MODELING THE EFFECT OF SEDIMENT OXYGEN UPTAKE ON WATER QUALITY IN A EUTROPHIC OXBOW LAKE

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INTRODUCTION

The consumption of dissolved oxygen in aquatic systems is a complex phenomenon with an interacting suite of physical, chemical, and biological factors that determine rate. Oxygen is only moderately soluble in water and diffusion rates are generally slow and dependent upon differences in gas partial pressure between the atmosphere and water (driving force) and turbulence at the air-water interface. In shallow, eutrophic lakes, dissolved oxygen consumption is dominated by phytoplankton respiration. However, in shallow lakes dissolved oxygen consumption by sediment may be an important contributor to overall respiration.

Dissolved oxygen consumption by sediment can be partitioned into biological and chemical components. The primary sink for dissolved oxygen at the sediment-water interface is related to the aerobic decomposition of organic matter, especially recently settled detritus derived from phytoplankton, mediated by the heterotrophic microbial community. The nitrification of ammonia requires oxygen and the chemoautotrophic bacteria mediating the process are thus sensitive to low dissolved oxygen. The extent of the nitrification process at the sediment-water interface is limited by the penetration of dissolved oxygen into the sediment. Benthic organisms represent a minor sink for dissolved oxygen in sediments, although sediment bioturbation through burrow irrigation and feeding can increase the flux of dissolved oxygen into sediment. Dissolved oxygen is also consumed at the sediment-water interface by the chemical oxidation of reduced substances (e.g., S^{2-}, Fe^{2+}, Mn^{3+}) diffusing in response to concentration gradients to the sediment surface. A thin layer of oxidized sediment functions as a barrier to the diffusion of reduced substances to overlying water.

Eagle Lake is a shallow, eutrophic oxbow lake located north of Vicksburg, Mississippi, and nearly adjacent to the Mississippi River. The lake is isolated from periodic inundation by the Mississippi River by a system of water control structures and earthen levees. Water level within the lake can be manipulated during most of the year and is usually drawn down during the winter to expose the shallow lake margins normally supporting luxuriant macrophytic plant growth to the effects of desiccation and cold. Concern has grown in recent years over a perceived decline in the fishery, particularly for centrarchid fishes, in the lake and studies are underway to evaluate possible causal mechanisms. One plausible mechanism responsible for the decline of the fishery may be related to the increased frequency of acute, massive mortalities of fish and possible reduced fish recruitment associated with dissolved oxygen depletions. The relative importance of various sinks for oxygen in shallow aquatic systems implicates the potentially important role of the sediment to overall oxygen consumption. The purpose of this study was to evaluate the contribution of sediment respiration to oxygen consumption in Eagle Lake in an effort to evaluate options for reducing the frequency of fish mortalities associated with dissolved oxygen depletions and improving water quality to support a centrarchid fishery.

MATERIALS AND METHODS

Ten sampling stations were established along the upper section of the eastern arm of Eagle Lake. Four stations were established adjacent to dense stands of aquatic vegetation (primarily *Najas* spp.), three stations were established along the western shore, and three stations were established along the eastern shore. Stations were approximately 3-5 m from the edge of vegetation or 5-10 m from shore. All stations were approximately 100 m apart and were established at 1-1.5 m water depth.

Sediment oxygen uptake (SOU) was evaluated using *in situ* respirometry based on a respirometer design developed by Murphy and Hicks (1986). Respirometers consisted of aluminum chambers 45.7 cm in diameter by 18 cm in height and with a volume of 27.4 L. Three chambers were used during testing at each location. Two chambers were exposed to the sediment (0.152 m^2). A third chamber was fitted with a metal plate on the bottom and was therefore not exposed to the sediment. This chamber served as a blank and represented the respiration of water only. Respiration in the two test chambers represented the sum of oxygen consumption by water and sediment. The SOU could then be calculated as a function of the difference between the average decrease of dissolved oxygen in the test chambers and the blank chamber.

Each chamber was fitted with a 12 VDC submersible pump connected to tubing that slowly circulated water within each chamber. Water velocity did not exceed 0.03 m/s (0.1 ft/s) and was insufficient to induce sediment suspension.

Dissolved oxygen was measured within each chamber with a YSI Model 58 meter with a polarographic probe equipped with a stirrer (Yellow Springs International, Yellow Springs, Ohio). Probes were inserted into a hole cut into a rubber stopper that, in turn, fit into a hole cut into the top of each chamber.

Tests were initiated as follows. Each chamber was filled with water near the lake surface. The chambers were inverted and inspected to verify the absence of air bubbles. The pump was activated by connecting wire leads to battery terminals and evidence of circulation was confirmed. The dissolved oxygen probe assembly was placed in the hole cut into the top of the chamber. The chamber was then placed carefully on the sediment surface, taking care to minimize disturbance. The stirrer attached to the dissolved oxygen probe was activated and the chamber allowed to stabilize for 10 to 15 minutes before initiating dissolved oxygen readings. Dissolved oxygen concentration values from each respirometer were recorded every 5 minutes for 65 minutes. Dissolved oxygen concentration usually declined by >1 mg L^{-1} during this interval and never declined below 4.9 mg L^{-1}. Tests were conducted during daylight and initial dissolved oxygen concentrations usually exceeded saturation. Temperature ranged from 28.2 to 33.8 C (average=31.1 C) during test runs. Sediment respirometry measurements were conducted between 5 to 7 August 1996.

The slope of the line describing dissolved oxygen concentration within each chamber as a function of time was determined by linear regression. Occasionally, initial observations were discarded if the fit of the line could be improved (as indicated by increased coefficient of determination). The slope parameter represented the volumetric respiration rate (mg L^{-1} h-1). The SOU was calculated by subtracting the slope parameter determined for incubation of the blank chamber from that determined for each test chamber and, after application of appropriate conversion factors, expressing the result as mass of oxygen consumed per unit area per unit time (g O_2 m^{-2} h^{-1}). The SOU at each station represented the average calculated from results of the two test chambers.

Samples of sediment at five stations (1, 3, 5, 7, and 9) were collected with a core tube fitted with 5-cm diameter plastic liners. Cores were subsequently extruded and fractionated into segments representing 0-1, 1-2, 2-5, and 5-10 cm intervals. Moisture content was determined by drying core segments at 105 C for 24 h. Loss-on-ignition was determined by combustion of a dried and mixed sample of each core segment at 500 C for 10 minutes and was subsequently used to estimate sediment organic content.

RESULTS AND DISCUSSION

The overall SOU (n=10 stations) was 189 mg m^{-2} h^{-1} (4.55 g m^{-2} d^{-1}). The SOU of sediments of commercial channel catfish ponds located in the nearby Mississippi River alluvial valley was 184 mg m^{-2} h^{-1} (Berthelson et al. 1996). Sediment oxygen uptake is strongly temperature dependent and the SOU measured in this study can be expected to represent the maximum rate as water temperature was near the annual maxima. Smith and Fisher (1986) developed a regression equation of sediment oxygen demand (SOD) as a function of temperature from various published studies [SOD (mmol m^{-2} h^{-1}) = 0.287*T - 2.5]. Application of this equation to data collected at Eagle Lake results in an estimated SOU at 31 C of 206 mg m^{-2} h^{-1}. The results of our study are therefore consistent with other studies conducted on dynamic, predominately mineral sediments.

Sediment water content decreased from 70% by volume in the 0 to 1 cm fraction to about 50% by volume in the 5 to 10 cm fraction (Figure 1). Sediment organic content ranged from 2.3 to 2.7% by volume in all sediment fractions. Sediment oxygen uptake is directly related to sediment organic matter concentration. In this study, sediment organic matter concentration did not affect SOU. The failure to detect the effect of organic matter on SOU may be related to the low organic content of Eagle Lake sediment and the small sample size (5 cores) used to evaluate this relationship.

The incubation of a blank chamber simultaneously with test chambers allowed resolution of the contribution of water and sediment to overall lake respiration. Oxygen consumption by lake water was 0.44 mg L^{-1} h^{-1}. Assuming water and sediment were the two primary sinks for dissolved oxygen in Eagle Lake, a model based on data collected in this study was developed to describe the relative contribution of each sink term as a function of lake depth (Figure 2). In shallow water (<0.5 m), the contribution of sediment to lake respiration is proportionally larger than that of the water. As water depth increases, the relative contribution of the sediment to overall respiration decreases. However, sediment contribution to overall respiration remains substantial (approx. 20%) in water depth >2 m. At 0.5 m water depth in Eagle Lake, approximately 50% of the overall respiration can be attributed to the sediment and 50% can be attributed to the water.

Dissolved oxygen concentration in eutrophic aquatic systems is characterized by wide diel fluctuation in which minimum concentrations are usually measured near dawn. Critically-low dissolved oxygen concentrations (<2 mg L^{-1}) for any extended period may result in the acute and catastrophic mortality of large numbers of fish. Estimation of the occurrence of critical dissolved oxygen concentration at dawn by fishery biologists and lake managers introduces the possibility of water quality management, such as aeration or mixing, to mitigate the potential negative impacts associated with dissolved oxygen depletion. Therefore, a model was developed to predict dissolved oxygen concentration at dawn as a function of:

- -dissolved oxygen concentration at dusk (mg L^{-1})
- -water respiration rate (mg L^{-1} h^{-1})
- -sediment respiration (SOU) rate (g m^{-2} h^{-1})
- -water depth (m)

The model assumes no horizontal mixing and completely mixed conditions within a vertical segment of the water column. Both assumptions are likely violated in a stratified, eutrophic lake such as Eagle Lake. Epilimnetic dissolved oxygen concentration at dawn is likely higher than predicted due to diffusion from the atmosphere (reaeration), and hypolimnetic dissolved oxygen concentration at dawn is likely lower due to low rates of dissolved oxygen diffusion from surface waters of stratified lakes, such as Eagle Lake. However, the model does not account for surface reaeration and lake mixing and, therefore, model assumptions are conservative. The model was described by the following equation:

$$DO_{dawn} = DO_{dusk} - \{12 * [\ (SOD/depth) + \text{water respiration}\ ]\}$$

The results of the model were used to develop scenarios in which critical dissolved oxygen concentrations were obtained (Figure 3). The model indicates the important effect of dissolved oxygen concentration at dusk and the important effect of sediment respiration rate on dissolved oxygen at dawn at a water depth <2 m. Based on the conditions prevailing during the sampling period, a dissolved oxygen concentration at dusk of 8 mg L^{-1} would result in a critical dissolved oxygen concentration at dawn (2 mg L^{-1}) at any depth. The probability of a critical dissolved oxygen concentration at dawn in water depth <1 m are increased when dissolved oxygen concentration at dusk is <9 mg L^{-1}. Application of the model to measurements of lake bathymetry and dissolved oxygen concentration at dusk can be used to predict dissolved oxygen concentrations at dawn for different regions of the lake. Given the large horizontal heterogeneity in water quality in shallow lakes, the model can be used to predict areas of the lake where dissolved oxygen concentrations at dawn are likely to reach critical concentrations.

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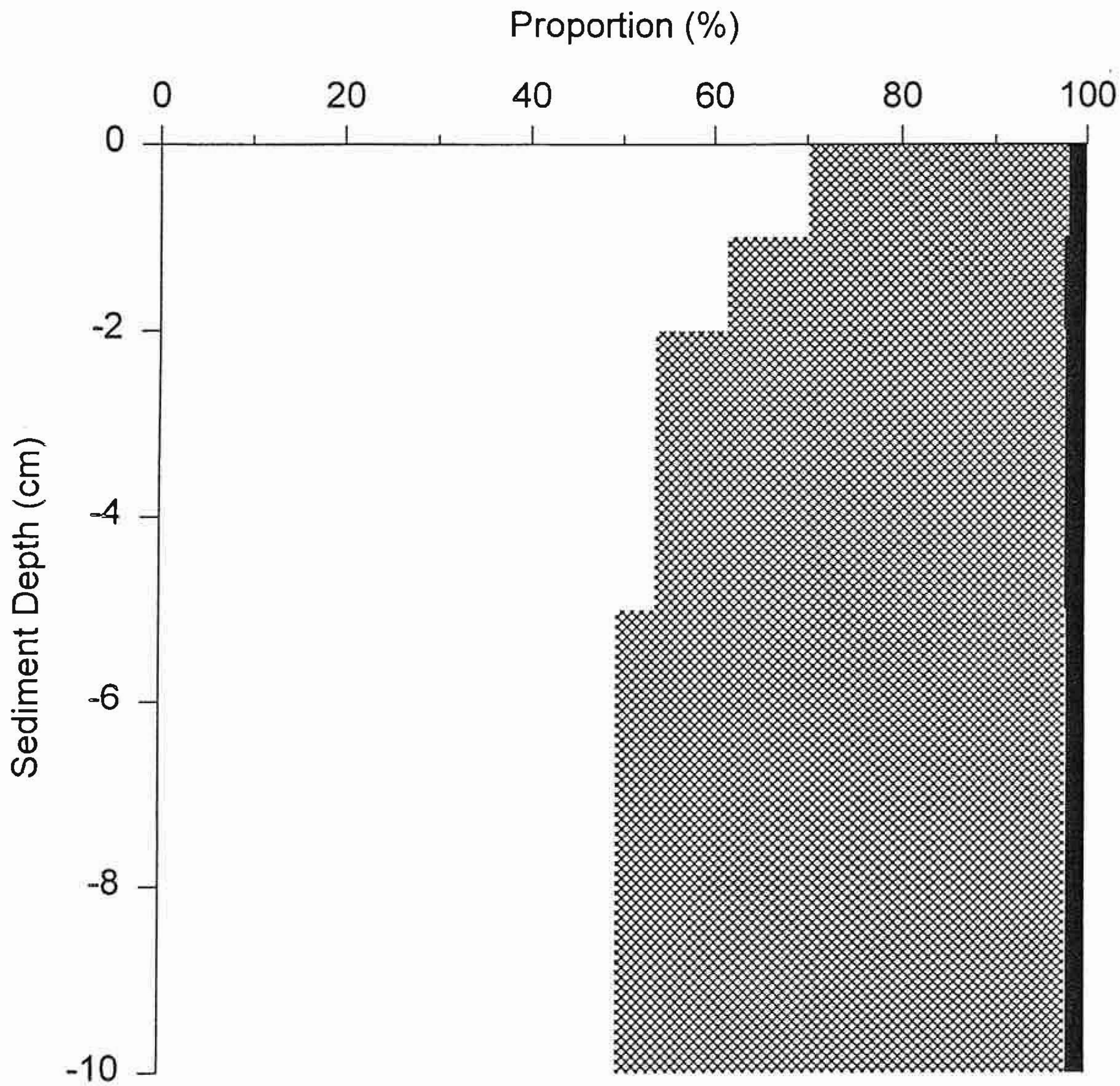

Figure 1. Proportional (%) volume of water (white), mineral matter (hatched), and organic matter (black) as a function of sediment depth from five cores collected from Eagle Lake, Mississippi, 7 August 1996.

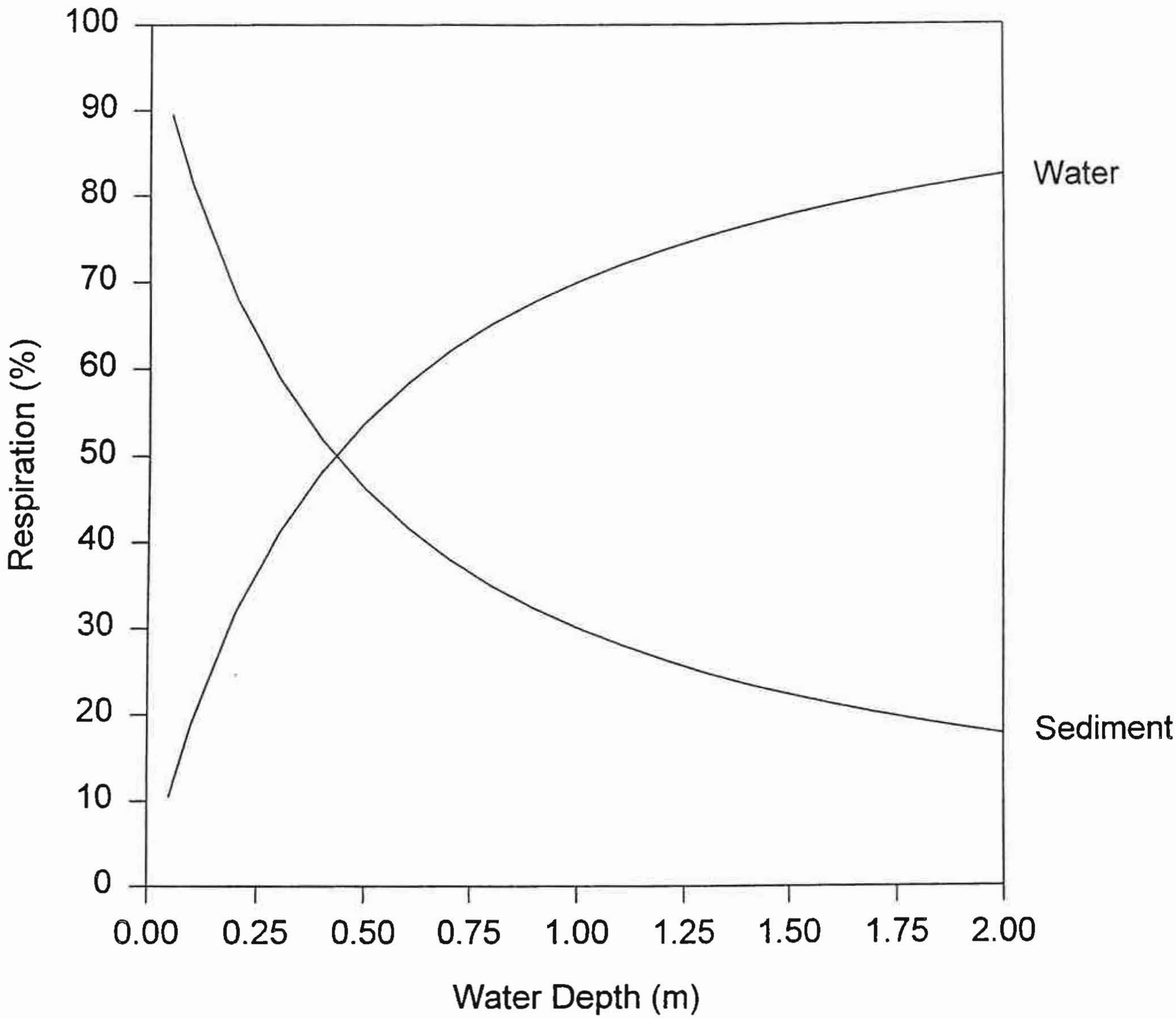

Figure 2. Estimated proportional (%) contribution of water respiration and sediment respiration as a function of water depth during mid-summer in Eagle Lake, Mississippi.

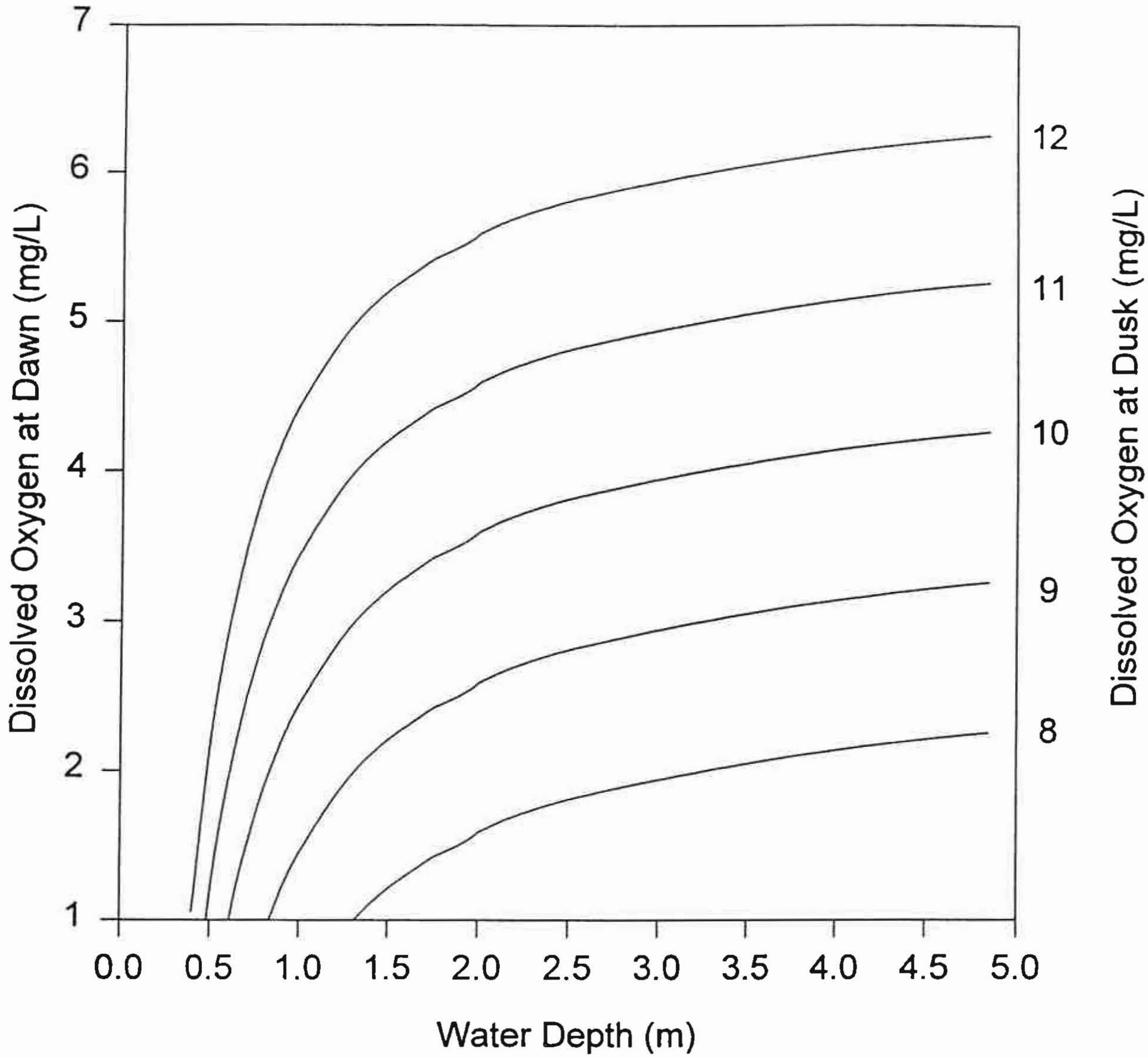

Figure 3. Estimated dissolved oxygen concentration at dawn as a function of dissolved oxygen concentration at dusk and water depth during mid-summer in Eagle Lake, Mississippi.