Model Calibration Data for Dynamic Water Quality Simulations of a Eutrophic Reservoir:
Nutrient-Algae-Oxygen Interactions in Lake Greenwood, SC.

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with

Phytoplankton Taxonomic Composition
(Appendix A)

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ABSTRACT

Lake Greenwood is the first major impoundment on the Saluda River, located approximately 100 km downstream from the Saluda headwaters in the SC Blue Ridge Mountains. The reservoir has a productive fishery although excess nutrient loading and eutrophication may threaten water quality and biotic habitat. This presentation provides information from a year of intensive sampling to help quantify key interactions among nutrient distributions, algal productivity and oxygen depletion in the lake.

During 2004, phosphorus concentrations in the upper tributaries (Saluda and Reedy River Arms) were typically high (0.1-0.2 mg/L), well above the State standard (0.06 mg/L), and consistent with the recent placement of Lake Greenwood on the list of nutrient-impaired waters (SCDHEC). While these elevated concentrations often extended through the upper half of the lake, surface concentrations typically declined downstream (0.02-0.05 mg/L) due to sedimentation and dilution. In contrast, bottom-water concentrations increased considerably downstream (0.3-0.4 mg/L) due to the settling of particulate phosphorus into deeper layers and the release of soluble phosphorus from anoxic benthic sediments. These data will help quantify

key differences between external loading from tributary inputs and internal loading from benthic sediments.

Patterns of phytoplankton productivity (oxygen change in light/dark bottles) varied considerably as functions of season (light and temperature), nutrient concentration, and turbidity. During mid-summer, the upper, nutrient-rich zone exhibited higher rates of net production in the surface waters (4 mg L^{-1} d^{-1}) which attenuated rapidly with depth due to turbid upstream conditions. In contrast, stations farther downstream displayed less production in the surface (0.5-2.0 mg L^{-1} d^{-1}) due to lower nutrients, but sustained higher levels of net production in deeper levels, due to lower turbidity. In further analysis, these patterns will be correlated with ambient conditions (temperature, phosphorus concentration, algal biomass, and solar radiation) to calibrate production coefficients and to quantify the total photosynthetic input of organic matter to the lake. Algal biomass (chlorophyll a) exhibited seasonal peaks in the upper half of the lake; with bloom conditions (> 40 µg L^{-1}) developing in the early spring and late fall. The algal community was dominated by cyanobacteria (blue-green algae) throughout most of the lake in the summer, with a pronounced Cryptophyte bloom in late fall (Nov) in the mid-lake area.

Hypolimnetic oxygen in the lower end of the lake declined rapidly from well-mixed oxic conditions in March (8-10 mg L^{-1}) to stratified, hypoxic conditions (< 2 mg L^{-1}) by mid-May. This rate of oxygen depletion (> 4 mg L^{-1} mo^{-1}) culminated in bottom-water DO concentrations in the forebay < 0.2 mg/L from May through October. Late fall mixing (mid-November) re-aerated bottom waters and corresponded to a late-season algal bloom in the middle portions of the lake.

These data will be used to calibrate a dynamic water quality model for Lake Greenwood, relating magnitude and timing of nutrient loads to overall water quality and habitat quality in the lake.

INTRODUCTION

Lake Greenwood is the first major impoundment on the Saluda River, located approximately 100 km downstream from the Saluda headwaters in the SC Blue Ridge Mountains. With a total surface area of 11,400 A, the reservoir has a productive fishery although excess nutrient loading and eutrophication may threaten water quality and biotic habitat. The primary goal of this 2-Yr study is to develop a dynamic simulation model of water quality in Lake Greenwood. The model will help quantify interactions among lake hydrology, nutrient loading and water quality in the lake. Furthermore, the model will help predict implications of alternate management plans for water quality protection and will help formulate long-term plans for water quality enhancement and aquatic habitat protection. Once developed for Lake Greenwood, this model could be expanded to examine related issues of water and habitat quality for the series of river/reservoir segments along the Saluda River and other drainage basins.

The basic conceptual scope of this modeling effort (Fig. 1) is to link information on inputs from the larger watershed (point-source dischargers and nonpoint source runoff) to ecological/water quality patterns and interactions within the lake. We plan to use a state-of-the-art, reservoir-modeling platform (CE-QUALl-W2) to simulate in-lake processes as they respond to input hydrology and nutrient loading. The primary objective of Yr-1 of the study (2004) has been to develop a detailed, comprehensive data set on key parameters needed for model development and calibration (phosphorus distributions; algal productivity, biomass, and taxonomic composition; and rates of oxygen depletion).

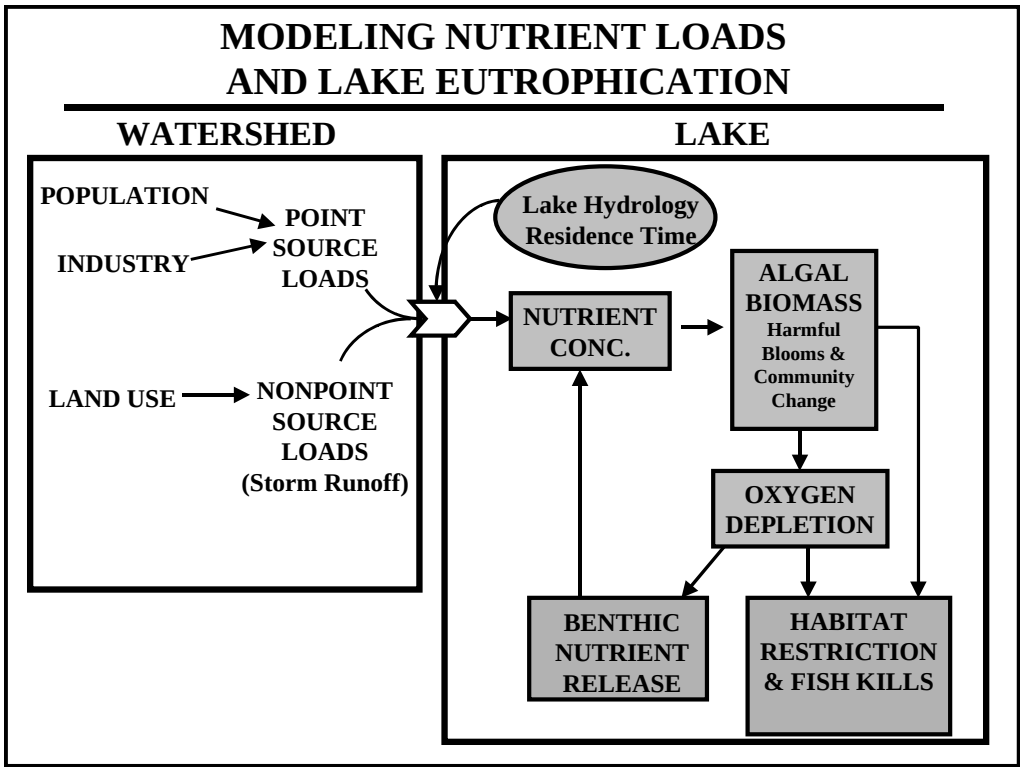

Fig. 1 Conceptual Diagram of Watershed/Water Quality Interactions

MATERIALS AND METHODS

Field Sampling

A total of 12 sampling sites were established this year (Fig. 2) to quantify the spatial detail in the reservoir from the input tributaries (Saluda and Reedy River Arms) to the downstream forebay. Most of the sampling sites were located along the main axis of the lake, with one site in a mid-lake embayment (Mid-Cane Creek Embayment, Fig. 2). Table 1 indicates the study components at each of the stations. In addition, ongoing work by Clemson University and the Saluda-Reedy Watershed Consortium will be available to quantify trends in land use, water quality and nutrient loading in the major catchments flowing into Lake Greenwood.

Sampling Schedule and Analysis

Starting in January 2004, the original sampling protocol included monthly sampling for all study components (Table 1) throughout the annual cycle. While this sampling protocol was adequate to capture broad-scale seasonal patterns, it was not designed to quantify key, short-term events such as short-lived algal blooms and storm events. With additional support from the Saluda-Reedy Watershed Consortium, we increased sampling frequency to twice monthly through the active growing season (May-Oct 2004) with additional sampling during major storm events. This additional support also provided funds for quantifying algal community structure (pigment analyses and microscopic examinations) to complement our own studies of algal biomass and production. During 2004, we sampled the lake for distributions of oxygen, phosphorus, algae distributions and productivity on 35 days, including 9 days of sampling before and after 3 major storm events (Tropical storm Bonnie and Hurricane Frances, and Hurricane Jeanne).

Field Measurements and Laboratory Analyses

Temperature/Oxygen Profiles. At all 12 sampling sites (Fig. 2), a detailed vertical profile of water temperature and dissolved oxygen (YSI-58 DO Meter) was examined at 1-m depth intervals from the surface to the bottom. The oxygen sensor was air-calibrated and checked daily; the YSI-58 thermistor was calibrated against a certified, NIST-traceable thermometer (FisherBrand, SN:1295). To insure a high level of quality control in field data collection, our laboratory secured SC certification for field measures of temperature and oxygen profiles (Lab.ID 40570, 21 May 2004).

Phosphorus and Chlorophyll Concentrations. At 7 of the sampling sites, we collected - water samples for analysis of algal biomass (chlorophyll-a) and phosphorus, a critical limiting nutrient for algal production and eutrophication. Surface water samples for chlorophyll-a were placed in opaque HDPE bottles, labeled and placed immediately on ice. Phosphorus samples were collected from both surface and bottom waters and were partitioned into 3 HDPE bottles designated for analysis of total phosphorus, total soluble phosphorus, and soluble ortho-phosphate. Samples for total phosphorus were preserved with 1 ml H_2SO_4. Only surface water samples were collected at the upper tributary arms (Upper Saluda and Upper Reedy) which were < 5m total depth. All sample bottles were immediately labeled, placed on ice and transported to a certified analytical laboratory within 24 hrs of sample collection. Shealy Environmental

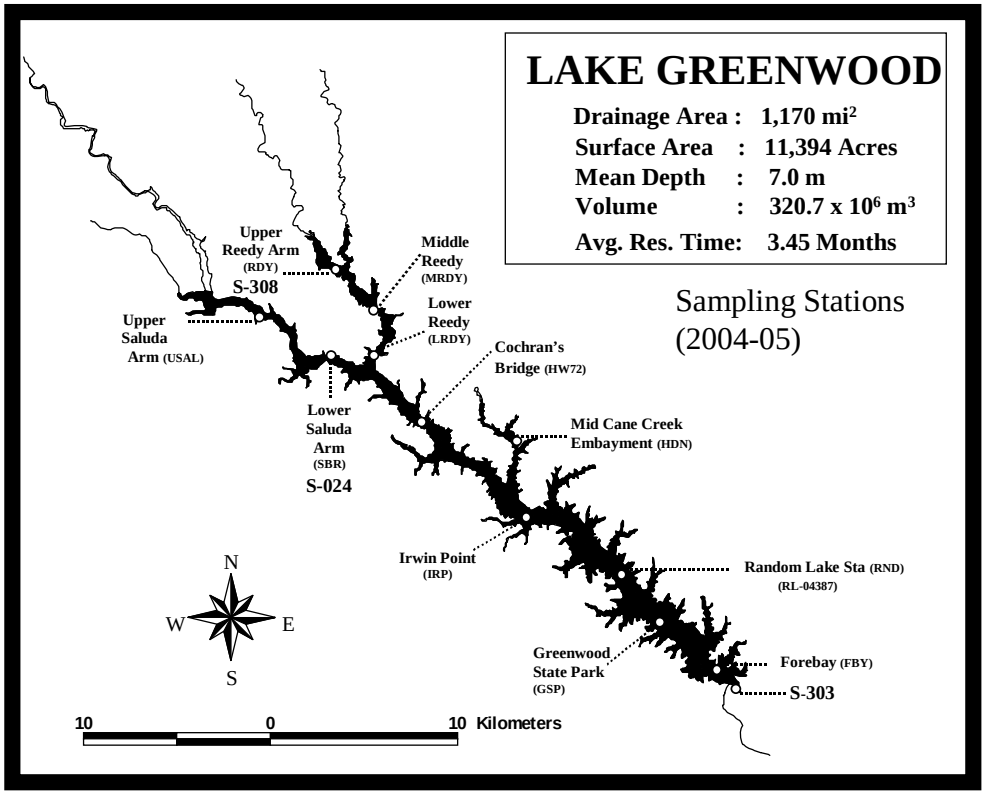

Fig. 2. Sampling Stations. SCDNR monitoring sites are shown as named stations (with 3-4 letter data codes). Additional data will be available from SCDHEC monitoring sites (S-306, S-024, S-303, and RL-04387)

Table 1. Site Locations and Study Components

Site Locations	Temperature/ Oxygen Profiles	Phosphorus/ Chlorophyll Concentrations	Plankton Productivity
Upper Saluda Arm	*	*	
Saluda Bridge	*	*	
Upper Reedy Arm	*	*	*
Middle Reedy Arm	*		
Lower Reedy Arm	*		
Highway 72 Bridge	*	*	*
Irvin's Point	*		
Cane Creek Embayment	*	*	
Irwin's Point	*		
Random Lake Station	*	*	*
Greenwood State Park	*		
Forebay	*	*	*

Services (Lab. ID32010) performed the phosphorus analyses, using acid-persulfate digestion and ascorbic acid reduction (EPA Method 365.2). Two sets of samples for chlorophyll-*a* analyses were collected and placed on ice in amber or foil-covered HDPE bottles. The first set was analyzed by SEAUS, Inc (Cert. Lab ID 36001) using acetone extraction and fluorometric analysis (APHA 1998, Standard Method 10200H). The SCDNR Freshwater Fisheries Research Lab analyzed the second set using acetone extraction and a modified, non-acidification fluorometric analysis (Welschmeyer 1994, Arar and Collins 1997, APHA 1998,); the DNR lab was subsequently certified (Cert. ID 4057) for continued studies in 2005.

Algal Productivity. The vertical distribution of algal productivity was quantified monthly, based on oxygen changes in a vertical array of light and dark bottles incubated *in situ* at 4 of the sampling sites (Table 1, Fig. 3). The 4 stations were selected to provide a wide range of nutrient and light conditions for robust estimates of production coefficients in the model. At each station and time, a 15-L sample of surface water was collected, stirred vigorously to insure homogenous conditions, and then used to fill 14 light bottles (300 ml BOD bottles) and 4 dark bottles. After the initial oxygen concentration was determined in 2 of the bottles (using a aYSI-58 DO meter and 5905 bottle probe) the remaining light bottles were suspended at 0.1, 0.3, 0.6, 1.1, 1.6, 2.1, 2.6, 3.1, 4.1, 5.1. and 6.1 m depths, with duplicate bottles at the 0.1m level. The depth range from 0 to 6.1 m was usually in the photic zone at these stations.

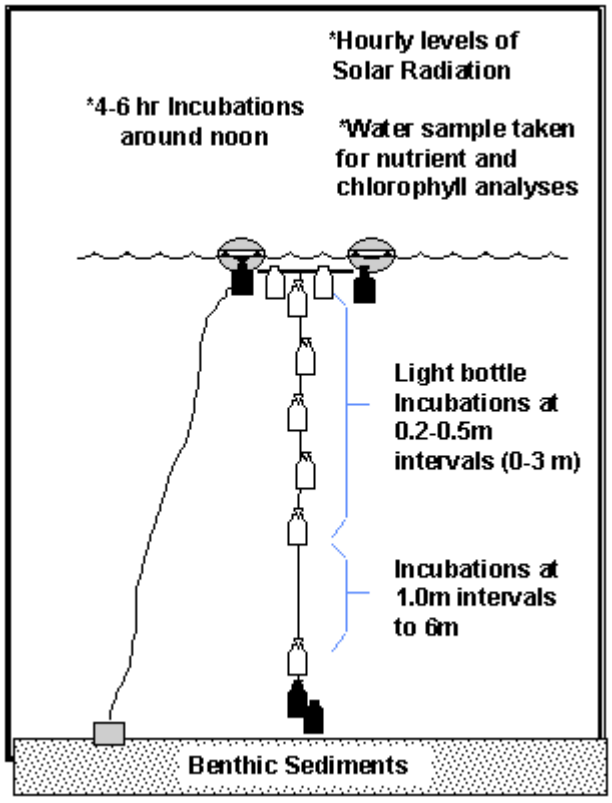

Fig. 3. Schematic View of the Vertical Array of Light and Dark Bottles for Evaluating Algal Production and Water Column Respiration. Stations at the Forebay, Lower-Lake, and Mid-Lake were > 6m deep, so the "Benthic Sediments" were well below the vertical array. (The station in the upper Reedy River Arm was < 3 m deep so the vertical array extended only to the 2.1 m level).

Dark bottles were suspended in duplicate near the surface (0.1m) and just below the lower light bottles. After a 4 to 6-hr *in situ* incubation, the bottles were retrieved and the change in oxygen concentration determined. Net productivity (Pn, mg L^{-1} h^{-1}) for each depth in the vertical array was calculated as (L-I)/t, where L was the final oxygen concentration in each light bottle, I was the initial oxygen concentration, and t was the time of incubation (h). Respiration (R, mg L^{-1} h^{-1}) was calculated as (I-D)/t where D was the final oxygen concentration in the dark bottles. Gross productivity (Pg, mg L^{-1} h^{-1}) was then calculated for each depth in the vertical array as Pn + R. During winter and fall, R was evenly distributed between the upper and lower levels of the vertical array and the mean R from all 4 dark bottles was used to calculate Pg for each depth in the vertical array. However, during periods of thermal stratification in the top 6 m (May-August), the deeper dark bottles were often cooler (2-7 ^{o}C) than surface dark bottles and exhibited correspondingly lower rates of respiration. During these periods, R for each level in the vertical array was computed as an exponential function of the observed temperature profile as follows:

$$R = (k_1)\, \mathbf{e}^{(k2)T}$$

Where k1 and k2 were determined from an exponential regression (EXCEL) of R vs T for the shallow and deeper dark bottles. Hourly levels of gross productivity were extrapolated to daily rates (mg L^{-1} d^{-1}) by the following calculation:

$$Pg(\text{mg } L^{-1} d^{-1}) = Pg(\text{mg } L^{-1} h^{-1})(t)(Ld)/Li$$

where t = the duration (h) of incubation, Ld = total solar radiation for the day (µmol m^{-2} da^{-1}), and Li = total solar radiation during the incubation (µmol m^{-2}). Ld and Li were derived from continuous recordings of photosynthetically active radiation (PAR) using a LiCor Li-190SA quantum sensor and Campbell CR21X data logger, deployed on a dock at a mid-lake location near Station HW72 (Fig. 2). Additional information on light distribution through the water column was gained by vertical profiles of PAR at 0.5 to 1.0m intervals throughout the photic zone at each station (LiCor 250A underwater quantum meter). Secchi disk observations were also recorded as an additional indication of water clarity at each station and time.

Phytoplankton Taxonomy. To determine the succession of algal dominants during this study and to assess the potential for harmful algal blooms, additional samples were collected for taxonomic analysis by the SC Algal Ecology Lab in Charleston SC (Hollings Marine Lab and SCDNR Marine Resources Research Inst). This analysis included microscopic screening of preserved water samples and High Performance Liquid Chromatography (HPLC) analysis of extracted pigments of known taxonomic importance to algal identification. The details of methodology and results are provided in Appendix A.

RESULTS AND DISCUSSION

While most of the data is still being analyzed, the following results provide a preliminary examination of the kinds of information gained so far and potential interpretations regarding water quality dynamics in Lake Greenwood.

Basic Hydrology

Water quality in reservoirs typically responds directly or indirectly to changes in basic hydrology such as tributary inflows, outflows and resultant residence time and water level. During 2004, water level in Lake Greenwood was maintained according to an operating "rule curve" approved by FERC (Fig. 4) The rule curve calls for water level reductions through the late fall and winter to a late January minimum of 434.5 ft (MSL). Beginning in February, the water level increased gradually to 439 ft by mid-April. This level was maintained through summer and early fall with a gradual drawdown beginning again in November. Some fluctuations in water level (+/- 1 ft) occurred in response to several major storm events in September and December.

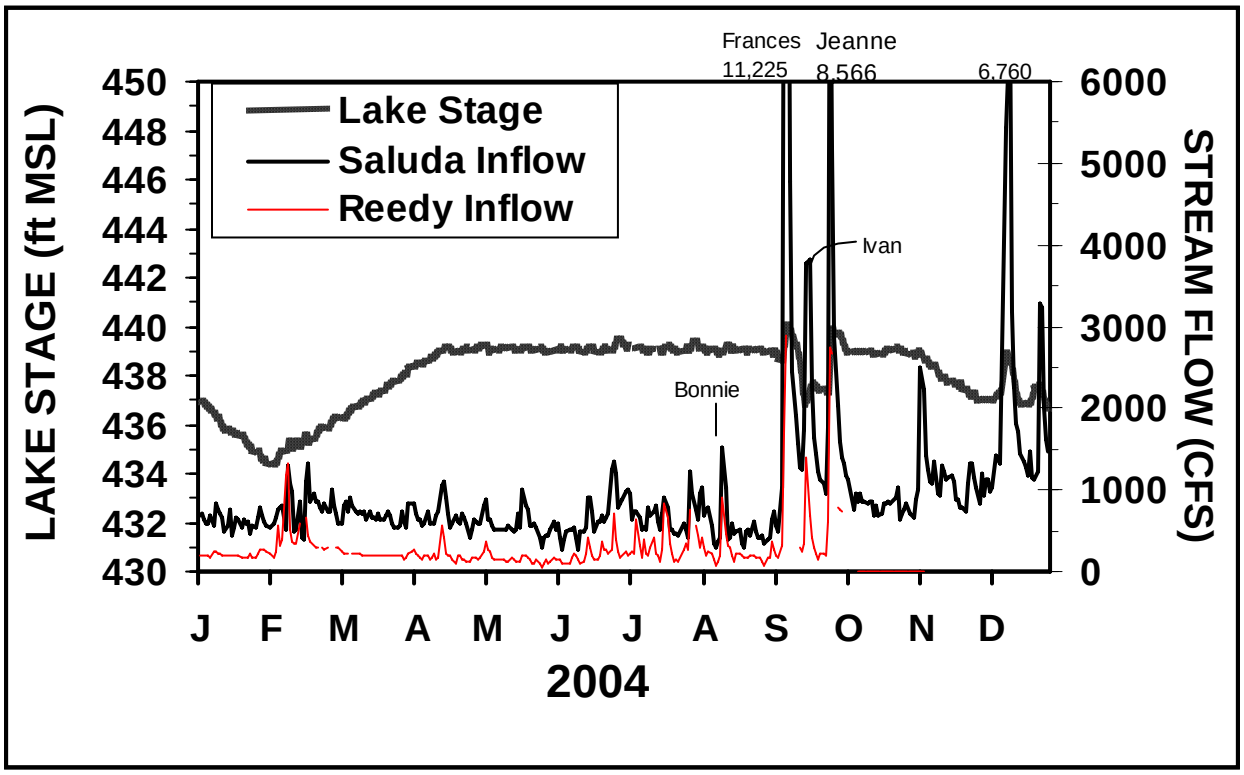

Fig. 4. Daily water level (lake stage) in Lake Greenwood and the major inflows from the Saluda and Reedy Rivers for 2004. Data from http://nwis.waterdata.usgs.gov.

The Saluda and Reedy Rivers represent the major sources of inflow to Lake Greenwood. Long-term mean daily discharge (since 1939) in the Saluda (976 cfs, http://nwis.waterdata.usgs.gov) is about 2.8 times that in the Reedy (352 cfs). This relative relationship was roughly the same during 2004, except for a few short-term runoff events in February and July, when flow in the Reedy was approximately equivalent to those in the Saluda (Fig. 4). The major hydrologic events of the year were a series of tropical storms in September (Frances, Ivan, and Jeanne). The peak discharge in the Saluda following Hurricane Frances (11,225 cfs) was more than 10 times the long-term annual mean and was about 70% of the highest daily flow on record (16,100 cfs, Aug 27, 1995). The mean flow for September 2004 (2,837 cfs) was almost 5 times higher than the average flow for this month (594 cfs) and about 52% higher than the long-term maximum flows for September (1,862 cfs). Similar statistics for the Reedy were not available because of stream gauge damage during these storms.

Phosphorus and Chlorophyll Distributions

Phosphorus concentrations in the upper reaches of the lake (both the Saluda and Reedy River Arms, > 30 km upstream from the dam) were typically elevated above the SC water quality standard of 0.06 mg/L (Fig. 5). This observation was consistent with SCDHEC placement of Lake Greenwood on the State list of impaired waters due to high phosphorus concentrations. The overall mean concentration of total phosphorus in the Upper Saluda Arm (0.13 ± 0.03 mg $L^{-1;}$ Mean ± Std.Err) was very similar to the Upper Reedy (0.11 ± 0.02 mg L^{-1}), both with >70 % exceedence of the 0.06 mg L^{-1} standard. The highest concentrations (0.40-0.48 mg L^{-1}) were observed in both arms during discharge peaks related to Hurricanes Frances (Sep 9) and Jeanne (Sep 28, Fig. 4). These results suggest the importance of nonpoint sources of phosphorus in both tributaries during storm events.

Further downstream, surface water concentrations typically declined substantially (Fig. 5), probably due to particulate matter sedimentation and algal uptake. However, bottom water concentrations at the downstream, deeper stations were much higher than in the surface waters during the late summer. At the Lower Lake stations (15-20 m deep), average bottom water concentrations in Aug and Sep (0.15-0.30 mg L^{-1}) were 3-6 times higher than in the surface waters (0.05 mg L^{-1}). This increase of bottom water phosphorus was perhaps due to the accumulation of settling particulate matter and the potential of phosphorus release from anaerobic benthic sediments (see section on Oxygen Depletion, p. 15). These data will help quantify the importance of external loading (largely from the Saluda and Reedy River inputs) and internal loading from legacy phosphorus in the bottom sediments of Lake Greenwood.

Algal biomass (chlorophyll-*a*) also exhibited higher concentrations in the upper reaches of the lake (Fig. 6), extending downstream to the middle sections (20 km upstream) including the mid-lake tributary embayment (Cane Creek). Algal biomass reached moderate levels (10-20 µg L^{-1} chlorophyll *a*) throughout the lake during summer, with clear domination by cyanobacteria (blue-green algae) during August and September (Appendix A). Cyanobacteria are nitrogen-fixing species that commonly bloom in nutrient rich conditions with limited hydrodynamic flushing, particularly during the warmer months. Some genera of known toxin-producing species of Cyanophytes were identified (*Microcystis*, *Anabaena*, *Nitzchia*, *Aphanizamenon*, and

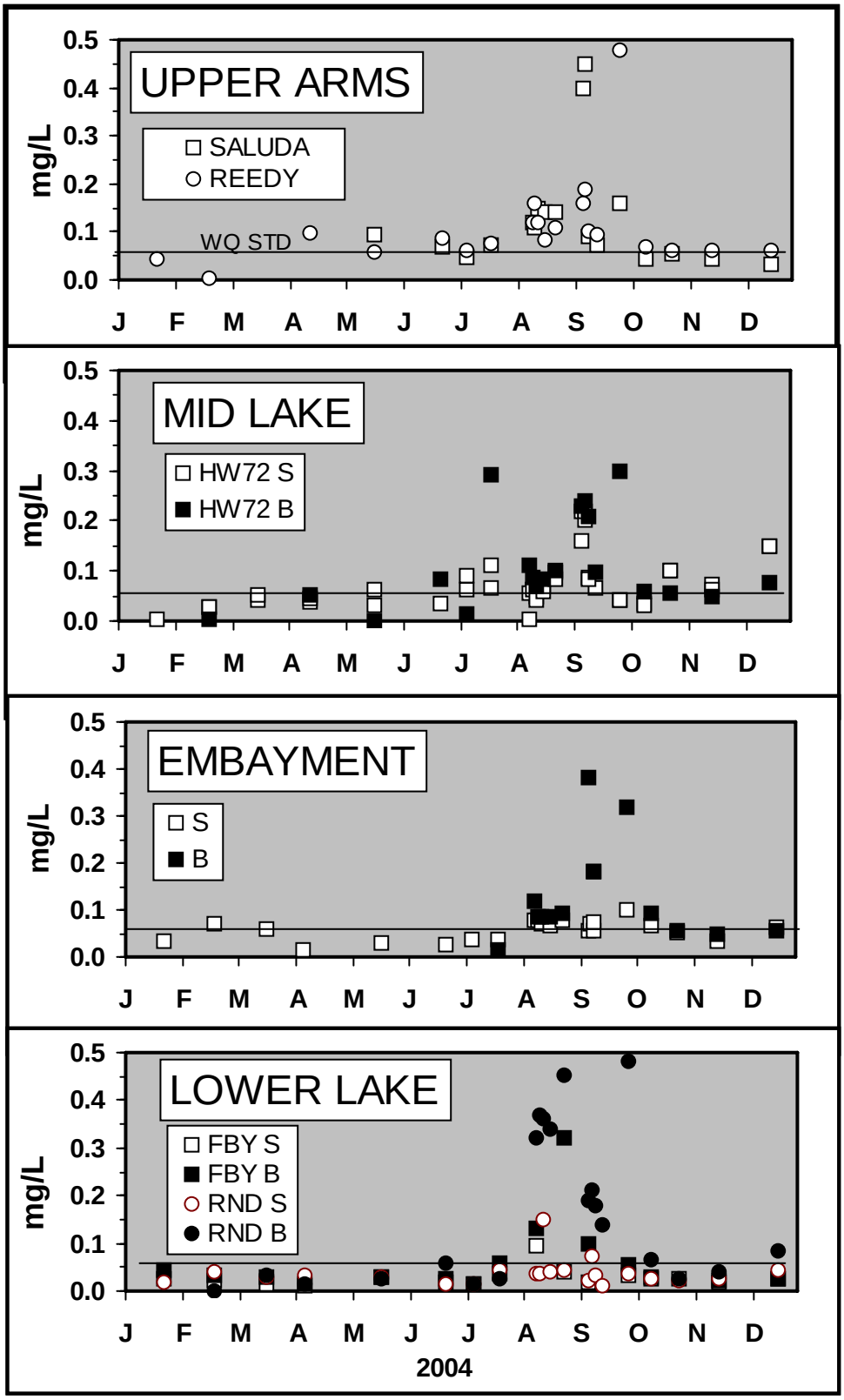

Fig. 5. Distributions of total phosphorus in surface (S) and bottom waters (B) of Lake Greenwood. The dashed line at 0.06 mg/L represents the SC water quality standard for total phosphorus.

Anabaeneopsis) although none of these genera was found in high concentrations (Appendix A). On the other hand, total algal biomass (as indicated by chlorophyll *a* concentrations) occasionally exceeded state standards (40 µg L^{-1}) in the upper and mid-lake sections. [1] The pronounced bloom at the Mid-Lake station in late fall (60-80 µg L^{-1}, Fig 6) was confirmed by both laboratories and was dominated by alloxanthin pigments (Cryptophytes, Appendix A). Cryptophytes are motile, protozoan-like algae that are not typically associated with harmful, toxin-producing algae. The highest persistent chlorophyll *a* concentrations occurred in the mid-lake tributary embayment, suggesting more pronounced blooms in protected embayments with low flushing. Cryptophytes also dominated the algal community in the embayment during these fall blooms (Appendix A).

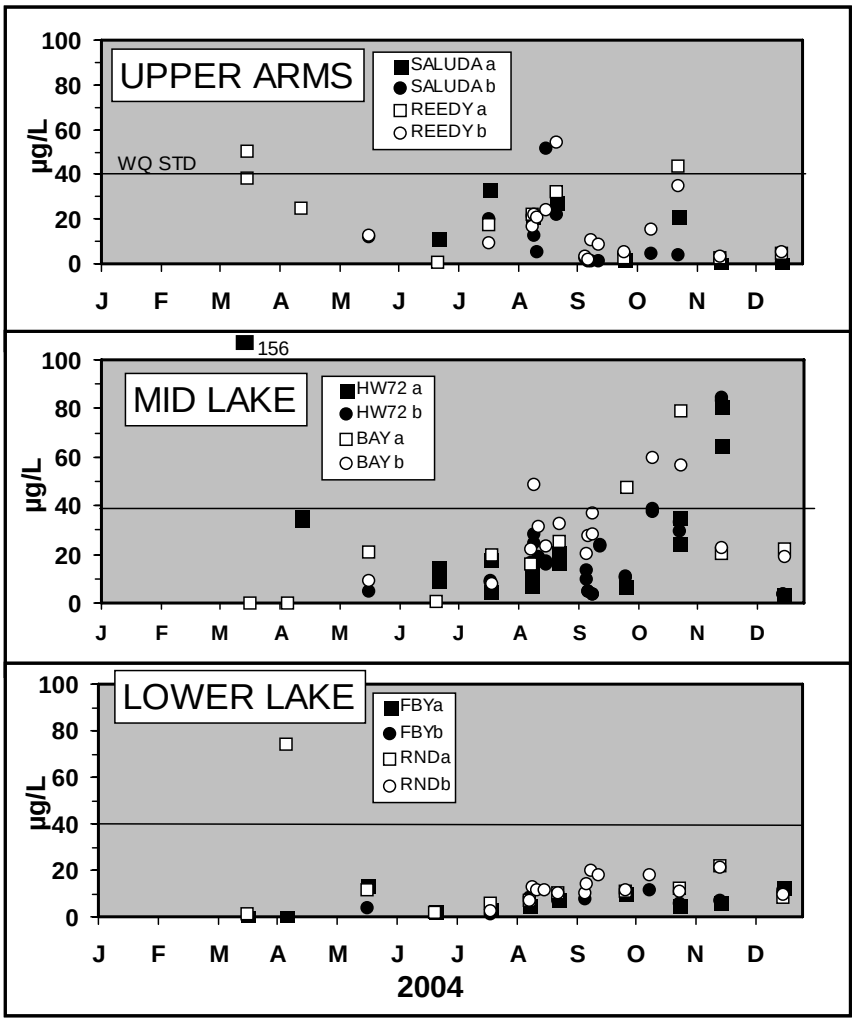

Fig. 6. Chlorophyll-*a* distribution in Lake Greenwood. The black and white symbols represent separate stations in each lake zone. The square and circle symbols (a and b) represent results from 2 laboratories, SEAUS, Inc (squares) and SCDNR, Freshwater Fisheries Lab (circles). The dashed lines indicate the water quality standard of 40 µg L^{-1}.

[1] The extremely high concentrations during March and April in mid- and lower-lake stations (HW22 and RND) were results from initial start-up sampling and are being reviewed as potential outliers.

Algal Productivity

Vertical patterns and the spatial variability of algal productivity typically exhibited some general correlations with phosphorus concentration, algal biomass, and turbidity. For example, during mid-summer conditions (Fig. 7, Table 2), the Upper Reedy Arm exhibited the highest levels of surface productivity (Pg(max), perhaps in response to higher phosphorus concentration and algal biomass. However, productivity in the Upper Reedy attenuated rapidly with depth due to more turbid conditions in the upper lake. The Mid-Lake station had similar phosphorus levels, although this station displayed somewhat less surface production, due in part to less algal biomass. However, at this station, water clarity was higher, light attenuation was lower and productivity extended through deeper levels of the water column, yielding the highest level of total water column production (Pg(int), Table 2). At the downstream regions of the lake (Lower Lake and Forebay), phosphorus and chlorophyll levels were much reduced, corresponding to considerably less algal production at the surface and through the water column. Continued

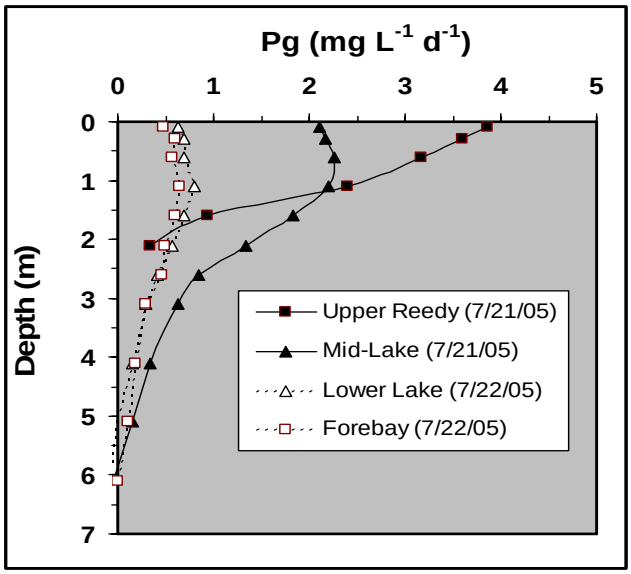

Fig. 7. Example of typical vertical patterns of gross oxygen production at 4 stations in Lake Greenwood (7/21-22/04).

Table. 2. Daily Oxygen Production, Phosphorus Concentration, Chlorophyll-*a*, and Light Attenuation In Lake Greenwood (7/21-22/04). Pg(max) is the maximum volumetric production rate in the water column, Pg(int) is the vertically integrated, area-based production through the water column, Kext is the light extinction coefficient.

Station	Pg(max) (mg L^{-1} d^{-1})	Pg (int) (g m^{-2} d^{-1})	Chlorophyll (µg L^{-1})	Tot. P (mg L^{-1})	Secchi (m)	Kext (m^{-1})
Upper Reedy	3.86	4.31	17.7	0.077	0.5	3.05
Mid-Lake	2.27	5.71	5.2	0.076	1.3	1.12
Lower Lake	0.80	2.07	6.1	0.042	2.7	0.78
Forebay	0.64	2.04	2.9	0.038	>3.0	0.82

analysis of these kinds of correlations will help quantify model parameters related to light, nutrient and biomass limitations of algal productivity in Lake Greenwood.

The maximum productivity in the surface waters (Pg(max)) exhibited a distinct seasonal patterns with a rapid increase at all stations in early spring (Fig. 8, upper panel). Throughout the rest of the growing season (May-Oct), Pg(max) was typically higher in the Upper Reedy and decreased from upper lake to lower lake stations (Fig. 8, Table 3), similar to patterns for total phosphorus and chlorophyll. The major deviation from this growing season pattern was in late September, when runoff from Hurricane Jeanne (Fig. 4) produced extremely high turbidity in the upper and mid-lake stations (secchi disk observations $\cong$ 0.1 m). This high turbidity greatly inhibited algal productivity at the upper and mid-lake stations. During this same time, surface water turbidity in the lower lake remained relatively low (Secchi disk values > 1 m) and productivity exhibited a moderate fall peak.

The daily integrated area-based productivity (Pg(int)), displayed a similar seasonal pattern (Fig. 8, lower panel). However, the spatial pattern of Pg(int) during growing season was more variable (Fig. 8, Table 3), reflecting combined influences of nutrients and turbidity. While phosphorus concentrations (and algal biomass) was typically higher in the upper and mid-lake stations, the lower turbidity in the lower lake stations allowed productivity to extend to deeper levels often resulting in higher integrated productivity. This was particularly evident in early spring and fall, when the vertically integrated productivity at both the Lower-Lake and Forebay stations was higher than in the Upper and Mid-Lake stations (Fig. 8). Respiration rates (R(int)) indicated higher rates of oxygen demand and general heterotrophic conditions (P:R ratio < 1) in the photic zone of the Upper to Mid-Lake areas (Table 3). In contrast, the lower lake stations indicated a more autotrophic photic zone (P:R ratio > 1) with a net production of organic matter through the growing season.

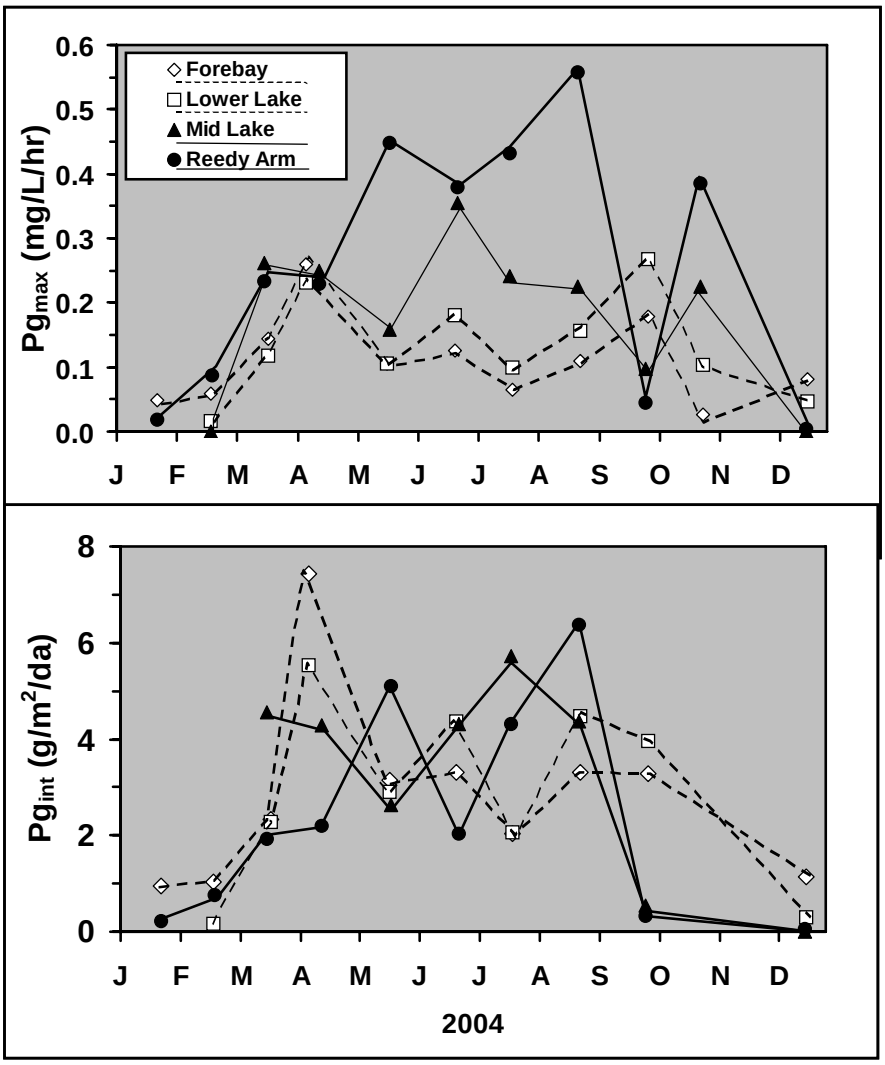

Fig. 8. Seasonal patterns of maximum surface productivity (Pg(max)) and vertically integrated productivity (Pg(int)) in Lake Greenwood, 2004.

Table 3. Growing Season Means (± standard error) for Pg(max), Pg(int), R(int), and P:R Ratios; May-Oct, 2004

Stations	Pg(max) (mg L^{-1} h^{-1})	Pg(int) (g m^{-2} d^{-1})	R(int) (g m^{-2} d^{-1})	P:R Ratio
Upper Reedy	0.375 ± 0.071	3.63 ± 1.09	3.80 ± 0.67	0.96
Mid-Lake	0.217 ± 0.035	3.51 ± 0.89	6.96 ± 2.20	0.50
Lower Lake	0.152 ± 0.027	3.55 ± 0.47	2.65 ± 0.84	1.34
Forebay	0.101 ± 0.021	3.01 ± 0.25	2.36 ± 1.09	1.27

Oxygen Depletion

Lake Greenwood has a history of hypolimnetic oxygen depletion that affects habitat availability (Snoots 1993). During the current sampling season (2004), the distribution of dissolved oxygen in Lake Greenwood exhibited a rapid depletion in the bottom waters from well-mixed conditions in March to highly stratified conditions in spring and early summer (Fig. 9). A linear regression of the mean oxygen concentration below 10 m (Fig. 10) indicates a relatively consistent rate of hypolimnetic oxygen depletion (0.14 mg L^{-1} d^{-1}; 4.2 mg L^{-1} mo^{-1}) at the deeper, lower lake stations from March to mid-May. Zones of hypoxia (<2.0 mg L^{-1}) below the thermocline (5-15 m) extended throughout most of the lake from mid-May through the fall (Fig. 9).

Although oxygen decline in the hypolimnion is a natural process, the intensity, duration, and spatial extent of hypoxic conditions in Lake Greenwood are related in part to the high rates of nutrient loading and eutrophic conditions in the upper regions of the lake. Since the pattern of oxygen distribution represents a key component of water quality (which responds directly to levels of nutrient loading and algal production), a major goal of the developing model will be to predict spatial and temporal distributions of oxygen as functions of hydrology and management alternatives. Understanding the patterns of temperature and oxygen distributions will contribute to a dynamic assessment of extent and variability of habitat quality in Lake Greenwood.

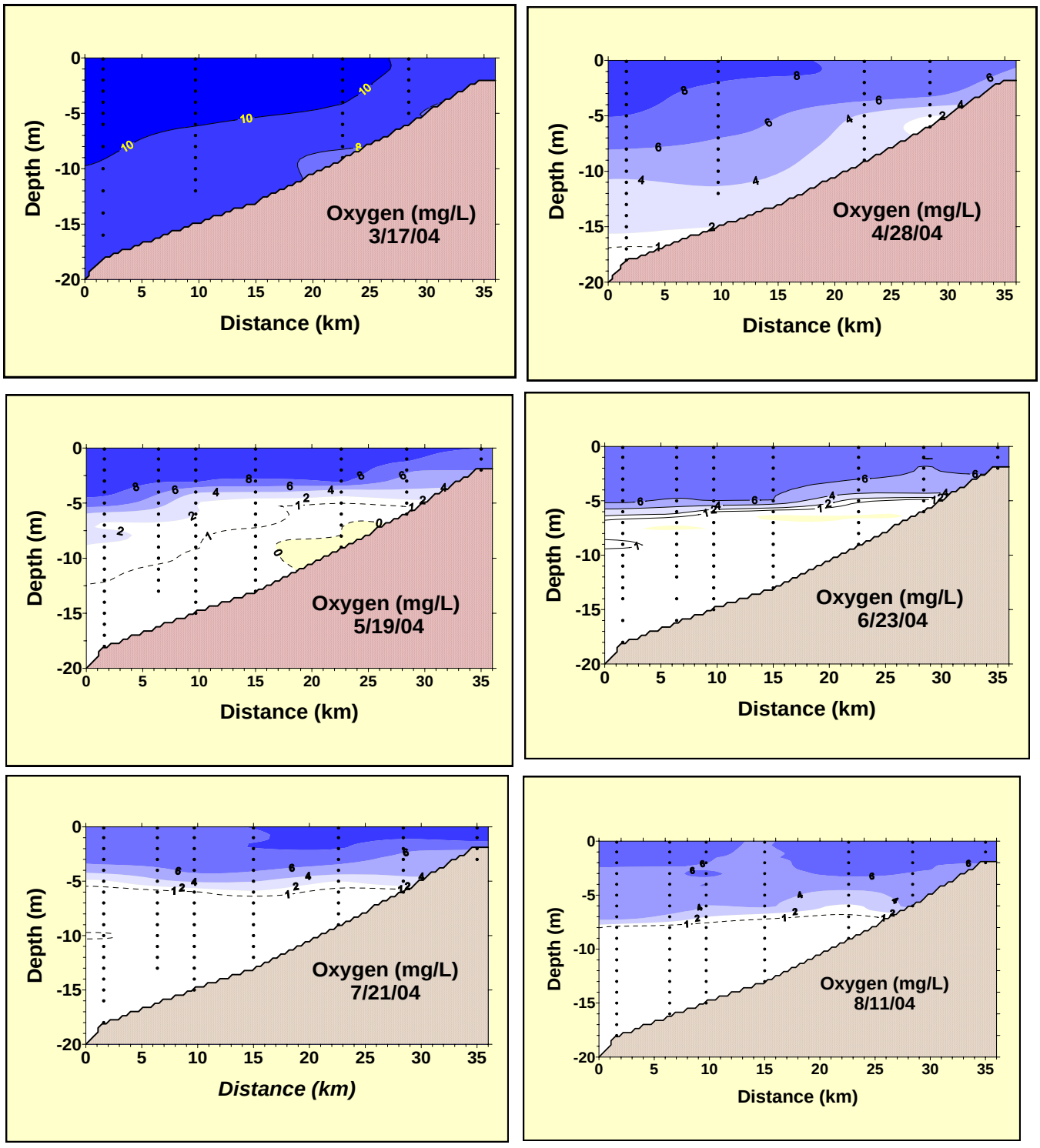

Fig. 9. Depth distributions of dissolved oxygen along the length of Lake Greenwood (Mar-Aug., 2005) Dark shades represent higher oxygen concentrations of oxygen; white indicates DO < 1 mg $L^{-1.}$ Continued on following page.

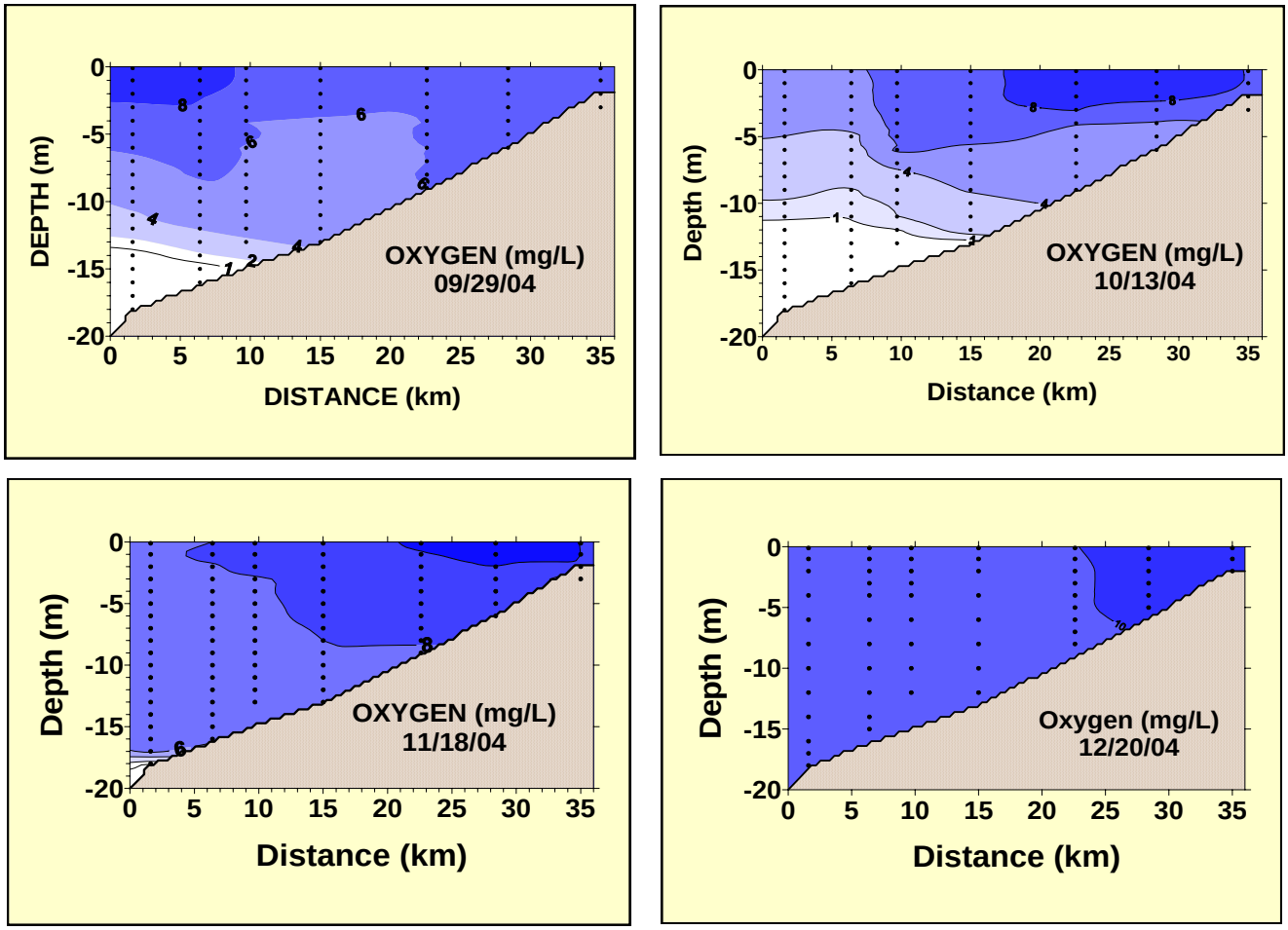

Fig. 9. (Continued) Depth distribution of dissolved oxygen along the length of Lake Greenwood (Sept-Dec., 2005)

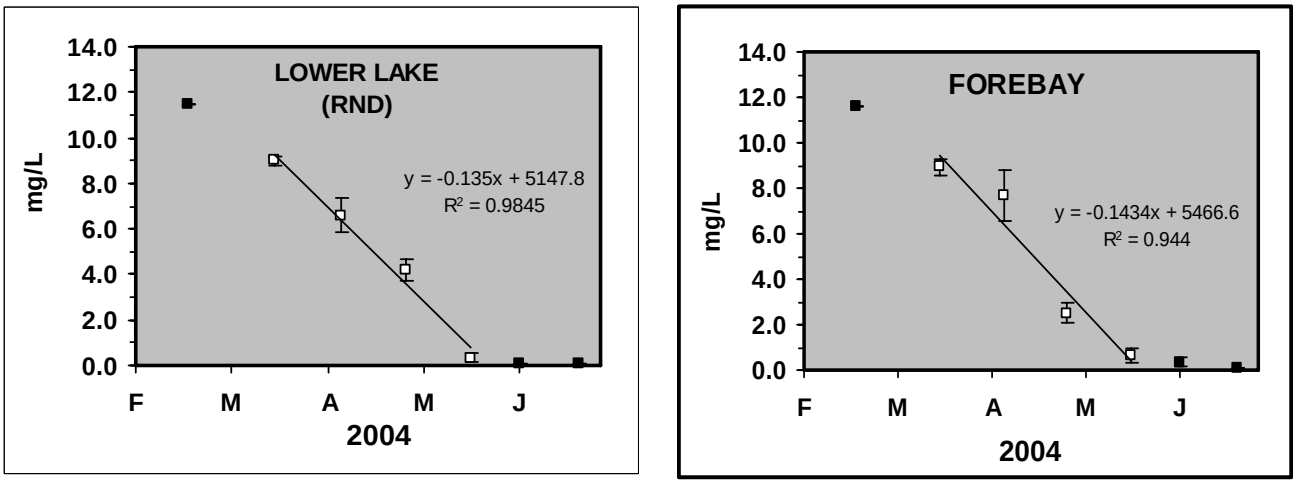

Fig. 10. Average oxygen concentration below 10m, in the Lower Lake and Forebay, Feb-June, 2004. Regression results for Mar-May indicate a linear rate of hypolimnetic oxygen depletion.

FUTURE OBJECTIVES

While, the database collected during 2004 represents a good foundation for initial model development and calibration, we recognize 3 focal points for data collection and model development to enhance the validity and application of this information.

(1) Although Year 1 data collection was initiated in Jan-Feb 2004, a standard, effective methodology for the contracted work on phosphorus and chlorophyll analyses was not finalized until April-May 2004. Preliminary analysis of the data indicates that the April-June period in Lake Greenwood was a very dynamic time, with intense algal blooms (chlorophyll > 40 µg/L) followed by rapid oxygen depletion in the hypolimnion (Fig. 7). Since the ecological interactions that culminate from the spring bloom dynamics may play a key role in subsequent water quality conditions, **we plan to continue monthly sampling through a second annual cycle for 2005.** With a complete data set for 2 annual cycles (2004-2005) we should have adequate information for calibration and validation of the simulation model.

(2) While we conducted detailed vertical profiles of oxygen and temperature in Lake Greenwood during 2004, our phosphorus/chlorophyll sampling included samples only at the surface and bottom waters. This sampling clearly identified the potential effects of phosphorus release from benthic sediments into the bottom waters (see Fig. 5). However, to accurately quantify the effect of benthic phosphorus releases, we need information from more detailed vertical profiles of phosphorus through the water column. **We recommend the extension of such profile sampling in the deeper sections of the lake through the peak of summer stratification and oxygen depletion (July-Sept).** Once we have detailed information on the vertical distribution of phosphorus fractions in the lake, functions of sediment phosphorus release can be more accurately incorporated into the model. This work will be directly related to planned research by Lander University (Deanhart), where laboratory measures of sediment phosphorus release will be conducted using deoxygenated sediment cores from Lake Greenwood.

(3) The model being developed in the current study plan will result in a dynamic simulation of in-lake interactions and water quality patterns in Lake Greenwood in response to the total nutrient loading from the contributing watersheds. While this model will represent a powerful tool in developing management plans for Lake Greenwood, long-term management plans for aquatic resources in the entire basin will require more comprehensive **modeling of lake/watershed interactions**. A modeling effort of this scope would seek to integrate information on land-use changes and resultant nonpoint sources of runoff, with additional information on projected population growth and related changes in wastewater processing and point source discharges. We are evaluating options for coupling the developing lake model (CE-QUAL-W2_ with a state-of-the-art watershed simulation model (WARMF, Watershed Analysis Risk Management Framework). WARMF was developed by Systech Engineering (Chen *et al.* 1995, 1996, 1997) as a physically based, dynamic simulation model which combines information on land use, soils, and meteorology to simulate runoff and nonpoint source loads from a network of catchments. The model further combines these results with information on point source discharges and reservoir release rates to route water through the basin and to simulate water quality dynamics in the streams and lakes. The water quality dynamics within the stream reaches and lake segments are simulated as interactions among sediments, nutrients, oxygen, and

biota; model functions are similar to those established in other EPA-supported modeling packages (Brown and Barnwell 1987, Ambrose, et al. 1993). One advatage of the WARMF model is that Systech has recently modified watershed simulation output files to be compatible with input requirement of the CE-QUALll-W2 lake model that we are now developing for Lake Greenwood. This scope of watershed modeling would address issues of water quality and aquatic resources throughout the entire Saluda River Basin, facilitating coordinated basin management.

These additional objectives will be supported by funds from SCDNR (Buzzards Roost Mitigation Funds) and by continued collaborations supported by the Saluda-Reedy Watershed Consortium (2005-2007). This scope of data collection and model development will be significantly enhanced by collaboration with ongoing analysis of temporal trends in water quality throughout the watershed (Hargett et al), trends in land use and storm water runoff (Jeffrey Allen and Steve Klaine, Clemson University) , wet-weather patterns of point source discharges (Anderson, Furman University), and laboratory evaluations of benthic sediment phosphorus release (Deanhart, Lander University).

ACKNOWLEDGMENTS

This study was supported by the Saluda Reedy Watershed Consortium and by the Buzzard's Roost Fisheries Mitigation Trust Fund administered by Duke Energy, US Fish and Wildlife Service, and SC Dept. Natural Resources. The authors gratefully acknowledge discussions with Gene Hayes (SCDNR) who provided guidance for the initiation of the Lake Greenwood modeling study. Thanks also go to those who provided expertise and assistance with field sampling; Becky Brown, Treye Byars, John Crane, Gene Hayes, Jean Leitner, Jennifer Price, Drew Robb, Ross Self. Michael Zavislak provided both field assistance and laboratory expertise for the certification of the SCDNR lab for chlorophyll analyses.

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APPENDIX A

PHYTOPLANKTON TAXONOMIC COMPOSITION

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HPLC Analysis. Phytoplankton community composition was estimated by High Performance Liquid Chromatographic (HPLC) pigment analysis (Kempton et al. 2002a, Lewitus et al. 2005). A volume of between 60 and 120 mL of whole water from each sample was filtered onto 25 mm GF/F filters and stored frozen until analyses. Filters were extracted in 2-3 mL of acetone, and filtered into an amber vial for HPLC analyses. Extracts were analyzed according to the method of Van Heukelem and Thomas (2001) on an Agilent Technologies (Palo Alto, CA) 1100 series HPLC. Briefly, 150 µL of extract was injected onto a C8, reverse-phase column (Eclipse™; Agilent Technologies). Methanol was the mobile phase, with tetrabutyl ammonium acetate added as an ion-pairing agent. Separate pigments were quantified by absorbance under visible light (450-665 nm), via diode array detector (Agilent Technologies), and identified by comparison with pure standards.

This method determines the concentration of 18 pigments of known chemotaxonomic importance to algal identification, Table 1 (Van Heukelem and Thomas, 2001). Data is presented on nine of these that are relatively less ambiguous with respect to taxonomic relevance. The marker pigments included fucoxanthin, peridinin, alloxanthin, 19'-hexanoyloxyfucoxanthin (19'-hex), chlorophyll c_3, chlorophyll *b*, zeaxanthin, canthaxanthin, and prasinoxanthin. Fucoxanthin is widely used as a marker for diatoms, a group in which it is universally present in high relative amounts. However, it is also found in some species of chrysophytes and prymnesiophytes (aka haptophytes), as well as a subset of dinoflagellates. Therefore, caution is warranted in extrapolating fucoxanthin values to diatom biomass. Peridinin is found in some species of dinoflagellates but no other phytoplankton. Therefore it is a specific marker for a subset of dinoflagellates. Alloxanthin is a specific marker for cryptophytes. 19'-hex is generally used as an indicator of some haptophytes, but also can occur in some dinoflagellates. Chlorophyll c_3 is a normally uncommon pigment that is associated with some dinoflagellates and haptophytes. Chlorophyll *b* is generally associated with green algae. Zeaxanthin has been used as a marker pigment for cyanobacteria (blue-green algae) but is also found in chlorophytes, prasinophytes, raphidophytes, and euglenophytes. Canthaxanthin can be found in some cyanobacteria and prasinoxanthin in some prasinophytes.

A formula was used to estimate the relative contribution of cyanobacteria vs. green algae to the zeaxanthin signal in HPLC profiles. While analyzing the pigment ratios of several species used in calibrating a pigment modeling program, CHEMTAX, Lewitus et al. (2005) found that the ratio of µg L^{-1} chlorophyll *b* to µg L^{-1} zeaxanthin in *Chlorella* sp.(a coccoid chlorophyte) and *Ankistrodesmus* sp. (a benthic conjugatophyte) was 23 (mean of all treatments). Based on this limited data set, the contribution of green algae to zeaxanthin concentrations should be chlorophyll *b* concentration divided by 23. Subtracting this number from zeaxanthin

concentration should give a qualitative index of the relative contribution of cyanobacteria to zeaxanthin concentration:

$\mu g\ L^{-1}$ Zeaxanthin – ($\mu g\ L^{-1}$ chlorophyll *b*/23)

By this reasoning, the contribution of cyanobacteria and green algae to zeaxanthin should be roughly equivalent when this index is 1. Values above 1 would correspond to greater relative contributions of cyanobacteria.

Microscopic Screening**.** Samples were received in 100 mL volumes fixed in 3% Lugol's solution. The samples were agitated gently to re-suspend settled cells, and 2 mL was placed in a Labtek ® chambered cover glass. Each sample was settled for at least 10 min and examined on a Nikon TE-2000 inverted microscope at 10X, 20X, and 40X objective magnification with both bright field and Differential Interference Contrast. Each sample was examined in a raster pattern in order to adequately cover the entire sample area. Algal species were identified to the highest taxonomic level possible given the limitations of Lugol's fixation. Therefore, it should be noted that the number of genera identified is certainly an underestimate the total number present.

RESULTS

Pigment Analysis. Figs. A1-A7 show three aspects of the HPLC pigment analyses for each sampling site. The top panel in each graph provides the marker pigment concentrations normalized to chlorophyll *a* concentration and therefore represents the relative contribution of marker pigment biomass to overall community biomass. The middle panel provides the absolute concentration (in $\mu g\ L^{-1}$) of each marker pigment, and the bottom panel, presents the zeaxanthin index, that shows qualitative estimates of the relative contribution of cyanobacteria (above an index value of 1) and green algae (below 1).

At most sample sites, cyanobacteria dominated the July 2004 phytoplankton communities, and a peak in cyanobacteria biomass occurred on 12 August 2004. A relatively high contribution of cyanobacteria over this period was indicated by a high proportion of zeaxanthin among accessory pigments, and a zeaxanthin index > 1 in all cases but at site FBY in July 2004.

Cyanobacteria did not appear to be important contributors to overall phytoplankton community biomass for the rest of the experimental period, which instead was dominated by taxa containing fucoxanthin (e.g. diatoms and other chromophytes) and alloxanthin (cryptophytes). Cryptophytes were an important contributor to phytoplankton biomass on 28 October 2004, and made up > 50% of accessory pigment biomass in the Lower Saluda Arm (SBR), Mid-Lake (Hwy 72), Lower Lake (RND), and the Forebay (FBY). Peridinin, an indicator of a subset of dinoflagellates, was rare except for relatively high contributions to community composition in the Forebay (FBY) on 9 July and 22 July 2004.

Microscopic Screening. In addition to cyanobacteria, the following algal groups were identified: xanthophytes (rare), haptophytes (rare), euglenophytes, dinoflagellates, diatoms, cryptophytes, chlorophytes, and raphidophytes. Chlorophytes and cryptophytes were the most diverse groups, with respect to numbers of genera. The dominant taxa in all sites were cryptophytes, including nearly monogeneric blooms of *Cryptomonas* in November of 2004, and March and April of 2005. Other dominant classes were chlorophytes, notably the genera of *Chloroella*, *Scendesmus* and *Staurastrum*. Some genera of known toxin-producing species were identified, including *Microcystis*, *Anabaena*, *Nitzchia*, *Aphanizamenon*, and *Anabaeneopsis*. However, all these genera were sparsely represented in samples.

The relative distribution of taxonomic classes is shown as a percentage of total genera at each station in Figs A8-A10. In the upper tributary arms of Lake Greenwood, the Upper Reedy showed a total of 126 genera over the 7 sampling dates (Fig. A8, upper panel). This site showed dynamic changes in diversity, with the summer dominance of chlorophytes dropping sharply in September 2004 and March 2005. Chrysophytes, represented by the genera *Chromulina*, *Dinobryon*, *Epipyxis*, and *Mallomonas* were present only in October 2004 and April 2005.

In the Upper Saluda Arm (Fig A8, middle panel), a total of 57 genera were identified, giving this site the least-diverse algal assemblage. Diatoms, though not always dominant, were better-represented throughout the year. December of 2004 was completely dominated by a single diatom genus, *Synedra*. The April 2005 sampling date showed that diversity among groups was returning, with a near-equal representation of Chlorophytes, diatoms, cryptophytes and haptophytes. In the Lower Saluda Arm (Fig A8, lower panel) a total of 91 genera were identified. A notable decrease in assemblage diversity occurred from July-September 2004 (chlorophytes, cyanobacteria, diatoms, and cryptophytes, in descending order of dominance) to one in which Chlorophytes made up >60% of genera in December 2004. Euglenophytes emerged as a dominant group in March and April of 2005.

Further downstream, a total of 129 genera were identified at the Mid-Lake station (HW72, Fig A9). Chlorophytes were the dominant genera, except for December 2004, when Diatoms and Cryptophytes made up 75% and 25% of genera, respectively. Raphidophytes were noted in October and November of 2004, yet absent in other months. In the mid-lake embayment (HDN), a total of 164 genera were identified, making this site the most diverse assemblage (Fig. A9, lower panel). Chlorophytes and cryptophytes dominated in nearly every month, except for April 2005. The percent of euglenophyte genera increased from July 2004 to April 2005. Cyanobacteria were co-dominants during late summer but were reduced in the fall and were entirely absent by December 2004.

In the most downstream sections of the lake, a total of 145 genera were identified at the Lower Lake station (Fig. A10 upper panel), with chlorophytes clearly dominating. Cyanobacterial genera were well-represented in this site, with the greatest diversity found in August 2004 (8 genera, including *Anabaena* and *Microcystis*). The raphidophytes *Gonyostomum* and *Vacuolaria* were present from October to December 2004. In the Forebay (Fig A10, lower panel), a total of 133 genera were identified. Chlorophytes were the most diverse group of genera in nearly all months, followed by cryptophytes, diatoms and cyanobacteria. The most diverse assemblage of genera was noted in September, 2004, and the fewest number of genera were found in March 2005. Two rare xanthophyte genera, *Pseudostaurastrum* and *Goniochloris* were found in September and October of 2004.

Table 1. Photopigments used for phytoplankton community analyses and their corresponding taxa.

Photopigment	Associated Taxa
Chlorophyll *a*	All algae
Chlorophyll *b*	Chlorophytes, euglenophytes, prasinophytes
Chlorophyll c_1	some chrysophytes, diatoms, dinoflagellates, haptophytes
Chlorophyll c_2	Chrysophytes, cryptophytes, diatoms, dinoflagellates, haptophytes
Chlorophyll c_3	Some dinoflagellates, some haptophytes
Fucoxanthin	Chrysophytes, diatoms, some dinoflagellates, haptophytes
Prasinoxanthin	some prasinophytes
Violaxanthin	Chlorophytes, prasinophytes
Zeaxanthin	Chlorophytes, cyanobacteria, euglenophytes, some prasinophytes
Neoxanthin	Chlorophytes, euglenophytes
Diatoxanthin	Chrysophytes, diatoms, dinoflagellates, euglenophytes, haptophytes
Diadinoxanthin	Chrysophytes, diatoms, dinoflagellates, euglenophytes, haptophytes
Alloxanthin	Cryptophytes
Peridinin	some dinoflagellates
19'-	some chrysophytes, some dinoflagellates, some haptophytes
19'-	some dinoflagellates, some haptophytes
Lutein	Chlorophytes, euglenophytes, some prasinophytes
Canthaxanthin	Some cyanobacteria
Carotenes	Most photosynthetic algae

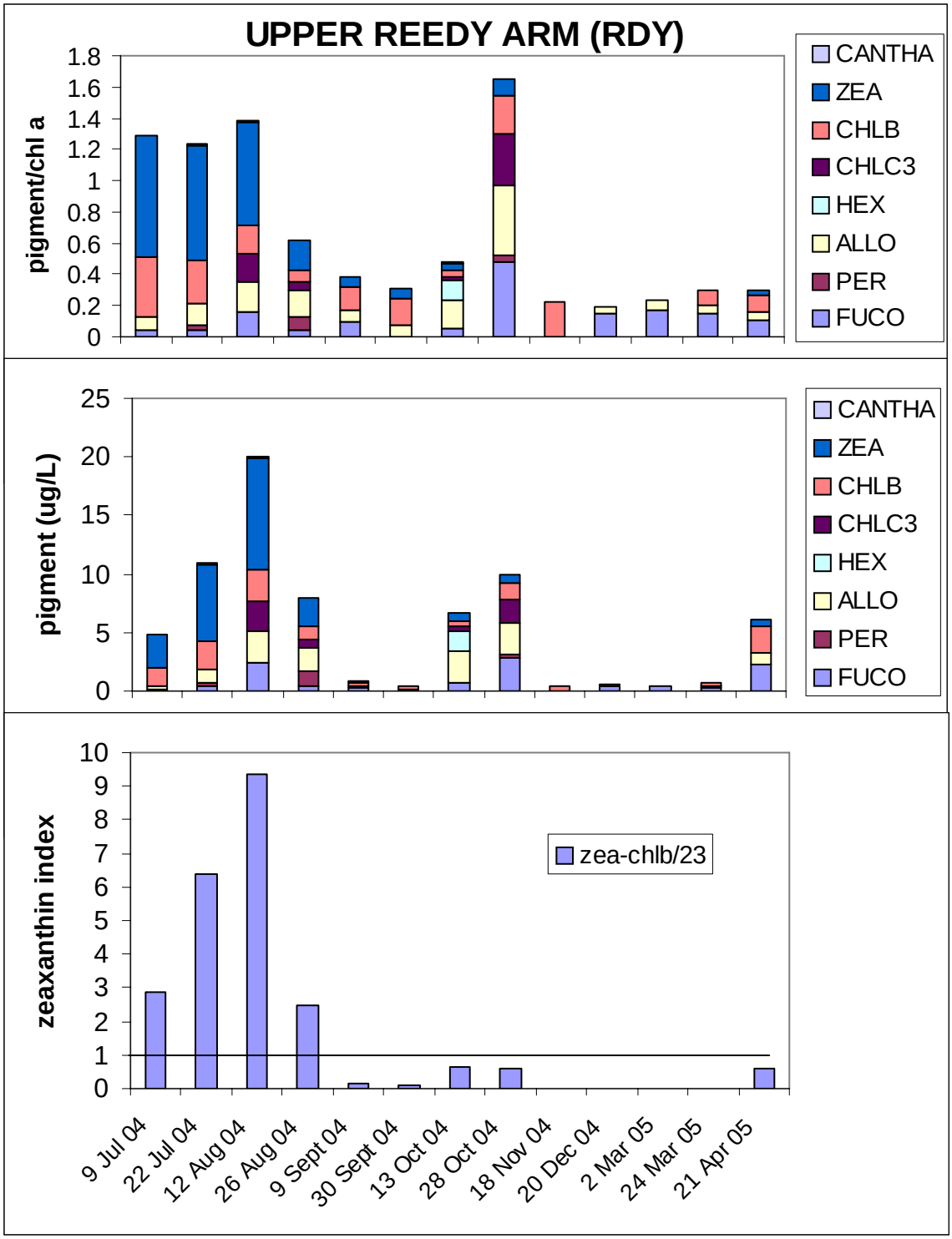

Fig. A1. HPLC pigment ratios to chlorophyll a (upper panel), pigment concentrations (middle panel) and zeaxanthin index (lower panel) for the Upper Reedy Arm (July 2004-Apr 2005). The index shows qualitative estimates of the relative contribution of cyanobacteria (values > 1) and green algae (values < 1).

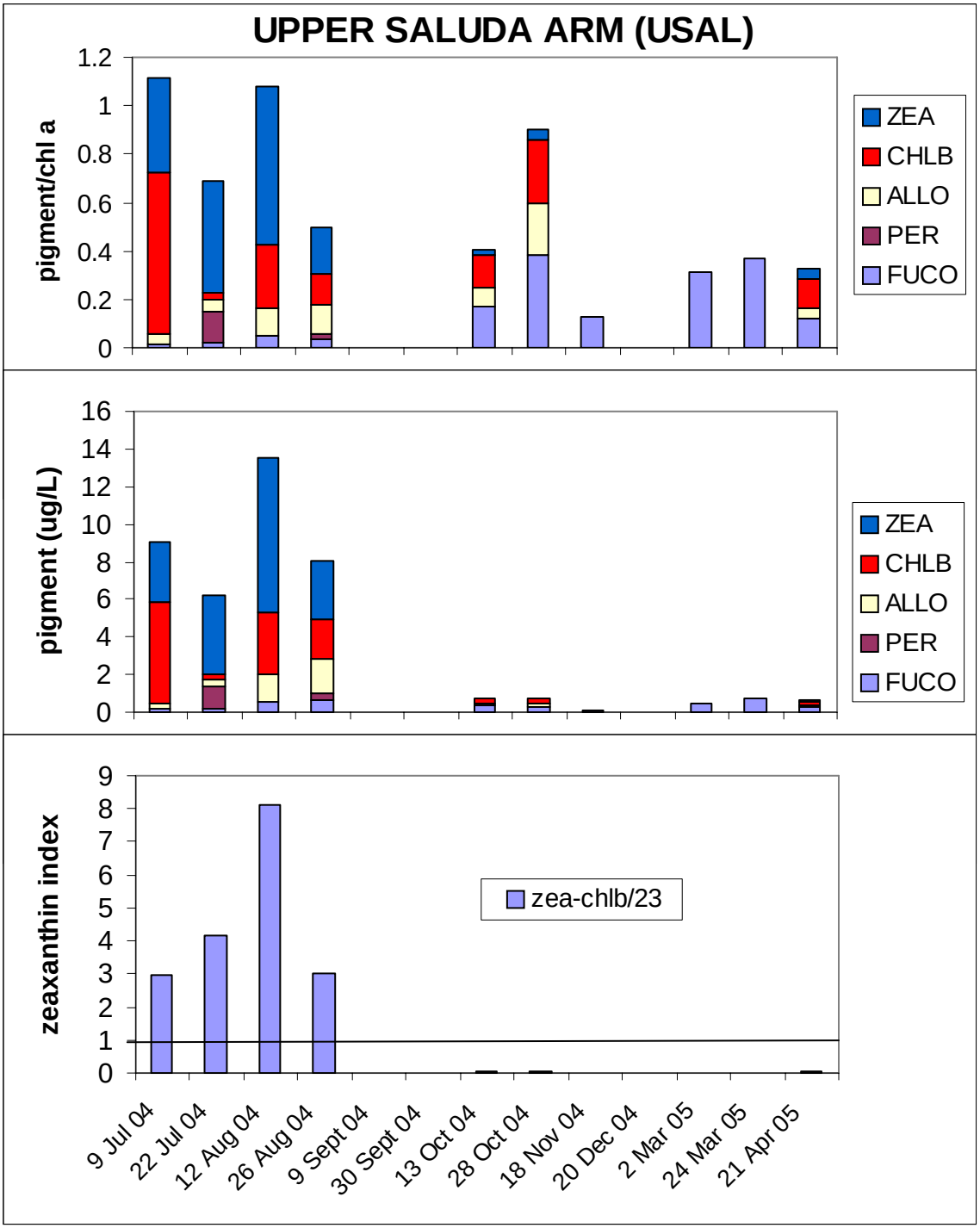

Fig. A2. HPLC pigment ratios to chlorophyll a (upper panel), pigment concentrations (middle panel) and zeaxanthin index (lower panel) for the Upper Saluda Arm (USAL); (July 2004-Apr 2005). The index shows qualitative estimates of the relative contribution of cyanobacteria (values > 1) and green algae (values < 1).

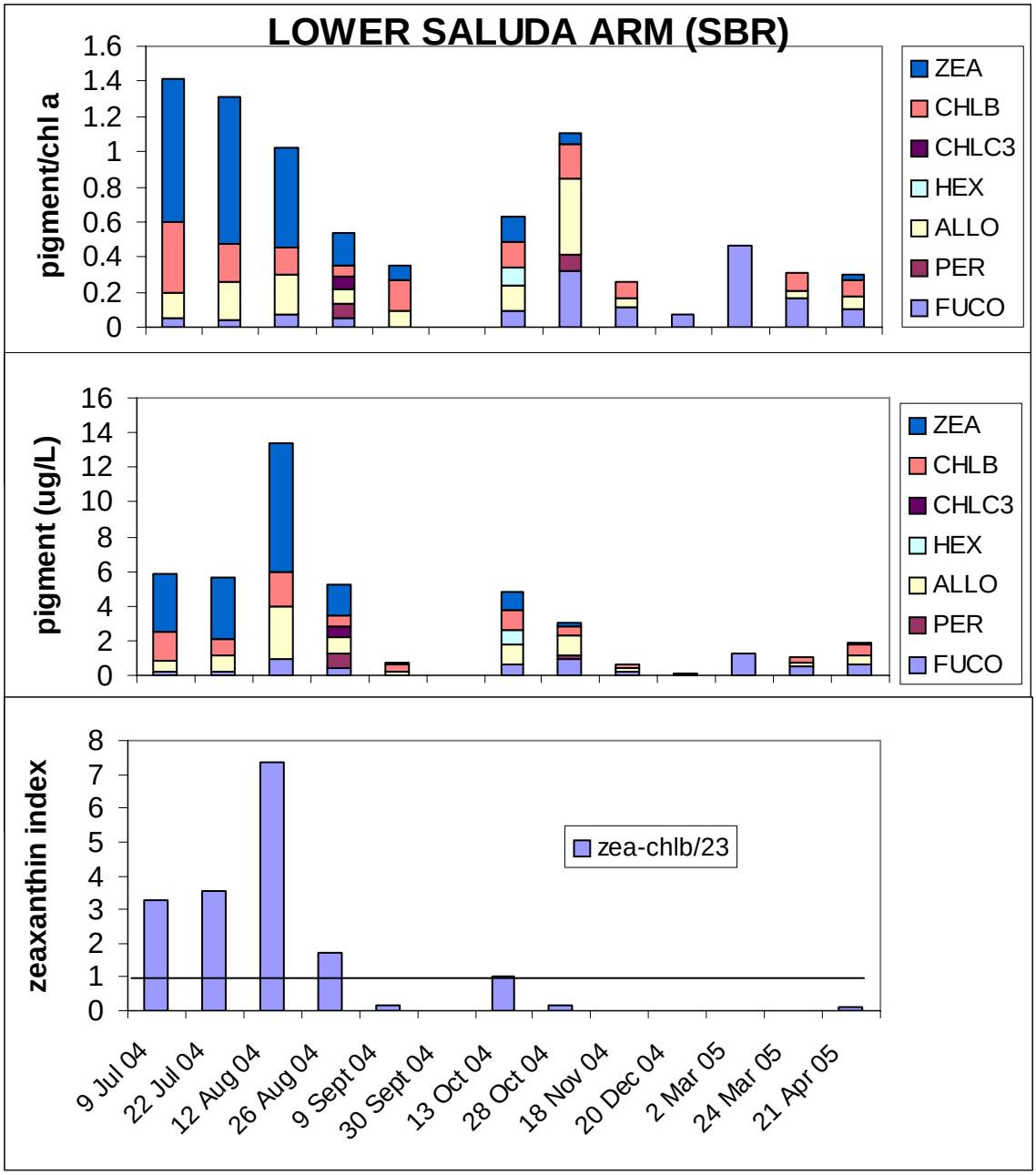

Fig. A3. HPLC pigment ratios to chlorophyll a (upper panel), pigment concentrations (middle panel) and zeaxanthin index (lower panel) for the Lower Saluda Arm (SBR)(July 2004-Apr 2005). The index shows qualitative estimates of the relative contribution of cyanobacteria (values > 1) and green algae (values < 1).

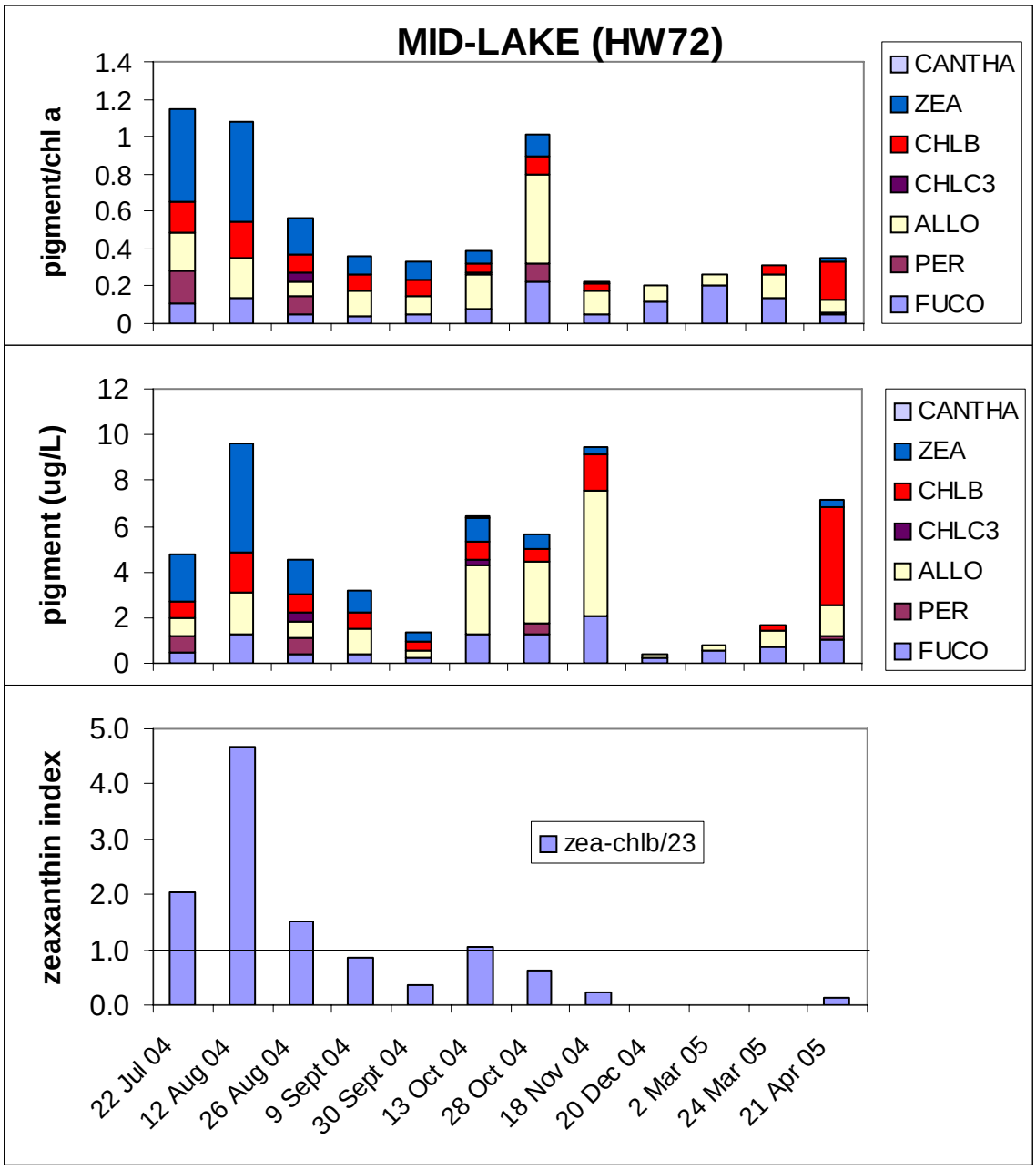

Fig. A4. HPLC pigment ratios to chlorophyll a (upper panel), pigment concentrations (middle panel) and zeaxanthin index (lower panel) for the Mid-Lake station (HW72) (July 2004-Apr 2005). The index shows qualitative estimates of the relative contribution of cyanobacteria (values > 1) and green algae (values < 1).

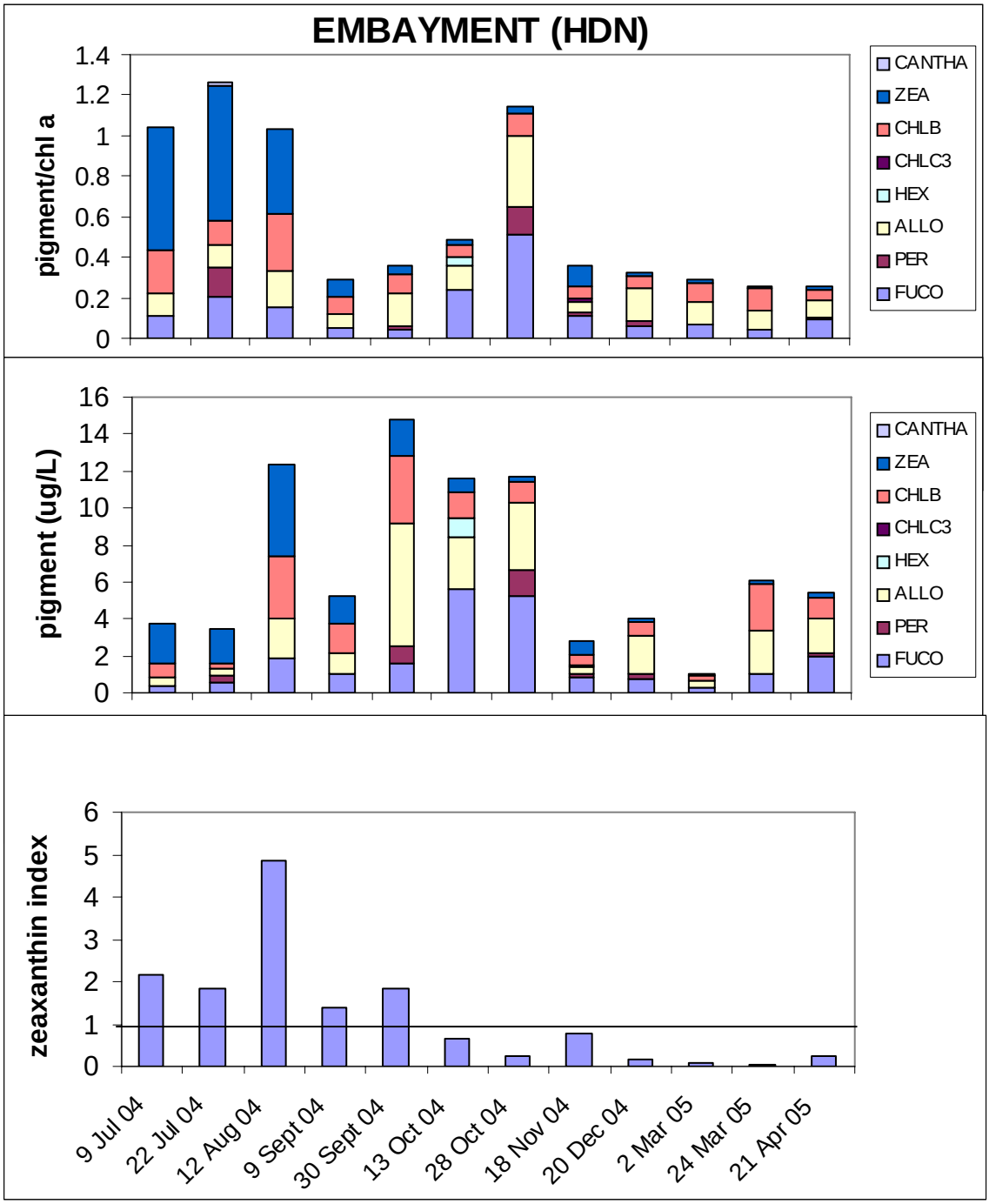

Fig. A5. HPLC pigment ratios to chlorophyll a (upper panel), pigment concentrations (middle panel) and zeaxanthin index (lower panel) for the Mid-Lake Embayment station on Cane Creek (HDN) (July 2004-Apr 2005). The index shows qualitative estimates of the relative contribution of cyanobacteria (values > 1) and green algae (values < 1).

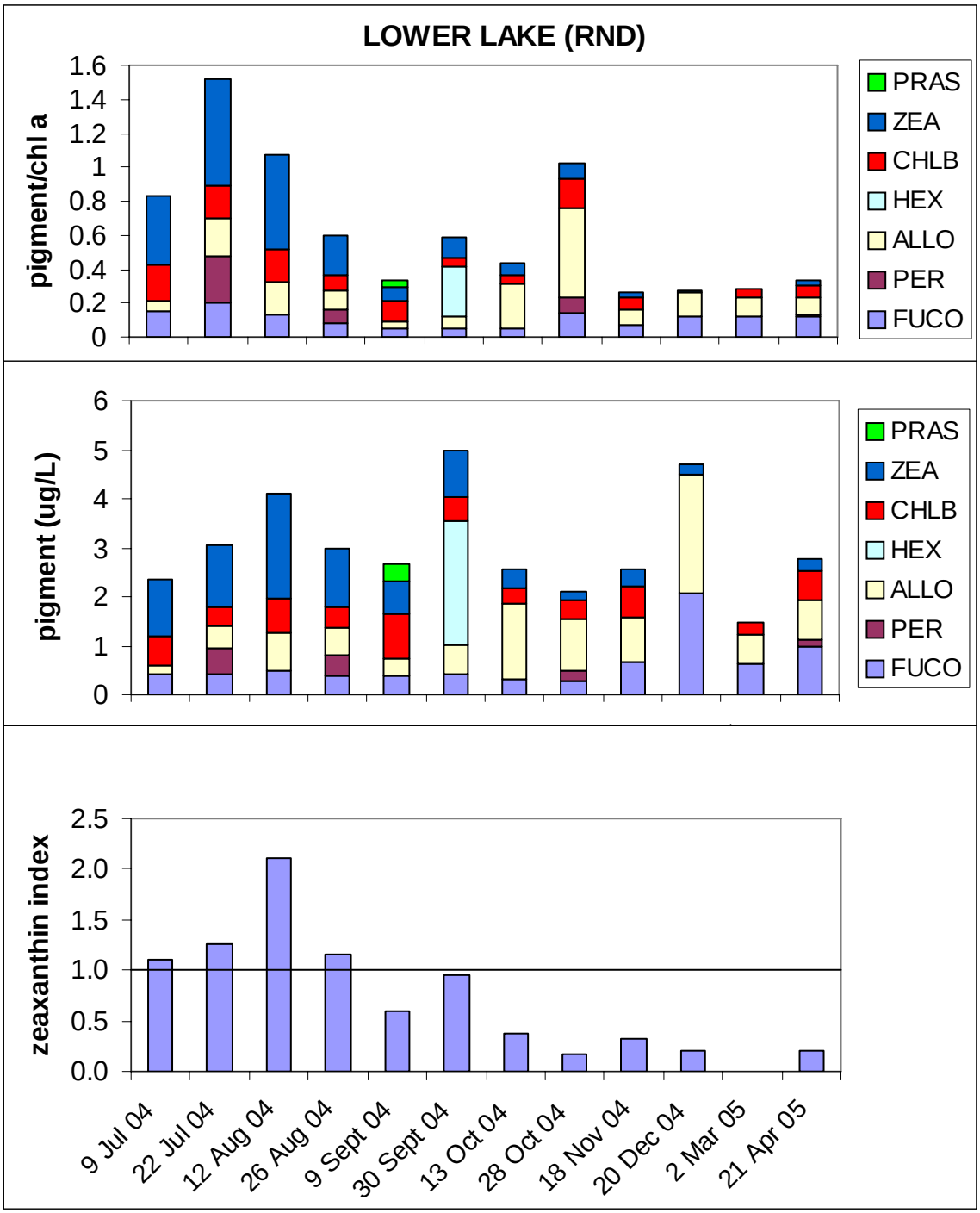

Fig. A6. HPLC pigment ratios to chlorophyll a (upper panel), pigment concentrations (middle panel) and zeaxanthin index (lower panel) for the Lower Lake station (RND) (July 2004-Apr 2005). The index shows qualitative estimates of the relative contribution of cyanobacteria (values > 1) and green algae (values < 1).

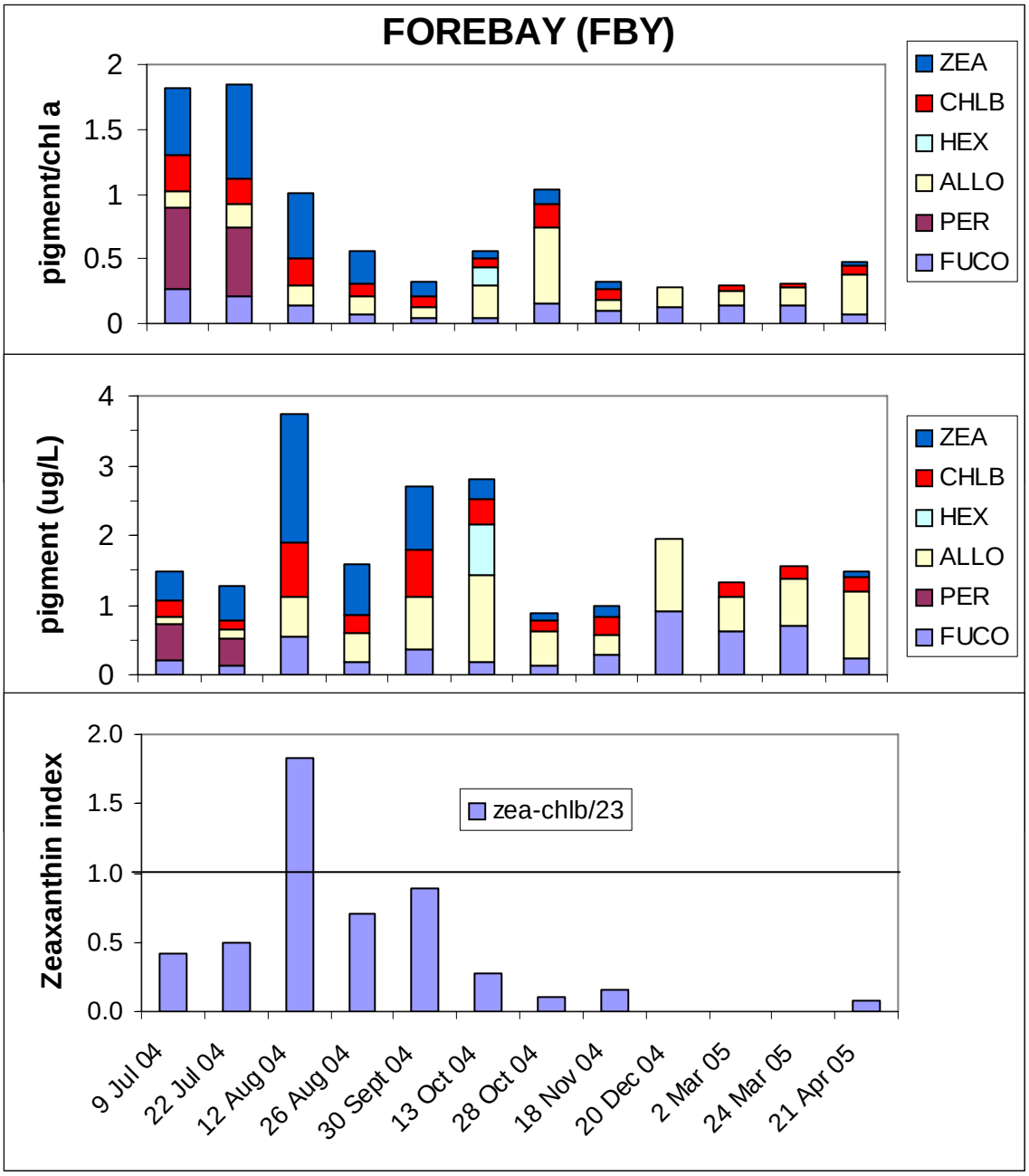

Fig. A7. HPLC pigment ratios to chlorophyll a (upper panel), pigment concentrations (middle panel) and zeaxanthin index (lower panel) for the Forebay (FBY) (July 2004-Apr 2005). The index shows qualitative estimates of the relative contribution of cyanobacteria (values > 1) and green algae (values < 1).

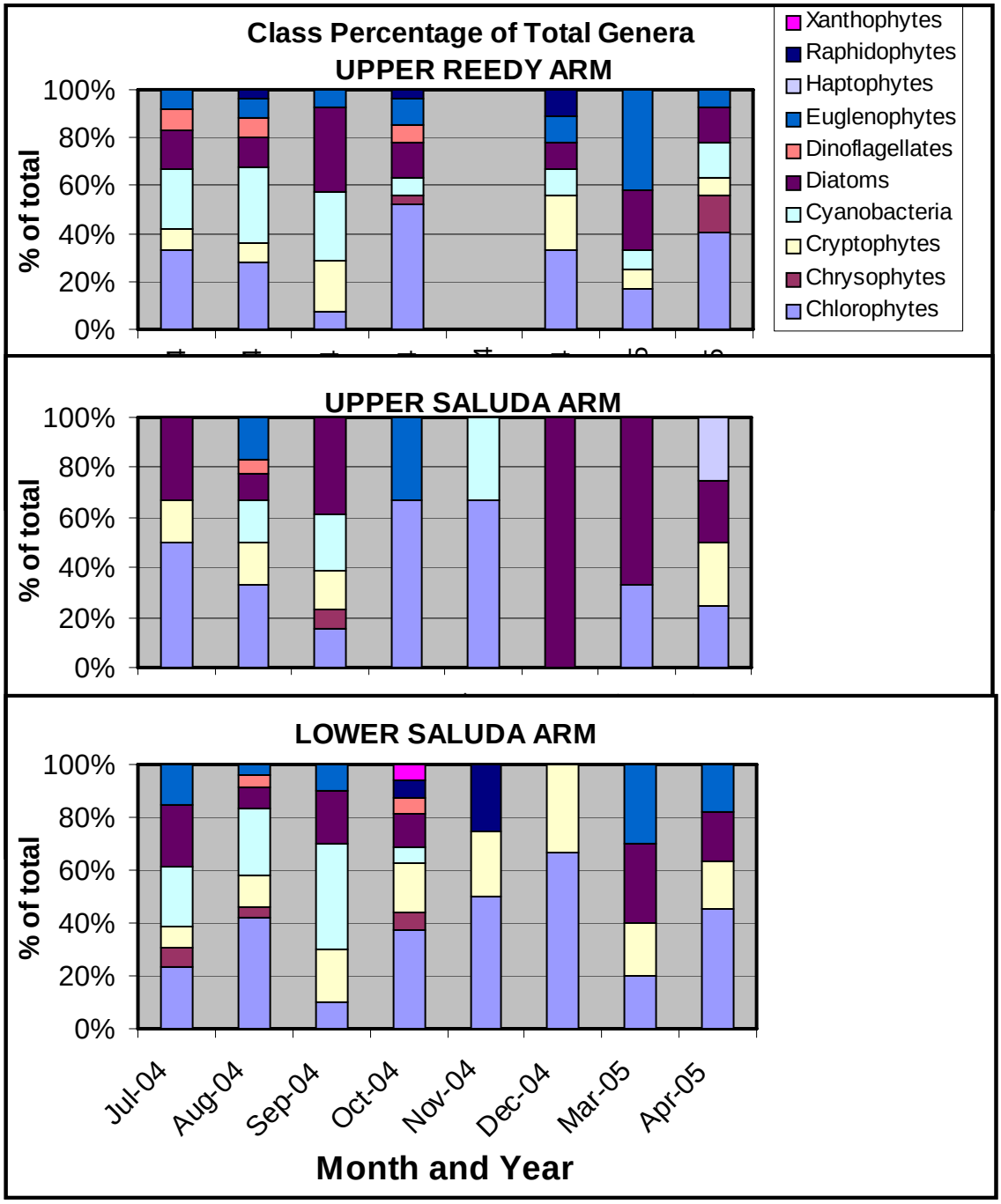

Fig. A8. Percentage of total genera represented by each taxonomic group in the upper arms of Lake Greenwood (July 2004-Apr 2005)

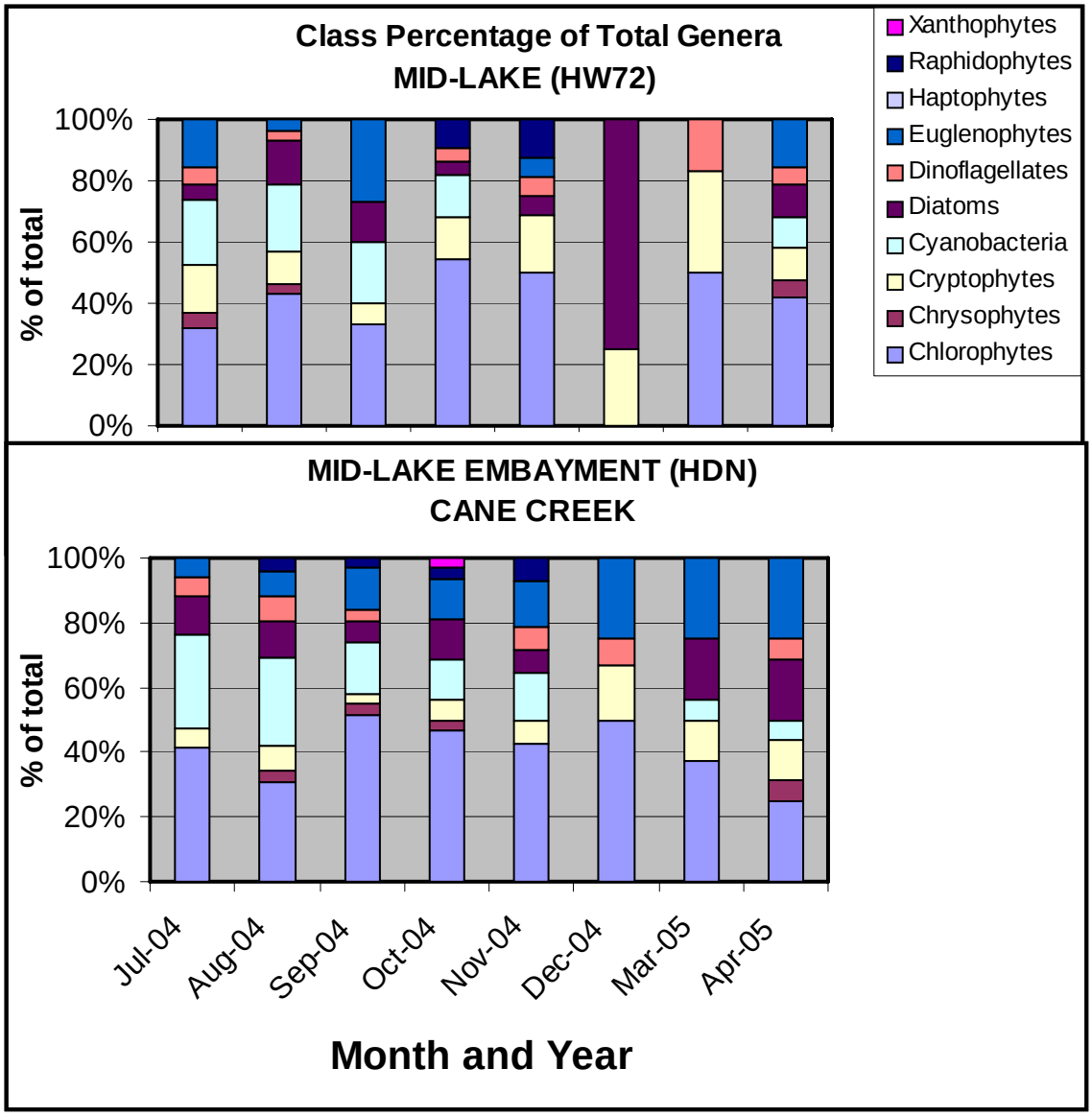

Fig. A9. Percentage of total genera represented by each taxonomic group at the Mid-Lake station (HW72) and the mid-lake embayment (HDN) of Lake Greenwood (July 2004-Apr 2005)

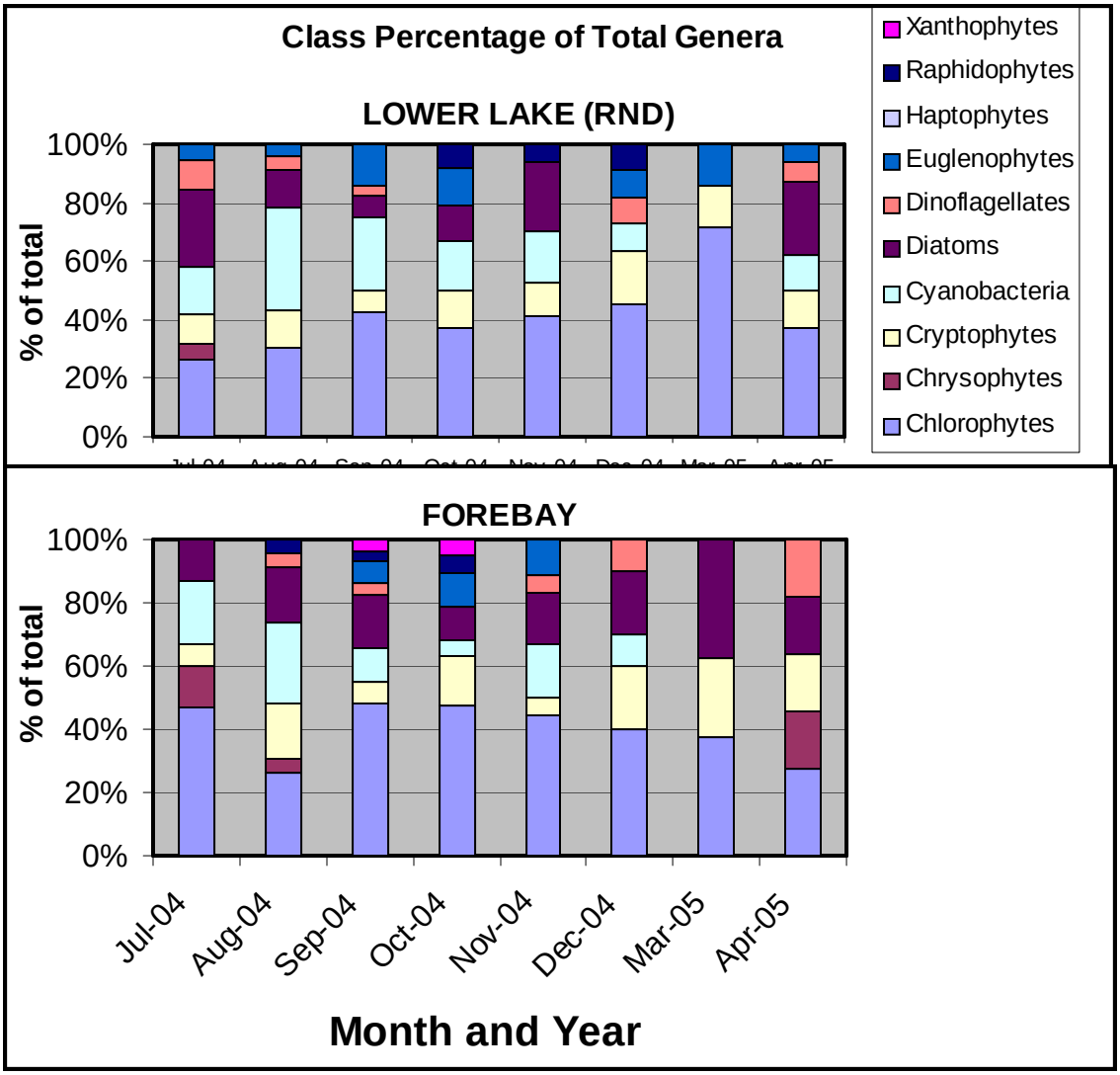

Fig. A10. Percentage of total genera represented by each taxonomic group at the Lower Lake station (RND) and the Forebay (FBY) of Lake Greenwood (July 2004-Apr 2005)

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