Analysis Addendum: Water Column and Hypolimnetic Oxygen Depletion Responses to Chlorophyll Levels in Mississippi Lakes/Reservoirs

Photos: Mississippi Department of Wildlife, Fisheries, and Parks

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Acknowledgements

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1 Introduction

As part of the lake and reservoir criteria development effort, MDEQ pursued the exploration of dissolved oxygen (DO) depletion in the water column and hypolimnia of lakes as an assessment endpoint identified to protect aquatic life use management goals. Dissolved oxygen is of clear importance to aquatic life, especially game and non-game fish species. In lakes and reservoirs, organic matter loading from the watershed or from autochthonous sources (e.g., primary production), drives respiration which removes oxygen.

During stratification, isolated layers (meta- and hypolimnia) do not exchange oxygen with the atmosphere through reaeration and exchange oxygen only slowly with the better mixed surface layer. Therefore, oxygen depletion progresses and, depending on the rate of depletion and length of the stratification, can result in oxygen stress including hypoxia and anoxia in the lower stratified layers. Under such conditions, fishes must navigate a conflict between surface oxygenated waters that are warm and have a larger metabolic cost and deeper waters that are cooler but have less oxygen, resulting in physiological stress (Coutant 1987, Schlagenhaft and Murphy 2012). As a result, many fish choose to spend some time, often during daylight, along the cooler thermocline in the metalimnion (middle) or in the hypolimnion (bottom), and then move to the warmer epilimnion (surface) at night (Coutant 1987, Sammons 2010). Such movements are constrained by the depth and extent of low oxygen.

Dissolved oxygen was a focus of the revised lake and reservoir analysis in Mississippi. Since that analysis, investigations of relationships between chlorophyll *a* and oxygen depletion have been published, highlighting this relationship as a supporting basis for criteria development (Yuan and Pollard 2014). The goal of this analysis was to examine the relationship between surface chlorophyll *a* and water column and hypolimnetic oxygen depletion to assess the extent to which a chlorophyll *a* target threshold of 20 ug/L would affect the percent of dissolved oxygen above critical habitat suitability limits in these waters.

2 Methods

Lake profile data collected from June to September were included in the analysis. Winter months were excluded as Mississippi lakes are generally warm monomictic and were presumably not stratified except during the summer-autumn. Lake profiles with fewer than 4 sampling depths (too little data) and chlorophyll *a* values < 1 µg/L (presumed errors) were excluded. The thermocline for each lake profile was identified by finding the depth at which the greatest rate of decrease in temperature per foot increase in sample depth occurred. The shallowest two points were excluded from consideration to avoid identifying rapid changes in temperature as a result of solar energy absorption near the surface (Kalff, 2002). Correct identification of the thermocline was confirmed by visual inspection of the lake temperature profiles. The layer below the thermocline defined the hypolimnion.

Since fish require both water column oxygen as well as oxygen in a portion of the hypolimnion, the proportion of water samples that were hypoxic were estimated on two scales: 1) as a proportion of the entire water column and 2) as a proportion of the hypolimnion. A critical low oxygen target was defined as dissolved oxygen (DO) < 4 mg/L. This is the instantaneous DO standard for dissolved oxygen in Mississippi and while only applied at the surface, is also a critical DO target for the growth of many warmwater game fishes. For example, growth of Largemouth Bass (*Micropterus salmoides*) and Smallmouth Bass (*M. dolomieui*) is substantially reduced below 4 mg/L (Stuber et al. 1982a, Edwards et al. 1983). Comparable values are 3-5

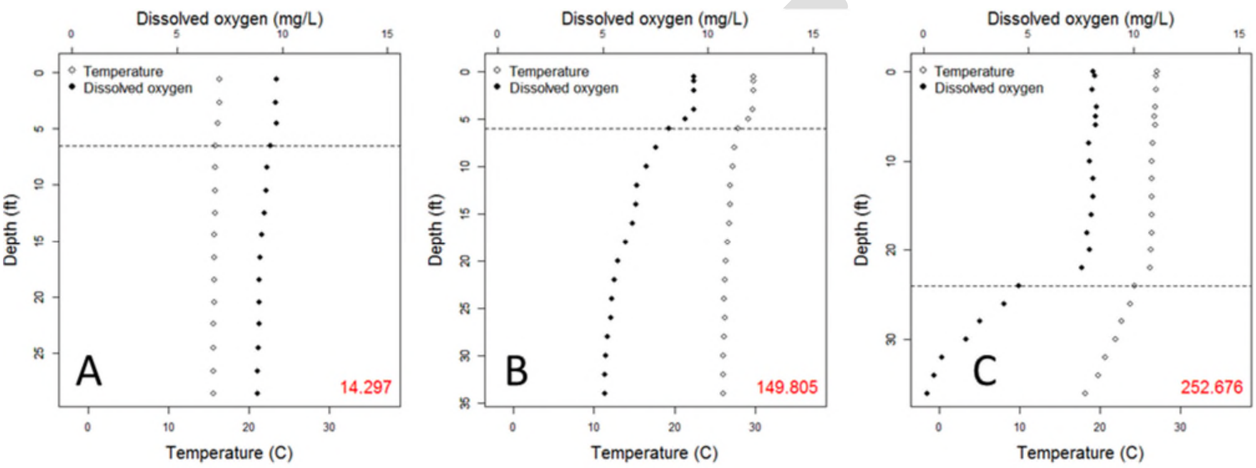

Figure 1. Typical lake temperature profiles with the thermocline represented as a dashed line and relative thermal resistance (RTR) printed in red. A. Unstratified lake. B. Stratified lake. C. Stratified lake in which the temperature in the metalimnion has not yet stabilized at the maximum depth.

mg/L for White Crappie (*Pomoxis annularis*), presumably

for Black Crappie (*P. nigromaculatus*) and Spotted Bass (*M. punctulatus*); and Bluegill (*Lepomis macrochirus*), and presumably Redear sunfish (*L. microlophus*), avoid concentrations < 3 mg/L (Edwards et al. 1982ab, Stuber et al. 1982b, McMahon et al. 1984, Twomey et al. 1984). For these reasons, the target DO concentration of 4 mg/L DO was selected as that which would provide sufficient protection for these species, which are also the main species considered in calculating the MSFish Index.

Water column hypoxia was then estimated as the proportion of DO measurements < 4 mg/L in the entire water column[1]. Hypolimnetic DO was estimated as the proportion of DO measurements < 4 mg/L at or below the thermocline. This last depth includes the metalimnion with the hypolimnion. Including the metalimnion was necessary, because, for many lake profiles, the lakes were not deep enough for the temperature to stabilize below the thermocline (Figure 1).

Because of the physical heterogeneity of Mississippi lakes, we wanted to consider the possibility that the relationship between epilimnetic chlorophyll *a* and water column or hypolimnetic DO might vary by lake physical characteristics. We therefore chose three lake properties that might also affect DO to use as classification variables. These included the lake type (oxbow or

[1] Note that we use a definition different than a traditional definition of hypoxia (< 2 mg/L), but the term hypoxia simply means "low oxygen".

reservoir), maximum depth, and, as an index of the strength of stratification, relative thermal resistance (RTR) (Kalff 2002). RTR was calculated as the difference in density between the top and bottom of the lake, using the mean temperature of the top two and bottom two samples to determine density:

$$Relative\ Thermal\ Resistance = \frac{\delta_{bottom} - \delta_{top}}{8 \times 10^{-6}}$$

where $\delta = 1\text{-}6.63*10^{6}(T\text{-}4)^{2}$, and T = temperature in °C.

Using RTR is necessary because density is a non-linear function of temperature and very small temperature differences at warm temperatures can produce stratification stronger than larger temperature differences at colder temperatures. RTR provides an absolute comparison.

To determine how physical characteristics might affect the epilimnetic chlorophyll *a*/DO relationship, we used TREED regression (Alexander and Grimshaw 1996). TREED regression is similar to classification and regression trees, but with differing models (in terms of parameters) in the end nodes, rather than response variables grouped by means. In effect, this process groups samples into subsets wherein the functional relationship between the dependent and independent variables in end nodes has minimal summed deviance across all models as compared to the deviance of the ungrouped model (Zeileis et al. 2008). This approach has been used on National Lakes Assessment data (NLA) to successfully identify groups of lakes in which epilimnetic chlorophyll *a* concentrations accurately predicted water column hypoxia (Yuan and Pollard, 2014). For the current analysis, we converted the proportion of water column hypoxia to a binomial variable in which profiles where >50% of the water column was hypoxic were assigned a value of 1 and ≤50%, 0. We used lake type, depth and RTR as splitting variables and ran the TREED models using the partykit package (Hothorn and Zeileis 2014) in R (R Core Team 2014).

Following identification of groups of lakes in which water column or hypolimnetic DO responded in similar ways with epilimnetic chlorophyll, we examined the relationship between chlorophyll *a* concentration (averaged from April to October) and the proportion of the water column or hypolimnion that was hypoxic using logistic regression. From the regression curves, we determined the probability of the occurrence of water column and hypolimnetic hypoxia at two potential chlorophyll threshold values, 10 and 20 µg/L.

3 Results

Of the lake longitudinal profiles, 1,047 had at least 4 sampling depths and available nutrient and chlorophyll data. Application of the TREED regression demonstrated that lakes with intermediate depths (11-43 ft.) had stronger positive relationships between epilimnetic chlorophyll *a* and water column hypoxia than shallower or deeper lakes (Figure 2). The subset of lakes with the highest levels of relative thermal resistance (largest stratification) had a negative relationships between chlorophyll *a* and hypoxia (Figure 3). Lake type (oxbow or reservoir) did not influence the observed relationship between water column or hypolimnetic DO and epilimnetic chlorophyll *a*.

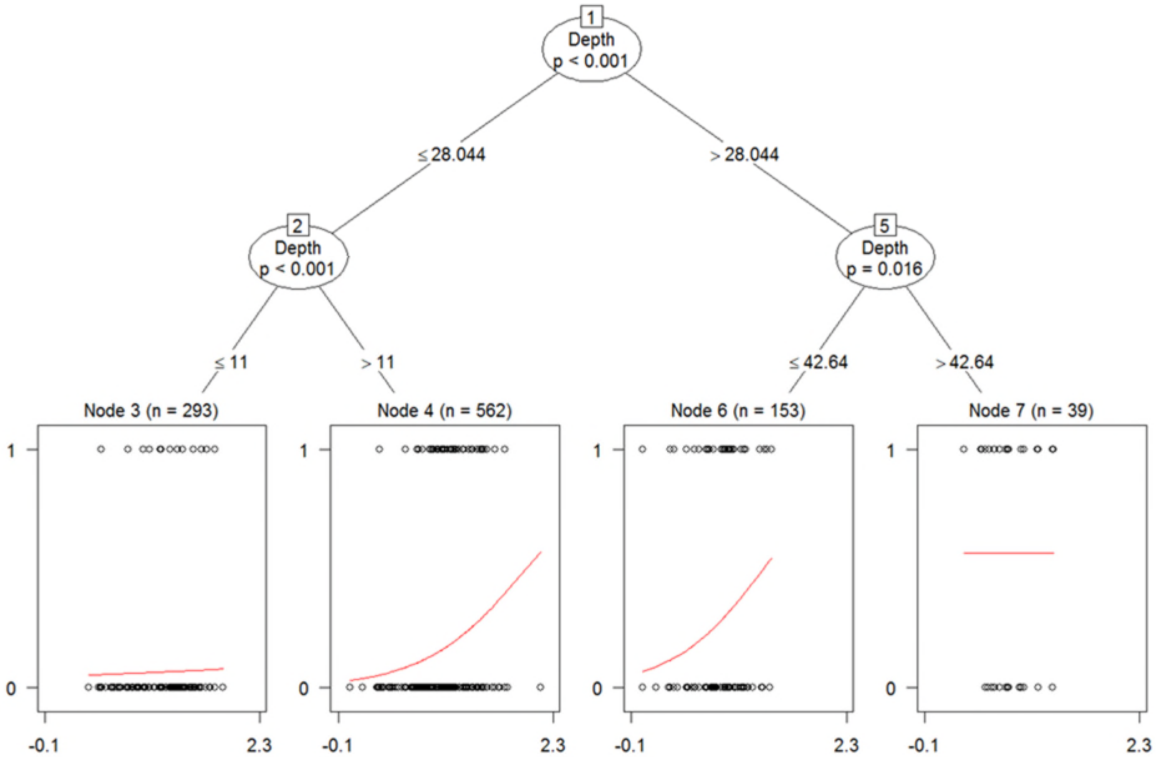

Figure 2. TREED regression of the proportion of water column samples that are hypoxic (DO < 4mg/L, expressed as a binomial variable with a 50% threshold, see text for details) on summer epilimnetic chlorophyll a, using lake depth as a splitting variable. The strongest relationships are among lakes of intermediate depths (between 11- 43 ft).

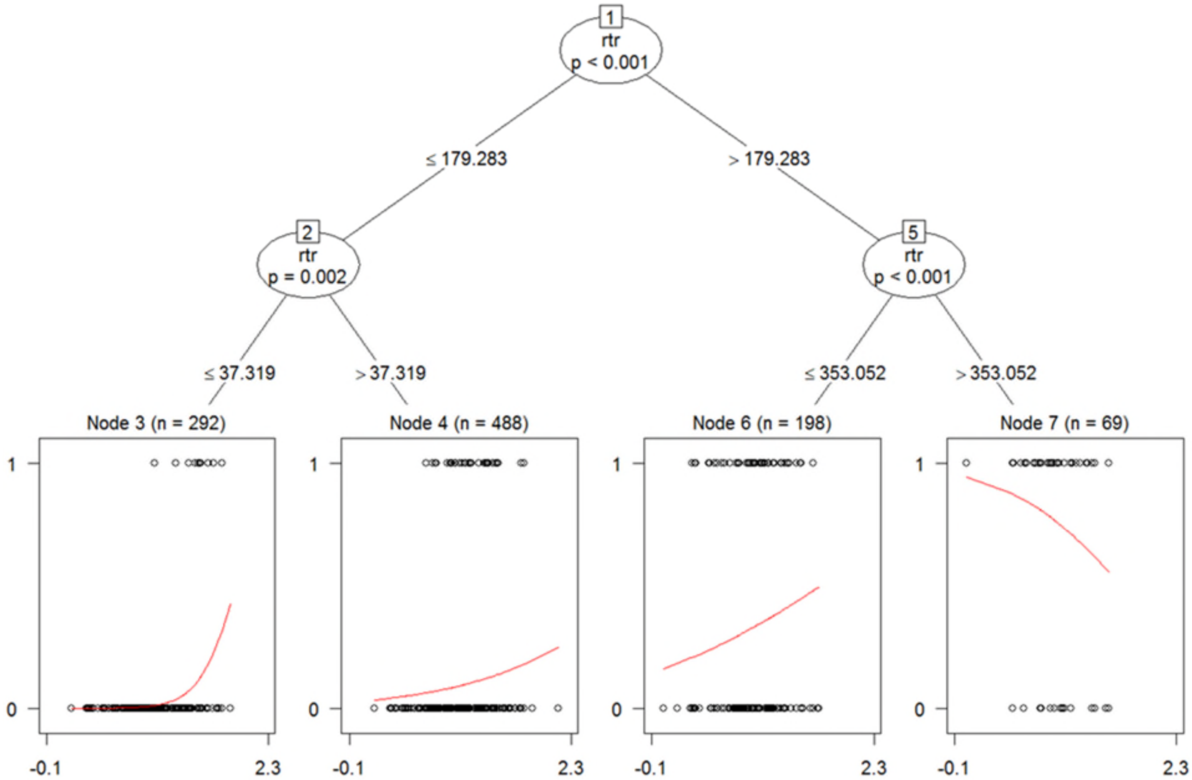

Figure 3. TREED regression of the proportion of water column samples that are hypoxic (DO < 4mg/L, expressed as a binomial variable with a 50% threshold, see text for details) on summer epilimnetic chlorophyll a, using relative thermal resistance as a splitting variable. The strongest positive relationships are among lakes outside the highest level of relative thermal resistance (<353).

The logistic regression models were statistically significant (Figure 4). They indicate that lakes with a chlorophyll *a* value of 20 µg/L have a 21% probability that greater than half of the water column DO samples are < 4 mg/L. For the same chlorophyll *a* value, there is a 53% probability that greater than half of the hypolimnion is hypoxic.

The value of 20 ug/L chlorophyll *a* has been proposed as a potential threshold for criterion setting. Therefore, it is important to note that, based on Figure 4, chlorophyll *a* values above this carry an increased risk of a greater percentage of water column depth with DO < 4 mg/L and of a hypolimnion where less than 50% of the depth supports oxygen above 4 mg/L. Both of these would result in reduced habitat meeting the oxygen requirements for optimal development and growth of game species considered valuable in Mississippi.

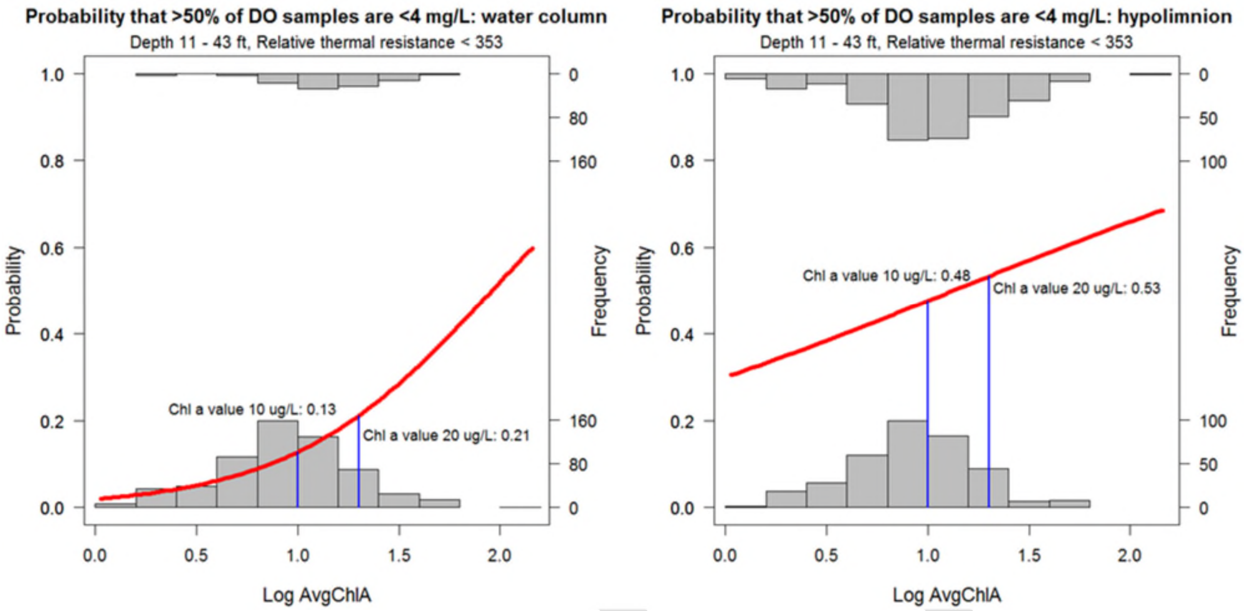

Figure 4. Relationship between water column (left) and hypolimnetic (right) hypoxia as a function of epilimnetic chlorophyll a in lakes between 11 and 43 ft. in depth, with relative thermal resistance < 353 (n=659). Blue lines represent chlorophyll a concentrations of 10 and 20 µg/L. Both models were statistically significant (p<0.01).

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