greater daytime DO concentrations but also lower nighttime minima, which the MDEQ DO criterion addresses. So we needed to estimate what DO minima would be given the DO samples taken during daytime.

Since it is well established that DO exhibits a sinusoidal pattern about the saturation concentration and water quality modelers assume as much, the approach we took was to estimate how far above DO saturation daytime samples were and assume that nighttime concentrations were depressed below DO saturation by an equal magnitude relative to DO saturation. Therefore, we had to estimate DO saturation for each sample, which we did using the common equation:

DO_{sat} (mg/L) = $-139.3 + (1.58 \times 10^5)/T - (6.64 \times 10^7)/T^2 + (1.24 \times 10^{10})/T^3 - (8.62 \times 10^{11})/T^4$, (1)

where T = temperature (degree C)(APHA 1985).

We then calculated the difference between observed DO (DO_{obs}) and DO_{sat} and subtracted the same amount from DO_{sat} to estimate nighttime minima (DO_{min}). We could then relate chlorophyll concentrations to DO_{min}, which were consistent with predictions that excess chlorophyll growth stimulated by nutrients would result in lower DO_{min} (Figure 2.3).

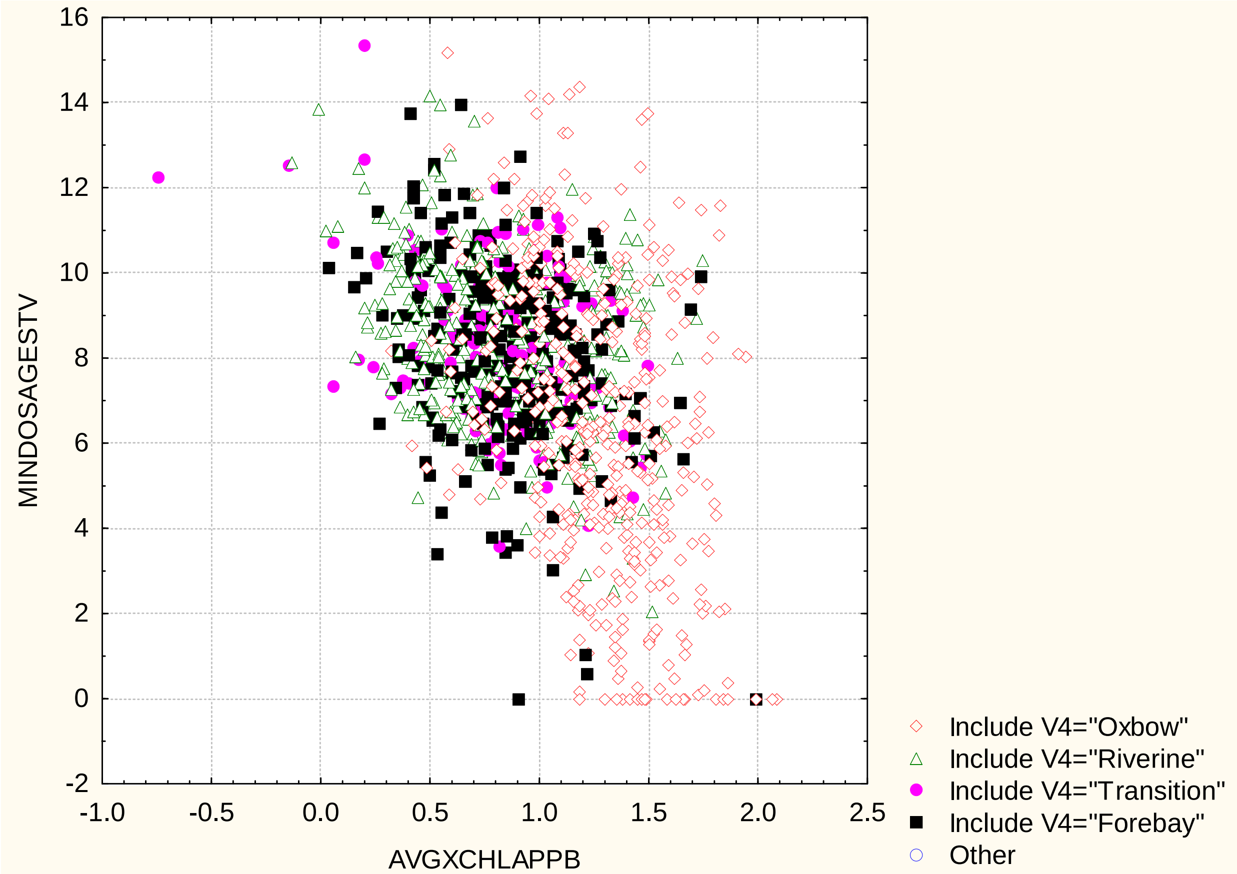

Figure 2-3 Average minimum dissolved oxygen (ppm, MINDOSAGESTV) versus $\log_{10}$average chlorophyll (ppb, AVGXCHLPPB) from samples in the MDEQ lake monitoring dataset.

We tested our hypotheses about DO symmetry about saturation using continuous diel DO data taken over several months (April – September) from Janous Pond near Grenada, MS (Paul Rodrigue, USDA NRCS). We calculated DO_{sat} using temperature data and the APHA (1985) equation above. DO varied about DO_{sat} in a sinusoidal pattern as predicted and, with some exceptions likely due to probe errors, was visually consistent with the symmetry hypothesis (Figure 2.4). We calculated absolute DO surplus (DO_{max}-DO_{sat}) and absolute DO deficit (DO_{min}-DO_{sat}) for each diel DO cycle. We then took the difference between these two estimates. If our hypothesis about DO symmetry is true, then the mean difference between these two values should be approximately zero. In fact, the average difference was approximately -1.4, meaning surplus was higher than deficit by approximately 1 mg/L, but the standard error was 1.4 indicating the difference was not likely significantly different from 0 ($p<0.05$). Similar results were obtained using long-term diel averages versus monthly averaged data (mean = -1.4±0.5). These results essentially confirm the hypothesis about symmetry, but may indicate that a difference in surplus minus deficit of 0.5 to 1.0 mg/L could also be assumed. For the subsequent analysis, we take a conservative approach of assuming symmetry.

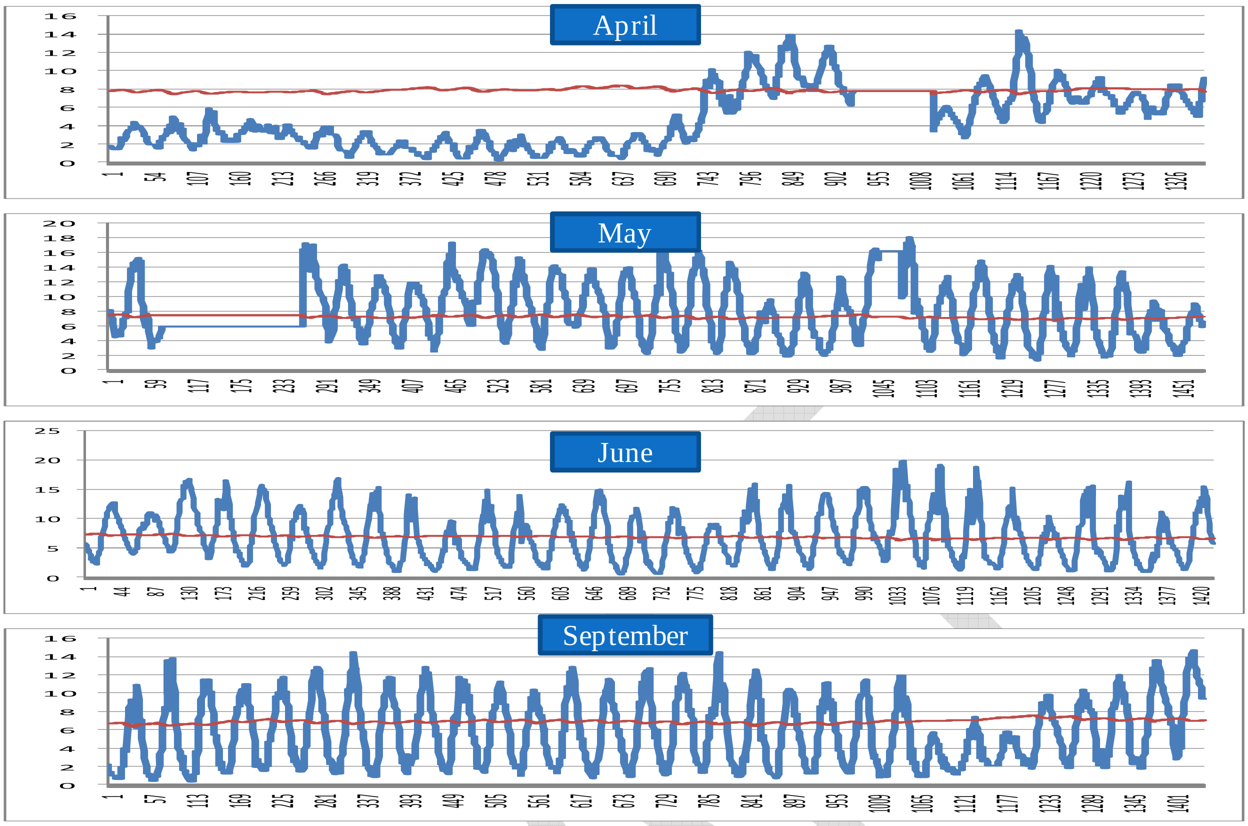

Figure 2-4 Plots of diel dissolved oxygen in Janous Pond for April, May, June, and September. Data for July and August were similar but are left off for readability. Red lines indicate DO saturation concentrations estimated using the APHA 1985 equation.

Table 2-1 Average monthly maximum surplus, maximum deficit, and average difference data from Janous Pond. The average difference over the 6 months is shown along with the standard error of the means.

Month	Mean Maximum Deficit	Mean Maximum Surplus	Mean Difference Deficit-Surplus
April	2.9	3.5	-0.6
May	4.9	7.3	-1.6
June	5.6	8.6	-3.1
July	5.9	8.9	-3.0
August	6.1	5.6	0.5
September	5.9	5.4	0.5
		Average	**-1.2±1.4**

Having supported our assumptions about symmetry about saturation, we then used the relationships generated to derive chloropyll endpoints in two ways. We used interpolation to estimate chlorophyll concentrations associated with DO_{min} concentrations below the state water quality standard. We used interpolation based on simple linear regressions as well as interpolation based on logistic regressions where DO_{min} was expressed as a binomial based on whether it was exceeding the MDEQ instantaneous DO criterion of 4 mg/L or not. The latter approach resulted in plots of probability of exceeding the DO criterion as a function of chlorophyll concentration. These analyses were performed within two different strata: the photic zone and the assessment depth.

2.1 Models using photic zone depth

The MDEQ instantaneous DO criterion is applied at assessment depths, as described in the standard above. However, the photic zone, that depth of water where light is sufficient for primary production, is also a well established depth for evaluating the response of primary producers to nutrient enrichment vis-à-vis oxygen response and is traditionally estimated as 2 to 2.5 times the Secchi depth (m)(e.g., Kalff 2001, MDEQ 2009b). It is also an easier depth to generally determine than evaluating stratification and applying the rules of the assessment process. So, we first conducted analysis within the photic zone.

We used the database of MDEQ lake and reservoir data developed for the original report (MDEQ 2007a), amended it with samples collected since that report was written, and determined photic zone depths based on reported Secchi depths for each sample. We then calculated average chlorophyll, nutrient, temperature, and DO data within the photic zone for each sample. Chlorophyll a values less than 0.1 were removed as methodological outliers because we doubted chlorophyll a was being measured to that concentration. Data were log-transformed as necessary to meet assumptions of normality. We calculated DO_{sat} for each sample using equation 1 above and average photic zone temperature. We then computed minimum estimated DO using the equation:

$$DO_{min} = DO_{sat} – (DO_{obs} - DO_{sat}) \qquad (2).$$

DO_{min} values were analyzed as raw data and converted into binomials with a value of 1 if values were less than the MDEQ instantaneous DO criterion (4 mg/L) and zeros if not.

The raw plots indicate that DO minima begin to violate the state instantaneous DO standard of 4 mg/L in the photic zone at chlorophyll *a* concentrations of approximately 3 ppb (log = 0.5), but that this dramatically increases above 10 ppb (log = 1.0)(Figure 2.5). The chlorophyll *a* concentration derived based on the MSFish index for reservoirs was 19.4 ppb (log = 1.3), whereas that for oxbow lakes was 45.6 ppb (log = 1.7). The chlorophyll concentrations where DO minima start violating the DO criteria are consistent with the reservoir chlorophyll a threshold, but not the oxbow threshold.

When minimum DO data were converted into binomial data, the logistic regression indicates that there is greater than a 10% likelihood of violating the instantaneous DO criteria for oxbows and all lakes at 10 and 20 ppb chlorophyll a respectively (Figure 2.6). For reservoirs, again the chlorophyll *a* value consistent with the MSFish based analysis (19.4 ppb; log = 1.3) is associated with a low probability of violations of the instantaneous DO criterion in the photic zone. The oxbow recommended chlorophyll *a* criterion of 46 ppb (log = 1.7) derived using the MSFish index is consistent with an approximately 50% probability of violating the instantaneous DO criterion of 4 ppm.

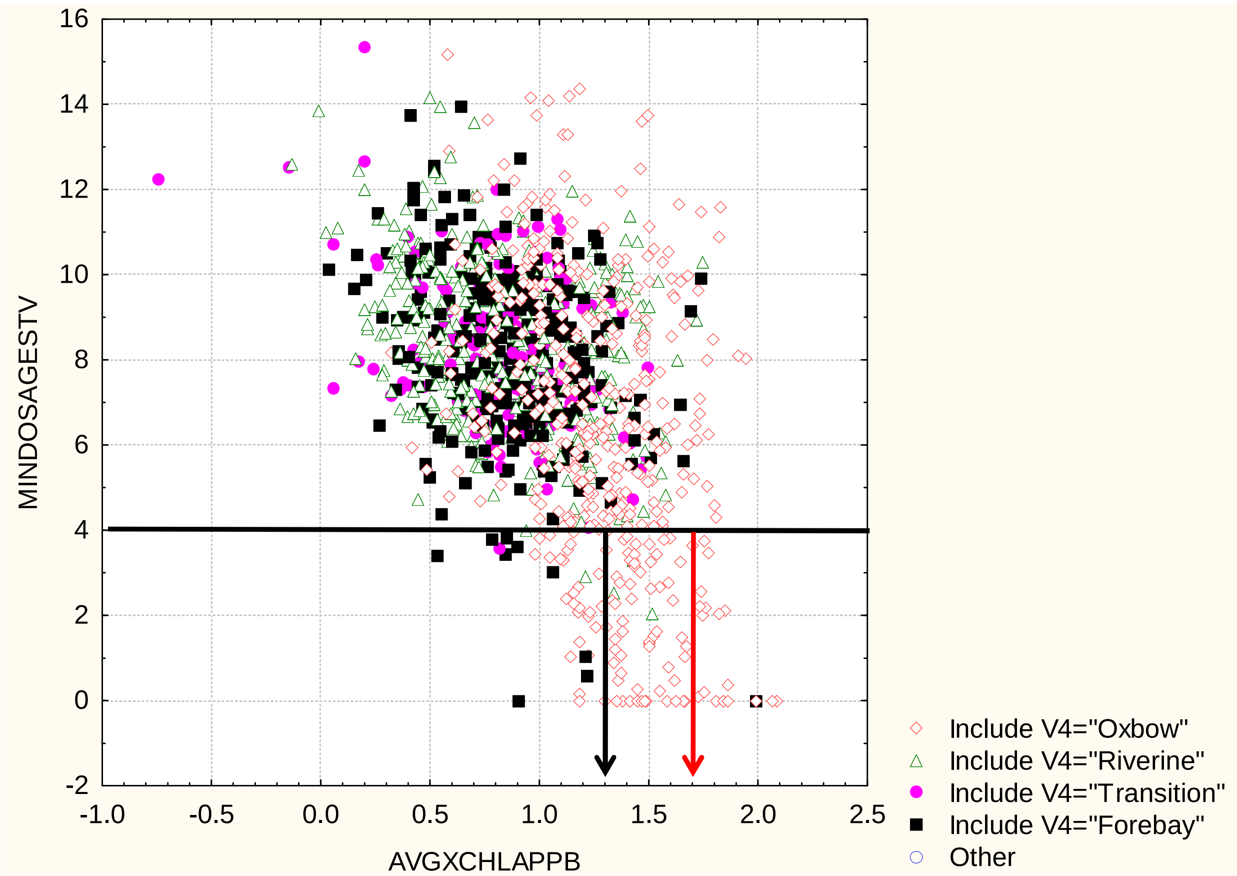

Figure 2-5 Average minimum dissolved oxygen (ppm, MINDOSAGESTV) versus $\log_{10}$average chlorophyll *a* (ppb, AVGXCHLPPB) from samples in the MDEQ lake monitoring dataset. The horizontal black line indicates the instantaneous DO standard of 4 mg/L, the black arrow indicates the chlorophyll *a* threshold based on the MSFish index for reservoirs (19.4 ppm) and the red arrow the chlorophyll *a* threshold based on the MSFish index for oxbows (45.6 ppm) .

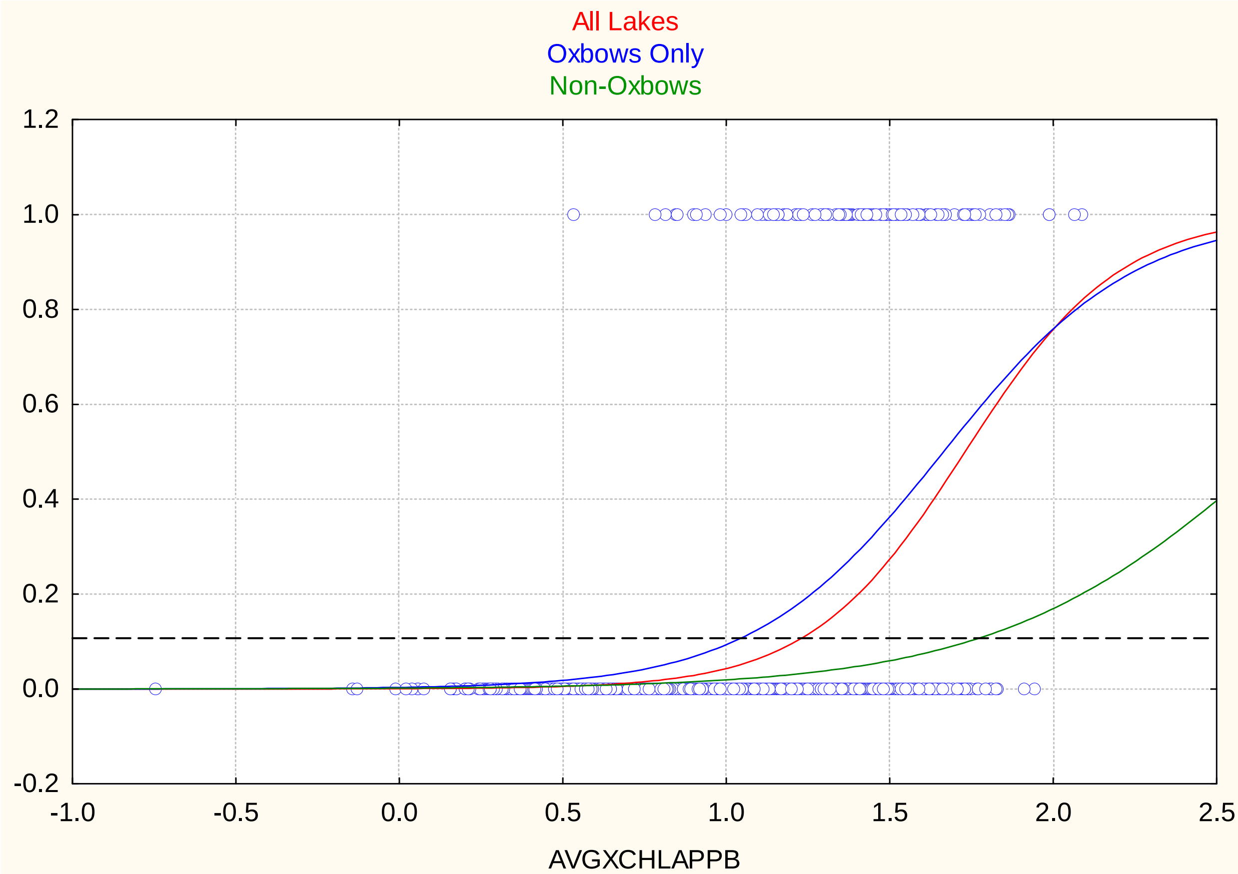

Figure 2-6 Logistic regression of probability of DO_{min} violating the instantaneous DO criterion (4 ppm). DO_{min} data plotted as a binomial (1 = DO_{min} violates the 4 mg/L DO criterion) and regressed against log_{10}average chlorophyll (ppb, AVGXCHLPPB) from samples in the MDEQ lake monitoring dataset. The horizontal hatched line is the 10 % probability line

Given the results of the photic zone analysis, the value of chlorophyll a derived using the MSFish based analysis in the original lake report (MDEQ 2007a) of 20 ppb would not likely result in instantaneous DO violations and is consistent with chlorophyll necessary to prevent those conditions from occurring. For oxbows, however, the MSFish based chlorophyll *a* threshold of 46 ppb is consistent with a significant likelihood of observing DO violations and it is more likely that a chlorophyll *a* concentration of 20 ppb would prevent that from occurring in those waterbodies.

2.2 Models using assessment depth

While the photic zone is a sensible depth at which to have conducted the dissolved oxygen analysis, MDEQ assesses lakes using an assessment depth that differs from that estimated using the photic zone depth model above. The assessment depth for lakes used by MDEQ is defined by the criteria language above for dissolved oxygen:

> For waters that are not thermally stratified, such as unstratified lakes, lakes during turnover, streams, and rivers:

At mid-depth if the total water column depth is 10 feet or less.
At 5 feet from the water surface if the total water column depth is greater than 10 feet.

For waters that are thermally stratified such as lakes, estuaries, and impounded streams:

At mid-depth of the epilimnion if the epilimnion depth is 10 feet or less.
At 5 feet from the water surface if the epilimnion depth is greater than 10 feet.

We used the dataset we had developed for the analysis above and added additional lake water quality profile data provided by the Army Corps of Engineers for Arkabutla, Enid, Grenada, and Sardis reservoirs in Mississippi (K. Myers, pers. Comm) to the already existing MDEQ lakes dataset. At the same time, we received an updated list of fertilized lakes from MDWFP (Dennis Riecke, pers. Comm) which we merged from the list of fertilized lakes identified in the first lakes report to identify lakes that received fertilization so we could compare the analyses with and without fertilized lakes included. We applied the assessment depth definition described above by identifying, first, if thermal stratification existed in a profile sample (greater than 1 degree temperature change per foot), and then by identifying the proper assessment depth based on maximum depths and/or epilimnion depth if stratified. Once assessment depths were identified, we identified the dissolved oxygen at the assessment depth and estimated the average chlorophyll a, temperature, and nutrient concentrations over the assessment depth. We then calculated DO saturation for the assessment depth using the formula above from Thomann and Mueller (1987) and the average temperature over the assessment depth. We then conducted the same analyses as described above for the photic zone depth t0 estimate DOmin.

The results of grab samples (Figures 2-7 to 2-9) were similar to those identified based on the grab sample data from the photic zone depth, which is likely not surprising since the assessment depths focused primarily on the photic zone. Essentially values above the 20 ug/L chlorophyll a criterion developed based on the MSFish Index analysis result in more likely violations of the instantaneous DO criterion of 4 mg/L.Values of chlorophyll a at or below 20 ug/L would minimize this risk and it is equal for both lake types.

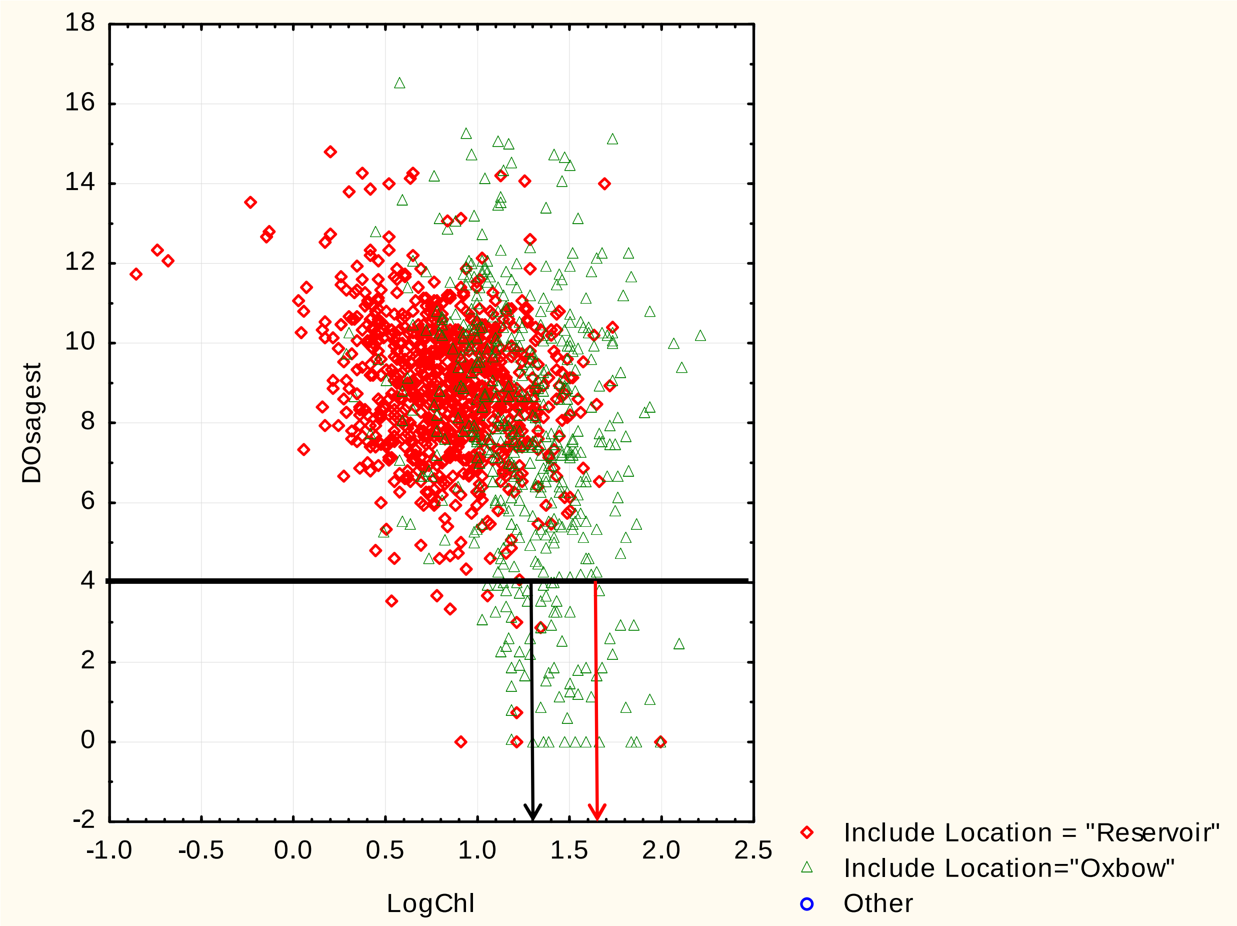

Figure 2-7 Minimum dissolved oxygen (ppm, DOsagest) versus log$_{10}$average chlorophyll *a* (ppb, LogChl) from individual samples in the MDEQ lake monitoring dataset at the assessment depth. The horizontal black line indicates the instantaneous DO standard of 4 mg/L, the black arrow indicates the chlorophyll *a* threshold based on the MSFish index for reservoirs (19.4 ppm) and the red arrow the chlorophyll *a* threshold based on the MSFish index for oxbows (45.6 ppm)

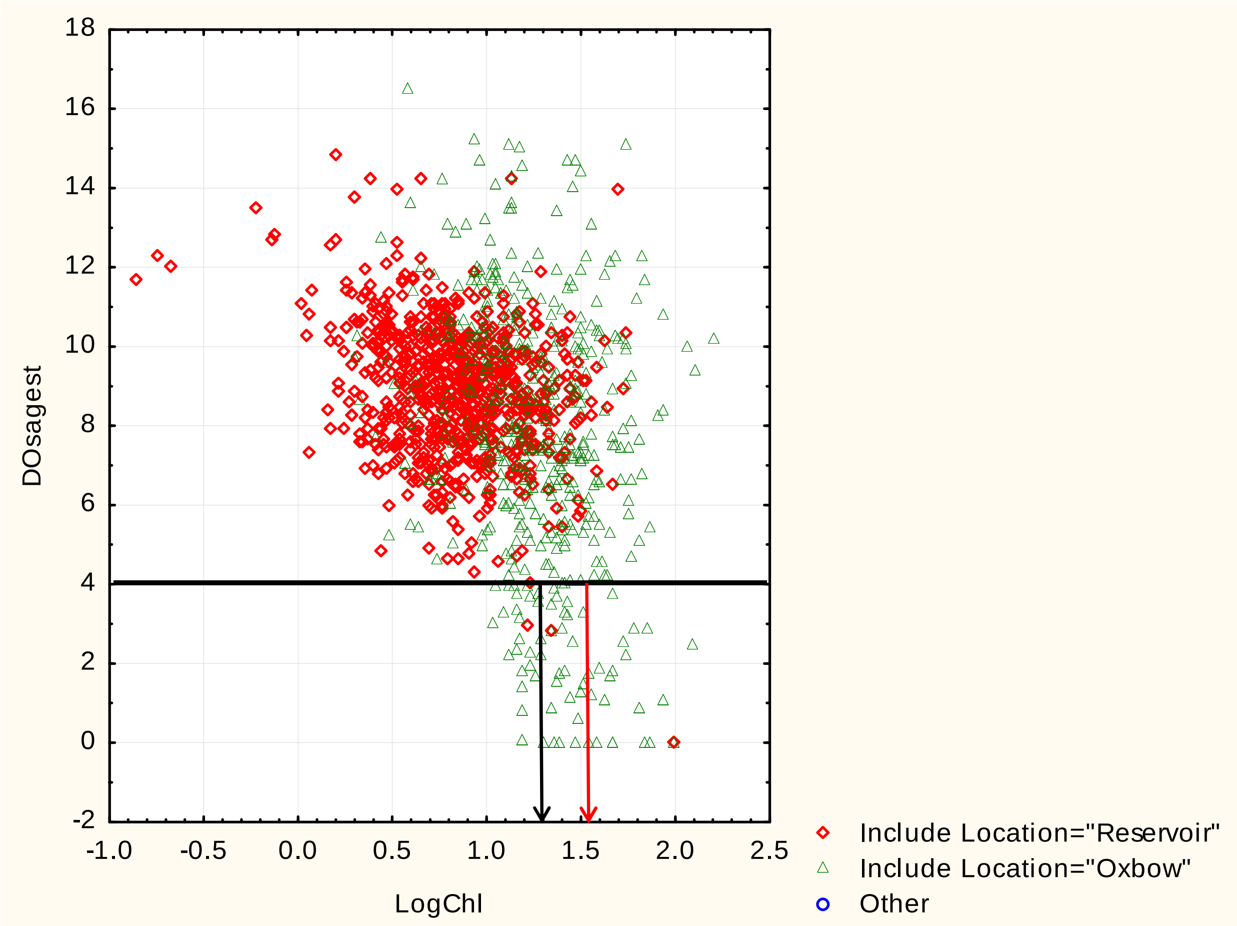

Figure 2-8 Same as Figure 2-7 but with fertilized lakes removed.

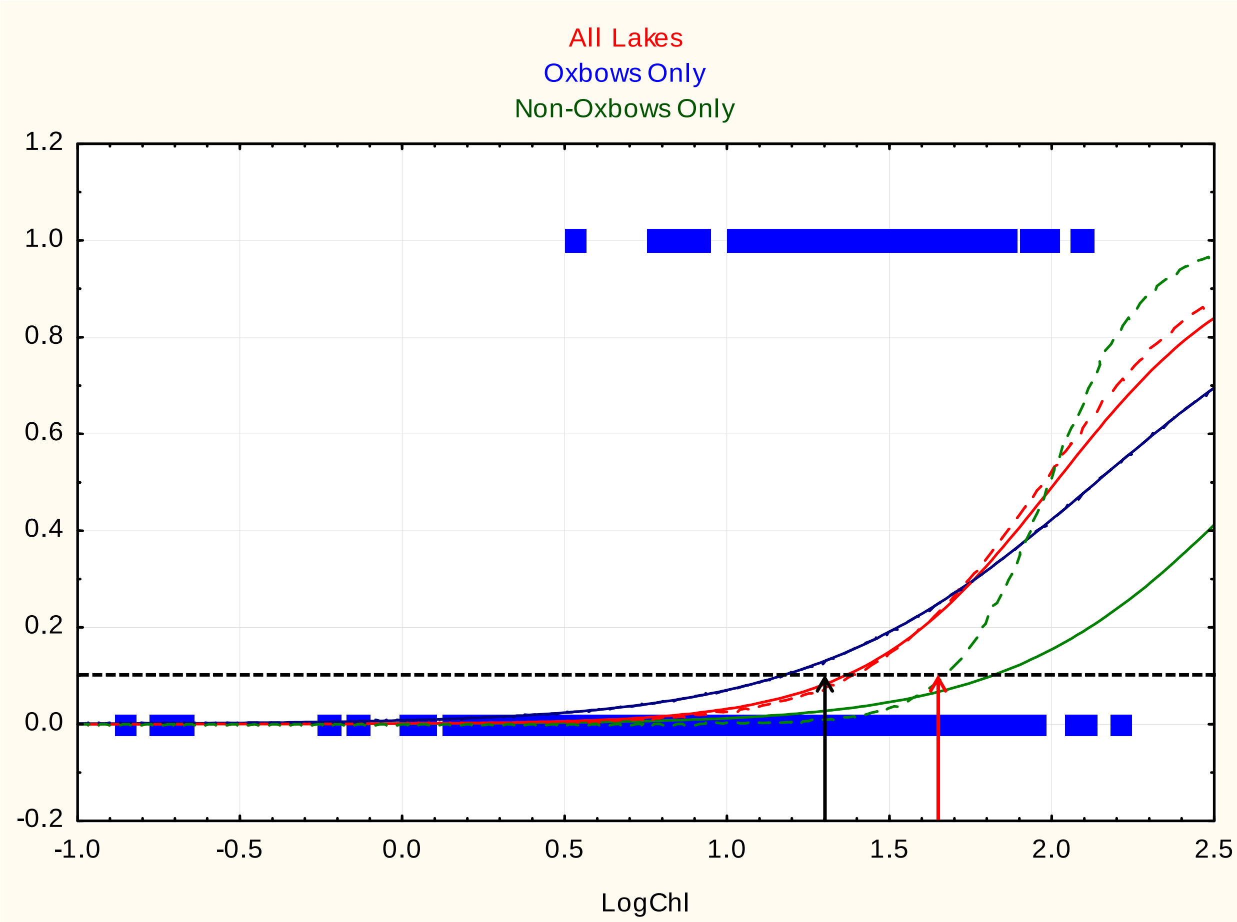

Figure 2-9 Logistic regression of probability of DO_{min} violating the instantaneous DO criterion (4 ppm) at the assessment depth. DO_{min} data plotted as a binomial (1 = DO_{min} violates the 4 mg/L DO criterion) and regressed against log_{10}average chlorophyll (ppb, LogChl). The horizontal hatched line is the 10 % probability line. Solid curves are the different lake types and hatched lines are the same population as the solid lines, but with fertilized lakes removed: red – all lakes, blue – oxbows, and green – non-oxbows. The black arrow indicates the chlorophyll *a* threshold based on the MSFish index for reservoirs (19.4 ppm) and the red arrow the chlorophyll *a* threshold based on the MSFish index for oxbows (45.6 ppm)

Since MDEQ assesses DO primarily during the growing season (June through October), we also analyzed the same data using grab samples taken only during the growing season for comparison. Data were analyzed as above for grabs based on the entire year.

Results are similar to the initial analysis, with a greater likelihood of DOmin violations in lakes and reservoirs above chlorophyll a of 20 ug/L (Figure 2-10). When fertilized reservoirs are excluded, there are only two seasonal grab sample DOmin values estimated to be below 4, but the frequency among oxbows is generally similar.

As before, we analyzed these seasonal grab DOmin violations with logit regression as well, estimating the probability of violating the DOmin criterion as chlorophyll a concentrations increase. Because there were only two observations of DOmin below 4 for unfertilized reservoirs, the lake data were kept as a combined dataset. Results from this analysis also recommend a chlorophyll a value of 20 ug/L to protect against DOmin violations (Figure 2-11).

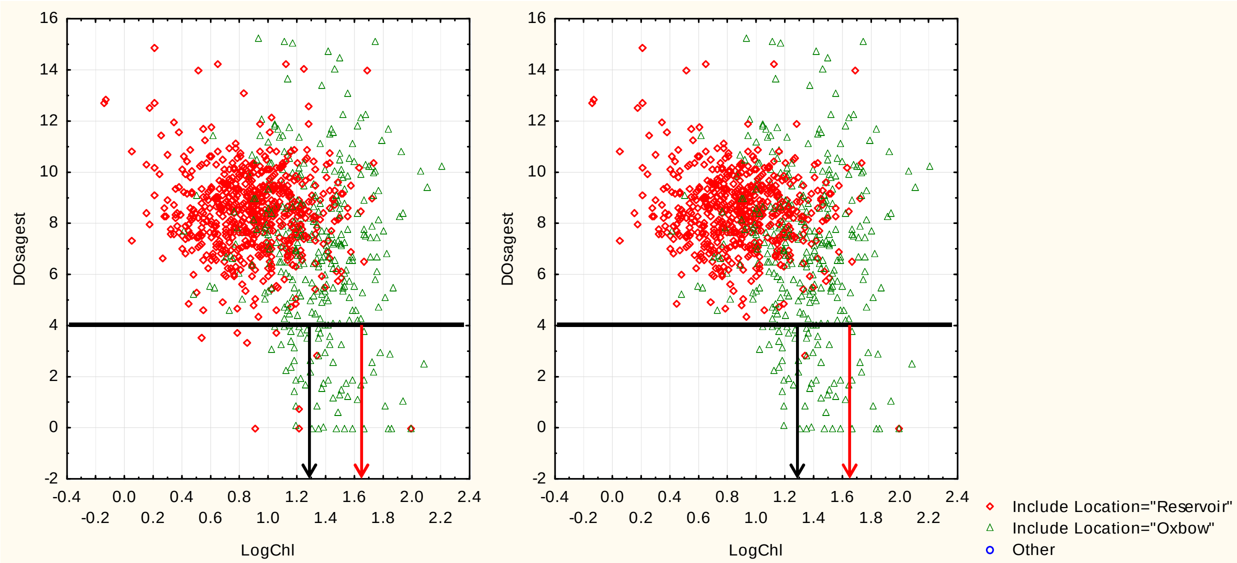

Figure 2-10 Seasonal grab sample minimum dissolved oxygen (ppm, DOsagest) versus $\log_{10}$average chlorophyll *a* (ppb, AvgLogChl) from the MDEQ lake monitoring dataset at the assessment depth. The horizontal black line indicates the instantaneous DO standard of 4 mg/L, the black arrow indicates the chlorophyll *a* threshold based on the MSFish index for reservoirs (19.4 ppm) and the red arrow the chlorophyll *a* threshold based on the MSFish index for oxbows (45.6 ppm). All lakes are shown on the left and fertilized lakes were removed for the plot on the right.

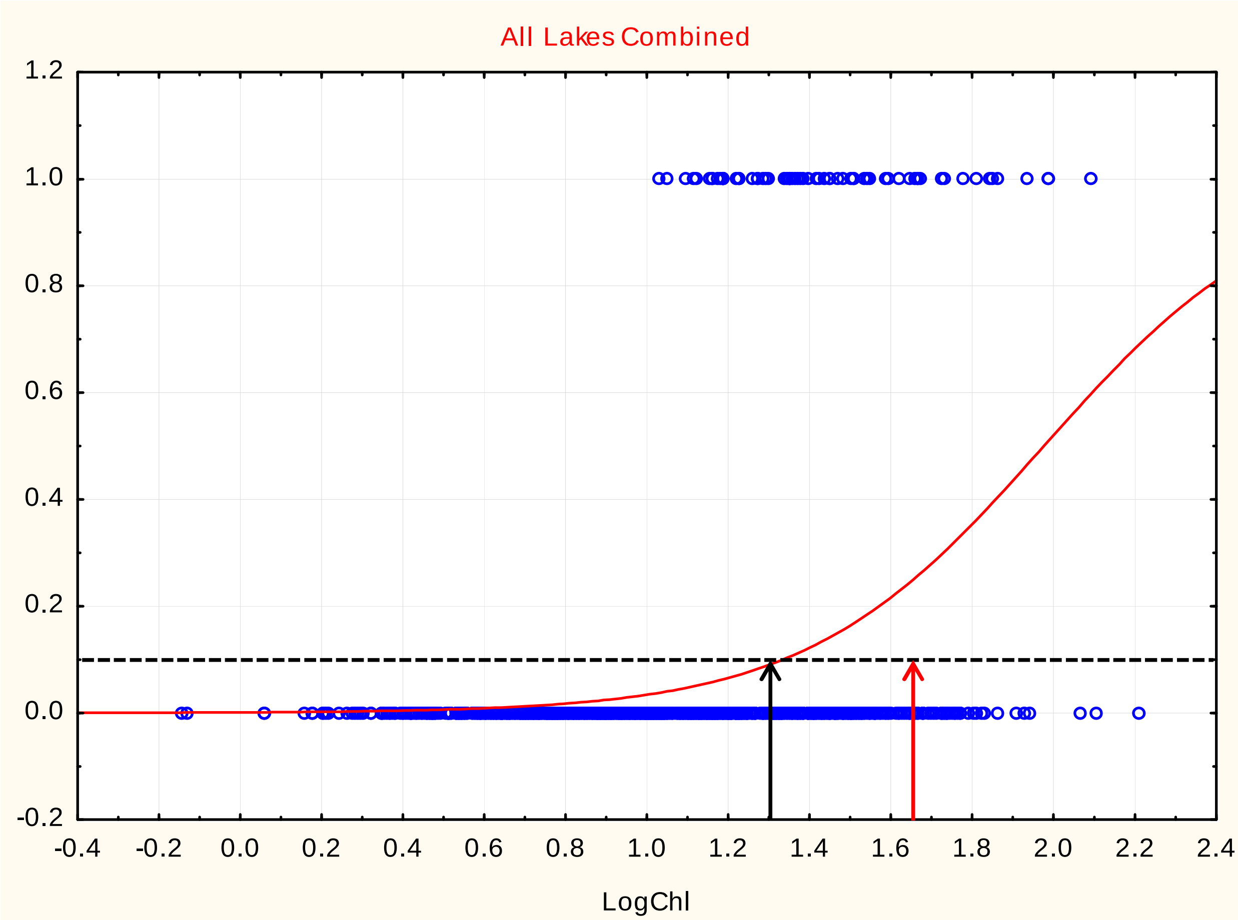

Figure 2-11 Logistic regression of probability of seasonal grab DO_{min} violating the instantaneous DO criterion (4 ppm) at the assessment depth. DO_{min} data plotted as a binomial (1 = DO_{min} violates the 4 mg/L DO criterion) and regressed against log_{10} seasonal grab chlorophyll (ppb, AvgLogChl). The horizontal hatched line is the 10 % probability line. Too few non-fertilized reservoirs samples were below the minimum DO to generate a logit regression line, therefore lakes are combined for this analysis. The black arrow indicates the chlorophyll *a* threshold based on the MSFish index for reservoirs (19.4 ppm) and the red arrow the chlorophyll *a* threshold based on the MSFish index for oxbows (45.6 ppm).

As above for annual data, we also calculated averages of all of the seasonal grab data. Data on each of the parameters, including DOmin, were first calculated for each grab and then averaged at each site over all samples taken during the growing season (June through October) each year. Different years were used as replicates.

The results of the growing season averaged data were, again, not unlike the results based on grab samples (Figure 2-12) although the logit model results suggest a greater risk of DOmin violations at a seasonal average chlorophyll a concentration of 20 ug/L than that based on grab samples over the year. This increased risk is largely due to the oxbow dataset; however, there were too few observations of seasonal DOmin below 4 in unfertilized reservoir sites to estimate a logit model, so a combined lake model has to be used (Figure 2-13). Therefore, it is still likely that the 20 ug/L chlorophyll a target would minimize DOmin criteria violations in reservoirs and oxbows.

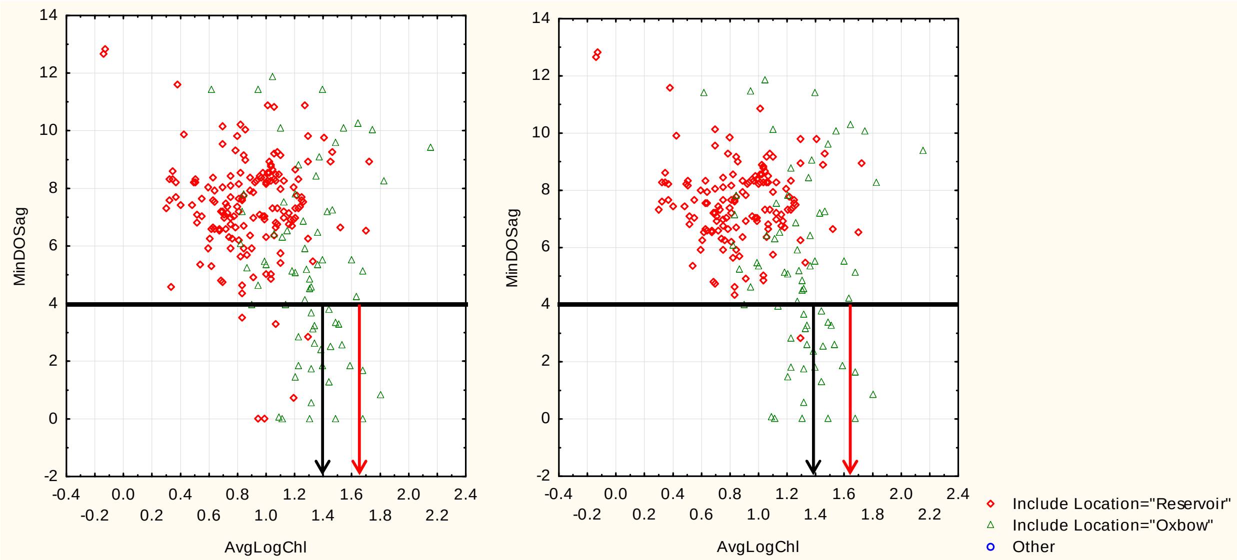

Figure 2-12 Seasonal average minimum dissolved oxygen (ppm, DOsagest) versus $\log_{10}$average chlorophyll *a* (ppb, AvgLogChl) from the MDEQ lake monitoring dataset at the assessment depth. The horizontal black line indicates the instantaneous DO standard of 4 mg/L, the black arrow indicates the chlorophyll *a* threshold based on the MSFish index for reservoirs (19.4 ppm) and the red arrow the chlorophyll *a* threshold based on the MSFish index for oxbows (45.6 ppm). All lakes are shown on the left and fertilized lakes were removed for the plot on the right.

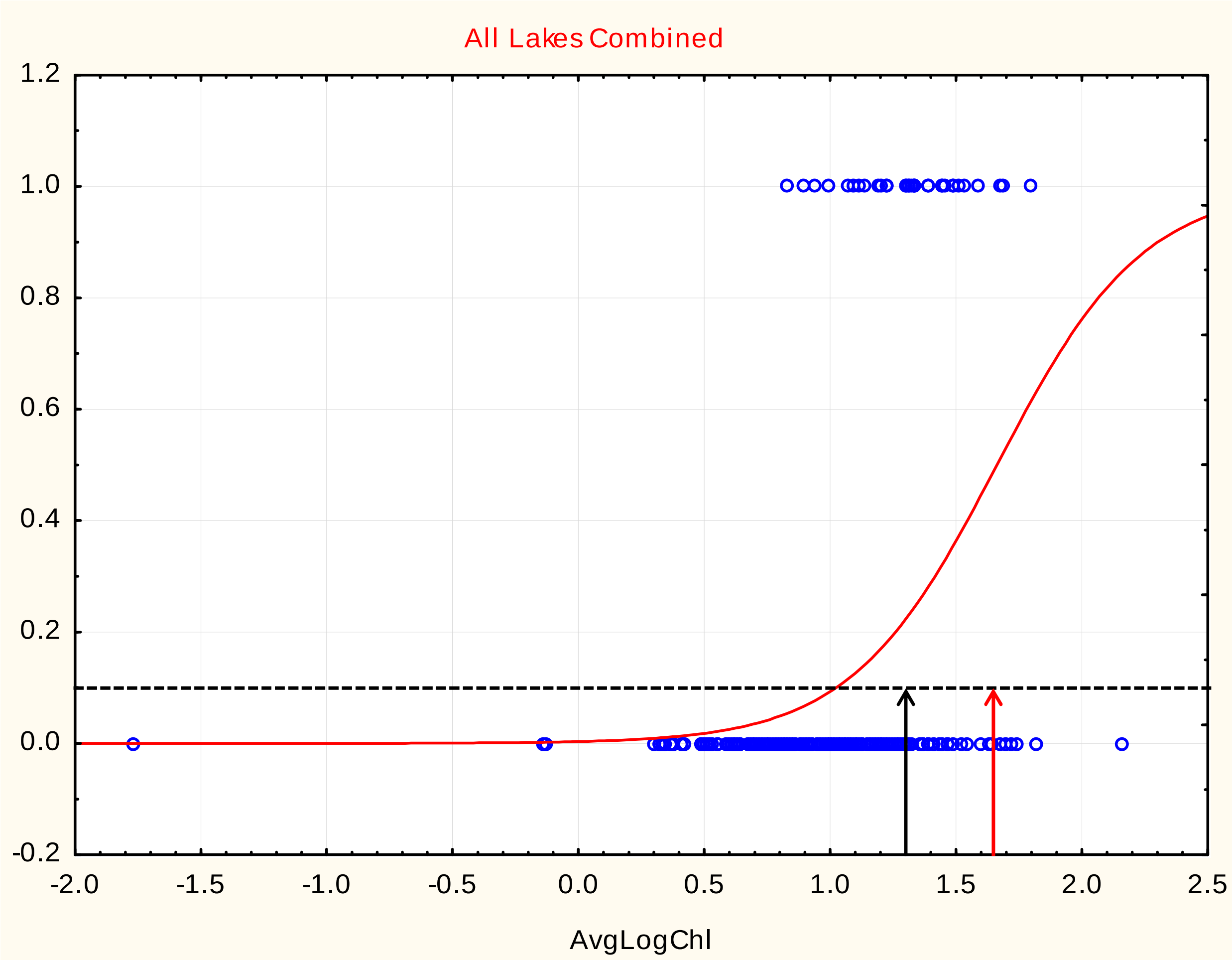

Figure 2-13 Logistic regression of probability of seasonal DO_{min} violating the instantaneous DO criterion (4 ppm) at the assessment depth. DO_{min} data plotted as a binomial (1 = DO_{min} violates the 4 mg/L DO criterion) and regressed against log_{10}average seasonal chlorophyll (ppb, AvgLogChl). The horizontal hatched line is the 10 % probability line. Too few non-fertilized reservoirs DOmin averages were below the minimum DO to generate a logit regression line, therefore lakes are combined for this analysis. The black arrow indicates the chlorophyll *a* threshold based on the MSFish index for reservoirs (19.4 ppm) and the red arrow the chlorophyll *a* threshold based on the MSFish index for oxbows (45.6 ppm).

For all of the above analyses, the logistic equations relating chlorophyll a to the probability of samples violating the DO criteria can be solved for any probability. Since 10% is the common exceedance used by MDEQ, this target was used and the logit equations solved for average chlorophyll concentration when p=0.1 (Table 2-2). In this table, we also show the results of solving the logit equation to estimate the proportion of observations at and below DOmin of 4 mg/L for a chlorophyll value of 20 ug/L, the previously proposed target based on MSFish for reservoirs.

The grab sample datasets, regardless of temporal scale (annual or seasonal), show exceedance likelihoods at 20 ug/L chlorophyll a consistent with the target of 10%. In contrast, averaged data, regardless of temporal scale, suggest that DOmin will likely be exceeded more frequently (approximately 30% of observations). This value is somewhat misleading, as the DOmin is simply that a DOmin < 4mg/L was observed over the averaged period and not that the DOmin averaged less than 4 mg/L. These results, therefore, support the chlorophyll a value for reservoirs and oxbows of 20 ug/L as protecting of DO. Values above this are associated with an increased risk of violating the current DOmin criterion.

Table 2-2 Chlorophyll a values predicted at DOmin proportion exceeding 10% (p=0.1) based on the logit models of assessment depth data.

Assessment Depth Dataset	Response Variable	Exceedance Probability Target (p)	Ln (p/(1-p))	Intercept	Slope	Predicted Chl a	Predicted exceedance probability (p) at Chl = 20 ug/L
Annual Grabs	DOmin < 4	0.1	-2.20	-6.82	3.39	**23.1**	**0.09**
Annual Grabs No Fertilized Lakes	DOmin < 4	0.1	-2.20	-7.36	3.73	**24.2**	**0.08**
Annual Avg	DOmin < 4	0.1	-2.20	-6.17	3.89	**10.5**	**0.33**
Annual Avg No Fertilized Lakes	DOmin < 4	0.1	-2.20	-7.11	4.55	**12.0**	**0.30**
Jun-Oct Grabs	DOmin < 4	0.1	-2.20	-6.21	3.06	**20.5**	**0.11**
Jun-Oct Grabs No Fertilized Lakes	DOmin < 4	0.1	-2.20	-6.76	3.42	**21.6**	**0.10**
Jun-Oct Average	DOmin < 4	0.1	-2.20	-5.72	3.44	**10.6**	**0.29**
Jun-Oct Average No Fertilized Lakes	DOmin < 4	0.1	-2.20	-6.51	3.95	**12.4**	**0.25**

3 Relating chlorophyll endpoints to nutrients

Annual Grab Samples

The chlorophyll endpoints generated from the above analysis of 20 ug/L for reservoirs and oxbows can be used to derive target TP and TN values using empirical equations relating nutrients to chlorophyll a from the MDEQ dataset. Such models were constructed (Figures 3.1 and 3.2) and are not appreciably different from those generated with a global dataset (MDEQ 2007a), although the slope of the MS-specific data is lower, indicate less chlorophyll yield per unit nutrient; a result not inconsistent with the presence of higher non-algal turbidity in MS lentic waterbodies.

TP value proposed from the MSFish based analysis (MDEQ 2007a) are consistent with values that would be derived based on the DO analysis above. A chlorophyll value of 20 ppb based on the MDEQ lake empirical chlorophyll-TP models equates to TP concentrations from 40 to 250 ppb based on the lower quartile prediction interval to the average response point. The proposed MSFish based value for reservoirs and oxbows of 80 and 90 ppb was in the middle of this range.

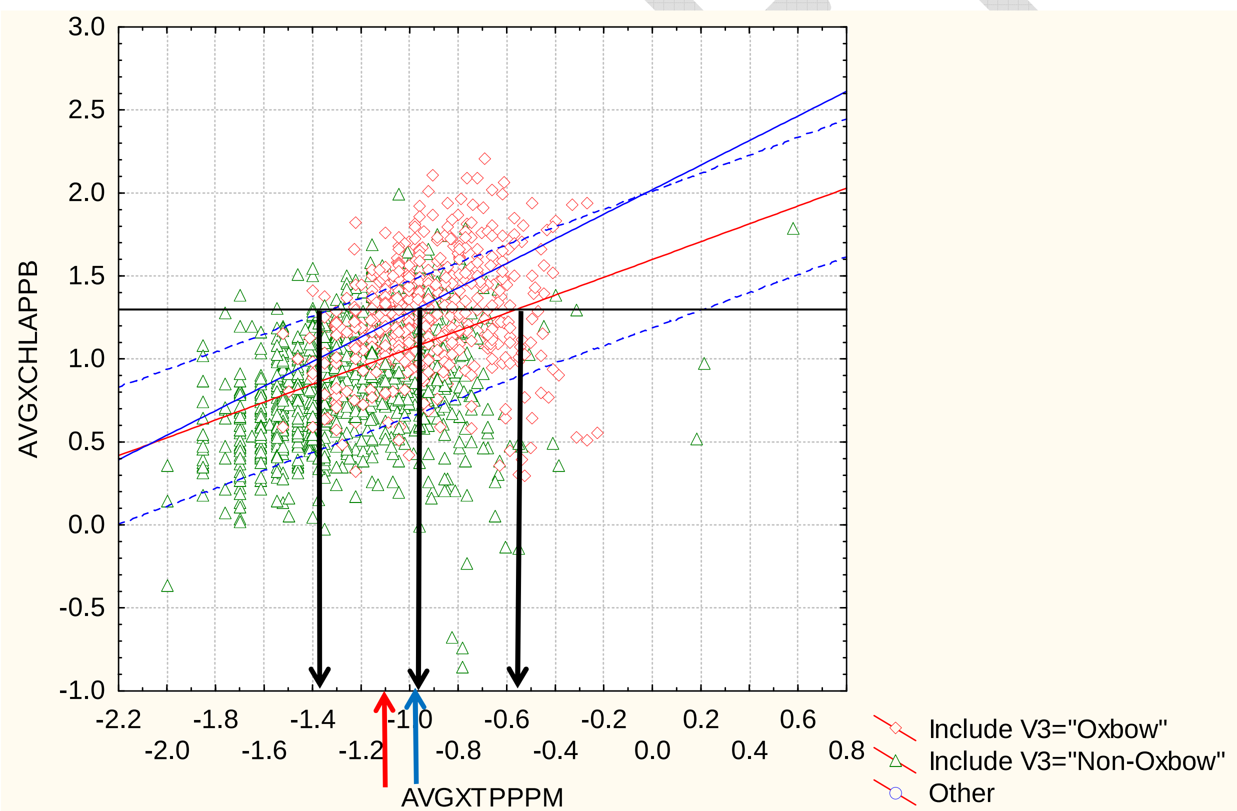

Figure 3-1 Annual grab sample $\log_{10}$chlorophyll a (AVGXCHLAPPB) versus $\log_{10}$total phosphorus (ppm, AVGXTPPPM) for MDEQ lake dataset. The blue hatched lines are 75th percentile prediction intervals and the blue solid line is the average of a large number of published empirical chlorophyll-TP regressions reported in MDEQ (2007a). The horizontal black line is the target chlorophyll a concentration of 20 ppb and the black arrows, from left to right, are TP concentrations associated with the lower quartile prediction interval, the average of the global model and the average of the MS specific model respectively. The red and blue arrows are the TP thresholds recommended from the MSFish based analysis (MDEQ 2007a)

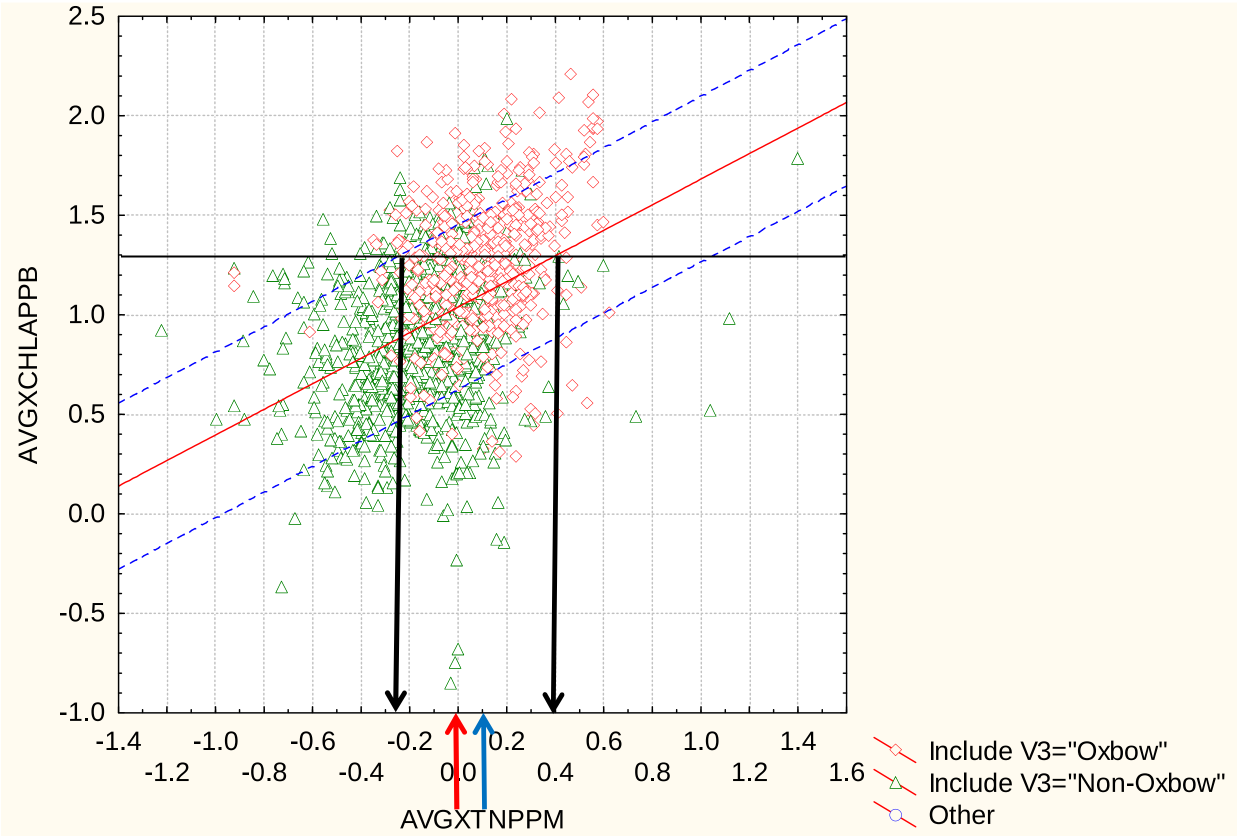

Figure 3-2 Log10chlorophyll a (AVGXCHLAPPB) versus log10total nitrogen (ppm, AVGXTNPPM) for MDEQ lake dataset. The blue hatched lines are 75th percentile prediction intervals and there was no global set of empirical chlorophyll-TN models. The horizontal black line is the target chlorophyll a concentration of 20 ppb and the black arrows, from left to right, are TN concentrations associated with the lower quartile prediction interval and the average of the MS specific model respectively. The red and blue arrows are the TN thresholds recommended from the MSFish based analysis (MDEQ 2007a).

The TN analysis led to similar conclusions to that for TP. The range in TN values represented by the lower quartile and average prediction intervals from the regression model that were associated with a chlorophyll *a* endpoint of 20 ppb were 562 to 2500 ppb TN. This range encompassed the values for TN derived from the MSFish based analysis (990 and 1250 ppb TN for reservoirs and oxbows, respectively).

Seasonal Average

MDEQ may also likely use seasonal average chlorophyll and nutrient values for the assessment, so the same analysis as above was run for data expressed as seasonal averages. The TP model identified two leverage points (Log_{10}Chlorophyll<0.0) with a strong influence on the overall regression model, so versions were run with and without the values included (Figure 3-3). It is unclear why these two average values had chlorophyll yields (Chl/TP) so different from the main distribution of sites. As above with annual grabs, the recommended TP criteria from the MSFish analysis are within the prediction interval (75th %) of TP associated with a Chlorophyll target of 20 ppb based on seasonal average values. The table below (Table 3-1) lists the values for TP associated with lower prediction interval quartile (0.052 ppm) and mean prediction (0.156 ppm).

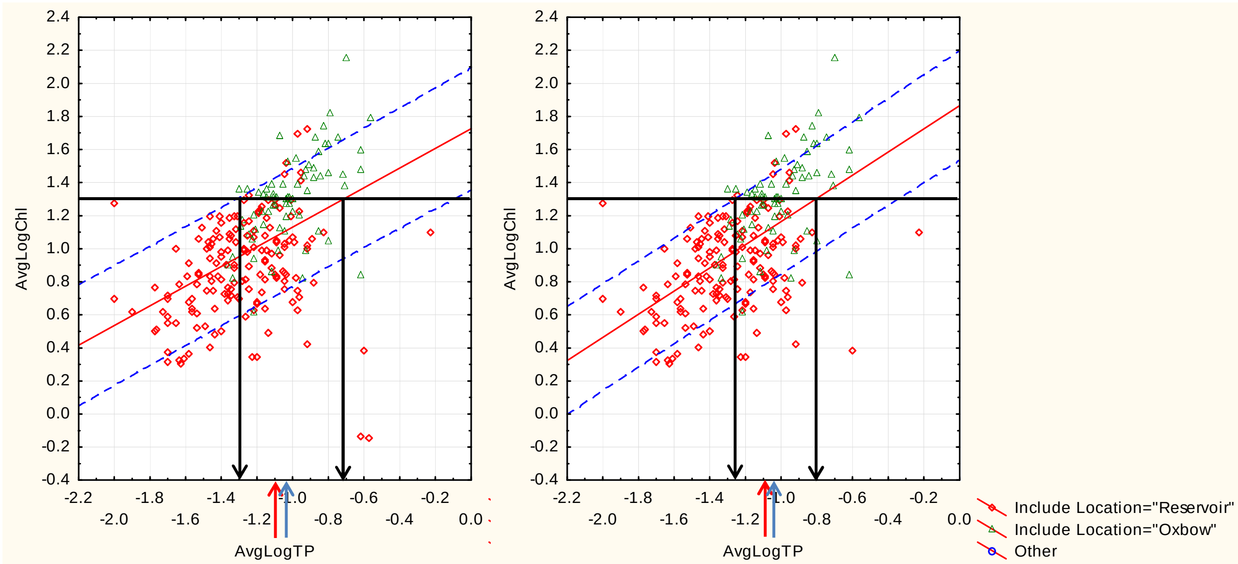

Figure 3-3 Seasonal average $\log_{10}$chlorophyll a (AvgLogChl) versus $\log_{10}$total phosphorus (AvgLogTP) for the MDEQ lake dataset. The blue hatched lines are 75th percentile prediction intervals. The horizontal black line is the target chlorophyll a concentration of 20 ppb and the black arrows, from left to right, are TP concentrations associated with the lower quartile prediction interval and the average of the MS specific model respectively. The red and blue arrows are the TP thresholds recommended from the MSFish based analysis (MDEQ 2007a). The figure on the right shows the model with the two chlorophyll leverage points (AvgLogChl<0.0) removed.

Table 3-1 Simple linear regression equations of total phosphorus vs. chlorophyll a for the seasonal average MDEQ lake dataset. Solutions for the mean and lower prediction interval TP for a target chlorophyll of 20 ppb are also shown.

	Chl Target	Log Chl	Intercept	Slope	Mean TP	Lower Quartile TP	r^2
Seasonal Avg	20	1.301	1.725	0.595	**0.194**	**0.045**	**0.23**
Seasonal Avg Leverage Removed	20	1.301	1.866	0.701	**0.156**	**0.052**	**0.33**

The results for the TN analysis were also similar. The recommended TN criteria from the MSFish analysis (990 and 1250 ppb TN for reservoirs and oxbows, respectively) are within the prediction interval (75th %) and mean of TN associated with a Chlorophyll target of 20 ppb based on seasonal averages (Figure 3-4). The table below (Table 3-2) lists the values for TN associated with lower prediction interval quartile (0.677 ppm) and mean prediction (1.697 ppm).

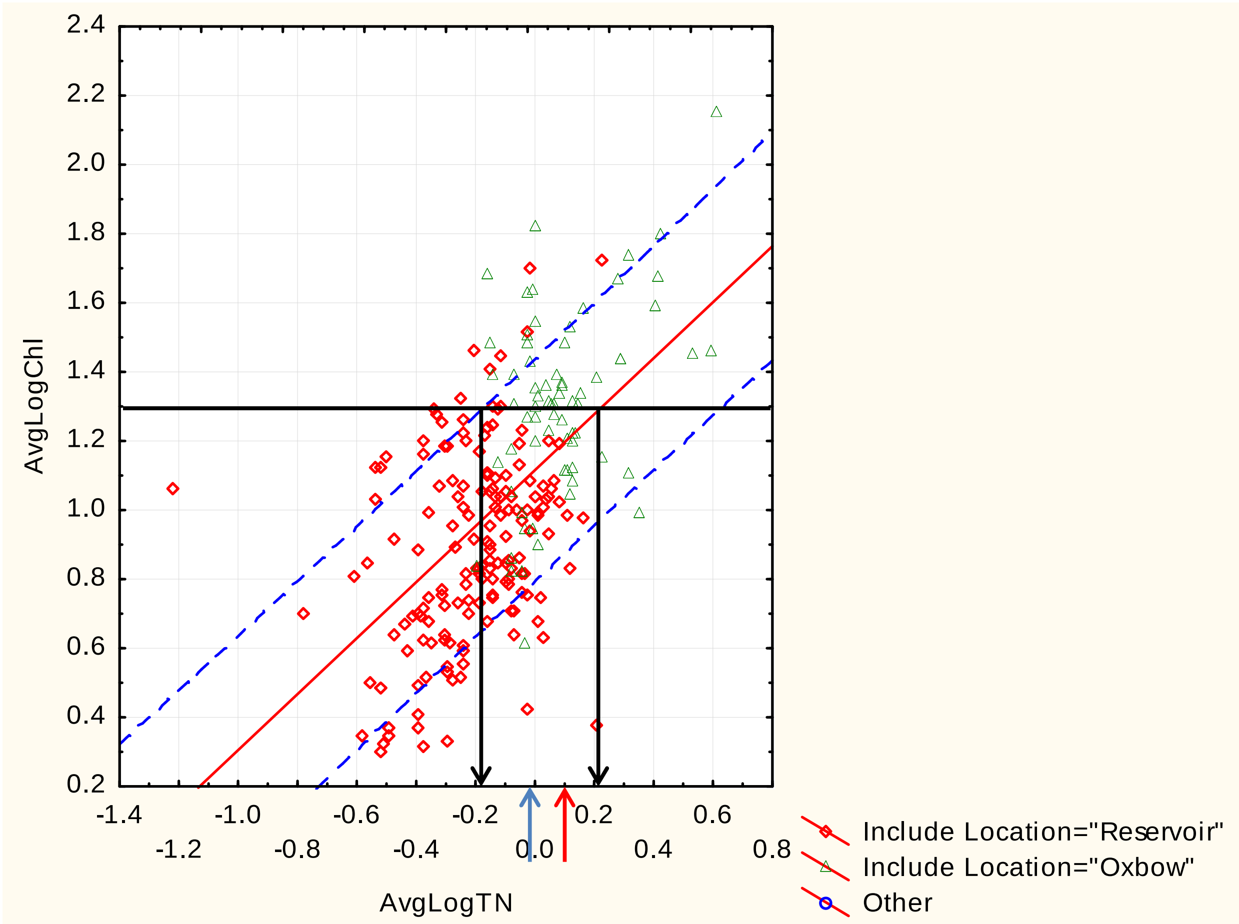

Figure 3-4 Seasonal average log_{10}chlorophyll a (AvgLogChl) versus log_{10}total nitrogen (AvgLogTN) for the MDEQ lake dataset. The blue hatched lines are 75th percentile prediction intervals. The horizontal black line is the target chlorophyll a concentration of 20 ppb and the black arrows, from left to right, are TP concentrations associated with the lower quartile prediction interval and the average of the MS specific model respectively. The red and blue arrows are the TP thresholds recommended from the MSFish based analysis (MDEQ 2007a).

Table 3-2 Simple linear regression equations of total nitrogen vs. chlorophyll a for the seasonal average MDEQ lake dataset. Solutions for the mean and lower prediction interval TP for a target chlorophyll of 20 ppb are also shown.

	Chl Target	Log Chl	Intercept	Slope	Mean TN	Lower Quartile TN	r^2
Seasonal Avg Leverage Removed	20	1.301	1.115	0.81	**1.697**	**0.677**	**0.32**

The result of this analysis suggests that the proposed TP and TN values from the MSFish analysis are likely sufficient to protect against DO violations as well, based on a chlorophyll *a* value of 20 ppb. However, the ranges from this analysis are presented as independent lines.

4 Summary of recommended nutrient criteria

The greatest change to the recommended thresholds derived from the MSFish analysis using DO endpoints was to recommend lower chlorophyll *a* thresholds for oxbows (Tables 4.1 to 4.3). The resulting recommended oxbow threshold of 20 ppb is now the same as that for reservoirs, which remains unchanged given its likelihood of protecting against DO violations. TP and TN values that were proposed earlier (MDEQ 2007a) based on the MSFish analysis are consistent with concentrations needed to protect against exceeding 20 ppb chlorophyll *a* and avoiding DO violations. Therefore, the original TN and TP concentrations remain unchanged (Tables 4.1 and 4.2). Tables 4.1 to 4.3 present the original report thresholds along with the additional DO based thresholds developed in this report and presented above.

Table 4-1 Recommended chlorophyll thresholds (ppb) based on different lines of evidence

	Chl a (ug/L)					
	Distribution Based (Ranges based on reservoir size)			Stressor-Response		Other Literature
	EPA Values	25th Percentile (MDEQ)	MBISQ Reference Streams into Reservoirs	MSFish	DO Based	
Reservoirs	3.0 – 5.0	7.6 – 9.5	N/A	19	20	5-40
Oxbows		25		46 – 68	20	

Table 4-2 Recommended TP thresholds (ppm) based on different lines of evidence. Values in parentheses for DO based endpoints are the predicted values based on the lower quartile and average prediction interval respectively.

	TP (mg/L)					
	Distribution Based (Ranges based on reservoir size)			Stressor-Response		Other Literature
	EPA Values	25th Percentile (MDEQ)	MBISQ Reference Streams into Reservoirs	MSFish	DO Based	
Reservoirs	0.010-0.020	0.020-0.040	0.060	0.080	0.040 – 0.250	0.020-2.000
Oxbows		0.070	N/A	0.090-0.150	0.040 – 0.250	

Table 4-3 Recommended TN thresholds (ppm) based on different lines of evidence. Values in parentheses for DO based endpoints are the predicted values based on the lower quartile and average prediction interval respectively

	TN (mg/L)					
	Distribution Based (Ranges based on reservoir size)			Stressor-Response		Other Literature
	EPA Values	25th Percentile (MDEQ)	MBISQ Reference Streams into Reservoirs	MSFish	DO Based	
Reservoirs	0.360-0.600	0.450-0.570	0.600	0.990	0.562 – 2.50	0.350 – 4.00
Oxbows		1.030	N/A	1.250-1.620	0.562 – 2.50	

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